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PE | Mechanical

Reference Handbook
Version 2.1

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Second post June 2026
Version 2.1

INTRODUCTION

About the Handbook

The Principles and Practice of Engineering (PE) Mechanical exam is computer based, and the *PE Mechanical Reference Handbook* is the only resource material you may use during the exam. Reviewing it before exam day will help you become familiar with the charts, formulas, tables, and other reference information provided. You will not be allowed to bring your personal copy of the *PE Mechanical Reference Handbook* into the exam room. Instead, the computer-based exam will include a PDF version of the handbook for your use. No printed copies of the handbook will be allowed in the exam room.

The PDF version of the *PE Mechanical Reference Handbook* that you use on exam day will be very similar to this one. However, pages not needed to solve exam questions—such as the cover and introductory material—will not be included in the exam version. In addition, NCEES will periodically revise and update the handbook, and each PE Mechanical exam will be administered using the version of the handbook in effect on the date the exam is given.

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1 BASIC ENGINEERING PRACTICE

1.1 Engineering Terms and Symbols

Measurement Relationships

Multiply	by	to Obtain
acre	43,560	square feet (ft^2)
ampere-hr (A-hr)	3,600	coulomb (C)
ångström (Å)	1×10^{-10}	meter (m)
atmosphere (atm)	76.0	cm, mercury (Hg)
atm, standard	29.92	in., mercury (Hg)
atm, std	14.70	lbf/in^2 abs (psia)
atm, std	33.90	ft, water
atm, std	1.013×10^5	pascal (Pa)
bar	1×10^5	pascal (Pa)
bar	0.987	atm
barrel–oil	42	gallon–oil
Btu	1,055	joule (J)
Btu	2.928×10^{-4}	kilowatt-hr (kWh)
Btu	778	ft-lbf
Btu/hr	3.930×10^{-4}	horsepower (hp)
Btu/hr	0.293	watt (W)
Btu/hr	0.216	ft-lbf/sec
calorie (gram calorie, cal)	3.968×10^{-3}	Btu
cal	1.560×10^{-6}	hp-hr
cal	4.186	joule (J)
cal/sec	4.184	watt (W)
cal	1.163×10^{-3}	watt-hr (Wh)
centimeter (cm)	3.281×10^{-2}	foot (ft)
cm	0.394	inch (in.)
centipoise (cP)	0.001	pascal•sec (Pa•s)
cP	1	g/(m•s)
cP	2.419	lbm/hr-ft
cP	1.0197×10^{-4}	$kgf•s/m^2$
cP	2.0885×10^{-5}	$lbf\text{-}sec/ft^2$
centistoke (cSt)	1×10^{-6}	m^2/sec (m^2/s)
cubic feet/sec (cfs)	0.646317	million gal/day (MGD)
cubic foot (ft^3)	7.481	gallon
cubic meter (m^3)	1,000	liter
electronvolt (eV)	1.602×10^{-19}	joule (J)
foot (ft)	30.48	centimeter (cm)
ft	0.3048	meter (m)
ft	304.8	millimeter (mm)
ft^2	0.0929	m^2
ft^3	7.48	gallon
ft-pound (ft-lbf)	1.285×10^{-3}	Btu
ft-lbf	3.766×10^{-7}	kilowatt-hr (kWh)
ft-lbf	0.324	calorie (g-cal)
ft-lbf	1.356	joule (J)
ft-lbf/sec	1.818×10^{-3}	horsepower (hp)
ft/sec	304.8	mm/s

Multiply	by	to Obtain
gallon (U.S. Liq)	3.785	liter (L)
gal (U.S. Liq)	0.134	ft^3
gal (U.S. Liq)	231	in^3
gal of water	8.34	pound of water
gamma (γ, Γ)	1×10^{-9}	tesla (T)
gauss	1×10^{-4}	T
gpm	0.0022	ft^3/sec
gpm	0.0631	L/S
gram (g)	2.205×10^{-3}	pound (lbm)
hectare	1×10^4	square meter (m^2)
hectare	2.47104	acre
horsepower (hp)	42.4	Btu/min
hp	745.7	watt (W)
hp	33,000	(ft-lbf)/min
hp	550	(ft-lbf)/sec
horsepower (boiler)	33,470	Btu/hr
horsepower (boiler)	9.81	kW
hp-hr	2,545	Btu
hp-hr	1.98×10^6	ft-lbf
hp-hr	2.68×10^6	joule (J)
hp-hr	0.746	kWh
inch (in.)	2.540	centimeter (cm)
in. of Hg	0.0334	atm
in. of Hg	13.60	in. of H_2O
in. of H_2O	0.0361	lbf/in^2 (psi)
in. of H_2O	0.002458	atm
in.-lbf (torque or moment)	113	mN•m
joule (J)	9.478×10^{-4}	Btu
J	0.7376	ft-lbf
J	1	newton•m (N•m)
J/s	1	watt (W)
kilogram (kg)	2.205	pound (lbm)
kgf	9.8066	newton (N)
kilometer (km)	3,281	feet (ft)
km/hr	0.621	mph
kilopascal (kPa)	0.145	lbf/in^2 (psi)
kilowatt (kW)	1.341	horsepower (hp)
kW	3,413	Btu/hr
kW	737.6	(ft-lbf)/sec
kW-hour (kWh)	3,413	Btu
kWh	1.341	hp-hr
kWh	3.6×10^6	joule (J)
kip (K)	1,000	lbf
K	4,448	newton (N)

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Measurement Relationships (cont'd)

Multiply	by	to Obtain
liter (L)	61.02	in^3
L	0.264	gal (U.S. Liq)
L	10^{-3}	m^3
L/sec (L/s)	2.119	ft^3/min (cfm)
L/s	15.85	gal (U.S.)/min (gpm)
meter (m)	3.281	foot (ft)
m	1.094	yard (yd)
m/sec (m/s)	196.8	foot/min (ft/min)
mile (statute)	5,280	ft
mile (statute)	1.609	kilometer (km)
mile/hr (mph)	88.0	ft/min (fpm)
MPa	145.03800	lb/in^2
mph	1.609	km/hr
mm of Hg	1.316×10^{-3}	atm
mm of H_2O	9.678×10^{-5}	atm
mm/s	0.0033	ft/sec
newton (N)	0.225	lbf
N	1	$kg•m/s^2$
N•m	0.7376	ft-lbf
N•m	1	joule (J)
pascal (Pa)	9.869×10^{-6}	atmosphere (atm)
Pa	1	newton/m^2 (N/m^2)
Pa•sec (Pa•s)	10	poise (P)
pound (lbm, avdp)	0.454	kilogram (kg)
lbf	4.448	N
lbf-ft	1.356	N•m
lbf/in^2 (psi)	0.068	atm
psi	2.307	ft of H_2O
psi	2.036	in. of Hg
psi	6,895	Pa

Multiply	by	to Obtain
radian	$180/\pi$	degree
reyn	1	$lb\text{-}sec/in^2$
reyn	6830	Pa•s
slug	32.2	lbm
stokes	1×10^{-4}	m^2/s
therm	1×10^5	Btu
ton (metric)	1,000	kilogram (kg)
ton (short)	2,000	pound (lb)
ton (refrigeration)	12,000	Btu/hr
watt (W)	3.412	Btu/hr
W	1.341×10^{-3}	horsepower (hp)
W	1	joule/s (J/s)
watt-hr (Wh)	859.85	cal
weber/m^2 (Wb/m^2)	10,000	gauss

1.1.1 Units

This handbook uses the International Systems of Units (SI) (metric) and the U.S. Customary System (imperial unit (IP) or inch-pound (I-P)). In the IP system of units, both force and mass are called pounds. Therefore, one must distinguish the pound-force (lbf) from the pound-mass (lbm).

$$1 \text{ lbf} = 32.174 \frac{\text{lbm-ft}}{\text{sec}^2}$$

$$F = \frac{ma}{g_c}$$

where

F is in lbf

m is in lbm

a is in $\frac{\text{ft}}{\text{sec}^2}$

Kinetic Energy: $KE = \frac{mv^2}{2g_c}$ with KE in ft-lbf

Potential Energy: $PE = \frac{mgh}{g_c}$ with PE in ft-lbf

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Fluid Pressure: $p = \frac{\rho g h}{g_c}$ with p in $\frac{\text{lbf}}{\text{ft}^2}$

Specific Weight: $SW = \frac{\rho g}{g_c}$ with SW in $\frac{\text{lbf}}{\text{ft}^3}$

Shear Stress: $\tau = \left(\frac{\mu}{g_c}\right)\left(\frac{dv}{dy}\right)$ with τ in $\frac{\text{lbf}}{\text{ft}^2}$

Metric Prefixes

Multiple	Prefix	Symbol
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{1}	deka	da
10^{2}	hecto	h
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T

Commonly Used Equivalents

1 gallon of water	=	8.34 lbm
1 cu ft of water	=	62.4 lbm = 7.48 gal
1 cu ft of mercury	=	844.9 lbm
mass of 1 cu m of water	=	1,000 kg
$1\ \frac{\text{mg}}{\text{L}}$	=	$8.34\ \frac{\text{lbm}}{\text{Mgal}} = \frac{8.34\ \text{lbm}}{10^6\ \text{gal}}$
1 cfs of water	=	448.83 gpm
1 in of mercury	=	0.491 psi
1 in of mercury	=	70.7 psf
1 in of water	=	5.199 psf
1 in of water	=	0.0735 in. of mercury (Hg)
1 psi	=	27.7 in. of water (H_2O)
1 ft	=	0.4331 psi × SG
1 psi	=	2.31 ft/SG
1 knot	=	1.151 statute miles per hour

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Temperature Conversions

$$°F = 1.8\,(°C) + 32$$
$$°C = (°F - 32)/1.8$$
$$°R = °F + 459.69$$
$$K = °C + 273.15$$

Standard Dry Air Conditions at Sea Level

$$\text{Density} = \frac{0.075 \text{ lb dry air}}{\text{ft}^3}$$
$$\text{Specific Volume} = \frac{13.35 \text{ ft}^3}{\text{lb dry air}}$$
$$\text{Temperature} = 69°F$$
$$\text{Pressure} = 14.696 \text{ psi (1 atm)}$$

Fundamental Constants

Constant	Symbol	SI	I-P (USCS)
Electron charge	e	1.6022×10^{-19} C	
Faraday constant	F	$96{,}485 \frac{\text{C}}{\text{mol}}$	
Standard gravity acceleration	g	$9.807 \frac{\text{m}}{\text{s}^2}$	$32.174 \frac{\text{ft}}{\text{sec}^2}$
Gravitational constant	g_c	$6.6743 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \cdot \text{s}^2}$	$32.174 \frac{\text{lbm-ft}}{\text{lbf-sec}^2}$
Molar volume of ideal gas (STP)	V_m	$22{,}414 \frac{\text{L}}{\text{kmol}}$	$359 \frac{\text{ft}^3}{\text{lb mole}}$
Speed of light in vacuum	c	$2.99792 \times 10^8 \frac{\text{m}}{\text{s}}$	$186{,}000 \frac{\text{miles}}{\text{sec}}$
Stefan-Boltzmann constant	σ	$5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$	$0.1713 \times 10^{-8} \frac{\text{Btu}}{\text{ft}^2\text{-hr-}°\text{R}^4}$
Specific gas constants			
Universal gas constant (ideal gas)	$\overline{R}$	$0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}$ $8{,}314 \frac{\text{J}}{\text{kmol} \cdot \text{K}}$ $8.314 \frac{\text{kPa} \cdot \text{m}^3}{\text{kmol} \cdot \text{K}}$	$1{,}545 \frac{\text{ft-lbf}}{\text{lb mole-°R}}$
Air	R_{air}	$0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$	$53.3 \frac{\text{ft-lbf}}{\text{lbm-°R}}$
Hydrogen	R_{H_2}	$4.12 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$	$766.8 \frac{\text{ft-lbf}}{\text{lbm-°R}}$
Carbon dioxide	R_{CO_2}	$0.189 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$	$35.1 \frac{\text{ft-lbf}}{\text{lbm-°R}}$
Helium	R_{He}	$2.08 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$	$386.3 \frac{\text{ft-lbf}}{\text{lbm-°R}}$

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1.2 Properties of Materials

1.2.1 Properties of Air at Atmospheric Pressure

Properties of Air at Atmospheric Pressure

	ρ	ν	μ
Temperature	**Density**	**Kinematic Viscosity**	**Absolute Viscosity**
°F	$\frac{\text{lbm}}{\text{ft}^3}$	$\times 10^{-5}$ ft²/sec	$\times 10^{-7}$ lbf-sec/ft²
0	0.0864	12.6	3.28
20	0.0827	13.6	3.50
40	0.0794	14.6	3.62
60	0.0763	15.8	3.74
68	0.0752	16.0	3.75
80	0.0735	16.9	3.85
100	0.0709	18.0	3.96
120	0.0684	18.9	4.07
250	0.0559	27.3	4.74

1.2.2 Critical Properties

Critical Properties

Substance	P_c in atm	T_c in °R	T_c in K
Air	37.2	239	131
Carbon dioxide	72.9	548	304.3
Carbon monoxide	34.5	239	134.6
Hydrogen	12.8	59.8	33.6
Nitrogen	33.5	227	126.2
Oxygen	49.8	278	154.5
Water	218	1,165	647.4

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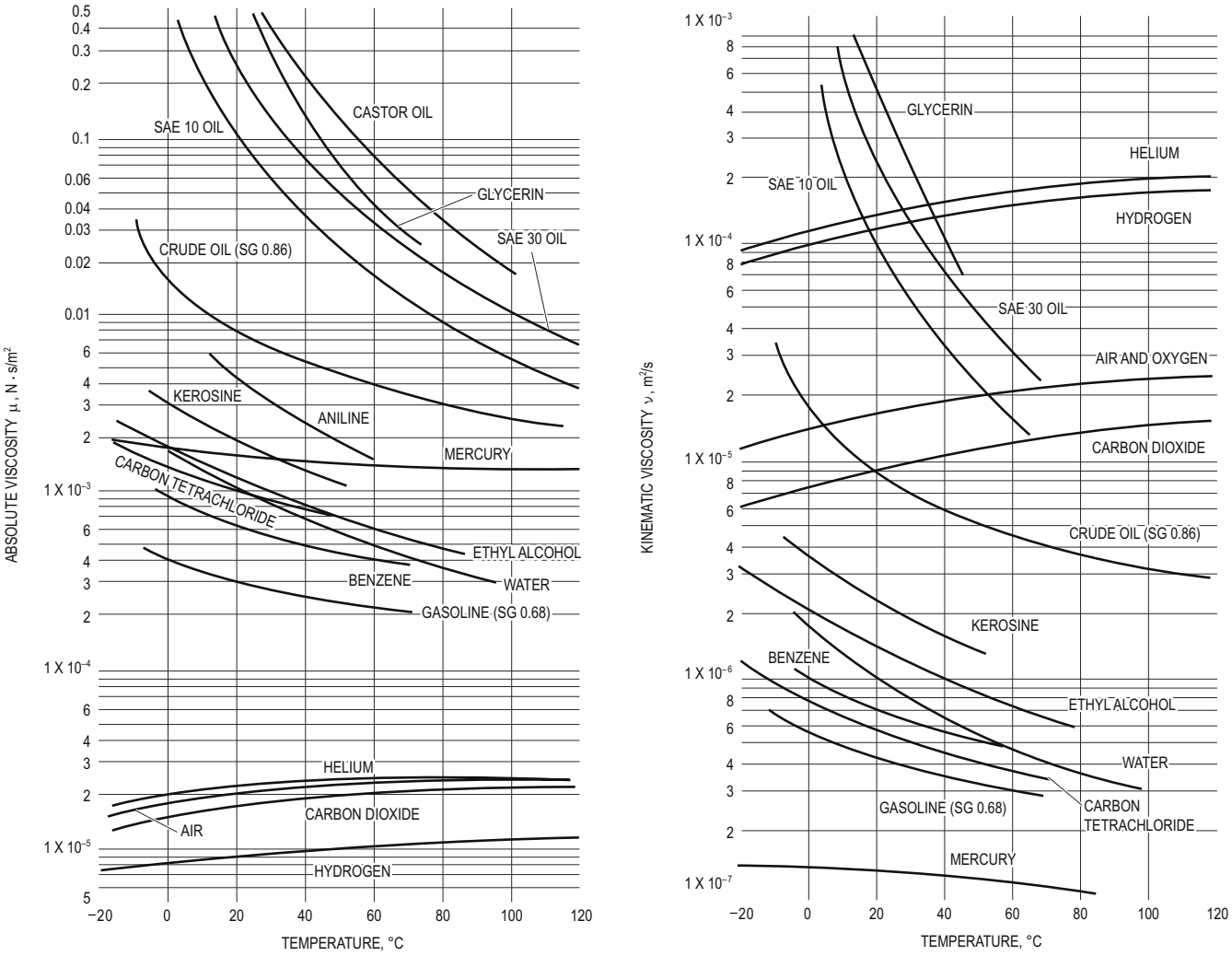
1.2.3 Thermal and Physical Properties of Ideal Gases (at Room Temperature)

Thermal and Physical Properties of Ideal Gases (at Room Temperature)								
Gas	Molecular Weight	R		c_P		c_V		k
		$\frac{\text{ft-lbf}}{\text{lbm-°R}}$	$\frac{\text{kJ}}{\text{kg•K}}$	$\frac{\text{Btu}}{\text{lbm-°R}}$	$\frac{\text{kJ}}{\text{kg•K}}$	$\frac{\text{Btu}}{\text{lbm-°R}}$	$\frac{\text{kJ}}{\text{kg•K}}$	
Air	29	53.35	0.2870	0.240	1.004	0.171	0.718	1.40
Argon	40	38.69	0.2082	0.125	0.520	0.076	0.312	1.67
Butane	58	26.58	0.1430	0.415	1.720	0.381	1.570	1.09
Carbon dioxide	44	35.11	0.1889	0.203	0.846	0.158	0.657	1.29
Carbon monoxide	28	55.17	0.2968	0.249	1.041	0.178	0.744	1.40
Ethane	30	51.40	0.2765	0.427	1.770	0.361	1.490	1.18
Helium	4	386.04	2.0770	1.250	5.193	0.753	3.116	1.67
Hydrogen	2	766.53	4.1242	3.430	14.209	2.440	10.200	1.40
Methane	16	96.32	0.5182	0.532	2.254	0.403	1.735	1.30
Neon	20	76.56	0.4119	0.246	1.030	0.148	0.618	1.67
Nitrogen	28	55.16	0.2968	0.248	1.042	0.177	0.743	1.40
Octane vapor	114	13.55	0.0729	0.409	1.710	0.392	1.640	1.04
Oxygen	32	48.29	0.2598	0.219	0.918	0.157	0.658	1.40
Propane	44	35.04	0.1885	0.407	1.680	0.362	1.490	1.12
Steam	18	85.78	0.4615	0.445	1.87	0.335	1.41	1.33

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1.2.4 Physical Properties of Fluids

Absolute Viscosity (Left) and Kinematic Viscosity (Right) of Common Fluids at 1 atm



Source: White, Frank M., *Fluid Mechanics*, 3rd ed., New York: McGraw-Hill, 1994.

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1.2.5 Engine Oil Viscosity Classification and Properties

Motor Oil Grades – Low Temperature

		Grade Designation					
		0W	**5W**	**10W**	**15W**	**20W**	**25W**
Dynamic Viscosity (mPa•s)	**Cranking Maximum**	6,200	6,600	7,000	7,000	9,500	13,000
	Temperature (°C)	–35	–30	–25	–20	–15	–10
	Pumping Maximum	60,000	60,000	60,000	60,000	60,000	60,000
	Temperature (°C)	–40	–35	–30	–25	–20	–15

Motor Oil Grades – High Temperature

	Grade Designation					
	20W	**30W**	**40W**	**40W**	**50W**	**60W**
Kinematic Viscosity (cSt) Low Shear Rate at 100°C	5.6 – 9.3	9.3 – 12.5	12.5 – 16.3	12.5 – 16.3	16.3 – 21.9	21.9 – 26.1
Dynamic Viscosity (mPa•s) High Shear Rate at 150°C	>2.6	>2.9	>2.9*	>3.7**	>3.7	>3.7

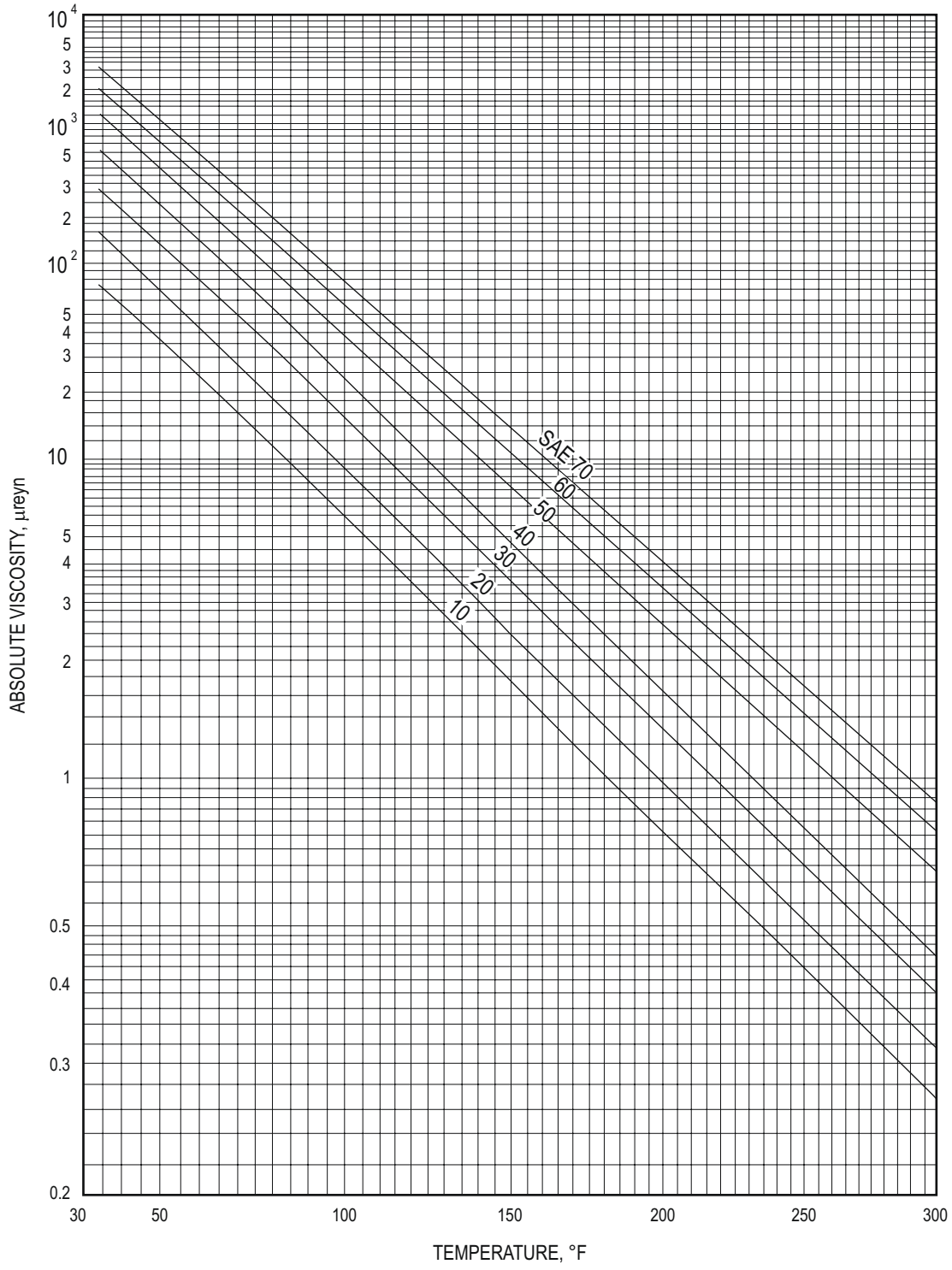
* 0W-40, 5W-40, 10W-40
** 15W-40, 20W-40, 25W-40

Adapted from Society of Automotive Engineers (SAE), *SAE J300 Engine Oil Viscosity Classification*, December 1999.

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Oil Viscosity-Temperature Chart

U.S. Customary Units

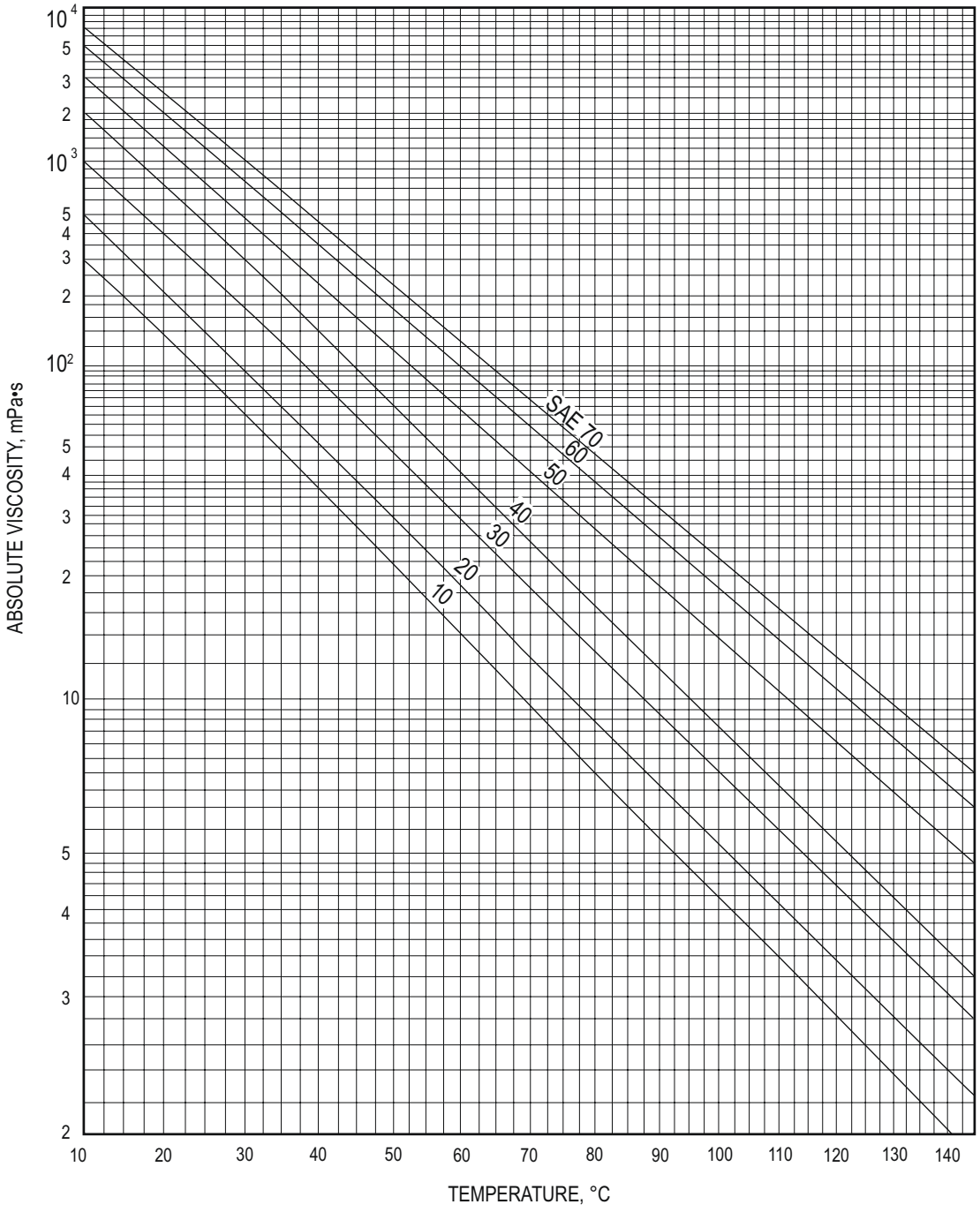


Source: Raimondi, A.A., and John Boyd, *Lubrication and Science Technology*, "A Solution for the Finite Journal Bearing and Its Application to Analysis and Design," Parts I, II, and III, vol. 1, no. 1, New York: Pergamon, 1958.

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Oil Viscosity-Temperature Chart

SI Units



Source: Raimondi, A.A., and John Boyd, *Lubrication and Science Technology*, "A Solution for the Finite Journal Bearing and Its Application to Analysis and Design," Parts I, II, and III, vol. 1, no. 1, New York: Pergamon, 1958.

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1.2.6 Compressible-Flow Functions

One-Dimensional Isentropic Compressible-Flow Functions $k = 1.4$

M	$\frac{T}{T_o}$	$\frac{p}{p_o}$	$\frac{\rho}{\rho_o}$	$\frac{A}{A^*}$
0.01	1.0000	0.9999	1.0000	57.8738
0.02	0.9999	0.9997	0.9998	28.9421
0.03	0.9998	0.9994	0.9996	19.3005
0.04	0.9997	0.9989	0.9992	14.4815
0.05	0.9995	0.9983	0.9988	11.5914
0.06	0.9993	0.9975	0.9982	9.6659
0.07	0.9990	0.9966	0.9976	8.2915
0.08	0.9987	0.9955	0.9968	7.2616
0.09	0.9984	0.9944	0.9960	6.4613
0.10	0.9980	0.9930	0.9950	5.8218
0.11	0.9976	0.9916	0.9940	5.2992
0.12	0.9971	0.9900	0.9928	4.8643
0.13	0.9966	0.9883	0.9916	4.4969
0.14	0.9961	0.9864	0.9903	4.1824
0.15	0.9955	0.9844	0.9888	3.9103
0.16	0.9949	0.9823	0.9873	3.6727
0.17	0.9943	0.9800	0.9857	3.4635
0.18	0.9936	0.9776	0.9840	3.2779
0.19	0.9928	0.9751	0.9822	3.1123
0.20	0.9921	0.9725	0.9803	2.9635
0.21	0.9913	0.9697	0.9783	2.8293
0.22	0.9904	0.9668	0.9762	2.7076
0.23	0.9895	0.9638	0.9740	2.5968
0.24	0.9886	0.9607	0.9718	2.4956
0.25	0.9877	0.9575	0.9694	2.4027
0.26	0.9867	0.9541	0.9670	2.3173
0.27	0.9856	0.9506	0.9645	2.2385
0.28	0.9846	0.9470	0.9619	2.1656
0.29	0.9835	0.9433	0.9592	2.0979
0.30	0.9823	0.9395	0.9564	2.0351
0.31	0.9811	0.9355	0.9535	1.9765
0.32	0.9799	0.9315	0.9506	1.9219
0.33	0.9787	0.9274	0.9476	1.8707
0.34	0.9774	0.9231	0.9445	1.8229
0.35	0.9761	0.9188	0.9413	1.7780
0.36	0.9747	0.9143	0.9380	1.7358
0.37	0.9733	0.9098	0.9347	1.6961
0.38	0.9719	0.9052	0.9313	1.6587
0.39	0.9705	0.9004	0.9278	1.6234
0.40	0.9690	0.8956	0.9243	1.5901

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One-Dimensional Isentropic Compressible-Flow Functions k = 1.4 (cont'd)

M	$\frac{T}{T_o}$	$\frac{p}{p_o}$	$\frac{\rho}{\rho_o}$	$\frac{A}{A^*}$
0.41	0.9675	0.8907	0.9207	1.5587
0.42	0.9659	0.8857	0.9170	1.5289
0.43	0.9643	0.8807	0.9132	1.5007
0.44	0.9627	0.8755	0.9094	1.4740
0.45	0.9611	0.8703	0.9055	1.4487
0.46	0.9594	0.8650	0.9016	1.4246
0.47	0.9577	0.8596	0.8976	1.4018
0.48	0.9559	0.8541	0.8935	1.3801
0.49	0.9542	0.8486	0.8894	1.3595
0.50	0.9524	0.8430	0.8852	1.3398
0.51	0.9506	0.8374	0.8809	1.3212
0.52	0.9487	0.8317	0.8766	1.3034
0.53	0.9468	0.8259	0.8723	1.2865
0.54	0.9449	0.8201	0.8679	1.2703
0.55	0.9430	0.8142	0.8634	1.2549
0.56	0.9410	0.8082	0.8589	1.2403
0.57	0.9390	0.8022	0.8544	1.2263
0.58	0.9370	0.7962	0.8498	1.2130
0.59	0.9349	0.7901	0.8451	1.2003
0.60	0.9328	0.7840	0.8405	1.1882
0.61	0.9307	0.7778	0.8357	1.1767
0.62	0.9286	0.7716	0.8310	1.1656
0.63	0.9265	0.7654	0.8262	1.1552
0.64	0.9243	0.7591	0.8213	1.1451
0.65	0.9221	0.7528	0.8164	1.1356
0.66	0.9199	0.7465	0.8115	1.1265
0.67	0.9176	0.7401	0.8066	1.1179
0.68	0.9153	0.7338	0.8016	1.1097
0.69	0.9131	0.7274	0.7966	1.1018
0.70	0.9107	0.7209	0.7916	1.0944
0.71	0.9084	0.7145	0.7865	1.0873
0.72	0.9061	0.7080	0.7814	1.0806
0.73	0.9037	0.7016	0.7763	1.0742
0.74	0.9013	0.6951	0.7712	1.0681
0.75	0.8989	0.6886	0.7660	1.0624
0.76	0.8964	0.6821	0.7609	1.0570
0.77	0.8940	0.6756	0.7557	1.0519
0.78	0.8915	0.6691	0.7505	1.0471
0.79	0.8890	0.6625	0.7452	1.0425
0.80	0.8865	0.6560	0.7400	1.0382
0.81	0.8840	0.6495	0.7347	1.0342

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One-Dimensional Isentropic Compressible-Flow Functions k = 1.4 (cont'd)

M	$\frac{T}{T_o}$	$\frac{p}{p_o}$	$\frac{\rho}{\rho_o}$	$\frac{A}{A^*}$
0.82	0.8815	0.6430	0.7295	1.0305
0.83	0.8789	0.6365	0.7242	1.0270
0.84	0.8763	0.6300	0.7189	1.0237
0.85	0.8737	0.6235	0.7136	1.0207
0.86	0.8711	0.6170	0.7083	1.0179
0.87	0.8685	0.6106	0.7030	1.0153
0.88	0.8659	0.6041	0.6977	1.0129
0.89	0.8632	0.5977	0.6924	1.0108
0.90	0.8606	0.5913	0.6870	1.0089
0.91	0.8579	0.5849	0.6817	1.0071
0.92	0.8552	0.5785	0.6764	1.0056
0.93	0.8525	0.5721	0.6711	1.0043
0.94	0.8498	0.5658	0.6658	1.0031
0.95	0.8471	0.5595	0.6604	1.0021
0.96	0.8444	0.5532	0.6551	1.0014
0.97	0.8416	0.5469	0.6498	1.0008
0.98	0.8389	0.5407	0.6445	1.0003
0.99	0.8361	0.5345	0.6392	1.0001
1.00	0.8333	0.5283	0.6339	1.0000
1.10	0.8052	0.4684	0.5817	1.0079
1.20	0.7764	0.4124	0.5311	1.0304
1.30	0.7474	0.3609	0.4829	1.0663
1.40	0.7184	0.3142	0.4374	1.1149
1.50	0.6897	0.2724	0.3950	1.1762
1.60	0.6614	0.2353	0.3557	1.2502
1.70	0.6337	0.2026	0.3197	1.3376
1.80	0.6068	0.1740	0.2868	1.4390
1.90	0.5807	0.1492	0.2570	1.5553
2.00	0.5556	0.1278	0.2300	1.6875
2.10	0.5313	0.1094	0.2058	1.8369
2.20	0.5081	0.0935	0.1841	2.0050
2.30	0.4859	0.0800	0.1646	2.1931
2.40	0.4647	0.0684	0.1472	2.4031
2.50	0.4444	0.0585	0.1317	2.6367
2.60	0.4252	0.0501	0.1179	2.8960
2.70	0.4068	0.0430	0.1056	3.1830
2.80	0.3894	0.0368	0.0946	3.5001
2.90	0.3729	0.0317	0.0849	3.8498
3.00	0.3571	0.0272	0.0762	4.2346
3.10	0.3422	0.0234	0.0685	4.6573
3.20	0.3281	0.0202	0.0617	5.1210

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One-Dimensional Isentropic Compressible-Flow Functions $k = 1.4$ (cont'd)

M	$\frac{T}{T_o}$	$\frac{p}{p_o}$	$\frac{\rho}{\rho_o}$	$\frac{A}{A^*}$
3.30	0.3147	0.0175	0.0555	5.6286
3.40	0.3019	0.0151	0.0501	6.1837
3.50	0.2899	0.0131	0.0452	6.7896
3.60	0.2784	0.0114	0.0409	7.4501
3.70	0.2675	0.0099	0.0370	8.1691
3.80	0.2572	0.0086	0.0335	8.9506
3.90	0.2474	0.0075	0.0304	9.7990
4.00	0.2381	0.0066	0.0277	10.7188
4.10	0.2293	0.0058	0.0252	11.7147
4.20	0.2208	0.0051	0.0229	12.7916
4.30	0.2129	0.0044	0.0209	13.9549
4.40	0.2053	0.0039	0.0191	15.2099
4.50	0.1980	0.0035	0.0174	16.5622
4.60	0.1911	0.0031	0.0160	18.0178
4.70	0.1846	0.0027	0.0146	19.5828
4.80	0.1783	0.0024	0.0134	21.2637
4.90	0.1724	0.0021	0.0123	23.0671
5.00	0.1667	0.0019	0.0113	25.0000

Source: *NACA Report 1135: Equations, Tables, and Charts for Compressible Flow*, Moffett Field, CA: National Advisory Committee for Aeronautics, Ames Aeronautical Laboratory, 1953, www.grc.nasa.gov.

where

M = local Mach number or Mach number upstream of a normal shock wave

$\frac{T}{T_o}$ = ratio of static temperature to total temperature

$\frac{p}{p_o}$ = ratio of static pressure to total pressure

$\frac{\rho}{\rho_o}$ = ratio of static density to total density

$\frac{A}{A^*}$ = ratio of local cross-sectional area of an isentropic stream tube to cross-sectional area at the point where $M = 1$

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Normal Shock Relationships, $k = 1.4$, $T_{0,1} = T_{0,2}$

M_1	M_2	P_2/P_1	ρ_2/ρ_1	T_2/T_1	$P_{0,2}/P_{0,1}$	$P_1/P_{0,2}$
1.00	1.0000	1.0000	1.0000	1.0000	1.0000	0.5283
1.05	0.9531	1.1196	1.0840	1.0328	0.9999	0.4979
1.10	0.9118	1.2450	1.1691	1.0649	0.9989	0.4689
1.15	0.8750	1.3763	1.2550	1.0966	0.9967	0.4413
1.20	0.8422	1.5133	1.3416	1.1280	0.9928	0.4154
1.25	0.8126	1.6563	1.4286	1.1594	0.9871	0.3911
1.30	0.7860	1.8050	1.5157	1.1909	0.9794	0.3685
1.35	0.7618	1.9596	1.6028	1.2226	0.9697	0.3475
1.40	0.7397	2.1200	1.6897	1.2547	0.9582	0.3280
1.45	0.7196	2.2863	1.7761	1.2872	0.9448	0.3098
1.50	0.7011	2.4583	1.8621	1.3202	0.9298	0.2930
1.55	0.6841	2.6363	1.9473	1.3538	0.9132	0.2773
1.60	0.6684	2.8200	2.0317	1.3880	0.8952	0.2628
1.65	0.6540	3.0096	2.1152	1.4228	0.8760	0.2493
1.70	0.6405	3.2050	2.1977	1.4583	0.8557	0.2368
1.75	0.6281	3.4063	2.2791	1.4946	0.8346	0.2251
1.80	0.6165	3.6133	2.3592	1.5316	0.8127	0.2142
1.85	0.6057	3.8263	2.4381	1.5693	0.7902	0.2040
1.90	0.5956	4.0450	2.5157	1.6079	0.7674	0.1945
1.95	0.5862	4.2696	2.5919	1.6473	0.7442	0.1856
2.00	0.5774	4.5000	2.6667	1.6875	0.7209	0.1773
2.05	0.5691	4.7363	2.7400	1.7285	0.6975	0.1695
2.10	0.5613	4.9783	2.8119	1.7705	0.6742	0.1622
2.15	0.5540	5.2263	2.8823	1.8132	0.6511	0.1553
2.20	0.5471	5.4800	2.9512	1.8569	0.6281	0.1489
2.25	0.5406	5.7396	3.0186	1.9014	0.6055	0.1428
2.30	0.5344	6.0050	3.0845	1.9468	0.5833	0.1371
2.35	0.5286	6.2763	3.1490	1.9931	0.5615	0.1317
2.40	0.5231	6.5533	3.2119	2.0403	0.5401	0.1266
2.45	0.5179	6.8363	3.2733	2.0885	0.5193	0.1218
2.50	0.5130	7.1250	3.3333	2.1375	0.4990	0.1173
2.55	0.5083	7.4196	3.3919	2.1875	0.4793	0.1130
2.60	0.5039	7.7200	3.4490	2.2383	0.4601	0.1089
2.65	0.4996	8.0262	3.5047	2.2902	0.4416	0.1051
2.70	0.4956	8.3383	3.5590	2.3429	0.4236	0.1014
2.75	0.4918	8.6562	3.6119	2.3966	0.4062	0.0979
2.80	0.4882	8.9800	3.6636	2.4512	0.3895	0.0946
2.85	0.4847	9.3096	3.7139	2.5067	0.3733	0.0915
2.90	0.4814	9.6450	3.7629	2.5632	0.3577	0.0885
2.95	0.4782	9.9862	3.8106	2.6206	0.3428	0.0856

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Normal Shock Relationships, k = 1.4, $T_{0,1} = T_{0,2}$ (cont'd)

M_1	M_2	P_2/P_1	ρ_2/ρ_1	T_2/T_1	$P_{0,2}/P_{0,1}$	$P_1/P_{0,2}$
3.00	0.4752	10.3333	3.8571	2.6790	0.3283	0.0829
3.05	0.4723	10.6863	3.9025	2.7383	0.3145	0.0803
3.10	0.4695	11.0450	3.9466	2.7986	0.3012	0.0778
3.15	0.4669	11.4096	3.9896	2.8598	0.2885	0.0755
3.20	0.4643	11.7800	4.0315	2.9220	0.2762	0.0732
3.25	0.4619	12.1563	4.0723	2.9851	0.2645	0.0711
3.30	0.4596	12.5383	4.1120	3.0492	0.2533	0.0690
3.35	0.4573	12.9263	4.1507	3.1142	0.2425	0.0670
3.40	0.4552	13.3200	4.1884	3.1802	0.2322	0.0651
3.45	0.4531	13.7196	4.2251	3.2472	0.2224	0.0633
3.50	0.4512	14.1250	4.2609	3.3151	0.2129	0.0616
3.55	0.4492	14.5363	4.2957	3.3839	0.2039	0.0599
3.60	0.4474	14.9533	4.3296	3.4537	0.1953	0.0583
3.65	0.4456	15.3763	4.3627	3.5245	0.1871	0.0567
3.70	0.4439	15.8050	4.3949	3.5962	0.1792	0.0553
3.75	0.4423	16.2396	4.4262	3.6689	0.1717	0.0538
3.80	0.4407	16.6800	4.4568	3.7426	0.1645	0.0525
3.85	0.4392	17.1262	4.4866	3.8172	0.1576	0.0511
3.90	0.4377	17.5783	4.5156	3.8928	0.1510	0.0499
3.95	0.4363	18.0362	4.5439	3.9694	0.1448	0.0486
4.00	0.4350	18.5000	4.5714	4.0469	0.1388	0.0475
4.05	0.4336	18.9696	4.5983	4.1254	0.1330	0.0463
4.10	0.4324	19.4450	4.6245	4.2048	0.1276	0.0452
4.15	0.4311	19.9262	4.6500	4.2852	0.1223	0.0442
4.20	0.4299	20.4133	4.6749	4.3666	0.1173	0.0431
4.25	0.4288	20.9062	4.6992	4.4489	0.1126	0.0422
4.30	0.4277	21.4050	4.7229	4.5322	0.1080	0.0412
4.35	0.4266	21.9096	4.7460	4.6165	0.1036	0.0403
4.40	0.4255	22.4200	4.7685	4.7017	0.0995	0.0394
4.45	0.4245	22.9362	4.7904	4.7879	0.0955	0.0385
4.50	0.4236	23.4583	4.8119	4.8751	0.0917	0.0377
4.55	0.4226	23.9862	4.8328	4.9632	0.0881	0.0369
4.60	0.4217	24.5200	4.8532	5.0523	0.0846	0.0361
4.65	0.4208	25.0596	4.8731	5.1424	0.0813	0.0353
4.70	0.4199	25.6050	4.8926	5.2334	0.0781	0.0346
4.75	0.4191	26.1562	4.9116	5.3254	0.0750	0.0339
4.80	0.4183	26.7133	4.9301	5.4184	0.0721	0.0332
4.85	0.4175	27.2762	4.9482	5.5124	0.0694	0.0325
4.90	0.4167	27.8450	4.9659	5.6073	0.0667	0.0319
4.95	0.4160	28.4196	4.9831	5.7032	0.0642	0.0312

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Normal Shock Relationships, k = 1.4, $T_{0,1} = T_{0,2}$ (cont'd)

M_1	M_2	P_2/P_1	ρ_2/ρ_1	T_2/T_1	$P_{0,2}/P_{0,1}$	$P_1/P_{0,2}$
5.00	0.4152	29.0000	5.0000	5.8000	0.0617	0.0306
5.05	0.4145	29.5862	5.0165	5.8978	0.0594	0.0300
5.10	0.4138	30.1783	5.0326	5.9966	0.0572	0.0295
5.15	0.4132	30.7762	5.0483	6.0964	0.0550	0.0289
5.20	0.4125	31.3800	5.0637	6.1971	0.0530	0.0283
5.25	0.4119	31.9896	5.0787	6.2988	0.0510	0.0278
5.30	0.4113	32.6050	5.0934	6.4014	0.0491	0.0273
5.35	0.4107	33.2262	5.1077	6.5051	0.0473	0.0268
5.40	0.4101	33.8533	5.1218	6.6097	0.0456	0.0263
5.45	0.4095	34.4862	5.1355	6.7153	0.0439	0.0258
5.50	0.4090	35.1250	5.1489	6.8218	0.0424	0.0254
5.55	0.4084	35.7696	5.1621	6.9293	0.0408	0.0249
5.60	0.4079	36.4200	5.1749	7.0378	0.0394	0.0245
5.65	0.4074	37.0762	5.1875	7.1472	0.0380	0.0241
5.70	0.4069	37.7383	5.1998	7.2577	0.0366	0.0236
5.75	0.4064	38.4062	5.2118	7.3691	0.0354	0.0232
5.80	0.4059	39.0800	5.2236	7.4814	0.0341	0.0228
5.85	0.4055	39.7596	5.2351	7.5948	0.0329	0.0225
5.90	0.4050	40.4450	5.2464	7.7091	0.0318	0.0221
5.95	0.4046	41.1362	5.2575	7.8243	0.0307	0.0217
6.00	0.4042	41.8333	5.2683	7.9406	0.0297	0.0214
6.05	0.4037	42.5362	5.2789	8.0578	0.0286	0.0210
6.10	0.4033	43.2450	5.2893	8.1760	0.0277	0.0207
6.15	0.4029	43.9596	5.2994	8.2951	0.0267	0.0203
6.20	0.4025	44.6800	5.3094	8.4153	0.0258	0.0200
6.25	0.4022	45.4062	5.3191	8.5364	0.0250	0.0197
6.30	0.4018	46.1383	5.3287	8.6584	0.0242	0.0194
6.35	0.4014	46.8762	5.3381	8.7815	0.0234	0.0191
6.40	0.4011	47.6200	5.3473	8.9055	0.0226	0.0188
6.45	0.4007	48.3696	5.3563	9.0305	0.0219	0.0185
6.50	0.4004	49.1250	5.3651	9.1564	0.0211	0.0182
6.55	0.4000	49.8862	5.3737	9.2834	0.0205	0.0180
6.60	0.3997	50.6533	5.3822	9.4113	0.0198	0.0177
6.65	0.3994	51.4262	5.3905	9.5401	0.0192	0.0174
6.70	0.3991	52.2050	5.3987	9.6700	0.0186	0.0172
6.75	0.3988	52.9896	5.4067	9.8008	0.0180	0.0169
6.80	0.3985	53.7800	5.4145	9.9326	0.0174	0.0167
6.85	0.3982	54.5762	5.4222	10.0653	0.0169	0.0164
6.90	0.3979	55.3783	5.4298	10.1990	0.0163	0.0162
6.95	0.3976	56.1862	5.4372	10.3337	0.0158	0.0160

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Normal Shock Relationships, $k = 1.4$, $T_{0,1} = T_{0,2}$ (cont'd)

M_1	M_2	P_2/P_1	ρ_2/ρ_1	T_2/T_1	$P_{0,2}/P_{0,1}$	$P_1/P_{0,2}$
7.00	0.3974	57.0000	5.4444	10.4694	0.0154	0.0157
7.05	0.3971	57.8196	5.4516	10.6060	0.0149	0.0155
7.10	0.3968	58.6450	5.4586	10.7436	0.0144	0.0153
7.15	0.3966	59.4762	5.4655	10.8822	0.0140	0.0151
7.20	0.3963	60.3133	5.4722	11.0218	0.0136	0.0149
7.25	0.3961	61.1562	5.4788	11.1623	0.0132	0.0147
7.30	0.3958	62.0050	5.4853	11.3038	0.0128	0.0145
7.35	0.3956	62.8596	5.4917	11.4462	0.0124	0.0143
7.40	0.3954	63.7200	5.4980	11.5897	0.0120	0.0141
7.45	0.3951	64.5862	5.5042	11.7341	0.0117	0.0139
7.50	0.3949	65.4583	5.5102	11.8795	0.0113	0.0137
7.55	0.3947	66.3362	5.5161	12.0258	0.0110	0.0135
7.60	0.3945	67.2200	5.5220	12.1732	0.0107	0.0134
7.65	0.3943	68.1096	5.5277	12.3214	0.0104	0.0132
7.70	0.3941	69.0050	5.5334	12.4707	0.0101	0.0130
7.75	0.3939	69.9062	5.5389	12.6210	0.0098	0.0129
7.80	0.3937	70.8133	5.5443	12.7722	0.0095	0.0127
7.85	0.3935	71.7262	5.5497	12.9243	0.0092	0.0125
7.90	0.3933	72.6450	5.5550	13.0775	0.0090	0.0124
7.95	0.3931	73.5696	5.5601	13.2316	0.0087	0.0122
8.00	0.3929	74.5000	5.5652	13.3867	0.0085	0.0121
8.05	0.3927	75.4362	5.5702	13.5428	0.0083	0.0119
8.10	0.3925	76.3783	5.5751	13.6998	0.0080	0.0118
8.15	0.3924	77.3262	5.5800	13.8578	0.0078	0.0116
8.20	0.3922	78.2800	5.5847	14.0168	0.0076	0.0115
8.25	0.3920	79.2396	5.5894	14.1768	0.0074	0.0114
8.30	0.3918	80.2050	5.5940	14.3377	0.0072	0.0112
8.35	0.3917	81.1762	5.5985	14.4996	0.0070	0.0111
8.40	0.3915	82.1533	5.6030	14.6625	0.0068	0.0110
8.45	0.3914	83.1362	5.6073	14.8263	0.0066	0.0108
8.50	0.3912	84.1250	5.6117	14.9911	0.0064	0.0107
8.55	0.3911	85.1196	5.6159	15.1569	0.0063	0.0106
8.60	0.3909	86.1200	5.6201	15.3237	0.0061	0.0105
8.65	0.3908	87.1262	5.6242	15.4914	0.0060	0.0103
8.70	0.3906	88.1383	5.6282	15.6601	0.0058	0.0102
8.75	0.3905	89.1562	5.6322	15.8298	0.0056	0.0101
8.80	0.3903	90.1800	5.6361	16.0004	0.0055	0.0100
8.85	0.3902	91.2096	5.6400	16.1720	0.0054	0.0099
8.90	0.3901	92.2450	5.6437	16.3446	0.0052	0.0098
8.95	0.3899	93.2862	5.6475	16.5182	0.0051	0.0097

Source: *NACA Report 1135: Equations, Tables, and Charts for Compressible Flow*, Moffett Field, CA: National Advisory Committee for Aeronautics, Ames Aeronautical Laboratory, 1953, www.grc.nasa.gov.

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where

M_1 = local Mach number or Mach number upstream of a normal shock wave
M_2 = Mach number downstream of a normal shock wave
P_2/P_1 = static pressure ratio across a normal shock wave
ρ_2/ρ_1 = static density ratio across a normal shock wave
T_2/T_1 = static temperature ratio across a normal shock wave
$P_{0,2}/P_{0,1}$ = total pressure ratio across a normal shock wave
$P_1/P_{0,2}$ = ratio of static pressure upstream of a normal shock wave to total pressure downstream
$T_{0,1}$ = total temperature upstream of a normal shock wave
$T_{0,2}$ = total temperature downstream of a normal shock wave

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Adiabatic Frictional Flow in a Constant Area Duct, $k = 1.4$

M	$\bar{f}L^*/D$	P/P^*	T/T^*	$\rho^*/\rho = V/V^*$	$P_o/P_o^* = \rho_o/\rho_o^*$
0.00			1.2000		
0.02	1778.4499	54.7701	0.0005	0.0219	28.9421
0.04	440.3522	27.3817	1.1996	0.0438	14.4815
0.06	193.0311	18.2508	1.1991	0.0657	9.6659
0.08	106.7182	13.6843	1.1985	0.0876	7.2616
0.10	66.9216	10.9435	1.1976	0.1094	5.8218
0.12	45.4080	9.1156	1.1966	0.1313	4.8643
0.14	32.5113	7.8093	1.1953	0.1531	4.1824
0.16	24.1978	6.8291	1.1939	0.1748	3.6727
0.18	18.5427	6.0662	1.1923	0.1965	3.2779
0.20	14.5333	5.4554	1.1905	0.2182	2.9635
0.22	11.5961	4.9554	1.1885	0.2398	2.7076
0.24	9.3865	4.5383	1.1863	0.2614	2.4956
0.26	7.6876	4.1851	1.1840	0.2829	2.3173
0.28	6.3572	3.8820	1.1815	0.3043	2.1656
0.30	5.2993	3.6191	1.1788	0.3257	2.0351
0.32	4.4467	3.3887	1.1759	0.3470	1.9219
0.34	3.7520	3.1853	1.1729	0.3682	1.8229
0.36	3.1801	3.0042	1.1697	0.3893	1.7358
0.38	2.7054	2.8420	1.1663	0.4104	1.6587
0.40	2.3085	2.6958	1.1628	0.4313	1.5901
0.42	1.9744	2.5634	1.1591	0.4522	1.5289
0.44	1.6915	2.4428	1.1553	0.4729	1.4740
0.46	1.4509	2.3326	1.1513	0.4936	1.4246
0.48	1.2453	2.2313	1.1471	0.5141	1.3801
0.50	1.0691	2.1381	1.1429	0.5345	1.3398
0.52	0.9174	2.0519	1.1384	0.5548	1.3034
0.54	0.7866	1.9719	1.1339	0.5750	1.2703
0.56	0.6736	1.8975	1.1292	0.5951	1.2403
0.58	0.5757	1.8282	1.1244	0.6150	1.2130
0.60	0.4908	1.7634	1.1194	0.6348	1.1882
0.62	0.4172	1.7026	1.1143	0.6545	1.1656
0.64	0.3533	1.6456	1.1091	0.6740	1.1451
0.66	0.2979	1.5919	1.1038	0.6934	1.1265
0.68	0.2498	1.5413	1.0984	0.7127	1.1097
0.70	0.2081	1.4935	1.0929	0.7318	1.0944
0.72	0.1721	1.4482	1.0873	0.7508	1.0806
0.74	0.1411	1.4054	1.0815	0.7696	1.0681
0.76	0.1145	1.3647	1.0757	0.7883	1.0570
0.78	0.0917	1.3261	1.0698	0.8068	1.0471

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Adiabatic Frictional Flow in a Constant Area Duct, $k = 1.4$

M	$\bar{f}L^*/D$	P/P^*	T/T^*	$\rho^*/\rho = V/V^*$	$P_o/P_o^* = \rho_o/\rho_o^*$
0.80	0.0723	1.2893	1.0638	0.8251	1.0382
0.84	0.0423	1.2208	1.0516	0.8614	1.0237
0.88	0.0218	1.1583	1.0391	0.8970	1.0129
0.92	0.0089	1.1011	1.0263	0.9320	1.0056
0.96	0.0021	1.0485	1.0132	0.9663	1.0014
1.00	0.0000	1.0000	1.0000	1.0000	1.0000
1.04	0.0018	0.9551	0.9866	1.0330	1.0013
1.08	0.0066	0.9133	0.9730	1.0653	1.0051
1.12	0.0138	0.8745	0.9593	1.0970	1.0113
1.16	0.0230	0.8383	0.9455	1.1280	1.0198
1.20	0.0336	0.8044	0.9317	1.1583	1.0304
1.24	0.0455	0.7726	0.9178	1.1879	1.0432
1.28	0.0582	0.7427	0.9038	1.2169	1.0581
1.32	0.0716	0.7147	0.8899	1.2452	1.0750
1.36	0.0855	0.6882	0.8760	1.2729	1.0940
1.40	0.0997	0.6632	0.8621	1.2999	1.1149
1.44	0.1142	0.6396	0.8482	1.3262	1.1379
1.48	0.1288	0.6172	0.8344	1.3520	1.1629
1.52	0.1433	0.5960	0.8207	1.3770	1.1899
1.56	0.1579	0.5759	0.8071	1.4015	1.2190
1.60	0.1724	0.5568	0.7937	1.4254	1.2502
1.64	0.1867	0.5386	0.7803	1.4487	1.2836
1.68	0.2008	0.5213	0.7670	1.4713	1.3190
1.72	0.2147	0.5048	0.7539	1.4935	1.3567
1.76	0.2284	0.4891	0.7410	1.5150	1.3967
1.80	0.2419	0.4741	0.7282	1.5360	1.4390
1.84	0.2551	0.4597	0.7155	1.5564	1.4836
1.88	0.2680	0.4460	0.7030	1.5763	1.5308
1.92	0.2806	0.4329	0.6907	1.5957	1.5804
1.96	0.2929	0.4203	0.6786	1.6146	1.6326
2.00	0.3050	0.4082	0.6667	1.6330	1.6875
2.04	0.3168	0.3967	0.6549	1.6509	1.7451
2.08	0.3282	0.3856	0.6433	1.6683	1.8056
2.12	0.3394	0.3750	0.6320	1.6853	1.8690
2.16	0.3503	0.3648	0.6208	1.7018	1.9354
2.20	0.3609	0.3549	0.6098	1.7179	2.0050
2.24	0.3712	0.3455	0.5989	1.7336	2.0777
2.28	0.3813	0.3364	0.5883	1.7488	2.1538
2.32	0.3911	0.3277	0.5779	1.7637	2.2333
2.36	0.4006	0.3193	0.5677	1.7781	2.3164

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Adiabatic Frictional Flow in a Constant Area Duct, $k = 1.4$

M	$\bar{f}L^*/D$	P/P^*	T/T^*	$\rho^*/\rho = V/V^*$	$P_o/P_o^* = \rho_o/\rho_o^*$
2.38	0.4053	0.3152	0.5626	1.7852	2.3593
2.42	0.4144	0.3072	0.5527	1.7991	2.4479
2.46	0.4233	0.2995	0.5429	1.8126	2.5403
2.50	0.4320	0.2921	0.5333	1.8257	2.6367
2.54	0.4404	0.2850	0.5239	1.8386	2.7372
2.58	0.4486	0.2781	0.5147	1.8510	2.8420
2.62	0.4565	0.2714	0.5057	1.8632	2.9511
2.66	0.4643	0.2650	0.4969	1.8750	3.0647
2.70	0.4718	0.2588	0.4882	1.8865	3.1830
2.74	0.4791	0.2528	0.4797	1.8978	3.3061
2.78	0.4863	0.2470	0.4714	1.9087	3.4342
2.82	0.4932	0.2414	0.4632	1.9193	3.5674
2.86	0.5000	0.2359	0.4552	1.9297	3.7058
2.90	0.5065	0.2307	0.4474	1.9398	3.8498
2.94	0.5129	0.2256	0.4398	1.9497	3.9993
2.98	0.5191	0.2206	0.4323	1.9593	4.1547
3.02	0.5252	0.2158	0.4249	1.9686	4.3160
3.06	0.5310	0.2112	0.4177	1.9777	4.4835
3.10	0.5368	0.2067	0.4107	1.9866	4.6573
3.14	0.5424	0.2024	0.4038	1.9953	4.8377
3.18	0.5478	0.1981	0.3970	2.0037	5.0248
3.22	0.5531	0.1940	0.3904	2.0119	5.2189
3.26	0.5582	0.1901	0.3839	2.0200	5.4201
3.30	0.5632	0.1862	0.3776	2.0278	5.6286
3.34	0.5681	0.1825	0.3714	2.0355	5.8448
3.38	0.5729	0.1788	0.3653	2.0429	6.0687
3.42	0.5775	0.1753	0.3594	2.0502	6.3007
3.46	0.5820	0.1718	0.3535	2.0573	6.5409
3.50	0.5864	0.1685	0.3478	2.0642	6.7896
3.54	0.5907	0.1653	0.3422	2.0709	7.0471
3.58	0.5949	0.1621	0.3368	2.0775	7.3135
3.62	0.5990	0.1590	0.3314	2.0840	7.5891
3.66	0.6030	0.1560	0.3262	2.0903	7.8742
3.70	0.6068	0.1531	0.3210	2.0964	8.1691
3.74	0.6106	0.1503	0.3160	2.1024	8.4739
3.78	0.6143	0.1475	0.3111	2.1082	8.7891
3.82	0.6179	0.1449	0.3062	2.1140	9.1148
3.86	0.6214	0.1423	0.3015	2.1195	9.4513
3.90	0.6248	0.1397	0.2969	2.1250	9.7990
3.94	0.6282	0.1372	0.2923	2.1303	10.1581
3.96	0.6298	0.1360	0.2901	2.1329	10.3420
3.98	0.6315	0.1348	0.2879	2.1355	10.5289
4.00	0.6331	0.1336	0.2857	2.1381	10.7188

Source: White, Frank M., *Fluid Mechanics*, 2nd ed., New York: McGraw-Hill, 1986.

where

$\overline{f}$ = average friction factor between $L = 0$ and L^*

L^* = duct length required to develop a flow from a Mach number to the sonic point

P^*, ρ^*, T^*, P_o^*, ρ_o^* are the sonic properties

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1.2.7 Properties of Air at Low Pressure, per Pound

T, °R	t, °F	c_p Btu/(lb-F)	c_v Btu/(lb-F)	$k = c_p/c_v$	Speed of Sound a ft/sec	G_{max}/p_i (lbm/sec-ft^2)/(lbf/in^2)	Dynamic Viscosity $\mu \times 10^7$ (1) lbm/sec-ft	Thermal Conductivity λ Btu/(hr-ft-F)	Prandtl Number $Pr = 3600 c_p \mu/\lambda$
100	-359.67	0.2393	0.1707	1.402	490.5	7.6601			
150	-309.67	0.2393	0.1707	1.402	600.7	6.2545	39.1	0.0044	0.758
200	-259.67	0.2393	0.1708	1.401	693.6	5.4165	52.6	0.0059	0.765
250	-209.67	0.2393	0.1708	1.401	775.5	4.8446	65.0	0.0074	0.759
300	-159.67	0.2393	0.1708	1.401	849.5	4.4225	76.7	0.0088	0.752
350	-109.67	0.2394	0.1708	1.401	917.5	4.0944	87.7	0.0102	0.742
400	-59.67	0.2394	0.1709	1.401	980.8	3.8299	98.0	0.0116	0.732
450	-9.67	0.2395	0.1710	1.401	1040.2	3.6107	107.9	0.0129	0.724
500	40.33	0.2397	0.1711	1.401	1096.3	3.4252	117.3	0.0141	0.717
550	90.33	0.2400	0.1714	1.400	1149.6	3.2655	126.3	0.0153	0.711
600	140.33	0.2404	0.1719	1.399	1200.3	3.1260	134.9	0.0165	0.708
650	190.33	0.2410	0.1724	1.398	1248.7	3.0028	143.1	0.0176	0.705
700	240.33	0.2417	0.1731	1.396	1295.1	2.8928	151.0	0.0187	0.703
750	290.33	0.2425	0.1739	1.394	1339.7	2.7937	158.7	0.0197	0.702
800	340.33	0.2435	0.1749	1.392	1382.5	2.7039	166.0	0.0208	0.700
900	440.33	0.2458	0.1773	1.387	1463.6	2.5468	180.2	0.0228	0.699
1000	540.33	0.2486	0.1800	1.381	1539.5	2.4132	193.5	0.0248	0.699
1100	640.33	0.2516	0.1830	1.375	1611.0	2.2978	206.1	0.0268	0.698
1200	740.33	0.2547	0.1862	1.368	1678.7	2.1968	218.1	0.0285	0.701
1300	840.33	0.2579	0.1894	1.362	1743.3	2.1074	229.5	0.0303	0.703
1400	940.33	0.2611	0.1925	1.356	1805.2	2.0278	240.6	0.0322	0.703
1500	1040.33	0.2641	0.1956	1.351	1864.7	1.9563	251.0	0.0340	0.703
1600	1140.33	0.2670	0.1985	1.345	1922.2	1.8916	261.3	0.0357	0.703
1700	1240.33	0.2698	0.2012	1.341	1977.9	1.8328	271.1	0.0373	0.706
1800	1340.33	0.2724	0.2038	1.336	2031.9	1.7790	280.7	0.0388	0.709
1900	1440.33	0.2748	0.2063	1.332	2084.5	1.7296	289.6	0.0403	0.711
2000	1540.33	0.2771	0.2085	1.329	2135.7	1.6841	299.0	0.0417	0.715
2100	1640.33	0.2792	0.2106	1.325	2185.8	1.6420	307.8	0.0430	0.719
2200	1740.33	0.2811	0.2126	1.323	2234.7	1.6029	315.8	0.0444	0.720
2300	1840.33	0.2829	0.2144	1.320	2282.6	1.5664	324.6	0.0456	0.725
2400	1940.33	0.2846	0.2161	1.317	2329.4	1.5323	332.6	0.0468	0.728
2600	2140.33	0.2877	0.2191	1.313	2420.5	1.4703	348.1	0.0492	0.733
2800	2340.33	0.2903	0.2218	1.309	2508.3	1.4152			
3000	2540.33	0.2927	0.2241	1.306	2593.1	1.3659			
3200	2740.33	0.2948	0.2262	1.303	2675.3	1.3214			
3400	2940.33	0.2966	0.2281	1.301	2755.0	1.2810			
3600	3140.33	0.2983	0.2297	1.298	2832.5	1.2441			
3800	3340.33	0.2998	0.2313	1.296	2907.9	1.2103			
4000	3540.33	0.3012	0.2327	1.295	2981.4	1.1790			
4200	3740.33	0.3025	0.2339	1.293	3053.1	1.1500			
4400	3940.33	0.3037	0.2351	1.292	3123.2	1.1231			
4600	4140.33	0.3048	0.2362	1.290	3191.7	1.0980			
4800	4340.33	0.3058	0.2372	1.289	3258.8	1.0745			
5000	4540.33	0.3067	0.2382	1.288	3324.5	1.0524			
5200	4740.33	0.3076	0.2391	1.287	3388.9	1.0316			
5400	4940.33	0.3085	0.2399	1.286	3452.1	1.0121			
5600	5140.33	0.3092	0.2407	1.285	3514.2	0.9936			
5800	5340.33	0.3100	0.2414	1.284	3575.2	0.9760			
6000	5540.33	0.3107	0.2421	1.283	3635.2	0.9594			
6200	5740.33	0.3113	0.2427	1.282	3694.2	0.9436			

(1) To get the value of μ, multiply number in table by 10^{-7}

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Air at Low Pressure, per Pound

T, °R	t, °F	h Btu/lb	p_r Rel. Press.	u Btu/lb	v_r Rel. Vol.	ϕ Btu/lb-°R
300	-160	71.61	0.17795	51.04	624.5	0.46007
310	-150	74.00	0.19952	52.75	575.6	0.46791
320	-140	76.40	0.22290	54.46	531.8	0.47550
330	-130	78.78	0.24819	56.16	492.6	0.48287
340	-120	81.18	0.27545	57.87	457.2	0.49002
350	-110	83.57	0.3048	59.58	425.4	0.49695
360	-99.7	85.97	0.3363	61.29	396.6	0.50369
370	-89.7	88.35	0.3700	62.99	370.4	0.51024
380	-79.7	90.75	0.4061	64.70	346.6	0.51663
390	-69.7	93.13	0.4447	66.40	324.9	0.52284
400	-59.7	95.53	0.4858	68.11	305.0	0.52890
410	-49.7	97.93	0.5295	69.82	286.8	0.53481
420	-39.7	100.32	0.5760	71.52	270.1	0.54058
430	-29.7	102.71	0.6253	73.23	254.7	0.54621
440	-19.7	105.11	0.6776	74.93	240.6	0.55172
450	-9.7	107.50	0.7329	76.65	227.45	0.55710
460	0.3	109.90	0.7913	78.36	215.33	0.56235
470	10.3	112.30	0.8531	80.07	204.08	0.56751
480	20.3	114.69	0.9182	81.77	193.65	0.57255
490	30.3	117.08	0.9868	83.49	183.94	0.57749
500	40.3	119.48	1.0590	85.20	174.90	0.58233
510	50.3	121.87	1.1349	86.92	166.46	0.58707
520	60.3	124.27	1.2147	88.62	158.58	0.59173
530	70.3	126.66	1.2983	90.34	151.22	0.59630
537	77.3	128.34	1.3593	91.53	146.34	0.59945
540	80.3	129.06	1.3860	92.04	144.32	0.60078
550	90.3	131.46	1.4779	93.76	137.85	0.60518
560	100	133.86	1.5742	95.47	131.78	0.60950
570	110	136.26	1.6748	97.19	126.08	0.61376
580	120	138.66	1.7800	98.90	120.70	0.61793
590	130	141.06	1.8899	100.62	115.65	0.62204
600	140	143.47	2.005	102.34	110.88	0.62607
610	150	145.88	2.124	104.06	106.38	0.63005
620	160	148.28	2.249	105.78	102.12	0.63395
630	170	150.68	2.379	107.50	98.11	0.63781
640	180	153.09	2.514	109.21	94.30	0.64159
650	190	155.50	2.655	110.94	90.69	0.64533
660	200	157.92	2.801	112.67	87.27	0.64902
670	210	160.33	2.953	114.40	84.03	0.65263
680	220	162.73	3.111	116.12	80.96	0.65621
690	230	165.15	3.276	117.85	78.03	0.65973
700	240	167.56	3.446	119.58	75.25	0.66321
710	250	169.98	3.623	121.32	72.60	0.66664
720	260	172.39	3.806	123.04	70.07	0.67002
730	270	174.82	3.996	124.78	67.67	0.67335
740	280	177.23	4.193	126.51	65.38	0.67665
750	290	179.66	4.396	128.25	63.20	0.67991
760	300	182.08	4.607	129.99	61.10	0.68312
770	310	184.51	4.826	131.73	59.11	0.68629
780	320	186.94	5.051	133.47	57.20	0.68942
790	330	189.38	5.285	135.22	55.38	0.69251
800	340	191.81	5.526	136.97	53.63	0.69558
810	350	194.25	5.775	138.72	51.96	0.69860
820	360	196.69	6.033	140.47	50.35	0.70160
830	370	199.12	6.299	142.22	48.81	0.70455
840	380	201.56	6.573	143.98	47.34	0.70747
850	390	204.01	6.856	145.74	45.92	0.71037
860	400	206.46	7.149	147.50	44.57	0.71323
870	410	208.90	7.450	149.27	43.26	0.71606
880	420	211.35	7.761	151.02	42.01	0.71886
890	430	213.80	8.081	152.80	40.80	0.72163
900	440	216.26	8.411	154.57	39.64	0.72438
910	450	218.72	8.752	156.34	38.52	0.72710
920	460	221.18	9.102	158.12	37.44	0.72979
930	470	223.64	9.463	159.89	36.41	0.73245
940	480	226.11	9.834	161.68	35.41	0.73509
950	490	228.58	10.216	163.46	34.45	0.73771
960	500	231.06	10.610	165.26	33.52	0.74030
970	510	233.53	11.014	167.05	32.63	0.74287

Air at Low Pressure, per Pound

T, °R	t, °F	h Btu/lb	p_r Rel. Press.	u Btu/lb	v_r Rel. Vol.	ϕ Btu/lb-°R
980	520	236.02	11.430	168.83	31.76	0.74540
990	530	238.50	11.858	170.63	30.92	0.74792
1000	540	240.98	12.298	172.43	30.12	0.75042
1010	550	243.48	12.751	174.24	29.34	0.75290
1020	560	245.97	13.215	176.04	28.59	0.75536
1030	570	248.45	13.692	177.84	27.87	0.75778
1040	580	250.95	14.182	179.66	27.17	0.76019
1050	590	253.45	14.686	181.47	26.48	0.76259
1060	600	255.96	15.203	183.29	25.82	0.76496
1070	610	258.47	15.734	185.10	25.19	0.76732
1080	620	260.97	16.278	186.93	24.58	0.76964
1090	630	263.48	16.838	188.75	23.98	0.77196
1100	640	265.99	17.413	190.58	23.40	0.77426
1110	650	268.52	18.000	192.41	22.84	0.77654
1120	660	271.03	18.604	194.25	22.30	0.77880
1130	670	273.56	19.223	196.09	21.78	0.78104
1140	680	276.08	19.858	197.94	21.27	0.78326
1150	690	278.61	20.51	199.78	20.771	0.78548
1160	700	281.14	21.18	201.63	20.293	0.78767
1170	710	283.68	21.86	203.49	19.828	0.78985
1180	720	286.21	22.56	205.33	19.377	0.79201
1190	730	288.76	23.28	207.19	18.940	0.79415
1200	740	291.30	24.01	209.05	18.514	0.79628
1210	750	293.86	24.76	210.92	18.102	0.79840
1220	760	296.41	25.53	212.78	17.700	0.80050
1230	770	298.96	26.32	214.65	17.311	0.80258
1240	780	301.52	27.13	216.53	16.932	0.80466
1250	790	304.08	27.96	218.40	16.563	0.80672
1260	800	306.65	28.80	220.28	16.205	0.80876
1270	810	309.22	29.67	222.16	15.857	0.81079
1280	820	311.79	30.55	224.05	15.518	0.81280
1290	830	314.36	31.46	225.93	15.189	0.81481
1300	840	316.94	32.39	227.83	14.868	0.81680
1310	850	319.53	33.34	229.73	14.557	0.81878
1320	860	322.11	34.31	231.63	14.253	0.82075
1330	870	324.69	35.30	233.52	13.958	0.82270
1340	880	327.29	36.31	235.43	13.670	0.82464
1350	890	329.88	37.35	237.34	13.391	0.82658
1360	900	332.48	38.41	239.25	13.118	0.82848
1370	910	335.09	39.49	241.17	12.851	0.83039
1380	920	337.68	40.59	243.08	12.593	0.83229
1390	930	340.29	41.73	245.00	12.340	0.83417
1400	940	342.90	42.88	246.93	12.095	0.83604
1410	950	345.52	44.06	248.86	11.855	0.83790
1420	960	348.14	45.26	250.79	11.622	0.83975
1430	970	350.75	46.49	252.72	11.394	0.84158
1440	980	353.37	47.75	254.66	11.172	0.84341
1450	990	356.00	49.03	256.60	10.954	0.84523
1460	1000	358.63	50.34	258.54	10.743	0.84704
1470	1010	361.27	51.68	260.49	10.537	0.84884
1480	1020	363.89	53.04	262.44	10.336	0.85062
1490	1030	366.53	54.43	264.38	10.140	0.85239
1500	1040	369.17	55.86	266.34	9.948	0.85416
1510	1050	371.82	57.30	268.30	9.761	0.85592
1520	1060	374.47	58.78	270.26	9.578	0.85767
1530	1070	377.11	60.29	272.23	9.400	0.85940
1540	1080	379.77	61.83	274.20	9.226	0.86113
1550	1090	382.42	63.40	276.17	9.056	0.86285
1560	1100	385.08	65.00	278.13	8.890	0.86456
1570	1110	387.74	66.63	280.11	8.728	0.86626
1580	1120	390.40	68.30	282.09	8.569	0.86794
1590	1130	393.07	70.00	284.08	8.414	0.86962
1600	1140	395.74	71.73	286.06	8.263	0.87130
1610	1150	398.42	73.49	288.05	8.115	0.87297
1620	1160	401.09	75.29	290.04	7.971	0.87462
1630	1170	403.77	77.12	292.03	7.829	0.87627
1640	1180	406.45	78.99	294.03	7.691	0.87791
1650	1190	409.13	80.89	296.03	7.556	0.87954
1660	1200	411.82	82.83	298.02	7.424	0.88116
1670	1210	414.51	84.80	300.03	7.295	0.88278

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Air at Low Pressure, per Pound						
T, °R	t, °F	h Btu/lb	p_r Rel. Press.	u Btu/lb	v_r Rel. Vol.	ϕ Btu/lb-°R
1680	1220	417.20	86.82	302.04	7.168	0.88439
1690	1230	419.89	88.87	304.04	7.045	0.88599
1700	1240	422.59	90.95	306.06	6.924	0.88758
1710	1250	425.29	93.08	308.07	6.805	0.88916
1720	1260	428.00	95.24	310.09	6.690	0.89074
1730	1270	430.69	97.45	312.10	6.576	0.89230
1740	1280	433.41	99.69	314.13	6.465	0.89387
1750	1290	436.12	101.98	316.16	6.357	0.89542
1760	1300	438.83	104.30	318.18	6.251	0.89697
1770	1310	441.55	106.67	320.22	6.147	0.89850
1780	1320	444.26	109.08	322.24	6.045	0.90003
1790	1330	446.99	111.54	324.29	5.945	0.90155
1800	1340	449.71	114.03	326.32	5.847	0.90308
1810	1350	452.44	116.57	328.37	5.752	0.90458
1820	1360	455.17	119.16	330.40	5.658	0.90609
1830	1370	457.90	121.79	332.45	5.566	0.90759
1840	1380	460.63	124.47	334.50	5.476	0.90908
1850	1390	463.37	127.18	336.55	5.388	0.91056
1860	1400	466.12	129.95	338.61	5.302	0.91203
1870	1410	468.86	132.77	340.66	5.217	0.91350
1880	1420	471.60	135.64	342.73	5.134	0.91497
1890	1430	474.35	138.55	344.78	5.053	0.91643
1900	1440	477.09	141.51	346.85	4.974	0.91788
1910	1450	479.85	144.53	348.91	4.896	0.91932
1920	1460	482.60	147.59	350.98	4.819	0.92076
1930	1470	485.36	150.70	353.05	4.744	0.92220
1940	1480	488.12	153.87	355.12	4.670	0.92362
1950	1490	490.88	157.10	357.20	4.598	0.92504
1960	1500	493.64	160.37	359.28	4.527	0.92645
1970	1510	496.40	163.69	361.36	4.458	0.92786
1980	1520	499.17	167.07	363.43	4.390	0.92926
1990	1530	501.94	170.50	365.53	4.323	0.93066
2000	1540	504.71	174.00	367.61	4.258	0.93205
2010	1550	507.49	177.55	369.71	4.194	0.93343
2020	1560	510.26	181.16	371.79	4.130	0.93481
2030	1570	513.04	184.81	373.88	4.069	0.93618
2040	1580	515.82	188.54	375.98	4.008	0.93756
2050	1590	518.61	192.31	378.08	3.949	0.93891
2060	1600	521.39	196.16	380.18	3.890	0.94026
2070	1610	524.18	200.06	382.28	3.833	0.94161
2080	1620	526.97	204.02	384.39	3.777	0.94296
2090	1630	529.75	208.06	386.48	3.721	0.94430
2100	1640	532.55	212.1	388.60	3.667	0.94564
2110	1650	535.35	216.3	390.71	3.614	0.94696
2120	1660	538.15	220.5	392.83	3.561	0.94829
2130	1670	540.94	224.8	394.93	3.510	0.94960
2140	1680	543.74	229.1	397.05	3.460	0.95092
2150	1690	546.54	233.5	399.17	3.410	0.95222
2160	1700	549.35	238.0	401.29	3.362	0.95352
2170	1710	552.16	242.6	403.41	3.314	0.95482
2180	1720	554.97	247.2	405.53	3.267	0.95611
2190	1730	557.78	251.9	407.66	3.221	0.95740
2200	1740	560.59	256.6	409.78	3.176	0.95868
2210	1750	563.41	261.4	411.92	3.131	0.95996
2220	1760	566.23	266.3	414.05	3.088	0.96123
2230	1770	569.04	271.3	416.18	3.045	0.96250
2240	1780	571.86	276.3	418.31	3.003	0.96376
2250	1790	574.69	281.4	420.46	2.961	0.96501
2260	1800	577.51	286.6	422.59	2.921	0.96626
2270	1810	580.34	291.9	424.74	2.881	0.96751
2280	1820	583.16	297.2	426.87	2.841	0.96876
2290	1830	585.99	302.7	429.01	2.803	0.96999
2300	1840	588.82	308.1	431.16	2.765	0.97123
2310	1850	591.66	313.7	433.31	2.728	0.97246
2320	1860	594.49	319.4	435.46	2.691	0.97369
2330	1870	597.32	325.1	437.60	2.655	0.97489

Air at Low Pressure, per Pound						
T, °R	t, °F	h Btu/lb	p_r Rel. Press.	u Btu/lb	v_r Rel. Vol.	ϕ Btu/lb-°R
2340	1880	600.16	330.9	439.76	2.619	0.97611
2350	1890	603.00	336.8	441.91	2.585	0.97732
2360	1900	605.84	342.8	444.07	2.550	0.97853
2370	1910	608.68	348.9	446.22	2.517	0.97973
2380	1920	611.53	355.0	448.38	2.483	0.98092
2390	1930	614.37	361.3	450.54	2.451	0.98212
2400	1940	617.22	367.6	452.70	2.419	0.98331
2410	1950	620.07	374.0	454.87	2.387	0.98449
2420	1960	622.92	380.5	457.02	2.356	0.98567
2430	1970	625.77	387.0	459.20	2.326	0.98685
2440	1980	628.62	393.7	461.36	2.296	0.98802
2450	1990	631.48	400.5	463.54	2.266	0.98919
2460	2000	634.34	407.3	465.70	2.237	0.99035
2470	2010	637.20	414.3	467.88	2.209	0.99151
2480	2020	640.05	421.3	470.05	2.180	0.99266
2490	2030	642.91	428.5	472.22	2.153	0.99381
2500	2040	645.78	435.7	474.40	2.1250	0.99497
2550	2090	660.12	473.3	485.31	1.9956	1.00064
2600	2140	674.49	513.5	496.26	1.8756	1.00623
2650	2190	688.90	556.3	507.25	1.7646	1.01172
2700	2240	703.35	601.9	518.26	1.6617	1.01712
2750	2290	717.83	650.4	529.31	1.5662	1.02244
2800	2340	732.33	702.0	540.40	1.4775	1.02767
2850	2390	746.88	756.7	551.52	1.3951	1.03282
2900	2440	761.45	814.8	562.66	1.3184	1.03788
2950	2490	776.05	876.4	573.84	1.2469	1.04288
3000	2540	790.68	941.4	585.04	1.1803	1.04779
3050	2590	805.34	1010.5	596.28	1.1181	1.05264
3100	2640	820.03	1083.4	607.53	1.0600	1.05741
3150	2690	834.75	1160.5	618.82	1.0056	1.06212
3200	2740	849.48	1241.7	630.12	0.9546	1.06676
3250	2790	864.24	1327.5	641.46	0.9069	1.07134
3300	2840	879.02	1418.0	652.81	0.8621	1.07585
3350	2890	893.83	1513.0	664.20	0.8202	1.08031
3400	2940	908.66	1613.2	675.60	0.7807	1.08470
3450	2990	923.52	1718.7	687.04	0.7436	1.08904
3500	3040	938.40	1829.3	698.48	0.7087	1.09332
3550	3090	953.30	1945.8	709.95	0.6759	1.09755
3600	3140	968.21	2067.9	721.44	0.6449	1.10172
3650	3190	983.15	2196.0	732.95	0.6157	1.10584
3700	3240	998.11	2330.3	744.48	0.5882	1.10991
3750	3290	1013.09	2471.1	756.04	0.5621	1.11393
3800	3340	1028.09	2618.4	767.60	0.5376	1.11791
3850	3390	1043.11	2772.9	779.19	0.5143	1.12183
3900	3440	1058.14	2934.4	790.80	0.4923	1.12571
3950	3490	1073.19	3103.4	802.43	0.4715	1.12955
4000	3540	1088.26	3280	814.06	0.4518	1.13334
4050	3590	1103.36	3464	825.72	0.4331	1.13709
4100	3640	1118.46	3656	837.40	0.4154	1.14079
4150	3690	1133.59	3858	849.09	0.3985	1.14446
4200	3740	1148.72	4067	860.81	0.3826	1.14809
4250	3790	1163.87	4285	872.53	0.3674	1.15168
4300	3840	1179.04	4513	884.28	0.3529	1.15522
4350	3890	1194.23	4750	896.04	0.3392	1.15874
4400	3940	1209.42	4997	907.81	0.3262	1.16221
4450	3990	1224.64	5254	919.60	0.3137	1.16565
4500	4040	1239.86	5521	931.39	0.3019	1.16905
4550	4090	1255.10	5800	943.21	0.2906	1.17241
4600	4140	1270.36	6089	955.04	0.2799	1.17575
4650	4190	1285.63	6389	966.88	0.2696	1.17905
4700	4240	1300.92	6701	978.73	0.2598	1.18232
4750	4290	1316.21	7026	990.60	0.2505	1.18556
4800	4340	1331.51	7362	1002.48	0.2415	1.18876
4850	4390	1346.83	7711	1014.37	0.2330	1.19194
4900	4440	1362.17	8073	1026.28	0.2248	1.19508
4950	4490	1377.51	8448	1038.20	0.2170	1.19820
5000	4540	1392.87	8837	1050.12	0.2096	1.20129

Source: Keenan, Joseph H., Jing Chao, and Joseph Kaye, *Gas Tables: Thermodynamic Properties of Air Products of Combustion and Component Gases, Compressible Flow Functions*, New York: John Wiley & Sons, 1980.

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1.2.8 Properties of Water at Standard Conditions

Specific heat, c_p: In I-P units: $\frac{1\ \text{Btu}}{\text{lb-°F}}$ at 68°F In SI units: $\frac{4.180\ \text{kJ}}{\text{kg} \cdot \text{K}}$ at 20°C

Density at standard conditions: $\frac{1{,}000\ \text{kg}}{\text{m}^3} = \frac{62.4\ \text{lbm}}{\text{ft}^3}$

Specific weight at standard conditions: $\frac{9{,}810\ \text{N}}{\text{m}^3} = \frac{9{,}810\ \text{kg}}{\text{m}^2 \cdot \text{s}^2} = \frac{62.4\ \text{lbf}}{\text{ft}^3}$

1.2.9 Properties of Water at Atmospheric Pressure

Properties of Water* (SI Units)

Temperature (°C)	Specific Weight** γ $\left(\frac{\text{kN}}{\text{m}^3}\right)$	Density** ρ $\left(\frac{\text{kg}}{\text{m}^3}\right)$	Absolute Dynamic Viscosity** μ $(\text{Pa} \cdot \text{s})$	Kinematic Viscosity** ν $\left(\frac{\text{m}^2}{\text{s}}\right)$	Vapor Pressure*** p_v (kPa)
0	9.805	999.8	0.001781	0.000001785	0.61
5	9.807	1,000.0	0.001518	0.000001518	0.87
10	9.804	999.7	0.001307	0.000001306	1.23
15	9.798	999.1	0.001139	0.000001139	1.70
20	9.789	998.2	0.001002	0.000001003	2.34
25	9.777	997.0	0.000890	0.000000893	3.17
30	9.764	995.7	0.000798	0.000000800	4.24
40	9.730	992.2	0.000653	0.000000658	7.38
50	9.689	988.0	0.000547	0.000000553	12.33
60	9.642	983.2	0.000466	0.000000474	19.92
70	9.589	977.8	0.000404	0.000000413	31.16
80	9.530	971.8	0.000354	0.000000364	47.34
90	9.466	965.3	0.000315	0.000000326	70.10
100	9.399	958.4	0.000282	0.000000294	101.33

* Compiled from many sources, including: *Handbook of Chemistry and Physics*, 54th ed., Boca Raton: CRC Press, 1973; and *Handbook of Tables for Applied Engineering Science*, Cleveland: Chemical Rubber Co., 1970.

** From "Hydraulic Models," *ASCE Manual of Engineering Practice*, No. 25, ASCE, 1942.

*** From Keenan, J.H., and F.G. Keyes, *Thermodynamic Properties of Steam*, New York: John Wiley & Sons, 1936.

Source: Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed., New York: John Wiley & Sons, 1982.

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Properties of Water* (I-P Units)

Temperature (°F)	Specific Weight** γ $\left(\frac{\text{lbf}}{\text{ft}^3}\right)$	Density** ρ $\left(\frac{\text{lbf-sec}^2}{\text{ft}^4}\right)$	Absolute Dynamic Viscosity** μ $\times \frac{10^{-5}\ \text{lbf-sec}}{\text{ft}^2}$	Kinematic Viscosity** ν $\times \frac{10^{-5}\ \text{ft}^2}{\text{sec}}$	Vapor Pressure*** p_v (psi)
32	62.42	1.940	3.746	1.931	0.09
40	62.43	1.940	3.229	1.664	0. 12
50	62.41	1.940	2.735	1.410	0. 18
60	62.37	1.938	2.359	1.217	0. 26
70	62.30	1.936	2.050	1.059	0.36
80	62.22	1.934	1.799	0.930	0.51
90	62.11	1.931	1.595	0.826	0.70
100	62.00	1.927	1.424	0.739	0.95
110	61.86	1.923	1.284	0.667	1.24
120	61.71	1.918	1.168	0.609	1.69
130	61.55	1.913	1.069	0.558	2.22
140	61.38	1.908	0.981	0.514	2.89
150	61.20	1.902	0.905	0.476	3.72
160	61.00	1.896	0.838	0.442	4.74
170	60.80	1.890	0.780	0.413	5.99
180	60.58	1.883	0.726	0.385	7.51
190	60.36	1.876	0.678	0.362	9.34
200	60.12	1.868	0.637	0.341	11.52
212	59.83	1.860	0.593	0.319	14.70

* Compiled from many sources, including: *Handbook of Chemistry and Physics*, 54th ed., Boca Raton: CRC Press, 1973; and *Handbook of Tables for Applied Engineering Science*, Cleveland: Chemical Rubber Co., 1970.

** From "Hydraulic Models," *ASCE Manual of Engineering Practice*, No. 25, ASCE, 1942.

*** From Keenan, J.H., and F.G. Keyes, *Thermodynamic Properties of Steam*, New York: John Wiley & Sons, 1936.

Source: Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed., New York: John Wiley & Sons, 1982.

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1.2.10 Thermal Properties

The *thermal expansion coefficient* is the ratio of engineering strain to the change in temperature:

$$\alpha = \frac{\varepsilon}{\Delta T}$$

where

α = thermal expansion coefficient

ε = engineering strain

ΔT = change in temperature

Specific heat (also called *heat capacity*) is the amount of heat required to raise the temperature of a material or an amount of material by 1 degree.

At constant pressure, the amount of heat (Q) required to increase the temperature of a material by ΔT is $C_p \Delta T$, where C_p is the constant-pressure heat capacity.

At constant volume, the amount of heat (Q) required to increase the temperature of a material by ΔT is $C_v \Delta T$, where C_v is the constant-volume heat capacity.

An object can have a heat capacity that would be expressed as $\frac{\text{energy}}{\text{degree}}$.

The heat capacity of a material can be reported as $\frac{\text{energy}}{\text{degree}}$ per unit mass or per unit volume.

1.2.11 Properties of Metals

Properties of Metals—I-P Units

Metal	Symbol	Atomic Weight	Density $\rho\left(\frac{\text{lb}}{\text{ft}^3}\right)$ (Water = 62.4)	Melting Point (°F)	Specific Heat $\frac{\text{Btu}}{\text{lb-°F}}$	Heat Conductivity λ $\frac{\text{Btu}}{\text{hr-ft-°R}}$ at 32°F (459.6 °R)
Aluminum	Al	26.98	168	1,220	0.21	136
Antimony	Sb	121.75	418	1,166	0.05	15
Arsenic	As	74.92	360	sublime 1,135	0.08	-
Barium	Ba	137.33	224	1,310	0.07	-
Beryllium	Be	9.012	115	2,345	0.49	126
Bismuth	Bi	208.98	612	519	0.03	5
Cadmium	Cd	112.41	540	609	0.06	56
Caesium	Cs	132.91	119	84	0.05	21
Calcium	Ca	40.08	95	1,544	0.15	-
Cerium	Ce	140.12	419	1,472	0.05	6
Chromium	Cr	52	449	3,380	0.10	56
Cobalt	Co	58.93	549	2,721	0.10	61
Copper	Cu	63.54	557	1,983	0.09	233
Gallium	Ga	69.72	368	86	0.08	24

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Properties of Metals—I-P Units (cont'd)

Metal	Symbol	Atomic Weight	Density $\rho\left(\frac{lb}{ft^3}\right)$ (Water = 62.4)	Melting Point (°F)	Specific Heat $\frac{Btu}{lb\text{-}\,°F}$	Heat Conductivity $\lambda\,\frac{Btu}{hr\text{-}ft\text{-}°R}$ at 32°F (459.6 °R)
Gold	Au	196.97	1,203	1,947	0.03	184
Indium	In	114.82	455	312	0.06	49
Iridium	Ir	192.22	1,405	4,436	0.03	85
Iron	Fe	55.85	491	2,804	0.11	48
Lead	Pb	207.2	708	620	0.03	21
Lithium	Li	6.94	33	356	1.09	50
Magnesium	Mg	24.31	108	1,202	0.25	91
Manganese	Mn	54.94	466	2,282	0.12	5
Mercury	Hg	200.59	845	-38	0.03	5
Molybdenum	Mo	95.94	638	4,748	0.07	80
Nickel	Ni	58.69	556	2,651	0.11	54
Niobium	Nb	92.91	535	4,397	0.06	31
Osmium	Os	190.2	1,409	5,486	0.03	51
Palladium	Pd	106.4	748	2,829	0.06	42
Platinum	Pt	195.08	1,338	3,221	0.03	42
Potassium	K	39.09	54	145	0.18	60
Rhodium	Rh	102.91	775	3,565	0.06	87
Rubidium	Rb	85.47	96	102	0.08	34
Ruthenium	Ru	101.07	771	4,190	0.06	68
Silver	Ag	107.87	655	1,760	0.06	247
Sodium	Na	22.989	60	208	0.30	82
Strontium	Sr	87.62	161	1,418	-	-
Tantalum	Ta	180.95	1,040	5,432	0.04	33
Thallium	Tl	204.38	741	579	0.03	6
Thorium	Th	232.04	732	3,092	0.03	31
Tin	Sn	118.69	455	449	0.06	39
Titanium	Ti	47.88	281	3,038	0.13	13
Tungsten	W	183.85	1,201	6,128	0.03	102
Uranium	U	238.03	1,189	2,075	0.03	16
Vanadium	V	50.94	380	3,488	0.12	18
Zinc	Zn	65.38	445	786	0.09	68
Zirconium	Zr	91.22	406	3,362	0.07	13

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Properties of Metals—SI Units

Metal	Symbol	Atomic Weight	Density $\rho\left(\frac{kg}{m^3}\right)$ (Water = 1,000)	Melting Point (°C)	Specific Heat $\frac{J}{kg \cdot K}$	Heat Conductivity $\lambda \frac{W}{m \cdot K}$ at 0°C (273.2 K)
Aluminum	Al	26.98	2,698	660	895.9	236
Antimony	Sb	121.75	6,692	630	209.3	25.5
Arsenic	As	74.92	5,776	subl. 613	347.5	-
Barium	Ba	137.33	3,594	710	284.7	-
Beryllium	Be	9.012	1,846	1,285	2051.5	218
Bismuth	Bi	208.98	9,803	271	125.6	8.2
Cadmium	Cd	112.41	8,647	321	234.5	97
Caesium	Cs	132.91	1,900	29	217.7	36
Calcium	Ca	40.08	1,530	840	636.4	-
Cerium	Ce	140.12	6,711	800	188.4	11
Chromium	Cr	52	7,194	1,860	406.5	96.5
Cobalt	Co	58.93	8,800	1,494	431.2	105
Copper	Cu	63.54	8,933	1,084	389.4	403
Gallium	Ga	69.72	5,905	30	330.7	41
Gold	Au	196.97	19,281	1,064	129.8	319
Indium	In	114.82	7,290	156	238.6	84
Iridium	Ir	192.22	22,550	2,447	138.2	147
Iron	Fe	55.85	7,873	1,540	456.4	83.5
Lead	Pb	207.2	11,343	327	129.8	36
Lithium	Li	6.94	533	180	4576.2	86
Magnesium	Mg	24.31	1,738	650	1046.7	157
Manganese	Mn	54.94	7,473	1,250	502.4	8
Mercury	Hg	200.59	13,547	-39	142.3	7.8
Molybdenum	Mo	95.94	10,222	2,620	272.1	139
Nickel	Ni	58.69	8,907	1,455	439.6	94
Niobium	Nb	92.91	8,578	2,425	267.9	53
Osmium	Os	190.2	22,580	3,030	129.8	88
Palladium	Pd	106.4	11,995	1,554	230.3	72
Platinum	Pt	195.08	21,450	1,772	134	72
Potassium	K	39.09	862	63	753.6	104
Rhodium	Rh	102.91	12,420	1,963	242.8	151
Rubidium	Rb	85.47	1,533	38.8	330.7	58
Ruthenium	Ru	101.07	12,360	2,310	255.4	117
Silver	Ag	107.87	10,500	961	234.5	428
Sodium	Na	22.989	966	97.8	1,235.1	142
Strontium	Sr	87.62	2,583	770	-	-
Tantalum	Ta	180.95	16,670	3,000	150.7	57
Thallium	Tl	204.38	11,871	304	138.2	10
Thorium	Th	232.04	11,725	1,700	117.2	54

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Properties of Metals—SI Units (cont'd)

Metal	Symbol	Atomic Weight	Density $\rho\left(\frac{kg}{m^3}\right)$ (Water = 1,000)	Melting Point (°C)	Specific Heat $\frac{J}{kg \cdot K}$	Heat Conductivity $\lambda \frac{W}{m \cdot K}$ at 0°C (273.2 K)
Tin	Sn	118.69	7,285	232	230.3	68
Titanium	Ti	47.88	4,508	1,670	527.5	22
Tungsten	W	183.85	19,254	3,387	142.8	177
Uranium	U	238.03	19,050	1,135	117.2	27
Vanadium	V	50.94	6,090	1,920	481.5	31
Zinc	Zn	65.38	7,135	419	393.5	117
Zirconium	Zr	91.22	6,507	1,850	284.7	23

1.2.12 Material Properties

Typical Material Properties

(Use these values if the specific alloy and temper are not listed on table of Average Mechanical Properties)

Material	Modulus of Elasticity, E [Mpsi (GPa)]	Modulus of Rigidity, G [Mpsi (GPa)]	Poisson's Ratio, ν	Coefficient of Thermal Expansion, α [10^{-6}/°F (10^{-6}/°C)]	Density, ρ [lb/in^3 (Mg/m^3)]
Steel	29.0 (200.0)	11.5 (80.0)	0.30	6.5 (11.7)	0.282 (7.8)
Aluminum	10.0 (69.0)	3.8 (26.0)	0.33	13.1 (23.6)	0.098 (2.7)
Cast Iron	14.5 (100.0)	6.0 (41.4)	0.21	6.7 (12.1)	0.246–0.282 (6.8–7.8)
Wood (Fir)	1.6 (11.0)	0.6 (4.1)	0.33	1.7 (3.0)	–
Brass	14.8–18.1 (102–125)	5.8 (40)	0.33	10.4 (18.7)	0.303–0.313 (8.4–8.7)
Copper	17 (117)	6.5 (45)	0.36	9.3 (16.6)	0.322 (8.9)
Bronze	13.9–17.4 (96–120)	6.5 (45)	0.34	10.0 (18.0)	0.278–0.314 (7.7–8.7)
Magnesium	6.5 (45)	2.4 (16.5)	0.35	14 (25)	0.061 (1.7)
Glass	10.2 (70)	–	0.22	5.0 (9.0)	0.090 (2.5)
Polystyrene	0.3 (2)	–	0.34	38.9 (70.0)	0.038 (1.05)
Polyvinyl Chloride (PVC)	<0.6 (<4)	–	–	28.0 (50.4)	0.047 (1.3)
Alumina Fiber	58 (400)	–	–	–	0.141 (3.9)
Aramide Fiber	18.1 (125)	–	–	–	0.047 (1.3)
Boron Fiber	58 (400)	–	–	–	0.083 (2.3)
Beryllium Fiber	43.5 (300)	–	–	–	0.069 (1.9)
BeO Fiber	58 (400)	–	–	–	0.108 (3.0)
Carbon Fiber	101.5 (700)	–	–	–	0.083 (2.3)
Silicon Carbide Fiber	58 (400)	–	–	–	0.116 (3.2)

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Average Mechanical Properties of Typical Engineering Materials[a]—I-P Units													
Materials		Specific Weight γ $\frac{lb}{in^3}$	Modulus of Elasticity E (10^3 ksi)	Modulus of Rigidity G (10^3 ksi)	Yield Strength (ksi) σ_y			Ultimate Strength (ksi) σ_u			% Elongation in 2-in Specimen	Poisson's Ratio ν	Coef. of Therm. Expansion α $\frac{10^{-6}}{°F}$
					Tens.	Comp.[b]	Shear	Tens.	Comp.[b]	Shear			
Metallic													
Aluminum Wrought Alloys	2014-T6	0.101	10.6	3.9	60	60	25	68	68	42	10	0.35	12.8
	6061-T6	0.098	10.0	3.7	37	37	19	42	42	27	12	0.35	13.1
Cast Iron Alloys	Gray ASTM 20	0.260	10.0	3.9	–	–	–	26	97	–	0.6	0.28	6.70
	Malleable ASTM A-197	0.263	25.0	9.8	–	–	–	40	83	–	5	0.28	6.60
Copper Alloys	Red Brass C83400	0.316	14.6	5.4	11.4	11.4	–	35	35	–	35	0.35	9.80
	Bronze C86100	0.319	15.0	5.6	50	50	–	95	95	–	20	0.34	9.60
Magnesium Alloy	Am 1004-T611	0.066	6.48	2.5	22	22	–	40	40	22	1	0.30	14.3
Steel Alloys	Structural A36	0.284	29.0	11.0	36	36	–	58	58	–	30	0.32	6.60
	Stainless 304	0.284	28.0	11.0	30	30	–	75	75	–	40	0.27	9.60
	Tool L2	0.295	29.0	11.0	102	102	–	116	116	–	22	0.32	6.50
Titanium Alloy	Ti-6Al-4V	0.160	17.4	6.4	134	134	–	145	145	–	16	0.36	5.20
Nonmetallic													
Concrete	Low Strength	0.086	3.20	–	–	–	1.8	–	–	–	–	0.15	6.0
	High Strength	0.086	4.20	–	–	–	5.5	–	–	–	–	0.15	6.0
Plastic, Reinforced	Kevlar 49	0.0524	19.0	–	–	–	–	104	70	10.2	2.8	0.34	–
	30% Glass	0.0524	10.5	–	–	–	–	13	19	–	–	0.34	–
Wood Select, Structural Grade	Douglas Fir	0.017	1.90	–	–	–	–	0.30[c]	3.78[d]	0.90[d]	–	0.29[c]	–
	White Spruce	0.130	1.40	–	–	–	–	0.36[c]	5.18[d]	0.97[d]	–	0.31[c]	–

[a] Specific values may vary for a particular material due to alloy or mineral composition, mechanical working of the specimen, or heat treatment.
[b] The yield strength and ultimate strength for ductile materials can be assumed equal for both tension and compression.
[c] Measured perpendicular to the grain
[d] Measured parallel to the grain
[e] Deformation measured perpendicular to the grain when the load is applied along the grain

Source: Hibbeler, Russell C., *Mechanics of Materials*, 4th ed., ©2000. Reprinted by permission of Pearson Education, Inc.

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1.3 Trigonometry

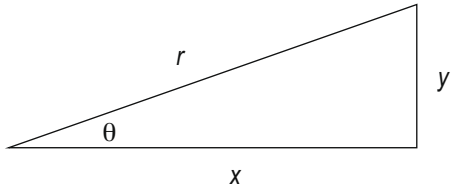
1.3.1 Basics

Trigonometric functions are defined using a right triangle:

$$\sin\theta = \frac{y}{r}, \cos\theta = \frac{x}{r}$$

$$\tan\theta = \frac{y}{x}, \cot\theta = \frac{x}{y}$$

$$\csc\theta = \frac{r}{y}, \sec\theta = \frac{r}{x}$$



Law of Sines:

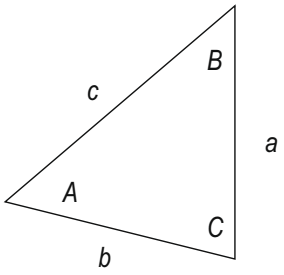
$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

Law of Cosines:

$$a^2 = b^2 + c^2 - 2bc\cos A$$

$$b^2 = a^2 + c^2 - 2ac\cos B$$

$$c^2 = a^2 + b^2 - 2ab\cos C$$



Source: Brink, R.W., *A First Year of College Mathematics*, Englewood Cliffs, NJ: D. Appleton-Century Co., Inc., 1937.

1.3.2 Identities

$$\cos\theta = \sin(\theta + \pi/2) = -\sin(\theta - \pi/2)$$

$$\sin\theta = \cos(\theta - \pi/2) = -\cos(\theta + \pi/2)$$

$$\csc\theta = \frac{1}{\sin\theta}$$

$$\sec\theta = \frac{1}{\cos\theta}$$

$$\tan\theta = \frac{\sin\theta}{\cos\theta}$$

$$\cot\theta = \frac{1}{\tan\theta}$$

$$\sin^2\theta + \cos^2\theta = 1$$

$$\tan^2\theta + 1 = \sec^2\theta$$

$$\cot^2\theta + 1 = \csc^2\theta$$

$$\sin(\alpha + \beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta$$

$$\cos(\alpha + \beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$

$$\sin 2\alpha = 2\sin\alpha\cos\alpha$$

$$\cos 2\alpha = \cos^2\alpha - \sin^2\alpha = 1 - 2\sin^2\alpha = 2\cos^2\alpha - 1$$

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$$\tan 2\alpha = \frac{2\tan\alpha}{1-\tan^2\alpha}$$

$$\cot 2\alpha = \frac{\cot^2\alpha - 1}{2\cot\alpha}$$

$$\tan(\alpha+\beta) = \frac{\tan\alpha+\tan\beta}{1-\tan\alpha\tan\beta}$$

$$\cot(\alpha+\beta) = \frac{\cot\alpha\cot\beta-1}{\cot\alpha+\cot\beta}$$

$$\sin(\alpha-\beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$$

$$\cos(\alpha-\beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

$$\tan(\alpha-\beta) = \frac{\tan\alpha-\tan\beta}{1+\tan\alpha\tan\beta}$$

$$\cot(\alpha-\beta) = \frac{\cot\alpha\cot\beta+1}{\cot\beta-\cot\alpha}$$

$$\sin\frac{\alpha}{2} = \pm\sqrt{\frac{1-\cos\alpha}{2}}$$

$$\cos\frac{\alpha}{2} = \pm\sqrt{\frac{1+\cos\alpha}{2}}$$

$$\tan\frac{\alpha}{2} = \pm\sqrt{\frac{1-\cos\alpha}{1+\cos\alpha}}$$

$$\cot\frac{\alpha}{2} = \pm\sqrt{\frac{1+\cos\alpha}{1-\cos\alpha}}$$

$$\sin\alpha\sin\beta = \frac{1}{2}[\cos(\alpha-\beta) - \cos(\alpha+\beta)]$$

$$\cos\alpha\cos\beta = \frac{1}{2}[\cos(\alpha-\beta) + \cos(\alpha+\beta)]$$

$$\sin\alpha\cos\beta = \frac{1}{2}[\sin(\alpha+\beta) + \sin(\alpha-\beta)]$$

$$\sin\alpha + \sin\beta = 2\sin\left[\frac{1}{2}(\alpha+\beta)\right]\cos\left[\frac{1}{2}(\alpha-\beta)\right]$$

$$\sin\alpha - \sin\beta = 2\cos\left[\frac{1}{2}(\alpha+\beta)\right]\sin\left[\frac{1}{2}(\alpha-\beta)\right]$$

$$\cos\alpha + \cos\beta = 2\cos\left[\frac{1}{2}(\alpha+\beta)\right]\cos\left[\frac{1}{2}(\alpha-\beta)\right]$$

$$\cos\alpha - \cos\beta = -2\sin\left[\frac{1}{2}(\alpha+\beta)\right]\sin\left[\frac{1}{2}(\alpha-\beta)\right]$$

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1.4 Mensuration of Areas and Volumes

1.4.1 Nomenclature

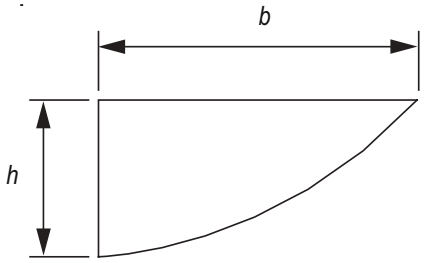
A = total surface area

P = perimeter

V = volume

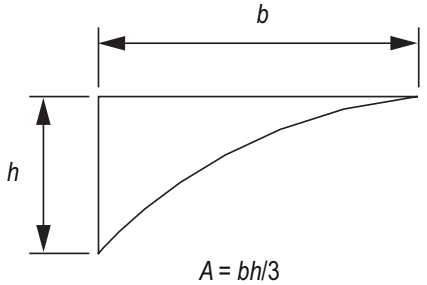
1.4.2 Parabola

Half parabola



$A = 2bh/3$

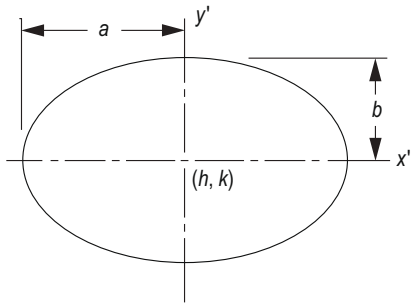
Complement of half parabola



$A = bh/3$

1.4.3 Ellipse

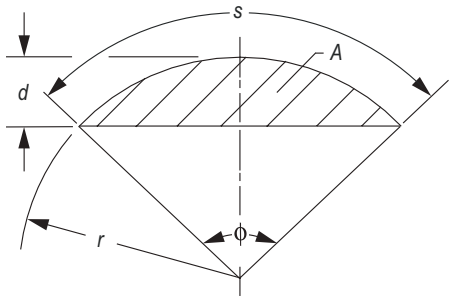
$$P_{\text{approx}} = 2\pi\sqrt{\frac{(a^2+b^2)}{2}}$$



$A = \pi ab$

1.4.4 Circular Segment

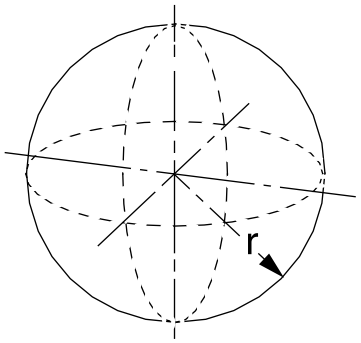
$$A = \frac{r^2\left(\phi - \sin\phi\right)}{2} \qquad \phi = \frac{s}{r} = 2\arccos\frac{\left(r-d\right)}{r}$$



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1.4.5 Sphere

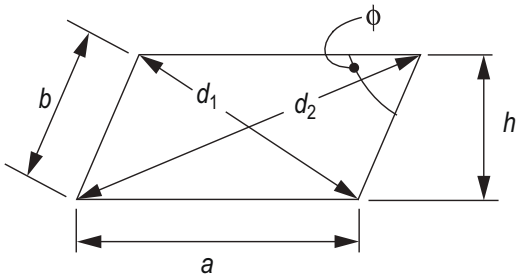
$$V = 4\pi r^3/3 = \pi d^3/6$$
$$A = 4\pi r^2 = \pi d^2$$



1.4.6 Parallelogram

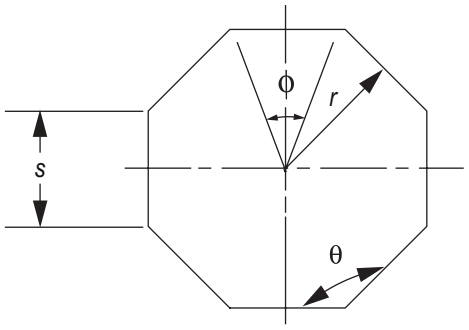
$$P = 2(a+b)$$
$$d_1 = \sqrt{a^2 + b^2 - 2ab\left(\cos\phi\right)}$$
$$d_2 = \sqrt{a^2 + b^2 + 2ab\left(\cos\phi\right)}$$
$$d_1^2 + d_2^2 = 2(a^2 + b^2)$$
$$A = ah = ab\left(\sin\phi\right)$$

If $a = b$, the parallelogram is a rhombus.



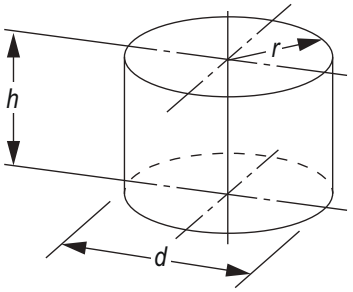
1.4.7 Regular Polygon with *n* Equal Sides

$$\phi = \frac{2\pi}{n}$$
$$\theta = \frac{\pi\left(n-2\right)}{n} = \pi\left(1 - \frac{2}{n}\right)$$
$$P = ns$$
$$s = 2r\left[\tan\left(\frac{\phi}{2}\right)\right]$$
$$A = \frac{nsr}{2}$$



1.4.8 Right Circular Cylinder

$$V = \pi r^2 h = \frac{\pi d^2 h}{4}$$
$$A = 2\pi r\left(h + r\right)$$



Source for Ellipse, Circular Segment, Sphere, Regular Polygon, and Right Circular Cylinder:
Gieck, K., and R. Gieck, *Engineering Formulas*, 1st American ed., New York: McGraw-Hill, 1971.

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1.4.9 Properties of Shapes

1.4.9.1 Centroids of Masses, Areas, Lengths, and Volumes

The following formulas are for discrete masses, areas, lengths, and volumes:

$$\boldsymbol{r}_c = \frac{\Sigma m_n \boldsymbol{r}_n}{\Sigma m_n}$$

where

m_n = the *mass of each particle* making up the system

$\boldsymbol{r}_n$ = the *radius vector* to each particle from a selected reference point

$\boldsymbol{r}_c$ = the *radius vector* to the *centroid of the total mass* from the selected reference point

The *moment of area* (M_a) is defined as

$$M_{ay} = \Sigma x_n a_n$$

$$M_{ax} = \Sigma y_n a_n$$

where

a_n = area of n^{th} element

x_n = distance from x axis to centroid of area a_n

y_n = distance from y axis to centroid of area a_n

The *centroid of area* is defined as

$$x_{ac} = \frac{M_{ay}}{A} = \Sigma x_n \frac{a_n}{A}$$

$$y_{ac} = \frac{M_{ax}}{A} = \Sigma y_n \frac{a_n}{A}$$

where $A = \Sigma a_n$

1.4.9.2 Moment of Inertia

The *moment of inertia*, or the second moment of area, is defined as

$$I_y = \int x^2 \, dA$$
$$I_x = \int y^2 \, dA$$

The *polar moment of inertia J* of an area about a point is equal to the sum of the moments of inertia of the area about any two perpendicular axes in the area and passing through the same point:

$$I_z = J = I_y + I_x = \int \left(x^2 + y^2\right) dA$$
$$= r_p^2 A$$

where

r_p = the *radius of gyration*, as defined below

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1.4.9.3 Mass Moment of Inertia

In general, $I = \int r^2\, dm$. The definitions for the mass moments of inertia about the coordinate axes are

$$I_x = \int \left(y^2 + z^2\right) dm$$
$$I_y = \int \left(x^2 + z^2\right) dm$$
$$I_z = \int \left(x^2 + y^2\right) dm$$

Parallel-Axis Theorem

$$I_{new} = I_G + md^2$$

where

I_{new} = mass moment of inertia about any specified axis

I_G = mass moment of inertia about an axis that is parallel to the above specified axis but passes through the body's mass center

m = mass of the body

d = normal distance from the body's mass center to the above-specified axis

1.4.9.4 Moment of Inertia Parallel Axis Theorem

$$I'_x = I_{x_c} + d_y^2 A$$
$$I'_y = I_{y_c} + d_x^2 A$$

where

d_x, d_y = distance between the two axes in question

I_{x_c}, I_{y_c} = the moment of inertia about the centroidal axis

I'_x , I'_y = the moment of inertia about the new axis

1.4.9.5 Radius of Gyration

The *radius of gyration* r_p, r_x, r_y is the distance from a reference axis at which all the area can be considered concentrated to produce the moment of inertia.

$$r_x = \sqrt{\frac{I_x}{A}};\quad r_y = \sqrt{\frac{I_y}{A}};\quad r_p = \sqrt{\frac{J}{A}}$$

1.4.9.6 Product of Inertia

The product of inertia (I_{xy}, etc.) is defined as

$$I_{xy} = \int xydA, \text{ with respect to the x-y coordinate system}$$

The parallel-axis theorem also applies:

$$I_{xy} = I_{xc\,yc} + d_x d_y A \text{ for the x-y coordinate system, etc.}$$

where

d_x = x-axis distance between the two axes in question

d_y = y-axis distance between the two axes in question

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1.4.9.7 Mass Radius of Gyration

The mass radius of gyration is defined as

$$r_m = \sqrt{\frac{I}{m}}$$

Rotation About an Arbitrary Fixed Axis

Rigid Body Motion About a Fixed Axis

Variable α	Constant $\alpha = \alpha_c$
$\alpha = \frac{d\omega}{dt}$	$\omega = \omega_0 + \alpha_c t$
$\omega = \frac{d\theta}{dt}$	$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha_c t^2$
$\omega d\omega = \alpha d\theta$	$\omega^2 = \omega_0^2 + 2\alpha_c(\theta - \theta_0)$

where

θ = angle of rotation

ω = angular velocity

α = angular acceleration

For rotation about some arbitrary fixed axis *q*:

$$\sum M_q = I_q \alpha$$

where

M_q = torque

I_q = mass moment of inertia

If the applied moment acting about the fixed axis is constant, then integrating with respect to time from $t = 0$ yields

$$\alpha = \frac{M_q}{I_q}$$

$$\omega = \omega_0 + \alpha t$$

$$\theta = \theta_0 + \omega_0 t + \alpha \frac{t^2}{2}$$

where ω_0 and θ_0 are the values of angular velocity and angular displacement, respectively, at time $t = 0$

Source: Hibbeler, R.C., *Engineering Mechanics*, 10th ed., New York: Pearson, 2003.

The change in kinetic energy is the work done in accelerating the rigid body from ω_0 to ω:

$$I_q \frac{\omega^2}{2} = I_q \frac{\omega_0^2}{2} + \int_{\theta_0}^{\theta} M_q d\theta$$

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Principles of Work Energy

In general, the kinetic energy for a rigid body may be written

$$KE = \frac{mv^2}{2} + I_c \frac{\omega^2}{2}$$

For motion in the x–y plane this reduces to

$$KE = m\frac{v_{cx}^2 + v_{cy}^2}{2} + I_c \frac{\omega_z^2}{2}$$

where

I_c = mass moment if inertia about rotation axis c

v_{cx} = center of mass velocity along x direction

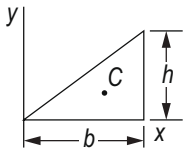
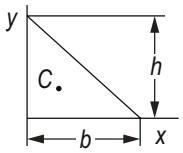
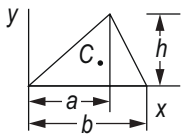
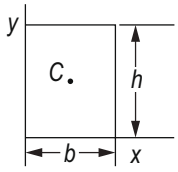
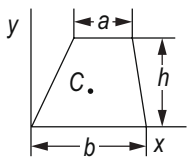
v_{cy} = center of mass velocity along y direction

For motion about an instant center:

$$KE = I_c \frac{\omega^2}{2}$$

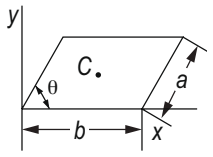
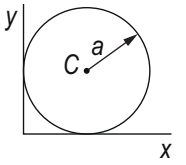
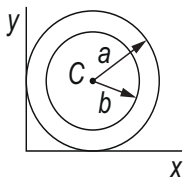
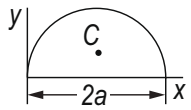
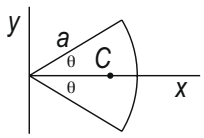
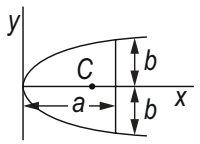
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Properties of Various Shapes

Shape	Area & Centroid	Area Moment of Inertia	(Radius of Gyration)^2	Product of Inertia
	$A = \frac{bh}{2}$ $x_c = \frac{2b}{3}$ $y_c = \frac{h}{3}$	$I_{x_c} = \frac{bh^3}{36}$ $I_{y_c} = \frac{b^3h}{36}$ $I_x = \frac{bh^3}{12}$ $I_y = \frac{b^3h}{4}$	$r_{x_c}^2 = \frac{h^2}{18}$ $r_{y_c}^2 = \frac{b^2}{18}$ $r_x^2 = \frac{h^2}{6}$ $r_y^2 = \frac{b^2}{2}$	$I_{x_cy_c} = \frac{Abh}{36} = \frac{b^2h^2}{72}$ $I_{xy} = \frac{Abh}{4} = \frac{b^2h^2}{8}$
	$A = \frac{bh}{2}$ $x_c = \frac{b}{3}$ $y_c = \frac{h}{3}$	$I_{x_c} = \frac{bh^3}{36}$ $I_{y_c} = \frac{b^3h}{36}$ $I_x = \frac{bh^3}{12}$ $I_y = \frac{b^3h}{12}$	$r_{x_c}^2 = \frac{h^2}{18}$ $r_{y_c}^2 = \frac{b^2}{18}$ $r_x^2 = \frac{h^2}{6}$ $r_y^2 = \frac{b^2}{6}$	$I_{x_cy_c} = -\frac{Abh}{36} = -\frac{b^2h^2}{72}$ $I_{xy} = \frac{Abh}{12} = \frac{b^2h^2}{24}$
	$A = \frac{bh}{2}$ $x_c = \frac{a+b}{3}$ $y_c = \frac{h}{3}$	$I_{x_c} = \frac{bh^3}{36}$ $I_{y_c} = \frac{bh(b^2 - ab + a^2)}{36}$ $I_x = \frac{bh^3}{12}$ $I_y = \frac{bh(b^2 + ab + a^2)}{12}$	$r_{x_c}^2 = \frac{h^2}{18}$ $r_{y_c}^2 = \frac{b^2 - ab + a^2}{18}$ $r_x^2 = \frac{h^2}{6}$ $r_y^2 = \frac{b^2 + ab + a^2}{6}$	$I_{x_cy_c} = \frac{Ah(2a-b)}{36} = \frac{bh^2(2a-b)}{72}$ $I_{xy} = \frac{Ah(2a-b)}{12} = \frac{bh^2(2a-b)}{24}$
	$A = bh$ $x_c = \frac{b}{2}$ $y_c = \frac{h}{2}$	$I_{x_c} = \frac{bh^3}{12}$ $I_{y_c} = \frac{b^3h}{12}$ $I_x = \frac{bh^3}{3}$ $I_y = \frac{b^3h}{3}$ $J = \frac{bh(b^2 + h^2)}{12}$	$r_{x_c}^2 = \frac{h^2}{12}$ $r_{y_c}^2 = \frac{b^2}{12}$ $r_x^2 = \frac{h^2}{3}$ $r_y^2 = \frac{b^2}{3}$ $r_p^2 = \frac{b^2 + h^2}{12}$	$I_{x_cy_c} = 0$ $I_{xy} = \frac{Abh}{4} = \frac{b^2h^2}{4}$
	$A = \frac{h(a+b)}{2}$ $y_c = \frac{h(2a+b)}{3(a+b)}$	$I_{x_c} = \frac{h^3(a^2 + 4ab + b^2)}{36(a+b)}$ $I_x = \frac{h^3(3a+b)}{12}$	$r_{x_c}^2 = \frac{h^2(a^2 + 4ab + b^2)}{18(a+b)}$ $r_x^2 = \frac{h^2(3a+b)}{6(a+b)}$	

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Properties of Various Shapes (cont'd)

Shape	Area & Centroid	Area Moment of Inertia	(Radius of Gyration)^2	Product of Inertia
	$A = ab\sin\theta$ $x_c = \frac{b + a\cos\theta}{2}$ $y_c = \frac{a\sin\theta}{2}$	$I_{x_c} = \frac{a^3 b\sin^3\theta}{12}$ $I_{y_c} = \frac{ab\sin\theta\left(b^2 + a^2\cos^2\theta\right)}{12}$ $I_x = \frac{a^3 b\sin^3\theta}{3}$ $I_y = \frac{ab\sin\theta\left(b + a\cos\theta\right)^2}{3} - \frac{a^2 b^2\sin\theta\cos\theta}{6}$	$r_{x_c}^2 = \frac{(a\sin\theta)^2}{12}$ $r_{y_c}^2 = \frac{b^2 + a^2\cos^2\theta}{12}$ $r_x^2 = \frac{(a\sin\theta)^2}{3}$ $r_y^2 = \frac{(b + a\cos\theta)^2}{3} - \frac{ab\cos\theta}{6}$	$I_{x_c y_c} = \frac{a^3 b\sin^2\theta\cos\theta}{12}$
	$A = \pi a^2$ $x_c = a$ $y_c = a$	$I_{x_c} = I_{y_c} = \frac{\pi a^4}{4}$ $I_x = I_y = \frac{5\pi a^4}{4}$ $J = \frac{\pi a^4}{2}$	$r_{x_c}^2 = r_{y_c}^2 = \frac{a^2}{4}$ $r_x^2 = r_y^2 = \frac{5a^2}{4}$ $r_p^2 = \frac{a^2}{2}$	$I_{x_c y_c} = 0$ $I_{xy} = Aa^2$
	$A = \pi\left(a^2 - b^2\right)$ $x_c = a$ $y_c = a$	$I_{x_c} = I_{y_c} = \frac{\pi\left(a^4 - b^4\right)}{4}$ $I_x = I_y = \frac{5\pi a^4}{4} - \pi a^2 b^2 - \frac{\pi b^4}{4}$ $J = \frac{\pi\left(a^4 - b^4\right)}{2}$	$r_{x_c}^2 = r_{y_c}^2 = \frac{a^2 + b^2}{4}$ $r_x^2 = r_y^2 = \frac{5a^2 + b^2}{4}$ $r_p^2 = \frac{a^2 + b^2}{2}$	$I_{x_c y_c} = 0$ $I_{xy} = Aa^2 = \pi a^2\left(a^2 - b^2\right)$
	$A = \frac{\pi a^2}{2}$ $x_c = a$ $y_c = \frac{4a}{3\pi}$	$I_{x_c} = \frac{a^4\left(9\pi^2 - 64\right)}{72\pi}$ $I_{y_c} = \frac{\pi a^4}{8}$ $I_x = \frac{\pi a^4}{8}$ $I_y = \frac{5\pi a^4}{8}$	$r_{x_c}^2 = \frac{a^2\left(9\pi^2 - 64\right)}{36\pi^2}$ $r_{y_c}^2 = \frac{a^2}{4}$ $r_x^2 = \frac{a^2}{4}$ $r_y^2 = \frac{5a^2}{4}$	$I_{x_c y_c} = 0$ $I_{xy} = \frac{2a^4}{3}$
	$A = a^2\theta$ $x_c = \frac{2a}{3}\ \frac{\sin\theta}{\theta}$ $y_c = 0$	$I_x = \frac{a^4\left(\theta - \sin\theta\cos\theta\right)}{4}$ $I_y = \frac{a^4\left(\theta + \sin\theta\cos\theta\right)}{4}$	$r_x^2 = \frac{a^2}{4}\ \frac{\theta - \sin\theta\cos\theta}{\theta}$ $r_y^2 = \frac{a^2}{4}\ \frac{\theta + \sin\theta\cos\theta}{\theta}$	$I_{x_c y_c} = 0$ $I_{xy} = 0$
	$A = \frac{4ab}{3}$ $x_c = \frac{3a}{5}$ $y_c = 0$	$I_{x_c} = I_x = \frac{4ab^3}{15}$ $I_{y_c} = \frac{16a^3 b}{175}$ $I_y = \frac{4a^3 b}{7}$	$r_{x_c}^2 = r_x^2 = \frac{b^2}{5}$ $r_{y_c}^2 = \frac{12a^2}{175}$ $r_y^2 = \frac{3a^2}{7}$	$I_{x_c y_c} = 0$ $I_{xy} = 0$

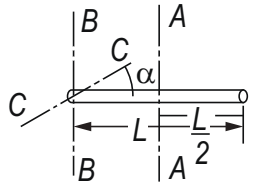
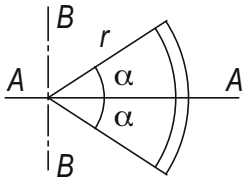
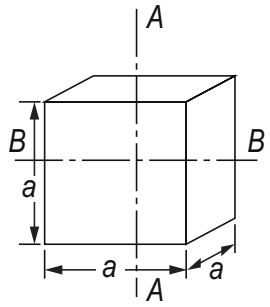
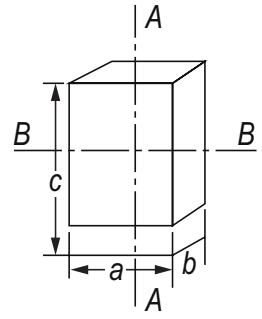
Source: Housner, George W., and Donald E. Hudson, *Applied Mechanics Dynamics*, 2nd ed., Princeton, NJ: D. Van Nostrand Co., Inc., 1959.

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1.4.10 Relations of Mass and Space

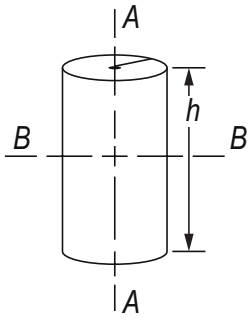
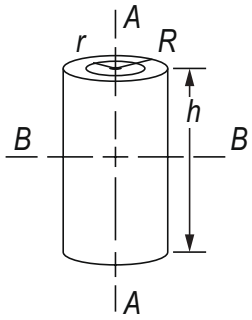
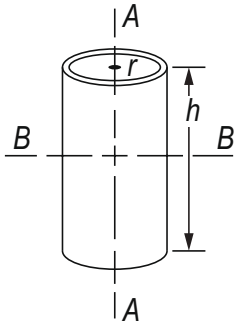
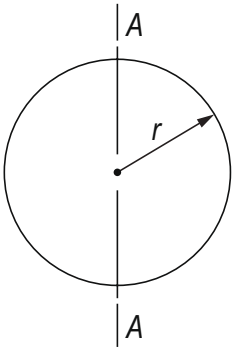
Properties of Various Solids

All axes pass through the center of gravity unless otherwise noted. $J_m = \frac{J}{g}$ *and* M *= total mass of the body.*

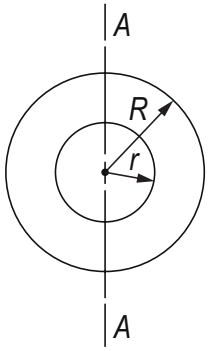
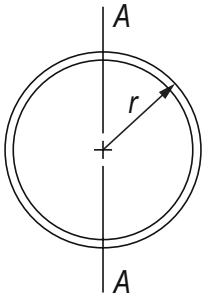
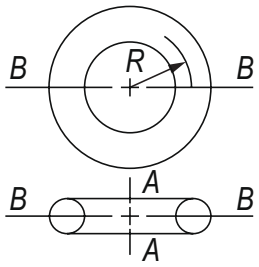
Solid	Moments of Inertia, J	Radius of Gyration, K
Straight Rod: 	$J_{AA} = \frac{1}{12}ML^2$ $J_{BB} = \frac{1}{3}ML^2$ $J_{CC} = \frac{1}{3}ML^2 \sin^2\alpha$	$K_{AA} = \frac{L}{\sqrt{12}}$ $K_{BB} = \frac{L}{\sqrt{3}}$ $K_{CC} = L\frac{\sin\alpha}{\sqrt{3}}$
Rod Bent into a Circular Arc: 	$J_{AA} = \frac{1}{2}Mr^2\left(1 - \frac{\sin\alpha\cos\alpha}{\alpha}\right)$ $J_{BB} = \frac{1}{2}Mr^2\left(1 + \frac{\sin\alpha\cos\alpha}{\alpha}\right)$	$K_{AA} = r\sqrt{\frac{1}{2}\left(1 - \frac{\sin\alpha\cos\alpha}{\alpha}\right)}$ $K_{BB} = r\sqrt{\frac{1}{2}\left(1 + \frac{\sin\alpha\cos\alpha}{\alpha}\right)}$
Cube: 	$J_{AA} = J_{BB} = \frac{1}{6}Ma^2$	$K_{AA} = K_{BB} = \frac{a}{\sqrt{6}}$
Rectangular Prism: 	$J_{AA} = \frac{1}{12}M\left(a^2 + b^2\right)$ $J_{BB} = \frac{1}{12}M\left(b^2 + c^2\right)$	$K_{AA} = \sqrt{\frac{a^2 + b^2}{12}}$ $K_{BB} = \sqrt{\frac{b^2 + c^2}{12}}$

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Properties of Various Solids (cont'd)

Solid	Moments of Inertia, J	Radius of Gyration, K
Right Circular Cylinder: 	$J_{AA} = \frac{1}{2}Mr^2$ $J_{BB} = \frac{1}{12}M\left(3r^2 + h^2\right)$	$K_{AA} = \frac{r}{\sqrt{2}}$ $K_{BB} = \sqrt{\frac{3r^2 + h^2}{12}}$
Hollow Right Circular Cylinder: 	$J_{AA} = \frac{1}{2}M\left(R^2 + r^2\right)$ $J_{BB} = \frac{1}{4}M\left(R^2 + r^2 + \frac{h^2}{3}\right)$	$K_{AA} = \sqrt{\frac{R^2 + r^2}{2}}$ $K_{BB} = \sqrt{\frac{3R^2 + 3r^2 + h^2}{12}}$
Thin Hollow Cylinder: 	$J_{AA} = Mr^2$ $J_{BB} = \frac{M}{2}\left(r^2 + \frac{h^2}{6}\right)$	$K_{AA} = r$ $K_{BB} = \sqrt{\frac{6r^2 + h^2}{12}}$
Sphere: 	$J_{AA} = \frac{2}{5}Mr^2$	$K_{AA} = \frac{2r}{\sqrt{10}}$

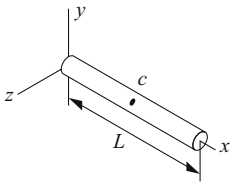
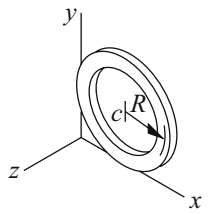
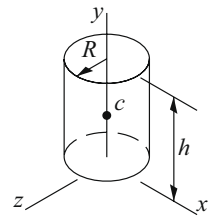
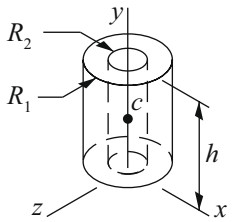
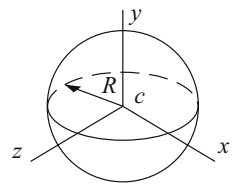
Properties of Various Solids (cont'd)

Solid	Moments of Inertia, J	Radius of Gyration, K
Hollow Sphere: 	$J_{AA} = \frac{2}{5} M \frac{R^5 - r^5}{R^3 - r^3}$	$K_{AA} = \sqrt{\frac{2}{5} \frac{(R^5 - r^5)}{(R^3 - r^3)}}$
Thin Hollow Sphere: 	$J_{AA} = \frac{2}{3} M r^2$	$K_{AA} = \frac{2r}{\sqrt{6}}$
Torus: 	$J_{AA} = M\left(R^2 + \frac{3}{4} r^2\right)$ $J_{BB} = M\left(\frac{R^2}{2} + \frac{5}{8} r^2\right)$	$K_{AA} = \frac{1}{2}\sqrt{4R^2 + 3r^2}$ $K_{BB} = \sqrt{\frac{4R^2 + 5r^2}{8}}$

Source: Hudson, Ralph G., *The Engineers' Manual*, New York: John Wiley & Sons, 1917.

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Mass and Mass Moments of Inertia of Geometric Shapes

Shape	Mass & Centroid	Mass Moment of Inertia	(Radius of Gyration)^2	Product of Inertia
	$M = \rho LA$ $x_c = \frac{L}{2}$ $y_c = 0$ $z_c = 0$ A = cross-sectional area of rod ρ = mass/vol.	$I_x = I_{x_c} = 0$ $I_{y_c} = I_{z_c} = \frac{ML^2}{12}$ $I_y = I_z = \frac{ML^2}{3}$	$r_x^2 = r_{x_c}^2 = 0$ $r_{y_c}^2 = r_{z_c}^2 = \frac{L^2}{12}$ $r_y^2 = r_z^2 = \frac{L^2}{3}$	$I_{x_cy_c}$, etc. = 0 I_{xy}, etc. = 0
	$M = 2\pi R\rho A$ $x_c = R$ = mean radius $y_c = R$ = mean radius $z_c = 0$ A = cross-sectional area of ring ρ = mass/vol.	$I_{x_c} = I_{y_c} = \frac{MR^2}{2}$ $I_{z_c} = MR^2$ $I_x = I_y = \frac{3MR^2}{2}$ $I_z = 3MR^2$	$r_{x_c}^2 = r_{y_c}^2 = \frac{R^2}{2}$ $r_{z_c}^2 = R^2$ $r_x^2 = r_y^2 = \frac{3R^2}{2}$ $r_z^2 = 3R^2$	$I_{x_cy_c}$, etc. = 0 $I_{z_cz_c}$, etc. = MR^2 $I_{xz} = I_{yz} = 0$
	$M = \pi R^2 \rho h$ $x_c = 0$ $y_c = \frac{h}{2}$ $z_c = 0$ ρ = mass/vol.	$I_{x_c} = I_{z_c} = \frac{M(3R^2 + h^2)}{12}$ $I_{y_c} = I_y = \frac{MR^2}{2}$ $I_x = I_z = \frac{M(3R^2 + 4h^2)}{12}$	$r_{x_c}^2 = r_{z_c}^2 = \frac{3R^2 + h^2}{12}$ $r_{y_c}^2 = r_y^2 = \frac{R^2}{2}$ $r_x^2 = r_z^2 = \frac{3R^2 + 4h^2}{12}$	$I_{x_cy_c}$, etc. = 0 I_{xy}, etc. = 0
	$M = \pi\left(R_1^2 - R_2^2\right)\rho h$ $x_c = 0$ $y_c = \frac{h}{2}$ $z_c = 0$ ρ = mass/vol.	$I_{x_c} = I_{z_c} = \frac{M\left(3R_1^2 + 3R_2^2 + h^2\right)}{12}$ $I_{y_c} = I_y = \frac{M\left(R_1^2 + R_2^2\right)}{2}$ $I_x = I_z = \frac{M\left(3R_1^2 + 3R_2^2 + 4h^2\right)}{12}$	$r_{x_c}^2 = r_{z_c}^2 = \frac{3R_1^2 + 3R_2^2 + h^2}{12}$ $r_{y_c}^2 = r_y^2 = \frac{R_1^2 + R_2^2}{2}$ $r_x^2 = r_z^2 = \frac{3R_1^2 + 3R_2^2 + 4h^2}{12}$	$I_{x_cy_c}$, etc. = 0 I_{xy}, etc. = 0
	$M = \frac{4}{3}\pi R^3 \rho$ $x_c = 0$ $y_c = 0$ $z_c = 0$ ρ = mass/vol.	$I_{x_c} = I_x = \frac{2MR^2}{5}$ $I_{y_c} = I_y = \frac{2MR^2}{5}$ $I_{z_c} = I_z = \frac{2MR^2}{5}$	$r_{x_c}^2 = r_x^2 = \frac{2R^2}{5}$ $r_{y_c}^2 = r_y^2 = \frac{2R^2}{5}$ $r_{z_c}^2 = r_z^2 = \frac{2R^2}{5}$	$I_{x_cy_c}$, etc. = 0

Source: Housner, George W., and Donald E. Hudson, *Applied Mechanics Dynamics*, 2nd ed., Princeton, NJ: D. Van Nostrand Co., Inc., 1959.

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1.5 Periodic Table

Periodic Table of the Elements

I												III	IV	V	VI	VII	VIII
1 **H** 1.0079	II																2 **He** 4.0026
3 **Li** 6.941	4 **Be** 9.0122											5 **B** 10.811	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.179
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.981	14 **Si** 28.086	15 **P** 30.974	16 **S** 32.066	17 **Cl** 35.453	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.88	23 **V** 50.941	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.847	27 **Co** 58.933	28 **Ni** 58.69	29 **Cu** 63.546	30 **Zn** 65.39	31 **Ga** 69.723	32 **Ge** 72.61	33 **As** 74.921	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.80
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.75	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57–71	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.85	75 **Re** 186.21	76 **Os** 190.2	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** 226.02	89–103	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 **Ds** (269)	111 **Rg** (272)	112 **Cn** (277)	113 **Uut** unknown	114 **Fl** (289)	115 **Uup** unknown	116 **Lv** (298)	117 **Uus** unknown	118 **Uuo** unknown

Atomic Number
Symbol
Atomic Weight

Lanthanide Series	57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.92	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
Actinide Series	89 **Ac** 227.03	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** 237.05	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (260)

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1.6 Economic Analysis

1.6.1 Nomenclature and Definitions

A = uniform amount per interest period

B = benefit

BV = book value

C = cost

CRF = capital recovery factor

d = inflation-adjusted interest rate per interest period

D_j = depreciation in year j

F = future worth, value, or amount

f = general inflation rate per interest period

G = uniform gradient amount per interest period

i = interest rate per interest period

i_e = annual effective interest rate

m = number of compounding periods per year

n = number of compounding periods; or the expected life of an asset

P = present worth, value, or amount

PMT = future equal payments

r = nominal annual interest rate

S_n = expected salvage value in year n

Break-even analysis—used to determine the point at which revenue received equals costs associated with earning the revenue

Payback period—period of time required for profit or other benefits of an investment to equal cost of the investment

Nonannual compounding interest = $i_e = \left(1 + \frac{r}{m}\right)^m - 1$

Subscripts

j = at time j

n = at time n

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Economic Factor Conversions

Factor Name	Converts	Symbol	Formula
Single Payment Compound Amount	to F given P	$F/P,\ i\%,\ n$	$(1+i)^n$
Single Payment Present Worth	to P given F	$P/F,\ i\%,\ n$	$(1+i)^{-n}$
Uniform Series Sinking Fund	to A given F	$A/F,\ i\%,\ n$	$\frac{i}{(1+i)^n-1}$
Capital Recovery	to A given P	$A/P,\ i\%,\ n$	$\frac{i(1+i)^n}{(1+i)^n-1}$
Uniform Series Compound Amount	to F given A	$F/A,\ i\%,\ n$	$\frac{(1+i)^n-1}{i}$
Uniform Series Present Worth	to P given A	$P/A,\ i\%,\ n$	$\frac{(1+i)^n-1}{i(1+i)^n}$
Uniform Gradient Present Worth	to P given G	$P/G,\ i\%,\ n$	$\frac{(1+i)^n-1}{i^2(1+i)^n}-\frac{n}{i(1+i)^n}$
Uniform Gradient † Future Worth	to F given G	$F/G,\ i\%,\ n$	$\frac{(1+i)^n-1}{i^2}-\frac{n}{i}$
Uniform Gradient Uniform Series	to A given G	$A/G,\ i\%,\ n$	$\frac{1}{i}-\frac{n}{(1+i)^n-1}$

$$\dagger\ = \frac{F}{G} = \frac{\left(\frac{F}{A}-n\right)}{i} = \frac{F}{A}\times\frac{A}{G}$$

Series of Equal Payments

$$CRF = PMT/P$$

$$CRF\ (i,\ n) = \frac{i(1+i)^n}{(1+i)^n-1} = \frac{i}{1-(1+i)^{-n}}$$

Improved Payback Analysis

$$n = \frac{\ln\left[CRF/(CRF-i)\right]}{\ln(1+i)}$$

Simple Payback Period

$$\frac{\text{Initial Investment} - \text{Salvage Value}}{\text{Net Annual Savings}}$$

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1.6.2 Economic Factor Tables

Factor Table: i = 1.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9901	0.9901	0.0000	1.0100	1.0000	1.0100	1.0000	0.0000
2	0.9803	1.9704	0.9803	1.0201	2.0100	0.5075	0.4975	0.4975
3	0.9706	2.9410	2.9215	1.0303	3.0301	0.3400	0.3300	0.9934
4	0.9610	3.9020	5.8044	1.0406	4.0604	0.2563	0.2463	1.4876
5	**0.9515**	**4.8534**	**9.6103**	**1.0510**	**5.1010**	**0.2060**	**0.1960**	**1.9801**
6	0.9420	5.7955	14.3205	10615	6.1520	0. 1725	0.1625	2.4710
7	0.9327	6.7282	19.9168	1.0721	7.2135	0.1486	0.1386	2.9602
8	0.9235	7.6517	26.3812	1.0829	8.2857	0.1307	0.1207	3.4478
9	0.9143	8.5650	33.6959	1.0937	9.3685	0.1167	0.1067	3.9337
10	**0.9053**	**9.4713**	**41.8435**	**1.l046**	**10.4622**	**0.1056**	**0.0956**	**4.4179**
11	0.8963	10.3676	50.8067	1.1157	11.5668	0.0965	0.0865	4.9005
12	0.8874	11.2551	60.5687	1.1268	12.6825	0.0888	0.0788	5.3815
13	0.8787	12.1337	71.1126	1.1381	13.8093	0.0824	0.0724	5.8607
14	0.8700	13.0037	82.4221	1.1495	14.9474	0.0769	0.0669	6.3384
15	**0.8613**	**13.8651**	**94.4810**	**1.1610**	**16.0969**	**0.0721**	**0.0621**	**6.8143**
16	0.8528	14.7179	107.2734	1.1726	17.2579	0.0679	0.0579	7.2886
17	0.8444	15.5623	120.7834	1.1843	18.4304	0.0643	0.0543	7.7613
18	0.8360	16.3983	134.9957	1.1961	19.6147	0.0610	0.0510	8.2323
19	0.8277	17.2260	149.8950	1.2081	20.8109	0.0581	0.0481	8.7017
20	**0.8195**	**18.0456**	**165.4664**	**1.2202**	**22.0190**	**0.0554**	**0.0454**	**9.1694**
21	0.8114	18.8570	181.6950	1.2324	23.2392	0.0530	0.0430	9.6354
22	0.8034	19.6604	198.5663	1.2447	24.4716	0.0509	0.0409	10.0998
23	0.7954	20.4558	216.0660	1.2572	25.7163	0.0489	0.0389	10.5626
24	0.7876	21.2434	234.1800	1.2697	26.9735	0.0471	0.0371	11.0237
25	**0.7798**	**22.0232**	**252.8945**	**1.2824**	**28.2432**	**0.0454**	**0.0354**	**11.4831**
30	0.7419	25.8077	355.0021	1.3478	34.7849	0.0387	0.0277	13.7557
40	0.6717	32.8347	596.8561	1.4889	48.8864	0.0305	0.0205	18.1776
50	0.6080	39.1961	879.4176	1.6446	64.4632	0.0255	0.0155	22.4363
60	0.5504	44.9550	1192.8061	1.8167	81.6697	0.0222	0.0122	26.5333
100	**0.3697**	**63.0289**	**2605.7758**	**2.7048**	**170.4814**	**0.0159**	**0.0059**	**41.3426**

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Factor Table: i = 1.50%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9852	0.9852	0.0000	1.0150	1.0000	1.0150	1.0000	0.0000
2	0.9707	1.9559	0.9707	1.0302	2.0150	0.5113	0.4963	0.4963
3	0.9563	2.9122	2.8833	1.0457	3.0452	0.3434	0.3284	0.9901
4	0.9422	3.8544	5.7098	1.0614	4.0909	0.2594	0.2444	1.4814
5	**0.9283**	**4.7826**	**9.4229**	**1.0773**	**5.1523**	**0.2091**	**0.1941**	**1.9702**
6	0.9145	5.6972	13.9956	1.0934	6.2296	0.1755	0.1605	2.4566
7	0.9010	6.5982	19.4018	1.1098	7.3230	0.1516	0.1366	2.9405
8	0.8877	7.4859	26.6157	1.1265	8.4328	0.1336	0.1186	3.4219
9	0.8746	8.3605	32.6125	1.1434	9.5593	0.1196	0.1046	3.9008
10	**0.8617**	**9.2222**	**40.3675**	**1.1605**	**10.7027**	**0.1084**	**0.0934**	**4.3772**
11	0.8489	10.0711	48.8568	1.1779	11.8633	0.0993	0.0843	4.8512
12	0.8364	10.9075	58.0571	1.1956	13.0412	0.0917	0.0767	5.3227
13	0.8240	11.7315	67.9454	1.2136	14.2368	0.0852	0.0702	5.7917
14	0.8118	12.5434	78.4994	1.2318	15.4504	0.0797	0.0647	6.2582
15	**0.7999**	**13.3432**	**89.6974**	**1.2502**	**16.6821**	**0.0749**	**0.0599**	**6.7223**
16	0.7880	14.1313	101.5178	1.2690	17.9324	0.0708	0.0558	7.1839
17	0.7764	14.9076	113.9400	1.2880	19.2014	0.0671	0.0521	7.6431
18	0.7649	15.6726	126.9435	1.3073	20.4894	0.0638	0.0488	8.0997
19	0.7536	16.4262	140.5084	1.3270	21.7967	0.0609	0.0459	8.5539
20	**0.7425**	**17.1686**	**154.6154**	**1.3469**	**23.1237**	**0.0582**	**0.0432**	**9.0057**
21	0.7315	17.9001	169.2453	1.3671	24.4705	0.0559	0.0409	9.4550
22	0.7207	18.6208	184.3798	1.3876	25.8376	0.0537	0.0387	9.9018
23	0.7100	19.3309	200.0006	1.4084	27.2251	0.0517	0.0367	10.3462
24	0.6995	20.0304	216.0901	1.4295	28.6335	0.0499	0.0349	10.7881
25	**0.6892**	**20.7196**	**232.6310**	**1.4509**	**30.0630**	**0.0483**	**0.0333**	**11.2276**
30	0.6398	24.0158	321.5310	1.5631	37.5387	0.0416	0.0266	13.3883
40	0.5513	29.9158	524.3568	1.8140	54.2679	0.0334	0.0184	17.5277
50	0.4750	34.9997	749.9636	2.1052	73.6828	0.0286	0.0136	21.4277
60	0.4093	39.3803	988.1674	2.4432	96.2147	0.0254	0.0104	25.0930
100	**0.2256**	**51.6247**	**1937.4506**	**4.4320**	**228.8030**	**0.0194**	**0.0044**	**37.5295**

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Factor Table: i = 2.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9804	0.9804	0.0000	1.0200	1.0000	1.0200	1.0000	0.0000
2	0.9612	1.9416	0.9612	1.0404	2.0200	0.5150	0.4950	0.4950
3	0.9423	2.8839	2.8458	1.0612	3.0604	0.3468	0.3268	0.9868
4	0.9238	3.8077	5.6173	1.0824	4.1216	0.2626	0.2426	1.4752
5	**0.9057**	**4.7135**	**9.2403**	**1.1041**	**5.2040**	**0.2122**	**0.1922**	**1.9604**
6	0.8880	5.6014	13.6801	1.1262	6.3081	0.1785	0.1585	2.4423
7	0.8706	6.4720	18.9035	1.1487	7.4343	0.1545	0.1345	2.9208
8	0.8535	7.3255	24.8779	1.1717	8.5830	0.1365	0.1165	3.3961
9	0.8368	8.1622	31.5720	1.1951	9.7546	0.1225	0.1025	3.8681
10	**0.8203**	**8.9826**	**38.9551**	**1.2190**	**10.9497**	**0.1113**	**0.0913**	**4.3367**
11	0.8043	9.7868	46.9977	1.2434	12.1687	0.1022	0.0822	4.8021
12	0.7885	10.5753	55.6712	1.2682	13.4121	0.0946	0.0746	5.2642
13	0.7730	11.3484	64.9475	1.2936	14.6803	0.0881	0.0681	5.7231
14	0.7579	12.1062	74.7999	1.3195	15.9739	0.0826	0.0626	6.1786
15	**0.7430**	**12.8493**	**85.2021**	**1.3459**	**17.2934**	**0.0778**	**0.0578**	**6.6309**
16	0.7284	13.5777	96.1288	1.3728	18.6393	0.0737	0.0537	7.0799
17	0.7142	14.2919	107.5554	1.4002	20.0121	0.0700	0.0500	7.5256
18	0.7002	14.9920	119.4581	1.4282	21.4123	0.0667	0.0467	7.9681
19	0.6864	15.6785	131.8!39	1.4568	22.8406	0.0638	0.0438	8.4073
20	**0.6730**	**16.3514**	**144.6003**	**1.4859**	**24.2974**	**0.0612**	**0.0412**	**8.8433**
21	0.6598	17.0112	157.7959	1.5157	25.7833	0.0588	0.0388	9.2760
22	0.6468	17.6580	171.3795	1.5460	27.2990	0.0566	0.0366	9.7055
23	0.6342	18.2922	185.3309	1.5769	28.8450	0.0547	0.0347	10.1317
24	0.6217	18.9139	199.6305	1.6084	30.4219	0.0529	0.0329	10.5547
25	**0.6095**	**19.5235**	**214.2592**	**1.6406**	**32.0303**	**0.0512**	**0.0312**	**10.9745**
30	0.5521	22.3965	291.7164	1.8114	40.568!	0.0446	0.0246	13.0251
40	0.4529	27.3555	461.9931	2.2080	60.4020	0.0366	0.0166	16.8885
50	0.3715	31.4236	642.3606	2.6916	84.5794	0.0318	0.0118	20.4420
60	0.3048	34.7609	823.6975	3.2810	114.0515	0.0288	0.0088	23.6961
100	**0.1380**	**43.0984**	**1464.7527**	**7.2446**	**312.2323**	**0.0232**	**0.0032**	**33.9863**

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Factor Table: i = 6.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9434	0.9434	0.0000	1.0600	1.0000	1.0600	1.0000	0.0000
2	0.8900	1.8334	0.8900	1.1236	2.0600	0.5454	0.4854	0.4854
3	0.8396	2.6730	2.5692	1.1910	3.1836	0.3741	0.3141	0.9612
4	0.7921	3.4651	4.9455	1.2625	4.3746	0.2886	0.2286	1.4272
5	**0.7473**	**4.2124**	**7.9345**	**1.3382**	**5.6371**	**0.2374**	**0.1774**	**1.8836**
6	0.7050	4.9173	11.4594	1.4185	6.9753	0.2034	0.1434	2.3304
7	0.6651	5.5824	15.4497	1.5036	8.3938	0.1791	0.1191	2.7676
8	0.6274	6.2098	19.8416	1.5938	9.8975	0.1610	0.1010	3.1952
9	0.5919	6.8017	24.5768	1.6895	11.4913	0.1470	0.0870	3.6133
10	**0.5584**	**7.3601**	**29.6023**	**1.7908**	**13.1808**	**0.1359**	**0.0759**	**4.0220**
11	0.5268	7.8869	34.8702	1.8983	14.9716	0.1268	0.0668	4.4213
12	0.4970	8.3838	40.3369	2.0122	16.8699	0.1193	0.0593	4.8113
13	0.4688	8.8527	45.9629	2.1329	18.8821	0.1130	0.0530	5.1920
14	0.4423	9.2950	51.7128	2.2609	21.0151	0.1076	0.0476	5.5635
15	**0.4173**	**9.7122**	**57.5546**	**2.3966**	**23.2760**	**0.1030**	**0.0430**	**5.9260**
16	0.3936	10.1059	63.4592	2.5404	25.6725	0.0990	0.0390	6.2794
17	0.3714	10.4773	69.4011	2.6928	28.2129	0.0954	0.0354	6.6240
18	0.3505	10.8276	75.3569	2.8543	30.9057	0.0924	0.0324	6.9597
19	0.3305	11.1581	81.3062	3.0256	33.7600	0.0896	0.0296	7.2867
20	**0.3118**	**11.4699**	**87.2304**	**3.2071**	**36.7856**	**0.0872**	**0.0272**	**7.6051**
21	0.2942	11.7641	93.1136	3.3996	39.9927	0.0850	0.0250	7.9151
22	0.2775	12.0416	98.9412	3.6035	43.3923	0.0830	0.0230	8.2166
23	0.2618	12.3034	104.7007	3.8197	46.9958	0.0813	0.0213	8.5099
24	0.2470	12.5504	110.3812	4.0489	50.8156	0.0797	0.0197	8.7951
25	**0.2330**	**12.7834**	**115.9732**	**4.2919**	**54.8645**	**0.0782**	**0.0182**	**9.0722**
30	0.1741	13.7648	142.3588	5.7435	79.0582	0.0726	0.0126	10.3422
40	0.0972	15.0463	185.9568	10.2857	154.7620	0.0665	0.0065	12.3590
50	0.0543	15.7619	217.4574	18.4202	290.3359	0.0634	0.0034	13.7964
60	0.0303	16.1614	239.0428	32.9877	533.1282	0.0619	0.0019	14.7909
100	**0.0029**	**16.6175**	**272.0471**	**339.3021**	**5638.3681**	**0.0602**	**0.0002**	**16.3711**

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Factor Table: i = 8.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9259	0.9259	0.0000	1.0800	1.0000	1.0800	1.0000	0.0000
2	0.8573	1.7833	0.8573	1.1664	2.0800	0.5608	0.4808	0.4808
3	0.7938	2.5771	2.4450	1.2597	3.2464	0.3880	0.3080	0.9487
4	0.7350	3.3121	4.6501	1.3605	4.5061	0.3019	0.2219	1.4040
5	**0.6806**	**3.9927**	**7.3724**	**1.4693**	**5.8666**	**0.2505**	**0.1705**	**1.8465**
6	0.6302	4.6229	10.5233	1.5869	7.3359	0.2163	0.1363	2.2763
7	0.5835	5.2064	14.0242	1.7138	8.9228	0.1921	0.1121	2.6937
8	0.5403	5.7466	17.8061	1.8509	10.6366	0.1740	0.0940	3.0985
9	0.5002	6.2469	21.8081	1.9990	12.4876	0.1601	0.0801	3.4910
10	**0.4632**	**6.7101**	**25.9768**	**2.1589**	**14.4866**	**0.1490**	**0.0690**	**3.8713**
11	0.4289	7.1390	30.2657	2.3316	16.6455	0.1401	0.0601	4.2395
12	0.3971	7.5361	34.6339	2.5182	18.9771	0.1327	0.0527	4.5957
13	0.3677	7.9038	39.0463	2.7196	21.4953	0.1265	0.0465	4.9402
14	0.3405	8.2442	43.4723	2.9372	24.2149	0.1213	0.0413	5.2731
15	**0.3152**	**8.5595**	**47.8857**	**3.1722**	**27.1521**	**0.1168**	**0.0368**	**5.5945**
16	0.2919	8.8514	52.2640	3.4259	30.3243	0.1130	0.0330	5.9046
17	0.2703	9.1216	56.5883	3.7000	33.7502	0.1096	0.0296	6.2037
18	0.2502	9.3719	60.8426	3.9960	37.4502	0.1067	0.0267	6.4920
19	0.2317	9.6036	65.0134	4.3157	41.4463	0.1041	0.0241	6.7697
20	**0.2145**	**9.8181**	**69.0898**	**4.6610**	**45.7620**	**0.1019**	**0.0219**	**7.0369**
21	0.1987	10.0168	73.0629	5.0338	50.4229	0.0998	0.0198	7.2940
22	0.1839	10.2007	76.9257	5.4365	55.4568	0.0980	0.0180	7.5412
23	0.1703	10.3711	80.6726	5.8715	60.8933	0.0964	0.0164	7.7786
24	0.1577	10.5288	84.2997	6.3412	66.7648	0.0950	0.0150	8.0066
25	**0.1460**	**10.6748**	**87.8041**	**6.8485**	**73.1059**	**0.0937**	**0.0137**	**8.2254**
30	0.0994	11.2578	103.4558	10.0627	113.2832	0.0888	0.0088	9.1897
40	0.0460	11.9246	126.0422	21.7245	259.0565	0.0839	0.0039	10.5699
50	0.0213	12.2335	139.5928	46.9016	573.7702	0.0817	0.0017	11.4107
60	0.0099	12.3766	147.3000	101.2571	1,253.2133	0.0808	0.0008	11.9015
100	**0.0005**	**12.4943**	**155.6107**	**2199.7613**	**27,484.5157**	**0.0800**		**12.4545**

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Factor Table: i = 10.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9091	0.9091	0.0000	1.1000	1.0000	1.1000	1.0000	0.0000
2	0.8264	1.7355	0.8264	1.2100	2.1000	0.5762	0.4762	0.4762
3	0.7513	2.4869	2.3291	1.3310	3.3100	0.4021	0.3021	0.9366
4	0.6830	3.1699	4.3781	1.4641	4.6410	0.3155	0.2155	1.3812
5	**0.6209**	**3.7908**	**6.8618**	**1.6105**	**6.1051**	**0.2638**	**0.1638**	**1.8101**
6	0.5645	4.3553	9.6842	1.7716	7.7156	0.2296	0.1296	2.2236
7	0.5132	4.8684	12.7631	1.9487	9.4872	0.2054	0.1054	2.6216
8	0.4665	5.3349	16.0287	2.1436	11.4359	0.1874	0.0874	3.0045
9	0.4241	5.7590	19.4215	2.3579	13.5735	0.1736	0.0736	3.3724
10	**0.3855**	**6.1446**	**22.8913**	**2.5937**	**15.9374**	**0.1627**	**0.0627**	**3.7255**
11	0.3505	6.4951	26.3962	2.8531	18.5312	0.1540	0.0540	4.0641
12	0.3186	6.8137	29.9012	3.1384	21.3843	0.1468	0.0468	4.3884
13	0.2897	7.1034	33.3772	3.4523	24.5227	0.1408	0.0408	4.6988
14	0.2633	7.3667	36.8005	3.7975	27.9750	0.1357	0.0357	4.9955
15	**0.2394**	**7.6061**	**40.1520**	**4.1772**	**31.7725**	**0.1315**	**0.0315**	**5.2789**
16	0.2176	7.8237	43.4164	4.5950	35.9497	0.1278	0.0278	5.5493
17	0.1978	8.0216	46.5819	5.0545	40.5447	0.1247	0.0247	5.8071
18	0.1799	8.2014	49.6395	5.5599	45.5992	0.1219	0.0219	6.0526
19	0.1635	8.3649	52.5827	6.1159	51.1591	0.1195	0.0195	6.2861
20	**0.1486**	**8.5136**	**55.4069**	**6.7275**	**57.2750**	**0.1175**	**0.0175**	**6.5081**
21	0.1351	8.6487	58.1095	7.4002	64.0025	0.1156	0.0156	6.7189
22	0.1228	8.7715	60.6893	8.1403	71.4027	0.1140	0.0140	6.9189
23	0.1117	8.8832	63.1462	8.9543	79.5430	0.1126	0.0126	7.1085
24	0.1015	8.9847	65.4813	9.8497	88.4973	0.1113	0.0113	7.2881
25	**0.0923**	**9.0770**	**67.6964**	**10.8347**	**98.3471**	0.1102	0.0102	**7.4580**
30	0.0573	9.4269	77.0766	17.4494	164.4940	0.1061	0.0061	8.1762
40	0.0221	9.7791	88.9525	45.2593	442.5926	0.1023	0.0023	9.0962
50	0.0085	9.9148	94.8889	117.3909	1163.9085	0.1009	0.0009	9.5704
60	0.0033	9.9672	97.7010	304.4816	3034.8164	0.1003	0.0003	9.8023
100	**0.0001**	**9.9993**	**99.9202**	**13,780.6123**	**137,796.1234**	**0.1000**		**9.9927**

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Factor Table: i = 12.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.8929	0.8929	0.0000	1.1200	1.0000	1.1200	1.0000	0.0000
2	0.7972	1.6901	0.7972	1.2544	2.1200	0.5917	0.4717	0.4717
3	0.7118	2.4018	2.2208	1.4049	3.3744	0.4163	0.2963	0.9246
4	0.6355	3.0373	4.1273	1.5735	4.7793	0.3292	0.2092	1.3589
5	**0.5674**	**3.6048**	**6.3970**	**1.7623**	**6.3528**	**0.2774**	**0.1574**	**1.7746**
6	0.5066	4.1114	8.9302	1.9738	8.1152	0.2432	0.1232	2.1720
7	0.4523	4.5638	11.6443	2.2107	10.0890	0.2191	0.0991	2.5515
8	0.4039	4.9676	14.4714	2.4760	12.2997	0.2013	0.0813	2.9131
9	0.3606	5.3282	17.3563	2.7731	14.7757	0.1877	0.0677	3.2574
10	**0.3220**	**5.6502**	**20.2541**	**3.1058**	**17.5487**	**0.1770**	**0.0570**	**3.5847**
11	0.2875	5.9377	23.1288	3.4785	20.6546	0.1684	0.0484	3.8953
12	0.2567	6.1944	25.9523	3.8960	24.1331	0.1614	0.0414	4.1897
13	0.2292	6.4235	28.7024	4.3635	28.0291	0.1557	0.0357	4.4683
14	0.2046	6.6282	31.3624	4.8871	32.3926	0.1509	0.0309	4.7317
15	**0.1827**	**6.8109**	**33.9202**	**5.4736**	**37.2797**	**0.1468**	**0.0268**	**4.9803**
16	0.1631	6.9740	36.3670	6.1304	42.7533	0.1434	0.0234	5.2147
17	0.1456	7.1196	38.6973	6.8660	48.8837	0.1405	0.0205	5.4353
18	0.1300	7.2497	40.9080	7.6900	55.7497	0.1379	0.0179	5.6427
19	0.1161	7.3658	42.9979	8.6128	63.4397	0.1358	0.0158	5.8375
20	**0.1037**	**7.4694**	**44.9676**	**9.6463**	**72.0524**	**0.1339**	**0.0139**	**6.0202**
21	0.0926	7.5620	46.8188	10.8038	81.6987	0.1322	0.0122	6.1913
22	0.0826	7.6446	48.5543	12.1003	92.5026	0.1308	0.0108	6.3514
23	0.0738	7.7184	50.1776	13.5523	104.6029	0.1296	0.0096	6.5010
24	0.0659	7.7843	51.6929	15.1786	118.1552	0.1285	0.0085	6.6406
25	**0.0588**	**7.8431**	**53.1046**	**17.0001**	**133.3339**	**0.1275**	**0.0075**	**6.7708**
30	0.0334	8.0552	58.7821	29.9599	241.3327	0.1241	0.0041	7.2974
40	0.0107	8.2438	65.1159	93.0510	767.0914	0.1213	0.0013	7.8988
50	0.0035	8.3045	67.7624	289.0022	2400.0182	0.1204	0.0004	8.1597
60	0.0011	8.3240	68.8100	897.5969	7471.6411	0.1201	0.0001	8.2664
100		**8.3332**	**69.4336**	**83,522.2657**	**696,010.5477**	**0.1200**		**8.3321**

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Factor Table: i = 18.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.8475	0.8475	0.0000	1.1800	1.0000	1.1800	1.0000	0.0000
2	0.7182	1.5656	0.7182	1.3924	2.1800	0.6387	0.4587	0.4587
3	0.6086	2.1743	1.9354	1.6430	3.5724	0.4599	0.2799	0.8902
4	0.5158	2.6901	3.4828	1.9388	5.2154	0.3717	0.1917	1.2947
5	**0.4371**	**3.1272**	**5.2312**	**2.2878**	**7.1542**	**0.3198**	**0.1398**	**1.6728**
6	0.3704	3.4976	7.0834	2.6996	9.4423	0.2859	0.1059	2.0252
7	0.3139	3.8115	8.9670	3.1855	12.1415	0.2624	0.0824	2.3526
8	0.2660	4.0776	10.8292	3.7589	15.3270	0.2452	0.0652	2.6558
9	0.2255	4.3030	12.6329	4.4355	19.0859	0.2324	0.0524	2.9358
10	**0.1911**	**4.4941**	**14.3525**	**5.2338**	**23.5213**	**0.2225**	**0.0425**	**3.1936**
11	0.1619	4.6560	15.9716	6.1759	28.7551	0.2148	0.0348	3.4303
12	0.1372	4.7932	17.4811	7.2876	34.9311	0.2086	0.0286	3.6470
13	0.1163	4.9095	18.8765	8.5994	42.2187	0.2037	0.0237	3.8449
14	0.0985	5.0081	20.1576	10.1472	50.8180	0.1997	0.0197	4.0250
15	**0.0835**	**5.0916**	**21.3269**	**11.9737**	**60.9653**	**0.1964**	**0.0164**	**4.1887**
16	0.0708	5.1624	22.3885	14.1290	72.9390	0.1937	0.0137	4.3369
17	0.0600	5.2223	23.3482	16.6722	87.0680	0.1915	0.0115	4.4708
18	0.0508	5.2732	24.2123	19.6731	103.7403	0.1896	0.0096	4.5916
19	0.0431	5.3162	24.9877	23.2144	123.4135	0.1881	0.0081	4.7003
20	**0.0365**	**5.3527**	**25.6813**	**27.3930**	**146.6280**	**0.1868**	**0.0068**	**4.7978**
21	0.0309	5.3837	26.3000	32.3238	174.0210	0.1857	0.0057	4.8851
22	0.0262	5.4099	26.8506	38.1421	206.3448	0.1848	0.0048	4.9632
23	0.0222	5.4321	27.3394	45.0076	244.4868	0.1841	0.0041	5.0329
24	0.0188	5.4509	27.7725	53.1090	289.4944	0.1835	0.0035	5.0950
25	**0.0159**	**5.4669**	**28.1555**	**62.6686**	**342.6035**	**0.1829**	**0.0029**	**5.1502**
30	0.0070	5.5168	29.4864	143.3706	790.9480	0.1813	0.0013	5.3448
40	0.0013	5.5482	30.5269	750.3783	4,163.2130	0.1802	0.0002	5.5022
50	0.0003	5.5541	30.7856	3927.3569	21,813.0937	0.1800		5.5428
60	0.0001	5.5553	30.8465	20,555.1400	114,189.6665	0.1800		5.5526
100		**5.5556**	**30.8642**	**15,424,131.91**	**85,689,616.17**	**0.1800**		**5.5555**

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1.6.3 Depreciation

Double Declining Balance

$$D_j = \frac{2 \times \text{book value}}{n} = \frac{2\,(C - \text{depreciation charge to date})}{n}$$

Sum of Year's Digits (SYD)

D_j = (remaining useful lifespan/SYD) × $(C - S_n)$

Units of Production

Depreciation per unit produced = $(C - S_n)$/units produced in lifetime

Straight Line

$$D_j = \frac{C - S_n}{n}$$

Sum-of-Years Digits Method

$$D_j = \frac{2\left(C - S_n\right)\left(n - j + 1\right)}{(n)(n+1)}$$

Modified Accelerated Cost Recovery System (MACRS)

D_j = (factor) C

A table of MACRS factors is provided below.

Modified Accelerated Cost Recovery System (MACRS)

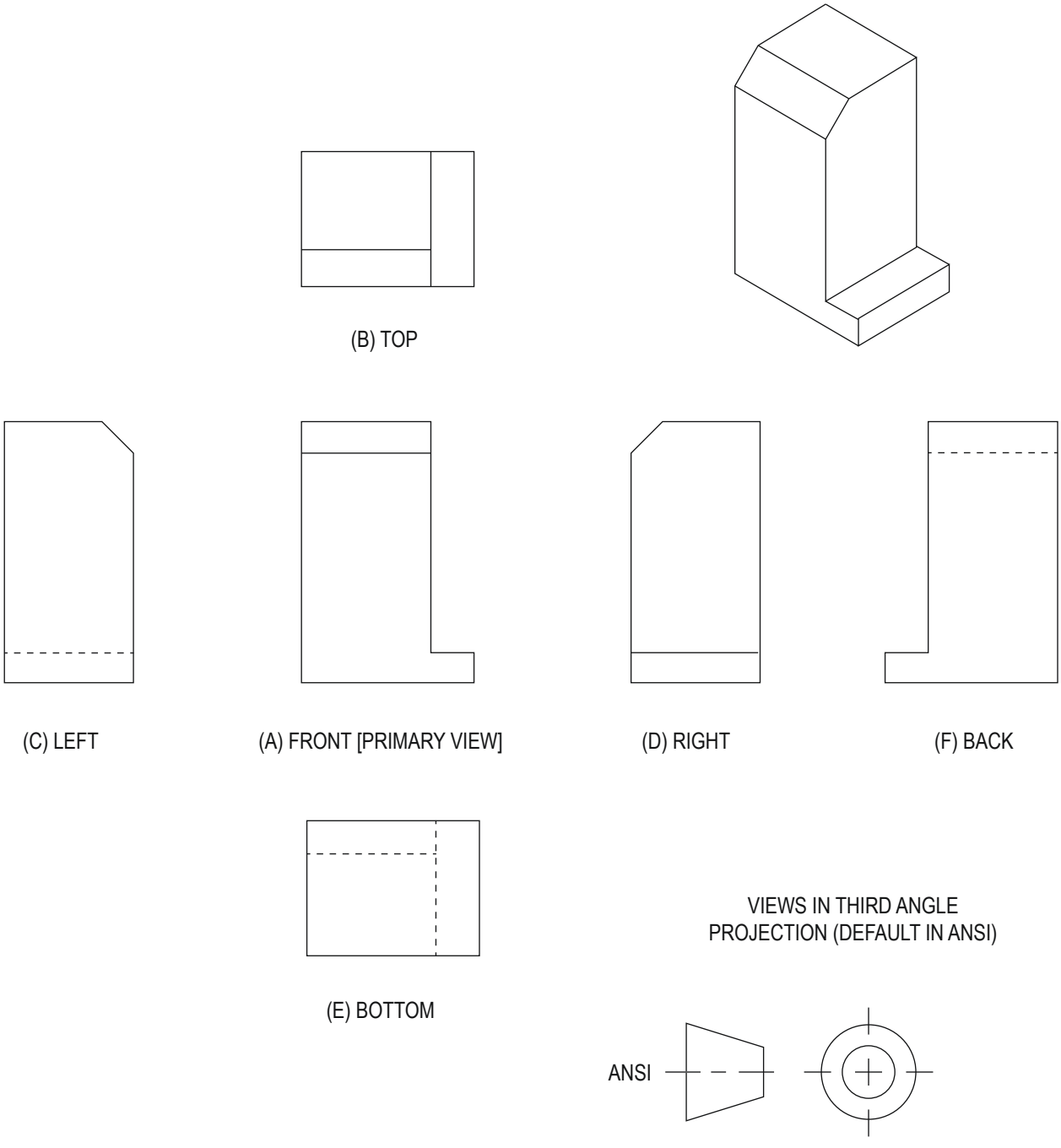
MACRS FACTORS				
Year	Recovery Period (Years)			
	3	5	7	10
	Recovery Rate (Percent)			
1	33.33	20.00	14.29	10.00
2	44.45	32.00	24.49	18.00
3	14.81	19.20	17.49	14.40
4	7.41	11.52	12.49	11.52
5		11.52	8.93	9.22
6		5.76	8.92	7.37
7			8.93	6.55
8			4.46	6.55
9				6.56
10				6.55
11				3.28

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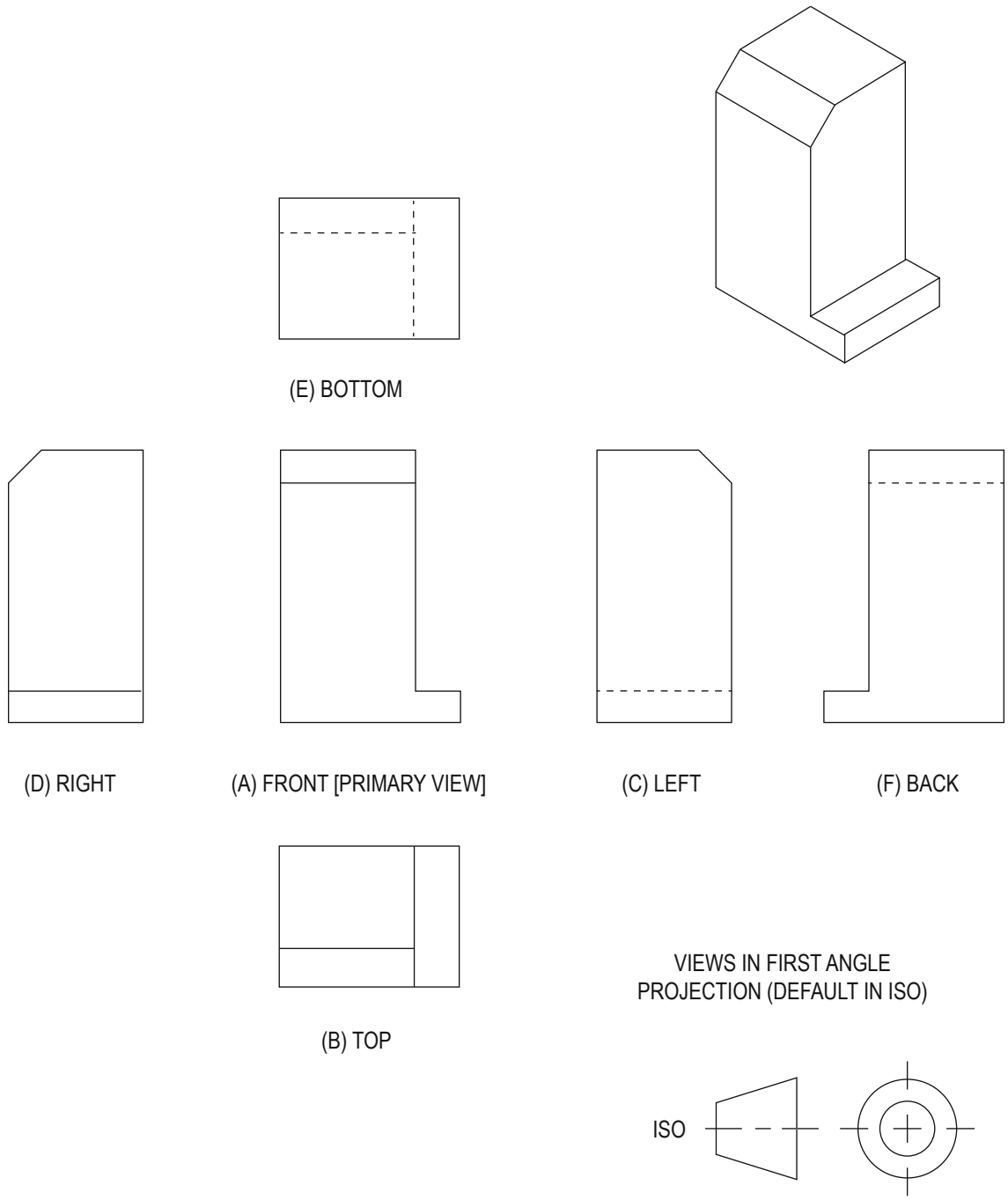
1.7 Interpretation of Technical Drawings

1.7.1 ANSI and ISO Orthographic Projection Styles

ANSI—Orthographic Projection Following Third-Angle Projection



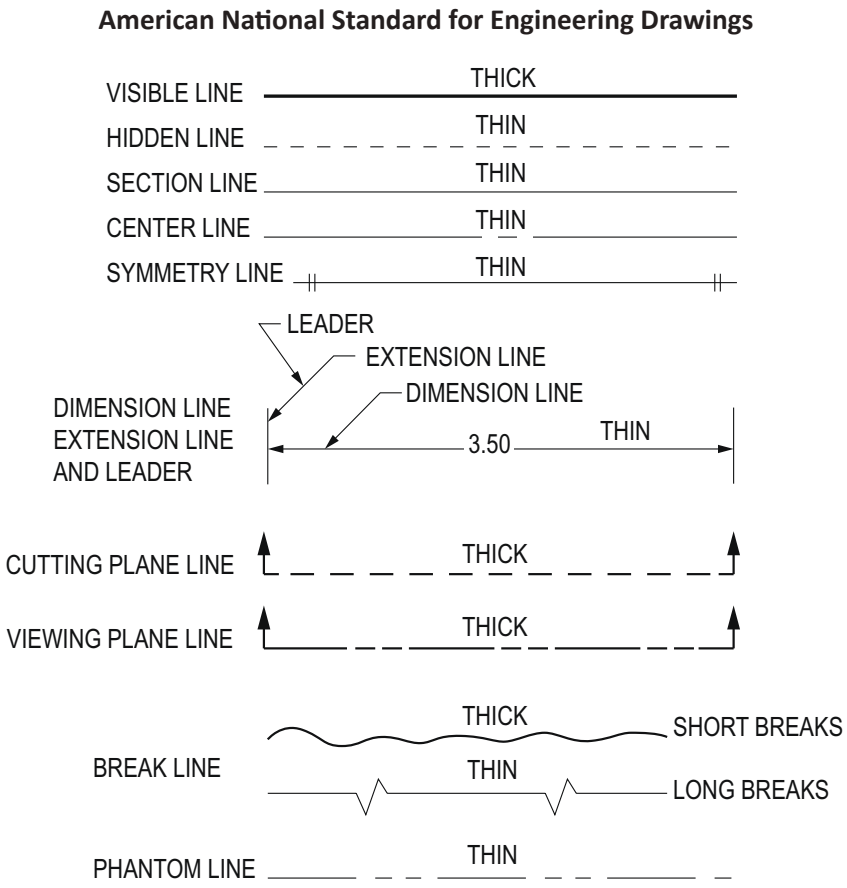
ISO—Orthographic Projection Following First-Angle Projection



Source: Oberg, Erik, Franklin D. Jones, Holbrook L. Horton, and Henry H. Ryffel, eds., *Machinery's Handbook*, 28th ed., South Norwalk, CT: Industrial Press, 2008.

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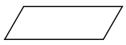
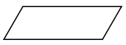
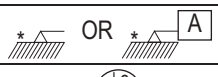
1.7.2 Symbols for Drawings



Source: MIL-STD-17B-1: *Military Standard Mechanical Symbols*, Washington, DC: U.S. Department of Defense, 1963.

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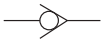
1.7.3 Symbols for Geometric Characteristics and Tolerances on Detail Drawings

Symbol For:	ANSI Y14.5	ISO
Straightness		
Flatness		
Circularity		
Cylindricity		
Profile of a line		
Profile of a surface		
All-around profile		NONE
Angularity		
Perpendicularity		
Parallelism		
Position		
Concentricity/coaxiality		
Symmetry	NONE	
Circular runout		
Total runout		
At maximum material condition	Ⓜ	Ⓜ
At least material condition	Ⓛ	NONE
Regardless of feature size	Ⓢ	NONE
Projected tolerance zone	Ⓟ	Ⓟ
Diameter	∅	∅
Basic dimension	50	50
Reference dimension	(50)	(50)
Datum feature		
Datum target		
Target point		
* May be filled in		

Source: Shigley, Joseph E. and Charles R. Mischke, *Standard Handbook of Machine Design*, New York: McGraw-Hill, 1986.

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ANSI Symbols for Hydraulic Power

 (a) spring (spring-loaded)	 (m) hydraulic motor, fixed capacity (two directions of flow)	 (y) flow control valve
 two winding or  one winding (b) solenoid	 (n) hydraulic motor, variable capacity (one direction of flow)	 (z) shutoff valve
 (c) adjustable symbol	 (o) actuating cylinder (single acting)	 (aa) electric motor
 (d) directional arrow (oil)	 (p) actuating cylinder (double acting)	 (bb) internal combustion engine
 (e) directional arrow (air or gas)	 (q) two-way, two-position control valve (normally closed)	 (cc) coupling
(f) fluid line flow	 (r) two-way, two-position control valve (normally open)	 (dd) accumulator
(g) shaft or lever	 (s) three-way, two-position control valve (normally open)	 (ee) cooler
 (h) reservoir (open)	 (t) four-way, two-position control valve	 (ff) heater
 (i) reservoir (closed)	 (u) check (nonreturn) valve	 (gg) pressure gage
 (j) filter or strainer	 (v) shuttle valve	 (hh) temperature gage
 (k) pump, fixed capacity (one direction of flow)	 (w) pressure control valve	 (ii) flow meter
 (l) pump, variable capacity (two directions of flow)	 (x) pressure relief valve	

Source: MIL-STD-17B-1: *Military Standard Mechanical Symbols*, Washington, DC: U.S. Department of Defense, 1963.

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ANSI Symbols for Piping

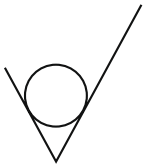
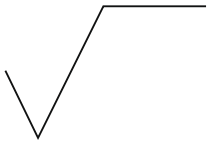
	FLANGED	SCREWED	WELDED
JOINT			
ELBOW–90°			
ELBOW–45°			
ELBOW–TURNED UP			
ELBOW–TURNED DOWN			
UNION			
TEE			
TEE–OUTLET UP			
TEE–OUTLET DOWN			
SIDE OUTLET TEE–OUTLET UP			

	FLANGED	SCREWED	WELDED
CROSS			
REDUCER–CONCENTRIC			
REDUCER–ECCENTRIC			
LATERAL			
GATE VALVE			
GLOBE VALVE			
CHECK VALVE			
STOP COCK			
SAFETY VALVE			

Source: MIL-STD-17B-1: *Military Standard Mechanical Symbols*, Washington, DC: U.S. Department of Defense, 1963.

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Surface Texture Symbols and Construction

Symbol	Meaning
	*Basic Surface Texture Symbol*. Surface may be produced by any method except when the bar or circle is specified.
	*Material Removal by Machining Is Required*. The horizontal bar indicates that material removal by machining is required to produce the surface and that material must be provided for that purpose.
	*Material Removal Allowance*. The number indicates the amount of stock to be removed by machining in millimeters (or inches). Tolerances may be added to the basic value shown or in general note.
	*Material Removal Prohibited*. The circle in the V indicates that the surface must be produced by processes such as casting, forging, hot finishing, cold finishing, die casting, powder metallurgy, or injection molding without subsequent removal of material.
	*Surface Texture Symbol*. Use when any surface characteristics are specified above the horizontal line or to the right of the symbol. Surface maybe produced by any method except when the bar or circle is specified.

Source: Oberg, Erik, Franklin D. Jones, Holbrook L. Horton, and Henry H. Ryffel, eds., *Machinery's Handbook*, 28th ed., South Norwalk, CT: Industrial Press, 2008.

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1.7.4 Geometric Dimensioning and Tolerancing (GD&T)

GD&T is used to communicate design intent. This reference provides materials drawn from the ASME Y14.5 standard: "GD&T is an essential tool for communicating design intent—that parts from technical drawings have the desired form, fit, function and interchangeability."

GD&T helps the designer provide information about the size, geometry, and location of features for mechanical parts.

Definitions used in ASME Y14.5

Regardless of Feature Size (RFS)
This is the default condition for geometric tolerances.

Least Material Condition (LMC)
This is a modifier for the geometric tolerance. The modifier defines the tolerance or acceptability where the part has the least amount of material or weighs the least.

Maximum Material Condition (MMC)
This is a modifier for the geometric tolerance. The modifier defines the tolerance or acceptability where the part has the most amount of material or weighs the most.

Feature Control Frame
From the ASME Y14.5 standard: "A feature control frame is a rectangle divided into compartments containing the geometric characteristic symbol followed by the tolerance value or description, modifiers, and any applicable datum reference features."

Datum
A datum is a plane, axis, point, or other reference geometry with respect to which the tolerance is specified.

Virtual Condition
The virtual condition is used to determine the clearance between mating parts. For an external feature, the virtual condition is equal to the MMC plus the related geometric tolerance. For an internal feature, it is equal to the MMC minus the related geometric tolerance.

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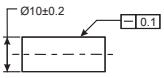
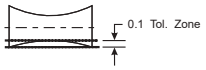
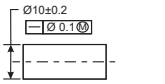
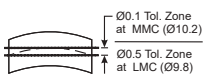
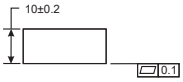
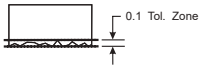
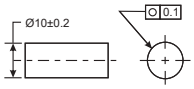
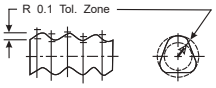
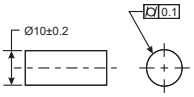
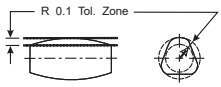
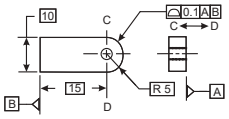
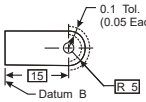
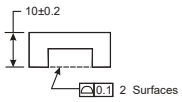
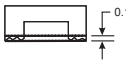
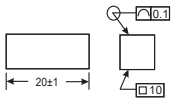
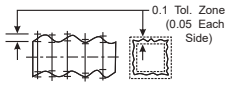
Modifying Symbols

Term	Symbol	Definitions
AT MAXIMUM MATERIAL CONDITION (When applied to a tolerance value) AT MAXIMUM MATERIAL BOUNDARY (When applied to a datum reference)	Ⓜ	The condition in which a feature of size contains the maximum amount of material within the stated limits of size, e.g., minimum hole diameter or maximum shaft diameter.
AT LEAST MATERIAL CONDITION (When applied to a tolerance value) AT LEAST MATERIAL BOUNDARY (When applied to a datum reference)	Ⓛ	An MMB and an LMB, where at least one boundary is a specified shape that is not a uniform offset from true profile.
PROJECTED TOLERANCE ZONE	Ⓟ	The symbolic means of indicating a projected tolerance zone.
DIAMETER	∅	The symbols used to indicate diameter, spherical diameter, radius, spherical radius, and controlled radius shall precede the value of a dimension or tolerance given as a diameter or radius, as applicable.
SPHERICAL DIAMETER	S∅	
RADIUS	R	
SPHERICAL RADIUS	SR	
SQUARE	□	Feature nominal size is square.
REFERENCE	( )	The symbolic means of indicating a dimension or other dimensional data as reference shall be to enclose the dimension (or dimensional data) within parentheses.
ARC LENGTH	⌒	The symbolic means of indicating a dimension is an arch length measured on a curved outline.
DIMENSION ORIGIN	⌖	The symbolic means of indicating a toleranced dimension between two features originates from one of these features and not the other.

Source: Adapted from ASME Y14.5–2018, American Society of Mechanical Engineers, 2018.

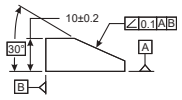
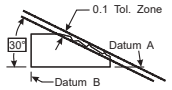
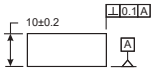
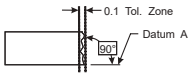
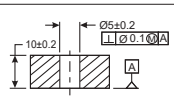
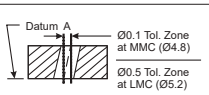
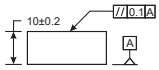
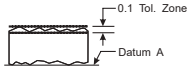
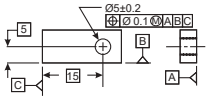
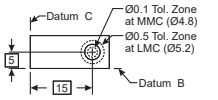
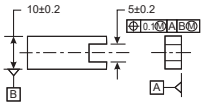
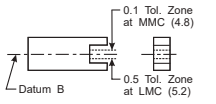
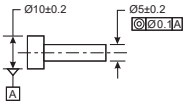
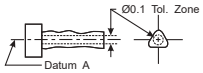
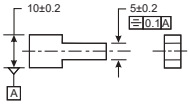
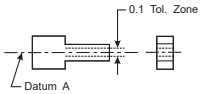
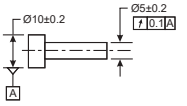
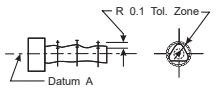
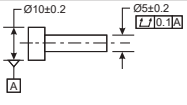
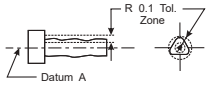
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Geometric Dimensioning and Tolerancing (GD&T)

Tolerance Types	ASME Symbol	Drawing Callout Example	Drawing Callout Meaning	Tolerance Zone Definition (for Example)	Zone Modifiers Allowed	Datums Used	Additional Comments
Form	Straightness			Parallel lines, within which the surface element must lie	No (Surface)	No	☐ Refinement of size. ☐ Tolerance value must be less than the size tolerance.
				Cylindrical boundary, within which the axis of the feature must lie (derived median line)	Yes (Axis)	No	☐ Not a refinement of size. ☐ Rule #1 only applies to each circular element. ☐ MMC or RFS only. ☐ Where necessary the geometric tolerance may be greater than the size tolerance.
	Flatness			Parallel planes, within which the elements of a surface must lie	No	No	☐ Refinement of size. ☐ Tolerance value must be less than the size tolerance.
	Circularity			Concentric circles, within which each circular element of the surface must lie	No	No	☐ Refinement of size. ☐ Does not control straightness or taper. ☐ Tolerance value must be less than the size tolerance.
	Cylindricity			Concentric cylinders, within which all surface elements must lie	No	No	☐ Refinement of size. ☐ Tolerance value must be less than the size tolerance. ☐ Cylindricity is a composite control of form which includes circularity, straightness and taper of a cylindrical feature.
Profile	Profile of a Surface			A uniform boundary equally disposed along the true (theoretically exact) profile within which the elements of the surface must lie	No	Yes	☐ Used to control form or combinations of size, form, orientation, and location. ☐ Tolerance zone can be bilateral or unilateral. ☐ Basic dimensions must be used to establish the true profile.
				Parallel planes, within which the elements of both surfaces must lie simultaneously	No	No (In this example)	☐ Used as a refinement of size, the profile tolerance must be contained within the size limits. ☐ Also controls flatness of each individual surface. ☐ If a datum was used with a linear dimension it would also control parallelism. ☐ Datum with a basic dimension would control the tolerance around the true profile.
	Profile of a Line			A uniform boundary equally disposed along the true (theoretically exact) profile, within which the surface elements of each cross-section must lie	No	No (In this example)	☐ Used to control form, or combination of size, form, orientation, and location. ☐ Tolerance zone can be bilateral or unilateral. ☐ Can be used as refinement of size. ☐ Datums can be used where necessary to define design intent differently.

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Geometric Dimensioning and Tolerancing (GD&T) (continued)

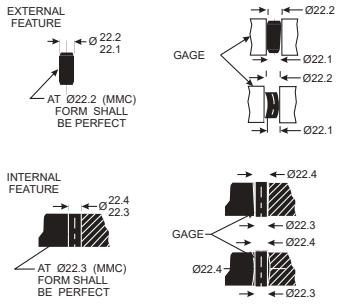
Tolerance Types	ASME Symbol	Drawing Callout Example	Drawing Callout Meaning	Tolerance Zone Definition (for Example)	Zone Modifiers Allowed	Datums Used	Additional Comments
Orientation	Angularity			Parallel planes, at a specified basic angle from a datum plane(s) within which all surface elements must lie	No (Surface)	Yes	☐ Also controls surface flatness. ☐ A basic angle must be used from the toleranced feature to the datum referenced. ☐ MMC can be used when angularity is applied to an axis or centerplane of a feature.
	Perpendicularity			Parallel planes, at 90 degrees basic (perpendicular) to a datum plane(s) within which the elements of a surface must lie	No (Surface)	Yes	☐ A refinement of size. ☐ Also controls surface flatness.
				Cylindrical boundary, at 90 degrees basic (perpendicular) to a datum plane within which the axis of the feature must lie	Yes (Axis)	Yes	☐ Not a refinement of size. ☐ Hole must also be within size limits. ☐ Calculation
	Parallelism			Parallel planes, parallel to a datum plane (or axis) within which the elements of a surface must lie	No (Surface)	Yes	☐ Refinement of size. ☐ Also controls surface flatness. ☐ Can be applied to an axis of a feature in which the zone could be parallel planes or a cylindrical tolerance zone. ☐ MMC can be used when parallelism is applied to an axis or centerplane of a feature.
Location	Position			Cylindrical boundary, within which the center axis of a cylindrical feature of size is permitted to vary from the true (theoretically exact) position	Yes	Yes	☐ Primary control for features of size. ☐ Tolerance zone also defines the limits of variation in attitude (perpendicularity) of the axis of a cylinder or slot in relationship to a datum(s). ☐ Where feature control frames contain the same datums in the same order of precedence with the same modifying symbols, they are considered a single composite pattern. If not required, it must state 'SEPARATE REQUIREMENT.'
				Parallel planes, within which the center plane of a slot is permitted to vary from the true (theoretically exact) position	Yes	Yes	
	Concentricity			Cylindrical boundary, within which the axis of all cross-sectional elements of a surface of revolution are common to the axis of the datum feature	No	Yes	☐ Median points to axis control. ☐ The specified tolerance and the datum reference apply only on an RFS basis. ☐ Used primarily for dynamically balanced comp. ☐ Involves complex analysis of the surface to determine axis location. ☐ Consider using position or profile before specifying concentricity.
	Symmetry			Parallel planes, within which the median points of all opposed or correspondingly located elements of a surface(s) are common to the center plane of the datum feature	No	Yes	☐ The specified tolerance and the datum reference apply only on an RFS basis. ☐ Involves complex analysis of the surface to determine location. ☐ Consider using position or profile before specifying symmetry.
Runout	Circular Runout			Two concentric circles, within which each circular element must lie in relationship to the datum axis	No	Yes	☐ An axis to surface control. ☐ A composite control which includes roundness and axis offset. ☐ Applies to each circular element independently. ☐ Datum applied on an RFS basis only.
	Total Runout			Two concentric cylinders, within which all circular elements must lie (simultaneously) in relationship to the datum axis	No	Yes	☐ An axis to surface control. ☐ Provides composite control of all surface elements. Used to control cumulative variations of circularity, straightness, taper, and axis offset. ☐ Datum applied on an RFS basis only.

Rule #1

Individual Feature of Size

Where only a tolerance of size is specified, the limits of size of an individual feature prescribe the extent to which variations in its geometric form, as well as size, are allowed.

Variations of Form (Envelope Principle) A feature shall not extend beyond a boundary (envelope) of perfect form at MMC.



Variations of Size

The actual local size of an individual feature at each cross section shall be within the specified tolerance of size.

Perfect Form at MMC Not Required

Where it is desired to permit a surface or surfaces of a feature to exceed the boundary of perfect form at MMC, a note such as PERFECT FORM AT MMC NOT REQUIRED is specifiied.

Rule #2

All Applicable Geometric Tolerances

RFS applies, with respect to the individual tolerance, datum reference, or both, where no modifying symbol is specified. MMC and LMC must be specified on the drawing where it is required.

Source: Courtesy of Dr. Greg Hetland, International Institute of Geometric Dimensioning & Tolerancing, www.iigdt.com.

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1.8 Project Planning and Scheduling

Critical path—The longest path of interdependent tasks within a project schedule that will lead to delay in the project if not completed on time

Deliverables—The product or service that is the resulting output of a project

Dependencies—The logical link between different activities that determines their order of execution, including start-to-start, start-to-finish, finish-to-start, and finish-to-finish

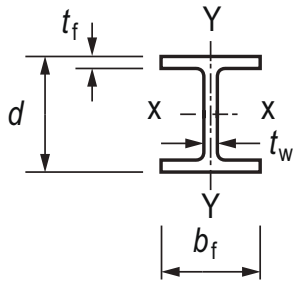
Float—The amount of time that a task can be delayed and not impact a subsequent task or the project completion

Gantt chart—A project schedule visualization tool that displays the project activities, dependencies, and deadlines on a horizontal bar chart

Key performance indicators (KPI)—Metrics used to evaluate the performance of a project

Lead time—The time required to complete a task or project

1.9 Structural Properties



W Shapes, Dimensions, and Properties

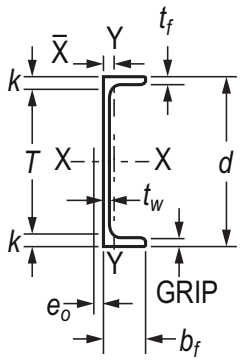
Shape	Area A	Depth d	Web t_w	Flange		X-X Axis				Y-Y Axis	
				b_f	t_f	I	S	r	Z	I	r
	in^2	in.	in.	in.	in.	in^4	in^3	in.	in^3	in^4	in.
W24 × 68	20 .1	23.7	0.415	8.97	0.585	1,830	154	9.55	177	70.4	1.87
W24 × 62	18.2	23.7	0.430	7.04	0.590	1,550	131	9.23	153	34.5	1.38
W24 × 55	16.3	23.6	0.395	7.01	0.505	1,350	114	9.11	134	29.1	1.34
W21 × 73	21.5	21 .2	0.455	8.30	0.740	1,600	151	8.64	172	70.6	1.81
W21 × 68	20.0	21 .1	0.430	8.27	0.685	1,480	140	8.60	160	64.7	1.80
W21 × 62	18.3	21 .0	0.400	8.24	0.615	1,330	127	8.54	144	57.5	1.77
W21 × 55	16.2	20.8	0.375	8.22	0.522	1,140	110	8.40	126	48.4	1.73
W21 × 57	16.7	21 .1	0.405	6.56	0.650	1,170	111	8.36	129	30.6	1.35
W21 × 50	14.7	20.8	0.380	6.53	0.535	964	94.5	8.18	110	24.9	1.30
W21 × 48	14.1	20.6	0.350	8.14	0.430	959	93.0	8.24	107	38.7	1.66
W21 × 44	13.0	20.7	0.350	6.50	0.450	843	81.6	8.06	95.4	20.7	1.26

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W Shapes, Dimensions, and Properties (cont'd)

Shape	Area A	Depth d	Web t_w	Flange		X-X Axis				Y-Y Axis	
				b_f	t_f	I	S	r	Z	I	r
	in^2	in.	in.	in.	in.	in^4	in^3	in.	in^3	in^4	in.
W18 × 71	20.8	18.5	0.495	7.64	0.810	1,170	127	7.50	146	60.3	1.70
W18 × 65	19.1	18.4	0.450	7.59	0.750	1,070	117	7.49	133	54.8	1.69
W18 × 60	17.6	18.2	0.415	7.56	0.695	984	108	7.47	123	50.1	1.68
W18 × 55	16.2	18.1	0.390	7.53	0.630	890	98.3	7.41	112	44.9	1.67
W18 × 50	14.7	18.0	0.355	7.50	0.570	800	88.9	7.38	101	40.1	1.65
W18 × 46	13.5	18.1	0.360	6.06	0.605	712	78.8	7.25	90.7	22.5	1.29
W18 × 40	11.8	17.9	0.315	6.02	0.525	612	68.4	7.21	78.4	19.1	1.27
W16 × 67	19.7	16.3	0.395	10.2	0.67	954	117	6.96	130	119	2.46
W16 × 57	16.8	16.4	0.430	7.12	0.715	758	92.2	6.72	105	43.1	1.60
W16 × 50	14.7	16.3	0.380	7.07	0.630	659	81.0	6.68	92.0	37.2	1.59
W16 × 45	13.3	16.1	0.345	7.04	0.565	586	72.7	6.65	82.3	32.8	1.57
W16 × 40	11.8	16.0	0.305	7.00	0.505	518	64.7	6.63	73.0	28.9	1.57
W16 × 36	10.6	15.9	0.295	6.99	0.430	448	56.5	6.51	64.0	24.5	1.52
W14 × 74	21.8	14.2	0.450	10. 1	0.785	795	112	6.04	126	134	2.48
W14 × 68	20.0	14.0	0.415	10.0	0.720	722	103	6.01	115	121	2.46
W14 × 61	17.9	13.9	0.375	9.99	0.645	640	92.1	5.98	102	107	2.45
W14 × 53	15.6	13.9	0.370	8.06	0.660	541	77.8	5.89	87.1	57.7	1.92
W14 × 48	14.1	13.8	0.340	8.03	0.595	484	70.2	5.85	78.4	51.4	1.91
W12 × 79	23.2	12.4	0.470	12.1	0.735	662	107	5.34	119	216	3.05
W12 × 72	21.1	12.3	0.430	12.0	0.670	597	97.4	5.31	108	195	3.04
W12 × 65	19.1	12.1	0.390	12.0	0.605	533	87.9	5.28	96.8	174	3.02
W12 × 58	17.0	12.2	0.360	10.0	0.840	475	78.0	5.28	86.4	107	2.51
W12 × 53	15.6	12. 1	0.345	9.99	0.575	425	70.6	5.23	77.9	95.8	2.48
W12 × 50	14.6	12.2	0.370	8.08	0.640	391	64.2	5.18	71.9	56.3	1.96
W12 × 45	13. 1	12. 1	0.335	8.05	0.575	348	57.7	5.15	64.2	50.0	1.95
W12 × 40	11.7	11.9	0.295	8.01	0.515	307	51 .5	5.13	57.0	44.1	1.94
W10 × 60	17.6	10.2	0.420	10.1	0.680	341	66.7	4.39	74.6	116	2.57
W10 × 54	15.8	10.1	0.370	10.0	0.615	303	60.0	4 .37	66.6	103	2.56
W10 × 49	14.4	10.0	0.340	10.0	0.560	272	54.6	4.35	60.4	93.4	2 .54
W10 × 45	13.3	10.1	0.350	8.02	0.620	248	49.1	4.32	54.9	53.4	2.01
W10 × 39	11.5	9.92	0.315	7.99	0.530	209	42.1	4.27	46.8	45.0	1.98

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Channels: American Standard Dimensions

Designation	Area A	Depth d	Web			Flange				Distance		Grip	Max. Flange Fastener	Nominal Weight per ft	$\bar{X}$
			Thickness t_w		$\frac{t_w}{2}$	Width b_f		Average Thickness t_f		T	k				
	in^2	in.	in.		in.	in.	in.	in.	in.	in.	in.	in.	in.	lb	in.
C 15 × 50	14.7	15.00	0.716	11/16	3/8	3.716	3 3/4	0.650	5/8	12 1/8	1 7/16	5/8	1	50	0.7989
× 40	11.8	15.00	0.520	l/2	1/4	3.520	3 1/2	0.650	5/8	12 1/8	1 7/16	5/8	1	40	0.777
× 33.9	9.96	15.00	0.400	3/8	3/16	3.400	3 3/8	0.650	5/8	12 1/8	1 7/16	5/8	1	33.9	0.787
C 12 × 30	8.82	12.00	0.510	l/2	1/4	3.170	3 1/8	0.501	1/2	9 3/4	1 1/8	l/2	7/8	30	0.674
× 25	7.35	12.00	0.387	3/8	3/16	3.047	3	0.501	1/2	9 3/4	1 1/8	1/2	7/8	25	0.674
× 20.7	6.09	12.00	0.282	5/16	1/8	2.942	3	0.501	1/2	9 3/4	1 1/8	1/2	7/8	20.7	0.698
C 10 × 30	8.82	10.00	0.673	11/16	5/16	3.033	3	0.436	7/16	8	1	7/16	3/4	30	0649
× 25	7.35	10.00	0.526	l/2	1/4	2.886	2 7/8	0.436	7/16	8	1	7/16	3/4	25	0.617
× 20	5.88	10.00	0.379	3/8	3/16	2.739	2 3/4	0.436	7/16	8	1	7/16	3/4	20	0.606
× 15.3	4.49	10.00	0.240	1/4	1/8	2.600	2 5/8	0.436	7/16	8	1	7/16	3/4	15.3	0.634
C 9 × 20	5.88	9.00	0.448	7/16	1/4	2.648	2 5/8	0.413	7/16	7 1/8	15/16	7/16	3/4	20	0.583
× 15	4.41	9.00	0.285	5/16	1/8	2.485	2 1/2	0.413	7/16	7 1/8	15/16	7/16	3/4	15	0.586
× 13.4	3.94	9.00	0.233	1/4	1/8	2.433	2 3/8	0.413	7/16	7 1/8	15/16	7/16	3/4	13.4	0.601

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Channels: American Standard Dimensions (cont'd)

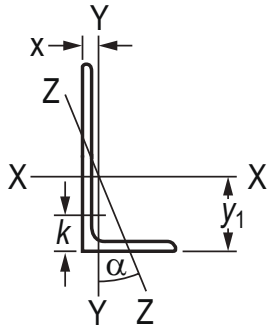
Designation	Area A	Depth d	Web			Flange				Distance		Grip	Max. Flange Fastener	Nominal Weight per ft	$\overline{X}$
			Thickness t_w		$\frac{t_w}{2}$	Width b_f		Average Thickness t_f		T	k				
	in^2	in.	in.		in.	in.	in.	in.	in.	in.	in.	in.	in.	lb	in.
C 8 × 18.75	5.51	8.00	0.487	1/2	1/4	2.527	2 1/2	0.390	3/8	6 1/8	15/16	3/8	3/4	18.75	0.565
× 40	4.04	8.00	0.303	5/16	1/8	2.343	2 3/8	0.390	3/8	6 1/8	15/16	3/8	3/4	40	0.553
× 11.5	3.38	8.00	0.220	l/4	1/8	2.260	2 1/4	0.390	3/8	6 1/8	15/16	3/8	3/4	11.5	0.571
C 7 × 14.75	4.33	7.00	0.419	7/16	3/16	2.299	2 1/4	0.366	3/8	5 1/4	7/8	3/8	5/8	14.75	0.532
× 12.25	3.60	7.00	0.314	5/16	3/16	2.194	2 1/4	0.366	3/8	5 1/4	7/8	3/8	5/8	12.25	0.525
× 9.8	2.87	7.00	0.210	3/16	1/8	2.090	2 1/8	0.366	3/8	5 1/4	7/8	3/8	5/8	9.8	0.540
C 6 × 13	3.83	6.00	0.437	7/16	3/16	2.157	2 1/8	0.343	5/16	4 3/8	13/16	5/16	5/8	13	0.514
× 10.5	3.09	6.00	0.314	5/16	3/16	2.034	2	0.343	5/16	4 3/8	13/16	3/8	5/8	10.5	0.499
× 8.2	2.40	6.00	0.200	3/16	1/8	1.920	1 7/8	0.343	5/16	4 3/8	13/16	5/16	5/8	8.2	0.511
C 5 × 9	2.64	5.00	0.325	5/16	3/16	1.885	1 7/8	0.320	5/16	3 1/2	3/4	5/16	5/8	5.9	0.478
× 6.7	1.97	5.00	0.190	3/16	1/8	1.750	1 3/4	0.320	5/16	3 1/2	3/4	-	-	6.7	0.484
C 4 × 7.25	2.13	4.00	0.321	5/16	3/16	1.721	1 3/4	0.296	5/16	2 5/8	11/16	5/16	5/8	7.25	0.459
× 5.4	!.59	4.00	0.184	3/16	1/16	1.584	1 5/8	0.296	5/16	2 5/8	11/16	-	-	5.4	0.457
C 3 × 6	1.76	3.00	0.356	3/8	3/16	1.596	1 5/8	0.273	1/4	1 5/8	11/16	-	-	6	0.455
× 5	1.47	3.00	0.258	1/4	1/8	1.498	1 1/2	0.273	1/4	1 5/8	11/16		-	5	0.438
× 4.1	1.21	3.00	0.170	3/16	1/16	1.410	1 3/8	0.273	1/4	1 5/8	11/16	-	-	4.1	0.436

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Channels: Additional American Standard Dimensions

Designation	Shear Center Location e_o	$\frac{d}{A_t}$	X-X Axis			Y-Y Axis		
			I	S	r	I	S	r
	in.		in^4	in^3	in.	in^4	in^3	in.
C 15 × 50	0.583	6.21	404	53.8	5.24	11.0	3.78	0.867
× 40	0.767	6.56	349	46.5	5.44	9.23	3.37	0.886
× 33.9	0.896	6.79	315	42.0	5.62	8.13	3.11	0.904
C 12 × 30	0.618	7.55	162	27.0	4.29	5.14	2.06	0.763
× 25	0.746	7.85	144	24.1	4.43	4.47	1.88	0.780
× 20.7	0.870	8.13	129	21.5	4.61	3.88	1.73	0.799
C 10 × 30	0.369	7.55	103	20.7	3.42	3.94	1.65	0.669
× 25	0.494	7.94	91.2	18.2	3.52	3.36	1.48	0.676
× 20	0.637	8.36	78.9	15.8	3.66	2.81	1.32	0.692
× 15.3	0.796	8.81	67.4	13.5	3.87	2.28	1.16	0.713
C 9 × 20	0.515	8.22	60.9	13.5	3.22	2.42	1.17	0.692
× 15	0.682	8.76	51.0	11.3	3.40	1.93	1.01	0.661
× 13.4	0.743	8.95	4.9	10.6	3.48	1.76	0.962	0.669
C 8 × 18.75	0.431	8.12	44.0	11.0	2.82	1.98	1.01	0.599
× 40	0.604	8.75	36.1	9.03	2.99	1.53	0.854	0.615
× 11.5	0.697	9.08	32.6	8.14	3.11	1.32	0.781	0.625
C 7 × 14.75	0.441	8.31	27.2	7.78	2.51	1.38	0.779	0.564
× 12.25	0.538	8.71	24.2	6.93	2.60	1.17	0.703	0.571
× 9.8	0.647	9.14	21.3	6.08	2.72	0.968	0.625	0.581
C 6 × 13	0.380	8.10	17.4	5.80	2.13	1.05	0.642	0.525
× 10.5	0.486	8.59	15.2	5.06	2.22	0.866	0.564	0.529
× 8.2	0.599	9.10	13.1	4.38	2.34	0.693	0.492	0.537
C 5 × 9	0.427	8.29	8.9	3.56	1.83	0.632	0.450	0.489
× 6.7	0.552	8.93	7.49	3.00	1.95	0.479	0.378	0.493
C 4 × 7.25	0.386	7.84	4.59	2.29	1.47	0.433	0.343	0.450
× 5.4	0.502	8.52	3.85	1.93	1.56	0.319	0.283	0.449
C 3 × 6	0.322	6.87	2.07	1.38	1.08	0.305	0.268	0.416
× 5	0.392	7.32	1.85	1.24	1.112	0.247	0.233	0.410
× 4.1	0.461	7.78	1.66	1.10	1.17	0.197	0.202	0.404

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Angles: Equal Legs and Unequal Legs—Properties for Designing

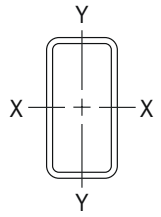
Size and Thickness	*k*	Weight per ft	Area	X-X Axis				Y-Y Axis				Z-Z Axis	
				I	*S*	*r*	*y*	*I*	*S*	*r*	*y*	*r*	Tan σ
in.	in.	lb	in^2	in^4	in^3	in.	in.	in^4	in^3	in.	in.	in.	
L 3 × 2 1/2 × 1/2	7/8	8.5	2.50	2.08	1.04	0.913	1.00	1.30	0.744	0.722	0.750	0.520	0.667
× 7/16	13/16	7.6	2.21	1.88	0.928	0.920	0.978	1.18	0.664	0.729	0.728	0.521	0.672
× 3/8	3/4	6.6	1.92	1.66	0.810	0.928	0.956	1.04	0.58I	0.736	0.706	0.522	0.676
× 5/16	11/16	5.6	1.62	1.42	0.688	0.937	0.933	0.898	0.494	0.744	0.683	0.525	0.680
× 1/4	5/8	4.5	1.31	1.17	0.561	0.945	0.911	0.743	0.404	0.753	0.661	0.528	0.684
× 3/16	9/16	3.39	0.996	0.907	0.430	0.954	0.888	0.577	0.310	0.761	0.638	0.533	0.688
L 3 × 2 ×1/2	13/16	7.7	2.25	1.92	1.00	0.924	1.08	0.672	0.474	0.546	0.583	0.428	0.414
× 7/16	3/4	6.8	2.00	1.73	0.894	0.932	1.06	0.609	0.424	0.553	0.561	0.429	0.421
× 3/8	11/16	5.9	1.73	1.53	0.781	0.940	1.04	0.543	0.371	0.559	0.539	0.430	0.428
× 5/16	5/8	5.0	1.46	1.32	0.664	0.948	1.02	0.470	0.317	0.567	0.516	0.432	0.435
× 1/4	9/16	4.1	1.19	1.09	0.542	0.957	0.993	0.392	0.260	0.574	0.493	0.435	0.440
× 3/16	1/2	3.07	0.902	0.842	0.415	0.966	0.970	0.307	0.200	0.583	0.470	0.439	0.446
L 2 1/2 × 2 1/2 × 1/2	13/16	7.7	2.25	1.23	0.724	0.739	0.806	1.23	0.724	0.739	0.806	0.487	1.000
× 3/8	11/16	5.9	1.73	0.984	0.566	0.753	0.762	0.984	0.566	0.753	0.762	0.487	1.000
× 5/16	5/8	5.0	1.46	0.849	0.482	0.761	0.740	0.849	0.482	0.761	0.740	0.489	1.000
× 1/4	9/16	4.1	1.19	0.703	0.394	0.769	0.717	0.703	0.394	0.769	0.717	0.491	1.000
× 3/16	1/2	3.07	0.902	0.547	0.303	0.778	0.694	0.547	0.303	0.778	0.694	0.495	1.000

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Angles: Equal Legs and Unequal Legs—Properties for Designing

Size and Thickness	*k*	Weight per ft	Area	X-X Axis				Y-Y Axis				Z-Z Axis	
				I	*S*	*r*	*y*	*I*	*S*	*r*	*y*	*r*	Tan σ
in.	in.	lb	in^2	in^4	in^3	in.	in.	in^4	in^3	in.	in.	in.	
L 2 1/2 × 2 × 3/8	11/16	5.3	1.55	0.912	0.547	0.768	0.831	0.514	0.363	0.577	0.581	0.420	0.614
× 5/16	5/8	4.5	1.31	0.788	0.466	0.776	0.809	0.446	0.310	0.584	0.559	0.422	0.620
× 1/4	9/16	3.62	1.06	0.654	0.381	0.784	0.787	0.372	0.254	0.592	0.537	0.424	0.626
× 3/16	1/2	2.75	0.809	0.509	0.293	0.793	0.764	0.291	0.196	0.600	0.514	0.427	0.631
L 2 × 2 × 3/8	5/8	4.7	1.36	0.479	0.351	0.594	0.636	0.479	0.351	0.594	0.636	0.389	1.000
× 5/16	9/16	3.92	1.15	0.416	0.300	0.601	0.614	0.416	0.300	0.601	0.614	0.390	1.000
× 1/4	1/2	3.19	0.938	0.348	0.247	0.609	0.592	0.348	0.247	0.609	0.592	0.391	1.000
× 3/16	7/16	2.44	0.715	0.272	0.190	0.617	0.569	0.272	0.190	0.617	0.569	0.394	1.000
1/8	3/8	1.65	0.484	0.190	0.131	0.626	0.546	0.190	0.131	0.626	0.546	0.398	1.000
L 1 3/4 × 1 3/4 × 1/4	1/2	2.77	0.813	0.227	0.227	0.529	0.529	0.227	0.227	0.529	0.529	0.341	1.000
× 3/16	7/16	2.12	0.621	0.179	0.144	0.537	0.506	0.179	0.144	0.537	0.506	0.343	1.000
L 1 1/2 × 1 1/2 × 1/4	7/16	2.34	0.688	0.139	0.134	0.449	0.466	0.139	0.134	0.449	0.466	0.292	1.000
× 3/16	3/8	1.80	0.527	0.110	0.104	0.457	0.444	0.110	0.104	0.457	0.444	0.293	1.000
L 1 1/4 × 1 1/4 × 1/4	7/16	1.92	0.563	0.077	0.091	0.369	0.403	0.077	0.091	0.369	0.403	0.243	1.000
× 3/16	3/8	1.48	0.434	0.061	0.071	0.377	0.381	0.061	0.071	0.377	0.381	0.244	1.000
L 1 1/8 × 1 1/8 × 1/8	7/32	0.900	0.266	0.032	0.040	0.345	0.327	0.032	0.040	0.345	0.327	0.221	1.000
L 1 × 1 × 1/8	1/4	0.800	0.234	0.022	0.031	0.304	0.296	0.022	0.031	0.304	0.296	0.196	1.000

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Structural Tubing: Rectangular Dimensions and Properties

Dimensions				Properties**									
Nominal* Size	Wall Thickness		Weight per ft	Area	X-X Axis				Y-Y Axis				J
					I_y	S_y	Z_y	r_y	I_y	S_y	Z_y	r_y	
in.	in.		lb	in^2	in^4	in^3	in^3	in.	in^4	in^3	in^3	in.	in^4
20 × 12	0.5000	1/2	103.30	30.4	1,650	165	201	7.37	750	125	141	4.97	1,650
	0.3750	3/8	78.52	23.1	1,280	128	154	7.45	583	97.2	109	50.3	1,270
	0.3125	5/16	65.87	19.4	1,080	108	130	7.47	495	82.5	91.8	5.06	1,070
20 × 8	0.5000	1/2	89.68	26.4	1,270	127	162	6.94	300	75.1	84.7	3.38	806
	0.3750	3/8	68.31	20.1	988	98.8	125	7.02	236	59.1	65.6	3.43	625
	0.3125	5/16	57.36	16.9	838	83.8	105	7.05	202	50.4	55.6	3.46	529
20 × 4	0.5000	1/2	76.07	22.4	889	88.9	123	6.31	61.6	30.8	36.0	1.66	205
	0.3750	3/8	58.10	17.1	699	69.9	95.3	6.40	50.3	25.1	28.5	1.72	165
	0.3125	5/16	48.86	14.4	596	59.6	80.8	6.44	43.7	21.8	24.3	1.74	143
18 × 6	0.5000	1/2	76.07	22.4	818	90.9	119	6.05	141	47.2	53.9	2.52	410
	0.3750	3/8	58.10	17.1	641	71.3	92.2	6.13	113	37.6	42.1	2.57	322
	0.3125	5/16	48.86	14.4	546	60.7	78.1	6.17	97.0	32.3	35.8	2.60	274
16 × 12	0.6250	5/8	110.36	32.4	1,160	145	175	5.98	742	124	144	4.78	1,460
	0.5000	1/2	89.68	26.4	962	120	144	6.04	618	103	118	4.84	1,200
	0.3750	3/8	68.31	20.1	748	93.5	111	6.11	482	80.3	91.3	4.90	922
	0.3125	5/16	57.36	16.9	635	79.4	93.8	6.14	409	68.2	77.2	4.93	777

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Structural Tubing: Rectangular Dimensions and Properties (cont'd)

Dimensions				Properties**									
Nominal* Size	Wall Thickness		Weight per ft	Area	X-X Axis				Y-Y Axis				J
					I_y	S_y	Z_y	r_y	I_y	S_y	Z_y	r_y	
in.	in.		lb	in^2	in^4	in^3	in^3	in.	in^4	in^3	in^3	in.	in^4
16 × 8	0.5000	1/2	76.07	22.4	722	90.2	113	5.68	244	61.0	69.7	3.30	599
	0.3750	3/8	58.10	17.1	565	70.6	87.6	5.75	193	48.2	54.2	3.36	465
	0.3125	5/16	48.86	14.4	481	60.1	74.2	5.79	165	41.2	45.9	3.39	394
16 × 4	0.5000	1/2	62.46	18.4	481	60.2	82.2	5.12	49.3	24.6	29.0	1.64	157
	0.3750	3/8	47.90	14.1	382	47.8	64.2	5.21	40.4	20.2	23.0	1.69	127
	0.3125	5/16	40.35	11.9	327	40.9	54.5	5.25	35.1	17.6	19.7	1.72	110
14 × 10	0.6250	5/8	93.34	27.4	728	104	127	5.15	431	86.2	101	3.96	885
	0.5000	1/2	76.07	22.4	608	86.9	105	5.22	361	72.3	83.6	4.02	730
	0.3750	3/8	58.10	17.1	476	68.0	81.5	5.28	284	56.8	64.8	4.08	564
	0.3125	5/16	48.86	14.4	405	57.9	69.0	5.31	242	48.4	54.9	4.11	477
7 × 4	0.5000	l/2	31.84	9.36	52.9	15.1	19.8	2.38	21.5	10.8	13.3	1.52	53.0
	0.3750	3/8	24.93	7.33	44.0	12.6	16.0	2.45	18.1	9.06	10.8	1.57	43.3
	0.3125	5/16	21.21	6.23	38.5	11.0	13.8	2.49	16.0	7.98	9.36	1.60	37.5
	0.2500	l/4	17.32	5.09	32.3	9.23	11.5	2.52	13.5	6.75	7.78	1.63	31.2
	0.1875	3/16	13.25	3.89	25.4	7.26	8.91	2.55	10.7	5.34	6.06	1.66	24.2
7 × 3	0.5000	l/2	28.43	8.36	42.3	12.1	16.6	2.25	10.5	6.99	8.84	1.12	29.8
	0.3750	3/8	22.37	6.58	35.7	10.2	13.5	2.33	9.08	6.05	7.32	1.18	25.1
	0.3125	5/16	19.08	5.61	31.5	9.00	11.8	2.37	8.11	5.41	6.40	1.20	22.0
	0.2500	l/4	15.62	4.59	26.6	7.61	9.79	2.41	6.95	4.63	5.36	1.23	18.5
	0.1875	3/16	11.97	3.52	21.1	6.02	7.63	2.45	5.57	3.71	4.21	1.26	14.6
7 × 2	0.2500	1/4	13.91	4.09	20.9	5.98	8.10	2.26	2.69	2.69	3.19	0.812	8.36
	0.1875	3/16	10.70	3.14	16.7	4.77	6.36	2.31	2.21	2.21	2.54	0.839	6.74

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Structural Tubing: Rectangular Dimensions and Properties (cont'd)

Dimensions				Properties**									
Nominal* Size	Wall Thickness		Weight per ft	Area	X-X Axis				Y-Y Axis				J
					I_y	S_y	Z_y	r_y	I_y	S_y	Z_y	r_y	
in.	in.		lb	in^2	in^4	in^3	in^3	in.	in^4	in^3	in^3	in.	in^4
6 × 5	0.5000	l/2	31.84	9.36	42.9	14.3	18.1	2.14	32.1	12.8	16.0	1.85	62.9
	0.3750	3/8	24.93	7.33	35.6	11.9	14.7	2.21	26.8	10.7	12.9	1.91	50.9
	0.3125	5/16	21.21	6.23	31.2	10.4	12.7	2.24.	23.5	9.40	11.2	1.94	43.9
	0.2500	l/4	17.32	5.09	26.2	8.74	10.5	2.27	19.8	7.91	9.26	1.97	36.3
	0.1875	3/16	13.25	3.89	20.6	6.87	8.15	2.30	15.6	6.23	7.20	2.00	28.1
6 × 4	0.5000	l/2	28.43	8.36	35.3	11.8	15.4	2.06	18.4	9.21	11.5	1.48	42.1
	0.3750	3/8	22.37	6.58	29.7	9.90	12.5	2.13	15.6	7.82	9.44	1.54	34.6
	0.3125	5/16	19.08	5.61	26.2	8.72	10.9	2.16	13.8	6.92	8.21	1.57	30.1
	0.2500	l/4	15.62	4.59	22.1	7.36	9.06	2.19	11.7	5.87	6.84	1.60	25.0
	0.1875	3/16	11.97	3.52	17.4	5.81	7.06	2.23	9.32	4.66	5.34	1.63	19.5
6 × 3	0.3750	3/8	19.82	5.83	23.8	7.92	10.4	2.02	7.78	5.19	6.34	1.16	20.3
	0.3125	5/16	16.96	4.98	21.1	7.03	9.11	2.06	6.98	4.65	5.56	1.18	17.9
	0.2500	l/4	13.91	4.09	17.9	5.98	7.62	2.09	6.00	4.00	4.67	1.21	15.1
	0.1875	3/16	10.70	3.14	14.3	4.76	5.97	2.13	4.83	3.22	3.68	1.24	11.9
6 × 2	0.3750	3/8	17.27	5.08	17.8	5.94	8.33	1.87	2.84	2.84	3.61	0.748	8.72
	0.3125	5/16	14.83	4.36	16.0	5.34	7.33	1.92	2.62	2.62	3.22	0.775	7.94
	0.2500	l/4	12.21	3.59	13.8	4.60	6.18	1.96	2.31	2.31	2.75	0.802	6.88
	0.1875	3/16	9.42	2.77	11.1	3.70	4.88	2.00	1.90	1.90	2.20	0.829	5.56
5 × 4	0.3750	3/8	19.82	5.83	18.7	7.50	9.44	1.79	13.2	6.58	8.08	1.5	26.3
	0.3125	5/16	16.96	4.98	16.6	6.65	8.24	1.83	11.7	5.85	7.05	1.53	22.9
	0.2500	l/4	13.91	4.09	14.1	5.65	6.89	1.86	9.98	4.99	5.90	1.56	19.1
	0.1875	3/16	10.70	3.14	11.2	4.49	5.39	1.89	7.96	3.98	4.63	1.59	14.9

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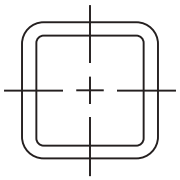
Structural Tubing: Rectangular Dimensions and Properties (cont'd)

Dimensions				Properties**									
Nominal* Size	Wall Thickness		Weight per ft	Area	X-X Axis				Y-Y Axis				J
					I_y	S_y	Z_y	r_y	I_y	S_y	Z_y	r_y	
in.	in.		lb	in^2	in^4	in^3	in^3	in.	in^4	in^3	in^3	in.	in^4
5 × 3	0.5000	1/2	21.63	6.36	16.9	6.75	9.20	1.63	7.33	4.88	6.35	1.07	18.2
	0.3750	3/8	17.27	5.08	14.7	5.89	7.71	1.70	6.48	4.32	5.35	1.13	15.6
	0.3125	5/16	14.83	4.36	13.2	5.27	6.77	1.74	5.85	3.90	4.72	1.16	13.8
	0.2500	1/4	12.21	3.59	11.3	4.52	5.70	1.77	5.05	3.37	3.99	1.19	11.7
	0.1875	3/16	9.42	2.77	9.06	3.62	4.49	1.81	4.08	2.72	3.15	1.21	9.21
5 × 2	0.3125	5/16	12.70	3.73	9.74	3.90	5.31	1.62	2.16	2.16	2.70	0.762	6.24
	0.2500	1/4	10.51	3.09	8.48	3.39	4.51	1.66	1.92	1.92	2.32	0.789	5.43
	0.1875	3/16	8.15	2.39	6.89	2.75	3.59	1.70	1.60	1.60	1.86	0.816	4.40
4 × 3	0.3125	5/16	12.70	3.73	7.45	3.72	4.75	1.41	4.71	3.14	3.88	1.12	9.89
	0.2500	1/4	10.51	3.09	6.45	3.23	4.03	1.45	4.10	2.74	3.30	1.15	. 8.41
	0.1875	3/16	8.15	2.39	5.23	2.62	3.20	1.48	3.34	2.23	2.62	1.18	6.67
4 × 2	0.3125	5/16	10.58	3.11	5.32	2.66	3.60	1.31	1.71	1.71	2.17	0.743	4.58
	0.2500	1/4	8.81	2.59	4.69	2.35	3.09	1.35	1.54	1.54	1.88	0.770	4.01
	0.1875	3/16	6.87	2.02	3.87	1.93	2.48	1.38	1.29	1.29	1.52	0.798	3.26
3.5 × 2.5	0.2500	1/4	8.81	2.59	3.97	2.27	2.88	1.24	2.33	1.86	2.28	0.948	4.99
	0.1875	3/16	6.87	2.02	3.26	1.86	2.31	1.27	1.93	1.54	1.83	0.977	4.02
3 × 2	0.2500	1/4	7.11	2.09	2.21	1.47	1.92	1.03	1.15	1.15	1.44	0.742	2.63
	0.1875	3/16	5.59	1.64	1.86	1.24	1.57	1.06	0.977	0.977	1.18	0.771	2.16

* Outside dimensions across flat sides

** Properties are based on a nominal outside corner radius equal to two times the wall thickness.

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Structural Tubing: Square Dimensions and Properties

Dimensions				Properties**					
Nominal* Size	Wall Thickness		Weight per ft	Area	*I*	*S*	*r*	*J*	*Z*
in.	in.		lb	in^2	in^4	in^3	in.	in^4	in^3
4.5 × 4.5	0.2500	1/4	13.91	4.09	12.1	5.36	1.72	19.7	6.43
	0.1875	3/16	10.70	3.14	9.60	4.27	1.75	15.4	5.03
4 × 4	0.5000	1/2	21.63	6.36	12.3	6.13	1.39	21.8	8.02
	0.3750	3/8	17.27	5.08	10.7	5.35	1.45	18.4	6.72
	0.3125	5/16	14.83	4.36	9.58	4.79	1.48	16.1	5.90
	0.2500	1/4	12.21	3.59	8.22	4.11	1.51	13.5	4.97
	0.1875	3/16	9.42	2.77	6.59	3.30	1.54	10.6	3.91
3.5 × 3.5	0.3125	5/16	12.70	3.73	6.09	3.48	1.28	10.4	4.35
	0.2500	1/4	10.51	3.09	5.29	3.02	1.31	8.82	3.70
	0.1875	3/16	8.81	2.39	4.29	2.45	1.34	6.99	2.93
3 × 3	0.3125	5/16	10.58	3.11	3.58	2.39	1.07	6.22	3.04
	0.2500	1/4	8.81	2.59	3.16	2.10	1.10	5.35	2.61
	0.1875	3/16	6.87	2.02	2.60	1.73	1.13	4.28	2.10
2.5 × 2.5	0.3125	5/16	8.45	2.48	1.87	1.50	0.868	3.32	1.96
	0.2500	1/4	7.11	2.09	1.69	1.35	0.899	2.92	1.71
	0.1875	3/16	5.59	1.64	1.42	1.14	0.930	2.38	1.40
2 × 2	0.3125	5/16	6.32	1.86	0.880	0.880	0.690	1.49	1.11
	0.2500	1/4	5.41	1.59	0.766	0.766	0.694	1.36	1.00
	0.1875	3/16	4.32	1.27	0.668	0.668	0.726	1.15	0.840

* Outside dimensions across flat sides

** Properties are based on a nominal outside corner radius equal to two times the wall thickness.

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1.10 Pipe and Tube Data

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Schedule 40 Steel Pipe

Nominal Pipe Size	Wall Thickness	Inside Diameter	Flow Area	Pipe Wt. per L.F.	Gallons per L.F.	Water Wt. per L.F.	Total Wt. per L.F.	Moment of Inertia	Section Modulus	Radius of Gyration
in.	in.	in.	in^2	lb		lb	lb	in^4	in^3	in.
0.5	0.109	0.622	0.304	0.85	0.016	0.13	0.98	0.017	0.041	0.261
0.75	0.113	0.824	0.533	1.13	0.028	0.23	1.36	0.037	0.071	0.334
1	0.133	1.049	0.864	1.68	0.044	0.37	2.05	0.087	0.133	0.421
1.25	0.140	1.380	1.495	2.27	0.078	0.65	2.92	0.195	0.235	0.540
1.5	0.145	1.610	2.035	2.72	0.106	0.88	3.60	0.310	0.326	0.623
2	0.154	2.067	3.354	3.65	0.174	1.46	5.11	0.666	0.561	0.787
2.5	0.203	2.469	4.785	5.79	0.249	2.08	7.87	1.530	1.064	0.947
3	0.216	3.068	7.389	7.58	0.383	3.20	10.78	3.020	1.724	1.164
4	0.237	4.026	12.724	10.79	0.660	5.51	16.30	7.230	3.210	1.510
5	0.258	5.047	19.996	14.62	1.039	8.68	23.30	15.170	5.450	1.878
6	0.280	6.065	28.876	18.97	1.499	12.51	31.48	28.140	8.500	2.245
8	0.322	7.981	50.002	28.55	2.598	21.69	50.24	72.500	16.810	2.938
10	0.365	10.020	78.814	40.48	4.085	34.10	74.58	160.800	29.900	3.670
12	0.406	11.938	111.875	53.53	5.810	48.50	102.03	300.000	47.100	4.370

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Schedule 80 Steel Pipe

Nominal Pipe Size	Wall Thickness	Inside Diameter	Flow Area	Pipe Wt. per L.F.	Gallons per L.F.	Water Wt. per L.F.	Total Wt. per L.F.	Moment of Inertia	Section Modulus	Radius of Gyration
in.	in.	in.	in^2	lb		lb	lb	in^4	in^3	in.
0.5	0.147	0.546	0.234	1.09	0.012	0.10	1.19	0.020	0.048	0.250
0.75	0.154	0.742	0.432	1.47	0.022	0.19	1.66	0.045	0.085	0.321
1	0.179	0.957	0.719	2.17	0.044	0.37	2.54	0.106	0.161	0.407
1.25	0.191	1.278	1.282	3.00	0.067	0.56	3.56	0.242	0.291	0.524
1.5	0.200	1.500	1.766	3.63	0.106	0.88	4.51	0.391	0.412	0.605
2	0.218	1.939	2.951	5.02	0.174	1.46	6.48	0.868	0.731	0.766
2.5	0.276	2.323	4.236	7.66	0.220	1.84	9.50	1.920	1.340	0.924
3	0.300	2.900	6.602	10.25	0.383	3.20	13.45	3.890	2.230	1.140
4	0.337	3.826	11.491	14.98	0.660	5.51	20.49	9.610	4.270	1.480
5	0.375	4.813	18.185	20.78	0.945	7.89	28.67	20.700	7.430	1.840
6	0.432	5.761	26.053	28.57	1.499	12.51	41.08	40.500	12.200	2.190
8	0.500	7.625	45.640	43.39	2.598	21.69	65.08	106.000	24.500	2.880
10	0.593	9.564	71.804	54.74	4.085	34.10	88.84	212.000	39.400	3.630
12	0.687	11.376	101.590	65.42	5.810	48.50	113.92	362.000	56.700	4.330

Double Extra Strong XX Steel Pipe

Nominal Pipe Size	Wall Thickness	Inside Diameter	Flow Area	Pipe Wt. per L.F.	Gallons per L.F.	Water Wt. per L.F.	Total Wt. per L.F.	Moment of Inertia	Section Modulus	Radius of Gyration
in.	in.	in.	in^2	lb		lb	lb	in^4	in^3	in.
2	0.436	1.503	1.773	9.03	0.174	1.46	10.49	1.310	1.100	0.703
2.5	0.552	1.771	2.462	13.69	0.128	1.07	14.76	2.870	2.000	0.844
3	0.600	2.300	4.153	18.58	0.383	3.20	21.78	5.990	3.420	1.050
4	0.674	3.152	7.799	27.54	0.660	5.51	33.05	15.300	6.790	1.370
5	0.750	4.063	12.959	38.55	0.674	5.62	44.17	33.600	12.100	1.720
6	0.864	4.897	18.825	53.16	1.499	12.51	65.67	66.300	20.000	2.060
8	0.875	6.875	37.104	72.42	2.598	21.69	94.11	162.000	37.600	2.760

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Copper Tube Data

Nominal Tube Size	Type	Wall Thickness	Inside Diameter	Tube Wt. per L.F.	Gallons per L.F.	Water Wt. per L.F.	Total Wt. per L.F.
in.		in.	in.	lb		lb	lb
0.5	K	0.049	0.527	0.344	0.011	0.09	0.44
	L	0.040	0.545	0.285	0.012	0.10	0.39
	M	0.028	0.569	0.203	0.013	0.11	0.31
0.75	K	0.065	0.745	0.641	0.023	0.19	0.83
	L	0.045	0.785	0.455	0.025	0.21	0.66
	M	0.032	0.811	0.328	0.027	0.22	0.55
1	K	0.065	0.995	0.839	0.044	0.37	1.21
	L	0.050	1.025	0.654	0.043	0.36	1.01
	M	0.035	1.055	0.464	0.045	0.38	0.84
1.25	K	0.065	1.245	1.037	0.063	0.53	1.56
	L	0.055	1.265	0.884	0.065	0.55	1.43
	M	0.042	1.291	0.682	0.068	0.57	1.25
1.5	K	0.072	1.481	1.361	0.106	0.88	2.24
	L	0.060	1.505	1.143	0.092	0.77	1.91
	M	0.049	1.527	0.940	0.095	0.79	1.73
2	K	0.083	1.959	2.063	0.174	1.46	3.52
	L	0.070	1.985	1.751	0.161	1.34	3.09
	M	0.058	2.009	1.459	0.165	1.37	2.83
2.5	K	0.095	2.435	2.926	0.242	2.02	4.95
	L	0.080	2.465	2.479	0.248	2.07	4.55
	M	0.065	2.495	2.026	0.254	2.12	4.15
3	K	0.109	2.907	4.002	0.383	3.20	7.20
	L	0.090	2.945	3.325	0.354	2.95	6.28
	M	0.072	2.981	2.676	0.363	3.03	5.70

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Ductile Iron Pipe Dimensions

Size (in.)	Outside Diameter (in.)	Thickness Class/Wall Thickness (in.)						
		50	51	52	53	54	55	56
3	3.96	–	0.25	0.28	0.31	0.34	0.37	0.40
4	4.80	–	0.26	0.29	0.32	0.35	0.38	0.41
6	6.90	0.25	0.28	0.31	0.34	0.37	0.40	0.43
8	9.05	0.27	0.30	0.33	0.36	0.39	0.42	0.45
10	11.10	0.29	0.32	0.35	0.38	0.41	0.44	0.47
12	13.20	0.31	0.34	0.37	0.40	0.43	0.46	0.49
14	15.30	0.33	0.36	0.39	0.42	0.45	0.48	0.51
16	17.40	0.34	0.37	0.40	0.43	0.46	0.49	0.52

1.11 Electrical Concepts of Motors

1.11.1 Efficiency

The *efficiency* of a motor is the ratio of useful power output to total power input. Since power input is usually given in kilowatts:

$$\text{Efficiency} = \frac{0.746 \times \text{horsepower output}}{\text{kilowatts input}}$$

$$\text{Kilowatts input} = \frac{0.746 \times \text{horsepower output}}{\text{efficiency}}$$

Motors of the same type and rating usually differ little in efficiency. Motors of different types, however, may have considerable differences in efficiency, especially adjustable-speed motors operating at reduced speeds. Efficiency of motors also varies considerably with the load and is usually highest at three-fourths or full load. At light loads, efficiency is quite low.

1.11.2 Power Factor

The *power factor* of a motor is the ratio of the kilowatt input to the kilovolt-ampere input, where:

$$\text{Kilovolt-amperes} = \frac{\text{volts} \times \text{amperes}}{1{,}000} \quad \text{for single-phase motors}$$

$$= \frac{1.73 \text{ volts} \times \text{amperes}}{1{,}000} \quad \text{for three-phase motors}$$

$$= \frac{2 \text{ volts} \times \text{amperes}}{1{,}000} \quad \text{for two-phase motors}$$

Thus the kilovolt-ampere input to a motor equals kilowatt input/power factor.

Direct-current motors and certain types of alternating-current motors have a power factor of unity (100%); that is, kilowatt input equals kilovolt-ampere input. However, the more common types of ac motors, such as induction motors, have a *lagging power factor* of less than unity.

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The product of the efficiency and the power factor of a motor is the *apparent efficiency*. Thus:

$$\text{Kilovolt-ampere input} = \frac{\text{kilowatts}}{\text{power factor}} = \frac{0.746 \times \text{hp}}{E \times \text{power factor}} = \frac{0.746 \times \text{hp}}{E_a}$$

where

E = efficiency

E_a = apparent efficiency

hp = horsepower

1.11.3 Full-Load Current

The *full-load current* of a motor, or I_{max}, is the current drawn from the line when the motor is carrying full load, with rated voltage and frequency applied for ac motors. It may be calculated as:

$$I_{max} = \frac{746 \times \text{horsepower}}{\text{efficiency} \times \text{voltage}} \quad \text{for direct-current motors}$$

$$I_{max} = \frac{746 \times \text{horsepower}}{\text{efficiency} \times \text{voltage} \times \text{power factor}} \quad \text{for single-phase ac motors}$$

$$I_{max} = \frac{746 \times \text{horsepower}}{1.73 \times \text{efficiency} \times \text{voltage} \times \text{power factor}} \quad \text{for three-phase ac motors}$$

$$I_{max} = \frac{746 \times \text{horsepower}}{2 \times \text{efficiency} \times \text{voltage} \times \text{power factor}} \quad \text{for two-phase ac motors}$$

Approximate values of full-load current for popular types and ratings of motors are given in the table in Section 1.11.6 below.

1.11.4 Torques

The *full-load torque* of a motor is fixed by its horsepower and speed rating:

$$\text{Full-load torque in pound-feet} = 5{,}250 \times \frac{\text{horsepower}}{\text{rpm}}$$

1.11.5 Synchronous Motor Speeds

Synchronous Speed Motors

Number of poles	2	4	6
Synchronous speed (rpm)	3,600	1,800	1,200

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1.11.6 Motor Phases

Power for Different Motor Phases

	Single-Phase	Three-Phase
I_{amps}	$\frac{P_{hp}(746)}{V\eta(pf)}$	$\frac{P_{hp}(746)}{\sqrt{3}\,V\eta(pf)}$
I_{amps}	$\frac{P_{kW}(1,000)}{V(pf)}$	$\frac{P_{kW}(1,000)}{\sqrt{3}\,V(pf)}$
I_{amps}	$\frac{P_{kVA}(1,000)}{V}$	$\frac{P_{kVA}(1,000)}{\sqrt{3}\,V}$
P_{kW}	$\frac{IV(pf)}{1,000}$	$\frac{\sqrt{3}\,IV(pf)}{1,000}$
P_{kVA}	$\frac{IV}{1,000}$	$\frac{\sqrt{3}\,IV}{1,000}$
P_{hp}	$\frac{IV\eta(pf)}{746}$	$\frac{\sqrt{3}\,IV\eta(pf)}{746}$

where

P = power

V = volts

pf = power factor

I = amperes

η = motor efficiency

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1.11.7 Basic Circuits

1.11.7.1 Ohm's Law

$$V = IR \quad \text{OR} \quad v(t) = i(t)R$$

where

V or $v(t)$ = voltage

I or $i(t)$ = current

R = resistance

1.11.7.2 Power

$$P = IV = \frac{V^2}{R} = I^2R$$

1.11.7.3 Kirchhoff's Voltage Law for Closed Path (Loop)

$$\sum V_{\text{rises}} = \sum V_{\text{drops}}$$

1.11.7.4 Kirchhoff's Current Law

$$\sum I_{\text{in}} = \sum I_{\text{out}}$$

1.11.7.5 Resistors in Parallel

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_N}$$

1.11.7.6 Resistors in Series

$$R_T = R_1 + R_2 + \cdots R_N$$

1.11.7.7 Mechanical Power

Conversion of electrical power to mechanical power:

$$\eta_m P_{\text{elec}} = P_{\text{mech}}$$

where η_m = electrical motor efficiency

1.11.7.8 Electrical Power

Conversion of mechanical power to electrical power:

$$\eta_G P_{\text{mech}} = P_{\text{elec}}$$

where η_G = electric generator efficiency

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2 MACHINE DESIGN AND MATERIALS

2.1 Elements of Machine Design Methodologies

1. Identifying requirements
    a. Functional performance
    b. Limits on size
    c. User interfaces
    d. External interfaces
    e. Production volume
    f. Costs
    g. Available materials
    h. Available production technologies
    i. Foreseeable usage conditions
    j. Foreseeable environmental conditions
    k. Foreseeable misuse
    l. Required safety factors
    m. Life cycle duration
    n. Product retirement

2. Risk assessment methodology examples
    a. Hierarchy of controls for addressing hazards (in decreasing order of effectiveness)
        i. Eliminate or substitute: Design to avoid hazard, or redesign to eliminate hazard.
        ii. Engineering controls: Limit access to the hazard through guards and barriers.
        iii. Administrative controls: Attempt to alert personnel to the presence of hazard through alarms, warnings, labels, instructions, work practices, training.
        iv. Personal protective equipment: Personnel must utilize protective gear because exposure to the hazard cannot be reliably avoided.

    b. Fault Tree Analysis (FTA). A top-down, logic-based methodology for analyzing a system failure condition and determining the contributing lower-level events. Steps include:
        i. Identify the system failure condition of interest.
        ii. Identify faults that could lead to the system failure condition.
        iii. Identify all known causes that could lead to the identified faults.
        iv. Connect causes, and link faults to causes, through Boolean logic gates AND and OR.
        v. Group common fault causes and refine logical connections.
        vi. Identify countermeasures to address fault causes.

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c. Failure Modes and Effects Analysis (FMEA). A risk analysis methodology to evaluate product/system components (or functions) for the following:
   i. Potential failure modes
   ii. Effects of the failure
   iii. Severity of the failure effects
   iv. Cause(s) of the failure
   v. Likelihood that a specific cause will occur
   vi. Likelihood that design controls (such as validation/verification) will prevent the occurrence (or reduce the rate of occurrence) of the cause/failure, or detect the cause/failure before the product/system is released to the customer

3. Verification and validation methodology examples
   a. Verification: Analysis of whether a product/system complies with codes, regulations, standards, specifications, or imposed conditions:
      i. Testing to requirements in codes, regulations, and standards
      ii. Evaluation of whether product/system was installed in accordance with controlling documents pertaining to the design, installation, operation, and performance of the product/system
   b. Validation: Analysis of whether a product/system meets the expectations of customers, end users, or external entities
      i. Usability studies
      ii. Prototyping
      iii. Evaluation of whether specifications are sufficient to create a product/system that meets customer expectations

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2.2 Cylindrical Fits and Tolerances

2.2.1 I-P System

ANSI B4.1 Fit Designations

RC Running or Sliding Clearance Fit	RC 1	*Close sliding fits* are intended for the accurate location of parts that must assemble without perceptible play.
	RC 2	*Sliding fits* are intended for accurate location, but with greater maximum clearance than Class RC 1. Parts made to this fit move and turn easily but are not intended to run freely, and in the larger sizes may seize with small temperature changes.
	RC 3	*Precision running fits* are about the closest fits that can be expected to run freely, and are intended for precision work at slow speeds and light journal pressures, but are not suitable where appreciable temperature differences are likely to be encountered.
	RC 4	*Close running fits* are intended chiefly for running fits on accurate machinery with moderate surface speeds and journal pressures, where accurate location and minimum play are desired.
	RC 5 and RC 6	*Medium running fits* are intended for higher running speeds, or heavy journal pressures, or both.
	RC 7	*Free running fits* are intended for use where accuracy is not essential, or where large temperature variations are likely to be encountered, or under both these conditions.
	RC 8 and RC 9	*Loose running fits* are intended for use where wide commercial tolerances may be necessary, together with an allowance, on the external member.
FN Force or Shrink Fit	FN 1	*Light drive fits* are those requiring light assembly pressures, and produce more or less permanent assemblies.
	FN 2	*Medium drive fits* are suitable for ordinary steel parts, or for shrink fits on light sections.
	FN 3	*Heavy drive fits* are suitable for heavier steel parts, or for shrink fits in medium sections.
	FN 4	*Force fits* are suitable for parts that can be highly stressed, or for shrink fits where the heavy pressing forces required are impractical.
	FN 5	
Locational Fits	LC	*Locational clearance fits* are intended for parts which are normally stationary, but that can be freely assembled or disassembled.
	LT	*Locational transition fits* are a compromise between clearance and interference fits, for applications where accuracy of location is important, but either a small amount of clearance or interference is permissible.
	LN	*Locational interference fits* are used where accuracy of location is of prime importance, and for parts requiring rigidity and alignment with no special requirements for bore pressure.

Source: Oberg, Erik, Franklin D. Jones, Holbrook L. Horton, and Henry H. Ryffel, eds., *Machinery's Handbook*, 28th ed., South Norwalk, CT: Industrial Press, 2008.

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2.2.2 SI System

ISO Symbols and Descriptions

	ISO Symbols		Description	
	Hole Basis	**Shaft Basis**		
Clearance Fits	H11/c11	C11/h11	*Loose running* fit for wide commercial tolerances or allowances on external members	↑ More Clearance
	H9/d9	D9/h9	*Free running* fit for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures.	
	H8/f7	F8/h7	*Close running* fit for running on accurate machines and for accurate speeds and journal pressures.	
	H7/g6	G7/h6	*Sliding fit* not intended to run freely, but to move and turn freely and locate accurately.	
	H7/h6	H7/h6	*Locational clearance* fit provides snug fit for locating stationary parts, but can be freely assembled and disassembled.	
Transition Fits	H7/k6	K7/h6	*Locational transition* fit for accurate location; a compromise between clearance and interference.	
	H7/n6	N7/h6	*Locational transition* fit for more accurate location where greater interference is permissible	
Interference Fits	H7/p6*	P7/h6	*Locational interference* fit for parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements.	More Interference ↓
	H7/s6	S7/h6	*Medium drive* fit for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron.	
	H7/u6	U7/h6	*Force* fit suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical.	

*Transition fit for basic sizes in range from 0 thru 3 mm

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2.2.3 Tables of Cylindrical Fits and Tolerances

American National Standard Running and Sliding Fits: *ANSI B4.1-1967 (R1987)*

Nominal Size Range, inches	Class RC 1			Class RC 2			Class RC 3			Class RC 4		
	Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits	
		Hole H5	Shaft g4		Hole H6	Shaft g5		Hole H7	Shaft f6		Hole H8	Shaft f7
Over To	Values shown below are in thousandths of an inch											
0 – 0.12	0.1 0.45	+0.2 0	–0.1 –0.25	0.1 0.55	+0.25 0	–0.1 –0.3	0.3 0.95	+0.4 0	–0.3 –0.55	0.3 1.3	+0.6 0	–0.3 –0.7
0.12 – 0.24	0.15 0.5	+0.2 0	–0.15 –0.3	0.15 0.65	+0.3 0	–0.15 –0.35	0.4 1.12	+0.5 0	–0.4 –0.7	0.4 1.6	+0.7 0	–0.4 –0.9
0.24 – 0.40	0.2 0.6	+0.25 0	–0.2 –0.35	0.2 0.85	+0.4 0	–0.2 –0.45	0.5 1.5	+0.6 0	–0.5 –0.9	0.5 2.0	+0.9 0	–0.5 –1.1
0.40 – 0.71	0.25 0.75	+0.3 0	–0.25 –0.45	0.25 0.95	+0.4 0	–0.25 –0.55	0.6 1.7	+0.7 0	–0.6 –1.0	0.6 2.3	+1.0 0	–0.6 –1.3
0.71 – 1.19	0.3 0.95	+0.4 0	–0.3 –0.55	0.3 1.2	+0.5 0	–0.3 –0.7	0.8 2.1	+0.8 0	–0.8 –1.3	0.8 2.8	+1.2 0	–0.8 –1.6
1.19 – 1.97	0.4 1.1	+0.4 0	–0.4 –0.7	0.4 1.4	+0.6 0	–0.4 –0.8	1.0 2.6	+1.0 0	–1.0 –1.6	1.0 3.6	+1.6 0	–1.0 –2.0
1.97 – 3.15	0.4 1.2	+0.5 0	–0.4 –0.7	0.4 1.6	+0.7 0	–0.4 –0.9	1.2 3.1	+1.2 0	–1.2 –1.9	1.2 4.2	+1.8 0	–1.2 –2.4
3.15 – 4.73	0.5 1.5	+0.6 0	–0.5 –0.9	0.5 2.0	+0.9 0	–0.5 –1.1	1.4 3.7	+1.4 0	–1.4 –2.3	1.4 5.0	+2.2 0	–1.4 –2.8
4.73 – 7.09	0.6 1.8	+0.7 0	–0.6 –1.1	0.6 2.3	+1.0 0	–0.6 –1.3	1.6 4.2	+1.6 0	–1.6 –2.6	1.6 5.7	+2.5 0	–1.6 –3.2
7.09 – 9.85	0.6 2.0	+0.8 0	–0.6 –1.2	0.6 2.6	+1.2 0	–0.6 –1.4	2.0 5.0	+1.8 0	–2.0 –3.2	2.0 6.6	+2.8 0	–2.0 –3.8
9.85 – 12.41	0.8 2.3	+0.9 0	–0.8 –1.4	0.8 2.9	+1.2 0	–0.8 –1.7	2.5 5.7	+2.0 0	–2.5 –3.7	2.5 7.5	+3.0 0	–2.5 –4.5
12.41 – 15.75	1.0 2.7	+1.0 0	–1.0 –1.7	1.0 3.4	+1.4 0	–1.0 –2.0	3.0 6.6	+2.2 0	–3.0 –4.4	3.0 8.7	+3.5 0	–3.0 –5.2
15.75 – 19.69	1.2 3.0	+1.0 0	–1.2 –2.0	1.2 3.8	+1.6 0	–1.2 –2.2	4.0 8.1	+2.5 0	–4.0 –5.6	4.0 10.5	+4.0 0	–4.0 –6.5

[a] Pairs of values shown represent minimum and maximum amounts of clearance resulting from application of standard tolerance limits.

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American National Standard Running and Sliding Fits: *ANSI B4.1-1967 (R1987)* (cont'd)

Nominal Size Range, inches	Class RC 5			Class RC 6			Class RC 7			Class RC 8			Class RC 9		
	Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits	
		Hole H8	Shaft e7		Hole H9	Shaft e8		Hole H9	Shaft d8		Hole H10	Shaft c9		Hole H11	Shaft
Over To	Values shown below are in thousandths of an inch														
0 – 0.12	0.6 1.6	+0.6 0	– 0.6 – 1.0	0.6 2.2	+ 1.0 0	– 0.6 – 1.2	1.0 2.6	+ 1.0 0	– 1.0 – 1.6	2.5 5.1	+ 1.6 0	– 2.5 – 3.5	4.0 8.1	+ 2.5 0	– 4.0 – 5.6
0.12 – 0.24	0.8 2.0	+0.7 0	– 0.8 – 1.3	0.8 2.7	+ 1.2 0	– 0.8 – 1.5	1.2 3.1	+ 1.2 0	– 1.2 – 1.9	2.8 5.8	+ 1.8 0	– 2.8 – 4.0	4.5 9.0	+ 3.0 0	– 4.5 – 6.0
0.24 – 0.40	1.0 2.5	+0.9 0	– 1.0 – 1.6	1.0 3.3	+ 1.4 0	– 1.0 – 1.9	1.6 3.9	+ 1.4 0	– 1.6 – 2.5	3.0 6.6	+ 2.2 0	– 3.0 – 4.4	5.0 10.7	+ 3.5 0	– 5.0 – 7.2
0.40 – 0.71	1.2 2.9	+1.0 0	– 1.2 – 1.9	1.2 3.8	+ 1.6 0	– 1.2 – 2.2	2.0 4.6	+ 1.6 0	– 2.0 – 3.0	3.5 7.9	+ 2.8 0	– 3.5 – 5.1	6.0 12.8	+ 4.0 0	– 6.0 – 8.8
0.71 – 1.19	1.6 3.6	+1.2 0	– 1.6 – 2.4	1.6 4.8	+ 2.0 0	– 1.6 – 2.8	2.5 5.7	+ 2.0 0	– 2.5 – 3.7	4.5 10.0	+ 3.5	– 4.5 – 6.5	7.0 15.5	+ 5.0 0	– 7.0 – 10.5
1.19 – 1.97	2.0 4.6	+1.6 0	– 2.0 – 3.0	2.0 6.1	+ 2.5 0	– 2.0 – 3.6	3.0 7.1	+ 2.5 0	– 3.0 – 4.6	5.0 11.5	+ 4.0 0	– 5.0 – 7.5	8.0 18.0	+ 6.0 0	– 8.0 – 12.0
1.97 – 3.15	2.5 5.5	+1.8 0	– 2.5 – 3.7	2.5 7.3	+ 3.0 0	– 2.5 – 4.3	4.0 8.8	+ 3.0 0	– 4.0 – 5.8	6.0 13.5	+ 4.5 0	– 6.0 – 9.0	9.0 20.5	+ 7.0 0	– 9.0 – 13.5
3.15 – 4.73	3.0 6.6	+2.2 0	– 3.0 – 4.4	3.0 8.7	+ 3.5 0	– 3.0 – 5.2	5.0 10.7	+ 3.5 0	– 5.0 – 7.2	7.0 15.5	+ 5.0 0	– 7.0 – 10.5	10.0 24.0	+ 9.0 0	– 10.0 – 15.0
4.73 – 7.09	3.5 7.6	+2.5 0	– 3.5 – 5.1	3.5 10.0	+ 4.0 0	– 3.5 – 6.0	6.0 12.5	+ 4.0 0	– 6.0 – 8.5	8.0 18.0	+ 6.0 0	– 8.0 – 12.0	12.0 28.0	+ 10.0 0	– 12.0 – 18.0
7.09 – 9.85	4.0 8.6	+2.8 0	– 4.0 – 5.8	4.0 11.3	+ 4.5 0	– 4.0 – 6.8	7.0 14.3	+ 4.5 0	– 7.0 – 9.8	10.0 21.5	+ 7.0 0	– 10.0 – 14.5	15.0 34.0	+ 12.0 0	– 15.0 – 22.0
9.85 – 12.41	5.0 10.0	+3.0 0	– 5.0 – 7.0	5.0 13.0	+ 5.0 0	– 5.0 – 8.0	8.0 16.0	+ 5.0 0	– 8.0 – 11.0	12.0 25.0	+ 8.0 0	– 12.0 – 17.0	18.0 38.0	+ 12.0 0	– 18.0 – 26.0
12.41 – 15.75	6.0 11.7	+3.5 0	– 6.0 – 8.2	6.0 15.5	+ 6.0 0	– 6.0 – 9.5	10.0 19.5	+ 6.0 0	– 10.0 – 13.5	14.0 29.0	+ 9.0 0	– 14.0 – 20.0	22.0 45.0	+ 14.0 0	– 22.0 – 31.0
15.75 – 19.69	8.0 14.5	+4.0 0	– 8.0 – 10.5	8.0 18.0	+ 6.0 0	– 8.0 – 12.0	12.0 22.0	+ 6.0 0	– 12.0 – 16.0	16.0 32.0	+ 10.0 0	– 16.0 – 22.0	25.0 51.0	+ 16.0 0	– 25.0 – 35.0

Tolerance limits given in body of table are added or subtracted to basic size (as indicated by + or – sign) to obtain maximum and minimum sizes of mating pairs.

All data above heavy lines are in accordance with American-British-Canadian (ABC) agreements. H5, g4, etc. are hole and shaft designations in ABC system. Limits for sizes above 19.69 inches are not covered by ABC agreements but are given in the ANSI Standard.

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American National Standard Clearance Locational Fits: ***ANSI B4.1-1967 (R1987)***

Nominal Size Range, inches	Class LC 1			Class LC 2			Class LC 3			Class LC 4			Class LC 5		
	Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits	
		Hole H6	Shaft h5		Hole H7	Shaft h6		Hole H8	Shaft h7		Hole H10	Shaft h9		Hole H7	Shaft g6
Over To	Values shown below are in thousandths of an inch														
0 – 0.12	0 0.45	+0.25 0	0 – 0.2	0 0.65	+ 0.4 0	0 – 0.25	0 1.0	+ 0.6 0	0 – 0.4	0 2.6	+ 1.6 0	0 – 1.0	0.1 0.75	+ 0.4 0	– 0.1 – 0.35
0.12 – 0.24	0 0.5	+0.3 0	0 – 0.2	0 0.8	+ 0.5 0	0 – 0.3	0 1.2	+ 0.7 0	0 0.5	0 3.0	+ 1.8 0	0 – 1.2	0.15 0.95	+ 0.5 0	– 0.15 – 0.45
0.24 – 0.40	0 0.65	+0.4 0	0 – 0.25	0 1.0	+ 0.6 0	0 – 0.4	0 1.5	+ 0.9 0	0 – 0.6	0 3.6	+ 2.2 0	0 – 1.4	0.2 1.2	+ 0.6 0	– 0.2 – 0.6
0.40 – 0.71	0 0.7	+0.4 0	0 – 0.3	0 1.1	+ 0.7 0	0 – 0.4	0 1.7	+ 1.0 0	0 – 0.7	0 4.4	+ 2.8 0	0 – 1.6	0.25 1.35	+ 0.7 0	– 0.25 – 0.65
0.71 – 1.19	0 0.9	+0.5 0	0 – 0.4	0 1.3	+ 0.8 0	0 – 0.5	0 2.0	+ 1.2 0	0 – 0.8	0 5.5	+ 3.5 0	0 – 2.0	0.3 1.6	+ 0.8 0	– 0.3 – 0.8
1.19 – 1.97	0 1.0	+0.6 0	0 – 0.4	0 1.6	+ 1.0 0	0 – 0.6	0 2.6	+ 1.6 0	0 – 1.0	0 6.5	+ 4.0 0	0 – 2.5	0.4 2.0	+ 1.0 0	– 0.4 – 1.0
1.97 – 3.15	0 1.2	+0.7 0	0 – 0.5	0 1.9	+ 1.2 0	0 – 0.7	0 3.0	+ 1.8 0	0 – 1.2	0 7.5	+ 4.5 0	0 – 3.0	0.4 2.3	+ 1.2 0	– 0.4 – 1.1
3.15 – 4.73	0 1.5	+0.9 0	0 – 0.6	0 2.3	+ 1.4 0	0 – 0.9	0 3.6	+ 2.2 0	0 – 1.4	0 8.5	+ 5.0 0	0 – 3.5	0.5 2.8	+ 1.4 0	– 0.5 – 1.4
4.73 – 7.09	0 1.7	+1.0 0	0 – 0.7	0 2.6	+ 1.6 0	0 – 1.0	0 4.1	+ 2.5 0	0 – 1.6	0 10.0	+ 6.0 0	0 – 4.0	0.6 3.2	+ 1.6 0	– 0.6 – 1.6
7.09 – 9.85	0 2.0	+1.2 0	0 – 0.8	0 3.0	+ 1.8 0	0 – 1.2	0 4.6	+ 2.8 0	0 – 1.8	0 11.5	+ 7.0 0	0 – 4.5	0.6 3.6	+ 1.8 0	– 0.6 – 1.8
9.85 – 12.41	0 2.1	+1.2 0	0 – 0.9	0 3.2	+ 2.0 0	0 – 1.2	0 5.0	+ 3.0 0	0 – 2.0	0 13.0	+ 8.0 0	0 – 5.0	0.7 3.9	+ 2.0 0	– 0.7 – 1.9
12.41 – 15.75	0 2.4	+1.4 0	0 –1.0	0 3.6	+ 2.2 0	0 – 1.4	0 5.7	+ 3.5 0	0 – 2.2	0 15.0	+ 9.0 0	0 – 6.0	0.7 4.3	+ 2.2 0	– 0.7 – 2.1
15.75 – 19.69	0 2.6	+1.6 0	0 –1.0	0 4.1	+ 2.5 0	0 – 1.6	0 6.5	+ 4.0 0	0 – 2.5	0 16.0	+ 10.0 0	0 – 6.0	0.8 4.9	+ 2.5 0	– 0.8 – 2.4

*Pairs of values shown represent minimum and maximum amounts of interference resulting from application of standard tolerance limits.

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American National Standard Clearance Locational Fits: *ANSI B4.1-1967 (R1987)* (cont'd)

Nominal Size Range, inches	Class LC 6			Class LC 7			Class LC 8			Class LC 9			Class LC 10			Class LC 11		
	Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits		Clearance[a]	Standard Tolerance Limits	
		Hole H9	Shaft f8		Hole H10	Shaft e9		Hole H10	Shaft d9		Hole H11	Shaft c10		Hole H12	Shaft		Hole H13	Shaft
Over To	Values shown below are in thousandths of an inch																	
0 – 0.12	0.3 1.9	+ 1.0 0	– 0.3 – 0.9	0.6 3.2	+ 1.6 0	– 0.6 – 1.6	1.0 2.0	+ 1.6 0	– 1.0 – 2.0	2.5 6.6	+ 2.5 0	– 2.5 – 4.1	4.0 12.0	+ 4 0	– 4 – 8	5 17	+ 6 0	–5 –11
0.12 – 0.24	0.4 2.3	+ 1.2 0	– 0.4 – 1.1	0.8 3.8	+ 1.8 0	– 0.8 – 2.0	1.2 4.2	+ 1.8 0	– 1.2 – 2.4	2.8 7.6	+ 3.0 0	– 2.8 – 4.6	4.5 14.5	+ 5 0	– 4.5 – 9.5	6 20	+ 7 0	–6 –13
0.24 – 0.40	0.5 2.8	+ 1.4 0	– 0.5 – 1.4	1.0 4.6	+ 2.2 0	– 1.0 – 2.4	1.6 5.2	+ 2.2 0	– 1.6 – 3.0	3.0 8.7	+ 3.5 0	– 3.0 – 5.2	5.0 17.0	+ 6 0	– 5 – 11	7 25	+ 9 0	–7 –16
0.40 – 0.71	0.6 3.2	+ 1.6 0	– 0.6 – 1.6	1.2 5.6	+ 2.8 0	– 1.2 – 2.8	2.0 6.4	+ 2.8 0	– 2.0 – 3.6	3.5 10.3	+ 4.0 0	– 3.5 – 6.3	6.0 20.0	+ 7 0	– 6 – 13	8 28	+ 10 0	–8 –18
0.71 – 1.19	0.8 4.0	+ 2.0 0	– 0.8 – 2.0	1.6 7.1	+ 3.5 0	– 1.6 – 3.6	2.5 8.0	+ 3.5 0	– 2.5 – 4.5	4.5 13.0	+ 5.0 0	– 4.5 – 8.0	7.0 23.0	+ 8 0	– 7 – 15	10 34	+ 12 0	–10 –22
1.19 – 1.97	1.0 5.1	+ 2.5 0	– 1.0 – 2.6	2.0 8.5	+ 4.0 0	– 2.0 – 4.5	3.6 9.5	+ 4.0 0	– 3.0 – 5.5	5.0 15.0	+ 6.0 0	– 5.0 – 9.0	8.0 28.0	+ 10 0	– 8 – 18	12 44	+ 16 0	–12 –28
1.97 – 3.15	1.2 6.0	+ 3.0 0	– 1.0 – 3.0	2.5 10.0	+ 4.5 0	– 2.5 – 5.5	4.0 11.5	+ 4.5 0	– 4.0 – 7.0	6.0 17.5	+ 7.0 0	– 6.0 – 10.5	10.0 34.0	+ 12 0	– 10 – 22	14 50	+ 18 0	–14 –32
3.15 – 4.73	1.4 7.1	+ 3.5 0	– 1.4 – 3.6	3.0 11.5	+ 5.0 0	– 3.0 – 6.5	5.0 13.5	+ 5.0 0	– 5.0 – 8.5	7.0 21.0	+ 9.0 0	– 7.0 – 12.0	11.0 39.0	+ 14 0	– 11 – 25	16 60	+ 22 0	–16 –38
4.73 – 7.09	1.6 8.1	+ 4.0 0	– 1.6 – 4.1	3.5 13.5	+ 6.0 0	– 3.5 – 7.5	6.0 16.0	+ 6.0 0	– 6.0 – 10.0	8.0 24.0	+ 10.0 0	– 8.0 – 14.0	12.0 44.0	+ 16 0	– 12 – 28	18 68	+ 25 0	–18 –43
7.09 – 9.85	2.0 9.3	+ 4.5 0	– 2.0 – 4.8	4.0 15.5	+ 7.0 0	– 4.0 – 8.5	7.0 18.5	+ 7.0 0	– 7.0 – 11.5	10.0 29.0	+ 12.0 0	– 10.0 – 17.0	16.0 52.0	+ 18 0	– 16 – 34	22 78	+ 28 0	–22 –50
9.85 – 12.41	2.2 10.2	+ 5.0 0	– 2.2 – 5.2	4.5 17.5	+ 8.0 0	– 4.5 – 9.5	7.0 20.0	+ 8.0 0	– 7.0 – 12.0	12.0 32.0	+ 12.0 0	– 12.0 – 20.0	20.0 60.0	+ 20 0	– 20 – 40	28 88	+ 30 0	–28 –58
12.41 – 15.75	2.5 12.0	+ 6.0 0	– 2.5 – 6.0	5.0 20.0	+ 9.0 0	– 5.0 – 11.0	8.0 23.0	+ 9.0 0	– 8.0 – 14.0	14.0 37.0	+ 14.0 0	– 14.0 – 23.0	22.0 66.0	+ 22 0	– 22 – 44	30 100	+ 35 0	–30 –65
15.75 – 19.69	2.8 12.8	+ 6.0 0	– 2.8 – 6.8	5.0 21.0	+ 10.0 0	– 5.0 – 11.0	9.0 25.0	+ 10.0 0	– 9.0 – 15.0	16.0 42.0	+ 16.0 0	– 16.0 – 26.0	25.0 75.0	+ 25 0	– 25 – 50	35 115	+ 40 0	–35 –75

Tolerance limits given in body of table are added or subtracted to basic size (as indicated by + or – sign) to obtain maximum and minimum sizes of mating pairs. All data above heavy lines are in accordance with American-British-Canadian (ABC) agreements. H6, H7, s6, etc. are hole and shaft designations in ABC system. Limits for sizes above 19.69 inches are not covered by ABC agreements but are given in the ANSI Standard.

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ANSI Standard Transition Locational Fits: ***ANSI B4.1-1967 (R1987)***

Nominal Size Range, inches	Class LT 1			Class LT 2			Class LT 3			Class LT 4			Class LT 5			Class LT 6		
	Fit*	Standard Tolerance Limits		Fit*	Standard Tolerance Limits		Fit*	Standard Tolerance Limits		Fit*	Standard Tolerance Limits		Fit*	Standard Tolerance Limits		Fit*	Standard Tolerance Limits	
		Hole H7	Shaft js6		Hole H8	Shaft js7		Hole H7	Shaft k6		Hole H8	Shaft k7		Hole H7	Shaft k7		Hole H7	Shaft n7
Over To	Values shown below are in thousandths of an inch																	
0 – 0.12	– 0.12 + 0.52	+ 0.4 0	+ 0.12 – 0.12	– 0.2 + 0.8	+ 0.6 0	+ 0.2 – 0.2							– 0.5 + 0.15	+ 0.4 0	+0.5 +0.25	– 0.65 + 0.15	+ 0.4 0	+ 0.65 + 0.25
0.12 – 0.24	– 0.15 + 0.65	+ 0.5 0	+ 0.15 – 0.15	– 0.25 + 0.95	+ 0.7 0	+ 0.25 – 0.25							– 0.6 + 0.2	+ 0.5 0	+0.6 +0.3	– 0.8 + 0.2	+ 0.5 0	+ 0.8 + 0.3
0.24 – 0.40	– 0.2 + 0.8	+ 0.6 0	+ 0.2 – 0.2	– 0.3 + 1.2	+ 0.9 0	+ 0.3 – 0.3	– 0.5 + 0.5	+ 0.6 0	+ 0.5 + 0.1	– 0.7 + 0.8	+ 0.9 0	+ 0.7 + 0.1	– 0.8 + 0.2	+ 0.6 0	+0.8 +0.4	– 1.0 + 0.2	+ 0.6 0	+ 1.0 + 0.4
0.40 – 0.71	– 0.2 + 0.9	+ 0.7 0	+ 0.2 – 0.2	– 0.35 + 1.35	+ 1.0 0	+ 0.35 – 0.35	– 0.5 + 0.6	+ 0.7 0	+ 0.5 + 0.1	– 0.8 + 0.9	+ 1.0 0	+ 0.8 + 0.1	– 0.9 + 0.2	+ 0.7 0	+0.9 +0.5	– 1.2 + 0.2	+ 0.7 0	+ 1.2 + 0.5
0.71 – 1.19	– 0.25 + 1.05	+ 0.8 0	+ 0.25 – 0.25	– 0.4 + 1.6	+ 1.2 0	+ 0.4 – 0.4	– 0.6 + 0.7	+ 0.8 0	+ 0.6 + 0.1	– 0.9 + 1.1	+ 1.2 0	+ 0.9 + 0.1	– 1.1 + 0.2	+ 0.8 0	+1.1 +0.6	– 1.4 + 0.2	+ 0.8 0	+ 1.4 + 0.6
1.19 – 1.97	– 0.3 + 1.3	+ 1.0 0	+ 0.3 – 0.3	– 0.5 + 2.1	+ 1.6 0	+ 0.5 – 0.5	– 0.7 + 0.9	+ 1.0 0	+ 0.7 + 0.1	– 1.1 + 1.5	+ 1.6 0	+ 1.1 + 0.1	– 1.3 + 0.3	+ 1.0 0	+1.3 +0.7	– 1.7 + 0.3	+ 1.0 0	+ 1.7 + 0.7
1.97 – 3.15	– 0.3 + 1.5	+ 1.2 0	+ 0.3 – 0.3	– 0.6 + 2.4	+ 1.8 0	+ 0.6 – 0.6	– 0.8 + 1.1	+ 1.2 0	+ 0.8 + 0.1	– 1.3 + 1.7	+ 1.8 0	+ 1.3 + 0.1	– 1.5 + 0.4	+ 1.2 0	+1.5 +0.8	– 2.0 + 0.4	+ 1.2 0	+ 2.0 + 0.8
3.15 – 4.73	– 0.4 + 1.8	+ 1.4 0	+ 0.4 – 0.4	– 0.7 + 2.9	+ 2.2 0	+ 0.7 – 0.7	– 1.0 + 1.3	+ 1.4 0	+ 1.0 + 0.1	– 1.5 + 2.1	+ 2.2 0	+ 1.5 + 0.1	– 1.9 + 0.4	+ 1.4 0	+1.9 +1.0	– 2.4 + 0.4	+ 1.4 0	+ 2.4 + 1.0
4.73 – 7.09	– 0.5 + 2.1	+ 1.6 0	+ 0.5 – 0.5	– 0.8 + 3.3	+ 2.5 0	+ 0.8 – 0.8	– 1.1 + 1.5	+ 1.6 0	+ 1.1 + 0.1	– 1.7 + 2.4	+ 2.5 0	+ 1.7 + 0.1	– 2.2 + 0.4	+ 1.6 0	+2.2 +1.2	– 2.8 + 0.4	+ 1.6 0	+ 2.8 + 1.2
7.09 – 9.85	– 0.6 + 2.4	+ 1.8 0	+ 0.6 – 0.6	– 0.9 + 3.7	+ 2.8 0	+ 0.9 – 0.9	– 1.4 + 1.6	+ 1.8 0	+ 1.4 + 0.2	– 2.0 + 2.6	+ 2.8 0	+ 2.0 + 0.2	– 2.6 + 0.4	+ 1.8 0	+2.6 +1.4	– 3.2 + 0.4	+ 1.8 0	+ 3.2 1.4
9.85 – 12.41	– 0.6 + 2.6	+ 2.0 0	+ 0.6 – 0.6	– 1.0 + 4.0	+ 3.0 0	+ 1.0 – 1.0	– 1.4 + 1.8	+ 2.0 0	+ 1.4 + 0.2	– 2.2 + 2.8	+ 3.0 0	+ 2.2 + 0.2	– 2.6 + 0.6	+ 2.0 0	+2.6 +1.4	– 3.4 + 0.6	+ 2.0 0	+ 3.4 + 1.4
12.41 – 15.75	– 0.7 + 2.9	+ 2.2 0	+ 0.7 – 0.7	– 1.0 + 4.5	+ 3.5 0	+ 1.0 – 1.0	– 1.6 + 2.0	+ 2.2 0	+ 1.6 + 0.2	– 2.4 + 3.3	+ 3.5 0	+ 2.4 + 0.2	– 3.0 + 0.6	+ 2.2 0	+3.0 +1.6	– 3.8 + 0.6	+ 2.2 0	+ 3.8 + 1.6
15.75 – 19.69	– 0.8 + 3.3	+ 2.5 0	+ 0.8 – 0.8	– 1.2 + 5.2	+ 4.0 0	+ 1.2 – 1.2	– 1.8 + 2.3	+ 2.5 0	+ 1.8 + 0.2	– 2.7 + 3.8	+ 4.0 0	+ 2.7 + 0.2	– 3.4 + 0.7	+ 2.5 0	+3.4 +1.8	– 4.3 + 0.7	+ 2.5 0	+ 4.3 + 1.8

*Pairs of values shown represent minimum (–) and maximum amount of clearance (+) resulting from application of standard tolerance limits.
All data above heavy lines are in accordance with American-British-Canadian (ABC) agreements. H7, js6, etc. are hole and shaft designations in ABC system.

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ANSI Standard Interference Locational Fits: ***ANSI B4.1-1967 (R1987)***

Nominal Size Range, inches	Class LN 1			Class LN 2			Class LN 3		
	Interference Limits*	Standard Tolerance Limits		Interference Limits*	Standard Tolerance Limits		Interference Limits*	Standard Tolerance Limits	
		Hole H6	Shaft n5		Hole H7	Shaft p6		Hole H7	Shaft r6
Over To	Values shown below are in thousandths of an inch								
0 – 0.12	0 0.45	+ 0.25 0	+ 0.45 + 0.25	0 0.65	+0.4 0	+0.65 +0.4	0.1 0.75	+0.4 0	+0.75 +0.5
0.12 – 0.24	0 0.5	+ 0.3 0	+ 0.5 + 0.3	0 0.8	+ 0.5 0	+ 0.8 + 0.5	0.1 0.9	+ 0.5 0	+ 0.9 + 0.6
0.24 – 0.40	0 0.65	+ 0.4 0	+ 0.65 + 0.4	0 1.0	+ 0.6 0	+ 1.0 + 0.6	0.2 1.2	+ 0.6 0	+ 1.2 + 0.8
0.40 – 0.71	0 0.8	+ 0.4 0	+ 0.8 + 0.4	0 1.1	+ 0.7 0	+ 1.1 + 0.7	0.3 1.4	+ 0.7 0	+ 1.4 + 1.0
0.71 – 1.19	0 1.0	+ 0.5 0	+ 1.0 + 0.5	0 1.3	+ 0.8 0	+ 1.3 + 0.8	0.4 1.7	+ 0.8 0	+ 1.7 + 1.2
1.19 – 1.97	0 1.1	+ 0.6 0	+ 1.1 + 0.6	0 1.6	+ 1.0 0	+ 1.6 + 1.0	0.4 2.0	+ 1.0 0	+ 2.0 + 1.4
1.97 – 3.15	0.1 1.3	+ 0.7 0	+ 1.3 + 0.8	0.2 2.1	+ 1.2 0	+ 2.1 + 1.4	0.4 2.3	+ 1.2 0	+ 2.3 + 1.6
3.15 – 4.73	0.1 1.6	+ 0.9 0	+ 1.6 + 1.0	0.2 2.5	+ 1.4 0	+ 2.5 + 1.6	0.6 2.9	+ 1.4 0	+ 2.9 + 2.0
4.73 – 7.09	0.2 1.9	+ 1.0 0	+ 1.9 + 1.2	0.2 2.8	+ 1.6 0	+ 2.8 + 1.8	0.9 3.5	+ 1.6 0	+ 3.5 + 2.5
7.09 – 9.85	0.2 2.2	+ 1.2 0	+ 2.2 + 1.4	0.2 3.2	+ 1.8 0	+ 3.2 + 2.0	1.2 4.2	+ 1.8 0	+ 4.2 + 3.0
9.85 – 12.41	0.2 2.3	+ 1.2 0	+ 2.3 + 1.4	0.2 3.4	+ 2.0 0	+ 3.4 + 2.2	1.5 4.7	+ 2.0 0	+ 4.7 + 3.5
12.41 – 15.75	0.2 2.6	+ 1.4 0	+ 2.6 + 1.6	0.3 3.9	+ 2.2 0	+ 3.9 + 2.5	2.3 5.9	+ 2.2 0	+ 5.9 + 4.5
15.75 – 19.69	0.2 2.8	+ 1.6 0	+ 2.8 + 1.8	0.3 4.4	+ 2.5 0	+ 4.4 + 2.8	2.5 6.6	+ 2.5 0	+ 6.6 + 5.0

All data in this table are in accordance with American-British-Canadian (ABC) agreements.

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ANSI Standard Force and Shrink Fits: ***ANSI B4.1-1967 (R1987)***

Nominal Size Range, inches	Class FN 1			Class FN 2			Class FN 3			Class FN 4			Class FN 5		
	Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits	
		Hole H6	Shaft		Hole H7	Shaft s6		Hole H7	Shaft t6		Hole H7	Shaft u6		Hole H8	Shaft x7
Over To	Values shown below are in thousandths of an inch														
0 – 0.12	0.05 0.5	+ 0.25 0	+ 0.5 + 0.3	0.2 0.85	+ 0.4 0	+ 0.85 + 0.6				0.3 0.95	+ 0.4 0	+ 0.95 + 0.7	0.3 1.3	+ 0.6 0	+ 1.3 + 0.9
0.12 – 0.24	0.1 0.6	+ 3.0 0	+ 0.6 + 0.4	0.2 1.0	+ 0.5 0	+ 1.0 + 0.7				0.4 1.2	+ 0.5 0	+ 1.2 + 0.9	0.5 1.7	+ 0.7 0	+ 1.7 + 1.2
0.24 – 0.40	0.1 0.75	+ 0.4 0	+ 0.75 + 0.5	0.4 1.4	+ 0.6 0	+ 1.4 + 1.0				0.6 1.6	+ 0.6 0	+ 1.6 + 1.2	0.5 2.0	+ 0.9 0	+ 2.0 + 1.4
0.40 – 0.56	0.1 0.8	+ 0.4 0	+ 0.8 + 0.5	0.5 1.6	+ 0.7 0	+ 1.6 + 1.2				0.7 1.8	+ 0.7 0	+ 1.8 + 1.4	0.6 2.3	+ 1.0 0	+ 2.3 + 1.6
0.56 – 0.71	0.2 0.9	+ 0.4 0	+ 0.9 + 0.6	0.5 1.6	+ 0.7 0	+ 1.6 + 1.2				0.7 1.8	+ 0.7 0	+ 1.8 + 1.4	0.8 2.5	+ 1.0 0	+ 2.5 + 1.8
0.71 – 0.95	0.2 1.1	+ 0.5 0	+ 1.1 + 0.7	0.6 1.9	+ 0.8 0	+ 1.9 + 1.4				0.8 2.1	+ 0.8 0	+ 2.1 + 1.6	1.0 3.0	+ 1.2 0	+ 3.0 + 2.2
0.95 – 1.19	0.3 1.2	+ 0.5 0	+ 1.2 + 0.8	0.6 1.9	+ 0.8 0	+ 1.9 + 1.4	0.8 2.1	+ 0.8 0	+ 2.1 1.6	1.0 2.3	+ 0.8 0	+ 2.3 + 1.8	1.3 3.3	+ 1.2 0	+ 3.3 + 2.5
1.19 – 1.58	0.3 1.3	+ 0.6 0	+ 1.3 + 0.9	0.8 2.4	+ 1.0 0	+ 2.4 + 1.8	1.0 2.6	+ 1.0 0	+ 2.6 + 2.0	1.5 3.1	+ 1.0 0	+ 3.1 + 2.5	1.4 4.0	+ 1.6 0	+ 4.0 + 3.0
1.58 – 1.97	0.4 1.4	+ 0.6 0	+ 1.4 + 1.0	0.8 2.4	+ 1.0 0	+ 2.4 + 1.8	1.2 2.8	+ 1.0 0	+ 2.8 + 2.2	1.8 3.4	+ 1.0 0	+ 3.4 + 2.8	2.4 5.0	+ 1.6 0	+ 5.0 + 4.0
1.97 – 2.56	0.6 1.8	+ 0.7 0	+ 1.8 + 1.3	0.8 2.7	+ 1.2 0	+ 2.7 + 2.0	1.3 3.2	+ 1.2 0	+ 3.2 + 2.5	2.3 4.2	+ 1.2 0	+ 4.2 + 3.5	3.2 6.2	+ 1.8 0	+ 6.2 + 5.0
2.56 – 3.15	0.7 1.9	+ 0.7 0	+ 1.9 + 1.4	1.0 2.9	+ 1.2 0	+ 2.9 + 2.2	1.8 3.7	+ 1.2 0	+ 3.7 + 3.0	2.8 4.7	+ 1.2 0	+ 4.7 + 4.0	4.2 7.2	+ 1.8 0	+ 7.2 + 6.0
3.15 – 3.94	0.9 2.4	+ 0.9 0	+ 2.4 + 1.8	1.4 3.7	+ 1.4 0	+ 3.7 + 2.8	2.1 4.4	+ 1.4 0	+ 4.4 + 3.5	3.6 5.9	+ 1.4 0	+ 5.9 + 5.0	4.8 8.4	+ 2.2 0	+ 8.4 + 7.0
3.94 – 4.73	1.1 2.6	+ 0.9 0	+ 2.6 + 2.0	1.6 3.9	+ 1.4 0	+ 3.9 + 3.0	2.6 4.9	+ 1.4 0	+ 4.9 + 4.0	4.6 6.9	+ 1.4 0	+ 6.9 + 6.0	5.8 9.4	+ 2.2 0	+ 9.4 + 8.0
4.73 – 5.52	1.2 2.9	+ 1.0 0	+ 2.9 + 2.2	1.9 4.5	+ 1.6 0	+ 4.5 + 3.5	3.4 6.0	+ 1.6 0	+ 6.0 + 5.0	5.4 8.0	+ 1.6 0	+ 8.0 + 7.0	7.5 11.6	+ 2.5 0	+ 116 + 10.0
5.52 – 6.3	1.5 3.2	+ 1.0 0	+ 3.2 + 2.5	2.4 5.0	+ 1.6 0	+ 5.0 + 4.0	3.4 6.0	+ 1.6 0	+ 6.0 + 5.0	5.4 8.0	+ 1.6 0	+ 8.0 + 7.0	9.5 13.6	+ 2.5 0	+ 13.6 + 12.0

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ANSI Standard Force and Shrink Fits: *ANSI B4.1-1967 (R1987)* (cont'd)

Nominal Size Range, inches	Class FN 1			Class FN 2			Class FN 3			Class FN 4			Class FN 5		
	Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits		Interference*	Standard Tolerance Limits	
		Hole H6	Shaft		Hole H7	Shaft s6		Hole H7	Shaft t6		Hole H7	Shaft u6		Hole H8	Shaft x7
Over To	Values shown below are in thousandths of an inch														
6.30 – 7.09	1.8 3.5	+ 1.0 0	+ 3.5 + 2.8	2.9 5.5	+ 1.6 0	+ 5.5 + 4.5	4.4 7.0	+ 1.6 0	+ 7.0 + 6.0	6.4 9.0	+ 1.6 0	+ 9.0 + 8.0	9.5 13.6	+ 2.5 0	+ 13.6 + 12.0
7.09 – 7.88	1.8 3.8	+ 1.2 0	+ 3.8 + 3.0	3.2 6.2	+ 1.8 0	+ 6.2 + 5.0	5.2 8.2	+ 1.8 0	+ 8.2 + 7.0	7.2 10.2	+ 1.8 0	+ 10.2 + 9.0	11.2 15.8	+ 2.8 0	+ 15.8 + 14.0
7.88 – 8.86	2.3 4.3	+ 1.2 0	+ 4.3 + 3.5	3.2 6.2	+ 1.8 0	+ 6.2 + 5.0	5.2 8.2	+ 1.8 0	+ 8.2 + 7.0	8.2 11.2	+ 1.8 0	+ 11.2 + 10.0	13.2 17.8	+ 2.8 0	+ 17.8 + 16.0
8.86 – 9.85	2.3 4.3	+ 1.2 0	+ 4.3 + 3.5	4.2 7.2	+ 1.8 0	+ 7.2 + 6.0	6.2 9.2	+ 1.8 0	+ 9.2 + 8.0	10.2 13.2	+ 1.8 0	+ 13.2 + 12.0	13.2 17.8	+ 2.8 0	+ 17.8 + 16.0
9.85 – 11.03	2.8 4.9	+ 1.2 0	+ 4.9 + 4.0	4.0 7.2	+ 2.0 0	+ 7.2 + 6.0	7.0 10.2	+ 2.0 0	+ 10.2 + 9.0	10.0 13.2	+ 2.0 0	+ 13.2 + 12.0	15.0 20.0	+ 3.0 0	+ 20.0 + 18.0
11.03 – 12.41	2.8 4.9	+ 1.2 0	+ 4.9 + 4.0	5.0 8.2	+ 2.0 0	+ 8.2 + 7.0	7.0 10.2	+ 2.0 0	+ 10.2 + 9.0	12.0 15.2	+ 2.0 0	+ 15.2 + 14.0	17.0 22.0	+ 3.0 0	+ 22.0 + 20.0
12.41 – 13.98	3.1 5.5	+ 1.4 0	+ 5.5 + 4.5	5.8 9.4	+ 2.2 0	+ 9.4 + 8.0	7.8 11.4	+ 2.2 0	+ 11.4 + 10.0	13.8 17.4	+ 2.2 0	+ 17.4 + 16.0	18.5 24.2	+ 3.5 0	+ 24.2 + 22.0
13.98 – 15.75	3.6 6.1	+ 1.4 0	+ 6.1 + 5.0	5.8 9.4	+ 2.2 0	+ 9.4 + 8.0	9.8 13.4	+ 2.2 0	+ 13.4 + 12.0	15.8 19.4	+ 2.2 0	+ 19.4 + 18.0	21.5 27.2	+ 3.5 0	+ 27.2 + 25.0
15.75 – 17.72	4.4 7.0	+ 1.6 0	+ 7.0 + 6.0	6.5 10.6	+ 2.5 0	+ 10.6 + 9.0	9.5 13.6	+ 2.5 0	+ 13.6 + 12.0	17.5 21.6	+ 2.5 0	+ 21.6 + 20.0	24.0 30.5	+ 4.0 0	+ 30.5 + 28.0
17.72 – 19.69	4.4 7.0	+ 1.6 0	+ 7.0 + 6.0	7.5 11.6	+ 2.5 0	+ 11.6 + 10.0	11.5 15.6	+ 2.5 0	+ 15.6 + 14.0	19.5 23.6	+ 2.5 0	+ 23.6 + 22.0	26.0 32.5	+ 4.0 0	+ 32.5 + 30.0

*Pairs of values shown represent minimum and maximum amounts of interference resulting from application of standard tolerance limits.
All data above heavy lines are in accordance with American-British-Canadian (ABC) agreements. Symbols H6, H7, s6, etc., are hole and shaft designations in the ABC system. Limits for sizes above 19.69 inches are not covered by ABC agreements but are given in the ANSI standard.

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American National Standard Preferred Hole Basis Metric Clearance Fits: *ANSI B4.2–1978(R1994)*

Basic Size[a]		Loose Running			Free Running			Close Running			Sliding			Locational Clearance		
		Hole H11	Shaft c11	Fit[b]	Hole H9	Shaft d9	Fit[b]	Hole H8	Shaft f7	Fit[b]	Hole H7	Shaft g6	Fit[b]	Hole H7	Shaft h6	Fit[b]
1	Max	1.060	0.940	0.180	1.025	0.980	0.070	1.014	0.994	0.030	1.010	0.998	0.018	1.010	1.000	0.016
	Min	1.000	0.880	0.060	1.000	0.995	0.020	1.000	0.984	0.006	1.000	0.992	0.002	1.000	0.994	0.000
1.2	Max	1.260	1.140	0.180	1.225	1.180	0.070	1.214	1.194	0.030	1.210	1.198	0.018	1.210	1.200	0.016
	Min	1.200	1.080	0.060	1.200	1.155	0.020	1.200	1.184	0.006	1.200	1.192	0.002	1.200	1.194	0.000
1.6	Max	1.660	1.540	0.180	1.625	1.580	0.070	1.614	1.594	0.030	1.610	1.598	0.018	1.610	1.600	0.016
	Min	1.600	1.480	0.060	1.600	1.555	0.020	1.600	1.584	0.006	1.600	1.592	0.002	1.600	1.594	0.000
2	Max	2.060	1.940	0.180	2.025	1.980	0.070	2.014	1.994	0.030	2.010	1.998	0.018	2.010	2.000	0.016
	Min	2.000	1.880	0.060	2.000	1.955	0.020	2.000	1.984	0.006	2.000	1.992	0.002	2.000	1.994	0.000
2.5	Max	2.560	2.440	0.180	2.525	2.480	0.070	2.514	2.494	0.030	2.510	2.498	0.018	2.510	2.500	0.016
	Min	2.500	2.380	0.060	2.500	2.455	0.020	2.500	2.484	0.006	2.500	2.492	0.002	2.500	2.494	0.000
3	Max	3.060	2.940	0.180	3.025	2.980	0.070	3.014	2.994	0.030	3.010	2.998	0.018	3.010	3.000	0.016
	Min	3.000	2.880	0.060	3.000	2.955	0.020	3.000	2.984	0.006	3.000	2.992	0.002	3.000	2.994	0.000
4	Max	4.075	3.930	0.220	4.030	3.970	0.090	4.018	3.990	0.040	4.012	3.996	0.024	4.012	4.000	0.020
	Min	4.000	3.855	0.070	4.000	3.940	0.030	4.000	3.978	0.010	4.000	3.988	0.004	4.000	3.992	0.000
5	Max	5.075	4.930	0.220	5.030	4.970	0.090	5.018	4.990	0.040	5.012	4.996	0.024	5.012	5.000	0.020
	Min	5.000	4.855	0.070	5.000	4.940	0.030	5.000	4.978	0.010	5.000	4.988	0.004	5.000	4.992	0.000
6	Max	6.075	5.930	0.220	6.030	5.970	0.090	6.018	5.990	0.040	6.012	5.996	0.024	6.012	6.000	0.020
	Min	6.000	5.855	0.070	6.000	5.940	0.030	6.000	5.978	0.010	6.000	5.988	0.004	6.000	5.992	0.000
8	Max	8.090	7.920	0.260	8.036	7.960	0.112	8.022	7.987	0.050	8.015	7.995	0.029	8.015	8.000	0.024
	Min	8.000	7.830	0.080	8.000	7.924	0.040	8.000	7.972	0.013	8.000	7.986	0.005	8.000	7.991	0.000
10	Max	10.090	9.920	0.260	10.036	9.960	0.112	10.122	9.987	0.050	10.015	9.995	0.029	10.015	10.000	0.024
	Min	10.000	9.830	0.080	10.000	9.924	0.040	10.000	9.972	0.013	10.000	9.986	0.005	10.000	9.991	0.000
12	Max	12.110	11905	0.315	12.043	11.956	0.136	12.027	11.984	0.061	12.018	11.994	0.035	12.018	12.000	0.029
	Min	12.000	11.795	0.095	12.000	11.907	0.050	12.000	11.966	0.016	12.000	11.983	0.006	12.000	11.989	0.000
16	Max	16.110	15.905	0.315	16.043	15.950	0.136	16.027	15.984	0.061	16.018	15.994	0.035	16.018	16.000	0.029
	Min	16.000	15.795	0.095	16.000	15.907	0.050	16.000	15.966	0.016	16.000	15.983	0.006	16.000	15.989	0.000
20	Max	20.130	19.890	0.370	20.052	19.935	0.169	20.033	19.980	0.074	20.021	19.993	0.041	20.021	20.000	0.034
	Min	20.000	19.760	0.110	20.000	19.883	0.065	20.000	19.959	0.020	20.000	19.980	0.007	20.000	19.987	0.000
25	Max	25.130	24.890	0.370	25.052	24.935	0.169	25.033	24.980	0.074	25.021	24.993	0.041	25.021	25.000	0.034
	Min	25.000	24.760	0.110	25.000	24.883	0.065	25.000	24.959	0.020	25.000	24.980	0.007	25.000	24.987	0.000
30	Max	30.130	29.890	0.370	30.052	29.935	0.169	30.033	29.980	0.074	30.021	29.993	0.041	30.021	30.000	0.034
	Min	30.000	29.760	0.110	30.000	29.883	0.065	30.000	29.959	0.020	30.000	29.980	0.007	30.000	29.987	0.000
40	Max	40.160	39.880	0.440	40.062	39.920	0.204	40.039	39.975	0.089	40.025	39.991	0.050	40.025	40.000	0.041
	Min	40.000	39.720	0.120	40.000	39.858	0.080	40.000	39.950	0.025	40.000	39.975	0.009	40.000	39.984	0.000

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American National Standard Preferred Hole Basis Metric Clearance Fits: *ANSI B4.2–1978(R1994)* (cont'd)

Basic Size[a]		Loose Running			Free Running			Close Running			Sliding			Locational Clearance		
		Hole H11	Shaft c11	Fit[b]	Hole H9	Shaft d9	Fit[b]	Hole H8	Shaft f7	Fit[b]	Hole H7	Shaft g6	Fit[b]	Hole H7	Shaft h6	Fit[b]
50	Max	50.160	49.870	0.450	50.062	49.920	0.204	50.039	49.975	0.089	50.025	49.991	0.050	50.025	50.000	0.041
	Min	50.000	49.710	0.130	50.000	49.858	0.080	50.000	49.950	0.025	50.000	49.975	0.009	50.000	49.984	0.000
60	Max	60.190	59.860	0.520	60.074	59.900	0.248	60.046	59.970	0.106	60.030	59.990	0.059	60.030	60.000	0.049
	Min	60.000	59.670	0.140	60.000	59.826	0.100	60.000	59.940	0.030	60.000	59.971	0.010	60.000	59.981	0.000
80	Max	80.190	79.850	0.530	80.074	79.900	0.248	80.046	79.970	0.106	80.030	79.990	0.059	80.030	80.000	0.049
	Min	80.000	79.660	0.150	80.000	79.826	0.100	80.000	79.940	0.030	80.000	79.971	0.010	80.000	79.981	0.000
100	Max	100.220	99.830	0.610	100.087	99.880	0.294	100.054	99.964	0.125	100.035	99.988	0.069	100.035	100.000	0.057
	Min	100.000	99.610	0.170	100.000	99.793	0.120	100.000	99.929	0.036	100.000	99.966	0.012	100.000	99.978	0.000
120	Max	120.220	119.820	0.620	120.087	119.880	0.294	120.054	119.964	0.125	120.035	119.988	0.069	120.035	120.000	0.057
	Min	120.000	119.600	0.180	120.000	119.793	0.120	120.000	119.929	0.036	120.000	119.966	0.012	120.000	119.978	0.000
160	Max	160.250	159.790	0.710	160.100	159.855	0.345	160.063	159.957	0.146	160.040	159.986	0.079	160.040	160.000	0.065
	Min	160.000	159.540	0.210	160.000	159.755	0.145	160.000	159.917	0.043	160.000	159.961	0.014	160.000	159.975	0.000
200	Max	200.290	199.760	0.820	200.115	199.830	0.400	200.072	199.950	0.168	200.046	199.985	0.090	200.046	200.000	0.075
	Min	200.000	199.470	0.240	200.000	199.715	0.170	200.000	199.904	0.050	200.000	199.956	0.015	200.000	199.971	0.000
250	Max	250.290	249.720	0.860	250.115	249.830	0.400	250.072	249.950	0.168	250.046	249.985	0.090	250.046	250.000	0.075
	Min	250.000	249.430	0.280	250.000	249.715	0.170	250.000	249.904	0.050	250.000	249.956	0.015	250.000	249.971	0.000
300	Max	300.320	299.670	0.970	300.130	299.810	0.450	300.081	299.944	0.189	300.052	299.983	0.101	300.052	300.000	0.084
	Min	300.000	299.350	0.330	300.000	299.680	0.190	300.000	299.892	0.056	300.000	299.951	0.017	300.000	299.968	0.000
400	Max	400.360	399.600	1.120	400.140	399.790	0.490	400.089	399.938	0.208	400.057	399.982	0.111	400.057	400.000	0.093
	Min	400.000	399.240	0.400	400.000	399.650	0.210	400.000	399.881	0.062	400.000	399.946	0.018	400.000	399.964	0.000
500	Max	500.400	499.520	1.280	500.155	499.770	0.540	500.097	499.932	0.228	500.063	499.980	0.123	500.063	500.000	0.103
	Min	500.000	499.120	0.480	500.000	499.615	0.230	500.000	499.869	0.068	500.000	499.940	0.020	500.000	499.960	0.000

[a] The sizes shown are first-choice basic sizes. Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1994).

[b] All fits shown in this table have clearance.

All dimensions are in millimeters.

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American National Standard Preferred Hole Basis Metric Transition and Interference Fits: *ANSI B4.2–1978(R1994)* (cont'd)

Basic Size[a]		Locational Transition			Locational Transition			Locational Interference			Medium Drive			Force		
		Hole H7	Shaft k6	Fit[b]	Hole H7	Shaft n6	Fit[b]	Hole H7	Shaft p6	Fit[b]	Hole H7	Shaft s6	Fit[b]	Hole H7	Shaft u6	Fit[b]
1	Max	1.010	1.006	+0.010	1.010	1.010	+0.006	1.010	1.012	+0.004	1.010	1.020	–0.004	1.010	1.024	–0.008
	Min	1.000	1.000	–0.006	1.000	1.004	–0.012	1.000	1.006	–0.012	1.000	1.014	–0.020	1.000	1.018	–0.024
1.2	Max	1.210	1.206	+0.010	1.210	1.210	+0.006	1.210	1.212	+0.004	1.210	1.220	–0.004	1.210	1.224	–0.008
	Min	1.200	1.200	–0.006	1.200	1.204	–0.010	1.200	1.206	–0.012	1.200	1.214	–0.020	1.200	1.218	–0.024
1.6	Max	1.610	1.606	+0.010	1.610	1.610	+0.006	1.610	1.612	+0.004	1.610	1.620	–0.004	1.610	1.624	–0.008
	Min	1.600	1.600	–0.006	1.600	1.604	–0.010	1.600	1.606	–0.012	1.600	1.614	–0.020	1.600	1.618	–0.024
2	Max	2.010	2.006	+0.010	2.010	2.010	+0.006	2.010	2.012	+0.004	2.010	2.020	–0.004	2.010	2.024	–0.008
	Min	2.000	2.000	–0.006	2.000	2.004	–0.010	2.000	2.006	–0.012	2.000	2.014	–0.020	2.000	2.018	–0.024
2.5	Max	2.510	2.506	+0.010	2.510	2.510	+0.006	2.510	2.512	+0.004	2.510	2.520	–0.004	2.510	2.524	–0.008
	Min	2.500	2.500	–0.006	2.500	2.504	–0.010	2.500	2.506	–0.012	2.500	2.514	–0.020	2.500	2.518	–0.024
3	Max	3.010	3.006	+0.010	3.010	3.010	+0.006	3.010	3.012	+0.004	3.010	3.020	–0.004	3.010	3.024	–0.008
	Min	3.000	3.000	–0.006	3.000	3.004	–0.010	3.000	3.006	–0.012	3.000	3.014	–0.020	3.000	3.018	–0.024
4	Max	4.012	4.009	+0.011	4.012	4.016	+0.004	4.012	4.020	0.000	4.012	4.027	–0.007	4.012	4.031	–0.011
	Min	4.000	4.001	–0.009	4.000	4.008	–0.016	4.000	4.012	–0.020	4.000	4.019	–0.027	4.000	4.023	–0.031
5	Max	5.012	5.009	+0.011	5.012	5.016	+0.004	5.012	5.020	0.000	5.012	5.027	–0.007	5.012	5.031	–0.011
	Min	5.000	5.001	–0.009	5.000	5.008	–0.016	5.000	5.012	–0.020	5.000	5.019	–0.027	5.000	5.023	–0.031
6	Max	6.012	6.009	+0.011	6.012	6.016	+0.004	6.012	6.020	0.000	6.012	6.027	–0.007	6.012	6.031	–0.011
	Min	6.000	6.001	–0.009	6.000	6.008	–0.016	6.000	6.012	–0.020	6.000	6.019	–0.027	6.000	6.023	–0.031
8	Max	8.015	8.010	+1.014	8.015	8.019	+0.005	8.015	8.024	0.000	8.015	8.032	–0.008	8.015	8.037	–0.013
	Min	8.000	8.001	–0.010	8.000	8.010	–0.019	8.000	8.015	–0.024	8.000	8.023	–0.032	8.000	8.028	–0.037
10	Max	10.015	10.010	+0.014	10.015	10.019	+0.005	10.015	10.024	0.000	10.015	10.032	–0.008	10.015	10.034	–0.013
	Min	10.000	10.001	–0.010	10.000	10.010	–0.019	10.000	10.015	–0.024	10.000	10.000	–0.032	10.000	10.028	–0.037
12	Max	12.018	12.012	+0.017	12.018	12.023	+0.006	12.018	12.029	0.000	12.018	12.039	–0.010	12.018	12.044	–0.015
	Min	12.000	12.001	–0.012	12.000	12.012	–0.023	12.000	12.018	–0.029	12.000	12.028	–0.039	12.000	12.033	–0.044
16	Max	16.018	16.012	+0.017	16.018	16.023	+0.006	16.018	16.029	0.000	16.018	16.039	–0.010	16.018	16.044	–0.015
	Min	16.000	16.001	–0.012	16.000	16.012	–0.023	16.000	16.018	–0.029	16.000	16.028	–0.039	16.000	16.033	–0.044
20	Max	20.021	20.015	+0.019	20.021	20.028	+0.006	20.021	20.035	–0.001	20.021	20.048	–0.014	20.021	20.054	–0.020
	Min	20.000	20.002	–0.015	20.000	20.015	–0.028	20.000	20.022	–0.035	20.000	20.035	–0.048	20.000	20.041	–0.054
25	Max	25.021	25.015	+0.019	25.021	25.028	+0.006	25.021	25.035	–0.001	25.021	25.048	–0.014	25.021	25.061	–0.027
	Min	25.000	25.002	–0.015	25.000	25.015	–0.028	25.000	25.022	–0.035	25.000	25.035	–0.048	25.000	25.048	–0.061
30	Max	30.021	30.015	+0.019	30.021	30.028	+0.006	30.021	30.035	–0.001	30.021	30.048	–0.014	30.021	30.061	–0.027
	Min	30.000	30.002	–0.015	30.000	30.015	–0.028	30.000	30.022	–0.035	30.000	30.035	–0.048	30.000	30.048	–0.061
40	Max	40.025	40.018	+0.023	40.025	40.033	+0.008	40.025	40.042	–0.001	40.025	40.059	–0.018	40.025	40.076	–0.035
	Min	40.000	40.002	–0.018	40.000	40.017	–0.033	40.000	40.026	–0.042	40.000	40.043	–0.059	40.000	40.060	–0.076
50	Max	50.025	50.018	+0.023	50.025	50.033	+0.008	50.025	50.042	–0.001	50.025	50.059	–0.018	50.025	50.086	–0.045
	Min	50.000	50.002	–0.018	50.000	50.017	–0.033	50.000	50.026	–0.042	50.000	50.043	–0.059	50.000	50.070	–0.086

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American National Standard Preferred Hole Basis Metric Transition and Interference Fits: *ANSI B4.2–1978(R1994)* (cont'd)

Basic Size[a]		Locational Transition			Locational Transition			Locational Interference			Medium Drive			Force		
		Hole H7	Shaft k6	Fit[b]	Hole H7	Shaft n6	Fit[b]	Hole H7	Shaft p6	Fit[b]	Hole H7	Shaft s6	Fit[b]	Hole H7	Shaft u6	Fit[b]
60	Max	60.030	60.021	+0.028	60.030	60.039	+0.010	60.030	60.051	–0.002	60.030	60.072	–0.023	60.030	60.106	–0.057
	Min	60.000	60.002	–0.021	60.000	60.020	–0.039	60.000	60.032	–0.051	60.000	60.053	–0.072	60.000	60.087	–0.106
80	Max	80.030	80.021	+0.028	80.030	80.039	+0.010	80.030	80.051	–0.002	80.030	80.078	–0.029	80.030	80.121	–0.072
	Min	80.000	80.002	–0.021	80.000	80.020	–0.039	80.000	80.032	–0.051	80.000	80.059	–0.078	80.000	80.102	–0.121
100	Max	100.035	100.025	+0.032	100.035	100.045	+0.012	100.035	100.059	–0.036	100.035	100.093	–0.036	100.035	100.146	–0.089
	Min	100.000	100.003	–0.025	100.000	100.023	–0.045	100.000	100.037	–0.059	100.000	100.071	–0.093	100.000	100.124	–0.146
120	Max	120.035	120.025	+0.032	120.035	120.045	+0.012	120.035	120.059	–0.002	120.035	120.101	–0.044	120.035	120.166	–0.109
	Min	120.000	120.003	–0.025	120.000	120.023	–0.045	120.000	120.037	–0.059	120.000	120.079	–0.101	120.000	120.144	–0.166
160	Max	160.040	160.028	+0.037	160.040	160.052	+0.013	160.040	160.068	–0.003	160.040	160.125	–0.060	160.040	160.215	–0.150
	Min	160.000	160.003	–0.028	160.000	160.027	–0.052	160.000	160.043	–0.068	160.000	160.100	–0.125	160.000	160.190	–0.215
200	Max	200.046	200.033	+0.042	200.046	200.060	+0.015	200.046	200.079	–0.004	200.046	200.151	–0.076	200.046	200.265	–0.190
	Min	200.000	200.004	–0.033	200.000	200.031	–0.060	200.000	200.050	–0.079	200.000	200.122	–0.151	200.000	200.236	–0.265
250	Max	250.046	250.033	+0.042	250.046	250.060	+0.015	250.046	250.079	–0.004	250.046	250.169	–0.094	250.046	250.313	–0.238
	Min	250.000	250.004	–0.033	250.000	250.031	–0.060	250.000	250.050	–0.079	250.000	250.140	–0.169	250.000	250.284	–0.313
300	Max	300.052	300.036	+0.048	300.052	300.066	+0.018	300.052	300.088	–0.004	300.052	300.202	–0.118	300.052	300.382	–0.298
	Min	300.000	300.004	–0.036	300.000	300.034	–0.066	300.000	300.056	–0.088	300.000	300.170	–0.202	300.000	300.350	–0.382
400	Max	400.057	400.040	+0.053	400.057	400.073	+0.020	400.057	400.098	–0.005	400.057	400.244	–0.151	400.057	400.471	–0.378
	Min	400.000	400.004	–0.040	400.000	400.037	–0.073	400.000	400.062	–0.098	400.000	400.208	–0.244	400.000	400.435	–0.471
500	Max	500.063	500.045	+0.058	500.063	500.080	+0.023	500.063	500.108	–0.005	500.063	500.292	–0.189	500.063	500.580	–0.477
	Min	500.000	500.005	–0.045	500.000	500.040	–0.080	500.000	500.068	–0.108	500.000	500.252	–0.292	500.000	500.540	–0.580

[a] The sizes shown are first-choice basic sizes. Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1994).

[b] A plus sign indicates clearance; a minus sign, interference.

All dimensions are in millimeters.

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American National Standard Preferred Shaft Basis Metric Clearance Fits: *ANSI B4.2–1978(R1994)*

Basic Size[a]		Loose Running			Free Running			Close Running			Sliding			Location clearance		
		Hole C11	Shaft h11	Fit[b]	Hole D9	Shaft h9	Fit[b]	Hole F8	Shaft h7	Fit[b]	Hole G7	Shaft h6	Fit[b]	Hole H7	Shaft h6	Fit[b]
1	Max	1.120	1.000	0.180	1.045	1.000	0.070	1.020	1.000	0.030	1.012	1.000	0.018	1.010	1.000	0.016
	Min	1.060	0.940	0.060	1.020	0.975	0.020	1.006	0.990	0.006	1.002	0.994	0.002	1.000	0.994	0.000
1.2	Max	1.320	1.200	0.180	1.245	1.200	0.070	1.220	1.200	0.030	1.212	1.200	0.018	1.210	1.200	0.016
	Min	1.260	1.140	0.060	1.220	1.175	0.020	1.206	1.190	0.006	1.202	1.194	0.002	1.200	1.194	0.000
1.6	Max	1.720	1.600	0.180	1.645	1.600	0.070	1.620	1.600	0.030	1.612	1.600	0.018	1.610	1.600	0.016
	Min	1.660	1.540	0.060	1.620	1.575	0.020	1.606	1.590	0.006	1.602	1.594	0.002	1.600	1.594	0.000
2	Max	2.120	2.000	0.180	2.045	2.000	0.070	2.020	2.000	0.030	2.012	2.000	0.018	2.010	2.000	0.016
	Min	2.060	1.940	0.060	2.020	1.975	0.020	2.006	1.990	0.006	2.002	1.994	0.002	2.000	1.994	0.000
2.5	Max	2.620	2.500	0.180	2.545	2.500	0.070	2.520	2.500	0.030	2.512	2.500	0.018	2.510	2.500	0.016
	Min	2.560	2.440	0.060	2.520	2.475	0.020	2.506	2.490	0.006	2.502	2.494	0.002	2.500	2.494	0.000
3	Max	3.120	3.000	0.180	3.045	3.000	0.070	3.020	3.000	0.030	3.012	3.000	0.018	3.010	3.000	0.016
	Min	3.060	2.940	0.060	3.020	2.975	0.020	3.006	2.990	0.006	3.002	2.994	0.002	3.000	2.994	0.000
4	Max	4.145	4.000	0.220	4.060	4.000	0.090	4.028	4.000	0.040	4.016	4.000	0.024	4.012	4.000	0.020
	Min	4.070	3.925	0.070	4.030	3.970	0.030	4.010	3.988	0.010	4.004	3.992	0.004	4.000	3.992	0.000
5	Max	5.145	5.000	0.220	5.060	5.000	0.090	5.028	5.000	0.040	5.016	5.000	0.024	5.012	5.000	0.020
	Min	5.070	4.925	0.070	5.030	4.970	0.030	5.010	4.988	0.010	5.004	4.992	0.004	5.000	4.992	0.000
6	Max	6.145	6.000	0.220	6.060	6.000	0.090	6.028	6.000	0.040	6.016	6.000	0.024	6.012	6.000	0.020
	Min	6.070	5.925	0.070	6.030	5.970	0.030	6.010	5.988	0.010	6.004	5.992	0.004	6.000	5.992	0.000
8	Max	8.170	8.000	0.260	8.076	8.000	0.112	8.035	8.000	0.050	8.020	8.000	0.029	8.015	8.000	0.024
	Min	8.080	7.910	0.080	8.040	7.964	0.040	8.013	7.985	0.013	8.005	7.991	0.005	8.000	7.991	0.000
10	Max	10.170	10.000	0.260	10.076	10.000	0.112	10.035	10.000	0.050	10.020	10.000	0.029	10.015	10.000	0.024
	Min	10.080	9.910	0.080	10.040	9.964	0.040	10.013	9.985	0.013	10.005	9.991	0.005	10.000	9.991	0.000
12	Max	12.205	12.000	0.315	12.093	12.000	0.136	12.043	12.000	0.061	12.024	12.000	0.035	12.018	12.000	0.029
	Min	12.095	11.890	0.095	12.050	11.957	0.050	12.016	11.982	0.016	12.006	11.989	0.006	12.000	11.989	0.000
16	Max	16.205	16.000	0.315	16.093	16.000	0.136	16.043	16.000	0.061	16.024	16.000	0.035	16.018	16.000	0.029
	Min	16.095	15.890	0.095	16.050	15.957	0.050	16.016	15.982	0.016	16.006	15.989	0.006	16.000	15.989	0.000
20	Max	20.240	20.000	0.370	20.117	20.000	0.169	20.053	20.000	0.074	20.028	20.000	0.041	20.021	20.000	0.034
	Min	20.110	19.870	0.110	20.065	19.948	0.065	20.020	19.979	0.020	20.007	19.987	0.007	20.000	19.987	0.000
25	Max	25.240	25.000	0.370	25.117	25.000	0.169	25.053	25.000	0.074	25.028	25.000	0.041	25.021	25.000	0.034
	Min	25.110	24.870	0.110	25.065	24.948	0.065	25.020	24.979	0.020	25.007	24.987	0.007	25.000	24.987	0.000
30	Max	30.240	30.000	0.370	30.117	30.000	0.169	30.053	30.000	0.074	30.028	30.000	0.41	30.021	30.000	0.034
	Min	30.110	29.870	0.110	30.065	29.948	0.065	30.020	29.979	0.020	30.007	29.987	0.007	30.000	29.987	0.000
40	Max	40.280	40.000	0.440	40.142	40.000	0.204	40.064	40.000	0.089	40.034	40.000	0.050	40.025	40.000	0.041
	Min	40.120	39.840	0.120	40.080	39.938	0.080	40.025	39.975	0.025	40.009	39.984	0.009	40.000	39.984	0.000
50	Max	50.290	50.000	0.450	50.142	50.000	0.204	50.064	50.000	0.089	50.034	50.000	0.050	50.025	50.000	0.041
	Min	50.130	49.840	0.130	50.080	49.938	0.080	50.025	49.975	0.025	50.009	49.984	0.009	50.000	49.984	0.000

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American National Standard Preferred Shaft Basis Metric Clearance Fits: *ANSI B4.2–1978(R1994)* (cont'd)

Basic Size[a]		Loose Running			Free Running			Close Running			Sliding			Locational Clearance		
		Hole C11	Shaft h11	Fit[b]	Hole D9	Shaft h9	Fit[b]	Hole F8	Shaft h7	Fit[b]	Hole G7	Shaft h6	Fit[b]	Hole H7	Shaft h6	Fit[b]
60	Max	60.330	60.000	0.520	60.174	60.000	0.248	60.076	60.000	0.106	60.040	60.000	0.050	60.030	60.000	0.049
	Min	60.140	59.810	0.140	60.100	59.926	0.100	60.030	59.970	0.030	60.010	59.981	0.010	60.000	59.981	0.000
80	Max	80.340	80.000	0.530	80.174	80.000	0.248	80.076	80.000	0.106	80.040	80.000	0.059	80.030	80.000	0.049
	Min	80.150	79.810	0.150	80.100	79.926	0.100	80.030	79.970	0.030	80.010	79.981	0.010	80.000	79.981	0.000
100	Max	100.390	100.000	0.610	100.207	100.000	0.294	100.090	100.000	0.125	100.047	100.000	0.069	100.035	100.000	0.057
	Min	100.170	99.780	0.170	100.120	99.913	0.120	100.036	99.965	0.036	100.012	99.978	0.012	100.000	99.978	0.000
120	Max	120.400	120.000	0.620	120.207	120.000	0.294	120.090	120.000	0.125	120.047	120.000	0.069	120.035	120.000	0.057
	Min	120.180	119.780	0.180	120.120	119.913	0.120	120.036	119.965	0.036	120.012	119.978	0.012	120.000	119.978	0.000
160	Max	160.460	160.000	0.710	160.245	160.000	0.345	160.160	160.000	0.146	160.054	160.000	0.079	160.040	160.000	0.065
	Min	160.210	159.750	0.210	160.145	159.900	0.145	160.043	159.960	0.043	160.014	159.975	0.014	160.000	159.975	0.000
200	Max	200.530	200.000	0.820	200.285	200.000	0.400	200.122	200.000	0.168	200.061	200.000	0.090	200.046	200.000	0.075
	Min	200.240	199.710	0.240	200.170	199.885	0.170	200.050	199.954	0.050	200.015	199.971	0.015	200.000	199.971	0.000
250	Max	250.570	250.000	0.860	250.285	250.000	0.400	250.122	250.000	0.168	250.061	250.000	0.090	250.046	250.000	0.075
	Min	250.280	249.710	0.280	250.170	249.885	0.170	250.050	249.954	0.050	250.015	249.971	0.015	250.000	249.971	0.000
300	Max	300.650	300.000	0.970	300.320	300.000	0.450	300.137	300.000	0.189	300.069	300.000	0.101	300.052	300.000	0.084
	Min	300.330	299.680	0.330	300.190	299.870	0.190	300.056	299.948	0.056	300.017	299.968	0.017	300.000	299.968	0.000
400	Max	400.760	400.000	1.120	400.350	400.000	0.490	400.151	400.000	0.208	400.075	400.000	0.111	400.057	400.000	0.093
	Min	400.400	399.640	0.400	400.210	399.860	0.210	400.062	399.943	0.062	400.018	399.964	0.018	400.000	399.964	0.000
500	Max	500.880	500.000	1.280	500.385	500.000	0.540	500.165	500.000	0.228	500.083	500.000	0.123	500.063	500.000	0.103
	Min	500.480	499.600	0.480	500.230	499.845	0.230	500.068	499.937	0.068	500.020	499.960	0.020	500.000	499.960	0.000

[a] The sizes shown are first-choice basic sizes. Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1994).

[b] All fits shown in this table have clearance.

All dimensions are in millimeters.

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American National Standard Preferred Shaft Basis Metric Transition and Interference Fits: *ANSI B4.2–1978(R1994)*

Basic Size[a]		Locational Transition			Locational Transition			Locational Interference			Medium Drive			Force		
		Hole K7	Shaft h6	Fit[b]	Hole N7	Shaft h6	Fit[b]	Hole P7	Shaft h6	Fit[b]	Hole S7	Shaft h6	Fit[b]	Hole U7	Shaft h6	Fit[b]
1	Max	1.000	1.000	+0.006	0.996	1.000	+0.002	0.994	1.000	0.000	0.986	1.000	–0.008	0.982	1.000	–0.012
	Min	0.990	0.994	–0.010	0.986	0.994	–0.014	0.984	0.994	–0.016	0.976	0.994	–0.024	0.972	0.994	–0.028
1.2	Max	1.200	1.200	+0.006	1.196	1.200	+0.002	1.194	1.200	0.000	1.186	1.200	–0.008	1.182	1.200	–0.012
	Min	1.190	1.194	–0.010	1.186	1.194	–0.014	1.184	1.194	–0.016	1.176	1.194	–0.024	1.172	1.984	–0.028
1.6	Max	1.600	1.600	+0.006	1.596	1.600	+0.002	1.594	1.600	0.000	1.586	1.600	–0.008	1.582	1.600	–0.012
	Min	1.590	1.594	–0.010	1.586	1.594	–0.014	1.584	1.594	–0.016	1.576	1.594	–0.024	1.572	1.594	–0.028
2	Max	2.000	2.000	+0.006	1.996	2.000	+0.002	1.994	2.000	0.000	1.986	2.000	–0.008	1.982	2.000	–0.012
	Min	1.990	1.994	–0.010	1.986	1.994	–0.014	1.984	1.994	–0.016	1.976	1.994	–0.024	1.972	1.994	–0.028
2.5	Max	2.500	2.500	+0.006	2.496	2.500	+0.002	2.494	2.500	0.000	2.486	2.500	–0.008	2.482	2.500	–0.012
	Min	2.490	2.494	–0.010	2.486	2.494	–0.014	2.484	2.494	–0.016	2.476	2.494	–0.024	2.472	2.494	–0.028
3	Max	3.000	3.000	+0.006	2.996	3.000	+0.002	2.994	3.000	0.000	2.986	3.000	–0.008	2.982	3.000	–0.012
	Min	2.990	2.994	–0.010	2.986	2.994	–0.014	2.984	2.994	–0.016	2.976	2.994	–0.024	2.972	2.994	–0.028
4	Max	4.003	4.000	+0.011	3.996	4.000	+0.004	3.992	4.000	0.000	3.985	4.000	–0.007	3.981	4.000	–0.011
	Min	3.991	3.992	–0.009	3.984	3.992	–0.016	3.980	3.992	–0.020	3.973	3.992	–0.027	3.969	3.992	–0.031
5	Max	5.003	5.000	+0.011	4.996	5.000	+0.004	4.992	5.000	0.000	4.985	5.000	–0.007	4.981	5.000	–0.011
	Min	4.991	4.992	–0.009	4.984	4.992	–0.016	4.980	4.992	–0.020	4.973	4.992	–0.027	4.969	4.992	–0.031
6	Max	6.003	6.000	+0.011	5.996	6.000	+0.004	5.992	6.000	0.000	5.985	6.000	–0.007	5.981	6.000	–0.011
	Min	5.991	5.992	–0.009	5.984	5.992	–0.016	5.980	5.992	–0.020	5.973	5.992	–0.027	5.969	5.992	–0.031
8	Max	8.005	8.000	+0.014	7.996	8.000	+0.005	7.991	8.000	0.000	7.983	8.000	–0.008	7.978	8.000	–0.013
	Min	7.990	7.991	–0.010	7.981	7.991	–0.019	7.976	7.991	–0.024	7.968	7.991	–0.032	7.963	7.991	–0.037
10	Max	10.005	10.000	+0.014	9.996	10.000	+0.005	9.991	10.000	0.000	9.983	10.000	–0.008	9.978	10.000	–0.013
	Min	9.990	9.991	–0.010	9.981	9.991	–0.019	9.976	9.991	–0.024	9.968	9.991	–0.032	9.963	9.991	–0.037
12	Max	12.006	12.000	+0.017	11.995	12.000	+0.006	11.989	12.000	0.000	11.979	12.000	–0.010	11.974	12.000	–0.015
	Min	11.988	11.989	–0.012	11.977	11.989	–0.023	11.971	11.989	–0.029	11.961	11.989	–0.039	11.956	11.989	–0.044
16	Max	16.006	16.000	+0.017	15.995	16.000	+0.006	15.989	16.000	0.000	15.979	16.000	–0.010	15.974	16.000	–0.015
	Min	15.988	15.989	–0.012	15.977	15.989	–0.023	15.971	15.989	–0.029	15.961	15.989	–0.039	15.956	15.989	–0.044
20	Max	20.006	20.000	+0.019	19.993	20.000	+0.006	19.986	20.000	–0.001	19.973	20.000	–0.014	19.967	20.000	–0.020
	Min	19.985	19.987	–0.015	19.972	19.987	–0.028	19.965	19.987	–0.035	19.952	19.987	–0.048	19.946	19.987	–0.054
25	Max	25.006	25.000	+0.019	24.993	25.000	+0.006	24.986	25.000	–0.001	24.973	25.000	–0.014	24.960	25.000	–0.027
	Min	24.985	24.987	–0.015	24.972	24.987	–0.028	24.965	24.987	–0.035	24.952	24.987	–0.048	24.939	24.987	–0.061
30	Max	30.006	30.000	+0.019	29.993	30.000	+0.006	29.986	30.000	–0.001	29.973	30.000	–0.014	29.960	30.000	–0.027
	Min	29.985	29.987	–0.015	29.972	29.987	–0.028	29.965	29.987	–0.035	29.952	29.987	–0.048	29.939	29.987	–0.061
40	Max	40.007	40.000	+0.023	39.992	40.000	+0.008	39.983	40.000	–0.001	39.966	40.000	–0.018	39.949	40.000	–0.035
	Min	39.982	39.984	–0.018	39.967	39.984	–0.033	39.958	39.984	–0.042	39.941	39.984	–0.059	39.924	39.984	–0.076
50	Max	50.007	50.000	+0.023	49.992	50.000	+0.008	49.983	50.000	–0.001	49.966	50.000	–0.018	49.939	50.000	–0.045
	Min	49.982	49.984	–0.018	49.967	49.984	–0.033	49.958	49.984	–0.042	49.941	49.984	–0.059	49.914	49.984	–0.086

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American National Standard Preferred Shaft Basis Metric Transition and Interference Fits: *ANSI B4.2–1978(R1994)* (cont'd)

Basic Size[a]		Locational Transition			Locational Transition			Locational Interference			Medium Drive			Force		
		Hole K7	Shaft h6	Fit[b]	Hole N7	Shaft h6	Fit[b]	Hole P7	Shaft h6	Fit[b]	Hole S7	Shaft h6	Fit[b]	Hole U7	Shaft h6	Fit[b]
60	Max	60.009	60.000	+0.028	59.991	60.000	+0.010	59.979	60.000	–0.002	59.958	60.000	–0.023	59.924	60.000	–0.087
	Min	59.979	59.981	–0.021	59.961	59.981	–0.039	59.949	59.981	–0.051	59.928	59.981	–0.072	59.894	59.894	–0.106
80	Max	80.009	80.000	+0.028	79.991	80.000	+0.010	79.979	80.000	–0.002	79.952	80.000	–0.029	79.909	80.000	–0.072
	Min	79.979	79.981	–0.021	79.961	79.981	–0.039	79.949	79.981	–0.051	79.922	79.981	–0.078	79.879	79.981	–0.121
100	Max	100.010	100.000	+0.032	99.990	100.000	+0.012	99.976	100.000	–0.002	99.942	100.000	–0.036	99.889	100.000	–0.089
	Min	99.975	99.978	–0.025	99.955	99.978	–0.045	99.941	99.978	–0.059	99.907	99.978	–0.093	99.854	99.978	–0.146
120	Max	120.010	120.000	+0.032	119.990	120.000	+0.012	119.976	120.000	–0.002	119.934	120.000	–0.044	119.869	120.000	–0.109
	Min	119.975	119.978	–0.025	119.955	119.978	–0.045	119.941	119.978	–0.059	119.899	119.978	–0.101	119.834	119.978	–0.166
160	Max	160.012	160.000	+0.037	159.988	160.000	+0.013	159.972	160.000	–0.003	159.915	160.000	–0.060	159.825	160.000	–0.150
	Min	159.972	159.975	–0.028	159.948	159.975	–0.052	159.932	159.975	–0.068	159.875	159.975	–0.125	159.785	159.975	–0.215
200	Max	120.013	200.000	+0.042	199.986	200.000	+0.015	199.967	200.000	–0.004	199.895	200.000	–0.076	199.781	200.000	–0.190
	Min	199.967	199.971	–0.033	199.940	199.971	–0.060	199.921	199.971	–0.079	199.849	199.971	–0.151	199.735	199.971	–0.265
250	Max	250.013	250.000	+0.042	249.986	250.000	+0.015	249.967	250.000	–0.004	249.877	250.000	–0.094	249.733	250.000	–0.238
	Min	249.967	249.971	–0.033	249.940	249.971	–0.060	249.921	249.971	–0.079	249.831	249.971	–0.169	249.687	249.971	–0.313
300	Max	300.016	300.000	+0.048	299.986	300.000	+0.018	299.964	300.000	–0.004	299.850	300.000	–0.118	299.670	300.000	–0.298
	Min	299.964	299.968	–0.036	299.934	299.968	–0.066	299.912	299.968	–0.088	299.798	299.968	–0.202	299.618	299.968	–0.382
400	Max	400.017	400.000	+0.053	399.984	400.000	+0.020	399.959	400.000	–0.005	399.813	400.000	–0.151	399.586	400.000	–0.378
	Min	399.960	399.964	–0.040	399.927	399.964	–0.073	399.902	399.964	–0.098	399.756	399.964	–0.244	399.529	399.964	–0.471
500	Max	500.018	500.000	+0.058	499.983	500.000	+0.023	499.955	500.000	–0.005	499.771	500.000	–0.189	499.483	500.000	–0.477
	Min	499.955	499.960	–0.045	499.920	499.960	–0.080	499.892	499.960	–0.108	499.708	499.960	–0.292	499.420	499.960	–0.580

[a] The sizes shown are first-choice basic sizes. Preferred fits for other sizes can be calculated from data given in ANSI B4.2-1978 (R1994).

[b] A plus sign indicates clearance; a minus sign, interference.

All dimensions are in millimeters.

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2.3 Quality Assurance/Quality Control

2.3.1 Dispersion, Mean, Median, and Mode Values

If $X_1, X_2, \ldots, X_n$ represent the values of a random sample of n items or observations, the *arithmetic mean* of these items or observations, denoted $\overline{X}$, is defined as

$$\overline{X} = \left(\frac{1}{n}\right)\left(X_1 + X_2 + \ldots + X_n\right) = \left(\frac{1}{n}\right)\sum_{i=1}^{n} X_i$$

$\overline{X} \rightarrow \mu$ for sufficiently large values of n.

The *weighted arithmetic mean* is

$$\overline{X}_w = \frac{\sum w_i X_i}{\sum w_i}$$

where

X_i = the value of the ith observation

w_i = the weight applied to X_i

The *variance* of the population is the arithmetic mean of the *squared deviations from the population mean*. If μ is the arithmetic mean of a discrete population of size N, the *population variance* is defined by

$$\sigma^2 = \left(\frac{1}{N}\right)\left[\left(X_1 - \mu\right)^2 + \left(X_2 - \mu\right)^2 + \ldots + \left(X_N - \mu\right)^2\right]$$
$$= \left(\frac{1}{N}\right)\sum_{i=1}^{N}\left(X_i - \mu\right)^2$$

Standard deviation formulas are

$$\sigma_{population} = \sqrt{\left(\frac{1}{N}\right)\Sigma\left(X_i - \mu\right)^2}$$

$$\sigma_{sum} = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2}$$

$$\sigma_{series} = \sigma\sqrt{n}$$

$$\sigma_{mean} = \frac{\sigma}{\sqrt{n}}$$

$$\sigma_{product} = \sqrt{A^2\sigma_b^2 + B^2\sigma_a^2}$$

The *sample variance* is $s^2 = \left(\frac{1}{n-1}\right)\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2$

The *sample standard deviation* is $s = \sqrt{\left(\frac{1}{n-1}\right)\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}$

The *sample coefficient of variation* is $CV = \frac{s}{\overline{X}}$

The *sample geometric mean* is $\sqrt[n]{X_1 X_2 X_3 \ldots X_n}$

The *sample root-mean-square value* is $\sqrt{\frac{1}{n}\sum X_i^2}$

When the discrete data are rearranged in increasing order and n is odd, the median is the value of the $\left(\frac{n+1}{2}\right)^{th}$ item.

When n is even, the median is the average of the $\left(\frac{n}{2}\right)^{th}$ and $\left(\frac{n}{2}+1\right)^{th}$ items.

The *mode* of a set of data is the value that occurs with greatest frequency.

The *sample range R* is the largest sample value minus the smallest sample value.

Confidence level: The probability that the value of a parameter falls within a specified range of values.

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2.3.2 Uncertainty Analysis

Suppose a set of measurements is made and the uncertainty in each measurement may be expressed with the same odds. These measurements are then used to calculate some desired result of the experiments. We wish to estimate the uncertainty in the calculated result on the basis of the uncertainties in the primary measurements. The result R is a given function of the independent variables x_1, x_2, x_3, ..., x_n. Thus,

$$R = R(x_1, x_2, x_3, ..., x_n)$$

Let w_R be the uncertainty in the result and w_1, w_2, ..., w_n be the uncertainties in the independent variables. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given as:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + ... + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]^{\frac{1}{2}}$$

Source: Holman, J.P., *Experimental Methods for Engineers*, 4th ed., New York: McGraw-Hill, 1984.

2.4 Statistical Quality Control

Factors for Control-Chart Limits

Sample	For Averages		For Ranges				
Size n	A	A_2	d	D_1	D_2	D_3	D_4
2	2.12	1.88	1.128	0	3.69	0	3.27
3	1.73	1.02	1.693	0	4.36	0	2.57
4	1.50	0.73	2.059	0	4.70	0	2.28
5	1.34	0.58	2.326	0	4.92	0	2.11
6	1.22	0.48	2.534	0	5.08	0	2.00
7	1.13	0.42	2.704	0.21	5.20	0.08	1.92
8	1.06	0.37	2.847	0.39	5.31	0.14	1.86
9	1.00	0.34	2.970	0.55	5.39	0.18	1.82
10	0.95	0.31	3.078	0.69	5.47	0.22	1.78

Control-Limit Calculations

		Standards Given	No Standards Given
Average Chart	Upper limit line	$\mu^* + A\sigma^*$	$\overline{X} + A_2\overline{R}$
	Central line	μ^*	$\overline{X}$
	Lower limit line	$\mu^* - A\sigma^*$	$\overline{X} - A_2\overline{R}$
Range Chart	Upper limit line	$D_2\sigma^*$	$D_4\overline{R}$
	Central line	$d\sigma^*$	$\overline{R}$
	Lower limit line	$D_1\sigma^*$	$D_3\overline{R}$

The values of A, A_2, d, D_1, D_2, D_3, and D_4 depend upon n and can be found in the table above.

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where

μ^* = goal average

σ^* = goal standard deviation

n = number of observations

$\overline{X}$ = overall range $\quad \overline{X} = \sum_{i=1}^{K} \frac{\overline{X}_i}{K}$

$\overline{R}$ = average range $\quad \overline{R} = \sum_{i=1}^{K} \frac{r_i}{K}$

2.4.1 Tests for Out of Control, for Three-Sigma Control Limits

1. A single point falls outside the control limits.
2. Two out of three consecutive points fall on the same side of and more than two sigma units from the centerline.
3. Four out of five consecutive points fall on the same side of and more than one sigma unit from the centerline.
4. Eight consecutive points fall on the same side of the center line.
5. Seven consecutive points trending up or trending down.
6. Eight consecutive points on either side of the centerline and more than one sigma unit from the centerline.
7. Fourteen consecutive points alternating on either side of the centerline.
8. Fifteen consecutive points within one sigma unit of the centerline.

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2.4.2 Nondestructive Testing

Nondestructive Test Methods

Method	Measures of Detects	Applications	Advantages	Limitations
Acoustic Emission	Crack initiation and growth rate Internal cracking in welds during cooling Boiling or cavitation Friction or wear Plastic deformation Phase transformations	Pressure vessels Stressed structures Turbine or gearboxes Fracture mechanics research Weldments Sonic-signature analysis	Remote and continuous surveillance Permanent record Dynamic (rather than static) detection Portable Triangulation techniques to locate flaws	Transducers must be placed on part surface Highly ductile materials yield low-amplitude emissions Part must be stressed or operating Interfering noise needs to be filtered out
Acoustic Impact (Tapping)	Debonded areas or delaminations in metal or nonmetal composites or laminates Cracks under bolt or fastener heads Cracks in turbine wheels or turbine blades Loose rivets or fastener heads Crushed core	Brazed or adhesive-bonded structures Bolted or riveted assemblies Turbine blades Turbine wheels Composite structures Honeycomb assemblies	Portable Easy to operate May be automated Permanent record or positive meter readout No couplant required	Part geometry and mass influences test results Impactor and probe must be repositioned to fit geometry of part Reference standards required Pulser impact is critical for repeatability
D-Sight (Diffracto)	Enhances visual inspection for surface abnormalities such as dents, protrusions, or waviness Crushed core Lap joint corrosion Cold-worked holes Cracks	Detect impact damage to composites or honeycomb corrosion in aircraft lap joints Automotive bodies for waviness	Portable Fast, flexible Non contact Easy to use Documentable	Part surface must reflect light or be wetted with a fluid

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Nondestructive Test Methods (cont'd)

Method	Measures of Detects	Applications	Advantages	Limitations
Eddy Current	Surface and subsurface cracks and seams Alloy content Heat-treatment variations Wall thickness, coating thickness Crack depth Conductivity Permeability	Tubing Wire Ball bearings "Spot checks" on all types of surfaces Proximity gage Metal detector Metal sorting Measure conductivity in % IACS	No special operator skills required High speed, low cost Automation possible for symmetric parts No couplant or probe contact required	Conductive materials Shallow depth of penetration (thin walls only) Masked or false indications caused by sensitivity to variations such as part geometry Reference standards required Permeability variations
Magneto-optic Eddy-current Imager	Cracks Corrosion thinning in aluminum	Aluminium aircraft Structure	Real-time imaging Approximately 4 inch area coverage	Frequency range of 1.6 to 100 khz Surface contour Temperature range of 32 to 90°F
Eddy Sonic	Debonded areas in metal or metal-faced honeycomb structures Delaminations in metal laminates or composites Crushed core	Metal-core honeycomb Metal-faced honeycomb Conductive laminates such as boron or graphite-fiber composites Bonded-metal panels	Portable Simple to operate No couplant required Locates far-side debonded areas Access to only one surface required May be automated	Specimen or part must contain conductive materials to establish eddy-current field Reference standards required Part geometry
Electric Current	Cracks Crack depth Resistivity Wall thickness Corrosion-induced wall thinning	Metallic materials Electrically conductive materials Train rails Nuclear fuel elements Bars, plates, and other shapes	Access to only one surface required Battery or dc source Portable	Edge effect Surface contamination Good surface contact required Difficult to automate Electrode spacing Reference standards required

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Nondestructive Test Methods (cont'd)

Method	Measures of Detects	Applications	Advantages	Limitations
Electrified Particle	Surface flaws in nonconducting material Through-to-metal pinholes on metal-backed material Tension, compression, cyclic cracks Brittle-coating stress cracks	Glass Porcelain enamel Nonhomogeneous materials such as plastic or asphalt coatings Glass-to-metal seals	Portable Useful on materials not practical for penetrant inspection	Poor resolution on thin coatings False indications from moisture streaks or lint Atmospheric conditions High-voltage discharge
Filtered Particle	Cracks Porosity Differential absorption	Porous materials such as clay, carbon, powdered metals, concrete Grinding wheels High-tension insulators Sanitary ware	Colored or fluorescent particles Leaves no residue after baking part over 400°F Quickly and easily applied Portable	Size and shape of particles must be selected before use Penetrating power of suspension medium is critical Particle concentration must be controlled Skin irritation
Infrared (Radiometry) (Thermography)	Hot spots Lack of bond Heat transfer Isotherms Temperature ranges	Brazed joints Adhesive-boned joints Metallic platings or coatings; debonded areas or thickness Electrical assemblies Temperature monitoring	Sensitive to 0.1°F temperature variation Permanent record or thermal picture Quantitative Remote sensing; need not contact part Portable	Emissivity Liquid-nitrogen-cooled detector Critical time-temperature relationship Poor resolution for thick specimens Reference standards required
Leak Testing	Leaks: Helium Ammonia Smoke Water Air bubbles Radioactive gas Halogens	Joints: Welded Brazed Adhesive-bonded Sealed assemblies Pressure or vacuum chambers Fuel or gas leaks	High sensitivity to extremely small, light separations not detectable by other NDT methods Sensitivity related to method selected	Accessibility to both surfaces of part required Smeared metal or contaminants may prevent detection Cost related to sensitivity

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Nondestructive Test Methods (cont'd)

Method	Measures of Detects	Applications	Advantages	Limitations
Magnetic Particle	Surface and slightly subsurface flaws; cracks, seams, porosity, inclusions Permeability variations Extremely sensitive for locating small tight cracks	Ferrimagnetic materials; bar, plate, forgings, weldments, extrusions, etc.	Advantage over penetrant is that it indicates subsurface flaws, particularly inclusions Relatively fast and low cost May be portable	Alignment of magnetic field is critical Demagnetization of parts required after tests Parts must be cleaned before and after inspection Masking by surface coatings
Magnetic Field (Also Magnetic Flux Leakage)	Cracks Wall thickness Hardness Coercive force Magnetic anisotropy Magnetic field Nonmagnetic coating thickness on steel	Ferromagnetic materials Ship degaussing Liquid-level control Treasure hunting Wall thickness of nonmetallic materials Material sorting	Measurement of magnetic material properties May be automated Easily detected magnetic objects in nonmagnetic material Portable	Permeability Reference standards required Edge effect Probe lift-off
Microwave (300 MHz–300 GHz)	Cracks, holes, debonded areas, etc., in nonmetallic parts Changes in composition, degree of cure, moisture content Thickness measurement Dielectric constant Loss tangent	Reinforced plastics Chemical products Ceramics Resins Rubber Wood Liquids Polyurethane foam Radomes	Between radio waves and infrared in electromagnetic spectrum Portable Contact with part surface not normally required Can be automated	Will not penetrate metals Reference standards required Horn-to-part spacing critical Part geometry Wave interference Vibration
Liquid Penetrants (Dye or Fluorescent)	Flaws open to the surface of parts; cracks, porosity, seams, laps, etc. Through-wall leaks	All parts with nonabsorbent surfaces (forgings, weldments, castings, etc.). Note: Bleed-out from porous surfaces can mask indications of flaws	Low cost Portable Indications may be further examined visually Results easily interpreted	Surface films such as coatings, scale, and smeared metal may prevent detection of flaws Parts must be cleaned both before and after inspection Flaws must be open to surface

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Nondestructive Test Methods (cont'd)

Method	Measures of Detects	Applications	Advantages	Limitations
Fluoroscopy (Cinefluorography) (Kinefluorography)	Level of fill in containers Foreign objects Internal components Density variations Voids, thickness Spacing or position	Flow of liquids Presence of cavitation Operation of valves and switches Burning in small solid-propellant rocket motors	High-brightness images Real-time viewing Image magnification Permanent record Moving subject can be observed	Costly equipment Geometric unsharpness Thick specimens Speed of events to be studied Viewing area Radiation hazard
Neutron Radiology (Thermal Neutrons from Reactor, Accelerator, or Californium 252)	Hydrogen contamination of titanium or zirconium alloys Defective or improperly loaded pyrotechnic devices Improper assembly of metal, nonmetal parts Corrosion products	Pyrotechnic devices Metallic, nonmetallic assemblies Biological specimens Nuclear reactor fuel elements and control rods Adhesive-bonded structures	High neutron absorption by hydrogen, boron, lithium, cadmium, uranium, plutonium Low neutron absorption by most metals Complement to X-ray or gamma-ray radiography	Very costly equipment Nuclear reactor or accelerator required Radiation hazard Nonportable Indium or gadolinium screens required
Gamma Radiography (Cobalt 60, Iridium 192)	Internal flaws and variations, porosity, inclusions, cracks, lack of fusion, geometry variations, corrosion thinning	Usually where X-ray machines are not suitable because source cannot be placed in part with small openings and/or power source not available Panoramic imaging	Low initial cost Permanent records; film Small sources can be placed in parts with small openings Portable Low contrast	One energy level per source Source decay Radiation hazard Trained operators needed Lower image resolution Cost related to source size
X-ray Radiology	Internal flaws and variations; porosity, inclusions, cracks, lack of fusion, geometry variations, corrosion Density variations Thickness, gap, and position Misassembly Misalignment	Castings Electrical assemblies Weldments Small, thin, complex wrought products Nonmetallics Solid-propellant rocket motors Composites Container contents	Permanent records; film Adjustable energy levels (5keV–25meV) High sensitivity to density changes No couplant required Geometry variations do not affect direction of X-ray beam	High initial costs Orientation of linear flaws in part may not be favorable Radiation hazard Depth of flaw not indicated Sensitivity decreases with increase in scattered radiation

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Nondestructive Test Methods (cont'd)

Method	Measures of Detects	Applications	Advantages	Limitations
Radiometry X-ray, Gamma Ray, Beta Ray (Transmission or Back-scatter)	Wall thickness Plating thickness Variations in density or composition Fill level in cans or containers Inclusions or voids	Sheet, plate, strip, tubing Nuclear reactor fuel rods Cans or containers Plated parts Composites	Fully automatic Fast Extremely accurate In-line process control Portable	Radiation hazard Beta ray useful for ultrathin coatings only Source decay Reference standards required
Reverse-Geometry Digital X-ray	Cracks Corrosion Water in honeycomb Carbon epoxy honeycomb Foreign objects	Aircraft structure	High-resolution 10^6 pixel image with high contrast	Access to both sides of object Radiation hazard
X-ray Computed Tomography (CT)	Small density changes Cracks Voids Foreign objects	Solid-propellant rocket motors Rocket nozzles Jet-engine parts Turbine blades	Measures X-ray opacity of object along many paths	Very expensive Trained operator Radiation hazard
Shearography Electronic	Lack of bond Delaminations Plastic deformation Strain Crushed core Impact damage Corrosion in Al honeycomb	Composite-metal honeycomb Bonded structures Composite structures	Large area coverage Rapid setup and operation Noncontacting Video image easy to store	Requires vacuum thermal, ultrasonic, or microwave stressing of structure to cause surface strain
Thermal (Thermochromic Paint, Liquid Crystals)	Lack of bond Hot spots Heat transfer Isotherms Temperature ranges Blockage in coolant passages	Brazed joints Adhesive-bonded joints Metallic platings or coatings Electrical assemblies Temperature monitoring	Very low initial cost Can be readily applied to surfaces which may be difficult to inspect by other methods No special operator skills	Thin-walled surfaces only Critical time-temperature relationship Image retentivity affected by humidity Reference standards required

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Nondestructive Test Methods (cont'd)

Method	Measures of Detects	Applications	Advantages	Limitations
Sonic (< 0.1 MHz)	Debonded areas or delaminations in metal or nonmetal composites or laminates Cohesive bond strength under controlled conditions Crushed or fractured core Bond integrity of metal insert fasteners	Metal or nonmetal composite or laminates brazed or adhesive bonded Plywood Rocket-motor nozzles Honeycomb	Portable Easy to operate Locates far-side debonded areas May be automated Access to only one surface required	Surface geometry influences test results Reference standards required Adhesive or core-thickness variations influence results
Ultrasonic (0.1–25 MHz)	Internal flaws and variations; cracks, lack of fusion, porosity, inclusions, delaminations, lack of bond, texturing Thickness or velocity Poisson's ratio, elastic modulus	Metals Welds Brazed joints Adhesive-bonded joints Nonmetallics In-service parts	Most sensitive to cracks Test results known immediately Automating and permanent-record capability Portable High penetration capability	Couplant required Small, thin, or complex parts may be difficult to inspect Reference standards required Trained operators for manual inspection Special probes
Thermoelectric Probe	Thermoelectric potential Coating thickness Physical properties Thompson effect *P-N* junctions in semiconductors	Metal sorting Ceramic coating thickness on metals Semiconductors	Portable Simple to operate Access to only one surface required	Hot probe Difficult to automate Reference standards required Surface contaminants Conductive coatings

Source: Avallone, Eugene A., Theodore Baumeister III, and Ali M. Sadegh, *Marks' Standard Handbook for Mechanical Engineers*, 11th ed., New York: McGraw-Hill, 2007.

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2.5 Statics and Dynamics

2.5.1 Force

A *force* is a *vector* quantity. It is defined when (1) magnitude, (2) point of application, and (3) direction are known.

The vector form of a force is

$$\boldsymbol{F} = F_x\,\mathbf{i} + F_y\,\mathbf{j}$$

2.5.2 Resultant (Two Dimensions)

The *resultant*, F, of n forces with components $F_{x,i}$ and $F_{y,i}$ has the magnitude

$$F = \left[\left(\sum_{i=1}^{n} F_{x,i}\right)^2 + \left(\sum_{i=1}^{n} F_{y,i}\right)^2\right]^{1/2}$$

The resultant direction with respect to the x-axis is

$$\theta = \arctan \frac{\sum_{i=1}^{n} F_{y,i}}{\sum_{i=1}^{n} F_{x,i}}$$

2.5.3 Resolution of a Force

$$F_x = F\cos\theta_x \qquad F_y = F\cos\theta_y \qquad F_z = F\cos\theta_z$$

$$\cos\theta_x = \frac{F_x}{F} \qquad \cos\theta_y = \frac{F_y}{F} \qquad \cos\theta_z = \frac{F_z}{F}$$

Separating a force into components when the geometry of force is known and when $R = \sqrt{x^2 + y^2 + z^2}$:

$$F_x = \frac{x}{R}F \qquad F_y = \frac{y}{R}F \qquad F_z = \frac{z}{R}F$$

2.5.4 Moments (Couples)

A system of two forces that are equal in magnitude, opposite in direction, and parallel to each other is called a *couple*.

$\boldsymbol{M}$ = moment, cross product of radius vector and force

$\boldsymbol{r}$ = radius vector

$\boldsymbol{F}$ = force

$\boldsymbol{M} = \boldsymbol{r} \times \boldsymbol{F}$, therefore: $M_x = yF_z - zF_y$, $M_y = zF_x - xF_z$, and $M_z = xF_y - yF_x$

Note: the "×" symbolizes cross-product of vectors.

2.5.5 Systems of *n* Forces

$$\mathbf{F} = \Sigma\,\mathbf{F}_n$$

$$\mathbf{M} = \Sigma M_n = \Sigma r_n \times F_n$$

Equilibrium requirements:

$$\Sigma\,\mathbf{F}_n = 0$$

$$\Sigma\,\boldsymbol{M}_n = 0$$

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2.5.6 Friction

The largest frictional force is called the *limiting friction*.

Any further increase in applied forces will cause motion.

$$F \leq \mu_s N$$

where

F = friction force

μ_s = coefficient of static friction

N = normal force between surfaces in contact.

In general

$\boldsymbol{F} < \mu_s N$, no slip occurring

$\boldsymbol{F} = \mu_s N$, at the point of impending slip

$\boldsymbol{F} = \mu_k N$, when slip is occurring

where

μ_s = coefficient of static friction

μ_k = coefficient of kinetic friction

2.5.7 Cable with Distributed Load—Parabolic Cable

$$T\,\mathrm{Cos}\theta = F_H$$

where

T = tension in the cable

F_H = horizontal component of the cable tension

θ = angle the cable makes with the horizontal axis

For a symmetrically hanging cable with uniformly distributed load:

$$F_H = \frac{w_0 L^2}{8h}$$

where

w_0 = distributed load

L = span

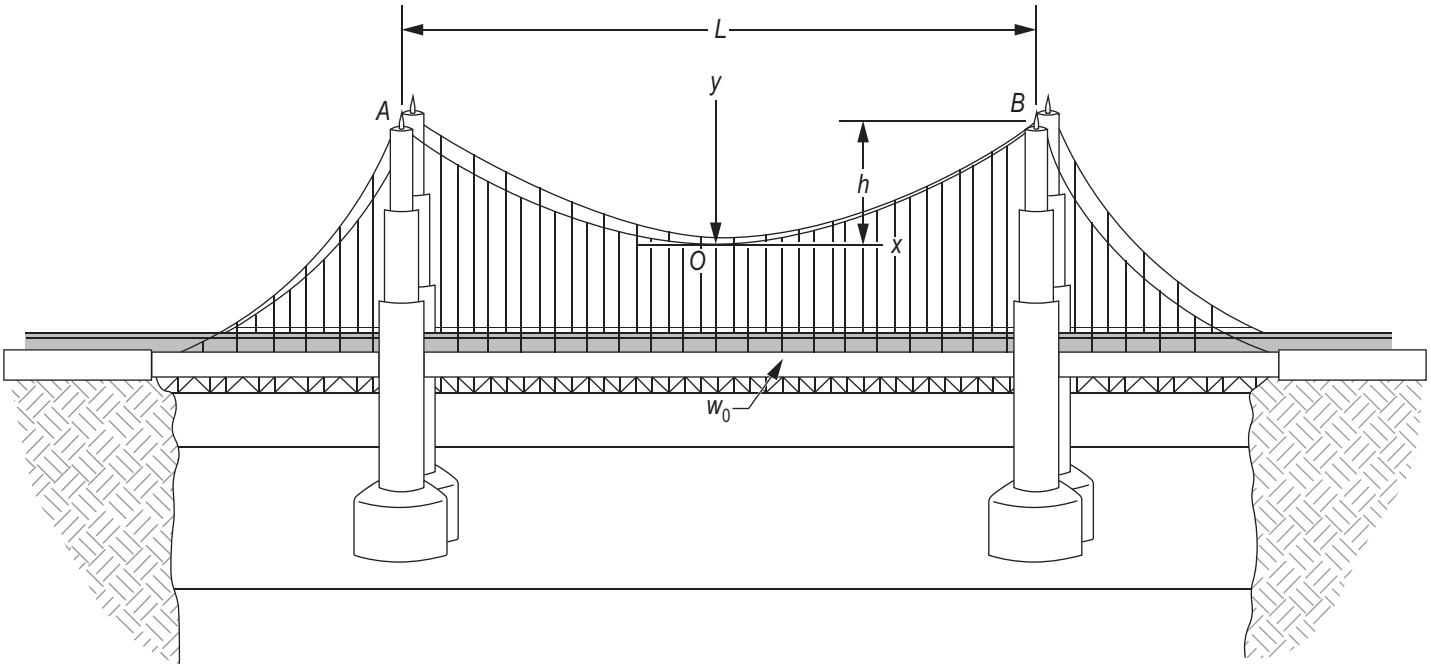
h = sag at the middle

and

$$T_{\max} = \frac{w_0 L}{2}\sqrt{1+\left(\frac{L}{4h}\right)^2} = \frac{F_H}{\mathrm{Cos}\left(\theta_{\max}\right)}$$

θ_{max} occurs at the cable end (Point B in the diagram)

T_{max} = maximum tension in the cable



Source: Hibbeler, Russell C., *Engineering Mechanics: Statics*, 14th ed., Hoboken: Pearson Education, ©2016, p. 386. Reprinted by permission of Pearson Education, Inc.

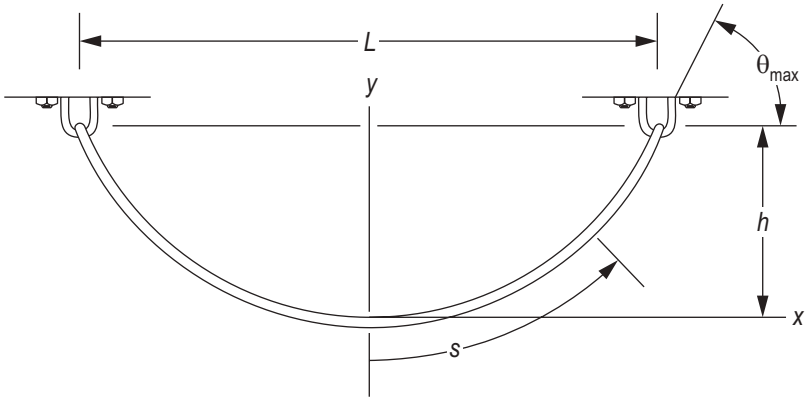
2.5.8 Cable Subjected to Its Own Weight

For symmetric cable with uniform self weight

$$h = \frac{F_H}{w_0}\left[\cosh\left(\frac{w_0 L}{2F_H}\right) - 1\right]$$

$$y = \frac{F_H}{w_0}\left[\cosh\left(\frac{w_0 x}{F_H}\right) - 1\right] \qquad \textit{Catenary curve}$$

$$T_{\max} = \frac{F_H}{\cos\theta_{\max}}$$



L = span

h = sag at the middle

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2.6 Laws of Motion

2.6.1 Constant Acceleration

Equations for velocity and displacement when acceleration is a constant are

$$a(t) = a_0$$

$$v(t) = a_0\,(t - t_0) + v_0$$

$$s(t) = \frac{a_0\left(t - t_0\right)^2}{2} + v_0\left(t - t_0\right) + s_0$$

where

s = distance along the line of travel

s_0 = displacement at time t_0

v = velocity along the direction of travel

v_0 = velocity at time t_0

a_0 = constant acceleration

t = time

t_0 = some initial time

For a free-falling body, $a_0 = -g$ (downward).

An additional equation for velocity as a function of position may be written

$$v^2 = v_0^2 + 2a_0\left(s - s_0\right)$$

2.6.2 Centripetal Acceleration

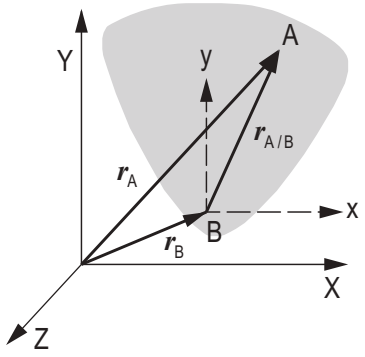
$$a = \frac{dv}{dt} = \frac{v^2}{r}$$

2.6.3 Relative Motion

The equations for the relative position, velocity, and acceleration may be written as

Translating Axis xyz, Fixed Axis XYZ

For a rigid body, the motion of Point A, with respect to B, is the same as the rotation of the body about Point B. If Point B on a rigid body has a known position, velocity, and acceleration, then any other Point A on the rigid body has the following:



$$\boldsymbol{r}_A = \boldsymbol{r}_B + \boldsymbol{r}_{A/B}$$

$$\boldsymbol{v}_A = \boldsymbol{v}_B + (\boldsymbol{\omega} \times \boldsymbol{r}_{A/B}) = \boldsymbol{v}_B + \boldsymbol{v}_{A/B}$$

$$\boldsymbol{a}_A = \boldsymbol{a}_B + (\boldsymbol{\alpha} \times \boldsymbol{r}_{A/B}) + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r}_{A/B}) = \boldsymbol{a}_B + \boldsymbol{a}_{A/B}$$

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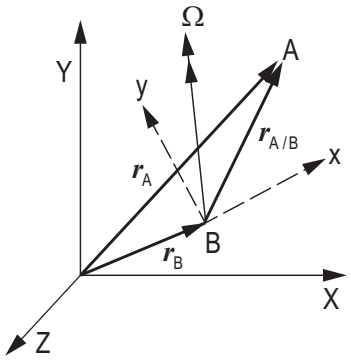
Translating and Rotating Axis xyz, Fixed Axis XYZ

Individual vector quantities on the R.H.S. show the frame of reference below to which they belong

$$\boldsymbol{r}_A = \boldsymbol{r}_B + \boldsymbol{r}_{A/B}$$

$$\boldsymbol{v}_A = \underbrace{\boldsymbol{v}_B + \left(\Omega \times \boldsymbol{r}_{A/B}\right)}_{XYZ} + \underbrace{\boldsymbol{v}_{A/B}}_{xyz}$$

$$\boldsymbol{a}_A = \underbrace{\boldsymbol{a}_B + \left(\dot{\Omega} \times \boldsymbol{r}_{A/B}\right) + \Omega \times \left(\Omega \times \boldsymbol{r}_{A/B}\right)}_{XYZ} + \underbrace{2\Omega \times \boldsymbol{v}_{A/B}}_{\text{Coriolis}} + \underbrace{\boldsymbol{a}_{A/B}}_{xyz}$$



r_A = position of Point A with respect to XYZ axes
r_B = position of Point B with respect to XYZ axes
$r_{A/B}$ = position of Point A with respect to B, i.e., xyz axes
v_A = velocity of Point A with respect to XYZ axes
v_B = velocity of Point B with respect to XYZ axes
$v_{A/B}$ = velocity of Point A with respect to B, i.e., xyz axes
a_A = acceleration of Point A with respect to XYZ axes
a_B = acceleration of Point B with respect to XYZ axes
$a_{A/B}$ = acceleration of Point A with respect to B, i.e., xyz axes
ω = angular velocity of the body about Point B in purely translating frame
α = angular acceleration of the body about Point B in purely translating frame
Ω = angular velocity of the rotating and translating frame with respect to XYZ axes
$\dot{\Omega}$ = angular acceleration of the rotating and translating frame with respect to XYZ axes

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2.6.4 Plane Circular Motion

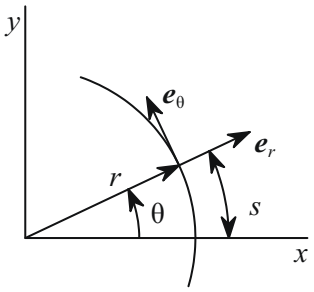
A special case of transverse and radial components is for constant radius rotation about the origin, or plane circular motion.

Here the vector quantities are defined as

$$\boldsymbol{r} = r\boldsymbol{e}_r$$

$$\boldsymbol{v} = r\omega\boldsymbol{e}_\theta$$

$$\boldsymbol{a} = \left(-r\omega^2\right)\boldsymbol{e}_r + r\alpha\boldsymbol{e}_\theta$$



where

$\boldsymbol{r}$ = radius of the circle

θ = angle between the x axis and $\boldsymbol{r}$

The magnitudes of the angular velocity and acceleration, respectively, are defined as

$$\omega = \dot{\theta}$$

$$\alpha = \dot{\omega} = \ddot{\theta}$$

Arc length, tangential velocity, and tangential acceleration, respectively, are

$$s = r\theta$$

$$v_t = r\omega$$

$$a_t = r\alpha$$

The normal acceleration is given by

$$a_n = -r\omega^2 \text{ (toward the center of the circle)}$$

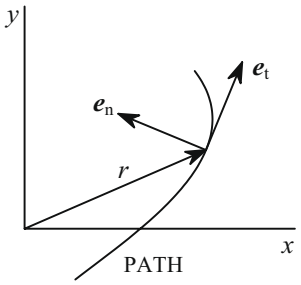
2.6.5 Normal and Tangential Components

Unit vectors $\boldsymbol{e}_t$ and $\boldsymbol{e}_n$ are, respectively, tangent and normal to the path with $\boldsymbol{e}_n$ pointing to the center of curvature. Thus,

$$\boldsymbol{v} = v(t)\boldsymbol{e}_t$$

$$\boldsymbol{a} = a(t)\boldsymbol{e}_t + \left(\frac{v_t^2}{\rho}\right)\boldsymbol{e}_n$$

where ρ = instantaneous radius of curvature



For constant angular acceleration, the equations for angular velocity and displacement are

$$\alpha(t) = \alpha_0$$

$$\omega(t) = \alpha_0\left(t - t_0\right) + \omega_0$$

$$\theta(t) = \alpha_0\frac{\left(t - t_0\right)^2}{2} + \omega_0\left(t - t_0\right) + \theta_0$$

where

θ = angular displacement

θ_0 = angular displacement at time t_0

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ω = angular velocity

ω_0 = angular velocity at time t_0

α_0 = constant angular acceleration

t = time

t_0 = some initial time

An additional equation for angular velocity as a function of angular position may be written as

$$\omega^2 = \omega_0^2 + 2\alpha_0(\theta - \theta_0)$$

For variable angular acceleration:

$$\omega(t) = \omega_0 + \int_{t_0}^{t} \alpha(\tau)\,d\tau$$

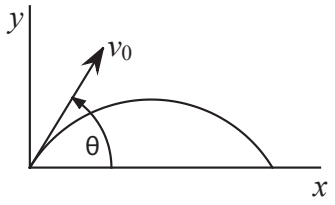
$$\theta(t) = \theta_0 + \int_{t_0}^{t} \omega(\tau)\,d\tau$$

where τ = variable of integration

2.6.6 Projectile Motion

The equations for common projectile motion may be obtained from the constant acceleration equations as

$$a_x = 0$$
$$v_x = v_0\cos(\theta)$$
$$x = v_0\cos(\theta)t + x_0$$
$$a_y = -g$$
$$v_y = -gt + v_0\sin(\theta)$$
$$y = -\frac{gt^2}{2} + v_0\sin(\theta)t + y_0$$
$$v_y^2 = (v_{y0})^2 - 2g(y - y_0)$$



2.6.7 Newton's Second Law (Equations of Motion)

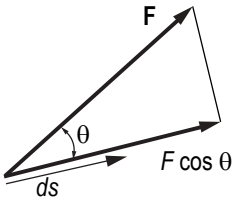
$$\sum \boldsymbol{F} = \frac{d(m\boldsymbol{v})}{dt} = m\boldsymbol{a}$$

where

$\sum \boldsymbol{F}$ = sum of the applied forces acting on the particle

m = mass of the particle

$\boldsymbol{v}$ = velocity of the particle



For constant mass:

$$\sum \boldsymbol{F} = m\frac{d\boldsymbol{v}}{dt} = m\boldsymbol{a}$$

For rotational motion:

$$\sum M = I\alpha$$

Concept of weight

$$W = mg$$

where

W = weight (N or lbf)

m = mass $\left(\text{kg or } \frac{\text{lbf-sec}^2}{\text{ft}}\right)$

g = local acceleration of gravity $\left(9.81 \frac{\text{m}}{\text{s}^2} \text{ or } 32.2 \frac{\text{ft}}{\text{sec}^2}\right)$

2.6.8 Motion of a Rigid Body

When motion exists only in a single dimension, then without loss of generality it may be assumed to be in the x direction, and

$$a_x = \frac{F_x}{m}$$

where

a_x = acceleration

F_x = resultant of the applied forces, which in general can depend on t, x, and v_x

m = mass

If F_x only depends on t, then:

$$a_x(t) = \frac{F_x(t)}{m}$$

$$v_x(t) = \int_{t_0}^{t} a_x(\tau)d\tau + v_{xt_0}$$

$$x(t) = \int_{t_0}^{t} v_x(\tau)d\tau + x_{t_0}$$

where

v_{xt_0} = velocity at time t_0

x_{t_0} = displacement at time t_0

τ = variable of integration

If the force is constant (i.e., independent of time, displacement, and velocity), then:

$$a_x = \frac{F_x}{m}$$

$$v_x = a_x(t - t_0) + v_{xt_0}$$

$$x = a_x\frac{(t - t_0)^2}{2} + v_{xt_0}(t - t_0) + x_{t_0}$$

For rigid body rotation:

$$\omega = \frac{d\theta}{dt}$$

$$\alpha = \frac{d\omega}{dt}$$

$$\alpha d\theta = \omega d\omega$$

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2.7 Principles of Work and Energy

2.7.1 Conservation of Energy Law

$$KE_1 + PE_{1-2} = KE_2 \quad \text{or} \quad KE_1 + PE_1 = KE_2 + PE_2 + W$$

where

KE = kinetic energy

PE = potential energy

W = work

2.7.2 Kinetic Energy

Elements of Kinetic Energy

Particle	$KE = \frac{1}{2}mv^2$
Rigid Body (Plane Motion)	$KE = \frac{1}{2}mv_c^2 + \frac{1}{2}I_c\omega^2$
Changing Velocity	$KE_2 - KE_1 = \frac{m\left(v_2^2 - v_1^2\right)}{2}$

where

c = center of mass

v_c = linear velocity of mass center

I_c = mass moment of inertia about center of mass

2.7.3 Potential Energy

Potential Energy in Gravity Field:

$$PE = mgh$$

where h = elevation above some specified datum

2.7.4 Work

Variable force: $W_F = \int F\cos\theta\, ds$

Constant force: $W_F = \left(F_c\cos\theta\right)\Delta s$

Weight: $W_w = -w\Delta s$

Spring: $W_s = \frac{1}{2}k\left(s_1^2 - s_2^2\right)$

where s_1 and s_2 = two different positions of the applied force end of the spring, with $|s_2| > |s_1|$.

Couple moment: $W_M = M\Delta\theta$

where

s = distance

w = weight

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$\Delta\theta$ = angle of rotation

M = couple

W = work

2.7.5 Power and Efficiency

$$P = \frac{dW}{dt} = \boldsymbol{F} \cdot \boldsymbol{v} \qquad \varepsilon = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{W_{\text{out}}}{W_{\text{in}}}$$

where

P = power

ε = efficiency

2.7.6 Linear Momentum

$$\sum m_i (\boldsymbol{v}_i)_{t_2} = \sum m_i (\boldsymbol{v}_i)_{t_1} + \sum \int_{t_1}^{t_2} \boldsymbol{F}_i \, dt$$

2.7.7 Angular Momentum

The angular momentum or the moment of momentum about point 0 for a particle is defined as

$$\mathbf{H}_0 = \mathbf{r} \times m\boldsymbol{v} \qquad \text{or} \qquad \mathbf{H}_0 = I_0 \omega$$

Taking the time derivative of the above, the equation of motion may be written as

$$\dot{\mathbf{H}}_0 = \frac{d\left(I_0 \omega\right)}{dt} = \mathbf{M}$$

where $\mathbf{M}$ = the moment applied to the particle

Now by integrating and summing over a system of any number of particles, this may be expanded to

$$\sum (\mathbf{H}_{0i})_{t_2} = \sum (\mathbf{H}_{0i})_{t_1} + \sum \int_{t_1}^{t_2} \mathbf{M}_{0i} \, dt$$

2.7.8 Coefficient of Restitution

For direct central impact with no external forces:

$$m_1 \boldsymbol{v}_1 + m_2 \boldsymbol{v}_2 = m_1 \boldsymbol{v}'_1 + m_2 \boldsymbol{v}'_2$$

where

m_1, m_2 = masses of the two bodies

$\boldsymbol{v}_1$, $\boldsymbol{v}_2$ = velocities of the bodies just before impact

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$\boldsymbol{v}'_1, \boldsymbol{v}'_2$ = velocities of the bodies just after impact

For impacts, the relative velocity expression is

$$e = \frac{(\boldsymbol{v}'_2)_n - (\boldsymbol{v}'_1)_n}{(\boldsymbol{v}_1)_n - (\boldsymbol{v}_2)_n}$$

where

e = coefficient of restitution

$(\boldsymbol{v}_i)_n$ = velocity normal to the plane of impact just before impact

$(\boldsymbol{v}'_i)_n$ = velocity normal to the plane of impact just after impact

The value of e is such that

$0 \le e \le 1$, with limiting values

$e = 1$, perfectly elastic (energy conserved)

$e = 0$, perfectly plastic (no rebound)

Knowing the value of e, the velocities after the impact are given as

$$(\boldsymbol{v}'_1)_n = \frac{m_2(\boldsymbol{v}_2)_n(1+e) + (m_1 - em_2)(\boldsymbol{v}_1)_n}{m_1 + m_2}$$

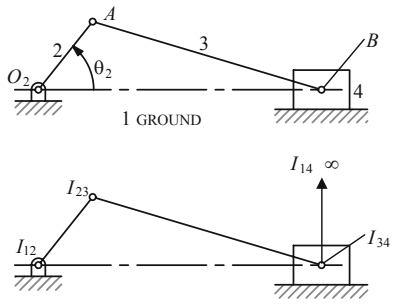
$$(\boldsymbol{v}'_2)_n = \frac{m_1(\boldsymbol{v}_1)_n(1+e) - (em_1 - m_2)(\boldsymbol{v}_2)_n}{m_1 + m_2}$$

2.8 Kinematics of Mechanisms

2.8.1 Instantaneous Center of Rotation (Instant Centers)

An instantaneous center of rotation (instant center) is a point, common to two bodies, at which each has the same velocity (magnitude and direction) at a given instant. It is also a point in space about which a body rotates, instantaneously.

Four-Bar Slider-Crank



Link 2 (the crank) rotates about the fixed center, O_2. Link 3 couples the crank to the slider (link 4), which slides against ground (link 1). Using the definition of an instant center (*IC*), we see that the pins at O_2, A, and B are *IC*s that are designated I_{12}, I_{23}, and I_{34}. The easily observable *IC* is I_{14}, which is located at infinity with its direction perpendicular to the interface between links 1 and 4 (the direction of sliding). To locate the remaining two *IC*s (for a four-bar), we must make use of Kennedy's rule:

2.8.1.1 Kennedy's Rule

When three bodies move relative to one another, they have three instantaneous centers, all of which lie on the same straight line.

The number of *IC*s, c, for a given mechanism is related to the number of links, n, by

$$c = \frac{n(n-1)}{2}$$

where

c = number of instantaneous centers, *IC*

n = number of links

Source: Erdman, Arthur G., George N. Sandor, and Sridhar Kota, *Mechanism Design*, Vol. 1, 4th ed., Upper Saddle River, NJ: Prentice Hall, 2002.

2.8.1.2 Modified Gruebler's Equation

Degrees of Freedom, $F = 3(n-1) - 2f_1 - 1f_2$

where

f_1 = number of pin joints

f_2 = number of roll-slide contact joints

n = number of links

Source: Erdman, Arthur G., George N. Sandor, and Sridhar Kota, *Mechanism Design*, Vol. 1, 4th ed., Upper Saddle River, NJ: Prentice Hall, 2002.

2.9 Material Properties

2.9.1 Atomic Bonding

2.9.1.1 Primary Bonds

Ionic (e.g., salts, metal oxides)

Covalent (e.g., within polymer molecules)

Metallic (e.g., metals)

2.9.2 Corrosion

The following table shows the standard electromotive potentials of metals.

Electrode Potentials (25°C; 1-Molar Solutions)

Anode Half-Cell Reaction*	Electrode Potential Used by Electrochemists and Corrosion Engineers, †V	
$Au \rightarrow Au^{3+} + 3\ e^-$	+ 1.50	Cathodic ↑ (noble)
$2\ H_2O \rightarrow O_2 + 4\ H^+ + 4\ e^-$	+ 1.23	
$Pt \rightarrow Pt^{4+} + 4\ e^-$	+ 1.20	
$Ag \rightarrow Ag^+ + e^-$	+ 0.80	
$Fe^2 \rightarrow Fe^{3+} + e^-$	+ 0.77	
$4(OH)^- \rightarrow O_2 + 2\ H_2O + 4\ e^-$	+ 0.40	
$Cu \rightarrow Cu^{2+} + 2\ e^-$	+ 0.34	
$H_2 \rightarrow 2\ H^+ + 2\ e^-$	0.000	Reference
$Pb \rightarrow Pb^{2+} + 2\ e^-$	– 0.13	Anodic ↓ (active)
$Sn \rightarrow Sn^{2+} + 2\ e^-$	– 0.14	
$Ni \rightarrow Ni^{2+} + 2\ e^-$	– 0.25	
$Fe \rightarrow Fe^{2+} + 2\ e^-$	– 0.44	
$Cr \rightarrow Cr^{2+} + 2\ e^-$	– 0.56	
$Zn \rightarrow Zn^{2+} + 2\ e^-$	– 0.76	
$Al \rightarrow Al^{3+} + 3\ e^-$	– 1.66	
$Mg \rightarrow Mg^{2+} + 2\ e^-$	– 2.36	
$Na \rightarrow Na^+ + e^-$	– 2.71	
$K \rightarrow K^+ + e^-$	– 2.92	
$Li \rightarrow Li^+ + e^-$	– 2.96	

* The arrows are reversed for the cathode half-cell reaction.

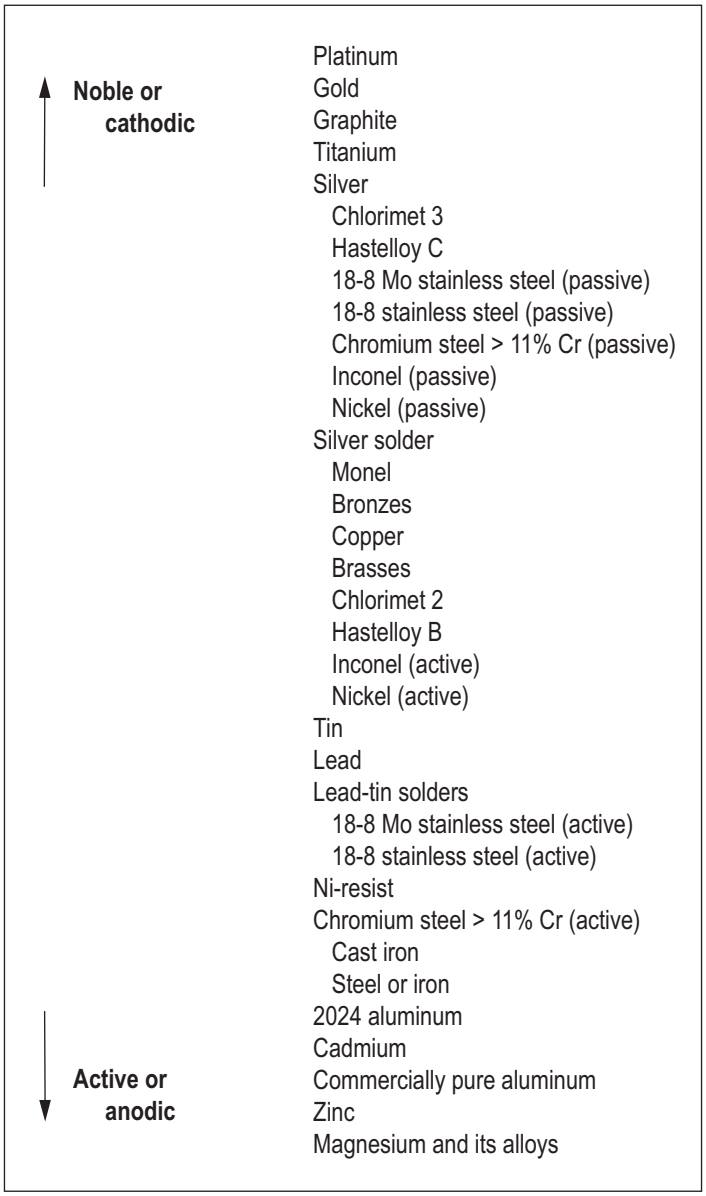
† The convention used by certain technical specialties is to interchange the + and – signs of these electrode potentials. (The choice is arbitrary.) IUPAC recommends the convention used in this table.

Source: Van Vlack, Lawrence H., *Elements of Materials Science and Engineering*, 6th ed., Reading, MA: Addison-Wesley, 1989.

For corrosion to occur, an anode and a cathode must be in electrical contact in the presence of an electrolyte.

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Galvanic Series of Some Commercial Metals and Alloys in Seawater



Source: Roberge, Pierre R., *Handbook of Corrosion Engineering*, New York: McGraw-Hill, 2000.

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Types of Corrosion

1	Uniform	Electrochemical corrosion that occurs with equivalent intensity over entire surface
2	Galvanic	Occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte
3	Crevice	Occurs when concentration differences of ions or dissolved gases exist in an electrolyte system with corrosion occurring preferentially at areas of low concentration
4	Pitting	A very localized form of corrosion similar to crevice corrosion, in which small holes or pits form
5	Intergranular	Occurs preferentially along grain boundaries of some alloys in certain environments
6	Selective Leaching	Occurs when one element is preferentially removed by a corrosion process from a solid solution alloy
7	Erosion-Corrosion	Occurs as a combined consequence of chemical attack and mechanical abrasion due to fluid motion
8	Stress-Corrosion	Occurs due to the combined influence of an applied tensile stress and a corrosive environment

2.9.3 Electrical Properties

Capacitance is the charge-carrying capacity of an insulating material.

Charge held by a capacitor:

$$q = CV$$

where

q = charge

C = capacitance

V = voltage

Capacitance of a parallel plate capacitor:

$$C = \frac{\varepsilon A}{d}$$

where

ε = permittivity of material

A = cross-sectional area of the plates

d = distance between the plates

Permittivity, ε, is also expressed as the product of the dielectric constant κ and the permittivity of free space:

$$\varepsilon_0 = 8.85 \times 10^{-12} \frac{\text{F}}{\text{m}}$$

where

F = Farad

m = meter

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Resistivity is the material property that determines the resistance of a resistor.

Resistivity of a material within a resistor:

$$\rho = \frac{RA}{L}$$

where

ρ = resistivity of the material

R = resistance of the resistor

A = cross-sectional area of the resistor

L = length of the resistor

Conductivity is the reciprocal of the resistivity.

2.9.4 Mechanical Properties

Creep is time-dependent deformation under load, usually measured by strain rate. For *steady-state creep* this is:

$$\frac{d\varepsilon}{dt} = A\sigma^{n} e^{-\frac{Q}{RT}}$$

where

A = pre-exponential constant

n = stress sensitivity

Q = activation energy for creep

R = ideal gas law constant

T = absolute temperature

Fatigue is time-dependent failure under cyclic load. *Fatigue life* is the number of cycles to failure.

Endurance limit is the stress below which fatigue failure is unlikely.

Fracture toughness is the combination of applied stress and the crack length in a brittle and elastic material. It is the stress intensity at which the material will fail:

$$K_{1C} = Y\sigma\sqrt{\pi a}$$

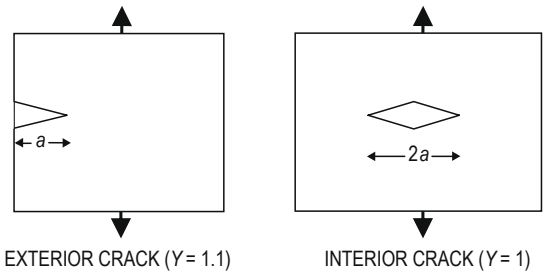
where

K_{1C} = fracture toughness

σ = applied engineering stress

a = crack length

Y = geometrical factor



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The critical value of stress intensity at which catastrophic crack propagation occurs, K_{1C}, is a material property.

Representative Values of Fracture Toughness

Material	$K_{1C}\left(\text{MPa} \cdot \text{m}^{\frac{1}{2}}\right)$	$K_{1C}\left(\text{ksi} \cdot \text{in}^{\frac{1}{2}}\right)$
Al 2014–T651	24.2	22
Al 2024–T3	44	40
52100 Steel	14.3	13
4340 Steel	46	42
Alumina	4.5	4.1
Silicon Carbide	3.5	3.2

2.9.5 Composite Materials

$$\rho_c = \Sigma f_i \rho_i$$

$$C_c = \Sigma f_i c_i$$

$$\left(\Sigma \frac{f_i}{E_i}\right)^{-1} \leq E_c \leq \Sigma f_i E_i$$

$$\sigma_c = \Sigma f_i \sigma_i$$

where

ρ_c = density of composite

C_c = heat capacity of composite per unit volume

E_c = Young's modulus of composite

f_i = volume fraction of individual material

c_i = heat capacity of individual material per unit volume

E_i = Young's modulus of individual material

σ_c = strength parallel to fiber direction

Also, for axially oriented, long, fiber-reinforced composites, the strains of the two components are equal:

$$\left(\frac{\Delta L}{L}\right)_1 = \left(\frac{\Delta L}{L}\right)_2$$

where

ΔL = change in length of the composite

L = original length of the composite

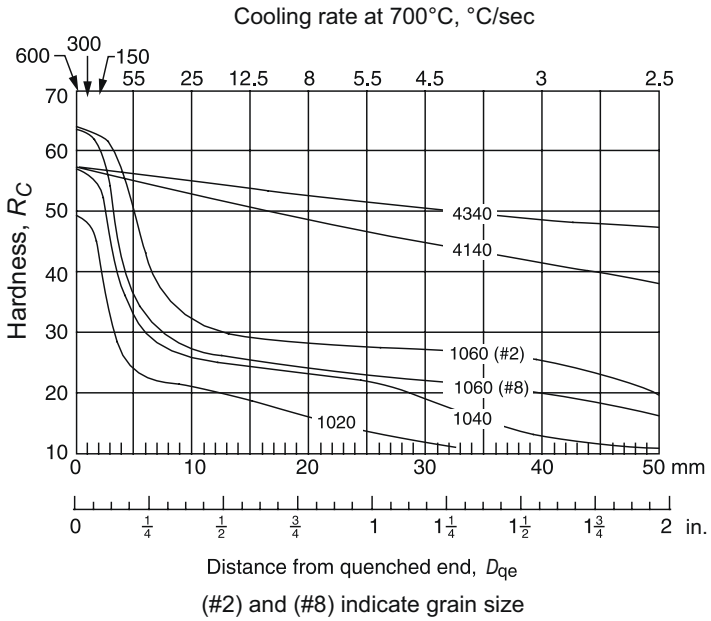
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2.9.6 Material Hardness

Hardness: Resistance to penetration, measured by denting a material under known load and measuring the size of the dent.

Hardenability: The "ease" with which hardness can be obtained.

Jominy Hardenability Curves for Six Steels

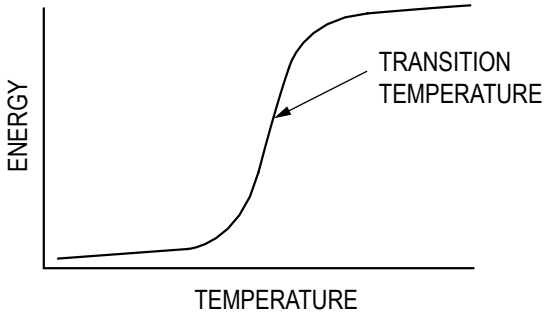


Source: Van Vlack, Lawrence H., *Elements of Materials Science and Engineering*, 4th ed., Reading, MA: Addison-Wesley, 1980.

2.9.7 Impact Test

The *Charpy Impact Test* is used to find energy required to fracture and to identify ductile-to-brittle transition.

Impact Test: Energy Required to Cause Failure



Impact tests determine the amount of energy required to cause failure in standardized test samples. The tests are repeated over a range of temperatures to determine the *ductile-to-brittle transition temperature*.

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2.9.8 Relationship Between Hardness and Tensile Strength

For plain carbon steels, the approximate relationship between the hardness and tensile strength is (based on tungston carbide 10-mm ball):

Tensile strength = Bhn × 515 (for Brinell numbers up to 175)

Tensile strength = Bhn × 490 (for Brinell numbers larger than 175)

The above formulas give the tensile strength in pounds per square inch for steels. These approximate relationships between hardness and tensile strength do not apply to nonferrous metals, with the possible exception of certain aluminum alloys.

Hardness Conversion Tables Based on Brinell (Approximate)

BRINELL HARDNESS		ROCKWELL HARDNESS				Diamond Pyramid Hardness Number (Vickers)
Diameter mm 3,000 Kg	Tungsten Carbide 10 mm Ball	A-Scale 60Kg Brale	B-Scale 100Kg l/16" Ball	C-Scale 150 Kg Brale	Superficial 30N	
....	....	86.5	....	70	86	1,076
....	....	86	....	69	85	1,004
....	....	85.6	....	68	84.4	940
....	....	85	....	67	83.6	900
....	757	84.4	....	65.9	82.7	860
2.25	745	84.1	....	65.3	82.2	840
....	722	83.4	....	64	81.1	800
....	710	83	....	63.3	80.4	780
2.35	682	82.2	....	61.7	79	737
2.4	653	81.2	....	60	77.5	697
2.45	627	80.5	....	58.7	76.3	667
2.5	601	79.8	....	57.3	75.1	640
2.55	578	79.1	....	56	73.9	615
2.6	555	78.4	....	54.7	72.7	591
2.65	534	77.8	....	53.5	71.6	569
2.7	514	76.9	....	52.1	70.3	547
2.75	495	76.3	....	51	69.4	528
2.8	477	75.6	....	49.6	68.2	508
2.85	461	74.9	....	48.5	67.2	491
2.9	444	74.2	....	47.1	65.8	472
2.95	429	73.4	....	45.7	64.6	455
3	415	72.8	....	44.5	63.5	440
3.05	401	72	....	43.1	62.3	425
3.1	388	71.4	....	41.8	61.1	410
3.15	375	70.6	....	40.4	59.9	396

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Hardness Conversion Tables Based on Brinell (Approximate) (cont'd)

BRINELL HARDNESS		ROCKWELL HARDNESS				Diamond Pyramid Hardness Number (Vickers)
Diameter mm 3,000 Kg	Tungsten Carbide 10 mm Ball	A-Scale 60Kg Brale	B-Scale 100Kg l/16" Ball	C-Scale 150 Kg Brale	Superficial 30N	
3.2	363	70	....	39.1	58.7	383
3.25	352	69.3	(110.0)	37.9	57.6	372
3.3	341	68.7	(109.0)	36.6	56.4	360
3.35	331	68.1	(108.5)	35.5	55.4	350
3.4	321	67.5	(108.0)	34.3	54.3	339
3.45	311	66.9	107.5	33.1	53.3	328
3.5	302	66.3	107	32.1	52.2	319
3.55	293	65.7	106	30.9	51.2	309
3.6	285	65.3	105.5	29.9	50.3	301
3.65	277	64.6	104.5	28.8	49.3	292
3.7	269	64.1	(104.0)	27.6	48.3	284
3.75	262	63.6	(103.0)	26.6	47.3	276
3.8	255	63	(102.0)	25.4	46.2	269
3.85	248	62.5	(101.0)	24.2	45.1	261
3.9	241	61.8	100	22.8	43.9	253
3.95	235	61.4	99	21.7	42.9	247
4	229	60.8	98.2	20.5	41.9	241
4.05	223	59.7	97.3	(18.8)	....	234
4.1	217	59.2	96.4	(17.5)	....	228
4.15	212	58.5	95.5	(16.0)	....	222
4.2	207	57.8	94.6	(15.2)		218
4.25	201	57.4	93.8	(13.8)	....	212
4.3	197	56.9	92.8	(12.7)	....	207
4.35	192	56.5	91.9	(11.5)	....	202
4.4	187	55.9	90.7	(10.0)	....	196
4.45	183	55.5	90	(9.0)	....	192
4.5	179	55	89	(8.0)	....	188
4.55	174	53.9	87.8	(6.4)	....	182
4.6	170	53.4	86.8	(5.4)	....	178
4.65	167	53	86	(4.4)	....	175
4.7	163	52.5	85	(3.3)	....	171
4.8	156	51	82.9	(0.9)	....	163
4.9	149	49.9	80.8	....	....	156
5	143	48.9	78.7	....	....	150
5.1	137	47.4	76.4	....	....	143

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Hardness Conversion Tables Based on Brinell (Approximate) (cont'd)

BRINELL HARDNESS		ROCKWELL HARDNESS				Diamond Pyramid Hardness Number (Vickers)
Diameter mm 3,000 Kg	Tungsten Carbide 10 mm Ball	A-Scale 60Kg Brale	B-Scale 100Kg l/16" Ball	C-Scale 150 Kg Brale	Superficial 30N	
5.2	131	46	74	....	....	137
5.3	126	45	72	....	....	132
5.4	121	43.9	69.8	....	....	127
5.5	116	42.8	67.6	....	....	122
5.6	111	41.9	65.7	....	....	117

Values in ( ) are beyond normal range and are given for information only.

The Brinell values in this table are based on the use of a 10mm tungsten carbide ball; at hardness levels of 429 Brinell and below, the values obtained with the tungsten carbide ball, the Hultgren ball, and the standard ball are the same.

The Hardness Conversion Tables are based on SAE J417 and ASTM E140.

Source: Republished with permission of ASTM International, from *Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness*, 2007; permission conveyed through Copyright Clearance Center, Inc.

AISI-SAE System of Designating Carbon and Alloy Steels

AISI-SAE Designation*	Type of Steel and Nominal Alloy Content (%)
	Carbon Steels
10xx	Plain Carbon (Mn 1.00% max.)
11xx	Resulfurized
12xx	Resulfurized and Rephosphorized
15xx	Plain Carbon (Max. Mn range 1.00 to 1.65%)
	Manganese Steels
13xx	Mn l. 75
	Nickel Steels
23xx	Ni 3.50
25xx	Ni 5.00
	Nickel-Chromium Steels
31xx	Ni 1.25; Cr 0.65 and 0.80
32xx	Ni 1.75, Cr 1.07
33xx	Ni 3.50; Cr 1.50 and 1.57
34xx	Ni 3.00; Cr 0.77
	Molybdenum Steels
40xx	Mo 0.20 and 0.25
44xx	Mo 0.40 and 0.52
	Chromium-Molybdenum Steels
41xx	Cr 0.50, 0.80, and 0.95; Mo 0.12, 0.20, 0.25, and 0.30
	Nickel-Chromium-Molybdenum Steels
43xx	Ni 1.82; Cr 0.50 and 0.80, Mo 0.25

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AISI-SAE System of Designating Carbon and Alloy Steels (cont'd)

AISI-SAE Designation*		Type of Steel and Nominal Alloy Content (%)
43BVxx		Ni 1.82; Cr 0.50; Mo 0.12 and 0.35; V 0.03 min.
47xx		Ni 1.05; Cr 0.45; Mo 0.20 and 0.35
81xx		Ni 0.30; Cr 0.40; Mo 0.12
86xx		Ni 0.55; Cr 0.50; Mo 0.20
87xx		Ni 0.55; Cr 0.50; Mo 0.25
88xx		Ni 0.55; Cr 0.50; Mo 0.35
93xx		Ni 3.25; Cr 1.20; Mo 0.12
94xx		Ni 0.45; Cr 0.40; Mo 0.12
97xx		Ni 0.55; Cr 0.20; Mo 0.20
98xx		Ni 1.00; Cr 0.80; Mo 0.25
		Nickel-Molybdenum Steels
46xx		Ni 0.85 and 1.82; Mo 0.20 and 0.25
48xx		Ni 3.50; Mo 0.25
		Chromium Steels
50xx		Cr 0.27, 0.40, 0.50, and 0.65
51xx		Cr 0.80, 0.87, 0.92, 0.95, 1.00, and 1.05
50xxx		Cr 0.50; C 1.00 min.
51xxx		Cr 1.02; C 1.00 min.
52xxx		Cr 1.45; C 1.00 min.
		Chromium-Vanadium Steels
61xx		Cr 0.60, 0.80, and 0.95; V 0.10 and 0.15 min.
		Tungsten-Chromium Steels
72xx		W 1.75; Cr 0.75
		Silicon-Manganese Steels
92xx		Si 1.40 and 2.00; Mn 0.65, 0.82, and 0.85; Cr 0.00 and 0.65
		High-Strength Low-Alloy Steels
9xx		Various SAE grades
xxBxx		B denotes boron steels
xxLxx		L denotes leaded steels
AISI	**SAE**	**Stainless Steels**
2xx	302xx	Chromium-Manganese-Nickel Steels
3xx	303xx	Chromium-Nickel Steels
4xx	514xx	Chromium Steels
5xx	515xx	Chromium Steels

* "xx" in the last two digits of the carbon and low-alloy designations (but not the stainless steels) indicates that the carbon content (in hundredths of a percent) is to be inserted.

Source: Oberg, Erik, Franklin D. Jones, Holbrook L. Horton, and Henry H. Ryffel, eds., *Machinery's Handbook*, 28th ed., South Norwalk, CT: Industrial Press, 2008.

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2.9.9 Binary Phase Diagrams

Binary phase diagrams enable determination of (1) what phases are present at equilibrium at any temperature and average composition, (2) the compositions of those phases, and (3) the fractions of those phases.

Eutectic reaction (liquid → two solid phases)

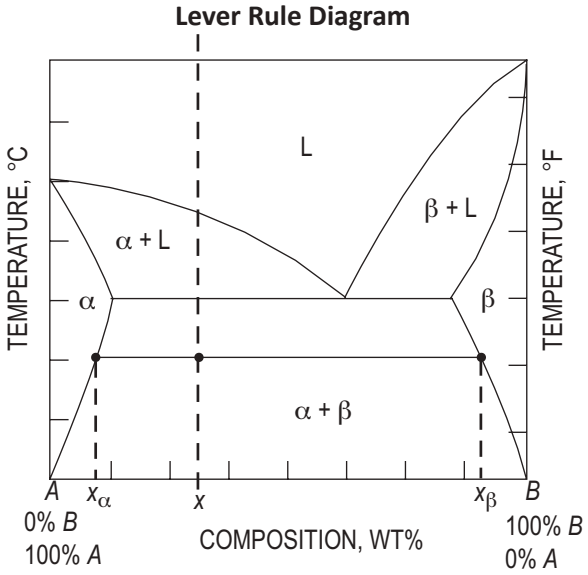
Eutectoid reaction (solid → two solid phases)

Peritectic reaction (liquid + solid → solid)

Peritectoid reaction (two solid phases → solid)

2.9.9.1 Lever Rule

The following phase diagram and equations illustrate how the weight of each phase in a two-phase system can be determined:



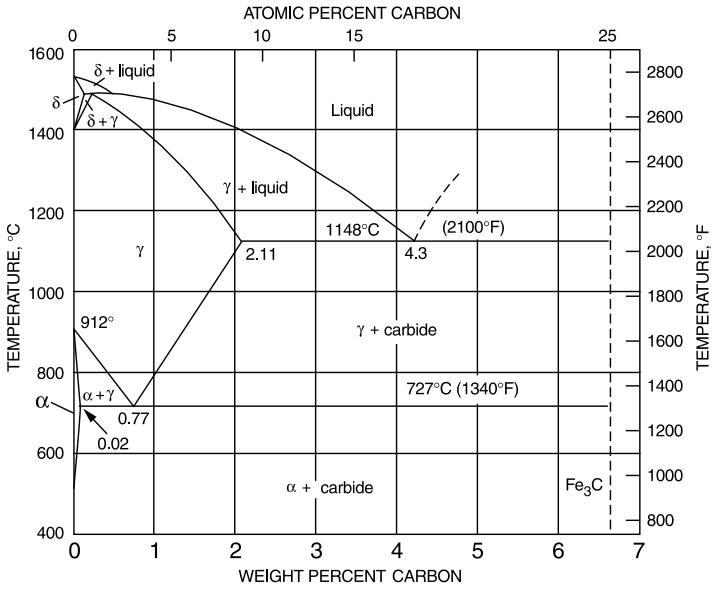
In the diagram, L = liquid. If x = the average composition at temperature T, then:

$$\text{wt}\%\alpha = \frac{x_\beta - x}{x_\beta - x_\alpha} \times 100$$

$$\text{wt}\%\beta = \frac{x - x_\alpha}{x_\beta - x_\alpha} \times 100$$

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Iron-Iron Carbide Phase Diagram



Source: Van Vlack, Lawrence H., *Elements of Materials Science and Engineering*, 4th ed., Reading, MA: Addison-Wesley, 1980.

2.9.10 Thermal and Mechanical Processing

Cold working (plastically deforming) a metal increases strength and lowers ductility.

Raising temperature causes (1) recovery (stress relief), (2) recrystallization, and (3) grain growth. *Hot working* allows these processes to occur simultaneously with deformation.

Quenching is rapid cooling from elevated temperature, preventing the formation of equilibrium phases.

In steels, quenching austenite (FCC [γ] iron) can result in martensite instead of equilibrium phases—ferrite (BCC [α] iron) and cementite (iron carbide).

2.10 Strength of Materials

2.10.1 Strain

2.10.1.1 Engineering Strain

$$\varepsilon = \frac{\Delta L}{L_o}$$

where

ε = engineering strain, in units per unit

ΔL = change in length of member, in units

L_o = original length of member, in units

2.10.1.2 True Strain

$$\varepsilon_T = \ln\frac{L}{L_o} = \ln(1+\varepsilon)$$

where

L = instantaneous length of member, in units

2.10.2 Percent Elongation

$$\%\ \text{elongation} = \frac{\Delta L}{L_o} \times 100$$

2.10.3 Percent Reduction in Area (RA)

The % reduction in area from initial area, A_i, to final area, A_f, is:

$$\%\text{RA} = \frac{A_i - A_f}{A_i} \times 100$$

2.10.4 Shear Stress-Strain

$$\gamma = \frac{\tau}{G}$$

where

γ = shear strain

τ = shear stress

G = shear modulus (constant in linear torsion-rotation relationship)

$$G = \frac{E}{2(1+\nu)}$$

where

E = modulus of elasticity (Young's modulus)

ν = *Poisson's ratio* = $-\dfrac{\text{lateral strain}}{\text{longitudinal strain}}$

2.10.5 Uniaxial Loading and Deformation

$$\sigma = \frac{P}{A}$$

where

σ = stress on the cross section

P = loading

A = instantaneous cross-sectional area

A_o = original cross-sectional area

$$\varepsilon = \frac{\delta}{L} = \frac{\Delta L}{L}$$

where

δ = elastic longitudinal deformation

L = length of member

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$$E = \frac{\sigma}{\varepsilon} = \frac{\frac{P}{A_o}}{\frac{\delta}{L}}$$

$$\delta = \frac{PL}{AE}$$

True stress is load divided by actual cross-sectional area, whereas engineering stress is load divided by the initial area.

$$\sigma_T = \frac{P}{A}$$

2.10.6 Thermal Deformations

$$\delta_t = \alpha L\,(T - T_o)$$

where

δ_t = deformation caused by a change in temperature

α = temperature coefficient of expansion

L = length of member

T = final temperature

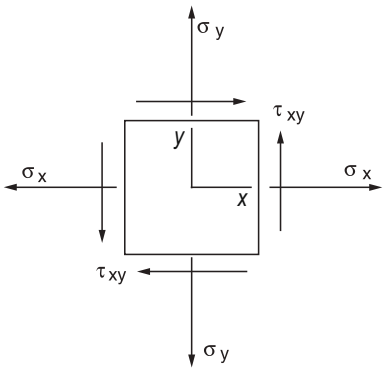
T_o = initial temperature

2.10.7 Principal Stresses

For the special case of a two-dimensional stress state, the equations for principal stress reduce to

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

Typical 2D Stress Element



Source: Crandall, S.H., and N.C. Dahl, *An Introduction to Mechanics of Solids*, 2nd ed., New York: McGraw-Hill, 1978.

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2.10.8 Mohr's Circle—Stress, 2D

To construct a *Mohr's circle*, follow these sign conventions:

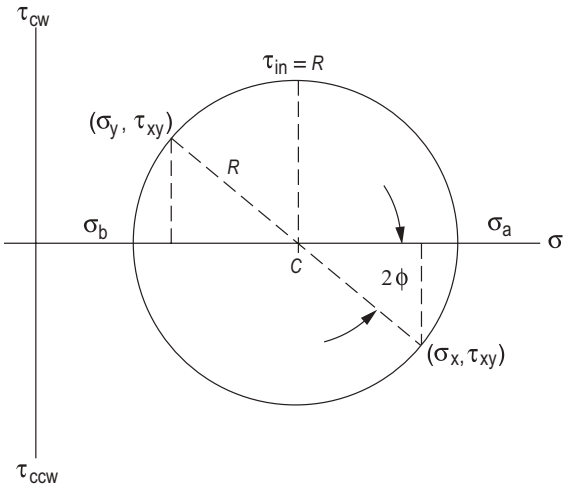
Draw the circle with the center on the normal stress (horizontal) axis, with center C and radius R, where

$$C = \frac{\sigma_x + \sigma_y}{2}, \qquad R = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

The two nonzero principal stresses are then

$$\sigma_a = C + R$$

$$\sigma_b = C - R$$



Source: Crandall, S.H., and N.C. Dahl, *An Introduction to Mechanics of Solids*, 2nd ed., New York: McGraw-Hill, 1978.

The maximum *inplane* shear stress is $\tau_{in} = R$. However, the maximum shear stress considering three dimensions is always

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

where σ_1 and σ_3 are the maximum and minimum principal stress, respectively.

2.10.9 Hooke's Law

Three-dimensional case (triaxial stress-strain):

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right] \qquad \gamma_{xy} = \frac{\tau_{xy}}{G}$$

$$\varepsilon_y = \frac{1}{E}\left[\sigma_y - \nu\left(\sigma_z + \sigma_x\right)\right] \qquad \gamma_{yz} = \frac{\tau_{yz}}{G}$$

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_x + \sigma_y\right)\right] \qquad \gamma_{zx} = \frac{\tau_{zx}}{G}$$

Plane stress case ($\sigma_z = 0$):

$$\varepsilon_x = \frac{1}{E}\left(\sigma_x - \nu\sigma_y\right)$$

$$\varepsilon_y = \frac{1}{E}\left(\sigma_y - \nu\sigma_x\right)$$

$$\varepsilon_z = -\frac{1}{E}\left(\nu\sigma_x + \nu\sigma_y\right)$$

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix} = \frac{E}{1-\nu^2}\begin{bmatrix}1 & \nu & 0\\ \nu & 1 & 0\\ 0 & 0 & \frac{1-\nu}{2}\end{bmatrix}\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{Bmatrix}$$

Uniaxial case ($\sigma_y = \sigma_z = 0$):

$$\sigma_x = E\varepsilon_x \text{ or } \sigma = E\varepsilon$$

where

$\varepsilon_x, \varepsilon_y, \varepsilon_z$ = normal strain

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σ_x, σ_y, σ_z = normal stress

γ_{xy}, γ_{yz}, γ_{zx} = shear strain

τ_{xy}, τ_{yz}, τ_{zx} = shear stress

E = modulus of elasticity

G = shear modulus

v = Poisson's ratio

2.10.10 Strain Energy

If a body of length l is deformed under force F or torque T, the resulting strain energy U is equal to:

strain energy, $U = \frac{1}{2}F\delta$

tension or compression, $U = \frac{F^2 l}{2AE}$

torsion, $U = \frac{T^2 l}{2GJ}$

shear, $U = \frac{F^2 l}{2AG}$

bending, $U = \int \frac{M^2 dx}{2EI}$

where

T = applied torque

Castigliano's theorem:

$$\delta_i = \frac{\partial U}{\partial F_i}$$

where δ_i = the displacement when a force F_i is applied

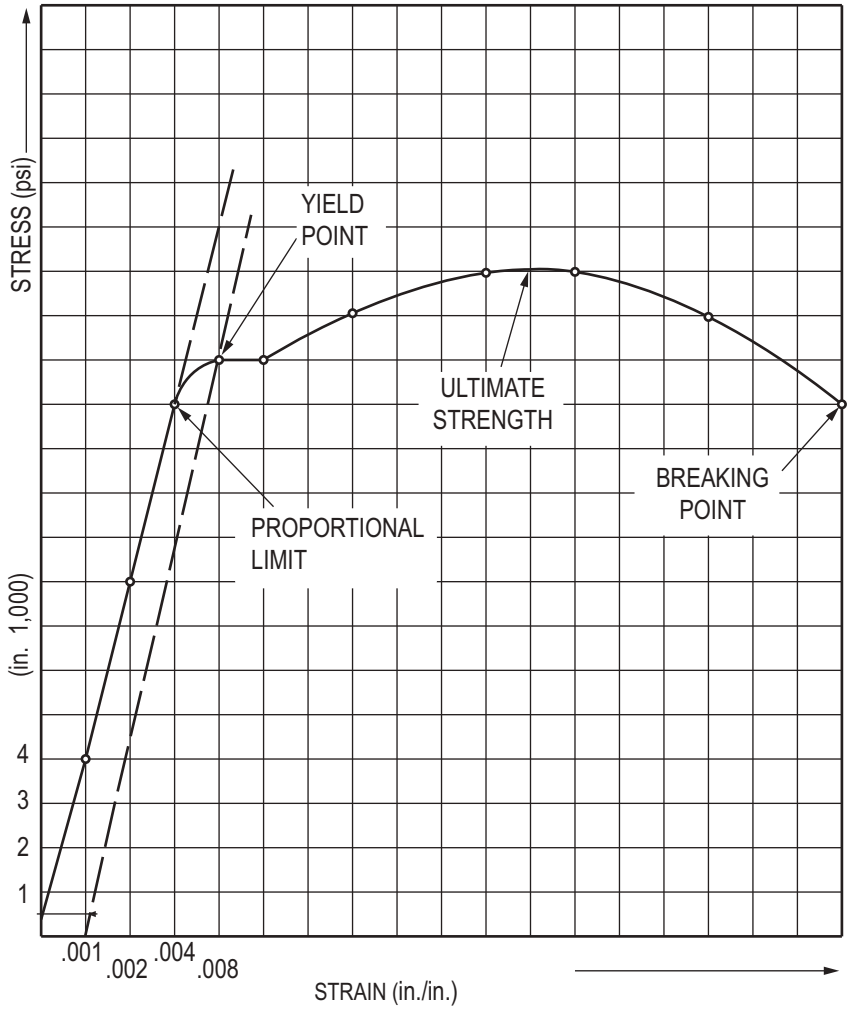
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2.10.11 Stress-Strain Curve for Mild Steel

In the stress-strain curve shown below, the slope of the linear portion of the curve equals the modulus of elasticity.

Typical Stress-Strain Curve of Mild Steel



Source: Linderbeck, John R., Roy S. Klein, and H.C. Kazanas, *Technology of Industrial Materials*, Peoria, IL: Bennett Publishing Co., 1979.

2.11 Stress Analysis

2.11.1 Torsion

Torsion stress in circular solid or thick-walled ($t > 0.1\ r$) shafts:

$$\tau = \frac{Tr}{J}$$

where J = polar moment of inertia

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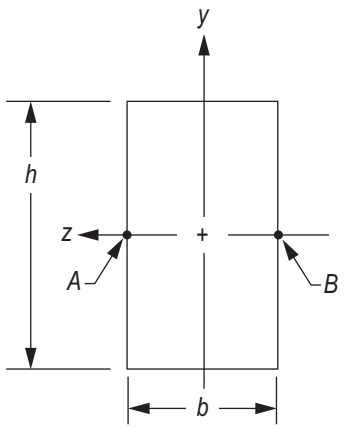
Torsional stress in non-circular cross sections:

$$\tau_{max} = k_1 \frac{T}{hb^2}$$

and the angle of twist is given by

$$\theta = k_2 \frac{(1+v)TL}{Ehb^3}$$

where the constants k_1 and k_2 are tabulated in the following table in terms of the ratio of h/b.



h/b	k_1	k_2	h/b	k_1	k_2
1	4.80	14.2	4	3.54	7.12
1.5	4.33	10.2	5	3.44	6.87
2.0	4.06	8.73	10	3.21	6.41
2.5	3.87	8.03	∞	3.00	6.00
3	3.74	7.60			

Source: Budynas, Richard G., *Advanced Strength and Applied Stress Analysis*, McGraw-Hill, 1977.

2.11.2 Torsional Strain

$$\gamma_{\phi z} = \lim_{\Delta z \to 0} r\left(\frac{\Delta\phi}{\Delta z}\right) = r\left(\frac{d\phi}{dz}\right)$$

The shear strain varies in direct proportion to the radius, from zero strain at the center to the greatest strain at the outside of the shaft. The twist per unit length or the rate of twist is $\frac{d\phi}{dz}$.

$$\tau_{\phi z} = G\gamma_{\phi z} = Gr\left(\frac{d\phi}{dz}\right)$$

$$T = G\left(\frac{d\phi}{dz}\right)\int_A r^2\, dA = GJ\left(\frac{d\phi}{dz}\right)$$

$$\phi = \int_o^L \frac{T}{GJ}\, dz = \frac{TL}{GJ}$$

where

ϕ = total angle (radians) of twist

T = torque

L = length of shaft

$\frac{T}{\phi}$ gives the *twisting moment per radian of twist*. This is called the *torsional stiffness* and is often denoted by the symbol k or c.

2.11.3 Interference-Fit Stresses

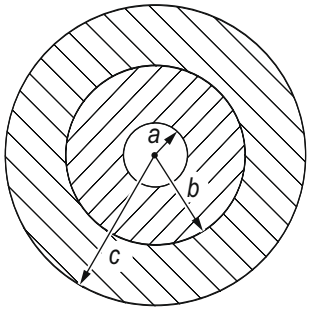
The contact pressure is

$$p = \frac{\delta}{bA}$$

where δ = radial interference

$$A = \frac{1}{E_i}\left(\frac{b^2 + a^2}{b^2 - a^2} - \nu_i\right) + \frac{1}{E_o}\left(\frac{c^2 + b^2}{c^2 - b^2} + \nu_o\right)$$

where



a, b, c = radii of the members

E_i, E_o = elastic moduli for the inner and outer cylinders, respectively

ν_i, ν_o = Poisson's ratio for the inner and outer cylinders, respectively

Increase in inner radius of outer member

$$\delta_o = \frac{pb}{E_o}\left(\frac{c^2 + b^2}{c^2 - b^2} + \nu_o\right)$$

Decrease in outer radius of inner member

$$\delta_i = -\frac{pb}{E_i}\left(\frac{b^2 + a^2}{b^2 - a^2} - \nu_i\right)$$

If the inner cylinder is solid, then $a = 0$ and

$$A = \frac{1}{E_i}(1 - \nu_i) + \frac{1}{E_o}\left(\frac{c^2 + b^2}{c^2 - b^2} + \nu_o\right)$$

When the mating parts have identical moduli and Poisson's ratio

$$p = \frac{E\delta}{b}\,\frac{(c^2 - b^2)(b^2 - a^2)}{2b^2(c^2 - a^2)}$$

If the inner cylinder is solid, with identical moduli and Poisson's ratio for mating parts, then

$$p = \frac{E\delta}{2bc^2}(c^2 - b^2)$$

Compatibility equation

$$\delta = |\delta_o| + |\delta_i|$$

For the outer member, the stresses at the contact surface are biaxial if the longitudinal direction is neglected:

$$\sigma_{ot} = p\frac{c^2 + b^2}{c^2 - b^2} \qquad \sigma_{or} = -p$$

where t and r = tangential and radial directions, respectively

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For the inner member, the stresses at the contact surface are

$$\sigma_{it} = -p\frac{b^2 + a^2}{b^2 - a^2} \qquad \sigma_{ir} = -p$$

The maximum torque that can be transmitted by a press fit-joint is approximately

$$T = 2\pi b^2 \mu p l$$

where

μ = coefficient of friction at the interface

l = length of hub engagement

2.11.4 Rotating Rings

- The outside radius of the ring, or disk, is large compared with the thickness: $r_o \geq 10t$.
- The thickness of the ring or disk is constant.
- The stresses are constant over the thickness.

The stresses are

$$\sigma_t = \rho\omega^2\left(\frac{3+\nu}{8}\right)\left(r_i^2 + r_o^2 + \frac{r_i^2 r_o^2}{r^2} - \frac{1+3\nu}{3+\nu}r^2\right)$$

$$\sigma_r = \rho\omega^2\left(\frac{3+\nu}{8}\right)\left(r_i^2 + r_o^2 - \frac{r_i^2 r_o^2}{r^2} - r^2\right)$$

where

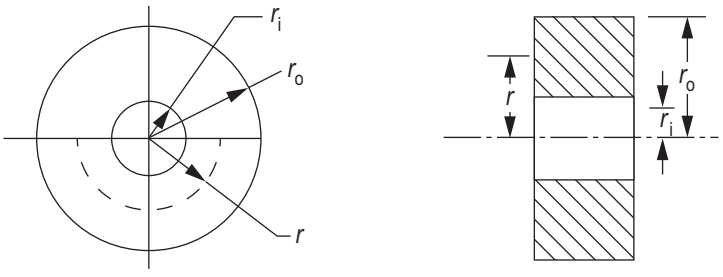
r = radius to the stress element under consideration

ρ = mass density

ω = angular velocity of the ring, in radians per second

For a rotating disk, use $r_i = 0$ in these equations.

Rotating Rings



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2.11.5 Hollow, Thin-Walled Shafts

$$\tau = \frac{T}{2A_m t} \qquad A_m = \pi R_m^2$$

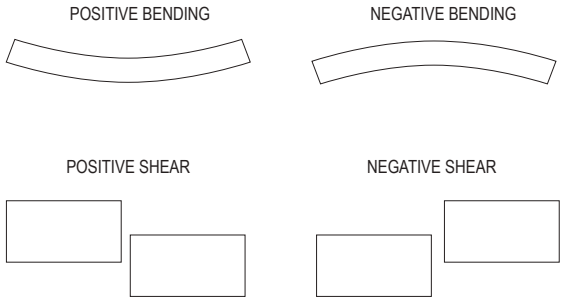
where

t = thickness of shaft wall

A_m = total mean area enclosed by the shaft, measured to the midpoint of the wall

2.11.6 Beams

Shearing Force and Bending Moment Sign Conventions



Source: Timoshenko, S., and Gleason H. McCullough, *Elements of Strengths of Materials*, 3rd ed., Princeton, NJ: D. Van Nostrand Company, Inc., 1949.

The relationship between the load (w), shear (V), and moment (M) equations are:

$$w(x) = -\frac{dV(x)}{dx}$$

$$V = \frac{dM(x)}{dx}$$

$$V_2 - V_1 = \int_{x_1}^{x_2} \left[-w(x)\right] dx$$

$$M_2 - M_1 = \int_{x_1}^{x_2} V(x)\, dx$$

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2.11.6.1 Stresses in Beams

The normal stress in a beam due to bending:

$$\sigma_x = -\frac{My}{I}$$

where

M = moment at the section

I = moment of inertia of the cross section

y = distance from the neutral axis to the fiber location above or below the neutral axis

The maximum normal stresses in a beam due to bending:

$$\sigma_x = \pm\frac{Mc}{I}$$

where

c = distance from the neutral axis to the outermost fiber of a symmetrical beam section

$$\sigma_x = -\frac{M}{s}$$

where

$s = I/c$, the elastic section modulus of the beam

Transverse shear stress:

$$\tau_{xy} = \frac{VQ}{Ib}$$

where

V = shear force

$Q = A'\overline{y'}$, where

A' = area above the layer (or plane) upon which the desired transverse shear stress acts

$\overline{y'}$ = distance from neutral axis to area centroid

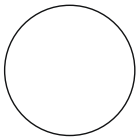
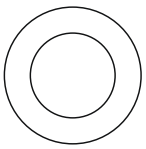
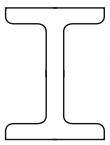
b = width or thickness of the cross section

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Transverse shear flow:

$$q = \frac{VQ}{I}$$

Formulas for Maximum Shear Stress Due to Bending

Beam Shape	Formula
Rectangular 	$\tau_{max} = \frac{3V}{2A}$
Circular 	$\tau_{max} = \frac{4V}{3A}$
Hollow Round 	$\tau_{max} = \frac{2V}{A}$
Structural  web	$\tau_{max} = \frac{V}{A_{web}}$

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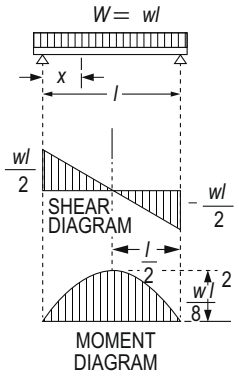
Bending Moment, Vertical Shear, and Deflection of Beams of Uniform Cross Section, Under Various Conditions of Loading

Source: Copyright © American Institute of Steel Construction. Reprinted with permission. All rights reserved.

P = concentrated loads, in lb
R_1, R_2 = reactions, in lb
w = uniform load per unit of length, in lb per in.
W = total uniform load on beam, in lb
l = length of beam, in in.
x = distance from support to any section, in in.
E = modulus of elasticity, in psi

I = moment of inertia, in in^4
V_x = vertical shear at any section, in lb
V = maximum vertical shear, in lb
M_x = bending moment at any section, in lb-in.
M = maximum bending moment, in lb-in.
y = maximum deflection, in in.
k = fraction of l to P

Simple Beam: Uniform Load



$$R_1 = R_2 = \frac{wl}{2}$$

$$V_x = \frac{wl}{2} - wx$$

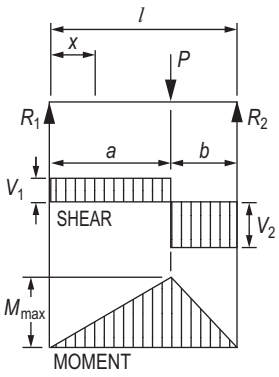
$$V = \pm\frac{wl}{2}\left(\text{when } \begin{cases} x = 0 \\ x = l \end{cases}\right)$$

$$M_x = \frac{wlx}{2} - \frac{wx^2}{2}$$

$$M = \frac{wl^2}{8}\left(\text{when } x = \frac{l}{2}\right)$$

$$y = \frac{5wl^4}{384EI} \text{ (at center of span)}$$

Simple Beam: Concentrated Load at Any Point



$$\text{Total Equiv. Uniform Load} = \frac{8Pab}{l^2}$$

$$R_1 = V_1 \,(= V_{\max} \text{ when } a < b) = \frac{Pb}{l}$$

$$R_2 = V_2 \,(= V_{\max} \text{ when } a > b) = \frac{Pa}{l}$$

$$M_{\max} \text{ (at point of load)} = \frac{Pab}{l}$$

$$M_x \text{ (when } x < a) = \frac{Pbx}{l}$$

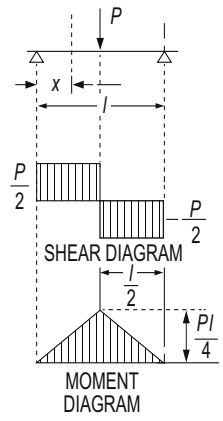
$$\Delta_{\max}\left[\text{at } x = \sqrt{\frac{a(a+2b)}{3}}, \text{ when } a > b\right]$$

$$= \frac{Pab\,(a+2b)\sqrt{3a(a+2b)}}{27EIl}$$

$$\Delta_a \text{ (at point of load)} = \frac{Pa^2b^2}{3EIl}$$

$$\Delta_x \text{ (when } x < a) = \frac{Pbx}{6EIl}\left(l^2 - b^2 - x^2\right)$$

Simple Beam: Concentrated Load at Center



$$R_1 = R_2 = \frac{P}{2}$$

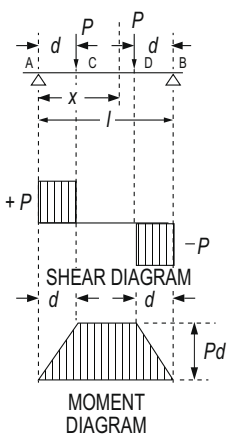
$$V_x = V = \pm\frac{P}{2}$$

$$M_x = \frac{Px}{2}$$

$$M = \frac{Pl}{4}\left(\text{when } x = \frac{l}{2}\right)$$

$$y = \frac{Pl^3}{48EI} \text{ (at center of span)}$$

Simple Beam: Two Equal Concentrated Loads at Equal Distances from Supports



$$R_1 = R_2 = P$$

$$V_x = P \quad (\text{for } AC)$$
$$= 0 \quad (\text{for } CD)$$
$$= -P \quad (\text{for } DB)$$

$$V = \pm P$$

$$M_x = Px \quad (\text{for } AC)$$
$$= Pd \quad (\text{for } CD)$$
$$= P(l - x) \quad (\text{for } DB)$$

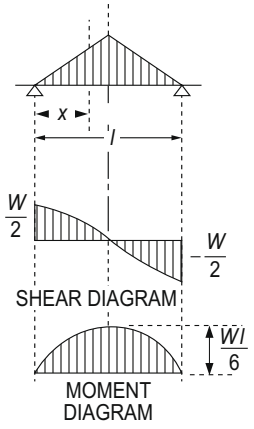
$$M = Pd$$

$$y = \frac{Pd}{24EI}\left(3l^2 - 4d^2\right)$$
$$\left(\text{at center of span}\right)$$

Bending Moment, Vertical Shear, and Deflection of Beams of Uniform Cross Section, Under Various Conditions of Loading (cont'd)

P = concentrated loads, in lb **R_1, R_2 = reactions, in lb** **w = uniform load per unit of length, in lb per in.** **W = total uniform load on beam, in lb** **l = length of beam, in in.** **x = distance from support to any section, in in.** **E = modulus of elasticity, in psi**	**I = moment of inertia, in in^4** **V_x = vertical shear at any section, in lb** **V = maximum vertical shear, in lb** **M_x = bending moment at any section, in lb-in.** **M = maximum bending moment, in lb-in.** **y = maximum deflection, in in.**

Simple Beam: Load Increasing Uniformly from Supports to Center of Span



$$R_1 = R_2 = \frac{W}{2}$$

$$V_x = W\left(\frac{1}{2} - \frac{2x^2}{l^2}\right)\left(\text{when } x < \frac{l}{2}\right)$$

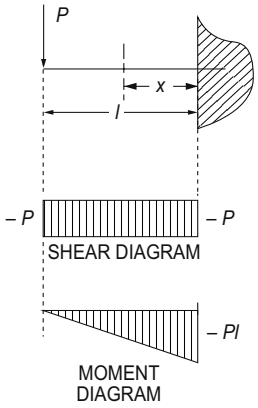
$$V = \pm\frac{W}{2}\left(\text{at supports}\right)$$

$$M_x = Wx\left(\frac{1}{2} - \frac{2x^2}{3l^2}\right)$$

$$M = \frac{Wl}{6}\left(\text{at center of span}\right)$$

$$y = \frac{Wl^3}{60EI}\left(\text{at center of span}\right)$$

Cantilever Beam: Load Concentrated at Free End



$$R = P$$

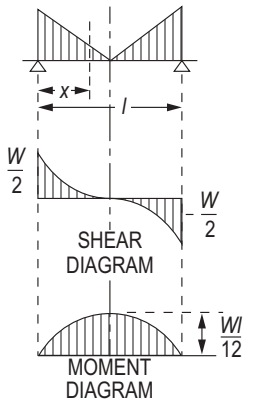
$$V_x = V = -P$$

$$M_x = -P\left(l - x\right)$$

$$M = -Pl\left(\text{when } x = 0\right)$$

$$y = \frac{Pl^3}{3EI}$$

Simple Beam: Load Increasing Uniformly from Center to Supports



$$R_1 = R_2 = \frac{W}{2}$$

$$V_x = -W\left(\frac{2x}{l} - \frac{2x^2}{l^2} - \frac{1}{2}\right)\left(\text{when } x < \frac{1}{2}\right)$$

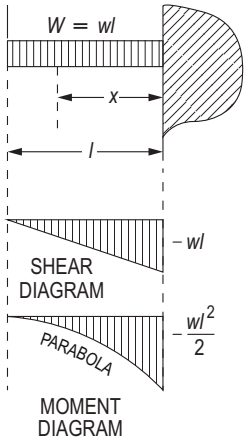
$$V = \pm\frac{W}{2}$$

$$M_x = Wx\left(\frac{1}{2} - \frac{x}{l} + \frac{2x^2}{3l^2}\right)\left(\text{when } x < \frac{1}{2}\right)$$

$$M = \frac{Wl}{12}\left(\text{at center of span}\right)$$

$$y = \frac{3Wl^3}{320EI}\left(\text{at center of span}\right)$$

Cantilever Beam: Uniform Load



$$R = W = wl$$

$$V_x = -w\left(l - x\right)$$

$$V = -wl\left(\text{when } x = 0\right)$$

$$M_x = -w\left(l - x\right)\left(\frac{l - x}{2}\right)$$

$$M = -\frac{wl^2}{2}\left(\text{when } x = 0\right)$$

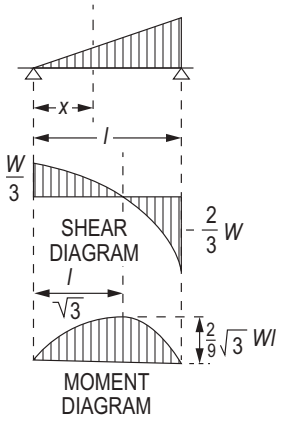
$$y = \frac{Wl^3}{8EI}$$

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Bending Moment, Vertical Shear, and Deflection of Beams of Uniform Cross Section, Under Various Conditions of Loading (cont'd)

P = concentrated loads, in lb R_1, R_2 = reactions, in lb w = uniform load per unit of length, in lb per in. W = total uniform load on beam, in lb l = length of beam, in in. x = distance from support to any section, in in. E = modulus of elasticity, in psi	I = moment of inertia, in in^4 V_x = vertical shear at any section, in lb V = maximum vertical shear, in lb M_x = bending moment at any section, in lb-in. M = maximum bending moment, in lb-in. y = maximum deflection, in in.

Simple Beam: Load Increasing Uniformly from One Support to the Other



$$R_1 = \frac{W}{3};\ R_2 = \frac{2}{3}W$$

$$V_x = W\left(\frac{1}{3} - \frac{x^2}{l^2}\right)$$

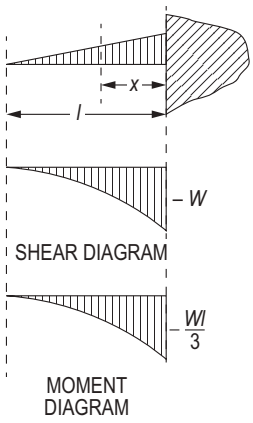
$$V = -\frac{2}{3}W \text{ (when } x = l\text{)}$$

$$M_x = \frac{Wx}{3}\left(1 - \frac{x^2}{l^2}\right)$$

$$M = \frac{2}{9\sqrt{3}}Wl \left(\text{when } x = \frac{l}{\sqrt{3}}\right)$$

$$y = \frac{0.01304}{EI}Wl^3$$

Cantilever Beam: Load Increasing Uniformly from Free End to Support



$$R = W$$

$$V_x = -W\frac{(l-x)^2}{l^2}$$

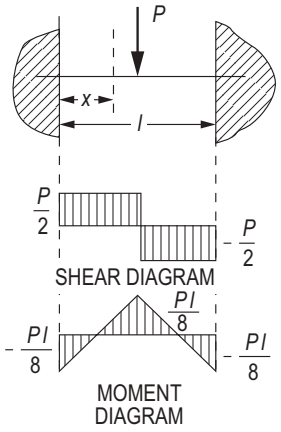
$$V = -W \text{ (when } x = 0\text{)}$$

$$M_x = -\frac{W}{3}\frac{(l-x)^3}{l^2}$$

$$M = -\frac{Wl}{3} \text{ (when } x = 0\text{)}$$

$$y = \frac{Wl^3}{15EI}$$

Fixed Beam: Concentrated Load at Center of Span



$$R_1 = R_2 = \frac{P}{2}$$

$$V_x = V = \pm\frac{P}{2}$$

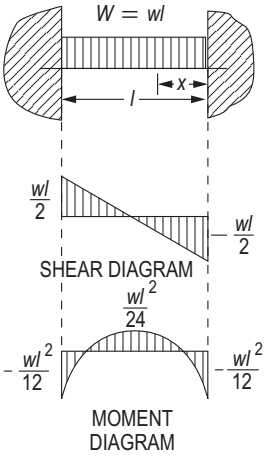
$$M_x = P\left(\frac{x}{2} - \frac{l}{8}\right)$$

$$M_x = -\frac{Pl}{8}\left(\text{when } \begin{cases} x = 0 \\ x = l \end{cases}\right)$$

$$M = +\frac{Pl}{8} \text{ (at center of span)}$$

$$y = \frac{Pl^3}{192EI}$$

Fixed Beam: Uniform Load



$$R_1 = R_2 = \frac{wl}{2} = \frac{W}{2}$$

$$V_x = \frac{wl}{2} - wx$$

$$V = \pm\frac{wl}{2} \text{ (at ends)}$$

$$M_x = -\frac{wl^2}{2}\left(\frac{1}{6} - \frac{x}{l} + \frac{x^2}{l^2}\right)$$

$$M = -\frac{1}{12}wl^2 \left(\text{when } \begin{cases} x = 0 \\ x = l \end{cases}\right)$$

$$M = \frac{wl^2}{24}\left(\text{when } x = \frac{l}{2}\right)$$

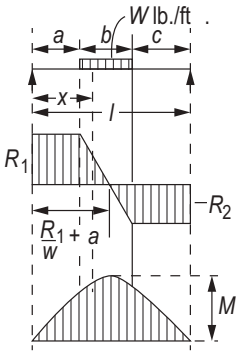
$$y = \frac{Wl^3}{384EI}$$

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Bending Moment, Vertical Shear, and Deflection of Beams of Uniform Cross Section, Under Various Conditions of Loading (cont'd)

P = concentrated loads, in lb **R_1, R_2 = reactions, in lb** **w = uniform load per unit of length, in lb per in.** **W = total uniform load on beam, in lb** **l = length of beam, in in.** **x = distance from support to any section, in in.** **E = modulus of elasticity, in psi**	**I = moment of inertia, in in^4** **V_x = vertical shear at any section, in lb** **V = maximum vertical shear, in lb** **M_x = bending moment at any section, in lb-in.** **M = maximum bending moment, in lb-in.** **y = maximum deflection, in in.**

Simple Beam: Distributed Load Over Part of Beam



$$R_1 = \frac{wb(2c+b)}{2l}$$

$$R2 = \frac{wb(2a+b)}{2l}$$

$$V_x = \frac{wb(2c+b)}{2l} - w(x-a)$$

$$V = R_1 \text{ (when } a < c\text{)}$$

$$= R_2 \text{ (when } a > c\text{)}$$

$$M_x = \frac{wbx(2c+b)}{2l} \text{ (when } x < a\text{)}$$

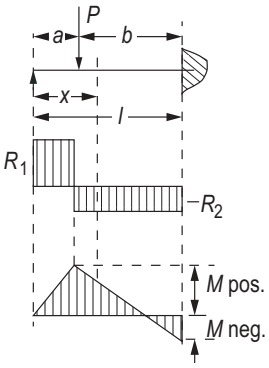
$$= R_1 x - \frac{w(x-a)^2}{2}$$

$$\text{(when } a < x < a+b\text{)}$$

$$= R_2(l-x) \text{ (when } l-x < c\text{)}$$

$$M = \frac{wb(2c+b)\left[4al + b(2c+b)\right]}{8l^2}$$

Beam Supported at One End, Fixed at Other: Concentrated Load at Any Point



$$R_1 = \frac{Pb^2(2l+a)}{2l^3}$$

$$R_2 = P - R_1$$

$$V_x = R_1 \text{ (when } x < a\text{)}$$

$$= R_2 \text{ (when } x > a\text{)}$$

$$M_x = \frac{Pb^2x(2l+a)}{3l^3}$$

$$\text{(when } x < a\text{)}$$

$$= R_1 x - P(x-a)$$

$$\text{(when } x > a\text{)}$$

$$M \text{ positive} = \frac{Pab^2(2l+a)}{2l^3}$$

$$\text{(when } x = a\text{)}$$

$$M \text{ negative} = -\frac{Pab(l+a)}{2l^2}$$

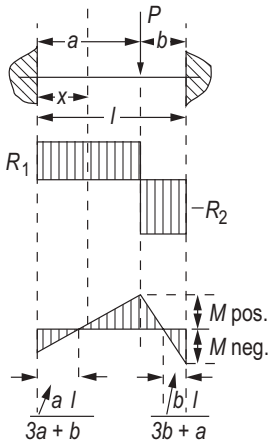
$$\text{(when } x = l\text{)}$$

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Bending Moment, Vertical Shear, and Deflection of Beams of Uniform Cross Section, Under Various Conditions of Loading (cont'd)

P = concentrated loads, in lb **R_1, R_2 = reactions, in lb** **w = uniform load per unit of length, in lb per in.** **W = total uniform load on beam, in lb** **l = length of beam, in in.** **x = distance from support to any section, in in.** **E = modulus of elasticity, in psi**	**I = moment of inertia, in in^4** **V_x = vertical shear at any section, in lb** **V = maximum vertical shear, in lb** **M_x = bending moment at any section, in lb-in.** **M = maximum bending moment, in lb-in.** **y = maximum deflection, in in.**

Fixed Beam: Concentrated Load at Any Point



$$R_1 = \frac{Pb^2(l+2a)}{l^3} \qquad a > b$$

$$R_2 = \frac{Pa^2(l+2b)}{l^3}$$

$$V_x = R_1 \text{ (when } x < a\text{)}$$

$$= R_2 \text{ (when } x > a\text{)}$$

$$V = R_2$$

$$M_x = R_1 x - \frac{Pab^2}{l^2} \text{ (when } x < a\text{)}$$

$$= R_2(l-x) - \frac{Pa^2b}{l^2}$$

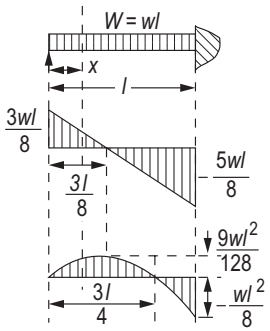
(when $x > a$)

$$M \text{ positive} = \frac{2Pa^2b^2}{l^3}$$

$$M \text{ negative} = \frac{-Pa^2b}{l^2}$$

$$y = -\frac{2Pa^3b^2}{3EI(3a+b)^2}$$

Beam Supported at One End, Fixed at Other: Distributed Load



$$R_1 = \frac{3wl}{8}$$

$$R_2 = \frac{5wl}{8}$$

$$V_x = \frac{3wl}{8} - wx$$

$$V = \frac{3wl}{8} \text{ (at left support)}$$

$$= \frac{5wl}{8} \text{ (at right support)}$$

$$M_x = wx\left(\frac{3l}{8} - \frac{x}{2}\right)$$

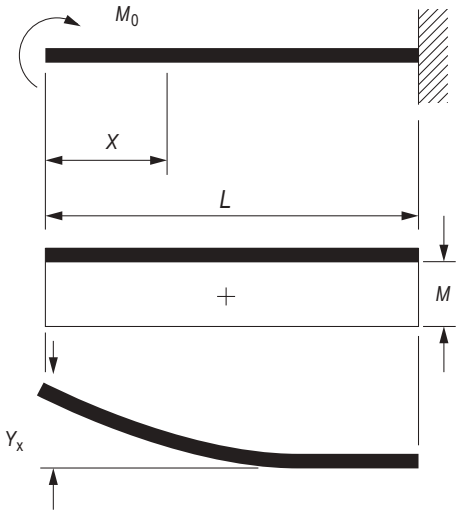
$$M \text{ positive} = \frac{9wl^2}{128}$$

$$M \text{ negative} = -\frac{wl^2}{8}$$

$$y = -\frac{0.0054wl^4}{EI}$$

(at $0.4215l$ from R_1)

Cantilevered Beam With End Moment



Reactions:

$R_l = 0$

$R_r = 0$

Shear:

$V = 0$

Moments:

$M = M_0 = M_{max}$

End slope:

$$\phi_l = -\frac{M_0 L}{EI}$$

$\phi_r = 0$

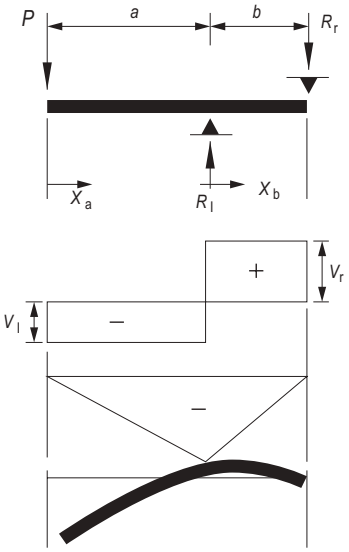
Deflection:

$$y_x = \left(+\frac{M_0}{2EI}\right) \times \left(L^2 - 2xL + x^2\right)$$

$$y_{max} = +\frac{M_0 L^2}{2EI} \text{ at } x = 0$$

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Simple Beam With Overhung Load



Reactions:

$$R_l = \left(\frac{P}{b}\right)(b+a)$$

$$R_r = \frac{-Pa}{b}$$

Shear:

$$V_l = -P$$

$$V_r = \frac{Pa}{b}$$

Moments:

$$M_a = Px_a$$

$$M_b = \left(\frac{Pa}{b}\right)(b - x_b)$$

$M_{\max} = Pa$ at $x_a = a$

Deflections:

$$y_a = \left(\frac{P}{3EI}\right)\left[(a^2 + ab)(a - x_a) + \left(\frac{x_a}{2}\right)(x_a^2 - a^2)\right]$$

$$y_b = \left(\frac{Pax_b}{6EI}\right)\left[3x_b - \left(\frac{x_b^2}{b}\right) - 2b\right]$$

$$y_{\text{tip}} = \left(\frac{Pa^2}{3EI}\right)(a+b) \quad \text{[max down]}$$

$$y_{\max} = 0.06415\left(\frac{Pab^2}{EI}\right) at\ x_b = 0.4226b \quad \text{[max up]}$$

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2.12 Intermediate- and Long-Length-Column Determination

The *slenderness ratio* of a column is

$$S_r = \frac{l}{r}$$

where

l = length of the column

r = radius of gyration

The *radius of gyration* of a column cross section is

$$r = \sqrt{\frac{I}{A}}$$

where

I = moment of inertia

A = cross-sectional area

2.12.1 Intermediate Columns

A column is considered to be intermediate if its slenderness ratio is less than or equal to $(S_r)_D$

where

$$S_r \le (S_r)_D$$

$$(S_r)_D = \sqrt{\frac{2\pi^2 E}{K^2 S_y}}$$

and where

$(S_r)_D$ = column stress determination factor

E = Young's modulus of respective member

S_y = yield strength of the column material

K = effective-length factor to account for end supports

For intermediate columns, the *critical buckling load* is

$$P_{cr} = A\left[S_y - \frac{K^2}{E}\left(\frac{S_y S_r}{2\pi}\right)^2\right]$$

where

P_{cr} = critical buckling load

A = cross-sectional area of the column

S_y = yield strength of the column material

E = Young's modulus of respective member

S_r = slenderness ratio

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2.12.2 Long Columns

Critical axial load for long columns subject to buckling: *Euler's Formula*

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

where

L = unbraced column length

K = effective-length factor to account for end supports

Critical buckling stress for long columns:

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 E}{\left(\frac{Kl}{r}\right)^2}$$

where

r = *radius of gyration* $\sqrt{\frac{I}{A}}$

$\frac{Kl}{r}$ = effective slenderness ratio for the column

Approximate Values of Effective Length Factor, K

BUCKLED SHAPE OF COLUMN IS SHOWN BY DASHED LINE.						
THEORETICAL *K* VALUE	0.5	0.7	1.0	1.0	2.0	2.0
RECOMMENDED DESIGN VALUE WHEN IDEAL CONDITIONS ARE APPROXIMATED	0.65	0.80	1.2	1.0	2.10	2.0
END CONDITION CODE	 *ROTATION FIXED AND TRANSLATION FIXED* *ROTATION FREE AND TRANSLATION FIXED* *ROTATION FIXED AND TRANSLATION FREE* *ROTATION FREE AND TRANSLATION FREE*					

FOR COLUMN ENDS SUPPORTED BY, BUT NOT RIGIDLY CONNECTED TO, A FOOTING OR FOUNDATION, K IS THEORETICALLY INFINITY BUT UNLESS DESIGNED AS A TRUE FRICTION-FREE PIN, MAY BE TAKEN AS 10 FOR PRACTICAL DESIGNS. IF THE COLUMN END IS RIGIDLY ATTACHED TO A PROPERLY DESIGNED FOOTING, K MAY BE TAKEN AS 1.0. SMALLER VALUES MAY BE USED IF JUSTIFIED BY ANALYSIS.

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2.13 Failure Theories

In this section, σ_1 = maximum principal stress, σ_2 = intermediate principal stress, σ_3 = minimum principal stress

2.13.1 Brittle Materials

Maximum-Normal-Stress Theory: If $\sigma_1 \geq \sigma_2 \geq \sigma_3$, then failure occurs whenever $\sigma_1 \geq S_{ut}$ or $\sigma_3 \leq -S_{uc}$, where S_{ut} and S_{uc} are tensile and compressive strengths, respectively.

2.13.2 Ductile Materials

Maximum Shear Stress Theory: If $\sigma_1 \geq \sigma_2 \geq \sigma_3$, then yielding occurs whenever $\tau_{max} \geq \frac{S_y}{2}$

where S_y = yield strength

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

Distortion-Energy (Von Mises Stress) Theory: Yielding will occur whenever

$$\left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}\right]^{\frac{1}{2}} \geq S_y$$

For a biaxial stress state, the effective stress becomes

$$\sigma' = \left(\sigma_A^2 - \sigma_A \sigma_B + \sigma_B^2\right)^{\frac{1}{2}}$$

or

$$\sigma' = \left(\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2\right)^{\frac{1}{2}}$$

where

σ_A, σ_B = the two nonzero principal stresses

$\sigma_x, \sigma_y, \tau_{xy}$ = the stresses in orthogonal directions

2.14 Variable Loading Failure Theories

Modified Goodman Theory: The modified Goodman theory states that a fatigue failure will occur whenever

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} \geq 1 \quad \text{or} \quad \frac{\sigma_{max}}{S_y} \geq 1 \quad \text{when} \quad \sigma_m \geq 0$$

where

S_e = fatigue strength

S_{ut} = ultimate strength

S_y = yield strength

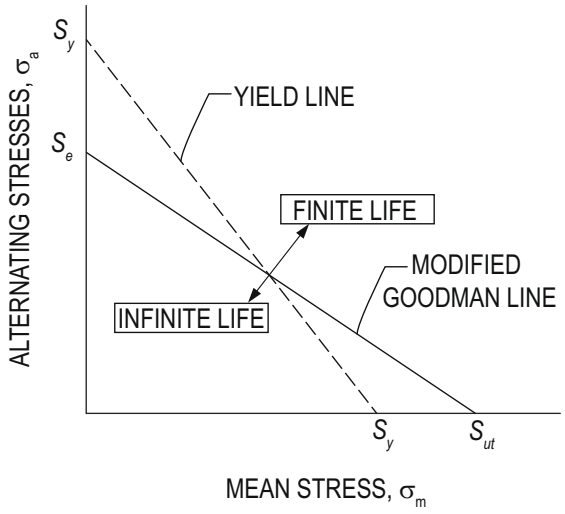
σ_a = alternating stress = $\frac{1}{2}(\sigma_{max} - \sigma_{min})$

σ_m = mean stress = $\frac{\sigma_{max} + \sigma_{min}}{2}$

$\sigma_{max} = \sigma_m + \sigma_a$

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The modified Goodman relationship is often shown graphically as in the figure below.



A *Goodman equivalent stress* approximates a biased alternating stress as an equivalent fully reversed alternating stress which can be directly compared with published endurance limits of a material (e.g., an S-N curve) and can be calculated as:

$$\sigma_{eq} = \sigma_a + \left(\frac{S_e}{S_{ut}}\right)\sigma_m$$

Goodman Line:

$$\sigma_{eq} = \frac{\sigma_a}{1 - \left(\frac{\sigma_m}{S_{ut}}\right)}$$

Soderberg Theory: The Soderberg theory states that a fatigue failure will occur whenever

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_y} \geq 1 \quad \text{when} \quad \sigma_m \geq 0$$

Miner's Rule:

$$\sum \frac{n_i}{N_i} = C \qquad C \text{ is typically equal to } 1.$$

where n_i = number of cycles applied at a load corresponding to a lifetime of N_i

Endurance Limit for Steels: When test data is unavailable, the endurance limit for steels may be estimated as

$$S'_e = \begin{Bmatrix} 0.5\, S_{ut} & S_{ut} \leq 1{,}400 \text{ MPa} \\ 700 \text{ MPa} & S_{ut} > 1{,}400 \text{ MPa} \end{Bmatrix}$$

When different stress levels are known, the fatigue stress S_f is related to cycles of life N by $S_f = aN^b$

where

$b = \log (S_{f1}/S_{f2})/\log (N_1/N_2)$

$a = S_{f1}/N_1{}^b$

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*Endurance Limit Modifying Factor*s:

S'_e = rotating beam endurance limit

$S_e = k_a k_b k_c k_d k_e S'_e$, modified endurance limit

where

Surface Factor $k_a = aS_{ut}^b$

Surface Finish	Factor *a*		Exponent *b*
	ksi	MPa	
Ground	1.34	1.58	–0.085
Machined or CD	2.70	4.51	–0.265
Hot-rolled	14.4	57.7	–0.718
As forged	39.9	272.0	–0.995

Size Factor, k_b:

For bending and torsion:

$d \le 8$ mm; $k_b = 1$

8 mm $\le d \le$ 250 mm; $k_b = 1.189 d_{eff}^{-0.097}$

$d >$ 250 mm; $0.6 \le k_b \le 0.75$

For axial loading: $k_b = 1$

Load Factor, k_c:

$k_c = 0.923$ axial loading, $S_{ut} \le$ 1,520 MPa

$k_c = 1$ axial loading, $S_{ut} >$ 1,520 MPa

$k_c = 1$ bending

$k_c = 0.577$ torsion

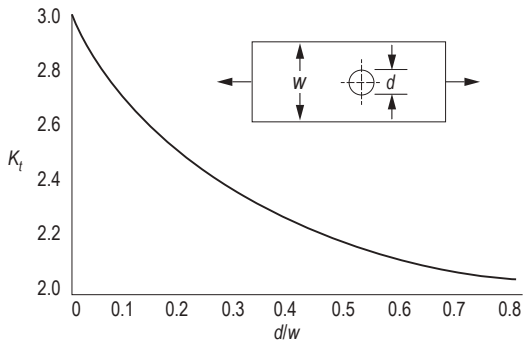
Temperature Factor, k_d:

for T ≤ 450°C $k_d = 1$

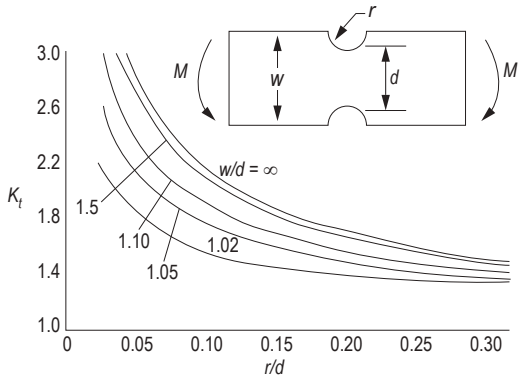
Miscellaneous Effects Factor, k_e: Used to account for strength reduction effects such as corrosion, plating, and residual stresses. In the absence of known effects, use $k_e = 1$.

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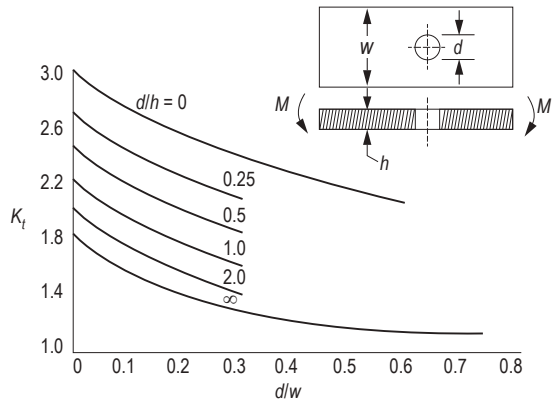
Charts of Theoretical Stress-Concentration Factors K_t



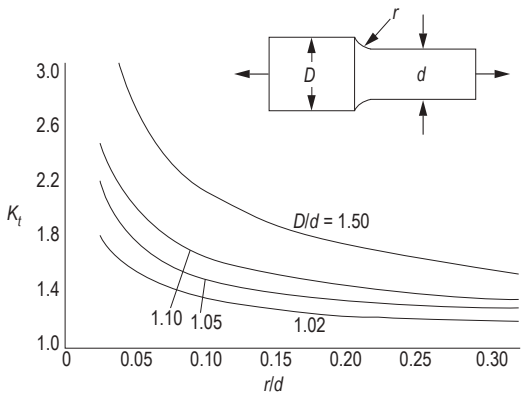
Bar in tension or simple compression with a transverse hole. $\sigma_o = F/A$, where $A = (w - d)t$ and t is the thickness.



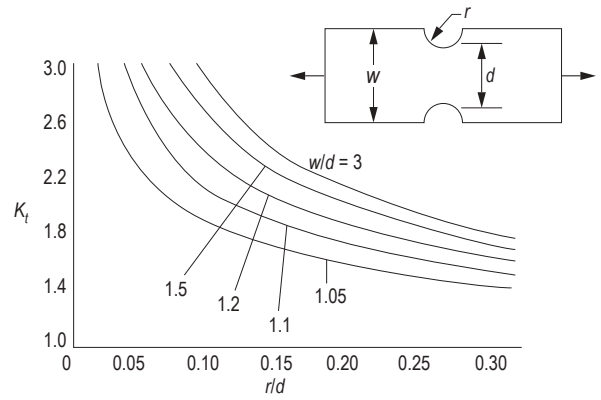
Notched rectangular bar in bending. $\sigma_o = Mc/I$, where $c = d/2$, $I = td^3/12$, and t is the thickness.



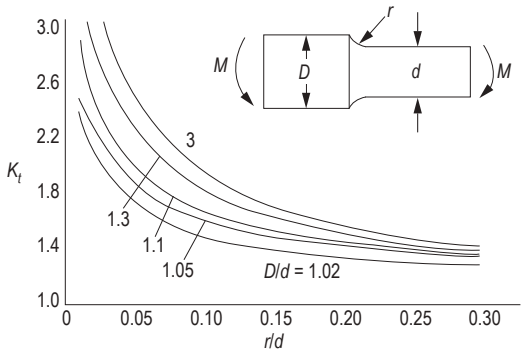
Rectangular bar with a transverse hole in bending. $\sigma_o = Mc/I$, where $I = (w - d)h^3/12$.



Rectangular filleted bar in tension or simple compression. $\sigma_o = F/A$, where $A = dt$ and t is the thickness.

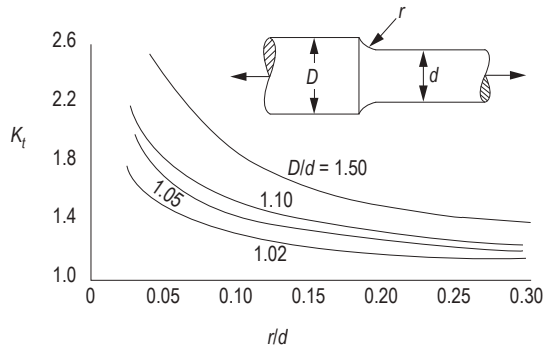


Notched rectangular bar in tension or simple compression. $\sigma_o = F/A$, where $A = dt$ and t is the thickness.

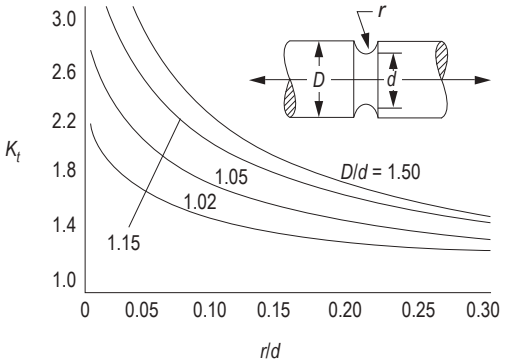


Rectangular filleted bar in bending. $\sigma_o = Mc/I$, where $c = d/2$, $I = td^3/12$, and t is the thickness.

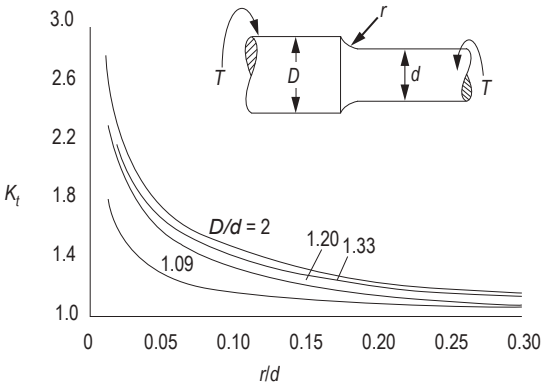
Charts of Theoretical Stress-Concentration Factors K_t (cont'd)



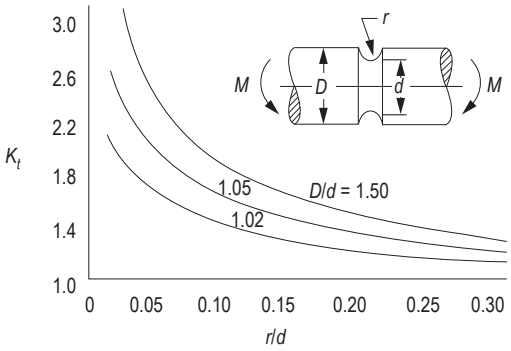
Round shaft with shoulder fillet in tension. $\sigma_o = FIA$, where $A = \pi d^2/4$.



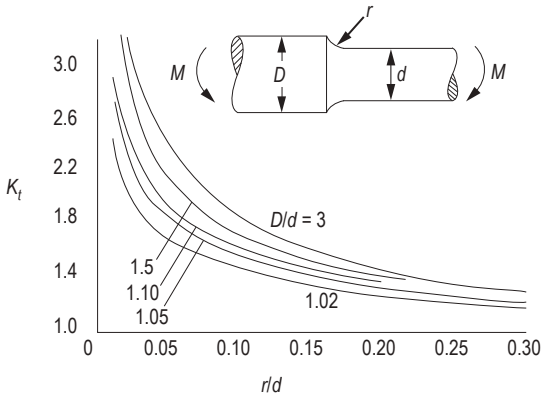
Grooved round bar in tension $\sigma_o = FIA$, where $A = \pi d^2/4$.



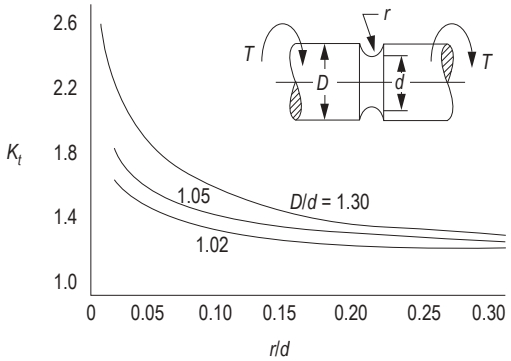
Round shaft with shoulder fillet in torsion. $\tau_o = Tc/J$, where $c = d/2$ and $J = \pi d^4/32$.



Grooved round bar in bending. $\sigma_o = Mc/L$, where $c = d/2$ and $I = \pi d^4/64$.



Round shaft with shoulder fillet in bending. $\sigma_o = Mc/I$, where $c = d/2$ and $I = \pi d^4/64$.



Grooved round bar in torsion $\tau_o = Tc/J$, where $c = d/2$ and $J = \pi d^4/32$.

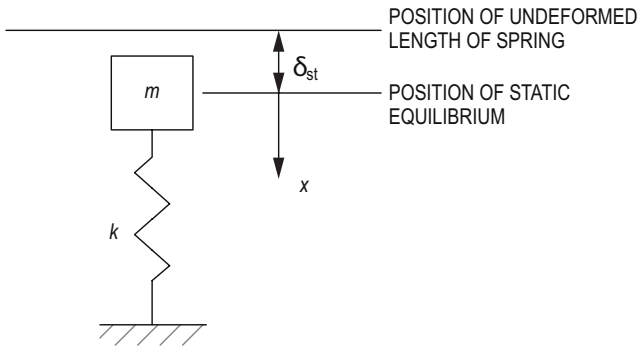
Source: Used with permission of McGraw Hill LLC, from *Mechanical Engineering Design*, Joseph E. Shigley and Charles R. Mischke, 5th ed., McGraw-Hill, 1989; permission conveyed through Copyright Clearance Center, Inc.

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2.15 Vibration/Dynamic Analysis

2.15.1 Free Vibration

A Single Degree-of-Freedom System



$$m\ddot{x} = mg - k\left(x + \delta_{st}\right)$$

where

m = mass of the system

k = spring constant of the system

δ_{st} = static deflection of the system

x = displacement of the system from static equilibrium

$mg = k\delta_{st}$

$$m\ddot{x} + kx = 0$$

The solution of this differential equation is

$$x(t) = C_1 \cos(\omega_n t) + C_2 \sin(\omega_n t)$$

where

$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{g}{\delta_{st}}}$, the undamped natural circular frequency

C_1, C_2 = constants of integration, whose values are determined from the initial conditions

If the initial conditions are $x(0) = x_0$ and $\dot{x}(0) = v_0$, then

$$x(t) = x_0 \cos\left(\omega_n t\right) + \left(\frac{v_0}{\omega_n}\right)\sin\left(\omega_n t\right) \qquad \omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{g}{\delta_{st}}}$$

The undamped natural period of vibration:

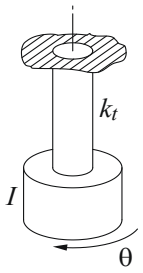
$$\tau_n = \frac{2\pi}{\omega_n} = \frac{2\pi}{\sqrt{\frac{k}{m}}} = \frac{2\pi}{\sqrt{\frac{g}{\delta_{st}}}} = \frac{1}{f}$$

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2.15.2 Torsional Vibration (Pendulum)

For torsional free vibrations:

$$\ddot{\theta} + \left(\frac{k_t}{I}\right)\theta = 0$$



where

θ = angular displacement of the system

k_t = torsional stiffness of the massless rod

I = mass moment of inertia of the end mass

In terms of the initial conditions $\theta(0) = \theta_0$ and $\dot{\theta}(0) = \dot{\theta}_0$:

$$\theta(t) = \theta_0 \cos(\omega_n t) + (\dot{\theta}_0/\omega_n)\sin(\omega_n t)$$

Undamped, natural circular frequency:

$$\omega_n = \sqrt{\frac{k_t}{I}}$$

The *torsional stiffness* of a solid round rod:

$$k_t = \frac{GJ}{L}$$

where

J = polar moment of inertia

L = length

G = shear modulus of elasticity

Thus, the *undamped, natural circular frequency* for a system with a solid round supporting rod:

$$\omega_n = \sqrt{\frac{GJ}{IL}}$$

Undamped natural period:

$$\tau_n = 2\pi/\omega_n = \frac{2\pi}{\sqrt{\frac{k_t}{I}}} = \frac{2\pi}{\sqrt{\frac{GJ}{IL}}}$$

Critical damping constant:

$$C_C = 2m\omega_n$$

Logarithmic decrement:

$$\delta = \ln\frac{x_1}{x_2} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$$

Damped natural frequency:

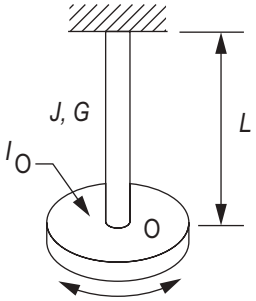
$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

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2.15.2.1 Torsional Mass and Spring (Pendulum)

Angular natural frequency

$$\omega = \sqrt{\frac{JG}{I_O L}}$$



Linear natural frequency

$$f = \left(\frac{1}{2\pi}\right)\sqrt{\frac{JG}{I_O L}}$$

Time period

$$T = 2\pi\sqrt{\frac{I_O L}{JG}}$$

where

I_O = mass moment of inertia of the thin disk

L = length of the circular shaft

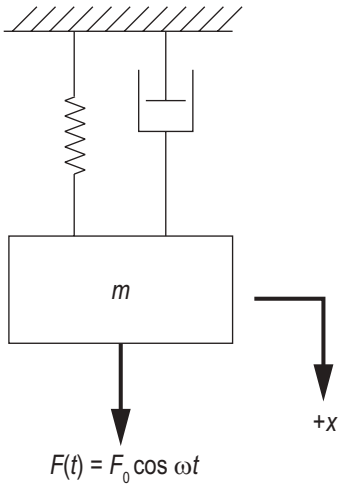
J = polar moment of inertia of the circular shaft

G = shear modulus of the circular shaft

Source: Kelly, Graham, *Fundamentals of Mechanical Vibrations*, 2nd ed., p. 25.

2.15.3 Forced Vibration Under Harmonic Force

$$m\ddot{x} + c\dot{x} + kx = F_0 \cos \omega t$$



Magnification factor/amplitude ratio/amplification factor = $\frac{X}{\delta_{st}}$

$$= M = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}}$$

The phase angle is given by

$$\tan \phi = \frac{2\zeta r}{1 - r^2}$$

where

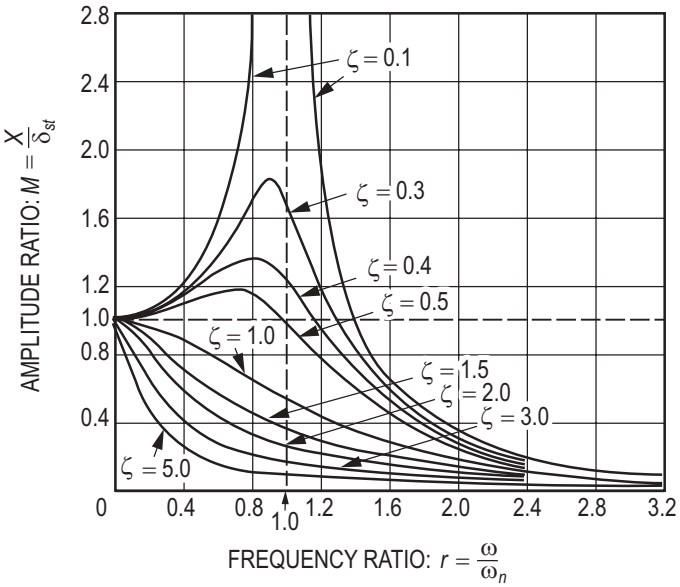
$\delta_{st} = \frac{F_0}{k}$ = deflection under the static force F_0

$r = \frac{\omega}{\omega_n}$ = frequency ratio

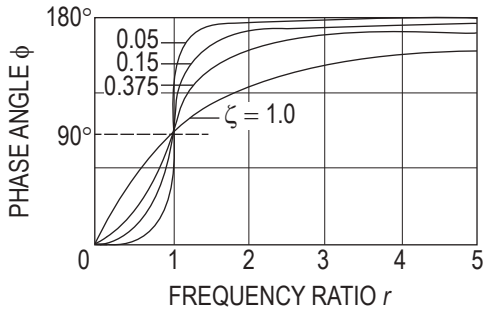
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$$\zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{mk}} = \text{damping ratio}$$

X = amplitude of the response (displacement)



Source: Rao, Singiresu, *Mechanical Vibrations*, 6th ed., Hoboken: Pearson Education, 2017, p. 283.



Source: Thomson, William T., *Theory of Vibration with Applications,* 2nd ed., Englewood Cliffs, NJ: Prentice Hall, 1981.

2.15.4 Vibration Transmissibility, Base Motion

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0$$

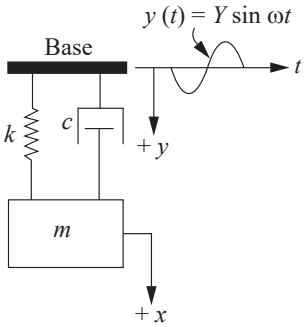
where

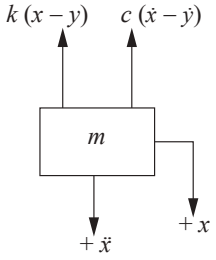
c = damping coefficient

k = spring constant

Force transmissibility can be written as

$$\frac{F_T}{F_o} = \left[\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}\right]^{\frac{1}{2}}$$





where

F_T = amplitude or maximum value of the transmitted force

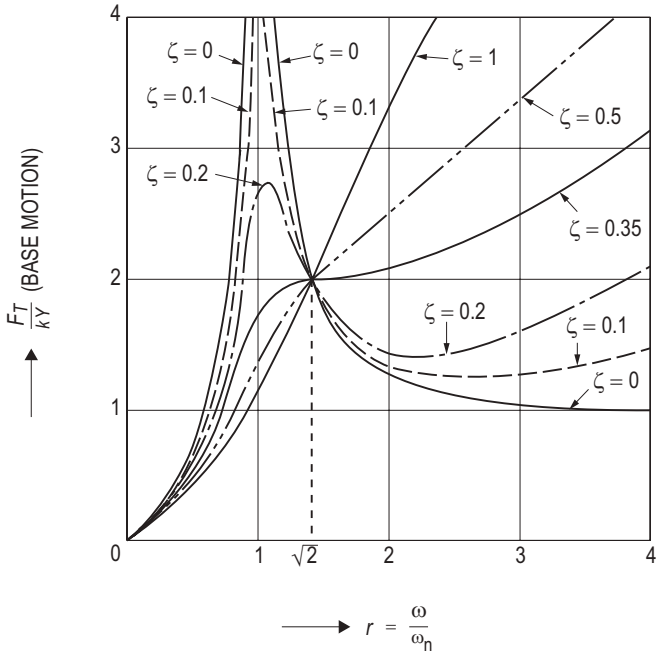
F_o = force due to static deflection of the system = kY

r = frequency ratio = $\frac{\omega}{\omega_n}$

The *damping ratio* is

$$\zeta = \frac{c}{C_C}$$

Transmitting Vibrations



Source: Rao, Singiresu, *Mechanical Vibrations*, 2nd ed., Reading, MA: Addison-Wesley Publishing Company, Inc., 1990.

Amplitude Ratio or Magnification Factor: The ratio of the maximum amplitude of vibration to the static deflection of the system.

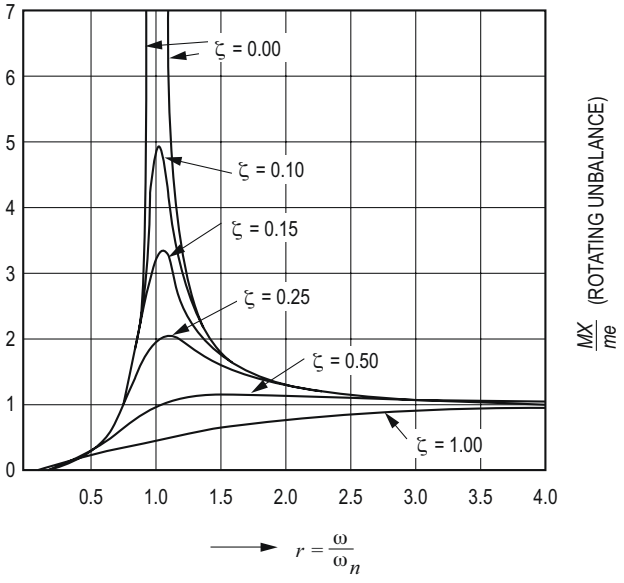
2.15.5 Vibration—Rotating Unbalance

$$\frac{MX}{me} = \frac{r^2}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}},$$

where m is the eccentric mass with eccentricity e, (M-m) is the non-rotating mass, and X is the displacement of the non-rotating mass.

and seen as

Forced Vibration with Rotating Unbalance



Source: Rao, Singiresu, *Mechanical Vibrations*, 2nd ed., Reading, MA: Addison-Wesley Publishing Company, Inc., 1990.

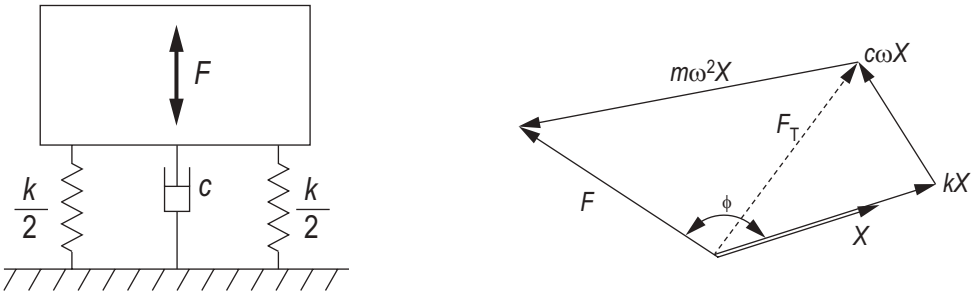
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2.15.6 Vibration Isolation—Fixed Base

Equation of Motion: $m\ddot{x} + c\dot{x} + kx = F_0 \cos \omega t$

Vibratory forces generated by machines and engines are often unavoidable; however, their effect on a dynamical system can be reduced substantially by properly designed springs, which are referred to as isolators. In the figure below, let $F_o \sin \omega t$ be the exciting force acting on the single degree of freedom system. The transmitted force through the springs and damper is

$$F_T = \sqrt{(kX)^2 + (c\omega X)^2} = kX\sqrt{1 + \left(\frac{c\omega}{k}\right)^2}$$



Disturbing Force Transmitted through Springs and Damper

Since the amplitude X developed under the force $F_0 \sin \omega t$ is given by the equations

$$X = \frac{\frac{F_0}{k}}{\sqrt{\left(1 - \frac{m\omega^2}{k}\right)^2 + \left(\frac{c\omega}{k}\right)^2}} \qquad \text{and} \qquad \tan \phi = \frac{\frac{c\omega}{k}}{1 - \frac{m\omega^2}{k}}$$

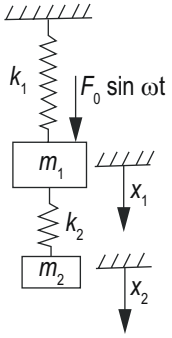
the above equation reduces to

$$\frac{F_T}{F_0} = \frac{\sqrt{1 + \left(\frac{c\omega}{k}\right)^2}}{\sqrt{\left[1 - \frac{m\omega^2}{k}\right]^2 + \left[\frac{c\omega}{k}\right]^2}} = \frac{\sqrt{1 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\frac{\omega}{\omega_n}\right]^2}} = \frac{\sqrt{1 + (2\zeta r)^2}}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}}$$

Source: Thomson, William T., and Marie Dillon, *Theory of Vibration with Applications*, 5th ed., Englewood Cliffs, NJ: Prentice Hall, 1998. Reprinted by permission of Pearson Education, Inc.

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2.15.7 Vibration Absorber



A spring-mass system k_2, m_2, tuned to frequency of the exciting force such that $\omega^2 = k_2/m_2$, will act as a vibration absorber and reduce the motion of the main mass m_1 to zero.

$$\omega_{11}^2 = \frac{k_1}{m_1} \qquad \omega_{22}^2 = \frac{k_2}{m_2}$$

Assuming harmonic motion, the amplitude X_1 can be equal to

$$\frac{X_1 k_1}{F_0} = \frac{\left[1 - \left(\frac{\omega}{\omega_{22}}\right)^2\right]}{\left[1 + \frac{k_2}{k_1} - \left(\frac{\omega}{\omega_{11}}\right)^2\right]\left[1 - \left(\frac{\omega}{\omega_{22}}\right)^2\right] - \frac{k_2}{k_1}}$$

At $\omega = \omega_{22}$, the amplitude $X_1 = 0$ and the absorber mass undergoes an amplitude equal to

$$X_2 = -\frac{F_0}{k_2}$$

Since the acting force on m_2 is:

$$k_2 X_2 = \omega^2 m_2 X_2 = -F_0$$

the absorber system k_2, m_2 exerts a force equal and opposite to the disturbing force. The size of k_2 and m_2 depends on the allowable value of X_2.

Source: Thomson, William T., *Theory of Vibration with Applications*, 2nd ed., Englewood Cliffs, NJ: Prentice Hall, 1981.

2.15.8 Dunkerley's Equation

$$\frac{1}{\omega^2} = \frac{1}{\omega_1^2} + \frac{1}{\omega_2^2} + \ldots + \frac{1}{\omega_i^2}$$

where

ω_i = critical speed with mass i only

ω = critical speed with all n masses together

2.15.9 Viscous Damping

$$F_d = c\dot{x}$$

where

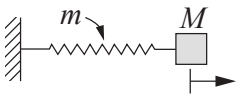
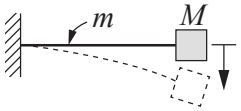
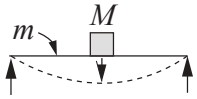
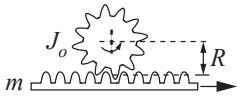
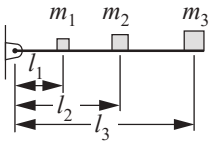
c = coefficient of damping

$\dot{x}$ = velocity

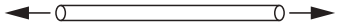
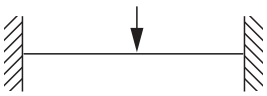
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2.15.10 Equivalent Masses, Springs, and Dampers

Equivalent Masses

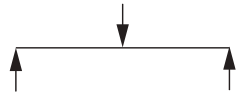
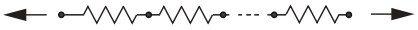
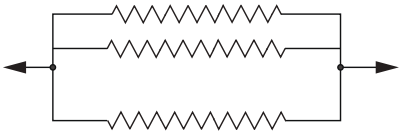
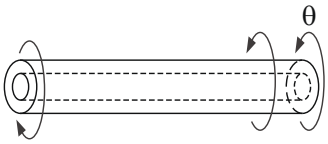
	Mass M attached at end of spring of mass m	$m_{eq} = M + \frac{m}{3}$
	Cantilever beam of mass m carrying an end mass M	$m_{eq} = M + 0.23\ m$
	Simply supported beam of mass m carrying a mass M at the middle	$m_{eq} = M + 0.5\ m$
	Coupled translational and rational masses	$m_{eq} = M + \frac{J_0}{R^2}$ $J_{eq} = J_0 + mR^2$
	Masses on a hinged bar Equivalent mass at distance l	$m_{eq} = \left(\frac{l_1}{l}\right)^2 m_1 + \left(\frac{l_2}{l}\right)^2 m_2 + \left(\frac{l_3}{l}\right)^2 m_3$

Equivalent Springs

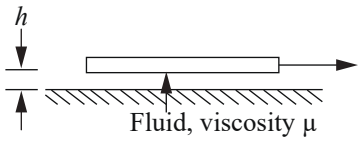
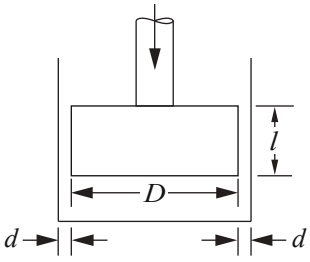
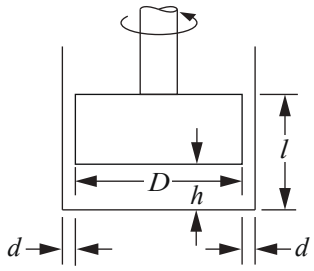
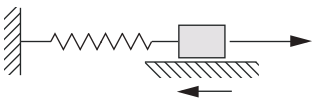
	Rod under axial load (l = length, A = cross sectional area)	$k_{eq} = \frac{EA}{l}$
	Tapered rod under axial load (D, d = end diameters)	$k_{eq} = \frac{\pi EDd}{4l}$
	Helical spring under axial load (d = wire diameter, D = mean coil diameter, n = number of active turns)	$k_{eq} = \frac{Gd^4}{8nD^3}$
	Fixed-fixed beam with load at the middle	$k_{eq} = \frac{192EI}{l^3}$
	Cantilever beam with end load	$k_{eq} = \frac{3EI}{l^3}$

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Equivalent Springs (cont'd)

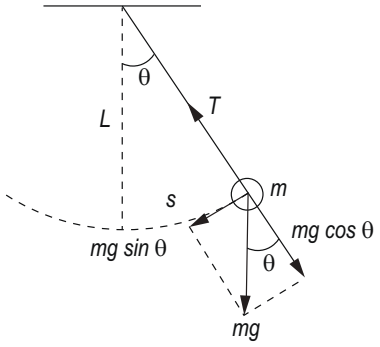
	Simply supported beam with load at the middle	$k_{eq} = \frac{48EI}{l^3}$
	Springs in series	$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2} + ... + \frac{1}{k_n}$
	Springs in parallel	$k_{eq} = k_1 + k_2 + ... + k_n$
	Hollow shaft under torsion (l = length, D = outer diameter, d = inner diameter)	$k_{eq} = \frac{\pi G}{32l}(D^4 - d^4)$

Equivalent Viscous Dampers

	Relative motion between parallel surfaces (A = area of smaller plate)	$c_{eq} = \frac{\mu A}{h}$
	Dashpot (axial motion of a piston in a cylinder)	$c_{eq} = \mu \frac{3\pi D^3 l}{4d^3}\left(1 + \frac{2d}{D}\right)$
	Torsional damper	$c_{eq} = \frac{\pi \mu D^2 (l - h)}{2d} + \frac{\pi \mu D^3}{32h}$
	Dry friction (Coulomb damping) (fN = friction force, ω = frequency, X = amplitude of vibration)	$c_{eq} = \frac{4fN}{\pi \omega X}$

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2.15.11 Pendulum Motion



The angular frequency and period are

$$\omega = \sqrt{\frac{g}{L}} \quad \text{and} \quad T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{L}{g}}$$

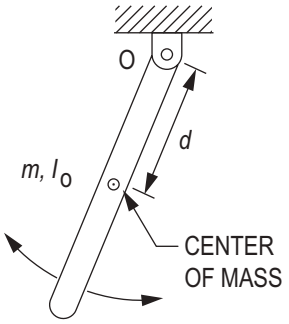
2.15.12 Compound Pendulum

Natural frequency

$$\omega = \sqrt{\frac{mgd}{I_0}}$$

Period

$$T = 2\pi\sqrt{\frac{I_0}{mgd}}$$



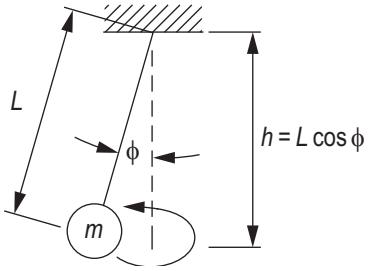
2.15.13 Conical Pendulum

Natural frequency

$$\omega = \sqrt{\frac{g}{h}}$$

Period

$$T = 2\pi\sqrt{\frac{h}{g}}$$



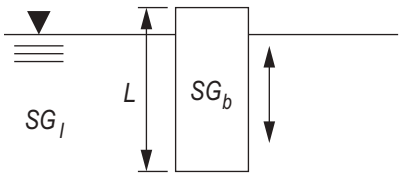
2.15.14 Floating Block

Natural frequency

$$\omega = \sqrt{\frac{g(sG_l)}{L(SG_b)}}$$

Period

$$T = 2\pi\sqrt{\frac{L(SG_b)}{g(SG_l)}}$$



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2.16 Mechanical Components

2.16.1 Springs

2.16.1.1 Spring Energy

For a linear elastic spring with modulus, stiffness, or spring constant, the force in the spring is

$$F_s = k\,x$$

where x = change in length of the spring from the undeformed length of the spring

The potential energy stored in the spring when compressed or extended by an amount x is

$$U = k\,\frac{x^2}{2}$$

In changing the deformation in the spring from position x_1 to x_2, the change in the potential energy stored in the spring is

$$U_2 - U_1 = k\,\frac{\left(x_2^2 - x_1^2\right)}{2}$$

2.16.1.2 Mechanical Springs

Helical Compression Springs: The shear stress in a helical compression spring is

$$\tau = K_s\,\frac{8FD}{\pi d^3}$$

where

$K_s = \dfrac{4C+2}{4C-3}$, where C = spring index = $\dfrac{D}{d}$

F = applied force

D = mean spring diameter

d = wire diameter

The deflection and force are related by $F = kx$ where the spring rate (spring constant) k is given by

$$k = \frac{d^4 G}{8D^3 N}$$

where

G = shear modulus of elasticity

N = number of active coils

The minimum tensile strength of common spring steels may be determined from

$$S_{ut} = \frac{A}{d^m}$$

where

S_{ut} = tensile strength (MPa or kpsi)

A = material constant

d = wire diameter (mm or inches)

m = constant (see table)

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Some measurements for A and m are listed in the following table.

Constants for Calculating Minimum Tensile Strength of Common Spring Steels

Material	ASTM	m	A, MPa	A, kpsi
Music wire	A228	0.145	2,211	201
O Q & T wire	A229	0.187	1,855	147
Hard-drawn wire	A227	0.190	1,783	140
Chrome vanadium wire	A232	0.168	2,005	169
Chrome silicon wire	A401	0.108	1,974	202

Maximum allowable torsional stress for static applications may be approximated as

$S_{sy} = \tau = 0.45\ S_{ut}$ cold-drawn carbon steel (A227, A228, A229 in previous table)

$S_{sy} = \tau = 0.50\ S_{ut}$ hardened and tempered carbon and low-alloy steels (A232, A401)

$S_y = \sigma = 0.61\ S_{ut}$ austenitic stainless steels and nonferrous alloys

$$S_{ys} = \tau_{max,\ failure} = \frac{S_{yt}}{\sqrt{3}} = 0.577\ S_{yt}$$

Compression Spring Dimensions

	Type of Spring Ends			
Term	Plain	Plain and Ground	Squared and Closed	Squared and Ground
End coils, N_e	0	1	2	2
Total coils, N_t	N	$N + 1$	$N + 2$	$N + 2$
Free length, L_0	$pN + d$	$p(N + 1)$	$pN + 3d$	$pN + 2d$
Solid length, L_s	$d(N_t + 1)$	dN_t	$d(N_t + 1)$	dN_t
Pitch, p	$\frac{(L_0 - d)}{N}$	$\frac{L_0}{(N + 1)}$	$\frac{(L_0 - 3d)}{N}$	$\frac{(L_0 - 2d)}{N}$

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Helical Torsion Springs: The bending stress is given as

$$\sigma = K_i \frac{32Fr}{\pi d^3}$$

where

K_i = correction factor = $\frac{4C^2 - C - 1}{4C(C-1)}$

F = applied load

r = radius from the center of the coil to the load

$C = \frac{D}{d}$ = spring index

The deflection θ and moment Fr are related by

$$Fr = k\theta$$

where the spring rate k is given by

$$k = \frac{d^4 E}{64DN}$$

where k has units of $N \cdot \frac{m}{rad}$ and θ is in radians.

Spring Material: The allowable stress σ is then given by

$S_y = \sigma = 0.78\ S_{ut}$ cold-drawn carbon steel (A227, A228, A229)

$S_y = \sigma = 0.87\ S_{ut}$ hardened and tempered carbon and low-alloy steel (A232, A401)

2.16.2 Bearings

2.16.2.1 Ball/Roller Bearing Selection

The minimum required *basic load rating* (load for which 90% of the bearings from a given population will survive 1 million revolutions) is given by

$C = PL^{\frac{1}{a}}$ This is sometimes called the *bearing life regression equation*.

where

C = minimum required basic load rating

P = design radial load

L = design life (in millions of revolutions)

a = 3 for ball bearings; $\frac{10}{3}$ for roller bearings

When a ball bearing is subjected to both radial and axial loads, an equivalent radial load must be used in the basic load rating equation. The equivalent radial load is

$$P_{eq} = XVF_r + YF_a$$

where

P_{eq} = equivalent radial load

F_r = applied constant radial load

F_a = applied constant axial (thrust) load

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For radial contact, deep-groove ball bearings:

V = 1 if inner ring rotating, 1.2 if outer ring rotating

If $\frac{F_a}{VF_r} > e$, then $X = 0.56$ and $Y = 0.840\left(\frac{F_a}{C_0}\right)^{-0.247}$

where

$e = 0.513\left(\frac{F_a}{C_0}\right)^{0.236}$

C_0 = basic static load rating from bearing catalog

If $\frac{F_a}{VF_r} \leq e$, then $X = 1$ and $Y = 0$.

$F_R = F_D\left(\frac{L_D}{L_R}\right)^{\frac{1}{a}}$ cycles based

$F_R = F_D\left(\frac{\mathcal{L}_D N_D}{\mathcal{L}_R N_R}\right)^{\frac{1}{a}}$ hours based

where

F_R = catalog radial rating (lb or kN)

F_D = required radial design load (lb or kN)

L_D = design life (cycles)

L_R = rating life (cycles)

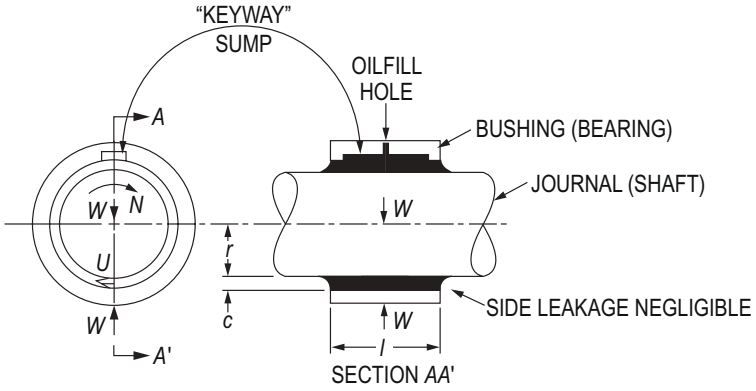
$\mathcal{L}_D$ = design life (hr)

$\mathcal{L}_R$ = rating life (hr)

N_D = required design speed (rev per min)

N_R = catalog rated speed (rev per min)

Journal Bearing Design



Petroff's lightly loaded journal bearing, consisting of a shaft journal and a bushing with an axial-groove internal lubricant reservoir. The linear velocity gradient is shown in the end view. The clearance c is several thousandths of an inch and is grossly exaggerated for presentation purposes.

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Torque: $T = (\tau A)(r) = \left(\frac{2\pi r \mu N}{c}\right)(2\pi r l)(r) = \frac{4\pi^2 r^3 l \mu N}{c}$ (Petroff's Law)

Frictional torque: $T = f\,Wr = (f)(2rlP)(r) = 2r^2 f\,lP$

Coefficient of friction: $f = 2\pi^2 \frac{\mu N}{P}\frac{r}{c}$

Bearing pressure: $P = \frac{W}{2rl}$

where

r = journal radius (inches)

c = radial clearance (inches)

μ = dynamic or absolute viscosity $\left(\text{reyn or } \frac{\text{lb-sec}}{\text{in}^2}\right)$

N = significant speed (rps)

P = load per unit of projected bearing area (psi)

τ = shear stress in fluid (psi)

A = area (in^2)

l = bearing length (inches)

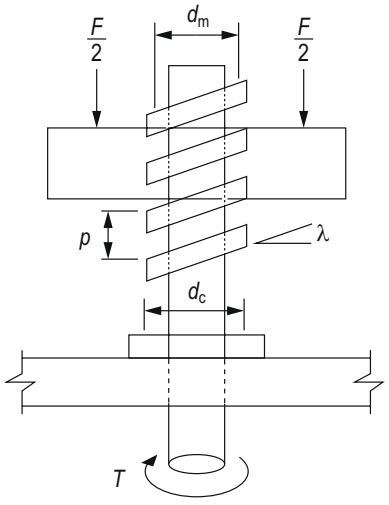
2.16.3 Power Screws

In *square-thread power screws*: The torque required to raise, T_R, or to lower, T_L, a load is

$$T_R = \frac{Fd_m}{2}\left(\frac{L + \pi\mu d_m}{\pi d_m - \mu L}\right) + \frac{F\mu_c d_c}{2}$$

$$T_L = \frac{Fd_m}{2}\left(\frac{\pi\mu d_m - L}{\pi d_m + \mu L}\right) + \frac{F\mu_c d_c}{2}$$

Power Screw With Thrust Collar



where

d_c = mean collar diameter

d_m = mean thread diameter = $\frac{\text{major thread diameter + minor thread diameter}}{2}$

L = lead = Np

where

N = number of starts

p = pitch

λ = lead angle = $\tan^{-1}\left(\frac{\text{lead}}{\pi d_m}\right)$

F = load

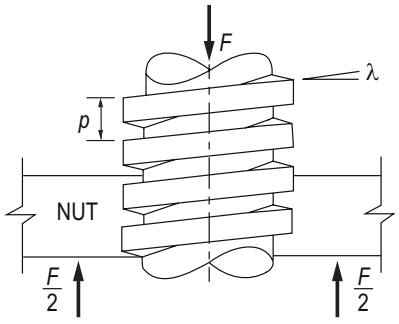
μ = coefficient of friction for thread

μ_c = coefficient of friction for collar

Source: Shigley, Joseph E., and Larry D. Mitchell, *Mechanical Engineering Design*, 4th ed., New York: McGraw-Hill, 1983.

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Power Screw Without Thrust Collar



The efficiency of a power screw may be expressed as

$$\eta = \frac{FL}{2\pi T_R}$$

The condition for self-locking (ignoring collar friction) is

$$\pi\mu d_m > L$$

$$\mu > \tan\lambda$$

Source: Shigley, Joseph E., and Larry D. Mitchell, *Mechanical Engineering Design*, 4th ed., New York: McGraw-Hill, 1983.

2.16.4 Power Transmission

2.16.4.1 Shafts and Axles (for Solid Shafts)

Static Loading: The maximum shear stress and the *von Mises stress* may be calculated in terms of the loads from

$$\tau_{max} = \frac{2}{\pi d^3}\left[(8M + Fd)^2 + (8T)^2\right]^{\frac{1}{2}}$$

$$\sigma' = \frac{4}{\pi d^3}\left[(8M + Fd)^2 + 48T^2\right]^{\frac{1}{2}}$$

where

M = bending moment
F = axial load
T = torque
d = diameter

Fatigue Loading: Using the maximum shear stress theory combined with the Soderberg line for fatigue, the diameter and safety factor are related by

$$\frac{\pi d^3}{32} = n\left[\left(\frac{M_m}{S_y} + \frac{K_f M_a}{S_e}\right)^2 + \left(\frac{T_m}{S_y} + \frac{K_{fs} T_a}{S_e}\right)^2\right]^{\frac{1}{2}}$$

where

d = diameter
n = safety factor
M_a = alternating moment
M_m = mean moment
T_a = alternating torque

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T_m = mean torque

S_e = fatigue limit

S_y = yield strength

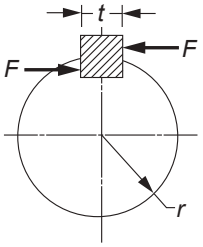
K_f = fatigue strength reduction factor

K_{fs} = fatigue strength reduction factor for shear

Keyways

$$\frac{S_{sy}}{n} = \frac{F}{tl}$$

$$\frac{S_y}{n} = \frac{F}{tl/2}$$



where

S_{sy} = shear strength

S_y = yield strength

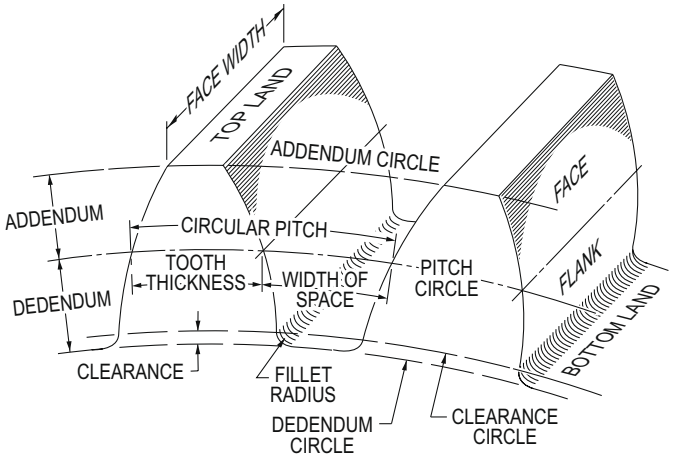
l = key length

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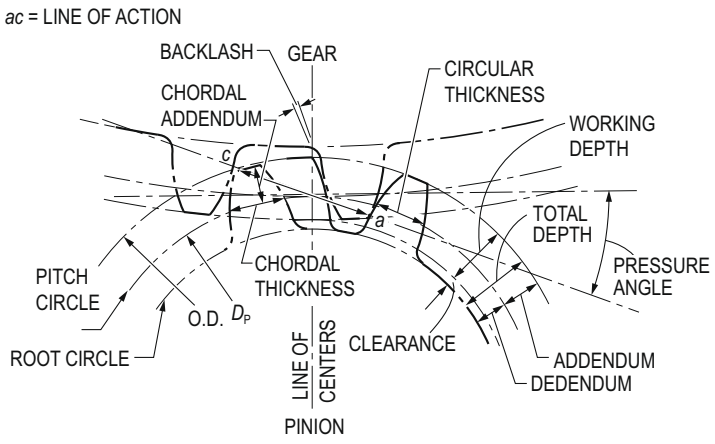
2.16.5 Gears

2.16.5.1 Involute Gear

Gear Teeth Nomenclature



Gear Mesh Nomenclature



Source: Shigley, Joseph E., and Larry D. Mitchell, *Mechanical Engineering Design*, 4th ed., New York: McGraw-Hill, 1983.

Standard and Commonly Used Tooth Systems for Spur Gears

Tooth System	Pressure Angle ϕ	Addendum *a*	Dedendum *b*
Full depth	20°	$1/P_d$ or $1m$	$1.25/P_d$ or $1.25m$
			$1.35/P_d$ or $1.35m$
	22 1/2°	$1/P_d$ or $1m$	$1.25/P_d$ or $1.25m$
			$1.35/P_d$ or $1.35m$
	25°	$1/P_d$ or $1m$	$1.25/P_d$ or $1.25m$
			$1.35/P_d$ or $1.35m$
Stub	20°	$0.8/P_d$ or $0.8m$	$1/P_d$ or $1m$

Source: Shigley, Joseph E., and Charles R. Mischke, *Standard Handbook of Machine Design*, New York: McGraw-Hill, 1986.

2.16.5.2 Involute Gear Tooth Nomenclature

Circular pitch $p_c = \frac{\pi d}{N} = \pi m$

Diametral pitch $p_d = \frac{N}{d}$

Center distance between mating gears $C = \frac{d_1 + d_2}{2}$

Base pitch $p_b = p_c \cos \phi$

Module $m = \frac{d}{N}$

where

N = number of teeth on pinion or gear

d = pitch circle diameter

ϕ = pressure angle

Contact ratio = average number of teeth in contact between meshing gears

2.16.5.3 Spur Gears

$$V = \frac{\pi d n}{12}$$

where

V = pitch-line velocity (ft per min)

d = gear diameter (in.)

n = gear speed (rev per min)

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Transmitted load in customary units:

$$W_t = \frac{33{,}000\,H}{V}$$

where

W_t = transmitted load (lbf)

H = power (hp)

V = pitch-line velocity (ft per min)

The corresponding equation in SI is

$$W_t = \frac{60{,}000\,H}{\pi d n}$$

where

W_t = transmitted load (kN)

H = power (kW)

d = gear diameter (mm)

n = speed (rev per min)

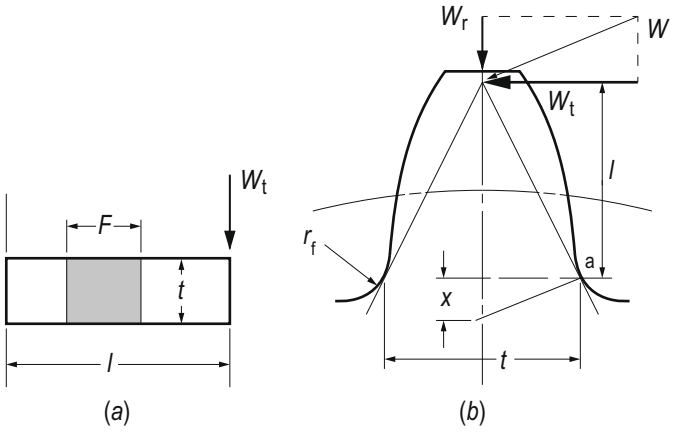
Maximum bending stress in a gear tooth:

$$\sigma = \frac{W_t P_d}{FY}$$

Lewis form factor:

$$Y = \frac{2xP_d}{3}$$

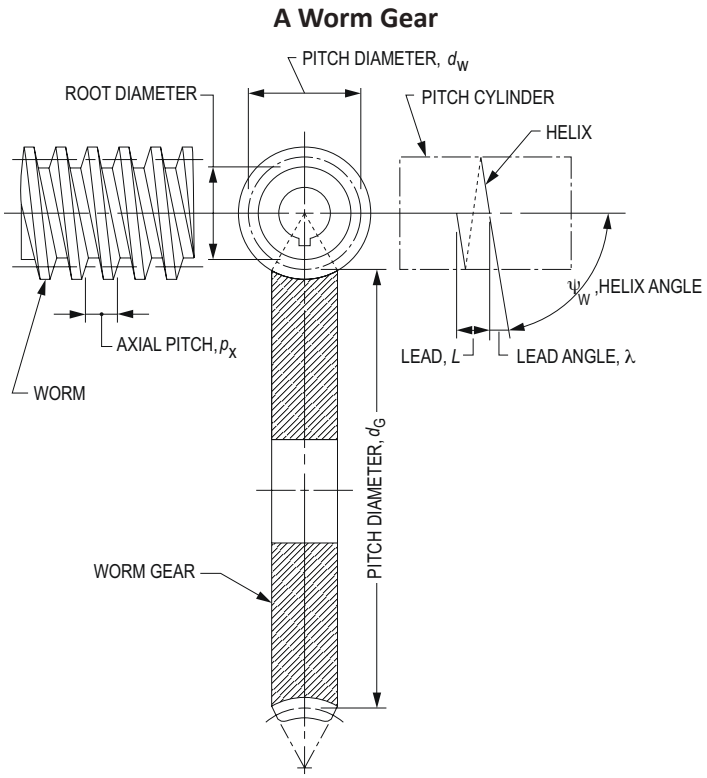
Spur Gears



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2.16.5.4 Worm Gears



$$VR = \frac{N_G}{N_W} = \frac{d_G}{d_W \tan\lambda} \quad \text{and} \quad d_G = \frac{N_G\, p_t}{\pi}$$

where

VR = velocity ratio

d_G = diameter gear

d_W = diameter worm

N_G = number of gear teeth

N_W = number of worm teeth

λ = lead angle of worm

p_t = transverse circular pitch

p_x = axial pitch

L = lead

ϕ_n = pressure angle

μ = coefficient of friction

η = efficiency when the worm drives the gear set

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The *lead L* and the *lead angle* λ of the worm have the following relations:

$$L = p_x N_W$$

$$\tan\lambda = \frac{L}{\pi d_w}$$

$$\eta = \frac{\cos\phi_n - \mu\tan\lambda}{\cos\phi_n + \mu\cot\lambda}$$

Source: Shigley, Joseph E., and Larry D. Mitchell, *Mechanical Engineering Design*, 4th ed., New York: McGraw-Hill, 1983.

2.16.5.5 Bevel Gears

$$W_t = \frac{T}{r_{av}}$$

where

T = torque

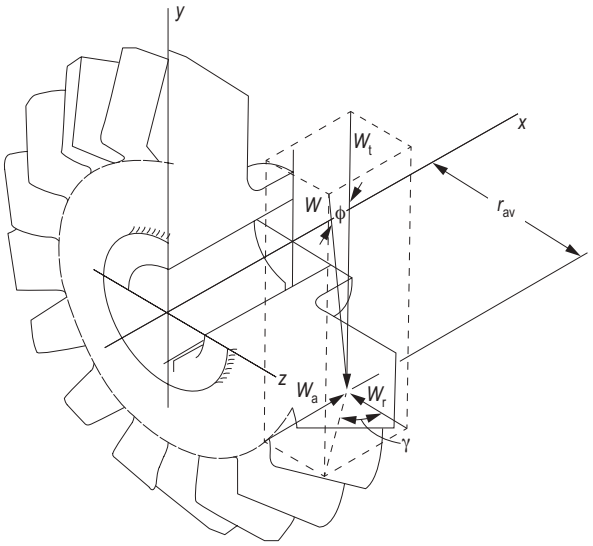
r_{av} = pitch radius at midpoint of the tooth for the gear under consideration

The forces acting at the center of the tooth are shown in the figure below. The resultant force W has three components: a tangential force W_t, a radial force W_r, and an axial force W_a. From the trigonometry of the figure:

$$W_r = W_t \tan\phi \cos\gamma$$

$$W_a = W_t \tan\phi \sin\gamma$$

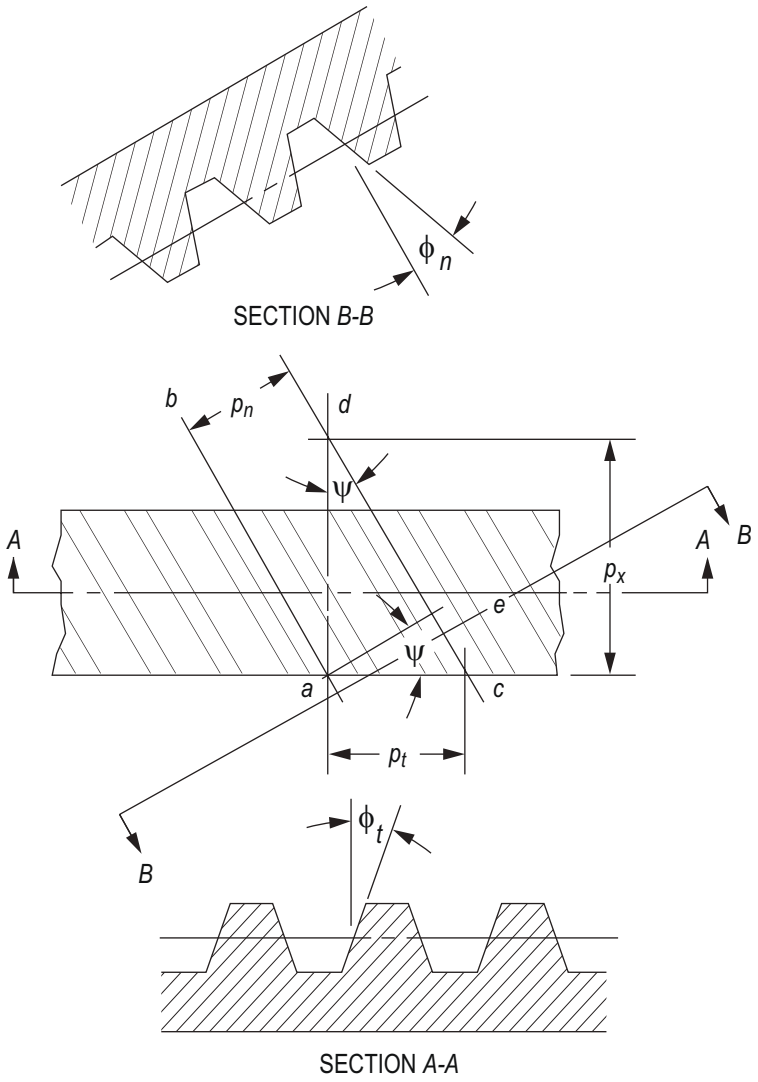
Forces Acting in Bevel Gears



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2.16.5.6 Helical Gears



Nomenclature of helical gears

Lines *ab* and *cd* are the centerlines of two adjacent helical teeth taken on the pitch plane. The angle ψ is the *helix angle*. The distance *ac* is the *transverse circular pitch* p_t in the plane of rotation (usually called the *circular pitch*). The distance *ae* is the *normal circular pitch* p_n and is related to the transverse circular pitch as follows:

$$p_n = p_t \cos\psi$$

The distance *ad* is called the *axial pitch* p_x and is related by the expression

$$p_x = \frac{p_t}{\tan\psi}$$

Since $p_n P_n = \pi$, the *normal diametral pitch* is

$$P_n = \frac{P_t}{\cos\psi}$$

The pressure angle ϕ_n in the normal direction is different from the pressure angle ϕ_t in the direction of rotation, because of the angularity of the teeth. These angles are related by the equation

$$\cos\psi = \frac{\tan\phi_n}{\tan\phi_t}$$

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Helical Gears—Force Analysis

The following figure is a three-dimensional view of the forces acting against a helical-gear tooth. The point of application of the forces is in the pitch plane and in the center of the gear face. From the geometry of the figure, the three components of the total (normal) tooth force W are

$$W_r = W \sin \phi_n$$

$$W_t = W \cos \phi_n \cos \psi$$

$$W_a = W \cos \phi_n \sin \psi$$

where

W = total force

W_r = radial component

W_t = tangential component; also called transmitted load

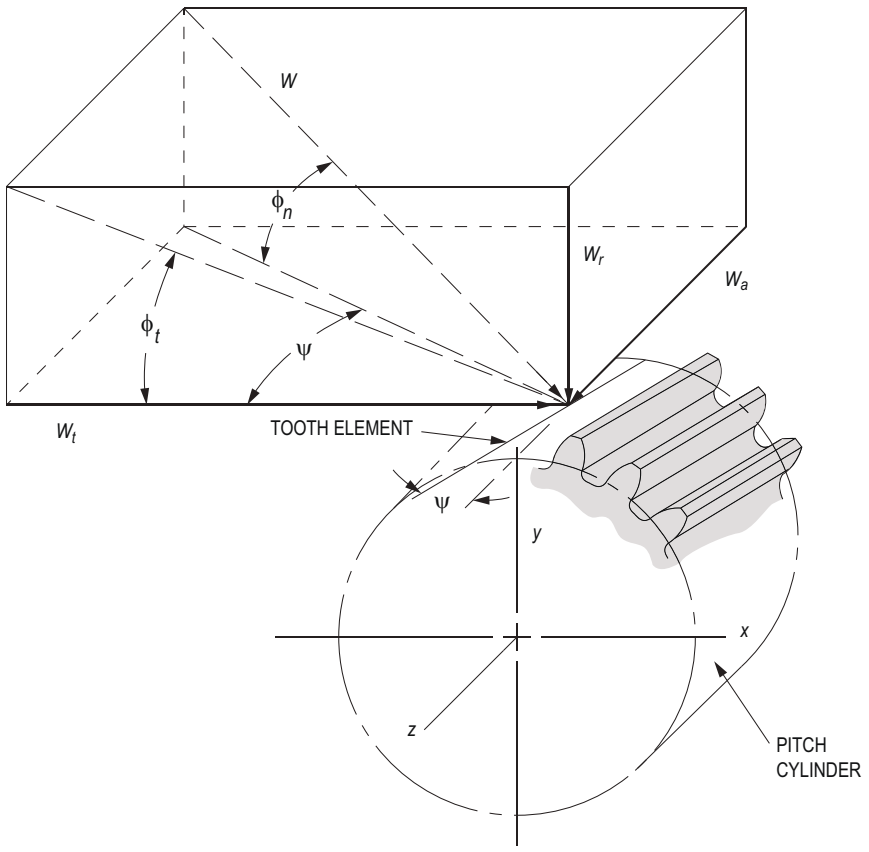
W_a = axial component; also called thrust load

Usually W_t is given and the other forces are desired. In this case, it is not difficult to discover that

$$W_r = W_t \tan \phi_t$$

$$W_a = W_t \tan \psi$$

$$W = \frac{W_t}{\cos \phi_n \cos \psi}$$

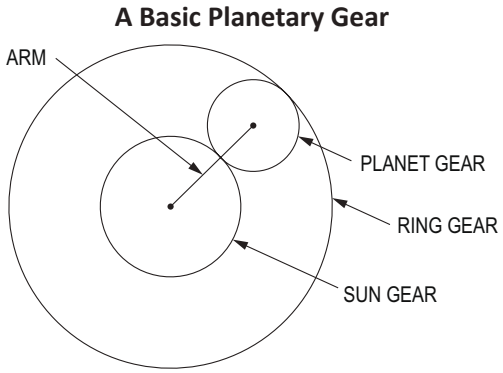


Tooth forces acting on a right-hand helical gear

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2.16.5.7 Planetary Gear Terms and Ratios



In the following diagrams:

D = Rotation of *driver* per revolution of *follower* or driven member.

F = Rotation of *follower* or driven member per revolution of *driver*. (In Figures 1 through 4, *F* = rotation of planet type follower about its axis.)

A = Size of driving gear (use either pitch diameter or number of teeth). When *follower* derives its motion both from A and from a *secondary driving member*, *A* = size of *initial* driving gear, and formula gives speed relationship between *A* and *follower*.

B = Size of *driven gear* or *follower* (use either pitch diameter or number of teeth).

C = Size of *fixed gear* (use either pitch diameter or number of teeth).

x = Size of *planet gear* as shown by diagram below (use either pitch diameter or number of teeth).

y = Size of *planet gear* as shown by diagram below (use either pitch diameter or number of teeth).

z = Size of secondary or *auxiliary driving gear*, when *follower* derives its motion from two driving members.

S = Rotation of *secondary driver*, per revolution of *initial driver*. *S* is negative when secondary and *initial* drivers rotate in opposite directions. (Formulas in which *S* is used give the speed relationship between *follower* and initial driver.)

Note: In all cases, if *D* is known, $F = 1 \div D$ or, if *F* is known, $D = 1 \div F$.

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Types of Planetary Gears

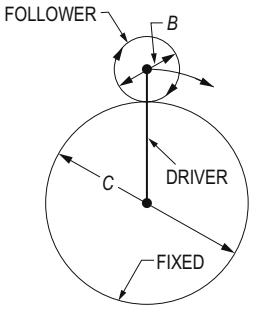


FIG. 1

$$F = 1 + \frac{C}{B}$$

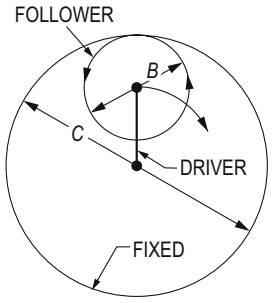


FIG. 2

$$F = 1 - \frac{C}{B}$$

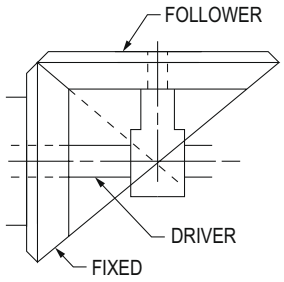


FIG. 3

$$F = \frac{C}{B}$$

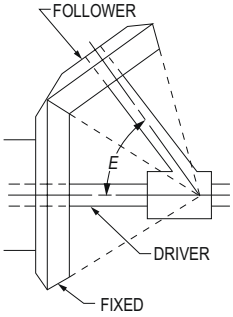


FIG. 4

$$F = \cos E + \frac{C}{B}$$

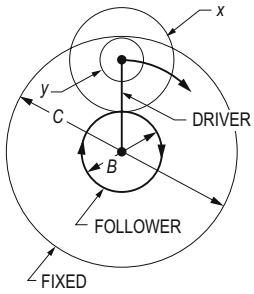


FIG. 5

$$F = 1 + \frac{x \times C}{y \times B}$$

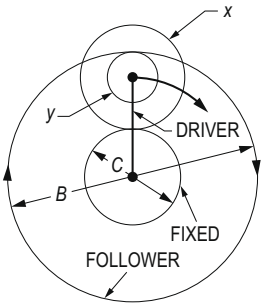


FIG. 6

$$F = 1 + \frac{y \times C}{x \times B}$$

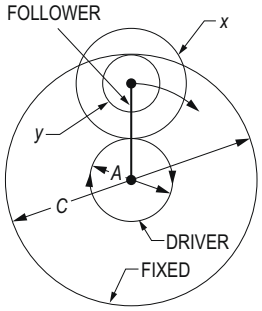


FIG. 7

$$D = 1 + \frac{x \times C}{y \times A}$$

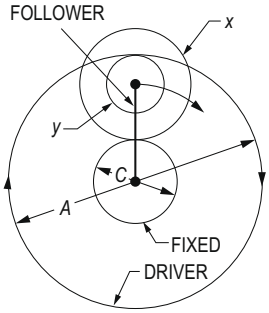


FIG. 8

$$D = 1 + \frac{y \times C}{x \times A}$$

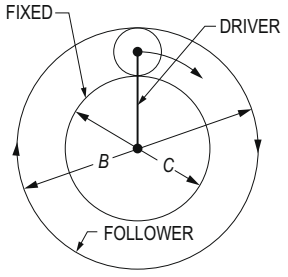


FIG. 9

$$F = 1 + \frac{C}{B}$$

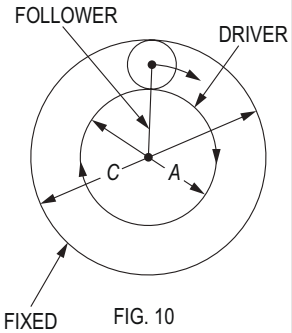


FIG. 10

$$D = 1 + \frac{C}{A}$$

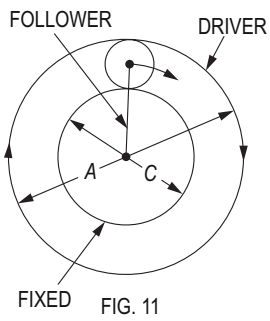


FIG. 11

$$D = 1 + \frac{C}{A}$$

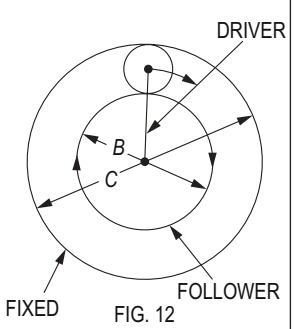


FIG. 12

$$F = 1 + \frac{C}{B}$$

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2.16.6 Belts, Pulleys, and Chain Drives

2.16.6.1 Belt Friction

$$F_1 = F_2 e^{\mu\theta}$$

where

F_1 = force being applied in the direction of impending motion

F_2 = force applied to resist impending motion

μ = coefficient of static friction

θ = the total angle of contact between the surfaces expressed in radians

2.16.6.2 Shaft-Horsepower Relationship and Force-Horsepower Relationship

$$HP = \frac{T \times n}{63,025}$$

where

HP = horsepower

T = torque (in.-lb)

n = shaft speed (rpm)

$$HP = \frac{F \times V}{33,000}$$

where

F = force (lb)

V = velocity (ft per min)

Force-Power Relationship for SI Units:

$$P = FV$$

where

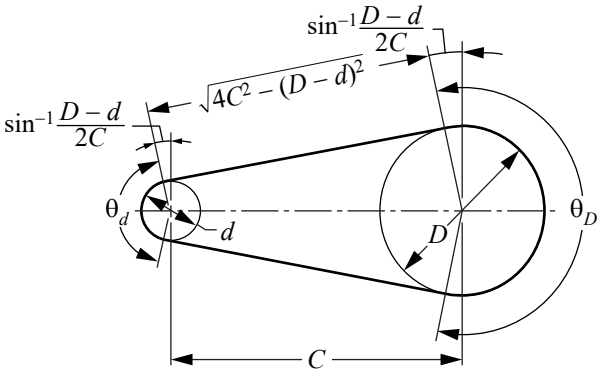
P = power (watts)

F = force (newtons)

V = velocity (m/s)

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Open and Crossed Belts

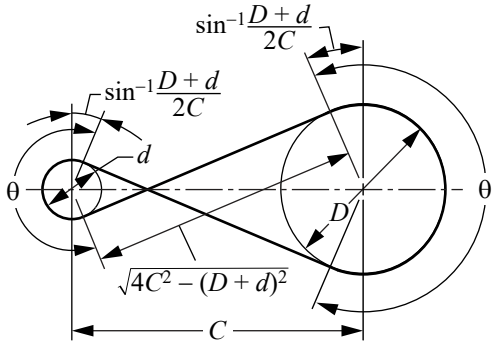


$$\theta_d = \pi - 2\sin^{-1}\frac{D-d}{2C}$$

$$\theta_D = \pi + 2\sin^{-1}\frac{D-d}{2C}$$

$$L = \sqrt{4C^2-(D-d)^2} + \frac{1}{2}(D\theta_D + d\theta_d)$$

OPEN BELT



$$\theta = \pi + 2\sin^{-1}\frac{D+d}{2C}$$

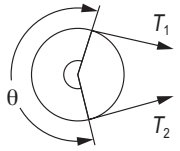
$$L = \sqrt{4C^2-(D+d)^2} + \frac{1}{2}(D+d)\theta$$

CROSSED BELT

Source: Used with permission of McGraw Hill LLC, from *Shigley's Mechanical Engineering Design*, Richard G. Budynas and J. Keith Nisbett, 8th ed., 2008; permission conveyed through Copyright Clearance Center, Inc.

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Tensions in Belts and Bands



$$\frac{T_1}{T_2} = e^{\mu\theta}$$

where

T_1 = tension in the tight side

T_2 = tension in the slack side

θ = angle of wrap, expressed in radians

μ = coefficient of static friction between band/belt and surface of contact

2.16.6.3 Centrifugal Force (Belt)

$$F_c = mv^2$$

where

m = mass of belt per unit length

v = length per second

$$\frac{F_1 - F_c}{F_2 - F_c} = e^{\mu\theta}$$

where

F_1 = tight side

F_2 = slack side

F_c = centrifugal force

2.16.6.4 Horsepower Ratings for Roller Chain-1986

To properly use the following tables, you must consider these factors:

1. *Service Factors*:

Roller Chain Drive Service Factors

Type of Driven Load	Type of Input Power		
	Internal Combustion Engine with Hydraulic Drive	Electric motor or Turbine	Internal Combustion Engine with Mechanical Drive
Smooth	1.0	1.0	1.2
Moderate Shock	1.2	1.3	1.4
Heavy Shock	1.4	1.5	1.7

Source: Oberg, Erik, Franklin D. Jones, Holbrook L. Horton, and Henry H. Ryffel, eds., *Machinery's Handbook*, 28th ed., South Norwalk, CT: Industrial Press, 2008.

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2. *Multiple Strand Factors*: For two strands, the multiple strand factor is 1.7; for three strands, it is 2.5; and for four strands, it is 3.3.
3. *Lubrication*: The required type of lubrication is indicated at the bottom of each roller-chain size section of the following five tables.

   Type A–Manual or drip lubrication
   Type B–Bath or disc lubrication
   Type C–Oil stream lubrication

To find the required horsepower rating, use:

$$\text{required } hp \text{ rating} = \frac{hp \text{ to be transmitted} \times \text{service factor}}{\text{multiple strand factor}}$$

Horsepower Ratings for 1/4-Inch Roller Chain

	No. of Teeth Small Spkt.	Revolutions per Minute—Small Sprocket												
		50	100	300	500	700	900	1,200	1,500	1,800	2,100	2,500	3,000	3,500
		Horsepower Rating												
1/4 inch Pitch Standard Single-Strand Roller Chain—No. 25	11	0.03	0.05	0.14	0.23	0.31	0.39	0.50	0.62	0.73	0.83	0.98	1.15	1.32
	12	0.03	0.06	0.16	0.25	0.34	0.43	0.55	0.68	0.80	0.92	1.07	1.26	1.45
	13	0.04	0.06	0.17	0.27	0.37	0.47	0.60	0.74	0.87	1.00	1.17	1.38	1.58
	14	0.04	0.07	0.19	0.30	0.40	0.50	0.65	0.80	0.94	1.08	1.27	1.49	1.71
	15	0.04	0.08	0.20	0.32	0.43	0.54	0.70	0.86	1.01	1.17	1.36	1.61	1.85
	16	0.04	0.08	0.22	0.34	0.47	0.58	0.76	0.92	1.09	1.25	1.46	1.72	1.98
	17	0.05	0.09	0.23	0.37	0.50	0.62	0.81	0.99	1.16	1.33	1.56	1.84	2.11
	18	0.05	0.09	0.25	0.39	0.53	0.66	0.86	1.05	1.24	1.42	1.66	1.96	2.25
	19	0.05	0.10	0.26	0.41	0.56	0.70	0.91	1.11	1.31	1.50	1.76	2.07	2.38
	20	0.06	0.10	0.28	0.44	0.59	0.74	0.96	1.17	1.38	1.59	1.86	2.19	2.52
	21	0.06	0.11	0.29	0.46	0.62	0.78	1.01	1.24	1.46	1.68	1.96	2.31	2.66
	22	0.06	0.11	0.31	0.48	0.66	0.82	1.07	1.30	1.53	1.76	2.06	2.43	2.79
	23	0.06	0.12	0.32	0.51	0.69	0.86	1.12	1.37	1.61	1.85	2.16	2.55	2.93
	24	0.07	0.13	0.34	0.53	0.72	0.90	1.17	1.43	1.69	1.94	2.27	2.67	3.07
	25	0.07	0.13	0.35	0.56	0.75	0.94	1.22	1.50	1.76	2.02	2.37	2.79	3.21
	26	0.07	0.14	0.37	0.58	0.79	0.98	1.28	1.56	1.84	2.11	2.47	2.91	3.34
	28	0.08	0.15	0.40	0.63	0.85	1.07	1.38	1.69	1.99	2.29	2.68	3.15	3.62
	30	0.08	0.16	0.43	0.68	0.92	1.15	1.49	1.82	2.15	2.46	2.88	3.40	3.90
	32	0.09	0.17	0.46	0.73	0.98	1.23	1.60	1.95	2.30	2.64	3.09	3.64	4.18
	35	0.10	0.19	0.51	0.80	1.08	1.36	1.76	2.15	2.53	2.91	3.41	4.01	4.61
	40	0.12	0.22	0.58	0.92	1.25	1.57	2.03	2.48	2.93	3.36	3.93	4.64	5.32
	45	0.13	0.25	0.66	1.05	1.42	1.78	2.31	2.82	3.32	3.82	4.47	5.26	6.05
		Type A				Type B								

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Horsepower Ratings for 3/4-Inch Roller Chain

	No. of Teeth Small Spkt.	Revolutions per Minute—Small Sprocket												
		25	50	100	150	200	300	400	500	600	700	800	900	1,000
		Horsepower Rating												
3/4 inch Pitch Standard Single-Strand Roller Chain - No. 60	11	0.41	0.77	1.44	2.07	2.69	3.87	5.02	6.13	7.23	8.3	9.36	10.4	11.4
	12	0.45	0.85	1.58	2.28	2.95	4.25	5.51	6.74	7.94	9.12	10.3	11.4	12.6
	13	0.50	0.92	1.73	2.49	3.22	4.64	6.01	7.34	8.65	9.94	11.2	12.5	13.7
	14	0.54	1.00	1.87	2.69	3.49	5.02	6.51	7.96	9.37	10.8	12.1	13.5	14.8
	15	0.58	1.08	2.01	2.90	3.76	5.41	7.01	8.57	10.1	11.6	13.1	14.5	16.0
	16	0.62	1.16	2.16	3.11	4.03	5.80	7.52	9.19	10.8	12.4	14.0	15.6	17.1
	17	0.66	1.24	2.31	3.32	4.30	6.20	8.03	9.81	11.6	13.3	15.0	16.7	18.3
	18	0.70	1.31	2.45	3.53	4.58	6.59	8.54	10.4	12.3	14.1	15.9	17.7	19.5
	19	0.75	1.39	2.60	3.74	4.85	6.99	9.05	11.1	13.0	15.0	16.9	18.8	20.6
	20	0.79	1.47	2.75	3.96	5.13	7.38	9.57	11.7	13.8	15.8	17.9	19.8	21.8
	21	0.83	1.55	2.90	4.17	5.40	7.78	10.1	12.3	14.5	16.7	18.8	20.9	23.0
	22	0.87	1.63	3.05	4.39	5.68	8.19	10.6	13.0	15.3	17.5	19.8	22.0	24.2
	23	0.92	1.71	3.19	4.60	5.96	8.59	11.1	13.6	16.0	18.4	20.8	23.1	25.4
	24	0.96	1.79	3.35	4.82	6.24	8.99	11.6	14.2	16.8	19.3	21.7	24.2	26.6
	25	1.00	1.87	3.50	5.04	6.52	9.40	12.2	14.9	17.5	20.1	22.7	25.3	27.8
	26	1.05	1.95	3.65	5.25	6.81	9.80	12.7	15.5	18.3	21.0	23.7	26.4	29.0
	28	1.13	2.12	3.95	5.69	7.37	10.6	13.8	16.8	19.8	22.8	25.7	28.5	31.4
	30	1.22	2.28	4.56	6.13	7.94	11.4	14.8	18.1	21.4	24.5	27.7	30.8	33.8
	32	1.31	2.45	4.56	6.57	8.52	12.3	15.9	19.4	22.9	26.3	29.7	33.0	36.3
	35	1.44	2.69	5.03	7.24	9.38	13.5	17.5	21.4	25.2	29.0	32.7	36.3	39.9
	40	1.67	3.11	5.81	8.37	10.8	15.6	20.2	24.7	29.1	33.5	37.7	42.0	46.1
	45	1.89	3.53	6.60	9.50	12.3	17.7	23.0	28.1	33.1	38.0	42.9	47.7	52.4
		Type A		Type B							Type C			

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Horsepower Ratings for 1-Inch Roller Chain

	No. of Teeth Small Spkt.	Revolutions per Minute—Small Sprocket												
		25	50	100	150	200	300	400	500	600	700	800	900	1,000
		Horsepower Rating												
1 - inch Pitch Standard Single-Strand Roller Chain - No. 80	11	0.97	1.8	3.36	4.84	6.28	9.04	11.7	14.3	16.9	19.4	21.9	23	19.6
	12	1.06	1.98	3.69	5.32	6.89	9.93	12.9	15.7	18.5	21.3	24	26.2	22.3
	13	1.16	2.16	4.03	5.8	7.52	10.8	14	17.1	20.2	23.2	26.2	29.1	25.2
	14	1.25	2.34	4.36	6.29	8.14	11.7	15.2	18.6	21.9	25.1	28.4	31.5	28.2
	15	1.35	2.52	4.7	6.77	8.77	12.6	16.4	20	23.6	27.1	30.6	34	31.2
	16	1.45	2.7	5.04	7.26	9.41	13.5	17.6	21.5	25.3	29	32.8	36.4	34.4
	17	1.55	2.88	5.38	7.75	10	14.5	18.7	22.9	27	31	35	38.9	37.7
	18	1.64	3.07	5.72	8.25	10.7	15.4	19.9	24.4	28.7	33	37.2	41.4	41.1
	19	1.74	3.25	6.07	7.74	11.3	16.3	21.1	25.8	30.4	35	39.4	43.8	44.5
	20	1.84	3.44	6.41	9.24	12	17.2	22.3	27.3	32.2	37	41.7	46.3	48.1
	21	1.94	3.62	6.76	9.74	12.6	18.2	23.5	28.8	33.9	39	43.9	48.9	51.7
	22	2.04	3.81	7.11	10.2	13.3	19.1	24.8	30.3	35.7	41	46.2	51.4	55.5
	23	2.14	4	7.46	10.7	13.9	20.1	26	31.8	37.4	43	48.5	53.9	59.3
	24	2.24	4.19	7.81	11.3	14.6	21	27.2	33.2	39.2	45	50.8	56.4	62
	25	2.34	4.37	8.16	11.8	15.2	21.9	28.4	34.7	40.9	47	53	59	64.8
	26	2.45	4.56	8.52	12.3	15.9	22.9	29.7	36.2	42.7	49.1	55.3	61.5	67.6
	28	2.65	4.94	9.23	13.3	17.2	24.8	32.1	39.3	46.3	53.2	59.9	66.7	73.3
	30	2.85	5.33	9.94	14.3	18.5	26.7	34.6	42.3	49.9	57.3	64.6	71.8	78.9
	32	3.06	5.71	10.7	15.3	19.9	28.6	37.1	45.4	53.5	61.4	69.2	77	84.6
	35	3.37	6.29	11.7	16.9	21.9	31.6	40.9	50	58.9	67.6	76.3	84.8	93.3
	40	3.89	7.27	13.6	19.5	25.3	36.4	47.2	57.7	68	78.1	88.1	99	108
	45	4.42	8.25	15.4	22.2	28.7	41.4	53.6	65.6	77.2	88.7	100	111	122
		Type A	Type B						Type C					

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Horsepower Ratings for 1-1/4-Inch Roller Chain

	No. of Teeth Small Spkt.	Revolutions per Minute—Small Sprocket												
		10	25	50	100	150	200	300	400	500	600	700	800	900
		Horsepower Rating												
1 1/4 inch Pitch Standard Single-Strand Roller Chain - No. 100	11	0.81	1.85	3.45	6.44	9.28	12.0	17.3	22.4	27.4	32.3	37.1	32.8	27.5
	12	0.89	2.03	3.79	7.08	10.2	13.2	19.0	24.6	30.1	35.5	40.8	37.3	31.3
	13	0.97	2.22	4.13	7.72	11.1	14.4	20.7	26.9	32.8	38.7	44.5	42.1	35.3
	14	1.05	2.40	4.48	8.36	12.0	15.6	22.5	29.1	35.6	41.9	48.2	47.0	39.4
	15	1.13	2.59	4.83	9.01	13.0	16.8	24.2	31.4	38.3	45.2	51.9	52.2	43.7
	16	1.22	2.77	5.17	9.66	13.9	18.0	26.0	33.6	41.1	48.4	55 .6	57.5	48.2
	17	1.30	2.96	5.52	10.3	14.8	19.2	27.7	35.9	43.9	51.7	59.4	63.0	52.8
	18	1.38	3.15	5.88	11.0	15.8	20.5	29.5	38.2	46.7	55.0	63.2	68.6	57.5
	19	1.46	3.34	6.23	11.6	16.7	21.7	31.2	40.5	49.5	58.3	67.0	74.4	62.3
	20	1.55	3.53	6.58	12.3	17.7	22.9	33.0	42.8	52.3	61.6	70.8	79.8	67.3
	21	1.63	3.72	6.94	13.0	18.7	24.2	34.8	45.1	55.1	65.0	74.6	84.2	72.4
	22	1.71	3.91	7.30	13.6	19.6	25.4	36.6	47.4	58.0	68.3	78.5	88.5	77.7
	23	1.80	4.10	7.66	14.3	20.6	26.7	38.4	49.8	60.8	71.7	82.3	92.8	83.0
	24	1.88	4.30	8.02	15.0	21.5	27 .9	40.2	52.1	63.7	75.0	86.2	97.2	88.5
	25	1.97	4.49	8.38	15.6	22.5	29.2	42.0	54.4	66.6	78.4	90.1	102	94.1
	26	2.05	4.68	8.74	16.3	23.5	30.4	43.8	56.8	69.4	81.8	94.0	106	99.8
	28	2.22	5.07	9.47	17.7	25.5	33.0	47.5	61.5	75.2	88.6	102	115	112
	30	2.40	5.47	10.2	19.0	27.4	35.5	51.2	66.3	81.0	95.5	110	124	124
	32	2.57	5.86	10.9	20.4	29.4	38.1	54.9	71.1	86.9	102	118	133	136
	35	2.83	6.46	12.0	22.5	32.4	42.0	60.4	78.3	95 .7	113	130	146	156
	40	3.27	7.46	13.9	26.0	37.4	48.5	69.8	90.4	111	130	150	169	188
	45	3.71	8.47	15.8	29.5	42.5	55.0	79.3	103	126	148	170	192	213
		Type A		Type B				Type C						

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Horsepower Ratings for 1-1/2-Inch Roller Chain

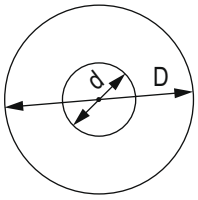
	No. of Teeth Small Spkt.	Revolutions per Minute—Small Sprocket												
		10	25	50	100	150	200	300	400	500	600	700	800	900
		Horsepower Rating												
1 1/2 inch Pitch Standard Single-Strand Roller Chain - No. 120	11	1.37	3.12	5.83	10.9	15 .7	20.3	29.2	37.9	46.3	54.6	46.3	37.9	31.8
	12	1.50	3.43	6.40	11.9	17.2	22.3	32. 1	41.6	50.9	59.9	52.8	42.3	36.2
	13	1.64	3.74	6.98	13.0	18.8	24.3	35.0	45.4	55.5	65.3	59.5	48.7	40.8
	14	1.78	4.05	7.56	14.1	20.3	26.3	37.9	49.1	60. 1	70.8	66.5	54.4	45.6
	15	1.91	4.37	8.15	15.2	21.9	28.4	40.9	53.0	64.7	76.3	73.8	60.4	50.6
	16	2.05	4.68	8.74	16.3	23.5	30.4	43.8	56.8	69.4	81.8	81.3	66.5	55.7
	17	2.19	5.00	9.33	17.4	25.1	32.5	46.8	60.6	74.1	87.3	89.0	72.8	61.0
	18	2.33	5.32	9.92	18.5	26.7	34.6	49.8	64.5	78.8	92.9	97.0	79.4	66.5
	19	2.47	5.64	10.5	19.6	28.3	36.6	52.8	68.4	83.6	98.5	105	86.1	72.1
	20	2.61	5.96	11.1	20.7	29.9	38.7	55.8	72.2	88.3	104	114	92.9	77.9
	21	2.75	6.28	11.7	21.9	31.5	40.8	58.8	76.2	93.1	110	122	100	83.8
	22	2.90	6.60	12.3	23.0	33.1	42.9	61.8	80.1	97.9	115	131	107	89.9
	23	3.04	6.93	12.9	24.1	34.8	45.0	64.9	84.0	103	121	139	115	96.1
	24	3.18	7.25	13.5	25.3	36.4	47.1	67.9	88.0	108	127	146	122	102
	25	3.32	7.58	14.1	26.4	38.0	49.3	71.0	91.9	112	132	152	130	109
	26	3.47	7.91	14.8	27.5	39.7	51.4	74.0	95.9	117	138	159	138	115
	28	3.76	8.57	16.0	29.8	43.0	55.7	80.2	104	127	150	172	154	129
	30	4.05	9.23	17.2	32.1	46.3	60.0	86.4	112	137	161	185	171	143
	32	4.34	9.90	18.5	34.5	49.6	64.3	92.6	120	147	173	199	188	158
	35	4.78	10.9	20.3	38.0	54.7	70.9	102	132	162	190	219	215	180
	40	5.52	12.6	23.5	43.9	63.2	81.8	118	153	187	220	253	...	...
	45	6.27	14.3	26.7	49.8	71.7	92.9	134	173	212	250	287	...	...
		Type A	Type B					Type C						

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2.16.7 Clutches and Brakes

Brake or Clutch Pad



Uniform Wear and Pressure on Clutches and Brakes

	Uniform Wear	Uniform Pressure
Normal Force (*F*)	$F = \frac{\pi p_{max} d}{2}(D - d)$	$F = \frac{\pi p_{max}}{4}(D^2 - d^2)$
Torque (*T*)	$T = \frac{Ff}{4}(D + d)$	$T = \frac{Ff}{3}\frac{(D^3 - d^3)}{(D^2 - d^2)}$

where

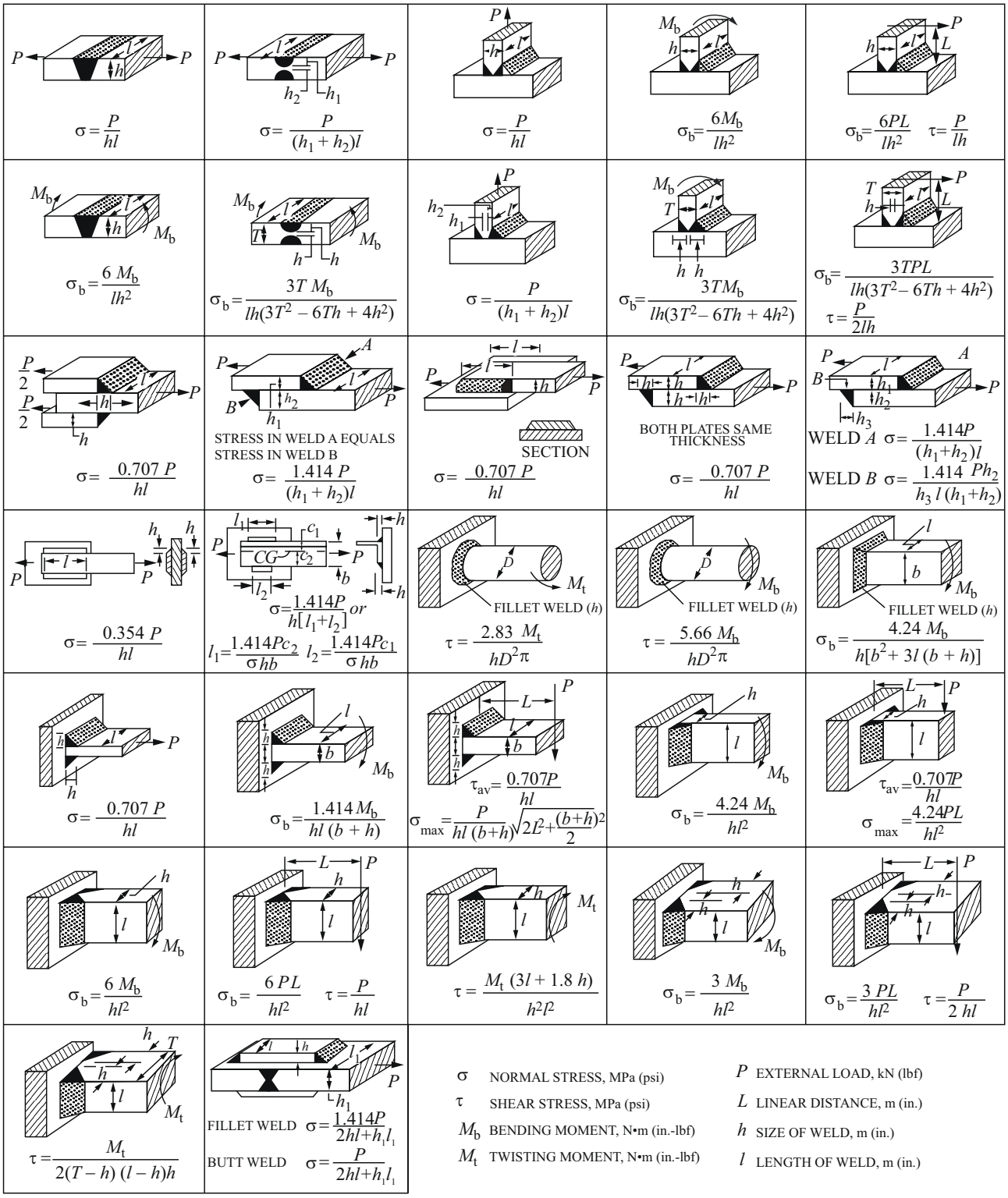
p_{max} = maximum pressure

f = coefficient of friction

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2.17 Welding

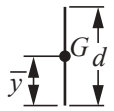
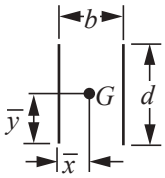
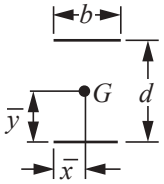
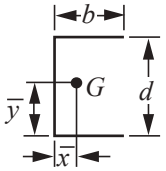
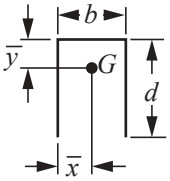
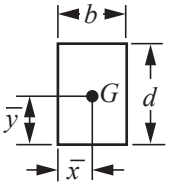
Types of Welds



Source: American Welding Association, *Welding Handbook*, 3rd ed., 1950.

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Bending and Torsional Properties of Fillet Welds

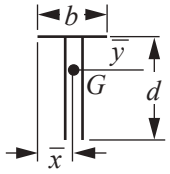
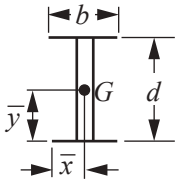
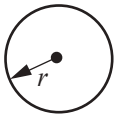
Weld	Throat Area	Location of G	Unit Second Moment of Area
	$A = 0.707\,hd$	$\bar{x} = 0$ $\bar{y} = d/2$	$I_u = \frac{d^3}{12}$ $\quad J_u = \frac{d^3}{12}$
	$A = 1.414\,hd$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \frac{d^3}{6}$ $J_u = \frac{d(3b^2 + d^2)}{6}$
	$A = 1.414\,hb$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \frac{bd^2}{2}$ $J_u = \frac{b(3d^2 + b^2)}{6}$
	$A = 0.707\,h\,(2b + d)$	$\bar{x} = \frac{b^2}{2b + d}$ $\bar{y} = d/2$	$I_u = \frac{d^2}{12}(6b + d)$ $J_u = \frac{1}{12}(2b + d)^3 - \frac{b^2(b + d)^2}{(2b + d)}$
	$A = 0.707\,h\,(b + 2d)$	$\bar{x} = b/2$ $\bar{y} = \frac{d^2}{b + 2d}$	$I_u = \frac{2d^3}{3} - 2d^2\bar{y} + (b + 2d)\,\bar{y}^2$ $J_u = \frac{1}{12}(b + 2d)^3 - \frac{d^2(b + d)^2}{(2d + b)}$
	$A = 1.414\,h\,(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \frac{d^2}{6}(3b + d)$ $J_u = \frac{1}{6}(b + d)^3$

For bending in welds:

$$I = 0.707\,h\,I_u$$

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Bending and Torsional Properties of Fillet Welds (cont'd)

Weld	Throat Area	Location of G	Unit Second Moment of Area
	$A = 0.707\,h\,(b + 2d)$	$\bar{x} = b/2$ $\bar{y} = \dfrac{d^2}{b + 2d}$	$I_u = \dfrac{2d^3}{3} - 2d^2\bar{y} + (b + 2d)\,\bar{y}^2$ $J_u = \dfrac{1}{12}(b + 2d)^3 - \dfrac{d^2(b + d)^2}{(b + 2d)}$
	$A = 1.414\,h\,(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$I_u = \dfrac{d^2}{6}(3b + d)$ $J_u = \dfrac{1}{6}(b^3 + 3bd^2 + d^3)$
	$A = 1.414\,\pi hr$		$I_u = \pi r^3$ $J_u = 2\pi r^3$

* I_u, unit second moment of area, is taken about a horizontal axis through G, the centroid of the weld group; h is weld size; the plane of the bending couple is normal to the plane of the paper and parallel to the y axis; all welds are the same size.

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Minimum Weld-Metal Properties

AWS Electrode Number	Tensile Strength kpsi (MPa)	Yield Strength kpsi (MPa)	Percent Elongation
E60xx	62 (427)	50 (345)	17–25
E70xx	70 (482)	57 (393)	22
E80xx	80 (551)	67 (462)	19
E90xx	90 (620)	77 (531)	14–17
E100xx	100 (689)	87 (600)	13–16
E120xx	120 (827)	107 (737)	14

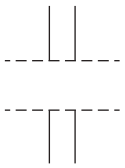
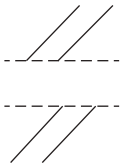
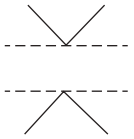
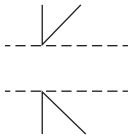
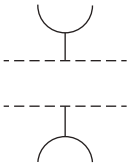
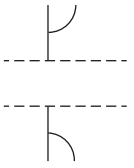
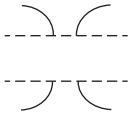
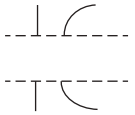
Stresses Permitted by the AISC Code for Weld Material

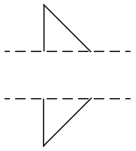
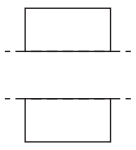
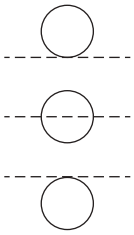
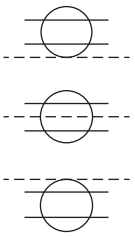
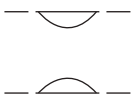
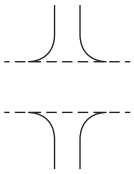
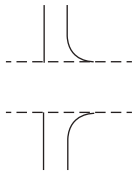
Type of Loading	Type of Weld	Permissible Stress	*n**
Tension	Butt	0.60 S_y	1.67
Bearing	Butt	0.90 S_y	1.11
Bending	Butt	0.60–0.66 S_y	1.52–1.67
Simple Compression	Butt	0.60 S_y	1.67
Shear	Butt or fillet	0.40 S_y	1.44

*The factor of safety n has been computed using the distortion-energy theory.

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Basic Weld Symbols

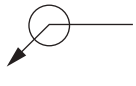
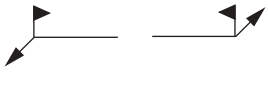
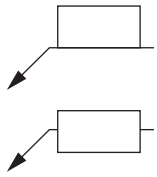
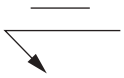
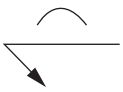
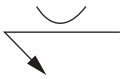
Groove							
Square Butt	Scarf*	V	Bevel	U	J	Flare-V	Flare-Bevel
							

Fillet	Plug or Slot	Spot or Projection	Seam	Back or Backing	Surfacing	Flange	
						Edge	Corner
							

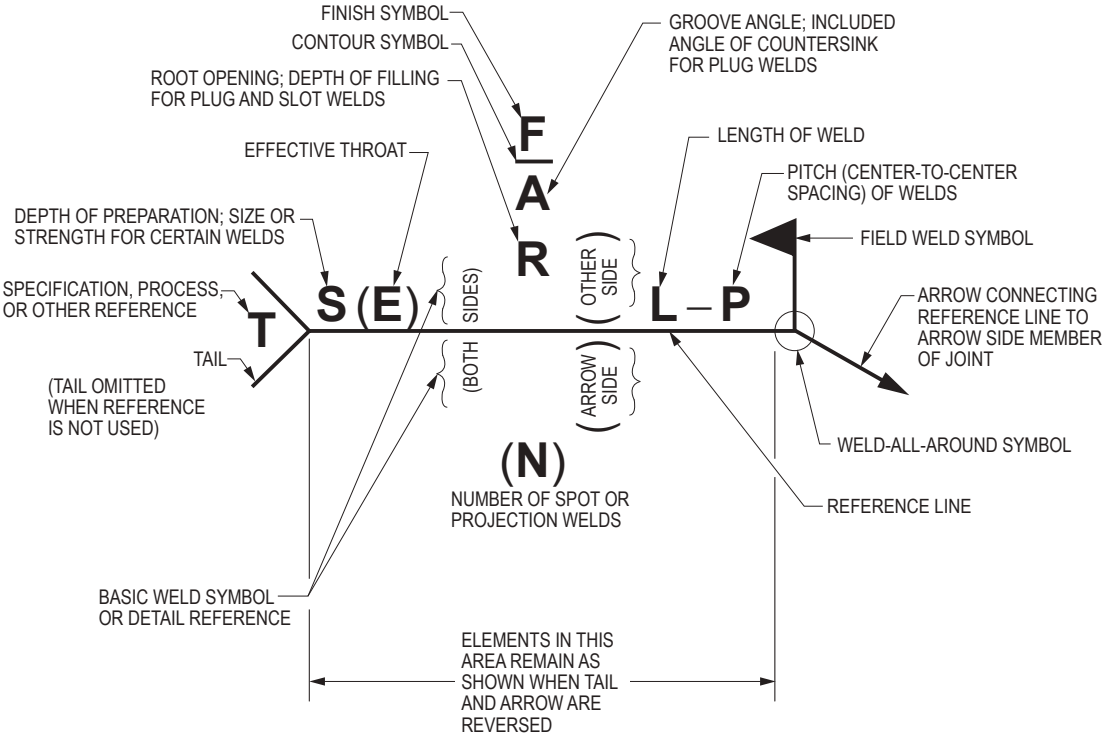
*Used for brazed joints only

Source: AWS A2.4: 2007. Square and Scarf figures reproduced with permission of the American Welding Society.

Supplementary Weld Symbols

Weld all Around	Field Weld	Melt-thru	Backing or Spacer Material	Contour		
				Flush	Convex	Concave
			 Spacer			

Standard Location of Elements of a Welding System



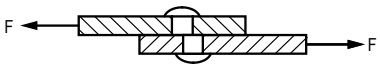
Source: American Welding Society, AWS A2.4: 2007: *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, Miami: American National Standard, 2007.

2.18 Joints and Fasteners

2.18.1 Bolts

2.18.1.1 Bolted and Riveted Joints Loaded in Shear

Failure by Pure Shear



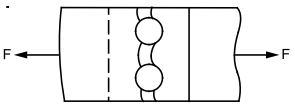
FASTENER IN SHEAR

$$\tau = \frac{F}{A}$$

where F = shear load

A = cross-sectional area of bolt or rivet

Failure by Rupture



MEMBER RUPTURE

$$\sigma = \frac{F}{A}$$

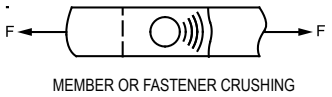
where F = load

A = net cross-sectional area of thinnest member

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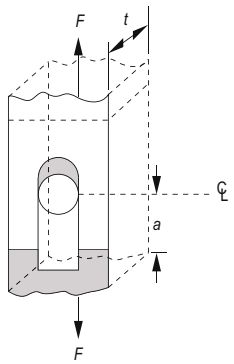
Failure by Crushing of Rivet or Member (Bearing Stress)

$$\sigma = \frac{F}{A}$$



where A = projected area of a single rivet = td, with the material thickness t and the rivet diameter d

Shear Tear-out



$$\sigma = \frac{F}{A}$$

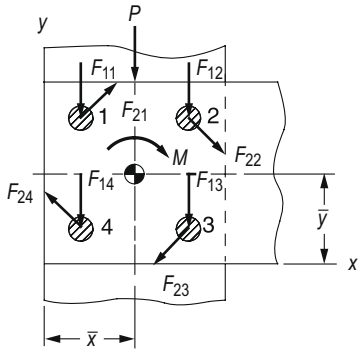
$$A = 2t(a)$$

where t = thickness

a = edge distance

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Fastener Groups in Shear



The location of the centroid of a fastener group with respect to any convenient coordinate frame is

$$\bar{x} = \frac{\sum_{i=1}^{n} A_i x_i}{\sum_{i=1}^{n} A_i}, \quad \bar{y} = \frac{\sum_{i=1}^{n} A_i y_i}{\sum_{i=1}^{n} A_i}$$

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where

n = total number of fasteners

i = index number of a particular fastener

A_i = cross-sectional area of the ith fastener

x_i = x-coordinate of the center of the ith fastener

y_i = y-coordinate of the center of the ith fastener

The magnitude of the direct shear force due to P is

$$|F_{1i}| = \frac{P}{n}$$

This force acts in the same direction as P.

The magnitude of the shear force due to M is

$$|F_{2i}| = \frac{Mr_i}{\sum_{i=1}^{n} r_i^2}$$

where r_i is the distance from the centroid of the fastener group to the center of the i^{th} fastener.

This force acts perpendicular to a line drawn from the group centroid to the center of a particular fastener. Its sense is such that its moment is in the same direction (CW or CCW) as M.

2.18.2 Tension Connections—External Loads

F_i = preload on bolt

P = externally applied tensile load

P_b = portion of P taken by bolt

P_m = portion of P taken by members

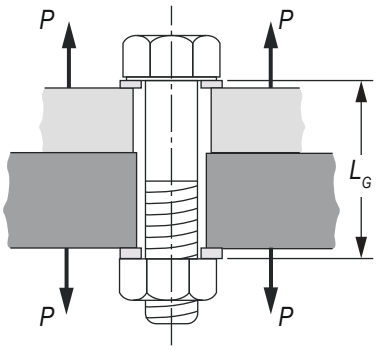
k_b = effective stiffness of bolt in the grip

k_m = effective stiffness of members in the grip

grip = total thickness of the clamped material

$F_b = P_b + F_i$ = resultant bolt load

$F_m = P_m - F_i$ = resultant load on members



$$P_b = PC = P\left(\frac{k_b}{k_b + k_m}\right)$$

Therefore the resultant bolt load is

$$F_b = P_b + F_i = P\left(\frac{k_b}{k_b + k_m}\right) + F_i \qquad F_m < 0$$

and the resultant load on the connected member is

$$F_m = P_m - F_i = P\left(\frac{k_m}{k_b + k_m}\right) - F_i \qquad F_m < 0$$

Stiffness constant of the joint; also called joint coefficient:

$$C = \frac{k_b}{k_b + k_m}$$

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2.18.2.1 Torque Requirements

$T = K F_i d$ = torque (in.-lb)

where

$$F_i = \begin{Bmatrix} 0.75F_p & \text{for reused connections} \\ 0.90F_p & \text{for permanent connections} \end{Bmatrix} \text{ preload on bolt (lb)}$$

K = torque coefficient

d = bolt diameter (inches)

where

F_p is the proof load, obtained from the equation

$$F_p = A_t S_p$$

where

A_t = tensile stress area of threaded portion (in^2)

S_p = proof stress (psi)

Here S_p is the proof strength obtained from "SAE Specifications for Steel Bolts" tables. For other materials, an approximate value is $S_p = 0.85\ S_y$.

Torque Coefficient (Surface Finish) Factor *K*

Bolt Condition	*K*
Nonplated, black finish	0.30
Zinc-plated (as supplied)	0.20
Lubricated	0.18
Cadmium-plated	0.16
With Bowman Anti-Seize	0.12
With Bowman-Grip nuts	0.09

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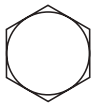
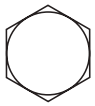
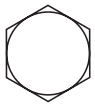
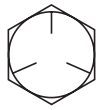
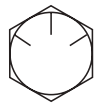
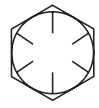
ASTM Specifications for Steel Bolts

ASTM Designation No.	Size Range Inclusive, in.	Minimum Proof Strength, kpsi	Minimum Tensile Strength, kpsi	Minimum Yield Strength, kpsi	Material	Head Marking
A307	1/4 – 1 1/2	33	60	36	Low carbon	
A325, type 1	1/2 – 1 1 1/8 – 1 1/2	85 74	120 105	92 81	Medium carbon, Q&T	
A325, type 2	1/2 – 1 1 1/8 – 1 1/2	85 74	120 105	92 81	Low-carbon martensite, Q&T	
A325, type 3	1/2 – 1 1 1/8 – 1 1/2	85 74	120 105	92 81	Weathering steel, Q&T	
A354, grade BC					Alloy-steel, Q&T	
A325, grade BD	1/4 – 4	120	150	130	Alloy steel, Q&T	
A449	1/4 – 1 1 1/8 – 1 1/2 1 3/4 – 3	85 74 55	120 105 90	92 81 58	Medium-carbon, Q&T	
A490, type 1	1/2 – 1 1/2	120	150	130	Alloy steel, Q&T	
A490, type 3					Weathering steel, O&T	

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SAE Specifications for Steel Bolts

SAE Grade No.	Size Range Inclusive, in.	Minimum Proof Strength, kpsi	Minimum Tensile Strength, kpsi	Minimum Yield Strength, kpsi	Material	Head Marking
1	1/4 – 1 1/2	33	60	36	Low or medium carbon	
2	1/4 – 3/4 7/8 – 1 1/2	55 33	74 60	57 36	Low or medium carbon	
4	1/4 – 1 1/2	65	115	100	Medium carbon, cold-drawn	
5	1/4 – 1 1 1/8 – 1 1/2	85 74	120 105	92 81	Medium carbon, Q&T	
5.2	1/4 – 1	85	120	92	Low-carbon martensite, Q&T	
7	1/4 – 1 1/2	105	133	115	Medium-carbon alloy, Q&T	
8	1/4 – 1 1/2	120	150	130	Medium-carbon alloy, Q&T	
8.2	1/4 – 1	120	150	130	Low-carbon martensite, Q&T	

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Metric Mechanical-Property Classes for Steel Bolts, Screws, and Studs

Property Class	Size Range Inclusive	Minimum Proof Strength, MPa	Minimum Tensile Strength, MPa	Minimum Yield Strength, MPa	Material	Head Marking
4.6	M5–M36	225	400	240	Low or medium carbon	
4.8	Ml.6–M16	310	420	340	Low or medium carbon	
5.8	M5–M24	380	520	420	Low or medium carbon	
8.8	M16–M36	600	830	660	Medium carbon, Q&T	
9.8	Ml.6–M16	650	900	720	Medium carbon, Q&T	
10.9	M5–M36	830	1,040	940	Low-carbon martensite, Q&T	
12.9	Ml.6–M36	970	1,220	1,100	Alloy, Q&T	

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Specifications and Identification Markings for Bolts, Screws, Studs, Sems,[a] and U Bolts

(Multiply the strengths in kpsi by 6.89 to get the strength in MPa)

SAE Grade	ASTM grade	Metric grade[b]	Nominal diameter, in.	Proof strength, kpsi	Tensile strength, kpsi	Yield strength,[c] kpsi	Core hardness, Rockwell min/max	Products[d]
1	A307	4.6	1/4 thru 1 1/2	33	60	36	B70/B100	B, Sc, St
2		5.8	1/4 thru 3/4	55	74	57	B80/B100	B, Sc, St
		4.6	Over 3/4 thru 1 1/2	33	60	36	B70/B100	B, Sc, St
4		8.9	1/4 thru 1 1/2	65[e]	115	100	C22/C32	St
5	A449 or A325 type1	8.8	1/4 thru 1	85	120	92	C25/C34	B, Sc, St
		7.8	Over 1 thru 1 1/2	74	105	81	Cl9/C30	B, Sc, St
		8.6	Over 1 1/2 to 3	55	90	58		B, Sc, St
5.1		8.8	No. 6 thru 5/8	85	120		C25/C40	Se
		8.8	No. 6 thru 1/2	85	120		C25/C40	B, Sc, St
5.2	A325 type 2	8.8	1/4 thru 1	85	120	92	C26/C36	B, Sc
7[f]		10.9	3/4 thru 1 1/2	105	133	115	C28/C34	B, Sc
8	A354 Grade BD	10.9	1/ 4 thru 1 1/2	120	150	130	C33/C39	B, Sc, St
8.1		10.9	1/4 thru 1 1/2	120	150	130	C32/C38	St
8.2		10.9	1/4 thru 1	120	150	130	C35/C42	B, Sc
	A574	12.9	0 thru 1/2	140	180	160	C39/C45	SHCS
		12.9	5/8 thru 1 1/2	135	170	160	C37/C45	SHCS

[a] Sems are screw and washer assemblies.
[b] Metric grade is *xx.x* where *xx* is approximately 0.01 S_y in MPa and *.x* is the ratio of the minimum S_y to S_w.

[c] Yield strength is stress at which a permanent set of 0.2% of gage length occurs.
[d] B = bolt, Sc= Screws, St= studs, Se= sems, and SHCS = socket head cap screws.
[e] Entry appears to be in error but conforms to the standard, ANSI/SAE J429j.
[f] Grade 7 bolts and screws are roll-threaded after heat treatment.

Note: Company catalogs should be consulted regarding *proof loads*. However, approximate values for proof loads may be calculated from: proof load = proof strength × stress area.

Compiled from ANSI/SAE J429j; ANSI B 18.3.1-1978; and ASTM A307, A325, A354, A449, and A574.

Source: Shigley, Joseph E., and Larry D. Mitchell, *Mechanical Engineering Design*, 4th ed., New York: McGraw-Hill, 1983.

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Basic Dimensions for Fine Thread Series (UNF/UNRF)

Nominal Size, in.	Basic Major Diameter D, in.	Threads per Inch n	Basic Pitch Diameter* E, in.	UNR Design Minor Diameter External K_s, in.	Basic Minor Diameter Internal K, in.	Section at Minor Diameter at $D - 2h_b$, in.	Tensile Stress Area‡, in.^{2}
0 (0.060)	0.0600	80	0.0519	0.0451	0.0465	0.00151	0.00180
1 (0.073)§	0.0730	72	0.0640	0.0565	0.0580	0.00237	0.00278
2 (0.086)	0.0860	64	0.0759	0.0674	0.0691	0.00339	0.00394
3 (0.099)§	0.0990	56	0.0874	0.0778	0.0797	0.00451	0.00523
4 (0.112)	0.1120	48	0.0985	0.0871	0.0894	0.00566	0.00661
5(0.125)	0.1250	44	0.1102	0.0979	0.1004	0.00716	0.00830
6 (1.138)	0.1380	40	0.1218	0.1082	0.1109	0.00874	0.01015
8(0.164)	0.1640	36	0.1460	0.1309	0.1339	0.01285	0.01474
10(0.190)	0.1900	32	0.1697	0.1528	0.1562	0.0175	0.0200
12 (0.216)§	0.2160	28	0.1928	0.1734	0.1773	0.0226	0.0258
1/4	0.2500	28	0.2268	0.2074	0.2113	0.0326	0.0364
5/16	0.3125	24	0.2854	0.2629	0.2674	0.0524	0.0580
3/8	0.3750	24	0.3479	0.3254	0.3299	0.0809	0.0878
7/16	0.4375	20	0.4050	0.3780	0.3834	0.1090	0.1187
1/2	0.5000	20	0.4675	0.4405	0.4459	0.1486	0.1599
9/16	0.5625	18	0.5264	0.4964	0.5024	0.189	0.203
5/8	0.6250	18	0.5889	0.5589	0.5649	0.240	0.256
3/4	0.7500	16	0.7094	0.6763	0.6823	0.351	0.373
7/8	0.8750	14	0.8286	0.7900	0.7977	0.480	0.509
1	1.0000	12	0.9459	0.9001	0.9098	0.625	0.663
1-1/8	1.1250	12	1.0709	1.0258	1.0348	0.812	0.856
1-1/4	1.2500	12	1.1959	1.1508	1.598	1.024	1.073
1-3/8	1.3750	12	1.3209	1.2758	1.2848	1.260	1.315
1-1/2	1.5000	12	1.4459	1.4008	1.4098	1.521	1.584

*British: effective diameter
‡ Design form
§Secondary sizes

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Basic Dimensions for Coarse Thread Series (UNC/UNRC)

Nominal Size, in.	Basic Major Diameter D, in.	Threads per Inch n	Basic Pitch Diameter* E, in.	UNR Design Minor Diameter External K_s, in.	Basic Minor Diameter Internal K, in.	Section at Minor Diameter at $D - 2h_b$, in.	Tensile Stress Area‡, in.^{2}
1 (0.073)§	0.0730	64	0.0629	0.0544	0.0561	0.00218	0.00263
2 (0.086)	0.0860	56	0.0744	0.0648	0.0667	0.00310	0.00370
3 (0.099)§	0.0990	48	0.0855	0.0741	0.0764	0.00406	0.00487
4 (0.112)	0.1120	40	0.0958	0.0822	0.0849	0.00496	0.00604
5(0.125)	0.1250	40	0.1088	0.0952	0.0979	0.00672	0.00796
6 (1.138)	0.1380	32	1.1177	0.1008	0.1042	0.00745	0.00909
8(0.164)	0.1640	32	0.1437	0.1268	0.1302	0.01196	0.0140
10(0.190)	0.1900	24	0.1629	0.1404	0.1449	0.01450	0.0175
12 (0.216)§	0.2160	24	0.1889	0.1664	0.1709	0.0206	0.0242
1/4	0.2500	20	0.2175	0.1905	0.1959	0.0269	0.0318
5/16	0.3125	18	0.2764	0.2464	0.2524	0.0454	0.0524
3/8	0.3750	16	0.3344	0.3005	0.3073	0.0678	0.0775
7/16	0.4375	14	0.3911	0.3525	0.3602	0.0933	0.1063
1/2	0.5000	13	0.4500	0.3334	0.4167	0.1257	0.1419
9/16	0.5625	12	0.5084	0.4633	0.4723	0.162	0.182
5/8	0.6250	11	0.5660	0.5168	0.5266	0.202	0.226
3/4	0.7500	10	0.6850	0.6309	0.6417	0.302	0.334
7/8	0.8750	9	0.8028	0.7427	0.7547	0.419	0.462
1	1.0000	8	0.9188	0.8512	0.8647	0.551	0.606
1 1/8	1.1250	7	1.0322	0.9549	0.9704	0.693	0.763
1 1/4	1.2500	7	1.1572	1.0799	1.0954	0.890	0.969
1 3/8	1.3750	6	1.2667	1.1766	1.1946	1.054	1.155
1 1/2	1.5000	6	1.3917	1.3016	1.3196	1.294	1.405
1 3/4	1.7500	5	1.6201	1.5119	1.5335	1.74	1.90
2	2.0000	4 1/2	1.8557	1.7353	1.7594	2.30	2.50
2 1/4	2.2500	4 1/2	2.1057	1.9853	2.0094	3.02	3.25
2 1/2	2.5000	4	2.3376	2.2023	2.2294	3.72	4.00
2 3/4	2.7500	4	2.5876	2.4523	2.4794	4.62	4.93
3	3.0000	4	2.8376	2.7023	2.7294	5.62	5.97
3 1/4	3.2500	4	3.0876	2.9523	2.9794	6.72	7.10
3 1/2	3.5000	4	3.3376	3.2023	3.2294	7.92	8.33
3 3/4	3.7500	4	3.5876	3.4523	3.4794	9.21	9.66
4	4.0000	4	3.8376	3.7023	3.7294	10.61	11.08

*British: effective diameter
‡ Design form
§Secondary sizes

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Metric (SI) System Thread Tensile Stress Area (A_s)

Nom. Diameter mm	Coarse Thread		Fine Thread	
	Thread Pitch mm	Tensile Stress Area mm sq.	Thread Pitch mm	Tensile Stress Area mm sq.
3	0.5	5.03		
3.5	0.6	6.78		
4	0.7	8.78		
5	0.8	14.2		
6	1	20.1		
7	1	28.9		
8	1.25	36.6	1	39.2
10	1.5	58.0	1.25	61.2
12	1.75	84.3	1.25	92.1
14	2	115	1.5	125
16	2	157	1.5	167
18	2.5	192	1.5	216
20	2.5	245	1.5	272
22	2.5	303	1.5	333
24	3	353	2	384
27	3	459	2	496
30	3.5	561	2	621
33	3.5	694	2	761
36	4	817	3	865
39	4	976	3	1,030

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Unified National Thread Tensile Stress Area (A_s)

Nominal Size (inches)		Coarse Thread		8 Thread Series		Fine Thread	
		Thread Pitch (tpi)	Tensile Stress Area (sq in.)	Thread Pitch (tpi)	Tensile Stress Area (sq in.)	Thread Pitch (tpi)	Tensile Stress Area (sq in.)
0	0.060					80	0.00180
1	0.073	64	0.00262			72	0.00278
2	0.086	56	0.00370			64	0.00394
3	0.099	48	0.00487			56	0.00523
4	0.112	40	0.00604			48	0.00661
5	0.125	40	0.00796			44	0.00831
6	0.138	32	0.00909			40	0.01015
8	0.164	32	0.0140			36	0.0147
10	0.190	24	0.0175			32	0.0200
12	0.216	24	0.0242			28	0.0258
1/4	0.250	20	0.0318			28	0.0364
5/16	0.313	18	0.0525			24	0.0581
3/8	0.375	16	0.0775			24	0.0878
7/16	0.438	14	0.106			20	0.119
1/2	0.500	13	0.142			20	0.160
9/16	0.563	12	0.182			18	0.203
5/8	0.625	11	0.226			18	0.256
3/4	0.750	10	0.335			16	0.373
7/8	0.875	9	0.462			14	0.510
1	1.000	8	0.606	8	0.606	12 UNF	0.663
1	1.000					14 UNS	0.680
1-1/8	1.125	7	0.763	8	0.791	12	0.856
1-1/4	1.250	7	0.969	8	1.000	12	1.073
1-3/8	1.375	6	1.155	8	1.234	12	1.315
1-1/2	1.500	6	1.406	8	1.492	12	1.581

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2.18.3 Adhesives and Bonding

Mechanical Performance of Various Types of Adhesives

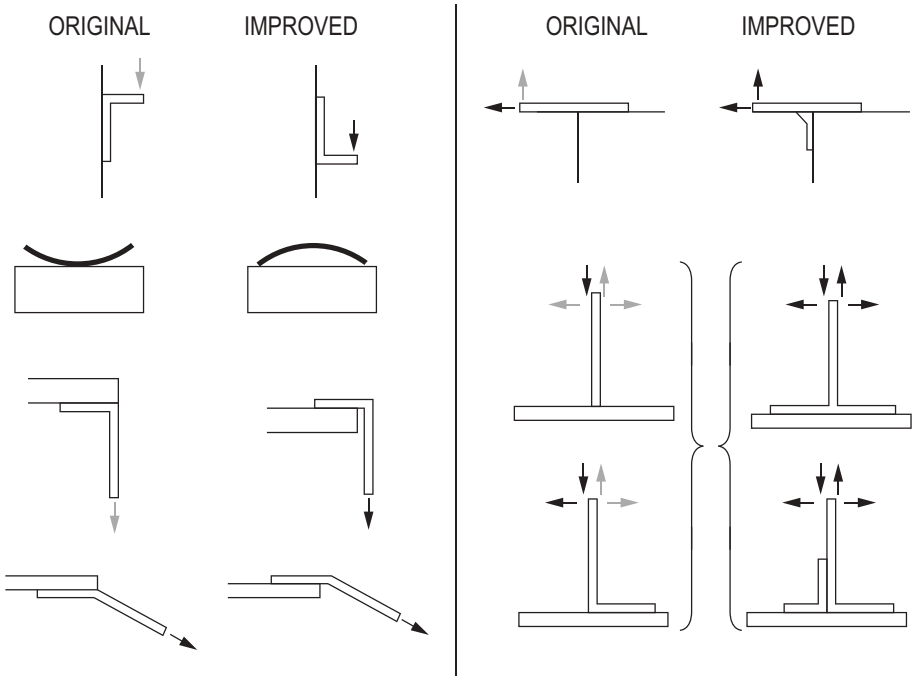
Adhesive Chemistry or Type	Room Temperature Lap-Shear Strength, MPa	psi	Peel Strength Per Unit Width, kN/m	lb/in.
Pressure-sensitive	0.01–0.07	2–10	0.18–0.88	1–5
Starch-based	0.07–0.7	10–100	0.18–0.88	1–5
Cellosics	0.35–3.5	50–500	0.18–1.8	1–10
Rubber-based	0.35–3.5	50–500	1.8–7	10–40
Formulated hot melt	0.35–4.8	50–700	0.88–3.5	5–20
Synthetically designed hot melt	0.7–6.9	100–1,000	0.88–3.5	5–20
PVAc emulsion (white glue)	1.4–6.9	200–1,000	0.88–1.8	5–10
Cyanoacrylate	6.9–13.8	1,000–2,000	0.18–3.5	1–20
Protein-based	6.9–13.8	1,000–2,000	0.18–1.8	1–10
Anaerobic acrylic	6.9–13.8	1,000–2,000	0.18–1.8	1–10
Urethane	6.9–17.2	1,000–2,500	1.8–8.8	10–50
Rubber-modified acrylic	13.8–24.1	2,000–3,500	1.8–8.8	10–50
Modified phenolic	13.8–27.6	2,000–4,000	3.6–7	20–40
Unmodified epoxy	10.3–27.6	1,500–4,000	0.35–1.8	2–10
Bis-maleimide	13.8–27.6	2,000–4,000	1.8–3.5	1–20
Polyimide	13.8–27.6	2,000–4,000	0.18–0.88	1–5
Rubber-modified epoxy	20.7–41.4	3,000–6,000	4.4–14	25–80

Source: Shigley, Joseph E., and Charles R. Mischke, *Mechanical Engineering Design*, 6th ed., New York: McGraw-Hill, 2001.

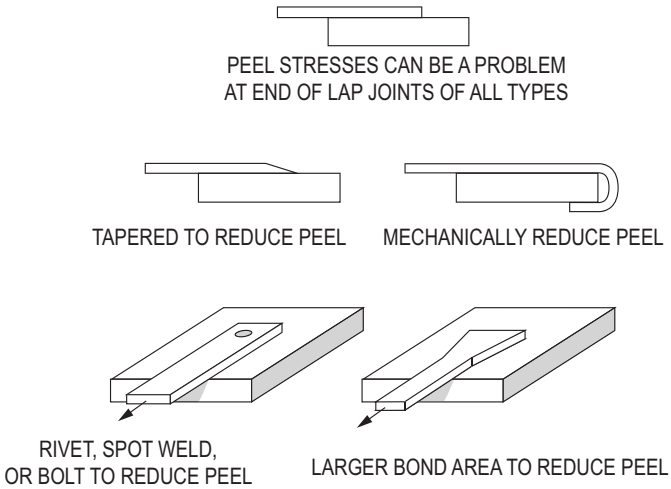
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Design Practices That Improve Adhesive Bonding

a) Avoid gray load vectors, because resulting strength is poor:



b) Various means to reduce peel stresses in lap-type joints:



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2.19 Pressure Vessels

2.19.1 Cylindrical Pressure Vessel

Stress σ	Surface	Internal Pressure	External Pressure
Tangential	Inner	$P_i \frac{\left(r_o^2 + r_i^2\right)}{\left(r_o^2 - r_i^2\right)}$	$-P_o \frac{2r_o^2}{\left(r_o^2 - r_i^2\right)}$
	Outer	$P_i \frac{2r_i^2}{\left(r_o^2 - r_i^2\right)}$	$-P_o \frac{\left(r_o^2 + r_i^2\right)}{\left(r_o^2 - r_i^2\right)}$
Radial	Inner	$-P_i$	0
	Outer	0	$-P_o$
Shear	Maximum occurs at inner interface surface	$\frac{P_i r_o^2}{\left(r_o^2 - r_i^2\right)}$	$P_o \frac{r_o^2}{\left(r_o^2 - r_i^2\right)}$

where

σ_t = tangential (hoop) stress

σ_r = radial stress

P_i = internal pressure

P_o = external pressure

r_i = inside radius

r_o = outside radius

To calculate wall thickness, t:

$$t = \frac{P_i r_i}{Se - 0.6P_i}$$

where

S = allowable code stress

e = code weld-joint efficiency

For vessels with end caps, the principal stresses are σ_t, σ_r, and σ_a.

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Axial Stress:

$$\sigma_a = P_i \frac{r_i^2}{r_o^2 - r_i^2}$$

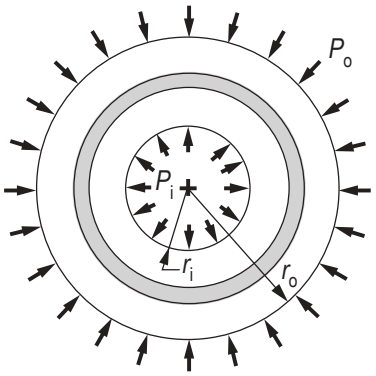
Tangential Stress:

$$\sigma_t = \frac{\left[P_i r_i^2 - P_o r_o^2 - r_i^2 r_o^2 \left(P_o - P_i\right)/r^2\right]}{r_o^2 - r_i^2}$$

Radial Stress:

$$\sigma_r = \frac{\left[P_i r_i^2 - P_o r_o^2 + r_i^2 r_o^2 \left(P_o - P_i\right)/r^2\right]}{r_o^2 - r_i^2}$$

Stresses in a Cylindrical Vessel



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For a thin-walled vessel, $\frac{D}{t} > 10$, and the tangential stress σ_t and longitudinal stress σ_l are:

$$\sigma_t = \frac{PD}{2t}$$

$$\sigma_l = \frac{PD}{4t}$$

where

P = internal pressure

D = diameter

t = wall thickness

Similarly, the maximum working pressure in thin-walled pipes, with maximum allowable stress (hoop stress) of S, is calculated with the Barlow formula:

$$P = \frac{2St}{D}$$

2.19.2 Definitions

Relief Valve Accumulation/Overpressure: That pressure above the relief valve lifting set point at which the relief valve is fully open.

Relief Valve Blowdown: That pressure below the relief valve lifting set point at which the relief valve is fully closed.

Thin-walled Spherical Tanks: There is no unique axis in a spherical tank or in the spherical ends of a cylindrical tank. Therefore, the hoop and longitudinal stresses are identical:

$$\sigma = \frac{pr}{2t}$$

Thin-walled Cylindrical Shells: The hoop and longitudinal stresses are respectively:

$$\sigma_h = \frac{P_i r_i}{t}$$

$$\sigma_l = \frac{P_i r_i}{2t}$$

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3 HYDRAULICS, FLUIDS, AND PIPE FLOW

3.1 Definitions

3.1.1 Density, Specific Weight, and Specific Gravity

$$\rho = \frac{m}{V}$$

$$\gamma = \frac{W}{V} = \rho g$$

$$SG = \frac{\gamma}{\gamma_w} = \frac{\rho}{\rho_w}$$

where

ρ = density (also called mass density)

m = mass

V = volume

γ = specific weight

W = weight

SG = specific gravity

ρ_w = density of water at standard conditions

γ_w = specific weight of water at standard conditions

3.1.2 Stress, Pressure, and Viscosity

Viscosity is the measure of a fluid's resistance to flow.

Absolute viscosity or dynamic viscosity:

$$\tau = \mu \frac{dv}{dy}$$

where

μ = absolute viscosity (dynamic viscosity) (N•s/m^2 or lbf-sec/ft^2)

τ = shear stress

v = tangential velocity (m/sec or ft/sec)

y = normal distance, measured from boundary (m or ft)

Kinematic viscosity

ν = kinematic viscosity $\left(\frac{m^2}{s} \text{ or } \frac{ft^2}{sec}\right)$

Kinematic viscosity is related to absolute viscosity by: $\nu = \frac{\mu}{\rho}$

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The compressibility β of a liquid is the reciprocal of its bulk modulus of elasticity K:

$$K = -\frac{dp}{dV/V} \qquad \beta = -\frac{1}{V}\frac{dV}{dp}$$

where

dp = change in pressure

dV = change in volume

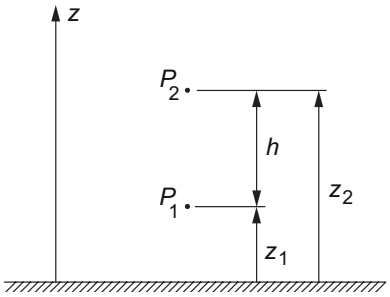
V = original volume

3.2 Characteristics of a Static Liquid

3.2.1 Pressure Field in a Static Liquid

The difference in pressure between two different points is

$$P_2 - P_1 = -\gamma\,(z_2 - z_1) = -\gamma h = -\rho g h$$



Source: Bober, W., and R.A. Kenyon, *Fluid Mechanics*, John Wiley & Sons, Inc., 1980.

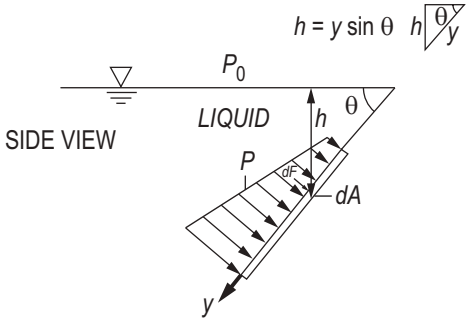
Absolute pressure = atmospheric pressure + gauge pressure reading

Absolute pressure = atmospheric pressure – vacuum gauge pressure reading

3.2.2 Forces on Submerged Surfaces and the Center of Pressure

The pressure on a point at a vertical distance h below the surface is

$$P = P_0 + \rho g h \qquad h \geq 0$$



where

P = pressure

P_0 = atmospheric pressure

y = slant distance from liquid surface to point on submerged surface

$y = \dfrac{h}{\sin\theta}$

θ = angle between liquid surface and edge of submerged surface

h = vertical distance from liquid surface to point on submerged surface

Source: Elger, Donald F., Barbara C. Williams, Clayton T. Crowe, and John A. Roberson, *Engineering Fluid Mechanics*, 10th ed., John Wiley & Sons, Inc., 2013. Reproduced with permission of John Wiley & Sons, Inc.

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3.2.3 Archimedes' Principle and Buoyancy

$$F_{\text{buoyant}} = \gamma V_{\text{displaced}}$$

F_{buoyant} = buoyant force

γ = specific weight

A floating body displaces a weight of fluid equal to its own weight.

The *center of buoyancy* is located at the centroid of the displaced fluid volume.

3.3 Principles of One-Dimensional Fluid Flow

3.3.1 Continuity Equation

$$Q = Av$$

$$\dot{m} = \rho Q = \rho Av$$

where

Q = volumetric flow rate

$\dot{m}$ = mass flow rate

A = cross-sectional area of flow

v = average flow velocity

ρ = fluid density

3.3.2 Bernoulli Equation

The energy equation for steady incompressible flow with no shaft device is either

$$\frac{P_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\gamma} + z_2 + \frac{v_2^2}{2g} + h_f \quad \text{or}$$

$$\frac{P_1}{\rho g} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{v_2^2}{2g} + h_f$$

The pressure drop $P_1 - P_2$ is

$$P_1 - P_2 = \gamma h_f = \rho g h_f$$

where

P_1, P_2 = pressure at sections 1 and 2

v_1, v_2 = average velocity of the fluid at sections 1 and 2

z_1, z_2 = vertical distance from a datum to sections 1 and 2 (their potential energy)

$\gamma, \rho g$ = specific weight of the fluid

g = acceleration of gravity

ρ = fluid density

h_f = head loss, considered a friction effect

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3.4 Fluid Flow

3.4.1 Reynolds Number

$$Re = \frac{vD\rho}{\mu} = \frac{vD}{\nu}$$

where

Re = Reynolds number (Newtonian fluid)

D = diameter of the pipe, dimension of the fluid streamline, or characteristic length

ρ = mass density

μ = dynamic viscosity

ν = kinematic viscosity

v = velocity of the fluid

For pipe flow:

Laminar Flow	$Re < 2{,}000$
Critical Zone (Flow Unstable)	$2{,}000 < Re < 4{,}000$
Transition Zone	$4{,}000 < Re < 12{,}000$
Fully Turbulent	$Re > 12{,}000$

3.4.2 Head Loss Due to Flow

3.4.2.1 Darcy-Weisbach Equation

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

where

f = the *Moody, Darcy, or Stanton friction factor* and is a function of Re and $\frac{\varepsilon}{D}$

$f = 64/Re$

for $Re < 2{,}000$ (laminar flow)

D = diameter of the pipe

L = length over which the pressure drop occurs

ε = roughness factor for the pipe

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3.4.2.2 Fanning Friction Factor Equation

$$h_f = \left(4f_{\text{Fanning}}\right)\frac{Lv^2}{D2g} = \frac{2f_{\text{Fanning}}\,Lv^2}{Dg}$$

where $f_{\text{Fanning}} = \frac{f}{4}$

3.4.2.3 Pressure Drop of Water Flowing in Circular Pipe (Hazen-Williams)

Expressed in feet of water

$$h_f = \frac{10.44\,Q^{1.85}}{C^{1.85}D^{4.87}}$$

Expressed as pressure

$$P = \frac{4.52\,Q^{1.85}}{C^{1.85}D^{4.87}}$$

where

h_f = friction head loss (ft per foot of pipe)

P = pressure loss (psi per foot of pipe)

Q = flow (gpm)

D = pipe inside diameter (inches)

C = Hazen-Williams coefficient

Values of Hazen-Williams Coefficient *C*

Pipe Material	*C*
Ductile iron	140
Concrete (regardless of age)	130
Copper/Brass	130
Cast iron: new 5 yr old 20 yr old	130 120 100
Welded steel: new old	120 100
Wood stave (regardless of age)	120
Vitrified clay	110
Riveted steel: new	110
Brick sewers	100
Asbestos-cement	140
Plastic	150

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3.4.2.4 Minor Losses in Pipe Fittings, Contractions, and Expansions

$$\frac{P_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\gamma} + z_2 + \frac{v_2^2}{2g} + h_f + h_{f,\text{ fitting}}$$

$$\frac{P_1}{\rho g} + z_1 + \frac{v_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{v_2^2}{2g} + h_f + h_{f,\text{ fitting}}$$

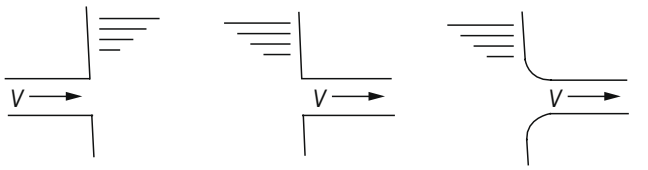
where

$$h_{f,\text{ fitting}} = k\frac{v^2}{2g}$$

$\frac{v^2}{2g}$ = velocity head

k = loss factor for entrance or exit

Values for k are:



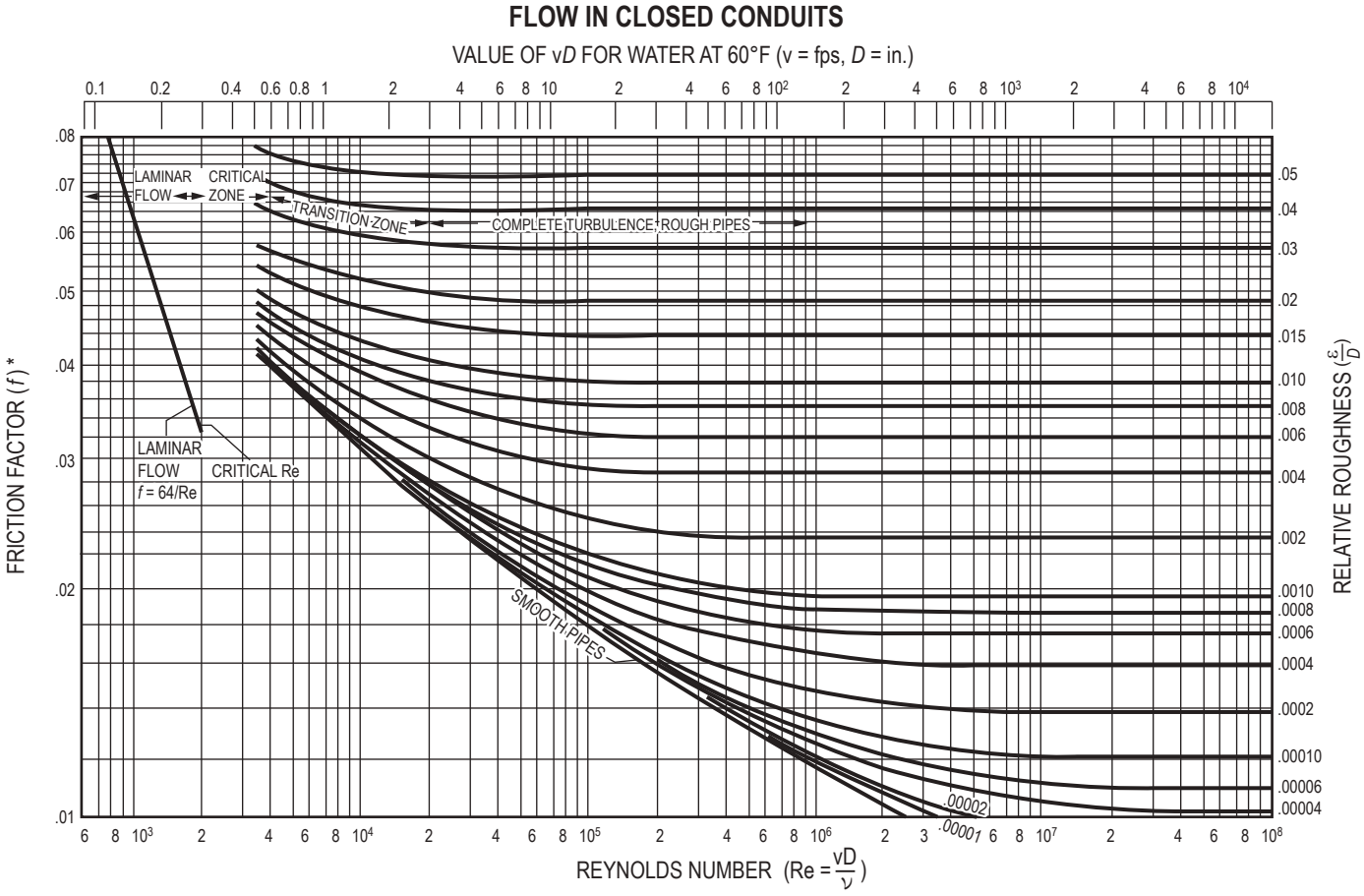
SHARP EXIT	SHARP ENTRANCE	ROUND ENTRANCE
k = 1.0	k = 0.5	k = 0.1

Source: Bober, W., and R.A. Kenyon, *Fluid Mechanics*, John Wiley & Sons, Inc., 1980.

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3.4.2.5 Flow in Closed Conduits

Moody Diagram (Stanton Diagram)



* The Fanning Friction is this factor divided by 4.

	ε (ft)	ε (mm)
GLASS, DRAWN BRASS, COPPER, LEAD	SMOOTH	SMOOTH
COMMERCIAL STEEL, WROUGHT IRON	0.0001–0.0003	0.03–0.09
ASPHALTED CAST IRON	0.0002–0.0006	0.06–0.18
GALVANIZED IRON	0.0002–0.0008	0.06–0.24
CAST IRON	0.0006–0.003	0.18–0.91
CONCRETE	0.001–0.01	0.30–3.0
RIVETED STEEL	0.003–0.03	0.91–9.1
CORRUGATED METAL PIPE	0.1–0.2	30–61
LARGE TUNNEL, CONCRETE OR STEEL LINED	0.002–0.004	0.61–1.2
BLASTED ROCK TUNNEL	1.0–2.0	300–610

Source: Chow, Ven Te, *Handbook of Applied Hydrology*, New York: McGraw-Hill, 1964.

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3.4.2.6 Flow in Noncircular Conduits

The *hydraulic radius* R_H and the *hydraulic diameter* D_H are

$$D_H = \frac{4 \times \text{cross-sectional area of flowing fluid}}{\text{wetted perimeter}} = 4R_H$$

3.4.2.7 Drag Force

The *drag force* F_D is

$$F_D = \frac{C_D \rho v^2 A}{2}$$

where

C_D = drag coefficient

v = velocity $\left(\frac{\text{m}}{\text{s}}\right)$ of the flowing fluid or moving object

A = projected area, in m^2, of blunt objects such as spheres, ellipsoids, and disks, as well as plates, cylinders, ellipses, and air foils with axes *perpendicular* to the flow

ρ = fluid density

For flat plates placed *parallel* with the flow:

$$C_D = \frac{1.33}{Re^{0.5}} \qquad 10^4 < Re < \left(5 \times 10^5\right)$$

$$C_D = \frac{0.031}{Re^{\frac{1}{7}}} \qquad 10^6 < Re < 10^9$$

3.4.2.8 Valve and Fittings Losses

$$\Delta p = K\left(\frac{\rho}{g_c}\right)\left(\frac{v^2}{2}\right)$$

or

$$\Delta h = K\left(\frac{v^2}{2g}\right)$$

where

Δp = pressure drop (lbf/ft^2)

Δh = head loss (ft)

ρ = fluid density at mean temperature (lbm/ft^3)

v = average velocity (fps)

K = geometry- and size-dependent loss coefficient

g_c = units conversion factor (32.2 ft-lbm/lbf-sec^2)

g = acceleration of gravity (ft/sec^2)

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3.4.2.9 K-Factors—Pipe Fittings

K-Factors—Threaded Steel Pipe Fittings

Nominal Pipe dia., in.	90° Standard Elbow	90° Long Radius Elbow	45° Elbow	Return Bend	Tee-Line	Tee-Branch	Globe Valve	Gate Valve	Angle Valve	Swing Check Valve	Bell Mouth Inlet	Square Inlet	Projected Inlet
0.375	2.5	–	0.38	2.5	0.90	2.7	20	0.40	–	8.0	0.05	0.5	1
0.50	2.1	–	0.37	2.1	0.90	2.4	14	0.33	–	5.5	0.05	0.5	1
0.75	1.7	0.92	0.35	1.7	0.90	2.1	10	0.28	6.1	3.7	0.05	0.5	1
1.00	1.5	0.78	0.34	1.5	0.90	1.8	9	0.24	4.6	3.0	0.05	0.5	1
1.25	1.3	0.65	0.33	1.3	0.90	1.7	8.5	0.22	3.6	2.7	0.05	0.5	1
1.50	1.2	0.54	0.32	1.2	0.90	1.6	8	0.19	2.9	2.5	0.05	0.5	1
2.00	1.0	0.42	0.31	1.0	0.90	1.4	7	0.17	2.1	2.3	0.05	0.5	1
2.50	0.85	0.35	0.30	0.85	0.90	1.3	6.5	0.16	1.6	2.2	0.05	0.5	1
3.00	0.80	0.31	0.29	0.80	0.90	1.2	6	0.14	1.3	2.1	0.05	0.5	1
4.00	0.70	0.24	0.28	0.70	0.90	1.1	5.7	0.12	1.0	2.0	0.05	0.5	1

Source: Engineering Data Book (Hydraulic Institute 1990)

K-Factors—Flanged Welded Steel Pipe Fittings

Nominal Pipe dia., in.	90° Standard Elbow	90° Long Radius Elbow	45° Long Radius Elbow	Return Bend Standard	Return Bend Long-Radius	Tee-Line	Tee-Branch	Globe Valve	Gate Valve	Angle Valve	Swing Check Valve
1.00	0.43	0.41	0.22	0.43	0.43	0.26	1.00	13	–	4.8	2.0
1.25	0.41	0.37	0.22	0.41	0.38	0.25	0.95	12	–	3.7	2.0
1.50	0.40	0.35	0.21	0.40	0.35	0.23	0.90	10	–	3.0	2.0
2.00	0.38	0.30	0.20	0.38	0.30	0.20	0.84	9	0.34	2.5	2.0
2.50	0.35	0.28	0.19	0.35	0.27	0.18	0.79	8	0.27	2.3	2.0
3.00	0.34	0.25	0.18	0.34	0.25	0.17	0.76	7	0.22	2.2	2.0
4.00	0.31	0.22	0.18	0.31	0.22	0.15	0.70	6.5	0.16	2.1	2.0
6.00	0.29	0.18	0.17	0.29	0.18	0.12	0.62	6	0.10	2.1	2.0
8.00	0.27	0.16	0.17	0.27	0.15	0.10	0.58	5.7	0.08	2.1	2.0
10.00	0.25	0.14	0.16	0.25	0.14	0.09	0.53	5.7	0.06	2.1	2.0
12.00	0.24	0.13	0.16	0.24	0.13	0.08	0.50	5.7	0.05	2.1	2.0

Source: Engineering Data Book (Hydraulic Institute 1990)

Source for above two tables: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 22, Pipe Sizing, Tables 3 and 4.

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3.4.2.10 Equivalent Lengths for Pipe Fittings

Friction Loss of Water in Pipe Fittings in Terms of Equivalent Length–(L)–Feet of Straight Pipe

Nominal Pipe Size	Actual Inside Diameter inches, *d*	Friction Factor, *f*	Gate Valve — Full Open	90° Elbow	Long Radius 90°or 45° Std Elbow	Std Tee — Thru Flow	Std Tee — Branch Flow	Close Return Bend	Swing Check Valve — Full Open	Angle Valve — Full Open	Globe Valve — Full Open	Butterfly Valve	90° Welding Elbow		Mitre Bend	
													r/d = 1	*r/d* = 2	45°	90°
1/2	0.622	0.027	0.41	1.55	0.83	1.04	3.11	2.59	5.18	7.78	17.6					
3/4	0.824	0.025	0.55	2.06	1.10	1.37	4.12	3.43	6.86	10.3	23.3					
1	1.049	0.023	0.70	2.62	1.40	1.75	5.25	4.37	8.74	13.1	29.7					
1 1/4	1.380	0.022	0.92	3.45	1.84	2.30	6.90	5.75	11.5	17.3	39.1					
1 1/2	1.610	0.021	1.07	4.03	2.15	2.68	8.05	6.71	13.4	20.1	45.6					
2	2.067	0.019	1.38	5.17	2.76	3.45	10.3	8.61	17.2	25.8	58.6	7.75	3.45	2.07	2.58	10.3
2 1/2	2.469	0.018	1.65	6.17	3.29	4.12	12.3	10.3	20.6	30.9	70.0	9.26	4.12	2.47	3.08	12.3
3	3.068	0.018	2.04	7.67	4.09	5.11	15.3	12.8	25.5	38.4	86.9	11.5	5.11	3.07	3.84	15.3
4	4.026	0.017	2.68	10.1	5.37	6.71	20.1	16.8	33.6	50.3	114	15.1	6.71	4.03	5.03	20.1
5	5.047	0.016	3.36	12.6	6.73	8.41	25.2	21.0	42.1	63.1	143	18.9	8.41	5.05	6.31	25.2
6	6.065	0.015	4.04	15.2	8.09	10.1	30.3	25.3	50.5	75.8	172	22.7	10.1	6.07	7.58	30.3
8	7.981	0.014	5.32	20.0	10.6	13.3	39.9	33.3	33.3	99.8	226	29.9	13.3	7.98	9.98	39.9
10	10.02	0.014	6.68	25.1	13.4	16.7	50.1	41.8	41.8	125	284	29.2	16.7	10.0	12.5	50.1
L/D			8	30	16	20	60	50	1/2 to 6 = 100 24 to 48 = 50	150	340		20	12	15	60

Source: Ingersoll-Rand; Cameron Hydraulic Data

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3.4.2.11 Steel Pipe Friction Tables—Water

Steel Pipe Friction Tables

Tables are for steel pipe with a surface roughness of C=100.
To adjust for different surface roughness factors, use the following correction factors:

Value of C	*150*	*140*	*130*	*120*	*110*	*100*	*90*	*80*	*70*	*60*
	0.47	*0.54*	*0.62*	*0.71*	*0.84*	*1.00*	*1.22*	*1.51*	*1.93*	*2.57*

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 0.5	**Pipe Dia., in. 0.622**	**Surface Rough *C* 100**
gpm	**Velocity, fps**	**hd. loss, ft/100 ft**
0.5	0.53	0.6
1.0	1.06	2.1
1.5	1.58	4.4
2.0	2.11	7.6
2.5	2.64	11.4
3.0	3.17	16.0
3.5	3.70	21.3
4.0	4.22	27.3
4.5	4.75	33.9
5.0	5.28	41.2

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 0.75	**Pipe Dia., in. 0.824**	**Surface Rough *C* 100**
gpm	**Velocity, fps**	**hd. loss, ft/100 ft**
1.5	0.90	1.1
2.0	1.20	1.9
2.5	1.50	2.9
3.0	1.80	4.1
3.5	2.11	5.4
4.0	2.41	6.9
4.5	2.71	8.6
5.0	3.01	10.5
5.5	3.31	12.5
6.0	3.61	14.7

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 1.0	**Pipe Dia., in. 1.049**	**Surface Rough *C* 100**
gpm	**Velocity, fps**	**hd. loss, ft/100 ft**
2	0.74	0.6
3	1.11	1.3
4	1.48	2.1
5	1.86	3.2
6	2.23	4.5
7	2.60	6.0
8	2.97	7.7
9	3.34	9.6
10	3.71	11.7
11	4.08	13.9
12	4.45	16.4

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 1.25	**Pipe Dia., in. 1.38**	**Surface Rough *C* 100**
gpm	**Velocity, fps**	**hd. loss, ft/100 ft**
5	1.07	0.9
6	1.29	1.2
7	1.50	1.6
8	1.72	2.0
9	1.93	2.5
10	2.15	3.1
12	2.57	4.3
14	3.00	5.7
16	3.43	7.3
18	3.86	9.1
20	4.29	11.1

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Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 1.5	Pipe Dia., in. 1.61	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
8	1.26	1.0
9	1.42	1.2
10	1.58	1.5
12	1.89	2.0
14	2.21	2.7
16	2.52	3.5
18	2.84	4.3
20	3.15	5.2
22	3.47	6.2
24	3.78	7.3
26	4.10	8.5
28	4.41	9.8
30	4.73	11.1
32	5.04	12.5
34	5.36	14.0
36	5.67	15.5
38	5.99	17.2
40	6.30	18.9
42	6.62	20.7

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 2.0	Pipe Dia., in. 2.067	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
14	1.34	0.8
16	1.53	1.0
18	1.72	1.3
20	1.91	1.6
22	2.10	1.9
24	2.29	2.2
26	2.49	2.5
28	2.68	2.9
30	2.87	3.3
32	3.06	3.7
34	3.25	4.1
36	3.44	4.6
38	3.63	5.1
40	3.82	5.6
42	4.02	6.1
44	4.21	6.7
46	4.40	7.3
48	4.59	7.8
50	4.78	8.5

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Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 2.5	Pipe Dia., in. 2.469	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
26	1.74	1.06
28	1.88	1.22
30	2.01	1.39
32	2.14	1.56
34	2.28	1.75
36	2.41	1.94
38	2.55	2.15
40	2.68	2.36
42	2.81	2.58
44	2.95	2.81
46	3.08	3.1
48	3.22	3.3
50	3.35	3.6
55	3.69	4.3
60	4.02	5.0
65	4.36	5.8
70	4.69	6.6
75	5.03	7.5
80	5.36	8.5
85	5.70	9.5
90	6.03	10.6
95	6.37	11.7
100	6.70	12.8
110	7.37	15.3
120	8.04	18.0

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 3.0	Pipe Dia., in. 3.068	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
40	1.74	0.82
42	1.82	0.90
44	1.91	0.98
46	2.00	1.06
48	2.08	1.15
50	2.17	1.24
55	2.39	1.48
60	2.60	1.74
65	2.82	2.01
70	3.04	2.31
75	3.25	2.62
80	3.47	3.0
85	3.69	3.3
90	3.91	3.7
95	4.12	4.1
100	4.34	4.5
110	4.77	5.3
120	5.21	6.3
130	5.64	7.3
140	6.08	8.3
150	6.51	9.5
160	6.94	10.7
170	7.38	11.9
180	7.81	13.2
190	8.25	14.6

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Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 4	Pipe Dia., in. 4.026	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
65	1.64	0.54
70	1.76	0.62
75	1.89	0.70
80	2.02	0.79
85	2.14	0.88
90	2.27	0.98
95	2.39	1.08
100	2.52	1.19
110	2.77	1.42
120	3.02	1.67
130	3.28	1.93
140	3.53	2.22
150	3.78	2.52
160	4.03	2.84
170	4.28	3.2
180	4.54	3.5
190	4.79	3.9
200	5.04	4.3
210	5.29	4.7
220	5.54	5.1
230	5.80	5.6
240	6.05	6.0
260	6.55	7.0
280	7.06	8.0
300	7.56	9.1

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 5.0	Pipe Dia., in. 5.047	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
160	2.57	0.95
170	2.73	1.06
180	2.89	1.18
190	3.05	1.30
200	3.21	1.43
210	3.37	1.56
220	3.53	1.70
230	3.69	1.85
240	3.85	2.00
260	4.17	2.32
280	4.49	2.66
300	4.81	3.0
320	5.13	3.4
380	6.09	4.7
400	6.41	5.2
420	6.74	5.6
440	7.06	6.1
460	7.38	6.7
480	7.70	7.2
500	8.02	7.8
520	8.34	8.4
540	8.66	9.0
560	8.98	9.6
580	9.30	10.2
600	9.62	10.9

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Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 6	Pipe Dia., in. 6.065	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
220	2.44	0.70
240	2.67	0.82
260	2.89	0.95
280	3.11	1.09
300	3.33	1.24
320	3.55	1.39
380	4.22	1.92
400	4.44	2.11
420	4.66	2.31
440	4.89	2.51
460	5.11	2.73
480	5.33	3.0
500	5.55	3.2
520	5.77	3.4
540	6.00	3.7
560	6.22	3.9
580	6.44	4.2
600	6.66	4.5
650	7.22	5.2
700	7.77	5.9
750	8.33	6.7
800	8.88	7.6
850	9.44	8.5
900	9.99	9.4
950	10.55	10.4

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 8	Pipe Dia., in. 7.981	Surface Rough C 100
gpm	Velocity, fps	hd. loss, ft/100 ft
460	2.95	0.72
480	3.08	0.78
500	3.21	0.84
520	3.33	0.90
540	3.46	0.97
560	3.59	1.03
580	3.72	1.10
600	3.85	1.17
650	4.17	1.36
700	4.49	1.56
750	4.81	1.77
800	5.13	2.00
850	5.45	2.23
900	5.77	2.48
950	6.09	2.74
1,000	6.41	3.0
1,050	6.73	3.3
1,100	7.05	3.6
1,150	7.38	3.9
1,200	7.70	4.2
1,250	8.02	4.6
1,300	8.34	4.9
1,350	8.66	5.3
1,400	8.98	5.6
1,450	9.30	6.0

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Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 10	Pipe Dia., in. 10.02	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
800	3.25	0.66
850	3.46	0.74
900	3.66	0.82
950	3.87	0.91
1,000	4.07	1.00
1,050	4.27	1.09
1,100	4.48	1.19
1,150	4.68	1.29
1,200	4.88	1.40
1,250	5.09	1.51
1,300	5.29	1.62
1,350	5.49	1.74
1,400	5.70	1.86
1,450	5.90	1.98
1,500	6.10	2.11
1,550	6.31	2.24
1,600	6.51	2.38
1,650	6.71	2.52
1,700	6.92	2.66
1,750	7.12	2.81
1,800	7.32	3.0
1,850	7.53	3.1
1,900	7.73	3.3
1,950	7.93	3.4
2,000	8.14	3.6
2,050	8.34	3.8
2,100	8.54	3.9
2,150	8.75	4.1
2,200	8.95	4.3
2,250	9.15	4.5
2,300	9.36	4.7

Friction Losses in Pipe: Standard Weight Steel		
Pipe Size, in. 12	Pipe Dia., in. 11.938	Surface Rough *C* 100
gpm	Velocity, fps	hd. loss, ft/100 ft
1,000	2.87	0.43
1,050	3.01	0.47
1,100	3.15	0.51
1,150	3.30	0.55
1,200	3.44	0.60
1,250	3.58	0.64
1,300	3.73	0.69
1,350	3.87	0.74
1,400	4.01	0.79
1,450	4.16	0.85
1,500	4.30	0.90
1,550	4.44	0.96
1,600	4.59	1.02
1,650	4.73	1.07
1,700	4.87	1.14
1,750	5.02	1.20
1,800	5.16	1.26
1,850	5.30	1.33
1,900	5.45	1.39
1,950	5.59	1.46
2,000	5.73	1.53
2,050	5.88	1.61
2,100	6.02	1.68
2,150	6.16	1.75
2,200	6.31	1.83
2,400	6.88	2.15
2,600	7.45	2.49
2,800	8.03	2.86
3,000	8.60	3.2
3,500	10.03	4.3
4,000	11.47	5.5

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3.4.2.12 Copper Pipe Friction Tables—Water

Copper Pipe Friction Tables

Tables are for copper tubing with a surface roughness of C = 130.

Nominal Size, in. 0.5	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 0.527 in. Velocity, fps	Head Loss ft/100 ft	Dia. 0.545 in. Velocity, fps	Head Loss ft/100 ft	Dia. 0.569 in. Velocity, fps	Head Loss ft/100 ft
0.5	0.74	0.80	0.69	0.68	0.63	0.55
1	1.47	2.89	1.38	2.46	1.26	1.99
1.5	2.21	6.1	2.06	5.2	1.89	4.22
2	2.94	10.4	2.75	8.9	2.52	7.2
2.5	3.68	15.8	3.44	13.4	3.15	10.9
3	4.41	22.1	4.13	18.8	3.79	15.2
3.5	5.15	29.4	4.81	24.9	4.42	20.2
4	5.88	37.6	5.50	31.9	5.05	25.9

Nominal Size, in. 0.75	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 0.745 in. Velocity, fps	Head Loss ft/100 ft	Dia. 0.785 in. Velocity, fps	Head Loss ft/100 ft	Dia. 0.811 in. Velocity, fps	Head Loss ft/100 ft
1	0.74	0.54	0.66	0.42	0.62	0.36
2	1.47	1.94	1.33	1.50	1.24	1.28
3	2.21	4.1	1.99	3.2	1.86	2.71
4	2.94	7.0	2.65	5.4	2.48	4.6
5	3.68	10.5	3.31	8.2	3.11	7.0
6	4.42	14.8	3.98	11.5	3.73	9.8
7	5.15	19.6	4.64	15.2	4.35	13.0
8	5.89	25.2	5.30	19.5	4.97	16.6

Nominal Size, in. 1	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 0.995 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.025 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.055 in. Velocity, fps	Head Loss ft/100 ft
2	0.83	0.47	0.78	0.41	0.73	0.36
3	1.24	1.00	1.17	0.87	1.10	0.75
4	1.65	1.71	1.56	1.48	1.47	1.28
5	2.06	2.58	1.94	2.23	1.84	1.94
6	2.48	3.6	2.33	3.1	2.20	2.72
7	2.89	4.8	2.72	4.2	2.57	3.6
8	3.30	6.2	3.11	5.3	2.94	4.6
10	4.13	9.3	3.89	8.0	3.67	7.0
11	4.54	11.1	4.28	9.6	4.04	8.3
12	4.95	13.0	4.67	11.3	4.40	9.8
13	5.36	15.1	5.05	13.1	4.77	11.4
14	5.78	17.3	5.44	15.0	5.14	13.0

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Copper Pipe Friction Tables (cont'd)

Tables are for copper tubing with a surface roughness of C = 130.

Nominal Size, in. 1.25	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 1.245 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.265 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.291 in. Velocity, fps	Head Loss ft/100 ft
5	1.32	0.87	1.28	1	1.23	0.73
6	1.58	1.21	1.53	1	1.47	1.02
7	1.84	1.62	1.79	1	1.72	1.35
8	2.11	2.07	2.04	2	1.96	1.73
9	2.37	2.57	2.30	2	2.21	2.16
10	2.64	3.1	2.55	3	2.45	2.62
11	2.90	3.7	2.81	3.4	2.70	3.1
12	3.16	4.4	3.06	4.1	2.94	3.7
13	3.43	5.1	3.32	4.7	3.19	4.3
14	3.69	5.8	3.57	5.4	3.43	4.9
15	3.95	6.6	3.83	6.1	3.68	5.5
20	5.27	11.3	5.11	10.4	4.90	9.4
25	6.59	17.0	6.38	15.8	6.13	14.3

Nominal Size, in. 1.5	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 1.481 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.505 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.527 in. Velocity, fps	Head Loss ft/100 ft
8	1.49	0.89	1.44	0.82	1.40	0.77
9	1.68	1.11	1.62	1.02	1.58	0.95
10	1.86	1.34	1.80	1.24	1.75	1.16
11	2.05	1.60	1.98	1.48	1.93	1.38
12	2.23	1.88	2.16	1.74	2.10	1.62
13	2.42	2.18	2.34	2.02	2.28	1.88
14	2.61	2.50	2.52	2.31	2.45	2.16
15	2.79	2.84	2.71	2.63	2.63	2.45
20	3.72	4.8	3.61	4.5	3.50	4.2
25	4.66	7.3	4.51	6.8	4.38	6.3
30	5.59	10.3	5.41	9.5	5.26	8.8
35	6.52	13.6	6.31	12.6	6.13	11.7
40	7.45	17.5	7.21	16.1	7.01	15.0

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Copper Pipe Friction Tables (cont'd)

Tables are for copper tubing with a surface roughness of C = 130.

Nominal Size, in. 2	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 1.959 in. Velocity, fps	Head Loss ft/100 ft	Dia. 1.985 in. Velocity, fps	Head Loss ft/100 ft	Dia. 2.009 in. Velocity, fps	Head Loss ft/100 ft
10	1.06	0.34	1.04	0.32	1.01	0.30
11	1.17	0.41	1.14	0.39	1.11	0.36
12	1.28	0.48	1.24	0.45	1.21	0.43
13	1.38	0.56	1.35	0.52	1.32	0.49
14	1.49	0.64	1.45	0.60	1.42	0.57
15	1.60	0.73	1.56	0.68	1.52	0.64
20	2.13	1.24	2.07	1.16	2.02	1.10
25	2.66	1.88	2.59	1.76	2.53	1.66
30	3.19	2.63	3.11	2.46	3.04	2.32
35	3.73	3.5	3.63	3.3	3.54	3.1
40	4.26	4.5	4.15	4.2	4.05	4.0
45	4.79	5.6	4.67	5.2	4.55	4.9
50	5.32	6.8	5.18	6.3	5.06	6.0
55	5.85	8.1	5.70	7.6	5.57	7.1
60	6.39	9.5	6.22	8.9	6.07	8.4
70	7.45	12.6	7.26	11.8	7.08	11.1

Nominal Size, in. 2.5	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 2.435 in. Velocity, fps	Head Loss ft/100 ft	Dia. 2.465 in. Velocity, fps	Head Loss ft/100 ft	Dia. 2.495 in. Velocity, fps	Head Loss ft/100 ft
20	1.38	0.43	1.34	0.41	1.31	0.38
25	1.72	0.65	1.68	0.61	1.64	0.58
30	2.07	0.91	2.02	0.86	1.97	0.81
35	2.41	1.21	2.35	1.14	2.30	1.08
40	2.76	1.55	2.69	1.46	2.62	1.38
45	3.10	1.93	3.03	1.82	2.95	1.72
50	3.44	2.35	3.36	2.21	3.28	2.08
55	3.79	2.80	3.70	2.64	3.61	2.49
60	4.13	3.3	4.03	3.1	3.94	2.92
65	4.48	3.8	4.37	3.6	4.27	3.4
70	4.82	4.4	4.71	4.1	4.59	3.9
75	5.17	5.0	5.04	4.7	4.92	4.4
80	5.51	5.6	5.38	5.3	5.25	5.0
85	5.86	6.3	5.71	5.9	5.58	5.6
90	6.20	7.0	6.05	6.6	5.91	6.2
95	6.55	7.7	6.39	7.2	6.23	6.8
100	6.89	8.5	6.72	8.0	6.56	7.5
105	7.23	9.3	7.06	8.7	6.89	8.2
110	7.58	10.1	7.40	9.5	7.22	9.0
115	7.92	11.0	7.73	10.3	7.55	9.7
120	8.27	11.9	8.07	11.2	7.87	10.5

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Copper Pipe Friction Tables (cont'd)

Tables are for copper tubing with a surface roughness of C = 130.

Nominal Size, in. 3	Type K Tubing		Type L Tubing		Type M Tubing	
gpm	Dia. 2.907 in. Velocity, fps	Head Loss ft/100 ft	Dia. 2.945 in. Velocity, fps	Head Loss ft/100 ft	Dia. 2.981 in. Velocity, fps	Head Loss ft/100 ft
20	0.97	0.18	0.94	0.17	0.92	0.16
25	1.21	0.27	1.18	0.26	1.15	0.24
30	1.45	0.39	1.41	0.36	1.38	0.34
35	1.69	0.51	1.65	0.48	1.61	0.45
40	1.93	0.66	1.88	0.62	1.84	0.58
45	2.18	0.82	2.12	0.77	2.07	0.72
50	2.42	0.99	2.36	0.93	2.30	0.88
60	2.90	1.39	2.83	1.30	2.76	1.23
70	3.38	1.85	3.30	1.73	3.22	1.63
80	3.87	2.36	3.77	2.22	3.68	2.09
90	4.35	2.94	4.24	2.76	4.14	2.60
100	4.83	3.6	4.71	3.4	4.60	3.2
110	5.32	4.3	5.18	4.0	5.06	3.8
120	5.80	5.0	5.65	4.7	5.52	4.4
130	6.28	5.8	6.12	5.4	5.98	5.1
140	6.77	6.7	6.59	6.3	6.44	5.9
150	7.25	7.6	7.07	7.1	6.90	6.7
160	7.73	8.5	7.54	8.0	7.36	7.5
170	8.22	9.5	8.01	9.0	7.81	8.4
180	8.70	10.6	8.48	9.9	8.27	9.4
190	9.18	11.7	8.95	11.0	8.73	10.4
200	9.67	12.9	9.42	12.1	9.19	11.4

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3.4.2.13 Natural Gas Pipe Sizing

Maximum Capacity of Steel Gas Pipe in Cubic Feet per Hour (cfh)

Nominal Iron Pipe Size, in.	Internal Diameter, in.	Length of Pipe, ft													
		10	20	30	40	50	60	70	80	90	100	125	150	175	200
1/4	0.364	32	22	18	15	14	12	11	11	10	9	8	8	7	6
3/8	0.493	72	49	40	34	30	27	25	23	22	21	18	17	15	14
1/2	0.622	132	92	73	63	56	50	46	43	40	38	34	31	28	26
3/4	0.824	278	190	152	130	115	105	96	90	84	79	72	64	59	55
1	1.049	520	350	285	245	215	195	180	170	160	150	130	120	110	100
1 1/4	1.380	1,050	730	590	500	440	400	370	350	320	305	275	250	225	210
1 1/2	1.610	1,600	1,100	890	760	670	610	560	530	490	460	410	380	350	320
2	2.067	3,050	2,100	1,650	1,450	1,270	1,150	1,050	990	930	870	780	710	650	610
2 1/2	2.469	4,800	3,300	2,700	2,300	2,000	1,850	1,700	1,600	1,500	1,400	1,250	1,130	1,050	980
3	3.068	8,500	5,900	4,700	4,100	3,600	3,250	3,000	2,800	2,600	2,500	2,200	2,000	1,850	1,700
4	4.026	17,500	12,000	9,700	8,300	7,400	6,800	6,200	5,800	5,400	5,100	4,500	4,100	3,800	3,500

Note: Capacity is in cubic feet per hour at gas pressures of 0.5 psig or less and a pressure drop of 0.3 inches of water; specific gravity = 0.60.

Source: Copyright by the American Gas Association and the National Fire Protection Association.

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Sizing equations

1. Low-pressure gas equation [less than 1 1/2 pounds per square inch (psi)(10.3 kPa)]

$$D = \frac{Q^{0.381}}{19.17\left(\frac{\Delta H}{C_r \times L}\right)^{0.206}}$$

2. High-pressure gas equation [1 1/2 psi (10.3 kPa) and above]

$$D = \frac{Q^{0.381}}{18.93\left(\frac{(P_1^2 - P_2^2) \times Y}{C_r \times L}\right)^{0.206}}$$

where

C_r = value determined by the table below

D = inside diameter of pipe (in. or mm)

Q = input rate appliance(s) [ft^3/hr at 60°F (16°C) and 30-in. mercury column]

P_1 = upstream pressure (psia) (P_1 + 14.7)

P_2 = downstream pressure (psia) (P_2 + 14.7)

L = equivalent length of pipe (ft)

Y = value determined by the table below

ΔH = pressure drop [in. water column (27.7-inch water column = 1 psi)]

C_r and Y Values for Natural Gas and Undiluted Propane at Standard Conditions

Gas	Equation Factors	
	C_r	Y
Natural gas	0.6094	0.9992
Undiluted propane	1.2462	0.9910

For SI: 1 ft^3 = 0.028 m^3, 1 ft = 305 mm, 1-in. water column = 0.2488 kPa, 1 lb/in^2 = 6.895 kPa, 1 Btu/hr = 0.293 W

Source: Section 402.4 and Table 402.4 are copyrighted excerpts from the 2021 *International Fuel Gas Code*. Copyright © 2020. International Code Council, Inc. All rights reserved. Reproduced with permission granted by ICC in April 2026. www.ICCSAFE.org.

3.4.2.14 Fuel Oil Pipe Sizing

Recommended Nominal Size for Fuel Oil Suction Lines from Tank to Pump (Residual Grades No. 5 and No. 6)

Pumping Rate, gph	Length of Run in Feet at Maximum Suction Lift of 15 ft									
	25	50	75	100	125	150	175	200	250	300
10	1 1/2	1 1/2	1 1/2	1 1/2	1 1/2	1 1/2	2	2	2 1/2	2 1/2
40	1 1/2	1 1/2	1 1/2	2	2	2 1/2	2 1/2	2 1/2	2 1/2	3
70	1 1/2	2	2	2	2	2 1/2	2 1/2	2 1/2	3	3
100	2	2	2	2 1/2	2 1/2	3	3	3	3	3
130	2	2	2 1/2	2 1/2	2 1/2	3	3	3	3	4
160	2	2	2 1/2	2 1/2	2 1/2	3	3	3	4	4
190	2	2 1/2	2 1/2	2 1/2	3	3	3	4	4	4
220	2 1/2	2 1/2	2 1/2	3	3	3	4	4	4	4

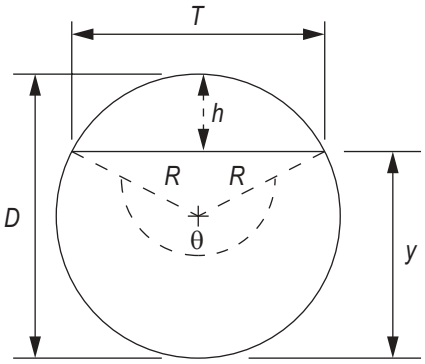
Recommended Nominal Size for Fuel Oil Suction Lines from Tank to Pump (Distillate Grades No. 1 and No. 2)

Pumping Rate, gph	Length of Run in Feet at Maximum Suction Lift of 10 ft									
	25	50	75	100	125	150	175	200	250	300
10	1/2	1/2	1/2	1/2	1/2	1/2	1/2	3/4	3/4	1
40	1/2	1/2	1/2	1/2	1/2	3/4	3/4	3/4	3/4	1
70	1/2	1/2	3/4	3/4	3/4	3/4	3/4	1	1	1
100	1/2	3/4	3/4	3/4	3/4	1	1	1	1	1 1/4
130	1/2	3/4	3/4	1	1	1	1	1	1 1/4	1 1/4
160	3/4	3/4	3/4	1	1	1	1	1 1/4	1 1/4	1 1/4
190	3/4	3/4	1	1	1	1	1 1/4	1 1/4	1 1/4	2
220	3/4	1	1	1	1	1 1/4	1 1/4	1 1/4	1 1/4	2

Notes:
1. Pipe sizes smaller than 1 in. IPS are not recommended for use with residual grade fuel oils.
2. Lines conveying fuel oil from pump discharge port to burners and tank return may be reduced by one or two sizes, depending on piping length and pressure losses.

Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 22, Pipe Design, Tables 41 and 42.

3.4.3 Drainage Piping



R = radius (ft or m)

D = diameter (ft or m)

h = distance from top of pipe to top of flow (ft or m = $D - y$)

y = depth of flow (ft or m = $D - h$)

T = top width (ft or m)

θ = central angle (radians) (0 for empty pipes; π for half-full pipe; 2π for full pipe)

For ≤ 1/2 full:

$$\theta = 2\arccos[(R - y)/R]$$

For ≥ 1/2 full:

$$\theta = \pi + 2\arcsin[(y - R)/R]$$

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Manning's Equation

$$Q = (1.486/n)AR_H^{2/3}S^{1/2} \quad \text{(IP units)} \qquad Q = (1.0/n)AR_H^{2/3}S^{1/2} \quad \text{(SI units)}$$

$$V = (1.486/n)R^{2/3}S^{1/2} \quad \text{(IP units)} \qquad V = (1.0/n)R_H^{2/3}S^{1/2} \quad \text{(SI units)}$$

$$A\frac{R^2}{2}(\theta - \sin\theta) = \frac{D^2}{8}(\theta - \sin\theta)$$

$$P = R\theta = \frac{1}{2}D\theta$$

$$R_H = \frac{A}{P} = \frac{D}{4}[1 - (\sin\theta/\theta)] \qquad R_H = \frac{D}{4} \text{ for half or full flow}$$

$$T = D[\sin(\theta/2)]$$

where

Q = discharge or rate of flow (ft^3/sec or m^3/s)

V = flow velocity (ft/sec or m/s)

n = Manning's roughness coefficient (dimensionless)

A = cross-sectional area of flow (ft^2 or m^2)

P = wetted perimeter (ft or m)

R = pipe radius (ft or m)

R_H = hydraulic radius (ft or m)

S = h_L/L = slope of the grade line (ft/ft or m/m)

h_L = head loss (ft or m)

L = pipe length (ft or m)

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3.4.3.1 Manning's Roughness Coefficient, n

Piping Material	*n*
Cast iron (coated)	0.012
Wrought iron pipe	0.015
Galvanized iron pipe	0.015
Copper	0.011
Corrugated storm pipe	0.024
Vitrified sewer pipe	0.014
Concrete pipe	0.013
Clay	0.013
Glass	0.010
Plastic	0.013
PVC	0.010
Polyethylene	0.012

3.4.3.2 Manning's Piping Slopes, S

Piping Slope, *S*		$S^{1/2}$
Slope (in./ft)	Slope (ft/ft)(m/m)	
1/16	0.0052	0.0722
1/8	0.0104	0.1021
1/4	0.0208	0.1443
1/2	0.0417	0.2041

For sanitary drain applications, drain piping is assumed to be half full unless otherwise specified, to allow adequate space for gas venting.

For storm drain applications, drain piping is assumed to be full.

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Manning's Tables—Velocity and Flow in Cast Iron Pipe with $n = 0.012$

	SLOPE		1/4 FULL				1/2 FULL				3/4 FULL				FULL			
Pipe Size in.	in./ft	ft/ft	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm
1 1/2	0.0240	0.0020	0.0031	0.0212	0.42	0.58	0.0061	0.0313	0.54	1.50	0.0092	0.0371	0.61	2.52	0.0123	0.0313	0.54	2.99
	0.0360	0.0030			0.51	0.71			0.67	1.83			0.75	3.08			0.67	3.66
	0.0480	0.0040			0.59	0.82			0.77	2.12			0.86	3.56			0.77	4.23
	0.0600	0.0050			0.66	0.91			0.86	2.37			0.96	3.98			0.86	4.73
	0.0720	0.0060			0.73	1.00			0.94	2.59			1.05	4.36			0.94	5.18
	0.0840	0.0070			0.78	1.08			1.02	2.80			1.14	4.71			1.02	5.60
	0.0960	0.0080			0.84	1.16			1.09	2.99			1.22	5.03			1.09	5.98
	0.1080	0.0090			0.89	1.23			1.15	3.17			1.29	5.34			1.15	6.35
	0.1200	0.0100			0.94	1.29			1.21	3.34			1.36	5.62			1.21	6.69
	0.2400	0.0200			1.33	1.83			1.72	4.73			1.93	7.95			1.72	9.46
	0.3600	0.0300			1.62	2.24			2.10	5.79			2.36	9.74			2.10	11.59
	0.4800	0.0400			1.88	2.58			2.43	6.69			2.72	11.25			2.43	13.38
	0.6000	0.0500			2.10	2.89			2.72	7.48			3.04	12.58			2.72	14.96
	0.7200	0.0600			2.30	3.16			2.97	8.19			3.34	13.78			2.97	16.39
	0.8400	0.0700			2.48	3.42			3.21	8.85			3.60	14.88			3.21	17.70
2	0.0240	0.0020	0.0052	0.0278	0.50	1.18	0.0105	0.0408	0.65	3.06	0.0157	0.0484	0.73	5.14	0.0210	0.0408	0.65	6.11
	0.0360	0.0030			0.61	1.44			0.80	3.74			0.89	6.29			0.80	7.48
	0.0480	0.0040			0.71	1.67			0.92	4.32			1.03	7.27			0.92	8.64
	0.0600	0.0050			0.79	1.87			1.03	4.83			1.15	8.12			1.03	9.66
	0.0720	0.0060			0.87	2.04			1.13	5.29			1.26	8.90			1.13	10.58
	0.0840	0.0070			0.94	2.21			1.22	5.72			1.36	9.61			1.22	11.43
	0.0960	0.0080			1.00	2.36			1.30	6.11			1.46	10.28			1.30	12.22
	0.1080	0.0090			1.06	2.50			1.38	6.48			1.55	10.90			1.38	12.96
	0.1200	0.0100			1.12	2.64			1.45	6.83			1.63	11.49			1.45	13.66
	0.2400	0.0200			1.59	3.73			2.05	9.66			2.30	16.25			2.05	19.32
	0.3600	0.0300			1.94	4.57			2.52	11.83			2.82	19.90			2.52	23.66
	0.4800	0.0400			2.24	5.28			2.91	13.66			3.26	22.98			2.91	27.33
	0.6000	0.0500			2.51	5.90			3.25	15.28			3.64	25.69			3.25	30.55
	0.7200	0.0600			2.75	6.46			3.56	16.73			3.99	28.14			3.56	33.47
	0.8400	0.0700			2.97	6.98			3.84	18.07			4.31	30.40			3.84	36.15
3	0.0240	0.0020	0.0119	0.0419	0.66	3.55	0.0239	0.0617	0.86	9.18	0.0358	0.0731	0.96	15.45	0.0478	0.0617	0.86	18.37
	0.0360	0.0030			0.81	4.34			1.05	11.25			1.18	18.92			1.05	22.50
	0.0480	0.0040			0.94	5.02			1.21	12.99			1.36	21.84			1.21	25.98
	0.0600	0.0050			1.05	5.61			1.35	14.52			1.52	24.42			1.35	29.04
	0.0720	0.0060			1.15	6.14			1.48	15.91			1.66	26.75			1.48	31.82
	0.0840	0.0070			1.24	6.63			1.60	17.18			1.80	28.90			1.60	34.36
	0.0960	0.0080			1.32	7.09			1.71	18.37			1.92	30.89			1.71	36.74
	0.1080	0.0090			1.40	7.52			1.82	19.48			2.04	32.76			1.82	38.97
	0.1200	0.0100			1.48	7.93			1.92	20.54			2.15	34.54			1.92	41.07
	0.2400	0.0200			2.09	11.21			2.71	29.04			3.04	48.84			2.71	58.09
	0.3600	0.0300			2.56	13.73			3.32	35.57			3.72	59.82			3.32	71.14
	0.4800	0.0400			2.96	15.86			3.83	41.07			4.29	69.07			3.83	82.15
	0.6000	0.0500			3.31	17.73			4.28	45.92			4.80	77.23			4.28	91.84
	0.7200	0.0600			3.62	19.42			4.69	50.31			5.26	84.60			4.69	100.61
	0.8400	0.0700			3.91	20.98			5.07	54.34			5.68	91.38			5.07	108.67

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Manning's Tables—Velocity and Flow in Cast Iron Pipe with $n = 0.012$ (cont'd)

	SLOPE		1/4 FULL				1/2 FULL				3/4 FULL				FULL			
Pipe Size in.	in./ft	ft/ft	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm	A, ft²	R_H, ft	Velocity ft/sec	Flow gpm
4	0.0240	0.0020	0.0212	0.0558	0.80	7.61	0.0423	0.0821	1.04	19.71	0.0635	0.0974	1.16	33.15	0.0847	0.0821	1.04	39.42
	0.0360	0.0030			0.98	9.32			1.27	24.14			1.42	40.59			1.27	48.28
	0.0480	0.0040			1.13	10.76			1.47	27.87			1.64	46.88			1.47	55.75
	0.0600	0.0050			1.27	12.03			1.64	31.16			1.84	52.41			1.64	62.33
	0.0720	0.0060			1.39	13.18			1.80	34.14			2.01	57.41			1.80	68.28
	0.0840	0.0070			1.50	14.24			1.94	36.87			2.18	62.01			1.94	73.75
	0.0960	0.0080			1.60	15.22			2.07	39.42			2.33	66.29			2.07	78.84
	0.1080	0.0090			1.70	16.14			2.20	41.81			2.47	70.31			2.20	83.62
	0.1200	0.0100			1.79	17.02			2.32	44.07			2.60	74.12			2.32	88.14
	0.2400	0.0200			2.53	24.07			3.28	62.33			3.68	104.82			3.28	124.65
	0.3600	0.0300			3.10	29.47			4.02	76.33			4.50	128.37			4.02	152.67
	0.4800	0.0400			3.58	34.03			4.64	88.14			5.20	148.23			4.64	176.29
	0.6000	0.0500			4.01	38.05			5.19	98.55			5.81	165.73			5.19	197.10
	0.7200	0.0600			4.39	41.68			5.68	107.95			6.37	181.55			5.68	215.91
	0.8400	0.0700			4.74	45.02			6.14	116.60			6.88	196.09			6.14	233.21
5	0.0240	0.0020	0.0333	0.0700	0.93	13.92	0.0666	0.1029	1.21	36.05	0.0998	0.1221	1.35	60.63	0.1331	0.1029	1.21	72.11
	0.0360	0.0030			1.14	17.05			1.48	44.16			1.66	74.26			1.48	88.31
	0.0480	0.0040			1.32	19.69			1.71	50.99			1.91	85.75			1.71	101.98
	0.0600	0.0050			1.47	22.01			1.91	57.01			2.14	95.87			1.91	114.01
	0.0720	0.0060			1.61	24.11			2.09	62.45			2.34	105.02			2.09	124.89
	0.0840	0.0070			1.74	26.04			2.26	67.45			2.53	113.43			2.26	134.90
	0.0960	0.0080			1.86	27.84			2.41	72.11			2.71	121.26			2.41	144.22
	0.1080	0.0090			1.98	29.53			2.56	76.48			2.87	128.62			2.56	152.96
	0.1200	0.0100			2.08	31.13			2.70	80.62			3.03	135.58			2.70	161.24
	0.2400	0.0200			2.95	44.02			3.82	114.01			4.28	191.74			3.82	228.03
	0.3600	0.0300			3.61	53.92			4.67	139.64			5.24	234.83			4.67	279.27
	0.4800	0.0400			4.17	62.26			5.40	161.24			6.05	271.16			5.40	322.48
	0.6000	0.0500			4.66	69.60			6.04	180.27			6.77	303.16			6.04	360.54
6	0.0240	0.0020	0.0481	0.0841	1.05	22.77	0.0962	0.1238	1.37	58.98	0.1443	0.1468	1.53	99.19	0.1924	0.1238	1.37	117.96
	0.0360	0.0030			1.29	27.89			1.67	72.24			1.88	121.48			1.67	144.47
	0.0480	0.0040			1.49	32.21			1.93	83.41			2.17	140.27			1.93	166.82
	0.0600	0.0050			1.67	36.01			2.16	93.26			2.42	156.83			2.16	186.51
	0.0720	0.0060			1.83	39.44			2.37	102.16			2.65	171.80			2.37	204.32
	0.0840	0.0070			1.97	42.60			2.56	110.34			2.86	185.56			2.56	220.69
	0.0960	0.0080			2.11	45.55			2.73	117.96			3.06	198.38			2.73	235.92
	0.1080	0.0090			2.24	48.31			2.90	125.12			3.25	210.41			2.90	250.24
	0.1200	0.0100			2.36	50.92			3.05	131.89			3.42	221.79			3.05	263.77
	0.2400	0.0200			3.34	72.02			4.32	186.51			4.84	313.66			4.32	373.03
	0.3600	0.0300			4.08	88.20			5.29	228.43			5.93	384.16			5.29	456.87
	0.4800	0.0400			4.72	101.85			6.11	263.77			6.85	443.58			6.11	527.54

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Manning's Tables—Velocity and Flow in Cast Iron Pipe with $n = 0.012$ (cont'd)

	SLOPE		1/4 FULL				1/2 FULL				3/4 FULL				FULL			
Pipe Size					Velocity	Flow			Velocity	Flow			Velocity	Flow			Velocity	Flow
in.	in./ft	ft/ft	A, ft²	R_H, ft	ft/sec	gpm	A, ft²	R_H, ft	ft/sec	gpm	A, ft²	R_H, ft	ft/sec	gpm	A, ft²	R_H, ft	ft/sec	gpm
8	0.0240	0.0020	0.0860	0.1125	1.28	49.42	0.1719	0.1654	1.66	128.00	0.2579	0.1962	1.86	215.26	0.3438	0.1654	1.66	256.01
	0.0360	0.0030			1.57	60.53			2.03	156.77			2.28	263.64			2.03	313.54
	0.0480	0.0040			1.81	69.90			2.35	181.03			2.63	304.43			2.35	362.05
	0.0600	0.0050			2.03	78.15			2.62	202.39			2.94	340.36			2.62	404.78
	0.0720	0.0060			2.22	85.60			2.87	221.71			3.22	372.85			2.87	443.42
	0.0840	0.0070			2.40	92.46			3.10	239.47			3.48	402.72			3.10	478.95
	0.0960	0.0080			2.56	98.85			3.32	256.01			3.72	430.53			3.32	512.02
	0.1080	0.0090			2.72	104.84			3.52	271.54			3.95	456.65			3.52	543.08
	0.1200	0.0100			2.86	110.52			3.71	286.23			4.16	481.35			3.71	572.45
	0.2400	0.0200			4.05	156.29			5.25	404.78			5.88	680.73			5.25	809.57
	0.3600	0.0300			4.96	191.42			6.42	495.76			7.20	833.72			6.42	991.52
	0.4800	0.0400			5.73	221.03			7.42	572.45			8.32	962.69			7.42	1144.90
10	0.0240	0.0020	0.1363	0.1417	1.50	91.50	0.2727	0.2083	1.94	236.98	0.4091	0.2471	2.17	398.52	0.5454	0.2083	1.94	473.95
	0.0360	0.0030			1.83	112.06			2.37	290.23			2.66	488.09			2.37	580.47
	0.0480	0.0040			2.11	129.40			2.74	335.13			3.07	563.59			2.74	670.27
	0.0600	0.0050			2.36	144.67			3.06	374.69			3.43	630.12			3.06	749.38
	0.0720	0.0060			2.59	158.48			3.35	410.45			3.76	690.26			3.35	820.91
	0.0840	0.0070			2.80	171.18			3.62	443.34			4.06	745.57			3.62	886.68
	0.0960	0.0080			2.99	183.00			3.87	473.95			4.34	797.04			3.87	947.90
	0.1080	0.0090			3.17	194.10			4.11	502.70			4.60	845.39			4.11	1005.40
	0.1200	0.0100			3.34	204.60			4.33	529.89			4.85	891.12			4.33	1059.79
	0.2400	0.0200			4.73	289.34			6.12	749.38			6.86	1260.24			6.12	1498.76
	0.3600	0.0300			5.79	354.37			7.50	917.80			8.41	1543.47			7.50	1835.60
	0.4800	0.0400			6.69	409.20			8.66	1059.79			9.71	1782.24			8.66	2119.57
12	0.0240	0.0020	0.1944	0.1691	1.68	146.90	0.3888	0.2488	2.18	380.46	0.5832	0.2950	2.44	639.81	0.7776	0.2488	2.18	760.91
	0.0360	0.0030			2.06	179.91			2.67	465.96			2.99	783.61			2.67	931.92
	0.0480	0.0040			2.38	207.75			3.08	538.05			3.46	904.83			3.08	1076.09
	0.0600	0.0050			2.66	232.27			3.45	601.55			3.86	1011.63			3.45	1203.11
	0.0720	0.0060			2.92	254.44			3.78	658.97			4.23	1108.19			3.78	1317.94
	0.0840	0.0070			3.15	274.82			4.08	711.77			4.57	1196.98			4.08	1423.54
	0.0960	0.0080			3.37	293.80			4.36	760.91			4.89	1279.63			4.36	1521.83
	0.1080	0.0090			3.57	311.62			4.63	807.07			5.19	1357.25			4.63	1614.14
	0.1200	0.0100			3.77	328.47			4.88	850.73			5.47	1430.67			4.88	1701.45
	0.2400	0.0200			5.32	464.53			6.89	1203.11			7.73	2023.27			6.89	2406.22
	0.3600	0.0300			6.52	568.94			8.44	1473.50			9.47	2477.99			8.44	2947.00
	0.4800	0.0400			7.53	656.95			9.75	1701.45			10.93	2861.33			9.75	3402.90
15	0.0240	0.0020	0.3113	0.2141	1.97	275.46	0.6226	0.3148	2.55	713.41	0.9340	0.3734	2.86	1199.74	1.2452	0.3148	2.55	1426.82
	0.0360	0.0030			2.41	337.36			3.13	873.75			3.51	1469.38			3.13	1747.49
	0.0480	0.0040			2.79	389.55			3.61	1008.91			4.05	1696.69			3.61	2017.83
	0.0600	0.0050			3.12	435.53			4.04	1128.00			4.53	1896.96			4.04	2256.00
	0.0720	0.0060			3.41	477.10			4.42	1235.66			4.96	2078.02			4.42	2471.33
	0.0840	0.0070			3.69	515.33			4.78	1334.67			5.35	2244.51			4.78	2669.34
	0.0960	0.0080			3.94	550.91			5.11	1426.82			5.72	2399.49			5.11	2853.64
	0.1080	0.0090			4.18	584.33			5.42	1513.37			6.07	2545.04			5.42	3026.74
	0.1200	0.0100			4.41	615.94			5.71	1595.23			6.40	2682.71			5.71	3190.47
	0.2400	0.0200			6.23	871.07			8.07	2256.00			9.05	3793.92			8.07	4512.00
	0.3600	0.0300			7.64	1066.84			9.89	2763.03			11.08	4646.58			9.89	5526.05
	0.4800	0.0400			8.82	1231.88			11.42	3190.47			12.80	5365.41			11.42	6380.94

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3.4.4 Water Hammer

The maximum surge pressure caused by water hammer for any moving fluid is:

$$\Delta p_h = \frac{\rho C_s v}{g_c}$$

where

Δp_h = pressure rise caused by water hammer $\left(\frac{\text{lbf}}{\text{ft}^2}\right)$

ρ = fluid density $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

C_s = velocity of sound in fluid (fps) (4,720 fps for water)

v = fluid flow velocity (fps)

3.5 Impulse-Momentum Principle

The resultant force in a given direction acting on the fluid equals the rate of change of momentum of the fluid.

$$\sum \boldsymbol{F} = \sum Q_2 \rho_2 v_2 - \sum Q_1 \rho_1 v_1$$

where

$\sum \boldsymbol{F}$ = the resultant of all external forces acting on the control volume

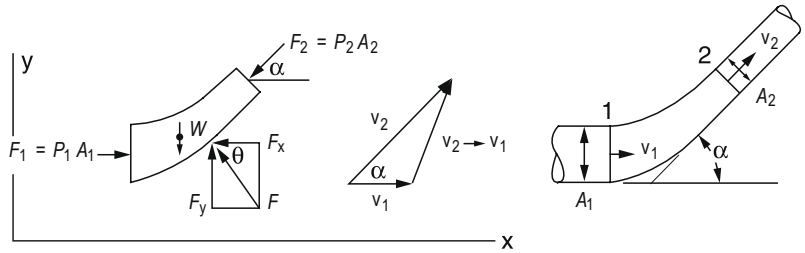
$\sum Q_1 \rho_1 v_1$ = the rate of momentum of the fluid flow entering the control volume in the same direction as the force

$\sum Q_2 \rho_2 v_2$ = the rate of momentum of the fluid flow leaving the control volume in the same direction as the force

3.5.1 Pipe Bends, Enlargements, and Contractions

The force exerted by a flowing fluid on a bend, enlargement, or contraction in a pipeline may be computed using the *impulse-momentum principle*.

Impulse-Momentum Principle



$$P_1 A_1 - P_2 A_2 \cos\alpha - \boldsymbol{F}_x = Q\rho\,(v_2 \cos\alpha - v_1)$$

$$\boldsymbol{F}_y - W - P_2 A_2 \sin\alpha = Q\rho\,(v_2 \sin\alpha - 0)$$

where

$\boldsymbol{F}$ = force exerted by the bend on the fluid (while force exerted by the fluid on the bend is equal in magnitude but opposite in sign)

$\boldsymbol{F}_x$, $\boldsymbol{F}_y$ = x-component and y-component of the force $\boldsymbol{F} = \sqrt{\boldsymbol{F}_x^2 + \boldsymbol{F}_y^2}$ and $\theta = \tan^{-1}\left(\frac{\boldsymbol{F}_y}{\boldsymbol{F}_x}\right)$

P = internal pressure in the pipeline

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A = cross-sectional area of the pipeline

W = weight of the fluid

v = velocity of the fluid flow

α = angle the pipe bend makes with the horizontal

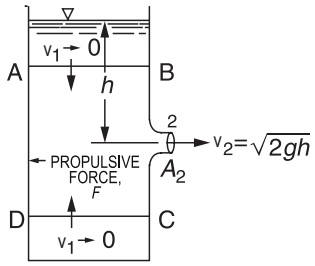
ρ = density of the fluid

Q = quantity of fluid flow

3.5.2 Jet Propulsion

$$\boldsymbol{F} = Q\rho\,(v_2 - 0)$$

$$\boldsymbol{F} = 2\gamma h A_2$$



where

$\boldsymbol{F}$ = propulsive force

γ = specific weight of the fluid

h = height of the fluid above the outlet

A_2 = area of the nozzle tip

$$Q = A_2\sqrt{2gh}$$

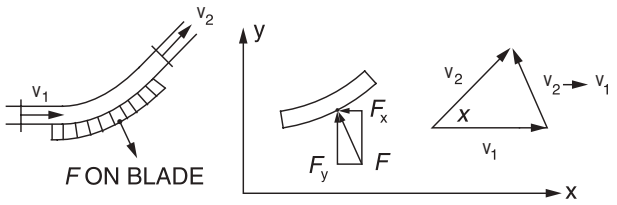
$$v_2 = \sqrt{2gh}$$

3.5.3 Deflectors and Blades

3.5.3.1 Fixed Blade

$$-\boldsymbol{F}_x = Q\rho\,(v_2 \cos\alpha - v_1)$$

$$\boldsymbol{F}_y = Q\rho\,(v_2 \sin\alpha - 0)$$

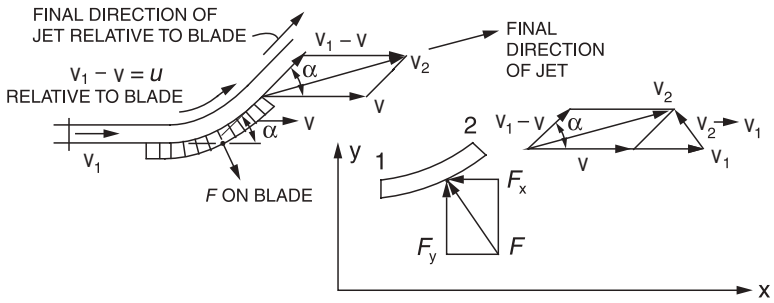


3.5.3.2 Moving Blade

$$-\boldsymbol{F}_x = Q\rho\,(v_{2x} - v_{1x}) = -Q\rho\,(v_1 - v)(1 - \cos\alpha)$$

$$\boldsymbol{F}_y = Q\rho\,(v_{2y} - v_{1y}) = +Q\rho\,(v_1 - v)\sin\alpha$$

where v = velocity of the blade



3.5.3.3 Impulse Turbine

$$\dot{W} = Q\rho\left(v_1 - v\right)\left(1 - \cos\alpha\right)v$$

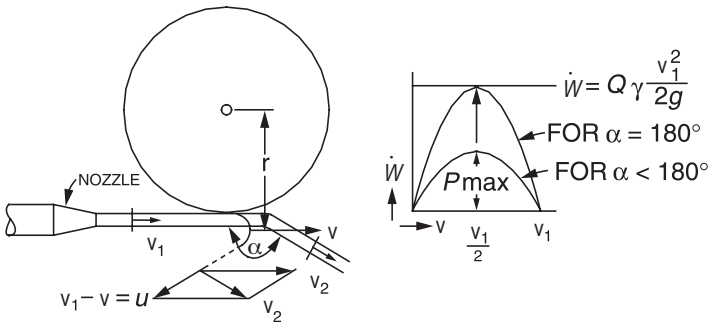
where

$\dot{W}$ = power of the turbine

$$\dot{W}_{max} = Q\rho\left(\frac{v_1^2}{4}\right)\left(1 - \cos\alpha\right)$$

When $\alpha = 180°$,

$$\dot{W}_{max} = \left(\frac{Q\rho v_1^2}{2}\right) = \left(\frac{Q\gamma v_1^2}{2g}\right)$$



Source: Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed., New York: John Wiley & Sons, 1982.

3.6 Compressible Flow

3.6.1 Mach Number

Speed of sound in a fluid:

$$c = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{1}{\beta\rho}}\,(\text{SI units})(\text{m/s})$$

$$c = \sqrt{\frac{Bg_c}{\rho}} = \sqrt{\frac{g_c}{\beta\rho}}\,(\text{I-P units})(\text{ft/sec})$$

where

B = bulk modulus $\left(\frac{\text{lbf}}{\text{ft}^2}\text{ (I-P) or Pa (SI)}\right)$

ρ = density $\left(\frac{\text{lbm}}{\text{ft}^3}\text{ (I-P) or }\frac{\text{kg}}{\text{m}^3}\text{ (SI)}\right)$

β = compressibility $\left(\frac{\text{ft}^2}{\text{lbf}}\text{ (I-P) or Pa}^{-1}\text{ (SI)}\right)$

Local speed of sound in an ideal gas

$$c = \sqrt{kRg_cT}\,(\text{I-P}) \qquad c = \sqrt{kRT}\,(\text{SI})$$

where

c = local speed of sound

k = ratio of specific heats = $\frac{c_p}{c_v}$ = 1.4 for air

R = specific gas constant = $\frac{\overline{R}}{\text{molecular weight}}$ $\qquad \frac{\text{ft-lbf}}{\text{lb}_{\text{mole}}\text{-°R}}\text{(I-P)} \qquad \text{kmol-K(SI)}$

T = absolute temperature, °R (I-P), K (SI)

The *Mach number* (M) is the ratio of the fluid velocity to the speed of sound:

$$\text{M} = \frac{V}{c}$$

where V = mean fluid velocity

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3.6.2 Isentropic Flow Relationships

In an *ideal gas* for an *isentropic process*, the following relationships exist between static properties at any two points in the flow:

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{k}{(k-1)}} = \left(\frac{\rho_2}{\rho_1}\right)^k$$

where

P = static pressure

ρ = static density

T = static temperature

P and T are in absolute terms.

The stagnation temperature, T_0, at a point in the flow is related to the static temperature, as follows:

$$T_0 = T + \frac{V^2}{2c_p}$$

The energy relation between two points is:

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

The relationship between the static and stagnation properties (T_0, P_0, and ρ_0) at any point in the flow can be expressed as a function of the Mach number M:

$$\frac{T_0}{T} = 1 + \frac{k-1}{2}\mathrm{M}^2$$

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\frac{k}{(k-1)}} = \left(1 + \frac{k-1}{2}\mathrm{M}^2\right)^{\frac{k}{(k-1)}}$$

$$\frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{\frac{1}{(k-1)}} = \left(1 + \frac{k-1}{2}\mathrm{M}^2\right)^{\frac{1}{(k-1)}}$$

Compressible flows are often accelerated or decelerated through a nozzle or diffuser. The point at which the Mach number is sonic is called the throat and its area is represented by the variable, A^*. The following area ratio holds for any Mach number.

$$\frac{A}{A^*} = \frac{1}{\mathrm{M}}\left[\frac{1 + \frac{1}{2}(k-1)\mathrm{M}^2}{\frac{1}{2}(k+1)}\right]^{\frac{(k+1)}{2(k-1)}}$$

where

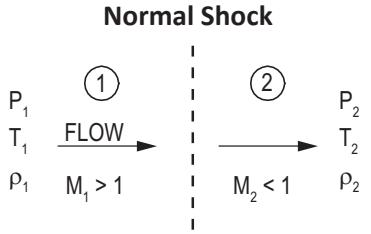
A = area (length^2)

A^* = area at the sonic point (M = 1.0)

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3.6.3 Normal Shock Relationships

A *normal shock wave* is a physical mechanism that slows a flow from supersonic to subsonic. Across the shock wave, the static pressure, temperature, and density increase almost instantaneously. The total enthalpy and total temperature are constant. There is a loss of total pressure across the shock wave. The entropy increases across the shock wave.



The following equations relate downstream flow conditions to upstream flow conditions for a normal shock wave.

$$M_2 = \sqrt{\frac{(k-1)M_1^{\,2}+2}{2kM_1^{\,2}-(k-1)}}$$

$$\frac{T_2}{T_1} = \left[2+(k-1)M_1^{\,2}\right]\frac{2kM_1^{\,2}-(k-1)}{(k+1)^2 M_1^{\,2}}$$

$$\frac{P_2}{P_1} = \frac{1}{k+1}\left[2kM_1^{\,2}-(k-1)\right]$$

$$\frac{\rho_2}{\rho_1} = \frac{V_1}{V_2} = \frac{(k+1)M_1^{\,2}}{(k-1)M_1^{\,2}+2}$$

$$T_{0,1} = T_{0,2}$$

$$\frac{\rho_2}{\rho_{0,1}} = \frac{2kM_1^2-(k-1)}{k+1}\left[\frac{2}{(k-1)M_1^2+2}\right]^{\frac{k}{k-1}}$$

$$\frac{P_{0,2}}{P_1} = \left[\frac{(k+1)M_1^2}{2}\right]^{\frac{k}{k-1}}\left[\frac{k+1}{2kM_1^2-(k-1)}\right]^{\frac{1}{k-1}}$$

$$\frac{P_{0,2}}{P_{0,1}} = \left[\frac{(k+1)M_1^2}{(k-1)M_1^2+2}\right]^{\frac{k}{k-1}}\left[\frac{k+1}{2kM_1^2-(k-1)}\right]^{\frac{1}{k-1}}$$

Refer to Chapter 1 tables for normal shock relationships.

3.6.4 Adiabatic Frictional Flow in Constant Area Ducts

The adiabatic frictional flow can be calculated from:

$$\frac{\bar{f}L^*}{D} = \frac{1-M^2}{kM^2}+\frac{k+1}{2k}\ln\frac{(k+1)M^2}{2+(k-1)M^2}$$

where

$\bar{f}$ = average friction factor between L = 0 and L*

L^* = duct length required to develop a flow from Mach number to the sonic point

The length of duct ΔL required to develop from M_1 to M_2 is:

$$\bar{f}\frac{\Delta L}{D} = \left(\frac{\bar{f}L^*}{D}\right)_1 - \left(\frac{\bar{f}L^*}{D}\right)_2$$

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Flow properties along the duct can be found from:

$$\frac{p}{p^*} = \frac{1}{\mathrm{M}}\left[\frac{k+1}{2+(k-1)\mathrm{M}^2}\right]^{1/2}$$

$$\frac{\rho}{\rho^*} = \frac{V^*}{V} = \frac{1}{\mathrm{M}}\left[\frac{2+(k-1)\mathrm{M}^2}{k+1}\right]^{1/2}$$

$$\frac{T}{T^*} = \frac{a^2}{a^{*2}} = \frac{k+1}{2+(k-1)\mathrm{M}^2}$$

$$\frac{p_o}{p_o^*} = \frac{\rho_o}{\rho_o^*} = \frac{1}{\mathrm{M}}\left[\frac{2+(k-1)\mathrm{M}^2}{k+1}\right]^{(1/2)(k+1)/(k-1)}$$

For finding changes between points M_1 and M_2 which are not sonic, products of these ratios are used.

$$\frac{p_2}{p_1} = \frac{p_2}{p^*}\frac{p^*}{p_1}$$

since p^* is a constant reference value for the flow.

P^*, ρ^*, T^*, P_o^*, and ρ_o^* are sonic properties.

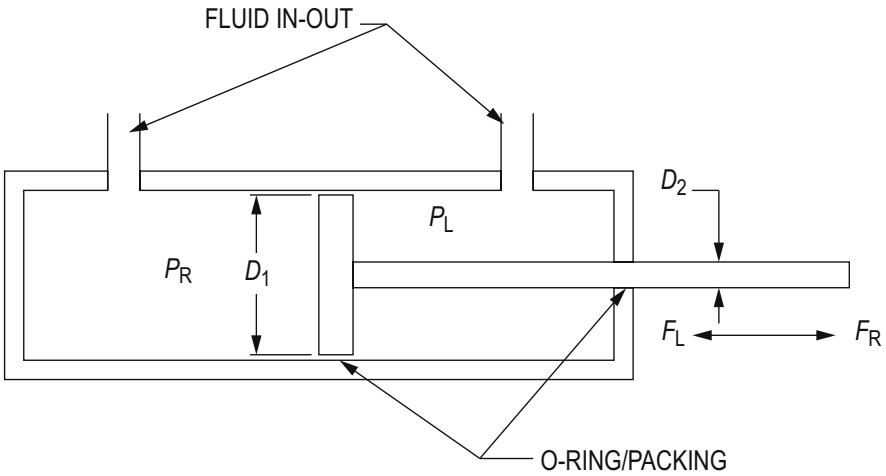
Refer to Chapter 1 for the Adiabatic Frictional Flow in a Constant Area Duct tables for $k = 1.4$.

Source: White, Frank M., *Fluid Mechanics*, 2nd ed., New York: McGraw-Hill, 1986.

3.7 Fluid Flow Machinery

3.7.1 Hydraulic Pneumatic Cylinder Forces

The following equations will determine the applicable force and pressures of a hydraulic or pneumatic cylinder. All units are given in inches.



Source: Engineers Edge, *Hydraulic Pneumatic Cylinder Forces*. www.engineersedge.com.

3.7.2 Force and Pressure to Extend Cylinder

$$F_R = \left(\frac{\pi D_1^2}{4}\right) P_R \qquad P_R = \frac{4F_R}{\pi D_1^2}$$

where:

F_R = force to extend (lb)

P_R = applied pressure (psi)

D_1 = piston diameter (inches)

3.7.3 Force and Pressure to Retract Cylinder

$$F_L = \frac{\pi\left(D_1^2 - D_2^2\right)P_L}{4} \qquad P_L = \frac{4F_L}{\pi\left(D_1^2 - D_2^2\right)}$$

where

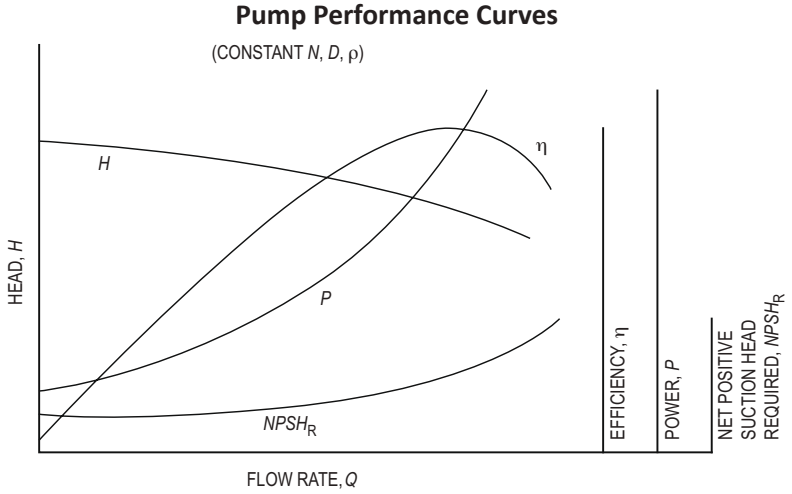
F_L = force to retract (lb)

P_L = applied pressure (psi)

D_1 = piston diameter (inches)

D_2 = rod diameter (inches)

3.7.4 Centrifugal Pump Characteristics



Net positive suction head available:

$$NPSH_A = h_p + h_z - h_{vpa} - h_f$$

For existing conditions

$$NPSH_a = h_a + h_s + \frac{V^2}{2g} - h_{vpa}$$

where

h_p = atmospheric pressure at fluid reservoir surface (ft)

h_z = elevation difference between the level of the fluid reservoir surface and the centerline of the pump suction inlet (ft) (negative if liquid level below pump inlet)

h_f = friction and head losses from fluid source to pump inlet (ft)

h_{vpa} = absolute vapor pressure at pumping temperature (ft)

h_a = atmospheric head for the elevation of installation (ft)

$\frac{V^2}{2g}$ = velocity head at point of measurement of h_s (ft)

h_s = head at inlet flange corrected to centerline of pump (negative if below atmospheric pressure) (ft)

V = fluid velocity at pump inlet

ρ = fluid density

g = gravitational constant

Fluid power

$$\dot{W}_{\text{fluid}} = \rho g H Q$$

Pump (brake) power

$$\dot{W} = \frac{\rho g H Q}{\eta_{\text{pump}}}$$

Purchased power

$$\dot{W}_{\text{purchased}} = \frac{\dot{W}}{\eta_{\text{motor}}}$$

where

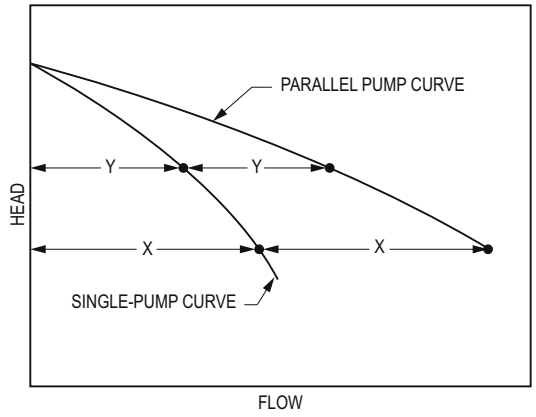
η_{pump} = pump efficiency (0 to 1)

η_{motor} = motor efficiency (0 to 1)

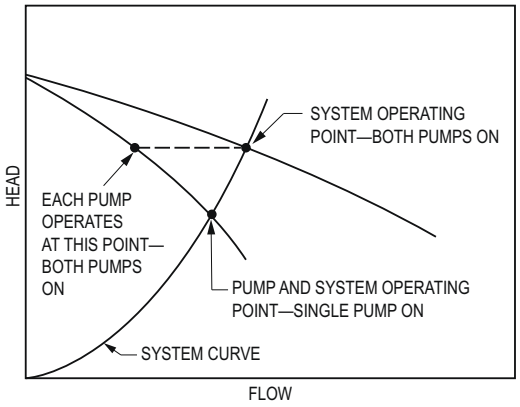
H = head increase provided by pump

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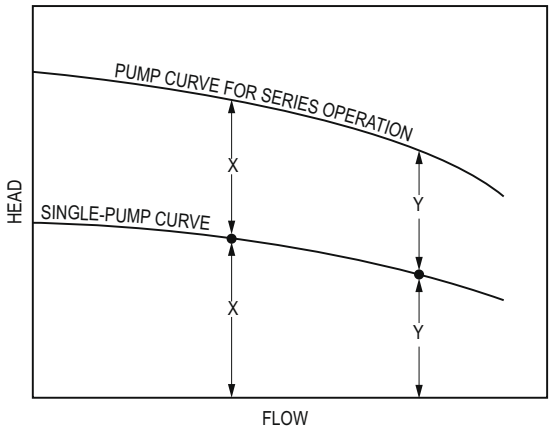
Pump Curve Construction for Parallel Operation



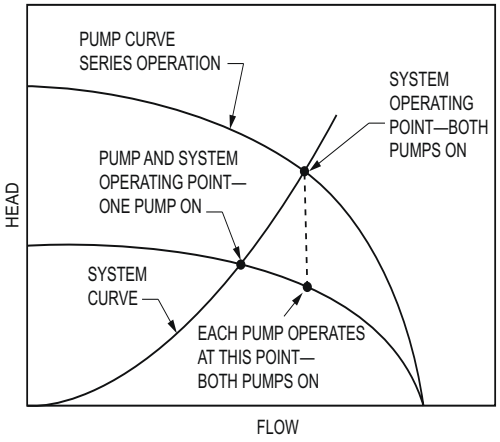
Operating Conditions for Parallel Operation



Pump Curve Construction for Series Operation



Operating Conditions for Series Operation



Source: ©ASHRAE, www.ashrae.org., *2012 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 44, Centrifugal Pumps, Figs. 34, 35, 38, and 39.

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3.7.5 Pump Power Equation

$$\dot{W} = \frac{Q\gamma h}{\eta_t} = \frac{Q\rho g h}{\eta_t}$$

where

Q = volumetric flow $\left(\frac{m^3}{s} \text{ or cfs}\right)$

h = head (m or ft) that the fluid has to be lifted

η_t = total efficiency $\left(\eta_{pump} \times \eta_{motor}\right)$

$\dot{W}$ = power $\left(\frac{kg \cdot m^2}{sec^3} \text{ or } \frac{\text{ft-lbf}}{\text{sec}}\right)$

For water:

Water (work) horsepower (*whp*): The theoretical power to circulate water in a hydronic system, calculated from

$$whp = \frac{\dot{m}\Delta h}{33{,}000}$$

where

$\dot{m}$ = mass flow of fluid (lb per min)

Δh = total head (ft of fluid)

33,000 = units conversion (ft-lb per min per hp)

At 68°F, water has a density of 62.3 lb per ft^3, so water horsepower becomes

$$whp = \frac{Q\Delta h}{3{,}960} = \frac{Q\Delta P}{1{,}714}$$

where

Q = fluid flow rate (gpm)

Δh = total head (ft)

ΔP = pressure (psi)

3,960 = units conversion (ft-gpm/hp)

$$\text{Brake HP} = \frac{Q\,\Delta h\,SG}{3{,}960\eta}$$

where

SG = specific gravity

η = efficiency of pump

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3.7.6 Pump Affinity Laws

Pump flow, head, and horsepower are related by the pump affinity laws.

Pump Affinity Laws

Function	Speed Change	Impeller Diameter Change	Specific Gravity Change
Flow	$Q_2 = Q_1\left(\frac{N_2}{N_1}\right)$	$Q_2 = Q_1\left(\frac{D_2}{D_1}\right)$	--
Head	$h_2 = h_1\left(\frac{N_2}{N_1}\right)^2$	$h_2 = h_1\left(\frac{D_2}{D_1}\right)^2$	--
Horsepower	$bhp_2 = bhp_1\left(\frac{N_2}{N_1}\right)^3$	$bhp_2 = bhp_1\left(\frac{D_2}{D_1}\right)^3$	$bhp_2 = bhp_1\left(\frac{SG_2}{SG_1}\right)$

where

D = impeller diameter

N = rotational speed

Q = volume flow rate

h = head

bhp = brake horsepower

SG = specific gravity

Source: Adapted from 2012 *ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 44, Centrifugal Pumps, Table 1.

3.8 Fluid Flow Measurement

3.8.1 Pitot Tubes

Stagnation pressure equation for an *incompressible fluid*:

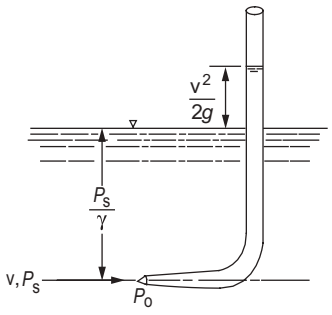
$$v = \sqrt{\left(\frac{2}{\rho}\right)\left(P_0 - P_s\right)} = \sqrt{2g\frac{\left(P_0 - P_s\right)}{\gamma}}$$

where

v = velocity of the fluid

P_0 = stagnation pressure

P_s = static pressure of the fluid at the elevation where the measurement is taken



For a *compressible fluid*. Use the equation for an incompressible fluid if the Mach number ≤ 0.3.

3.8.2 Pitot-Static Tubes

$$V = C\sqrt{\frac{2p_w g_c}{\rho}}$$

where

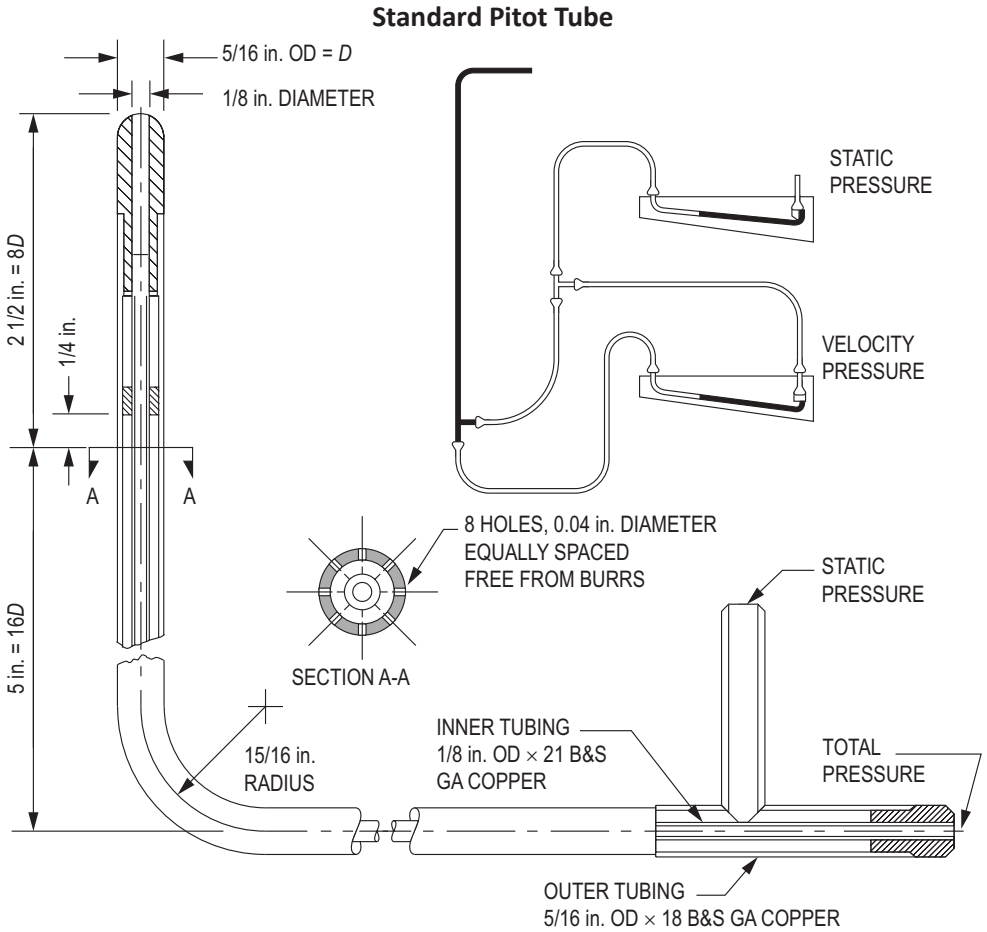
V = air velocity (fpm)

p_w = velocity pressure (pitot-tube manometer reading) (inches of water)

ρ = density of air $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

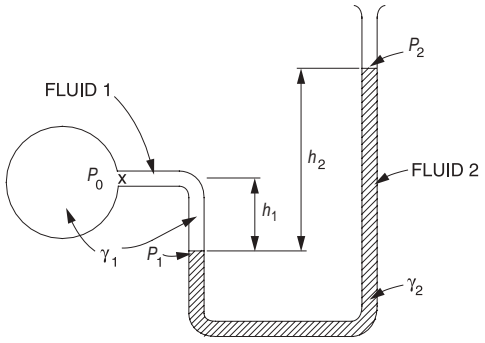
g_c = gravitation constant = 32.174 $\frac{\text{lbm-ft}}{\text{lbf-sec}^2}$

C = unit conversion factor = 136.8



Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 36, Measurement and Instruments, Fig. 6.

3.8.3 Manometers



Source: Bober, W., and R.A. Kenyon, *Fluid Mechanics*, John Wiley & Sons, Inc., 1980.

For a simple manometer:

$$P_0 = P_2 + \gamma_2 h_2 - \gamma_1 h_1 = P_2 + g\,(\rho_2 h_2 - \rho_1 h_1)$$

If $h_1 = h_2 = h$, then

$$P_0 = P_2 + (\gamma_2 - \gamma_1)h = P_2 + (\rho_2 - \rho_1)\,gh$$

Note that the difference between the two densities is used.

P = pressure

γ = specific weight of fluid

h = height

g = acceleration of gravity

ρ = fluid density

3.8.4 Venturi Meters

$$Q = \frac{C_v A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{2g\left(\frac{P_1}{\gamma} + z_1 - \frac{P_2}{\gamma} - z_2\right)}$$

where

Q = volumetric flow rate

C_v = coefficient of velocity

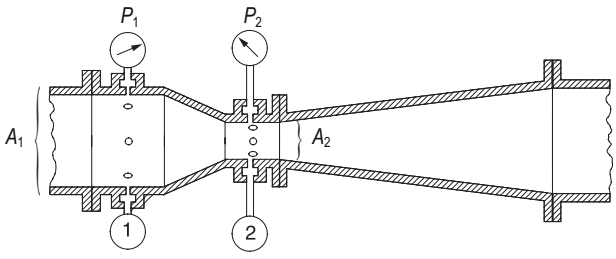
A = cross-sectional area of flow

P = pressure

γ = ρg

z_1 = elevation of venturi entrance

z_2 = elevation of venturi throat



The above equation is for incompressible fluids.

Source: Vennard, John K., and Robert L. Street. *Elementary Fluid Mechanics*, 6th ed., New York: John Wiley & Sons, 1982.

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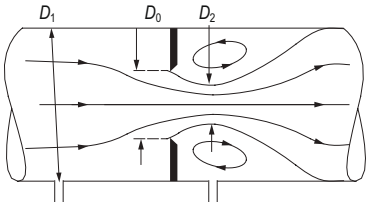
3.8.5 Orifices, Nozzles, and Venturis

An orifice is a restricted flow opening that can be used to measure flow.

D_1 = upstream pipe diameter

D_0 = orifice opening diameter

D_2 = flow diameter at the flow minimum area, referred to as a vena contracta



The contraction coefficient C_c relates the vena contracta area to the area of the orifice.

$$C_c = \frac{A_2}{A_0}$$

For a circular orifice, we get:

$$C_c = \frac{D_2}{D_0}$$

For low to moderate Reynolds numbers, viscous effects are significant. A coefficient of velocity C_v must be applied to the discharge equation.

The orifice discharge coefficient C_d is the product of $C_v C_c$:

$$C_d = C_v C_c$$

The flow coefficient K is determined from:

$$K = \frac{C_v C_c}{\sqrt{1 - C_c^2 \left(\frac{A_0}{A_1}\right)^2}}$$

For incompressible flow through a horizontal orifice meter installation:

$$Q = K A_0 \sqrt{\frac{2 g_c}{\rho}(P_1 - P_2)}$$

where

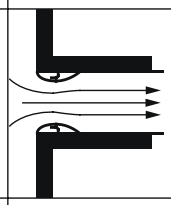
Q = discharge flow rate (cfs)

A_0 = orifice area (ft^2)

$P_1 - P_2$ = pressure drop as obtained by pressure taps (lbf/ft^2)

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Orifices and Their Nominal Coefficients

	SHARP EDGED	ROUNDED	SHORT TUBE	BORDA
				
K	0.61	0.98	0.80	0.51
K_c	0.62	1.00	1.00	0.52
K_v	0.98	0.98	0.80	0.98

To find the flow rate through an orifice or nozzle in gpm, the following formulas apply:

For D_0/D_1 greater than 0.3:

$$Q_{gpm} = 19.636\, KD_0^2 \sqrt{h} \sqrt{\frac{1}{1-\left(\frac{D_0}{D_1}\right)^4}}$$

For D_0/D_1 less than 0.3:

$$Q_{gpm} = 19.636\, KD_0^2 \sqrt{h}$$

where

Q_{gpm} = flow (gpm)

h = differential head at orifice (feet of liquid)

To find the flow rate through a venturi in gpm, the following formulas apply:

$$Q_{gpm} = 19.05\, D_v^2 \sqrt{H} \sqrt{\frac{1}{1-\left(\frac{D_v}{D_1}\right)^4}} \quad \text{for any venturi tube}$$

$$Q_{gpm} = 19.17\, D_v^2 \sqrt{H} \quad \text{for a venturi tube in which } D_v = \frac{1}{3} D_1$$

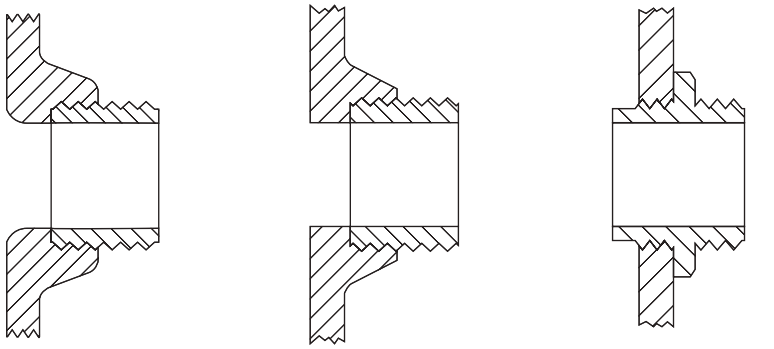
where

D_v = diameter of venturi throat (in.)

H = difference in head between upstream end and throat (ft)

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3.8.6 Fire Hydrant Orifice



Source: NFPA 291, *Recommended Practice for Fire Flow Testing and Marking of Hydrants*, 2019 edition. Copyright© 2018, National Fire Protection Association. Reproduced with permission of NFPA®, which owns all rights thereto.
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$$Q = 29.84 \frac{cd^2}{\sqrt{p}}$$

where

Q = flow (gpm)

c = coefficient of discharge

d = diameter of the outlet (in.)

p = pitot pressure (velocity head) (psi)

$$Q_M = 0.666 \frac{cd^2}{\sqrt{p_M}}$$

where

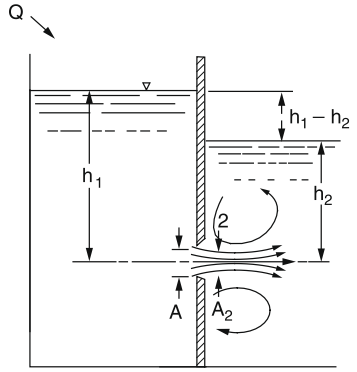
Q_M = flow (L/min)

c = coefficient of discharge

d = diameter of the outlet (mm)

p_M = pitot pressure (velocity head) (bar)

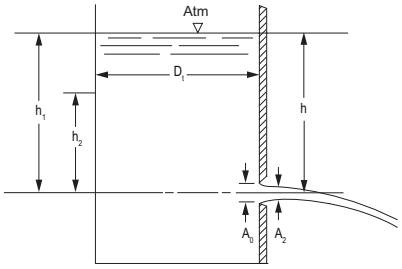
3.8.7 Submerged Orifice Operating under Steady-Flow Conditions



$$Q = A_2 v_2 = C_c C_v A\sqrt{2g(h_1 - h_2)}$$
$$= CA\sqrt{2g(h_1 - h_2)}$$

in which the product of C_c and C_v is defined as the *coefficient of discharge* of the orifice.
v_2 = velocity of fluid exiting orifice

3.8.8 Orifice Discharging Freely into Atmosphere



$$Q = CA_0\sqrt{2gh}$$

in which h is measured from the liquid surface to the centroid of the orifice opening.

Q = volumetric flow
A_0 = cross-sectional area of flow
g = acceleration of gravity
h = height of fluid above orifice
C = orifice coefficient

The equation can be rewritten as the discharge velocity equation by dividing out the area:

$$v = C_v\sqrt{2gh}$$

3.8.9 Open Channel Flow

The ratio of fluid inertia forces to gravity forces is a dimensionless number called the Froude number.

$$Fr = \frac{v}{\sqrt{gh}}$$

where

Fr = Froude number
v = fluid velocity
g = acceleration of gravity
h = depth of fluid

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3.9 Expansion or Compression Tanks

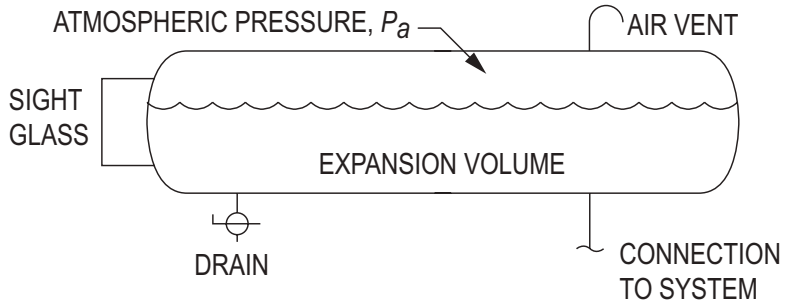
Closed hydronic systems require a method of accommodating changes in water density due to changes in water temperature. Plumbing systems behave as closed systems when all faucets and valves are closed and the domestic water source is protected with a backflow preventor.

Expansion tanks must be connected at a single point, and the connection point is the point of no pressure change whether the circulating pump is operating or not. The pressure losses in the piping between the tank and the system piping should be kept to a minimum.

There are three basic configurations of expansion tanks. These are:

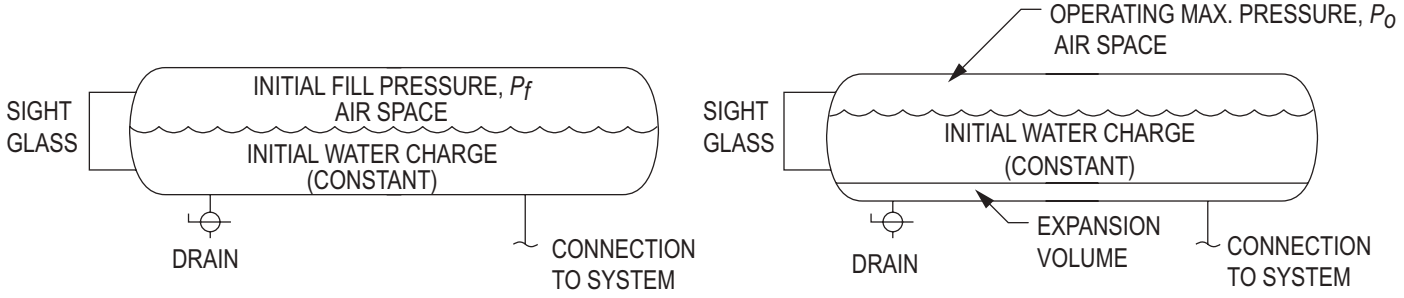
3.9.1 Open Tank

Tank open to atmosphere. Note that the connected system still acts as a closed system as the atmospheric pressure on the tank water surface establishes the system pressure. Tanks must be located at the highest point in the system.



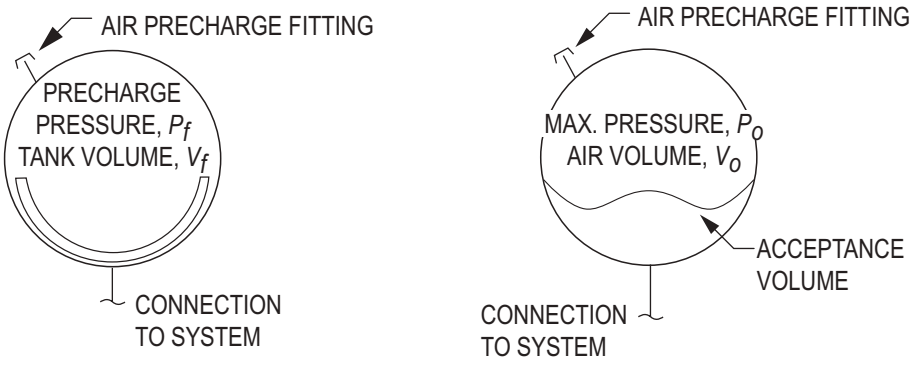
3.9.2 Closed Tank

Tank is not open to atmosphere and includes a volume of air above a volume of water with an air/water interface. The tank has an initial fill of water to provide the initial fill pressure that is greater than atmospheric.



3.9.3 Diaphragm Tank

Tank with a flexible membrane that forms an interface between a compressed air volume and the system water. The compressed air side is precharged to a determined fill pressure.



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The maximum operating pressure of the expansion tank must consider the maximum pressure allowed at any component in the system. Additive pressure effects such as circulating pumps and static head need to be accommodated. It is recommended that a minimum of 5 psig be provided at the top of the system for positive venting and assuring the system is full. A minimum of 10% of the relief valve rating should be deducted from the maximum operating pressure to avoid relief valve unintended activation.

The minimum operating pressure is to assure that water does not flash to steam and to avoid cavitation at the circulating pump.

Air can be released during the system warmup. This typically amounts to 2% of the total system volume and can be ignored in the expansion tank sizing. Also, system components such as water heaters, storage tanks, and piping will expand in volume as a result of thermal expansion of the materials, which reduces the tank size requirements. These are typically less than 9% and can be ignored.

3.9.4 Expansion Tank Sizing

3.9.4.1 Closed Tanks

For temperatures below 160°F:

$$V_t = \frac{V_s\left[\left(v_2/v_1\right)-1\right]}{\left(P_a/P_f\right)-\left(P_a/P_o\right)}$$

For temperatures between 160°F and 280°F:

$$V_t = \frac{(0.00041t-0.0466)V_s}{\left(P_a/P_f\right)-\left(P_a/P_o\right)}$$

where

V_t = total volume of expansion tank (gal)

V_s = volume of water in system (gal)

t = maximum average design temperature (°F)

P_a = atmospheric pressure (psia = 14.7)

P_f = initial fill or minimum operating pressure (psia)

P_o = final or maximum operating pressure at tank (psia)

v_1 = specific volume of water at fill temperature (ft^3/lb)

v_2 = specific volume of water at higher temperature (ft^3/lb)

$(P_a/P_f) - (P_a/P_o)$ is called the acceptance factor

Using Boyle's law where $P_1V_1 = P_2V_2$:

To calculate the tank air space volume at fill pressure:

$$P_aV_t = P_fV_f$$

Initial water charge in tank to provide fill pressure = $V_t - V_f$, which is constant

where

P_a = atmospheric pressure (psia = 14.7)

V_t = total volume of expansion tank (gal)

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P_f = initial fill or minimum operating pressure (psia)

V_f = volume of air space in tank at fill pressure (gal)

To calculate the tank air space volume at maximum operating pressure:

$$P_a V_t = P_o V_o$$

where

P_a = atmospheric pressure (psia = 14.7)

V_t = total volume of expansion tank (gal)

P_o = maximum operating pressure (psia)

V_o = volume of air space in tank at max. operating pressure (gal)

3.9.4.2 Diaphragm Tanks

For temperatures below 160°F:

$$V_t = \frac{V_s\left[\left(v_2 / v_1\right) - 1\right]}{1 - \left(P_f / P_o\right)}$$

For temperatures between 160°F and 280°F:

$$V_t = \frac{(0.00041t - 0.0466)V_s}{1 - \left(P_f / P_o\right)}$$

where

V_t = total volume of expansion tank (gal)

V_s = volume of water in system (gal)

t = maximum average design temperature (°F)

P_f = initial fill or minimum operating pressure (psia)

P_o = final or maximum operating pressure at tank (psia)

v_1 = specific volume of water at fill temperature (ft^3/lb)

v_2 = specific volume of water at higher temperature (ft^3/lb)

$1 - (P_f/P_o)$ is called the acceptance factor

Using Boyle's law where $P_1V_1 = P_2V_2$:

To calculate the tank air space volume at fill pressure:

$$P_f V_t = P_o V_o$$

Acceptance volume = volume of expanded water into tank = $V_t - V_o$

where

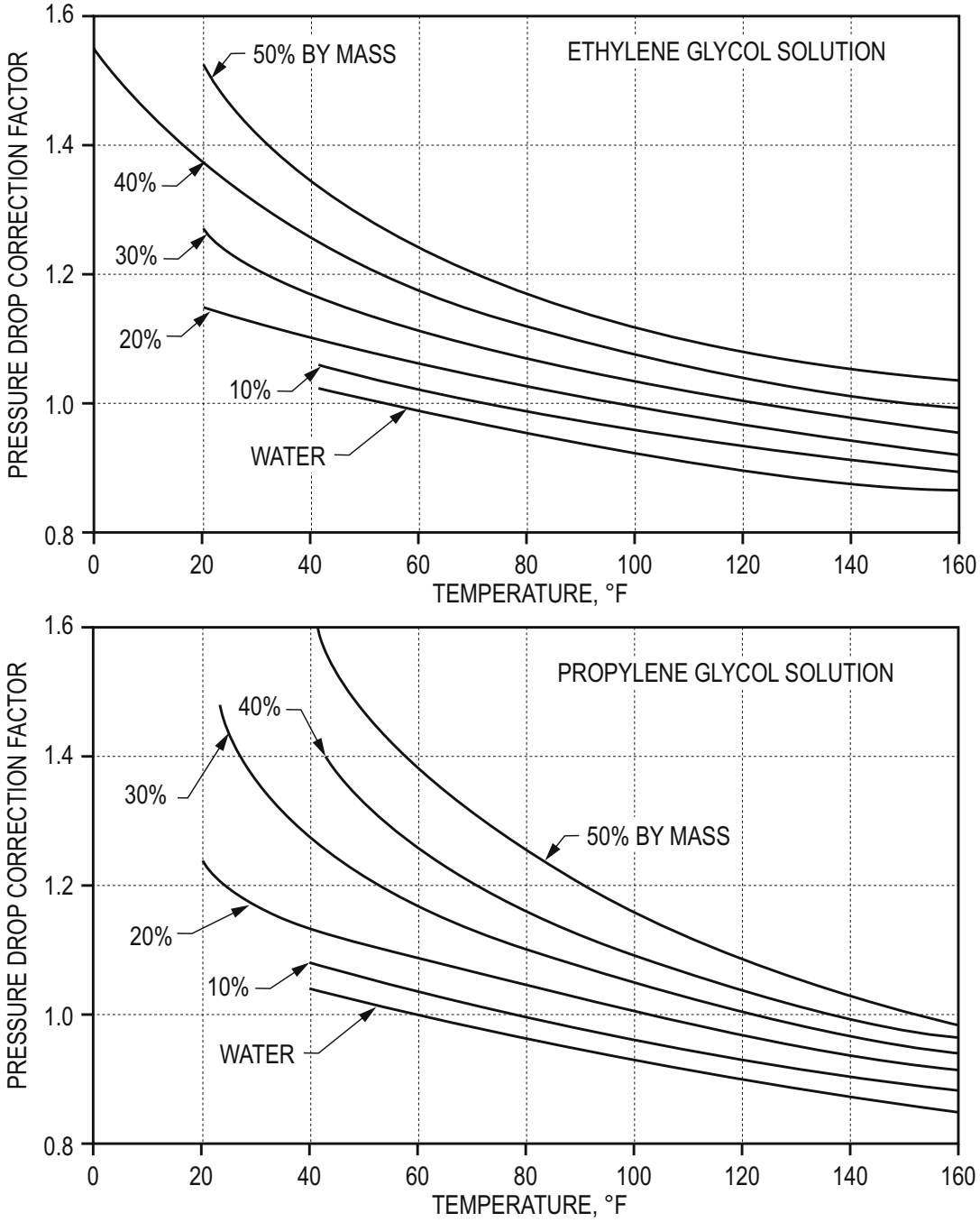
V_o = volume of air space in tank at maximum operating pressure (gal)

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3.10 Properties of Glycol/Water Solutions

3.10.1 Pressure Drop for Glycol Solutions

Physical Properties of Secondary Coolants (Brines)



Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 13, Hydronic Heating and Cooling, Fig. 44.

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3.10.2 Properties of Aqueous Solutions of Ethylene Glycol

Density of Aqueous Solutions of Ethylene Glycol

Concentrations in Volume Percent Ethylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	68.05
−10	--	67.04	67.98
0	--	66.97	67.90
10	65.93	66.89	67.80
20	65.85	66.80	67.70
30	65.76	66.70	67.59
40	65.66	66.59	67.47
50	65.55	66.47	67.34
60	65.43	66.34	67.20
70	65.30	66.20	67.05
80	65.17	66.05	66.90
90	65.02	65.90	66.73
100	64.86	65.73	66.55
110	64.70	65.56	66.37
120	64.52	65.37	66.17
130	64.34	65.18	65.97
140	64.15	64.98	65.75
150	63.95	64.76	65.53
160	63.73	64.54	65.30
170	63.51	64.31	65.05
180	63.28	64.07	64.80
190	63.04	63.82	64.54
200	62.79	63.56	64.27

Note: Density in $\frac{\text{lb}}{\text{ft}^3}$

Source: ©ASHRAE , www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 31, Physical Properties of Secondary Coolants (Brines), Table 6.

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Specific Heat of Aqueous Solutions of Ethylene Glycol

Concentrations in Volume Percent Ethylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	0.739
−10	--	0.794	0.744
0	--	0.799	0.749
10	0.849	0.803	0.754
20	0.853	0.808	0.759
30	0.857	0.812	0.765
40	0.861	0.816	0.770
50	0.864	0.821	0.775
60	0.868	0.825	0.780
70	0.872	0.830	0.785
80	0.876	0.834	0.790
90	0.880	0.839	0.795
100	0.883	0.843	0.800
110	0.887	0.848	0.806
120	0.891	0.852	0.811
130	0.895	0.857	0.816
140	0.898	0.861	0.821
150	0.902	0.865	0.826
160	0.906	0.870	0.831
170	0.910	0.874	0.836
180	0.913	0.879	0.842
190	0.917	0.883	0.847
200	0.921	0.888	0.852

Note: Specific heat in $\frac{\text{Btu}}{\text{lb-°F}}$

Source: ©ASHRAE , www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 31, Physical Properties of Secondary Coolants (Brines), Table 7.

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Thermal Conductivity of Aqueous Solutions of Ethylene Glycol

Concentrations in Volume Percent Ethylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	0.193
−10	--	0.212	0.197
0	--	0.216	0.200
10	0.238	0.220	0.204
20	0.243	0.224	0.207
30	0.247	0.227	0.210
40	0.251	0.231	0.212
50	0.255	0.234	0.215
60	0.259	0.237	0.218
70	0.263	0.240	0.220
80	0.266	0.243	0.223
90	0.269	0.246	0.225
100	0.272	0.248	0.227
110	0.275	0.251	0.229
120	0.277	0.253	0.230
130	0.280	0.255	0.232
140	0.282	0.256	0.233
150	0.284	0.258	0.235
160	0.285	0.259	0.236
170	0.287	0.261	0.237
180	0.288	0.262	0.238
190	0.289	0.263	0.239
200	0.290	0.263	0.240

Note: Thermal conductivity in $\frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-°F}}$

Source: ©ASHRAE , www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 31, Physical Properties of Secondary Coolants (Brines), Table 8.

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Viscosity of Aqueous Solutions of Ethylene Glycol

Concentrations in Volume Percent Ethylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	40.38
−10	--	19.58	27.27
0	--	13.76	19.34
10	6.83	10.13	14.26
20	5.38	7.74	10.85
30	4.33	6.09	8.48
40	3.54	4.91	6.77
50	2.95	4.04	5.50
60	2.49	3.38	4.55
70	2.13	2.87	3.81
80	1.84	2.46	3.23
90	1.60	2.13	2.76
100	1.41	1.87	2.39
110	1.25	1.64	2.08
120	1.11	1.46	1.82
130	1.00	1.30	1.61
140	0.90	1.17	1.43
150	0.82	1.05	1.28
160	0.75	0.95	1.15
170	0.68	0.87	1.04
180	0.63	0.79	0.94
190	0.58	0.73	0.85
200	0.54	0.67	0.78

Note: Viscosity in centipoise

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 31, Physical Properties of Secondary Coolants (Brines).

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3.10.3 Properties of Aqueous Solutions of Propylene Glycol

Density of Aqueous Solutions of Inhibited Propylene Glycol

Concentrations in Volume Percent Propylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	66.46
−10	--	--	66.35
0	--	65.71	66.23
10	65.00	65.60	66.11
20	64.90	65.48	65.97
30	64.79	65.35	65.82
40	64.67	65.21	65.67
50	64.53	65.06	65.50
60	64.39	64.90	65.33
70	64.24	64.73	65.14
80	64.08	64.55	64.95
90	63.91	64.36	64.74
100	63.73	64.16	64.53
110	63.54	63.95	64.30
120	63.33	63.74	64.06
130	63.12	63.51	63.82
140	62.90	63.27	63.57
150	62.67	63.02	63.30
160	62.43	62.76	63.03
170	62.18	62.49	62.74
180	61.92	62.22	62.45
190	61.65	61.93	62.14
200	61.37	61.63	61.83

Note: Density in $\frac{\text{lb}}{\text{ft}^3}$

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 31, Physical Properties of Secondary Coolants (Brines), Table 10.

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Specific Heat of Aqueous Solutions of Propylene Glycol

Concentrations in Volume Percent Propylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	0.799
−10	--	--	0.804
0	--	0.855	0.809
10	0.898	0.859	0.814
20	0.902	0.864	0.820
30	0.906	0.868	0.825
40	0.909	0.872	0.830
50	0.913	0.877	0.835
60	0.917	0.881	0.840
70	0.920	0.886	0.845
80	0.924	0.890	0.850
90	0.928	0.894	0.855
100	0.931	0.899	0.861
110	0.935	0.903	0.866
120	0.939	0.908	0.871
130	0.942	0.912	0.876
140	0.946	0.916	0.881
150	0.950	0.921	0.886
160	0.953	0.925	0.891
170	0.957	0.929	0.896
180	0.961	0.934	0.902
190	0.964	0.938	0.907
200	0.968	0.943	0.912

Note: Specific heat in $\frac{\text{Btu}}{\text{lb-°F}}$

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Thermal Conductivity of Aqueous Solutions of Propylene Glycol

Concentrations in Volume Percent Propylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	0.188
−10	--	--	0.191
0	--	0.211	0.194
10	0.235	0.215	0.196
20	0.239	0.218	0.199
30	0.243	0.222	0.201
40	0.247	0.225	0.204
50	0.251	0.227	0.206
60	0.254	0.230	0.208
70	0.258	0.233	0.210
80	0.261	0.235	0.211
90	0.263	0.237	0.213
100	0.266	0.239	0.214
110	0.268	0.241	0.215
120	0.270	0.243	0.217
130	0.272	0.244	0.218
140	0.274	0.245	0.218
150	0.276	0.246	0.219
160	0.277	0.247	0.220
170	0.278	0.248	0.220
180	0.279	0.249	0.221
190	0.280	0.249	0.221

Note: Thermal conductivity in $\frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-°F}}$

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Viscosity of Aqueous Solutions of Propylene Glycol

Concentrations in Volume Percent Propylene Glycol

Temperature, °F	30%	40%	50%
−20	--	--	156.08
−10	--	--	95.97
0	--	40.99	61.32
10	13.44	27.17	40.62
20	9.91	18.64	27.83
30	7.47	13.20	19.66
40	5.75	9.63	14.28
50	4.52	7.22	10.65
60	3.61	5.55	8.13
70	2.94	4.36	6.34
80	2.43	3.50	5.04
90	2.04	2.86	4.08
100	1.73	2.37	3.35
110	1.49	2.00	2.79
120	1.30	1.71	2.36
130	1.14	1.49	2.02
140	1.01	1.30	1.75
150	0.90	1.16	1.53
160	0.82	1.03	1.35
170	0.74	0.93	1.20
180	0.68	0.85	1.08
190	0.62	0.78	0.97
200	0.58	0.72	0.88

Note: Viscosity in centipoise

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4 THERMODYNAMICS

4.1 Properties of Single-Component Systems

4.1.1 Definitions

1. *Intensive properties* are independent of mass.
2. *Extensive properties* are proportional to mass.
3. *Specific properties* are extensive properties that are expressed on a per-mass basis; shown in lowercase.

Functions and Their Symbols and Units

Function	Symbol(s)	Unit (I-P *or* SI)
Absolute pressure	P	$\frac{\text{lbf}}{\text{in}^2}$ *or* Pa
Absolute temperature	T	°R *or* K
Volume	V	ft^3 *or* m^3
Specific volume	$v = \frac{V}{m}$	$\frac{\text{ft}^3}{\text{lbm}}$ *or* $\frac{\text{m}^3}{\text{kg}}$
Internal energy	U	Btu *or* kJ
Specific internal energy	$u = \frac{U}{m}$	$\frac{\text{Btu}}{\text{lbm}}$ *or* $\frac{\text{kJ}}{\text{kg}}$
Enthalpy	H	Btu *or* kJ
Specific enthalpy	$h = u + Pv = \frac{H}{m}$	$\frac{\text{Btu}}{\text{lbm}}$ *or* $\frac{\text{kJ}}{\text{kg}}$
Entropy	S	$\frac{\text{Btu}}{\text{°R}}$ *or* $\frac{\text{kJ}}{\text{K}}$
Specific entropy	$s = \frac{S}{m}$	$\frac{\text{Btu}}{\text{lbm-°R}}$ *or* $\frac{\text{kJ}}{\text{kg} \cdot \text{K}}$
Gibbs free energy	$G = h - Ts$	$\frac{\text{Btu}}{\text{lbm}}$ *or* $\frac{\text{kJ}}{\text{kg}}$
Helmholtz free energy	$A = u - Ts$	$\frac{\text{Btu}}{\text{lbm}}$ *or* $\frac{\text{kJ}}{\text{kg}}$

For a single-phase pure component, specifying any two intensive, independent properties is sufficient to determine all the rest.

Heat capacity at constant pressure:

$$c_P = \left(\frac{\partial h}{\partial T}\right)_P \qquad \frac{\text{Btu}}{\text{lbm-°R}} \text{ or } \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

Heat capacity at constant volume:

$$c_V = \left(\frac{\partial u}{\partial T}\right)_V \qquad \frac{\text{Btu}}{\text{lbm-°R}} \text{ or } \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

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4.1.2 Properties for Two-Phase (Vapor-Liquid) Systems

Quality x, for liquid-vapor systems at saturation, is defined as the mass fraction of the vapor phase:

$$x = \frac{m_g}{m_g + m_f}$$

where

m_g = mass of vapor

m_f = mass of liquid

Specific volume of a two-phase system can be expressed as:

$$v = xv_g + (1 - x)v_f \quad \text{or} \quad v = v_f + xv_{fg}$$

where

v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

v_{fg} = specific volume change upon vaporization = $v_g - v_f$

Similar expressions exist for u, h, and s:

$$u = xu_g + (1 - x)\, u_f \quad \text{or} \quad u = u_f + xu_{fg}$$

$$h = xh_g + (1 - x)\, h_f \quad \text{or} \quad h = h_f + xh_{fg}$$

$$s = xs_g + (1 - x)\, s_f \quad \text{or} \quad s = s_f + xs_{fg}$$

4.2 PVT Behavior for Gases

4.2.1 Ideal Gas

For an *ideal gas*, $Pv = RT$ or $PV = mRT$ and

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

where

P = pressure

v = specific volume

m = mass of gas

R = gas constant

T = absolute temperature

V = volume

R is *specific to each gas* but can be found from

$$R = \frac{\overline{R}}{(mol\ wt)}$$

where

$\overline{R}$ = universal gas constant (refer to Chapter 1 for value)

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For ideal gases, $c_P - c_V = R$

Ideal gas behavior is characterized by:

- Lack of intermolecular interactions
- Molecules occupying zero volume

Ideal gas properties reflect those of a single molecule and are attributable entirely to the structure of the molecule and to the system's absolute temperature (T).

For ideal gases:

$$\left(\frac{\partial h}{\partial P}\right)_T = 0 \quad \text{and} \quad \left(\frac{\partial u}{\partial v}\right)_T = 0$$

For cold air standard, heat capacities are assumed to be constant at their room temperature values. In that case, the following are true:

$$\Delta u = c_V \Delta T; \;\; \Delta h = c_P \, \Delta T$$

$$\Delta s = c_P \ln (T_2 / T_1) - R \ln (P_2 / P_1)$$

$$\Delta s = c_V \ln (T_2 / T_1) + R \ln (v_2 / v_1)$$

Also, for constant entropy processes:

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^k$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

where

$$k = \frac{c_P}{c_v}$$

4.2.2 Ideal Gas Mixtures

$i = 1, 2, \ldots, n$ constituents. Each constituent is an ideal gas.

Mole fraction:

$$x_i = \frac{N_i}{N}$$

$$N = \sum N_i$$

$$\sum x_i = 1$$

where

N_i = number of moles of component i

N = total moles in the mixture

Mass fraction:

$$y_i = \frac{m_i}{m}$$

$$m = \sum m_i$$

$$\sum y_i = 1$$

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Molecular weight:

$$M = \frac{m}{N} = \sum x_i M_i$$

To convert mole fractions x_i to mass fractions y_i:

$$y_i = \frac{x_i M_i}{\sum (x_i M_i)}$$

To convert mass fractions to mole fractions:

$$x_i = \frac{y_i / M_i}{\sum y_i / M_i}$$

Partial pressures:

$$P_i = \frac{m_i R_i T}{V} \quad \text{and} \quad P = \Sigma P_i$$

Partial volumes:

$$V_i = \frac{m_i R_i T}{P} \quad \text{and} \quad V = \Sigma V_i$$

where

P, V, T = pressure, volume, and temperature of the mixture

$$R_i = \frac{R}{M_i}$$

Combining the above generates the following additional expressions for mole fraction:

$$x_i = \frac{P_i}{P} = \frac{V_i}{V}$$

Other properties:

$$u = \sum (y_i u_i)$$
$$h = \sum (y_i h_i)$$
$$s = \sum (y_i s_i)$$

where

u_i and h_i are evaluated at T

s_i is evaluated at T and P_i

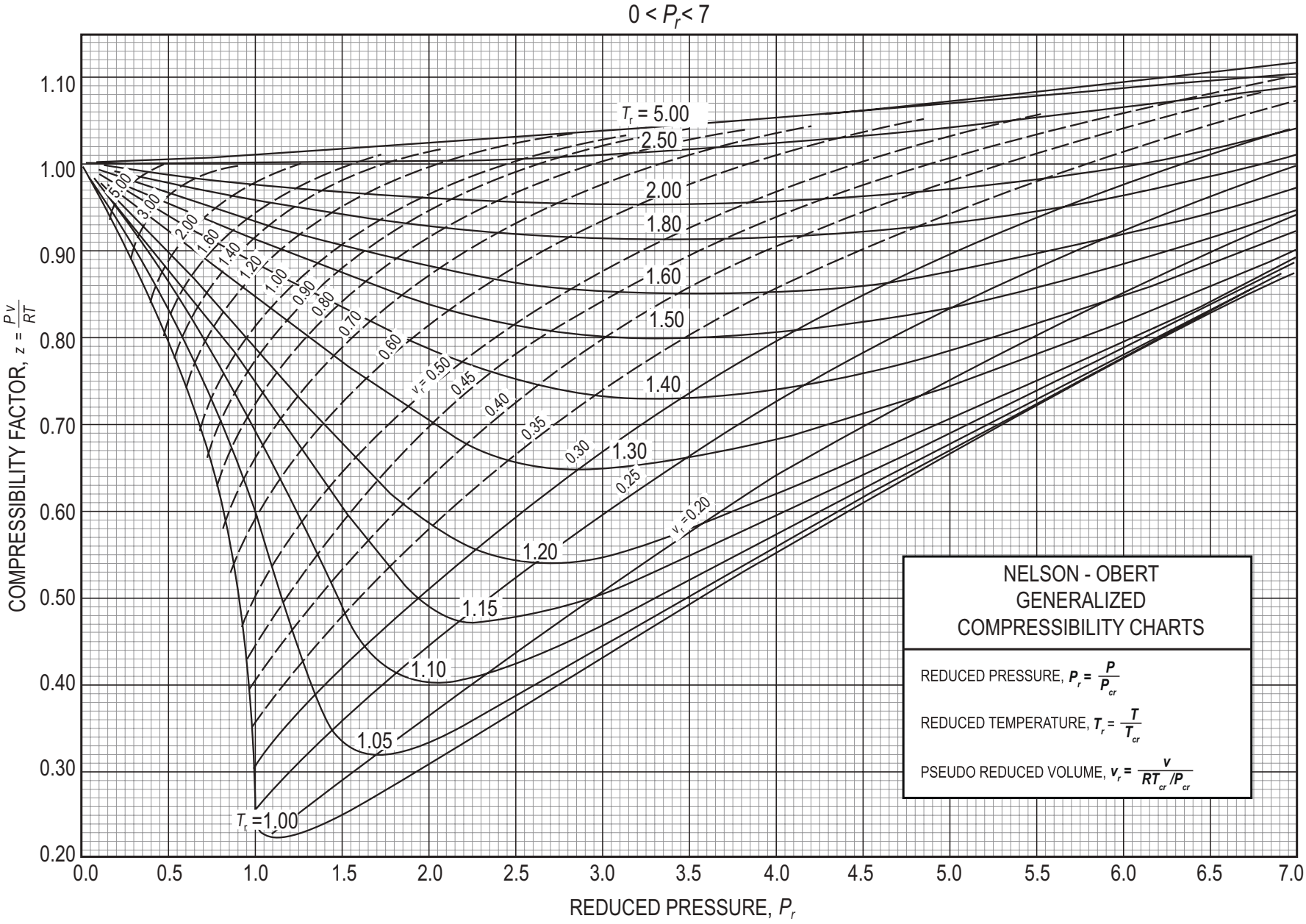
4.2.3 Compressibility Factor and Charts

The generalized compressibility chart provides reasonable estimates for the compressibility factor Z based on dimensionless reduced pressure P_R and reduced temperature T_R.

$$P_R = \frac{P}{P_C}; \; T_R = \frac{T}{T_C}$$

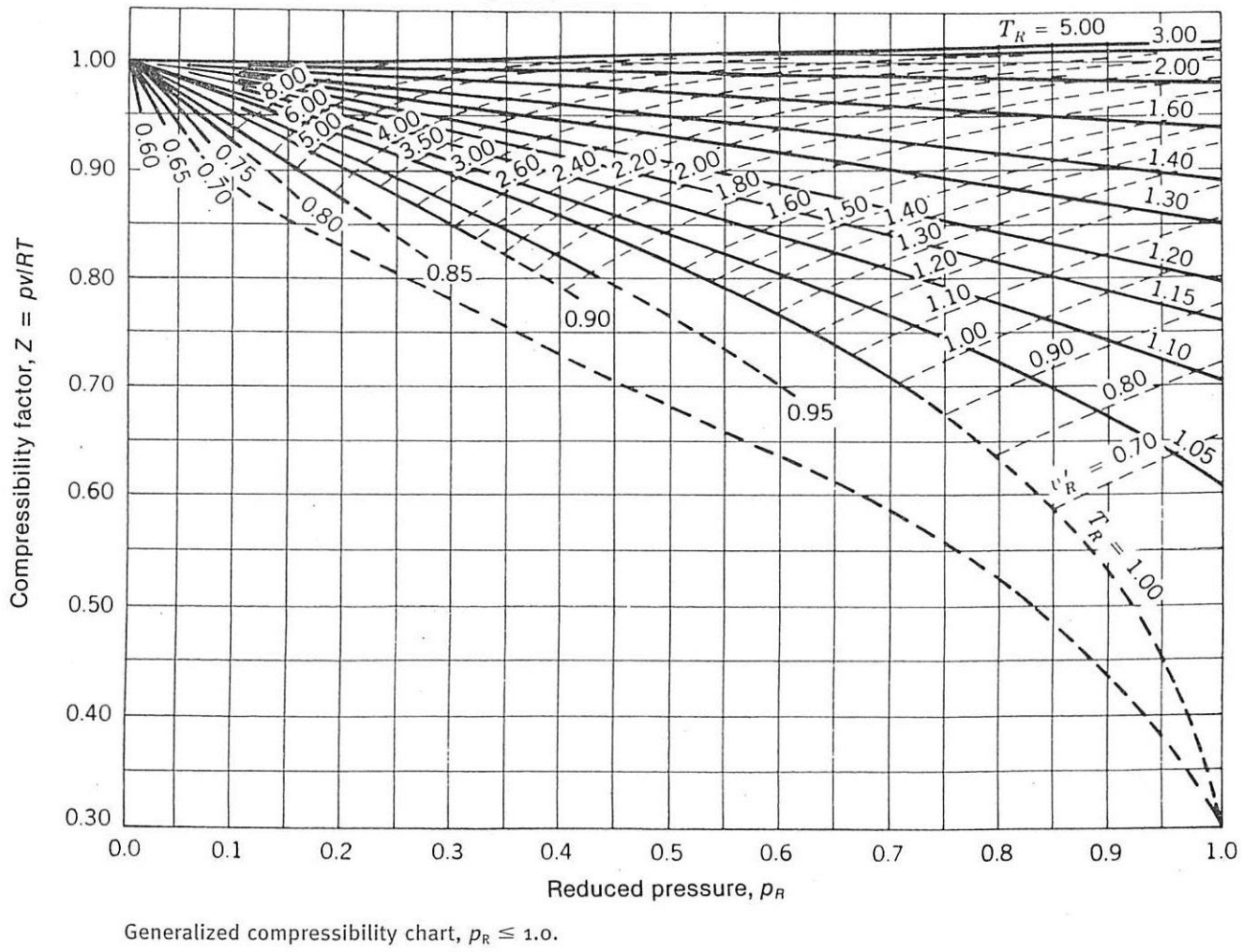
Where, P_C and T_C are the critical pressure and temperature respectively expressed in absolute units.

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Source: Moran, Michael J., Howard D. Shapiro, Daisie D. Boettner, and Margaret B. Bailey, *Fundamentals of Engineering Thermodynamics*, 8th ed., John Wiley & Sons, 2014.

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Generalized compressibility chart, $p_R \leq 1.0$.

Source: Moran, Michael J., Howard D. Shapiro, Daisie D. Boettner, and Margaret B. Bailey, *Fundamentals of Engineering Thermodynamics*, 8th ed., John Wiley & Sons, 2014.

4.2.4 Equations of State (EOS)

Equations of state (EOS) are used to quantify *PvT* behavior.

For ideal gas EOS (applicable only to ideal gases):

$$P = \left(\frac{RT}{v}\right)$$

For generalized compressibility EOS (applicable to all systems as gases, liquids, and/or solids):

$$P = \left(\frac{RT}{v}\right)Z$$

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4.3 First Law of Thermodynamics

The *First Law of Thermodynamics* is a statement of conservation of energy in a thermodynamic system. The net energy crossing the system boundary is equal to the change in energy inside the system.

Heat Q ($q = Q/m$) is energy transferred due to temperature difference and is considered positive if it is inward or added to the system.

Work W ($w = W/m$) is considered positive if it is outward or work done b*y* the system.

4.3.1 Closed Thermodynamic Systems

No mass crosses the system boundary:

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

where

ΔU = change in internal energy

ΔKE = change in kinetic energy

ΔPE = change in potential energy

4.3.1.1 Special Cases of Closed Systems (With No Change in Kinetic or Potential Energy)

Constant system pressure process (Charles's Law):

$$w_b = P\Delta v$$

T/v = constant for ideal gas

Constant volume process:

$$w_b = 0$$

T/P = constant for ideal gas

Isentropic process:

Pv^k = constant for ideal gas

$$w = \frac{\left(P_2 v_2 - P_1 v_1\right)}{1 - k}$$
$$= \frac{R\left(T_2 - T_1\right)}{1 - k}$$

Constant temperature process (Boyle's Law):

Pv = constant for ideal gas

$$w_b = RT\ln\left(\frac{v_2}{v_1}\right) = RT\ln\left(\frac{P_1}{P_2}\right)$$

Polytropic process:

Pv^n = constant for ideal gas

$$w = \frac{\left(P_2 v_2 - P_1 v_1\right)}{1 - n} \qquad n \neq 1$$

where n is the polytropic exponent or polytropic index

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4.3.2 Open Thermodynamic Systems

Mass does cross the system boundary. *Flow work* (Pv) is done by mass entering the system.

The *reversible flow work* can be expressed:

$$w_{rev} = -\int vdP + \Delta KE + \Delta PE$$

The First Law applies whether or not processes are reversible.

Open System First Law (energy balance):

$$\frac{d(m_s u_s)}{dt} = \Sigma \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gZ_i \right) - \Sigma \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gZ_e \right) + \dot{Q}_{in} - \dot{W}_{net}$$

where

$\dot{m}$ = mass flow rate (subscripts i and e refer to inlet and exit states of system)

g = acceleration of gravity

Z = elevation

V = velocity

m_s = mass of fluid within the system

u_s = specific internal energy of system

$\dot{Q}_{in}$ = rate of heat transfer (ignoring kinetic and potential energy of the system)

$\dot{W}_{net}$ = rate of net or shaft work

4.3.2.1 Special Cases of Open Systems (With No Change in Kinetic or Potential Energy)

Constant volume process:

$$w_{rev} = -v\,(P_2 - P_1)$$

Constant system pressure process:

$$w_{rev} = 0$$

Constant temperature process:

Pv = constant for ideal gas

$$w_{rev} = RT \ln\left(\frac{v_2}{v_1}\right) = RT \ln\left(\frac{P_1}{P_2}\right)$$

Isentropic process:

Pv^k = constant for ideal gas

$$w_{rev} = k\frac{(P_2 v_2 - P_1 v_1)}{1-k} = kR\frac{(T_2 - T_1)}{1-k}$$

$$w_{rev} = \frac{k}{k-1} RT_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{(k-1)}{k}} \right]$$

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Polytropic process:

Pv^n = constant for ideal gas

$$w_{rev} = \frac{n\left(P_2 v_2 - P_1 v_1\right)}{1-n}$$

where n is the polytropic exponent or polytropic index

4.3.3 Steady-Flow Systems

The *steady-flow system* does not change state with time. This assumption is valid for the steady operation of turbines, pumps, compressors, throttling valves, nozzles, and heat exchangers, including boilers and condensers.

$$\Sigma \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gZ_i\right) - \Sigma \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gZ_e\right) + \dot{Q}_{in} - \dot{W}_{out} = 0$$

and

$$\Sigma \dot{m}_i = \Sigma \dot{m}_e$$

where

$\dot{m}$ = mass flow rate (subscripts i and e refer to inlet and exit states of system)

g = acceleration of gravity

Z = elevation

V = velocity

$\dot{Q}$ = rate of heat transfer

$\dot{W}$ = rate of work

4.3.3.1 Special Cases of the Steady-Flow Energy Equation

For nozzles and diffusers, velocity terms are significant. There is no elevation change, no heat transfer, no work, and a single-mass stream.

$$h_i + \frac{V_i^2}{2} = h_e + \frac{V_e^2}{2}$$

$$\text{Isentropic Efficiency (nozzle)} = \frac{V_e^2 - V_i^2}{2\left(h_i - h_{es}\right)}$$

where h_{es} = enthalpy at isentropic exit state

Turbines, pumps, and compressors are often considered adiabatic (no heat transfer). Velocity terms usually can be ignored. There are significant work terms and a single-mass stream.

$$h_i = h_e + w$$

$$\text{Isentropic Efficiency (turbine)} = \frac{h_i - h_e}{h_i - h_{es}}$$

$$\text{Isentropic Efficiency (compressor, pump)} = \frac{h_{es} - h_i}{h_e - h_i}$$

For a pump only: $h_{es} - h_i = v_i(p_e - p_i)$

For throttling valves and throttling processes, there is no work, no heat transfer, and a single-mass stream. Velocity terms are often insignificant.

$$h_i = h_e$$

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For boilers, condensers, evaporators, and one side in a heat exchanger, heat-transfer terms are significant. For a single-mass stream:

$$h_i + q = h_e$$

Heat exchangers offer no heat loss to the surroundings or work. There are two separate flow rates, $\dot{m}_1$ and $\dot{m}_2$:

$$\dot{m}_1\left(h_{1i} - h_{1e}\right) = \dot{m}_2\left(h_{2e} - h_{2i}\right)$$

For mixers, separators, and open or closed feedwater heaters:

$$\Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e \quad \text{and} \quad \Sigma \dot{m}_i = \Sigma \dot{m}_e$$

4.4 Second Law of Thermodynamics

The *Second Law of Thermodynamics* deals with the direction of heat flow for a natural process for an isolated natural system. The entropy either will be constant or will increase.

For thermal energy reservoirs:

$$\Delta S_{\text{reservoir}} = \frac{Q}{T_{\text{reservoir}}}$$

where Q is measured with respect to the reservoir

4.4.1 Kelvin-Planck Statement of the Second Law

It is impossible to devise a cyclically operating device, the sole effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work.

Corollary to Kelvin-Planck: No heat engine can have a higher efficiency than a Carnot Cycle operating between the same reservoirs.

4.4.2 Clausius' Statement of the Second Law

It is impossible to construct a device which operates on a cycle and whose sole effect is the transfer of heat from a cooler body to a hotter body.

Corollary to Clausius: No refrigerator or heat pump can have a higher coefficient of performance (COP) than a Carnot Cycle refrigerator or heat pump.

4.4.3 Entropy

$$ds = \left(\frac{1}{T}\right)\delta q_{\text{rev}}$$

$$s_2 - s_1 = \int_1^2 \left(\frac{1}{T}\right)\delta q_{\text{rev}}$$

Isothermal, Reversible Process:

$$\Delta s = s_2 - s_1 = \frac{q}{T}$$

Isentropic Process:

$$\Delta s = 0;\ ds = 0$$

A reversible adiabatic process is isentropic.

Adiabatic Process:

$$q = 0;\ \Delta s \geq 0$$

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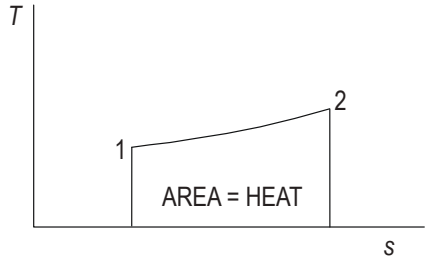
Increase of Entropy Principle:

$$\Delta s_{\text{total}} = \Delta s_{\text{system}} + \Delta s_{\text{surroundings}} \geq 0$$

$$\Delta \dot{s}_{\text{total}} = \Sigma \dot{m}_{\text{out}} s_{\text{out}} - \Sigma \dot{m}_{\text{in}} s_{\text{in}} - \Sigma \left(\frac{\dot{q}_{\text{external}}}{T_{\text{external}}} \right) \geq 0$$

Temperature-Entropy (*T*-*s*) Diagram

$$q_{\text{rev}} = \int_1^2 T\,ds$$



Entropy Change for Solids and Liquids:

$$ds = c\left(\frac{dT}{T}\right)$$

$$s_2 - s_1 = \int c\left(\frac{dT}{T}\right) = c_{\text{mean}} \ln\left(\frac{T_2}{T_1}\right)$$

where c = heat capacity of the solid or liquid

4.4.4 Vapor-Liquid Equilibrium (VLE)

4.4.4.1 Henry's Law at Constant Temperature

At equilibrium, the partial pressure of a gas in the vapor space above a liquid is proportional to its concentration in the liquid.

Henry's Law is valid for low concentrations, for example, $x \approx 0$.

$$P_i = Py_i = hx_i$$

where

h = Henry's Law constant

P_i = partial pressure of a gas in contact with a liquid

x_i = mol fraction of the gas in the liquid

y_i = mol fraction of the gas in the vapor

P = total pressure

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4.4.5 Phase Relations

Clapeyron Equation for phase transitions:

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}} = \frac{s_{fg}}{v_{fg}}$$

where

h_{fg} = enthalpy change for phase transitions

v_{fg} = volume change

s_{fg} = entropy change

T = absolute temperature

$\left(\frac{dP}{dT}\right)_{sat}$ = slope of phase transition (e.g.,vapor-liquid) saturation line

Clausius-Clapeyron Equation:

This equation results if it is assumed that (1) the volume change (v_{fg}) can be replaced with the vapor volume (v_g), (2) the latter can be replaced with $\frac{P}{\overline{R}T}$ from the ideal gas law, and (3) h_{fg} is independent of the temperature (T).

$$\ln_e\left(\frac{P_2}{P_1}\right) = \frac{h_{fg}}{\overline{R}}\frac{T_2 - T_1}{T_1 T_2}$$

Gibbs Phase Rule (non-reacting systems):

$$P + F = C + 2$$

where

P = number of phases making up a system

F = degrees of freedom

C = number of components in a system

4.5 Thermodynamic Cycles

4.5.1 Basic Cycles

Heat engines take in heat Q_H at a high temperature T_H, produce a net amount of work W, and reject heat Q_L at a low temperature T_L. The efficiency η of a heat engine is

$$\eta = \frac{W}{Q_H} = \frac{(Q_H - Q_L)}{Q_H}$$

The most efficient engine possible is the Carnot Cycle. Its efficiency is expressed:

$$\eta_c = \frac{(T_H - T_L)}{T_H}$$

where T_H and T_L = absolute temperatures (Kelvin or Rankine)

Refrigeration cycles are the reverse of heat-engine cycles. Heat is moved from low to high temperature requiring work, W. Cycles can be used either for refrigeration or as heat pumps.

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Coefficient of performance (COP) is defined as

$$\text{COP} = \frac{Q_H}{W} \text{ for heat pumps}$$

$$\text{COP} = \frac{Q_L}{W} \text{ for refrigerators and air conditioners}$$

The upper limit of COP is based on the reversed Carnot Cycle:

$$\text{COP}_c = \frac{T_H}{(T_H - T_L)} \text{ for heat pumps}$$

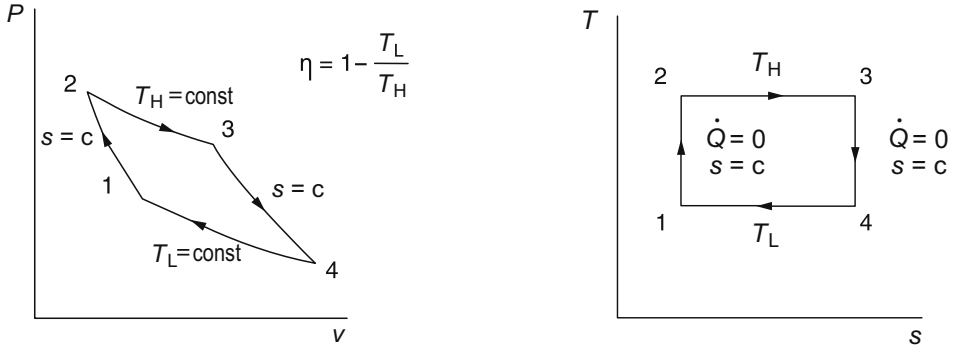
$$\text{COP}_c = \frac{T_L}{(T_H - T_L)} \text{ for refrigeration}$$

$$1 \text{ ton refrigeration} = 12{,}000 \frac{\text{Btu}}{\text{hr}} = 3{,}516 \text{ W}$$

Common cycles are plotted on *P*-*v* and *T*-*s* diagrams below.

4.5.2 Common Thermodynamic Cycles

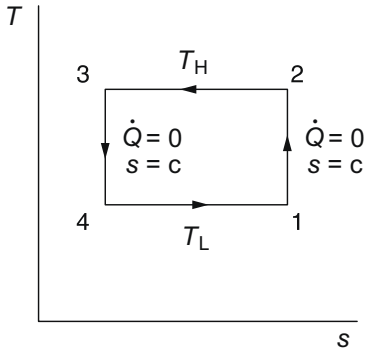
Carnot Cycle



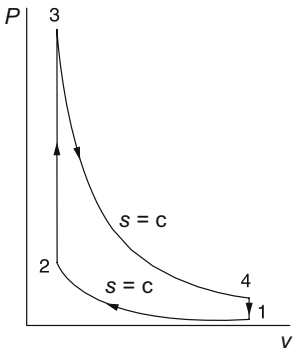
$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \qquad \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{k} \qquad \frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^{k}$$

Reversed Carnot Cycle



Otto Cycle (Gasoline Engine)

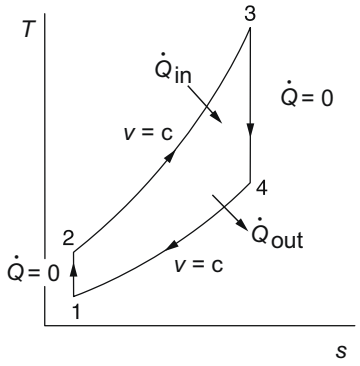


$$\eta = 1 - \frac{1}{r^{k-1}}$$

or

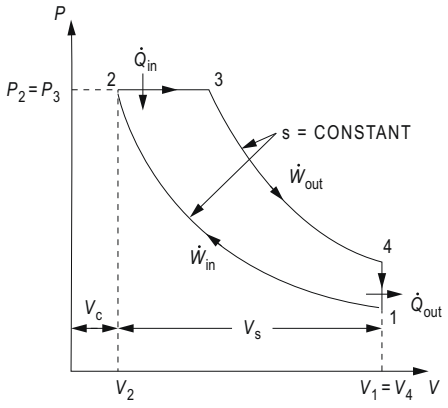
$$\eta = 1 - r^{1-k}$$

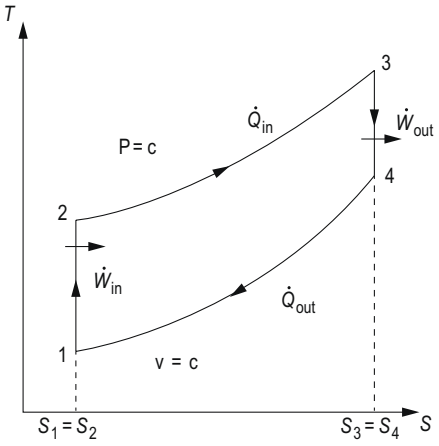
where $r = \frac{v_1}{v_2}$



$$\eta_{th} = \frac{W_{net}}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

Diesel Cycle





$$\eta_{th,diesel} = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$

where

$\eta_{th,diesel}$ = diesel thermal efficiency

u = internal energy

h = enthalpy

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4.5.2.1 Internal Combustion Engines

The *mean effective pressure* equals net work divided by volumetric displacement. Horsepower is derived from

$$\text{hp} = (\text{MEP})\frac{Lan}{33{,}000\frac{\text{ft-lbf}}{\text{min}}} \qquad \text{kW} = (\text{MEP})\frac{Lan}{60\frac{\text{s}}{\text{min}}}$$

where for two-stroke and four-stroke engines:

$$\text{MEP} = \text{mean effective pressure}\left(\frac{\text{lb}}{\text{in}^2}\ \text{or}\ \text{kPa}\right)$$

L = stroke (ft or m)

a = bore area of one cylinder (in^2 or m^2)

$$n = \frac{2N \times \text{number of cylinders}}{\text{number of strokes per cycle}} = \text{number of power strokes per minute}$$

N = engine RPM

Engine displacement is the total volume of all cylinders.

$$r_v = \text{compression ratio} = \frac{V_1}{V_2} = \frac{V_4}{V_3}$$

4.5.3 Compressors

Compressors consume power to add energy to the working fluid. This energy addition results in an increase in fluid pressure (head).

For an adiabatic compressor with $\Delta PE = 0$ and negligible ΔKE:

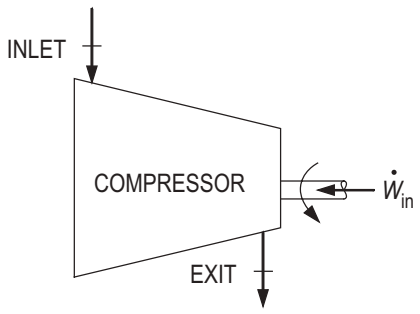
$$\dot{W}_{comp} = -\dot{m}\left(h_e - h_i\right)$$

For an ideal gas with constant specific heats:

$$\dot{W}_{comp} = -\dot{m}c_p\left(T_e - T_i\right)$$

Per unit mass:

$$w_{comp} = -c_p\left(T_e - T_i\right)$$



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Compressor Isentropic Efficiency is calculated as follows:

$$\eta_C = \frac{w_s}{w_a} = \frac{T_{es} - T_i}{T_e - T_i}$$

where

w_a ≡ actual compressor work per unit mass

w_s ≡ isentropic compressor work per unit mass

T_{es} ≡ isentropic exit temperature

T_e = exit temperature

T_i = inlet temperature

For a compressor where ΔKE is included:

$$\dot{W}_{comp} = -\dot{m}\left(h_e - h_i + \frac{V_e^2 - V_i^2}{2}\right) = -\dot{m}\left(c_p\left(T_e - T_i\right) + \frac{V_e^2 - V_i^2}{2}\right)$$

Adiabatic Compression:

$$\dot{W}_{comp} = \frac{\dot{m} P_i k}{(k-1)\rho_i \eta_c}\left[\left(\frac{P_e}{P_i}\right)^{1-\frac{1}{k}} - 1\right]$$

where

$\dot{W}_{comp}$ = fluid or gas power

P_i = inlet or suction pressure, absolute

P_e = exit or discharge pressure, absolute

k = ratio of specific heats

ρ_i = inlet gas density

η_c = isentropic compressor efficiency

Isothermal Compression:

$$\dot{W}_{comp} = \frac{\overline{R} T_i}{M \eta_c} \ln \frac{P_e}{P_i} (\dot{m})$$

where

$\overline{R}$ = universal gas constant

T_i = inlet temperature of gas (°R)

M = molecular weight of gas $\left(\frac{\text{lb}}{\text{mol}}\right)$

Multistage compressor analysis is similar to single stage compressor analysis. The work is minimized when the compression ratios of all stages are equal.

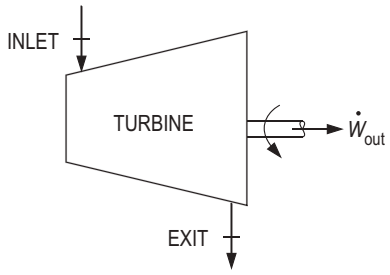
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4.5.4 Turbines

Turbines produce power by extracting energy from a working fluid. The energy loss shows up as a decrease in fluid pressure (head).

For an adiabatic turbine with $\Delta PE = 0$ and negligible ΔKE:

$$\dot{W}_{turb} = \dot{m}\left(h_i - h_e\right)$$



For an ideal gas with constant specific heats:

$$\dot{W}_{turb} = \dot{m}c_p\left(T_i - T_e\right)$$

Per unit mass:

$$w_{turb} = c_p\left(T_i - T_e\right)$$

Turbine Isentropic Efficiency:

$$\eta_T = \frac{w_a}{w_s} = \frac{T_i - T_e}{T_i - T_{es}}$$

where

T_i = inlet temperature

T_e = exit temperature

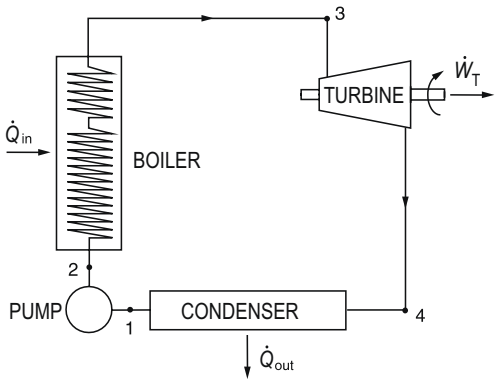
T_{es} = isentropic exit temperature

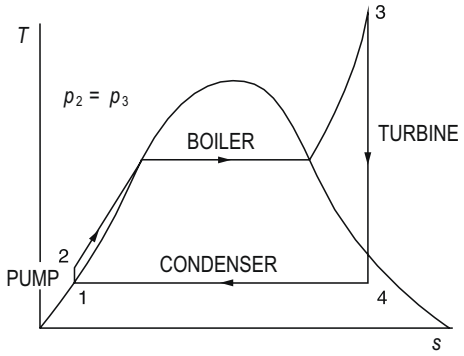
For a turbine where ΔKE is included:

$$\dot{W}_{turb} = \dot{m}\left(h_i - h_e + \frac{V_i^2 - V_e^2}{2}\right) = \dot{m}\left(c_p\left(T_i - T_e\right) + \frac{V_i^2 - V_e^2}{2}\right)$$

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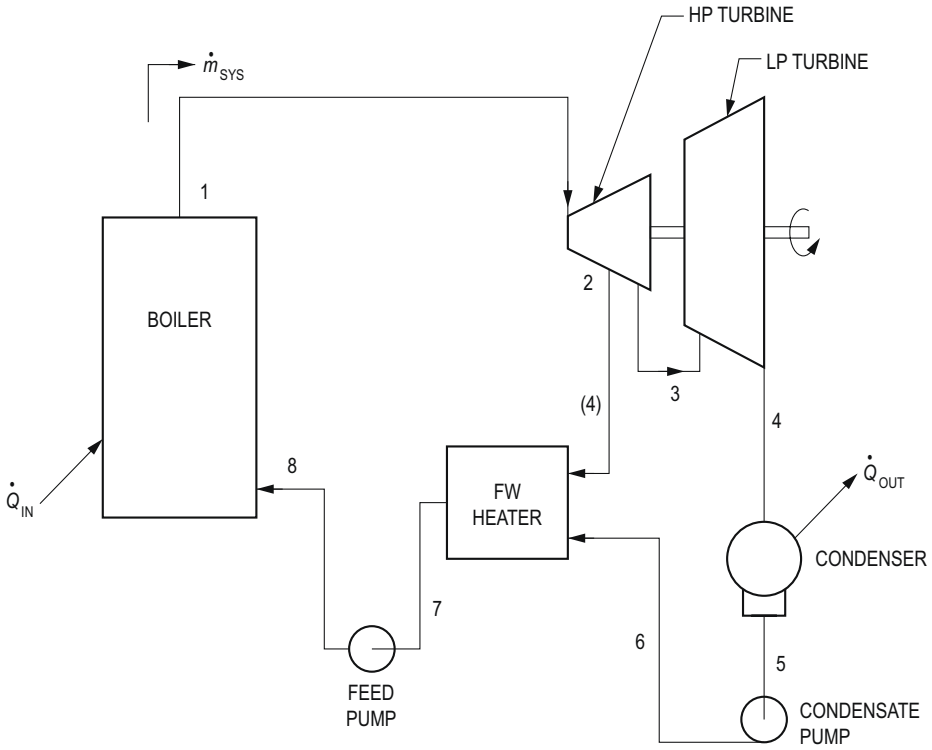
Rankine Cycle





$$\eta = \frac{\left(h_3 - h_4\right) - \left(h_2 - h_1\right)}{h_3 - h_2}$$

Rankine Cycle With Regeneration



$$\eta = \frac{\dot{Q}_{IN} - \dot{Q}_{OUT}}{\dot{Q}_{IN}}$$

$$w_{HP_{turbine}} = h_1 - h_2 + (h_2 - h_3) \qquad w_{LP_{turbine}} = h_3 - h_4$$

$$\dot{W}_{HP_{turbine}} = \dot{m}_{sys}(h_1 - h_2) + (1 - y)(\dot{m}_{sys})(h_2 - h_3) \qquad \dot{W}_{LP_{turbine}} = (1 - y)\dot{m}_{sys}(h_3 - h_4)$$

y = bleed fraction

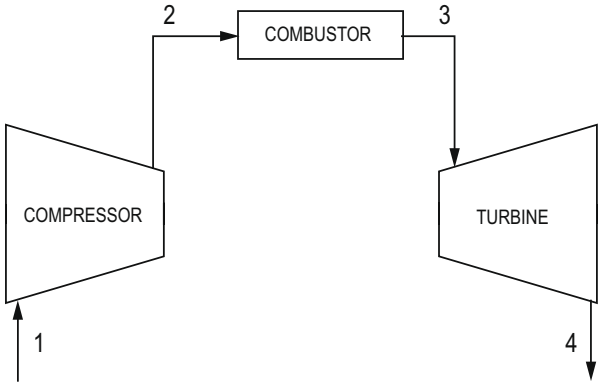
where

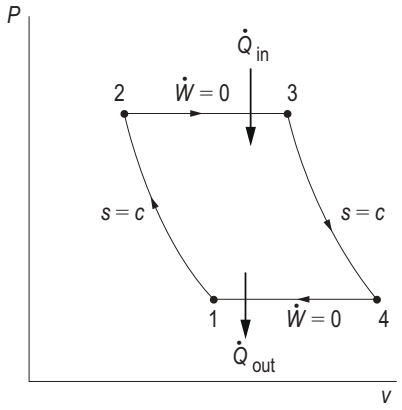
LP = low pressure

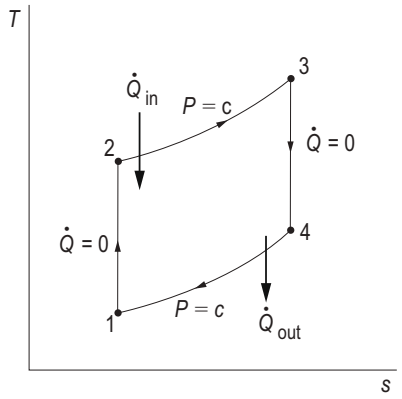
HP = high pressure

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Brayton Cycle (Steady-Flow Cycle)







$$\dot{W}_{12} = h_1 - h_2 = c_p(T_1 - T_2) \qquad \dot{Q}_{23} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$\dot{W}_{34} = h_3 - h_4 = c_p(T_3 - T_4) \qquad \dot{Q}_{41} = h_4 - h_1 = c_p(T_4 - T_1)$$

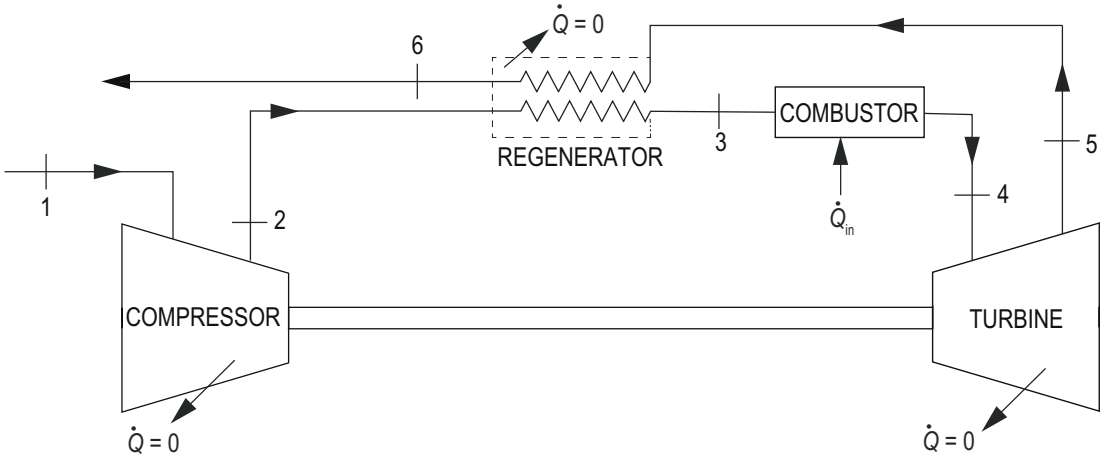
$$\dot{W}_{net} = \dot{W}_{12} + \dot{W}_{34} \qquad \dot{Q}_{net} = \dot{Q}_{23} + \dot{Q}_{41}$$

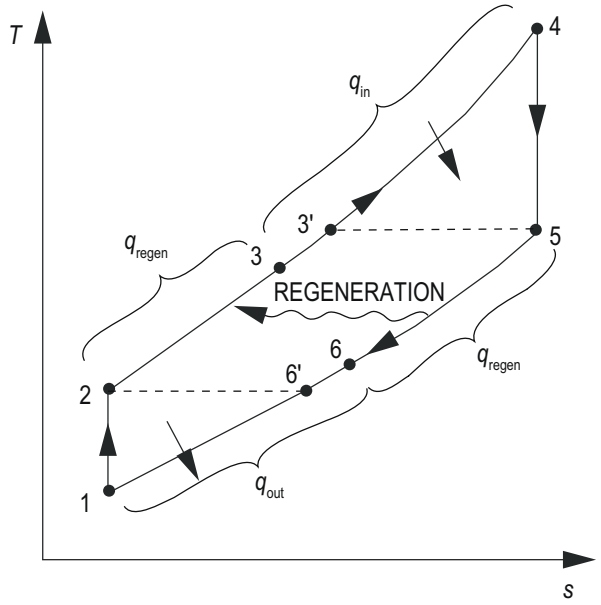
$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{23}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{k-1/k} \qquad \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{k-1/k}$$

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Brayton Cycle with Regeneration





$$q_{\text{regen, act}} = h_3 - h_2$$

$$q_{\text{regen, max}} = h_{3'} - h_2 = h_5 - h_2$$

Compressor

$$\dot{w}_{12} = h_2 - h_1 = c_p\left(T_2 - T_1\right)$$

Real Regeneration

$$q_{23} = h_3 - h_2 = c_p\left(T_3 - T_2\right)$$

$$q_{56} = h_6 - h_5 = c_p\left(T_6 - T_5\right)$$

Ideal Regeneration

$$q_{23'} = h_{3'} - h_2 = c_p\left(T_{3'} - T_2\right)$$

$$q_{56'} = h_{6'} - h_5 = c_p\left(T_{6'} - T_5\right)$$

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Ideal Regenerator

$$T_5 = T_3,$$

Pressure Ratio

$$r_p = \frac{P_2}{P_1}$$

Combustor

$$q_{34} = h_4 - h_3 = c_p\left(T_4 - T_3\right)$$

Turbine

$$\dot{w}_{45} = h_5 - h_4 = c_p\left(T_5 - T_4\right)$$

Cycle Efficiency

$$\eta_{cyc} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\left(h_4 - h_5\right) - \left(h_2 - h_1\right)}{h_4 - h_3}$$

Regenerator Effectiveness

$$\varepsilon_{reg} = \frac{h_3 - h_2}{h_5 - h_2}$$

Air Standard

$$\eta_{cyc} = \frac{\left(T_4 - T_5\right) - \left(T_2 - T_1\right)}{T_4 - T_3}$$

$$\varepsilon_{reg} = \frac{T_3 - T_2}{T_5 - T_2}$$

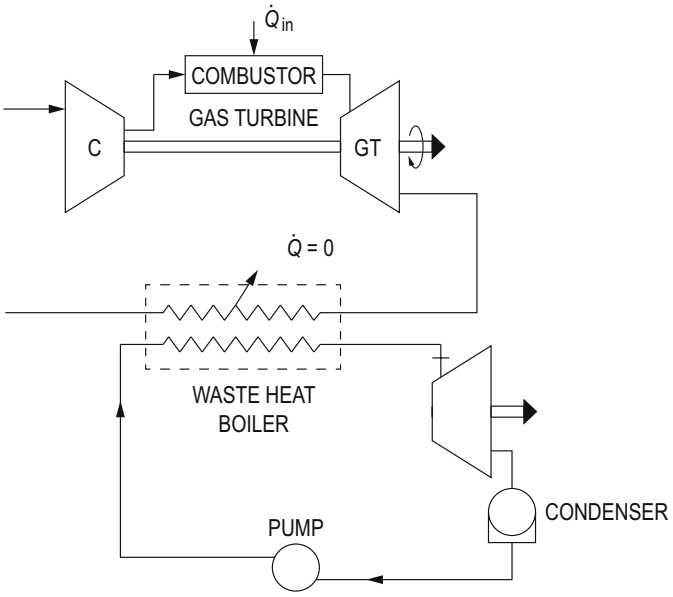
Ideal Turbine, Compressor, and Regenerator

$$\text{Ideal Efficiency } \eta_{cyc} = 1 - \left(\frac{T_1}{T_4}\right) r_p^{(k-1)/k}$$

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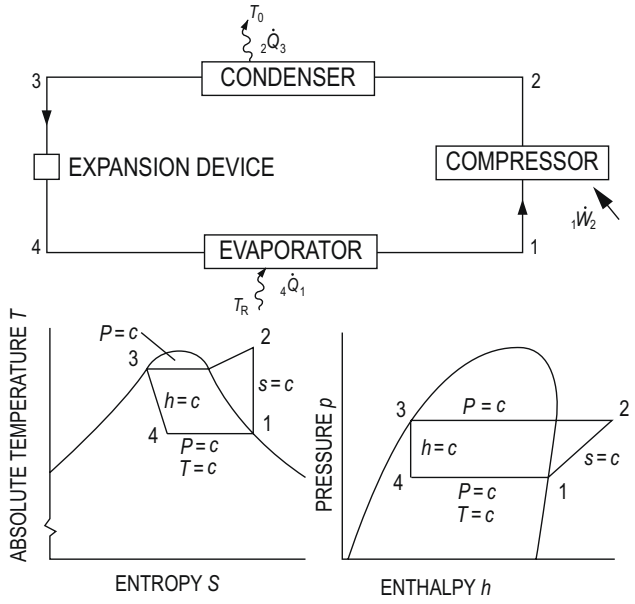
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Combined Cycle



$$\eta_C = \frac{\dot{W}_{OUT}}{\dot{Q}_{IN}}$$

Refrigeration Cycle—Single Stage



IF OPERATED AS REFRIGERATION CYCLE:

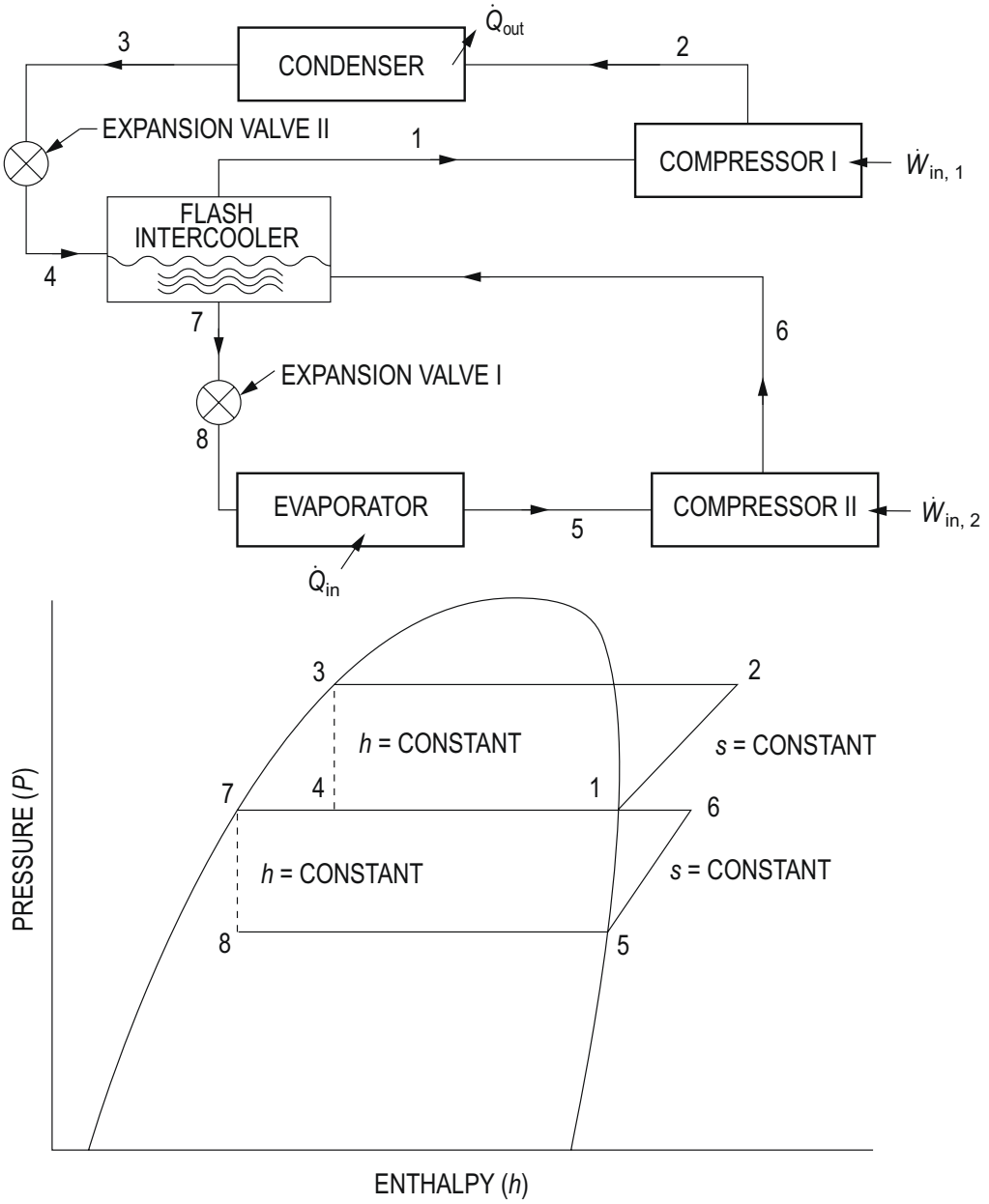
$$COP_{ref} = \frac{h_1 - h_4}{h_2 - h_1}$$

IF OPERATED AS HEAT PUMP CYCLE:

$$COP_{HP} = \frac{h_2 - h_3}{h_2 - h_1}$$

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Dual-Compression, Dual-Expansion Refrigeration Cycle



$$\text{COP}_{\text{ref}} = \frac{h_5 - h_8}{(h_6 - h_5) + (h_2 - h_1)}$$

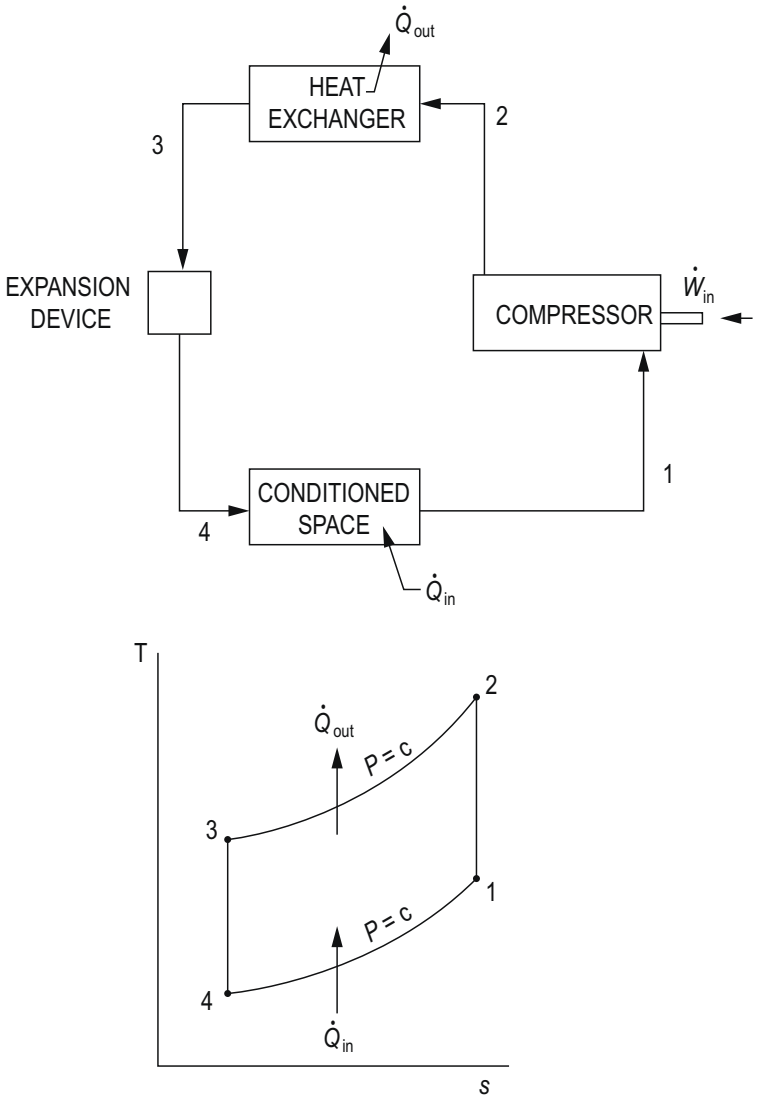
$$\text{COP}_{\text{ref}} = \frac{\dot{Q}_{\text{in}}}{\dot{W}_{\text{in},1} + \dot{W}_{\text{in},2}}$$

$$\text{COP}_{\text{HP}} = \frac{h_2 - h_3}{(h_2 - h_1) + (h_6 - h_5)}$$

$$\text{COP}_{\text{HP}} = \frac{\dot{Q}_{\text{out}}}{\dot{W}_{\text{in},1} + \dot{W}_{\text{in},2}}$$

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Air Refrigeration Cycle



IF OPERATED AS REFRIGERATION CYCLE:

$$\mathrm{COP}_{\mathrm{ref}} = \frac{h_1 - h_4}{(h_2 - h_1) - (h_3 - h_4)}$$

IF OPERATED AS HEAT PUMP CYCLE:

$$\mathrm{COP}_{\mathrm{HP}} = \frac{h_2 - h_3}{(h_2 - h_1) - (h_3 - h_4)}$$

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5 HEAT TRANSFER

5.1 Conduction

5.1.1 Fourier's Law of Conduction

$$\dot{Q} = -kA\frac{dT}{dx}$$

where

$\dot{Q}$ = rate of heat transfer $\left(\text{W or } \frac{\text{Btu}}{\text{hr}}\right)$

k = the thermal conductivity $\left(\frac{\text{W}}{\text{m} \cdot \text{K}} \text{ or } \frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}} \text{ or } \frac{\text{Btu}}{\text{hr-ft-°F}}\right)$

A = the surface area perpendicular to direction of heat transfer (m^2 or ft^2)

$\frac{dT}{dx}$ = temperature gradient $\left(\frac{\text{K}}{\text{m}} \text{ or } \frac{\text{°F}}{\text{ft}}\right)$

5.1.2 Thermal Diffusivity

Thermal diffusivity is a measure of the time required for a material to experience temperature change.

$$\alpha = \frac{k}{\delta c_p}$$

where

α = thermal diffusivity $\left(\frac{\text{ft}^2}{\text{hr}} \text{ or } \frac{\text{m}^2}{\text{s}}\right)$

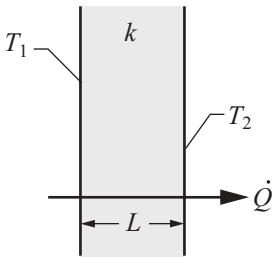
k = thermal conductivity $\left(\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}} \text{ or } \frac{\text{Btu}}{\text{hr-ft-°F}} \text{ or } \frac{\text{W}}{\text{m} \cdot \text{K}}\right)$

δ = density $\left(\frac{\text{lb}}{\text{ft}^3} \text{ or } \frac{\text{kg}}{\text{m}^3}\right)$

c_p = specific heat $\left(\frac{\text{Btu}}{\text{lb-°F}} \text{ or } \frac{\text{J}}{\text{kg} \cdot \text{K}}\right)$

5.1.3 Conduction Through a Uniform Material

$$\dot{Q} = \frac{-kA\left(T_2 - T_1\right)}{L}$$



where

$\dot{Q}$ = rate of heat transfer $\left(\text{W or } \frac{\text{Btu}}{\text{hr}}\right)$

A = wall surface area normal to heat flow (m^2 or ft^2)

L = wall thickness (m or ft)

T_1 = temperature of one surface of the wall (K or °F)

T_2 = temperature of the other surface of the wall (K or °F)

k = thermal conductivity

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5.1.4 Conduction Through a Cylindrical Wall (Heat Loss Through a Pipe)

For cylinders and spheres, the logarithmic mean area, A_m, should be used when calculating the heat transfer:

$$Q = UA_m(T_1 - T_2)$$

$$A_m = \frac{A_o - A_i}{\ln\left(\frac{A_o}{A_i}\right)}$$

The logarithmic mean area (excluding the ends) for a hollow pipe of length L and wall thickness $r_o - r_i$ is:

$$A_m = \frac{2\pi L(r_o - r_i)}{\ln\left(\frac{r_o}{r_i}\right)}$$

The overall radial heat transfer through an uninsulated pipe without films is:

$$\dot{Q} = qA_m = \frac{kA_m(T_1 - T_2)}{r_o - r_i} = \frac{2\pi kL(T_1 - T_2)}{\ln\left(\frac{r_o}{r_i}\right)}$$

The temperature at any point distance r from the center is:

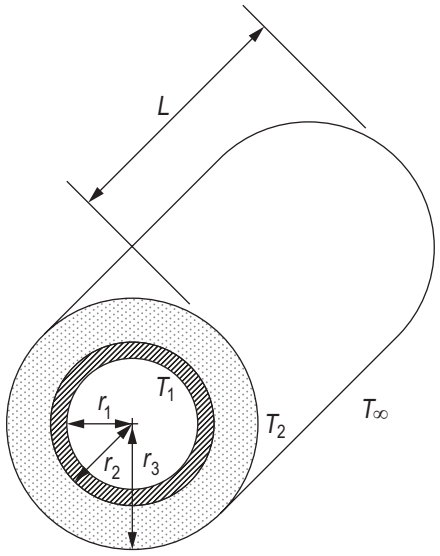
$$T_r = T_i - (T_i - T_o)\left[\frac{\ln\left(\frac{r}{r_i}\right)}{\ln\left(\frac{r_o}{r_i}\right)}\right]$$

For insulated pipe:

$$\dot{Q} = qA_m = \frac{2\pi L(T_1 - T_2)}{\frac{\ln\left(\frac{r_o}{r_a}\right)}{k_{\text{pipe}}} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_{\text{insulation}}}}$$

Considering films, this becomes the following, where h_b is a film coefficient representing contact or interface resistance, if any.

$$Q = \frac{2\pi L(T_i - T_o)}{\frac{1}{r_1 h_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{\text{pipe}}} + \frac{1}{r_2 h_2} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{\text{insulation}}} + \frac{1}{r_3 h_3}}$$



5.1.5 Critical Insulation Radius

The critical insulation radius is the outer radius of insulation which results in the maximum rate of heat transfer due to the increased surface area.

$$r_{cr} = \frac{k_{insulation}}{h_\infty}$$

For natural convection, a typical value for h_∞ is:

$$h_\infty = 6.8\frac{W}{m^2 \cdot C} = 1.2\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$$

5.2 Thermal Resistance (*R*)

$$\dot{Q} = \frac{A\Delta T}{R_{total}}$$

Resistances in series are added: $R_{total} = \sum R$

Plane Wall Conduction Resistance:

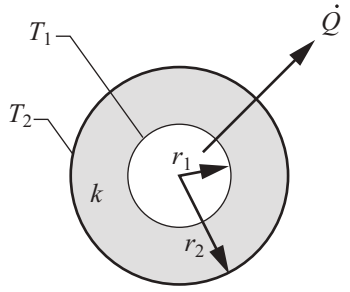
$$R = \frac{L}{kA}$$

where

L = wall thickness

k = thermal conductivity

A = area

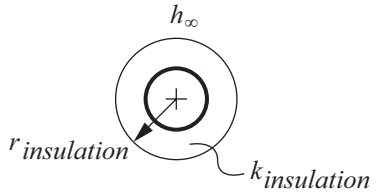


Cylinder (Length = L)

Cylindrical Wall Conduction Resistance:

$$R = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi kL}$$

where L = cylinder length



Convection Resistance:

$$R = \frac{1}{h}$$

5.2.1 Composite Plane Wall

Definitions and Terms:

$\dot{Q}$ = thermal transmission or rate of heat flow (W or Btu/hr)

k = thermal conductivity, the thermal transmission by conduction only for a unit temperature difference between surfaces (W/m•K or Btu-in./hr-ft^2-°F)

C = thermal conductance for a unit temperature difference (W/m^2•K or Btu/hr-ft^2-°F) = k/L

R = thermal resistance (m^2•K/W or ft^2-°F-hr/Btu) = $1/C$

h = film conductance or surface conductance (W/m^2•K or Btu/hr-ft^2-°F)

U = thermal transmittance or overall heat transfer coefficient (W/m^2•K or Btu/hr-ft^2-°F)

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L = material thickness (m or inches)

A = cross sectional area normal to heat flow (m^2 or ft^2)

ΔT = temperature difference across wall (°C or °F)

Parallel heat flow resistance of a composite wall is calculated similar to parallel electrical resistance.

For two or more parallel paths, assuming that the heat flow is two dimensional and no there is no lateral heat flow through the wall

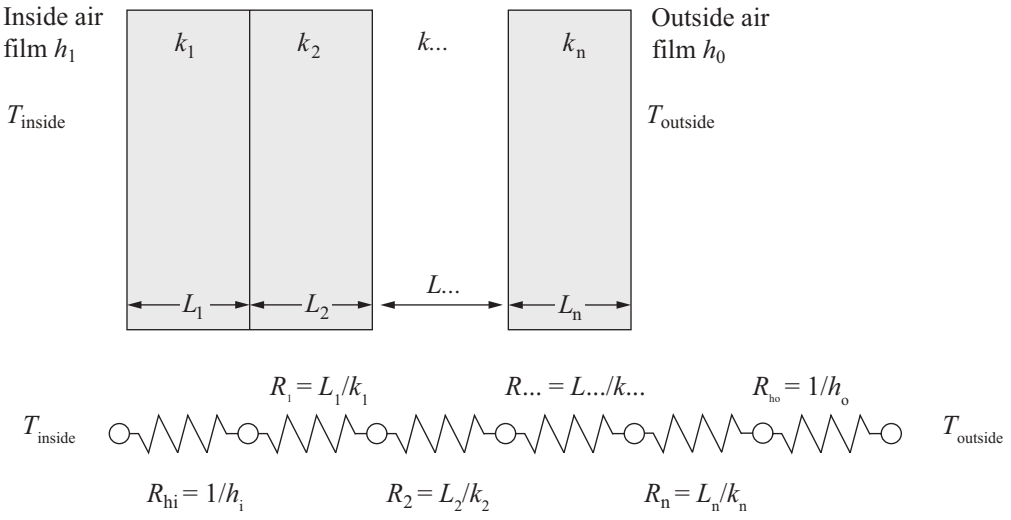
$$U_{overall} = \frac{U_a A_a + U_b A_b + U_c A_c + ... + U_n A_n}{A_o}$$

Where $U_{overall}$ is the average U value of the gross wall assembly, subscripts a, b, etc. are the U values and areas of the parallel components, and A_o is the gross area of the exterior walls ($A_o = A_a + A_b + A_c + ... + A_n$).

For a typical building consisting of insulated walls, doors, and windows, the overall U value is calculated from:

$$U_{overall} = \frac{U_{wall} A_{wall} + U_{windows} A_{windows} + U_{doors} A_{doors}}{A_o}$$

Series heat flow resistance of a composite wall is calculated similar to series electrical resistance.



$$R_{total} = 1/h_1 + L_1/k_1 + L_2/k_2 + ... + L_n/k_n + 1/h_o$$

$$R_{total} = 1/h_1 + R_1 + R_2 + ... + R_n + 1/h_o$$

$$U = 1/R_{total}$$

The heat flow through the wall section is calculated from:

$$\dot{Q} = UA\left(T_{inside} - T_{outside}\right)$$

The temperature at any interface location "x" can be calculated from:

$$\frac{R_x}{R_{total}} = \frac{\left(T_{inside} - T_x\right)}{T_{inside} - T_{outside}}$$

$$T_x = T_{inside} - \frac{R_x}{R_{total}}\left(T_{inside} - T_{outside}\right)$$

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5.2.2 Transient Conduction Using the Lumped Capacitance Model

The lumped capacitance model is valid if

$$\text{Biot number, Bi} = \frac{hV}{kA_s} \ll 1$$

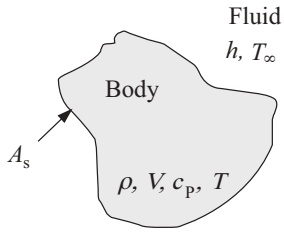
where

h = convection heat-transfer coefficient of the fluid $\left(\frac{\text{W}}{\text{m}^2 \cdot \text{K}} \text{ or } \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}\right)$

V = volume of the body (m^3)

k = thermal conductivity of the body $\left(\frac{\text{W}}{\text{m} \cdot \text{K}} \text{ or } \frac{\text{Btu - ft}}{\text{hr-ft}^2\text{-°F}}\right)$

A_s = surface area of the body (m^2 or ft^2)



5.2.3 Constant Fluid Temperature

If the temperature may be considered uniform within the body at any time, the heat-transfer rate at the body surface is

$$\dot{Q} = hA_s(T - T_\infty) = -\rho V(c_P)\left(\frac{dT}{dt}\right)$$

where

T = body temperature (K or °F)

T_∞ = fluid temperature (K or °F)

ρ = density of the body $\left(\frac{\text{kg}}{\text{m}^3} \text{ or } \frac{\text{lb}}{\text{ft}^3}\right)$

c_P = heat capacity of the body $\left(\frac{\text{J}}{\text{kg} \cdot \text{K}} \text{ or } \frac{\text{Btu}}{\text{lb - °F}}\right)$

t = time (s)

The temperature variation of the body with time is

$$T - T_\infty = (T_i - T_\infty)e^{-\beta t}$$

where

$$\beta = \frac{hA_s}{\rho V c_P}$$

$$\beta = \frac{1}{\tau}$$

τ = time constant (s)

The total heat transferred (Q_{total}) up to time t is

$$Q_{total} = \rho V c_P(T_i - T)$$

where

T_i = initial body temperature (K or °F)

T = body temperature at time t

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5.2.4 Fins

For a straight fin with uniform cross-section

$$\dot{Q} = \sqrt{hPkA_c}\left(T_b - T_\infty\right)\tanh\left(mL_c\right)$$

where

h = convection heat transfer coefficient of the fluid $\left(\frac{\text{W}}{\text{m}^2 \bullet \text{K}} \text{ or } \frac{\text{Btu}}{\text{hr - ft}^2 \text{ - °F}}\right)$

P = perimeter of exposed fin cross section (m or ft)

k = fin thermal conductivity $\left(\frac{\text{W}}{\text{m} \bullet \text{K}} \text{ or } \frac{\text{Btu - ft}}{\text{hr - ft}^2 \text{ - °F}}\right)$

A_c = fin cross-sectional area (m^2 or ft^2)

T = temperature at base of fin (K or °F)

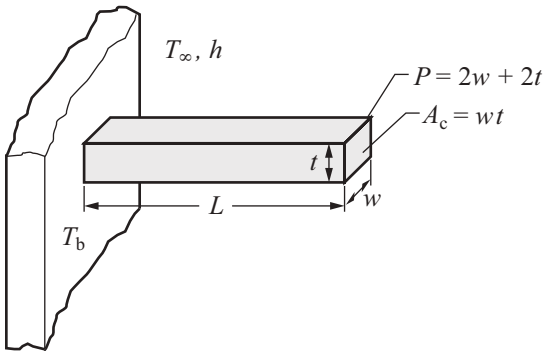
T_∞ = fluid temperature (K or °F)

$m = \sqrt{\frac{hP}{kA_c}}$

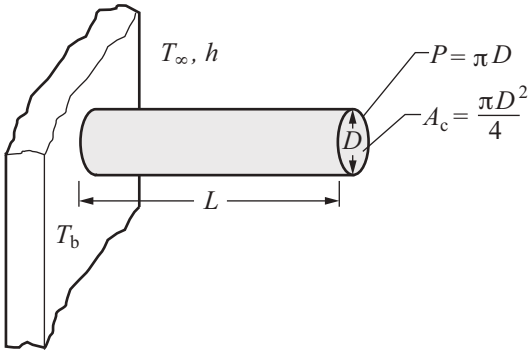
$L_c = L + \frac{A_c}{P}$, corrected length of fin (m or ft)

Fin Diagrams

Rectangular Fin



Pin Fin



5.3 Convection

5.3.1 Terms

D = diameter (m or ft)

$\overline{h}$ = average convection heat transfer coefficient of the fluid $\left(\frac{\text{W}}{\text{m}^2 \cdot \text{K}} \text{ or } \frac{\text{Btu}}{\text{hr - ft}^2 \text{ - °F}}\right)$

L = length (m or ft)

$\overline{Nu}$ = average Nusselt number

Pr = Prandtl number = $\frac{c_\text{P}\mu}{k}$

u_m = mean velocity of fluid $\left(\frac{\text{m}}{\text{s}} \text{ or } \frac{\text{ft}}{\text{sec}}\right)$

u_∞ = free stream velocity of fluid $\left(\frac{\text{m}}{\text{s}} \text{ or } \frac{\text{ft}}{\text{sec}}\right)$

μ = dynamic viscosity of fluid $\left(\frac{\text{kg}}{\text{s} \cdot \text{m}} \text{ or } \frac{\text{lb}}{\text{sec - ft}}\right)$

ρ = density of fluid $\left(\frac{\text{kg}}{\text{m}^3} \text{ or } \frac{\text{lb}}{\text{ft}^3}\right)$

5.3.2 Newton's Law of Cooling

$$\dot{Q} = hA\left(T_\text{w} - T_\infty\right)$$

where

h = convection heat transfer coefficient of the fluid $\left(\frac{\text{W}}{\text{m}^2 \cdot \text{K}} \text{ or } \frac{\text{Btu}}{\text{hr - ft}^2 \text{ - °F}}\right)$

A = convection surface area (m^2 or ft^2)

T_w = wall surface temperature (K or °F)

T_∞ = bulk fluid temperature (K or °F)

5.3.3 Grashof Number

The Grashof number Gr is a dimensionless number that is the ratio of buoyancy forces to viscous forces in a free convection flow system.

5.3.4 External Flow

In all cases of external flow, evaluate fluid properties at the average temperature between the body and flowing fluid.

Flat Plate of Length L in Parallel Flow:

$$\text{Re}_\text{L} = \frac{\rho u_\infty L}{\mu}$$

$$\overline{Nu}_\text{L} = \frac{\overline{h}L}{k} = 0.6640\,\text{Re}_\text{L}^{1/2}\,\text{Pr}^{1/3} \qquad \left(\text{Re}_\text{L} < 10^5\right)$$

$$\overline{Nu}_\text{L} = \frac{\overline{h}L}{k} = 0.0366\,\text{Re}_\text{L}^{0.8}\,\text{Pr}^{1/3} \qquad \left(\text{Re}_\text{L} > 10^5\right)$$

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5.3.5 External Flow: Cylinder of Diameter D in Cross Flow

$$\mathrm{Re_D} = \frac{\rho u_\infty D}{\mu}$$

$$\overline{Nu}_\mathrm{D} = \frac{\overline{h} D}{k} = C\,\mathrm{Re_D^{\,n}}\,\mathrm{Pr}^{1/3}$$

where

$\mathrm{Re_D}$	C	n
1–4	0.989	0.330
4–40	0.911	0.385
40–4,000	0.683	0.466
4,000–40,000	0.193	0.618
40,000–250,000	0.0266	0.805

5.3.6 External Flow Over a Sphere of Diameter D

$$\overline{Nu}_D = \frac{\overline{h} D}{k} = 2.0 + 0.60\,\mathrm{Re_D^{1/2}}\,\mathrm{Pr}^{1/3}$$

$$\left(1 < \mathrm{Re_D} < 70{,}000; \quad 0.6 < \mathrm{Pr} < 400\right)$$

5.3.7 Internal Flow

$$\mathrm{Re_D} = \frac{\rho u_\mathrm{m} D}{\mu}$$

5.3.8 Laminar Flow in Circular Tubes

For *laminar flow* ($\mathrm{Re_D} < 2{,}300$), with fully developed conditions:

$Nu_\mathrm{D} = 4.36$ (uniform heat flux)

$Nu_\mathrm{D} = 3.66$ (constant surface temperature)

For laminar flow ($\mathrm{Re_D} < 2{,}300$), combined entry length with constant surface temperature is expressed:

$$Nu_\mathrm{D} = 1.86\left(\frac{\mathrm{Re_D\,Pr}}{\frac{L}{D}}\right)^{1/3}\left(\frac{\mu_b}{\mu_s}\right)^{0.14}$$

where

L = length of tube (m)

D = tube diameter (m)

μ_b = dynamic viscosity of fluid $\left(\frac{\mathrm{kg}}{\mathrm{s \cdot m}}\right)\left(\frac{\mathrm{N\text{-}s}}{\mathrm{m^2}}\right)\left(\frac{\mathrm{lbm}}{\mathrm{ft\text{-}sec}}\right)$ at bulk temperature of fluid T_b

μ_s = dynamic viscosity of fluid $\left(\frac{\mathrm{kg}}{\mathrm{s \cdot m}}\right)\left(\frac{\mathrm{N\text{-}s}}{\mathrm{m^2}}\right)\left(\frac{\mathrm{lbm}}{\mathrm{ft\text{-}sec}}\right)$ at inside surface temperature of the tube T_s

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5.3.9 Turbulent Flow in Circular Tubes

For *turbulent flow* ($Re_D > 10^4$, $Pr > 0.7$), for either uniform surface temperature or uniform heat flux condition, *Sieder-Tate equation* offers good approximation:

$$Nu_D = 0.023\,Re_D^{0.8}\,Pr^{1/3}\left(\frac{\mu_b}{\mu_s}\right)^{0.14}$$

5.3.10 Film Temperature of a Tube

Using the average surface temperature T_s and the bulk temperature T_∞ of a tube, the mean boundary layer temperature T_f called the film temperature can be calculated.

$$T_f = \frac{T_s + T_\infty}{2}$$

5.4 Natural (Free) Convection

5.4.1 Vertical Flat Plate in Large Body of Stationary Fluid

Equation also can apply to vertical cylinder of sufficiently large diameter in large body of stationary fluid.

$$\overline{h} = C\left(\frac{k}{L}\right)Ra_L^n$$

where

L = length of the plate (cylinder) in the vertical direction

Ra_L = Rayleigh Number = $\dfrac{g\beta\left(T_s - T_\infty\right)L^3}{\nu^2}\,Pr$

T_s = surface temperature (K)

T_∞ = fluid temperature in (K)

β = coefficient of thermal expansion $\left(\dfrac{1}{K}\right)$

(For an ideal gas: $\beta = \dfrac{2}{T_s + T_\infty}$ with T in absolute temperature)

ν = kinematic viscosity in $\left(\dfrac{m^2}{s}\right)$

Range of Ra_L	C	n
10^4–10^9	0.59	$1/4$
10^9–10^{13}	0.10	$1/3$

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5.4.2 Long Horizontal Cylinder in Large Body of Stationary Fluid

$$\overline{h} = C\left(\frac{k}{D}\right)Ra_D^n$$

where

$$\mathrm{Ra_D} = \frac{g\beta\left(T_s - T_\infty\right)D^3}{\nu^2}\mathrm{Pr}$$

Ra_D	C	n
$10^{-3} - 10^2$	1.02	0.148
$10^2 - 10^4$	0.850	0.188
$10^4 - 10^7$	0.480	0.250
$10^7 - 10^{12}$	0.125	0.333

5.5 Heat Exchangers

5.5.1 Rate of Heat Transfer

The rate of heat transfer in a heat exchanger is

$$\dot{Q} = UAF\Delta T_{lm}$$

where

A = an area associated with the coefficient U (m^2 or ft^2)

F = correction factor for log mean temperature difference for more complex heat exchangers (shell-and-tube arrangements with several tube or shell passes, or cross-flow exchangers with mixed and unmixed flow); otherwise $F = 1$

U = overall heat-transfer coefficient based on area A and the log mean temperature difference $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} \text{ or } \frac{\mathrm{Btu}}{\mathrm{ft^2\text{-}^\circ F\text{-}hr}}\right)$

ΔT_{lm} = log mean temperature difference (K or °F)

5.5.2 Overall Heat-Transfer Coefficient for Concentric Tube and Shell-and-Tube Heat Exchangers

$$\frac{1}{UA} = \frac{1}{h_i A_i} + \frac{R_{fi}}{A_i} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi kL} + \frac{R_{fo}}{A_o} + \frac{1}{h_o A_o}$$

where

A_i = inside area of tubes (m^2 or ft^2)

A_o = outside area of tubes (m^2 or ft^2)

D_i = inside diameter of tubes (m or ft)

D_o = outside diameter of tubes (m or ft)

h_i = convection heat-transfer coefficient for inside of tubes $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} \text{ or } \frac{\mathrm{Btu}}{\mathrm{hr\text{-}ft^2\text{-}^\circ F}}\right)$

h_o = convection heat-transfer coefficient for outside of tubes $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}} \text{ or } \frac{\mathrm{Btu}}{\mathrm{hr\text{-}ft^2\text{-}^\circ F}}\right)$

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k = thermal conductivity of tube material $\left(\frac{\text{W}}{\text{m} \cdot \text{K}} \text{ or } \frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}\right)$

R_{fi} = fouling factor for inside of tube $\left(\frac{\text{m}^2 \cdot \text{K}}{\text{W}} \text{ or } \frac{\text{ft}^2\text{-°F-hr}}{\text{Btu}}\right)$

R_{fo} = fouling factor for outside of tube $\left(\frac{\text{m}^2 \cdot \text{K}}{\text{W}} \text{ or } \frac{\text{ft}^2\text{-°F-hr}}{\text{Btu}}\right)$

5.5.3 Log Mean Temperature Difference (LMTD)

For counterflow in heat exchangers:

$$\Delta T_{lm} = \frac{\left(T_{Ho} - T_{Ci}\right) - \left(T_{Hi} - T_{Co}\right)}{\ln\left(\frac{T_{Ho} - T_{Ci}}{T_{Hi} - T_{Co}}\right)}$$

If $(T_{Ho} - T_{CI}) = (T_{HI} - T_{Co})$ then $\Delta T_{lm} = (T_{Ho} - T_{Ci}) = (T_{Hi} - T_{Co})$

For parallel flow in heat exchangers:

$$\Delta T_{lm} = \frac{\left(T_{Ho} - T_{Co}\right) - \left(T_{Hi} - T_{Ci}\right)}{\ln\left(\frac{T_{Ho} - T_{Co}}{T_{Hi} - T_{Ci}}\right)}$$

Treat condensers (crossflow heat exchanger) as a counterflow heat exchanger.

where

ΔT_{lm} = log mean temperature difference (K or °F)

T_{Hi} = inlet temperature of the hot fluid (K or °F)

T_{Ho} = outlet temperature of the hot fluid (K or °F)

T_{Ci} = inlet temperature of the cold fluid (K or °F)

T_{Co} = outlet temperature of the cold fluid (K or °F)

5.5.4 Heat Exchanger Effectiveness, ε

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{\text{actual heat transfer rate}}{\text{maximum possible heat transfer rate}}$$

$$\varepsilon = \frac{C_H\left(T_{Hi} - T_{Ho}\right)}{C_{min}\left(T_{Hi} - T_{Ci}\right)} \quad \text{or} \quad \varepsilon = \frac{C_C\left(T_{Co} - T_{Ci}\right)}{C_{min}\left(T_{Hi} - T_{Ci}\right)}$$

where

$C_H = \left(\dot{m}c_P\right)_H$ = hot fluid capacity rate $\left(\frac{\text{W}}{\text{K}} \text{ or } \frac{\text{Btu}}{\text{hr-°F}}\right)$

$C_C = \left(\dot{m}c_P\right)_C$ = cold fluid capacity rate $\left(\frac{\text{W}}{\text{K}} \text{ or } \frac{\text{Btu}}{\text{hr-°F}}\right)$

C_{min} = smaller of C_C or C_H

5.5.5 Number of Transfer Units (NTU)

$$NTU = \frac{AU_{avg}}{C_{min}}$$

where

A is the same area used to define the overall coefficient U_{avg}

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5.5.6 Effectiveness-NTU Relations

$$C_r = \frac{C_{min}}{C_{max}} = \text{capacity rate ratio}$$

When $C_r = 0$, such as in condenser or evaporator units with effective $C_p = \infty$

$$\varepsilon = 1 - \exp(-NTU) \qquad C_r = 0$$

$$T_{LM} = \frac{(T_{Hi} - T_{Co})^{\varepsilon}}{NTU}$$

For parallel flow concentric tube heat exchanger:

$$\varepsilon = \frac{1 - \exp\left[-NTU\left(1 + C_r\right)\right]}{1 + C_r}$$

$$NTU = -\frac{\ln\left[1 - \varepsilon\left(1 + C_r\right)\right]}{1 + C_r}$$

For counterflow concentric tube heat exchanger:

$$\varepsilon = \frac{1 - \exp\left[-NTU\left(1 - C_r\right)\right]}{1 - C_r \exp\left[-NTU\left(1 - C_r\right)\right]} \qquad \left(C_r \neq 1\right)$$

$$\varepsilon = \frac{NTU}{1 + NTU} \qquad \left(C_r = 1\right)$$

$$NTU = \frac{1}{C_r - 1} \ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right) \qquad \left(C_r \neq 1\right)$$

$$NTU = \frac{\varepsilon}{1 - \varepsilon} \qquad \left(C_r = 1\right)$$

5.6 Radiation

5.6.1 Types of Bodies

For any body:

$$\alpha + \rho + \tau = 1$$

where

α = absorptivity (ratio of energy absorbed to incident energy)

ρ = reflectivity (ratio of energy reflected to incident energy)

τ = transmissivity (ratio of energy transmitted to incident energy)

For an *opaque body*:

$$\alpha + \rho = 1 \qquad \tau = 0$$

A *gray body* is one for which

$$\alpha = \varepsilon, \ (0 < \alpha < 1; \ 0 < \varepsilon < 1)$$

where ε = emissivity of the body

For a gray body:

$$\varepsilon + \rho = 1$$

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A *real body* is frequently approximated as a gray body.

A *black body* absorbs all energy incident upon it. It also emits radiation at the maximum rate for a body of a particular size at a particular temperature. For such a body,

$$\alpha = \varepsilon = 1 \qquad \rho = 0 \qquad \tau = 0$$

5.6.2 Emissivity of Various Surfaces and Effective Emittances of Facing Air Spaces

Emissivity of Surfaces and Effective Emittances of Facing Spaces[a]

		Effective Emittance, ε_{eff}, of Air Space	
Surface	**Average Emissivity ε**	**One Surface's Emittance ε; Other, 0.9**	**Both Surfaces' Emittance ε**
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil, with condensate just visible (>0.7 g/ft^2)	0.30[b]	0.29	--
Aluminum foil, with condensate clearly visible (>2.9 g/ft^2)	0.70[b]	0.65	--
Aluminum sheet	0.12	0.12	0.06
Aluminum-coated paper, polished	0.20	0.20	0.11
Brass, nonoxidized	0.04	0.038	0.02
Copper, black oxidized	0.74	0.41	0.59
Copper, polished	0.04	0.038	0.02
Iron and steel, polished	0.2	0.16	0.11
Iron and steel, oxidized	0.58	0.35	0.41
Lead, oxidized	0.27	0.21	0.16
Nickel, nonoxidized	0.06	0.056	0.03
Silver, polished	0.03	0.029	0.015
Steel, galvanized, bright	0.25	0.24	0.15
Tin, nonoxidized	0.05	0.047	0.026
Aluminum paint	0.50	0.47	0.35
Building materials: wood, paper, masonry, nonmetallic paints	0.90	0.82	0.82
Regular glass	0.84	0.77	0.72

a. Values apply in 4 to 40 μm range of electromagnetic spectrum. Also, oxidation, corrosion, and accumulation of dust and dirt can dramatically increase surface emittance. Emittance values of 0.05 should only be used where the highly reflective surface can be maintained over the service life of the assembly. Except as noted, data from VDI (1999).

b. Values based on data in Bassett and Trehowen (1984)

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 26, Heat, Air, and Moisture Control in Building Assemblies—Material Properties, Table 2.

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5.6.3 Shape Factor Relationships

Shape factor, also known as view factor or configuration factor, is the fraction of radiation leaving one surface that is intercepted by another surface.

5.6.4 Reciprocity

$$A_i F_{ij} = A_j F_{ji}$$

where

A_i = area of surface i (m^2)

F_{ij} = shape factor, i.e., fraction of radiation leaving surface i that is intercepted by surface j; $0 \le F_{ij} \le 1$

5.6.5 Summation Rule for N Surfaces

$$\sum_{j=1}^{N} F_{ij} = 1$$

5.6.6 Net Energy Exchange by Radiation Between Two Bodies

For a body that is small compared to its surroundings:

$$\dot{Q}_{12} = \varepsilon \sigma A \left(T_1^4 - T_2^4 \right)$$

where

$\dot{Q}_{12}$ = net heat-transfer rate from the body (W)

ε = emissivity of the body

A = body surface area (m^2 or ft^2)

σ = Stefan-Boltzmann constant

T_1 = absolute temperature of the body surface (K or °R)

T_2 = absolute temperature of the surroundings (K or °R)

5.6.7 Net Energy Exchange by Radiation Between Two Black Bodies

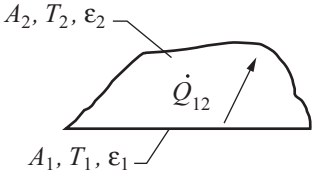
The net energy exchange by radiation between two black bodies that see each other is

$$\dot{Q}_{12} = A_1 F_{12} \sigma \left(T_1^4 - T_2^4 \right)$$

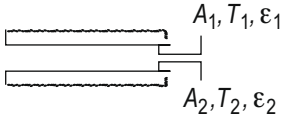
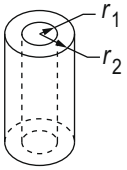
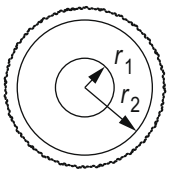
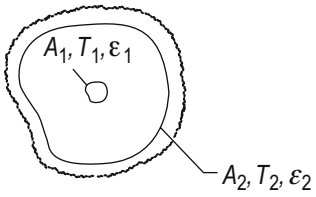
5.6.8 Net Energy Exchange by Radiation Between Two Diffuse Gray Surfaces That Form an Enclosure

For generalized cases:

$$\dot{Q}_{12} = \frac{\sigma \left(T_1^4 - T_2^4 \right)}{\frac{1 - \varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1 - \varepsilon_2}{\varepsilon_2 A_2}}$$



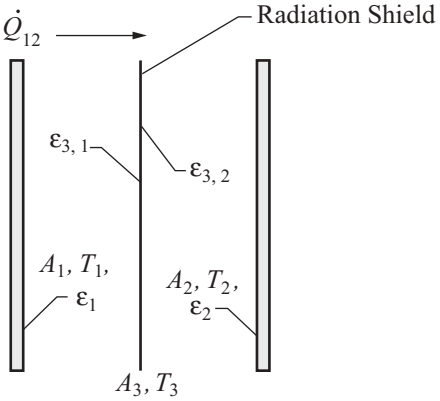
Special Diffuse, Gray, Two-Surface Enclosures

Large (Infinite) Parallel Planes		
	$A_1 = A_2 = A$ $F_{12} = 1$	$q_{12} = \dfrac{A\sigma\left(T_1^4 - T_2^4\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1}$
Long (Infinite) Concentric Cylinders		
	$\dfrac{A_1}{A_2} = \dfrac{r_1}{r_2}$ $F_{12} = 1$	$q_{12} = \dfrac{\sigma A_1\left(T_1^4 - T_2^4\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)}$
Concentric Spheres		
	$\dfrac{A_1}{A_2} = \dfrac{r_1^2}{r_2^2}$ $F_{12} = 1$	$q_{12} = \dfrac{\sigma A_1\left(T_1^4 - T_2^4\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{1-\varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)^2}$
Small Convex Object in a Large Cavity		
	$\dfrac{A_1}{A_2} \approx 0$ $F_{12} = 1$	$q_{12} = \sigma A_1 \varepsilon_1 \left(T_1^4 - T_2^4\right)$

Source: Incropera, Frank P. and David P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 4th ed., New York: John Wiley & Sons, 1996.

5.6.9 One-Dimensional Geometry with Thin, Low-Emissivity Shield Inserted Between Two Parallel Plates

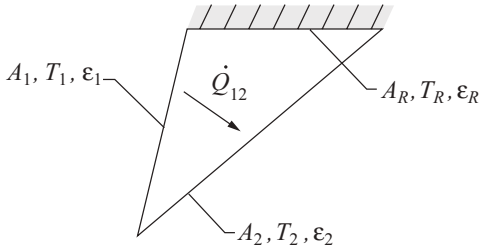
$$\dot{Q}_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\dfrac{1-\varepsilon_1}{\varepsilon_1 A_1} + \dfrac{1}{A_1 F_{13}} + \dfrac{1-\varepsilon_{3,1}}{\varepsilon_{3,1} A_3} + \dfrac{1-\varepsilon_{3,2}}{\varepsilon_{3,2} A_3} + \dfrac{1}{A_3 F_{32}} + \dfrac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$



5.6.10 Reradiating Surfaces

Reradiating surfaces are considered to be insulated or adiabatic $\left(\dot{Q}_R = 0\right)$.

$$\dot{Q}_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12} + \left[\left(\frac{1}{A_1 F_{1R}}\right) + \left(\frac{1}{A_2 F_{2R}}\right)\right]^{-1}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$



5.7 Adiabatic Mixing of Fluids

When two similar fluids of different temperatures and flow rates are blended together, the resulting mixed fluid temperature can be determined by:

$$T_{\text{mixed}} = \frac{T_1 \text{Q}_1 + T_2 Q_2}{\text{Q}_1 + \text{Q}_2}$$

where

T_{mixed} = mixed fluid temperature (ºF or ºC)

T_1 = fluid 1 temperature (ºF or ºC)

T_2 = fluid 2 temperature (ºF or ºC)

Q_1 = fluid 1 flow rate (gpm or cfm)

Q_2 = fluid 2 flow rate (gpm or cfm)

To determine the ratio of one fluid source required to blend with another fluid source to produce a desired mixed fluid temperature:

$$R_{\text{fluid 1}} = \frac{T_{\text{mixed}} - T_{\text{fluid 2}}}{T_{\text{fluid 1}} - T_{\text{fluid 2}}}$$

where

$R_{\text{fluid 1}}$ = fluid 1 ratio (dimensionless)

T_{mixed} = desired mixed fluid temperature (ºF or ºC)

$T_{\text{fluid 1}}$ = fluid 1 temperature (ºF or ºC)

$T_{\text{fluid 2}}$ = fluid 2 temperature (ºF or ºC)

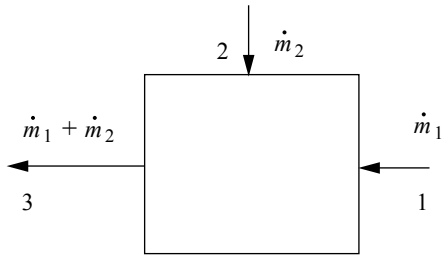
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6 STEAM

6.1 Steam Power Plants

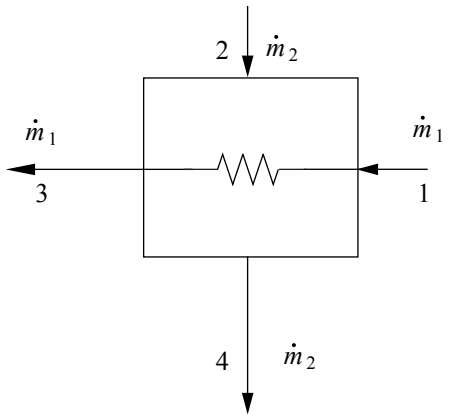
6.1.1 Feedwater Heaters

Open (Mixing) Feedwater Heater



$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = h_3 (\dot{m}_1 + \dot{m}_2)$$

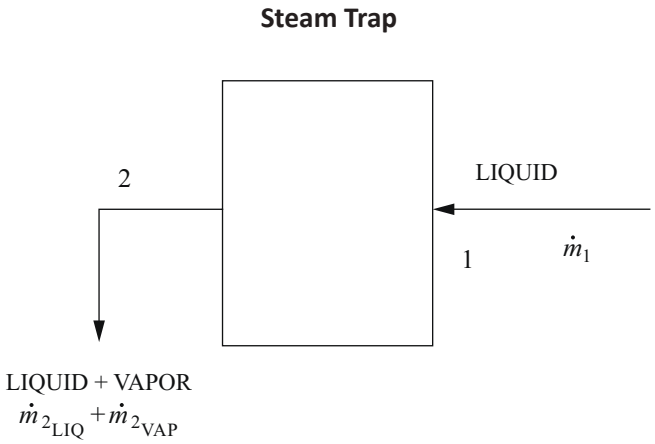
Closed (No Mixing) Feedwater Heater



$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_1 h_3 + \dot{m}_2 h_4$$

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6.1.2 Steam Traps



$$\dot{m}_1 h_1 = \dot{m}_{2_{LIQ}} h_{2_{LIQ}} + \dot{m}_{2_{VAP}} h_{2_{VAP}}$$

$$\dot{m}_1 = \dot{m}_{2_{LIQ}} + \dot{m}_{2_{VAP}}$$

6.1.3 Steam Quality and Volume Fraction

The *Quality x* of steam condensate downstream from the trap can be defined as:

$$x = \frac{m_{VAP}}{m_{LIQ} + m_{VAP}}$$

where

m_{VAP} = mass of saturated vapor in condensate

m_{LIQ} = mass of saturated liquid in condensate

The *Volume Fraction* V_c of the vapor in the condensate is expressed as:

$$V_c = \frac{V_{VAP}}{V_{LIQ} + V_{VAP}}$$

where

V_{VAP} = volume of saturated vapor in condensate

V_{LIQ} = volume of saturated liquid in condensate

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The quality and volume fraction of the condensate can be estimated from:

$$x = \frac{h_{LIQ} - h_{f_2}}{h_{g_2} - h_{f_2}} \quad \text{and} \quad v_c = \frac{x v_{g_2}}{v_{f_2}(1-x) + x v_{g_2}}$$

where

h_{LIQ} = enthalpy of liquid condensate entering steam trap evaluated at supply pressure for saturated condensate or at saturation pressure corresponding to temperature of subcooled liquid condensate

h_{f_2} = enthalpy of saturated liquid at return or downstream pressure of trap

h_{g_2} = enthalpy of saturated vapor at return or downstream pressure of trap

v_{f_2} = specific volume of saturated liquid at return or downstream pressure of trap

v_{g_2} = specific volume of saturated vapor at return or downstream pressure of trap

6.1.4 Flash Steam

The percent (by mass) flash steam that is formed when liquid condensate is discharged to a lower pressure can be calculated:

$$\% \text{ Flash Steam} = \frac{100\left(h_{f_1} - h_{f_2}\right)}{h_{fg_2}}$$

where

h_{f_1} = enthalpy of liquid at pressure p_1

h_{f_2} = enthalpy of liquid at pressure p_2

h_{fg_2} = latent heat of vaporization at pressure p_2

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6.2 Flow Rate of Steam in Schedule 40 Pipe

Flow Rate of Steam in Schedule 40 Pipe

Nominal Pipe Size, in	Pressure Drop Per 100 Feet of Length													
	1/16 psi (1 oz/in²)		1/8 psi (2 oz/in²)		1/4 psi (4 oz/in²)		1/2 psi (8 oz/in²)		3/4 psi (12 oz/in²)		1 psi		2 psi	
	Sat. Press., psig		Sat. Press., psig		Sat. Press., psig		Sat. Press., psig		Sat. Press., psig		Sat. Press., psig		Sat. Press., psig	
	3.5	12	3.5	12	3.5	12	3.5	12	3.5	12	3.5	12	3.5	12
0.75	9	11	14	16	20	24	29	35	36	43	42	50	60	73
1	17	21	26	31	37	46	54	66	68	82	81	95	114	137
1.25	36	45	53	66	78	96	111	138	140	170	162	200	232	280
1.5	56	70	84	100	120	147	174	210	218	260	246	304	360	430
2	108	134	162	194	234	285	336	410	420	510	480	590	710	850
2.5	174	215	258	310	378	460	540	660	680	820	780	950	1,150	1,370
3	318	380	465	550	660	810	960	1,160	1,190	1,430	1,380	1,670	1,950	2,400
4	640	800	950	1,160	1,410	1,690	1,980	2,400	2,450	3,000	2,880	3,460	4,200	4,900
5	1,200	1,430	1,680	2,100	2,440	3,000	3,570	4,250	4,380	5,250	5,100	6,100	7,500	8,600
6	1,920	2,300	2,820	3,350	3,960	4,850	5,700	6,800	7,000	8,600	8,400	10,000	11,900	14,200
8	3,900	4,800	5,570	7,000	8,100	10,000	11,400	14,300	14,500	17,700	16,500	20,500	24,000	29,500
10	7,200	8,800	10,200	12,600	15,000	18,200	21,000	26,000	26,200	32,000	30,000	37,000	42,700	52,000
12	11,400	13,700	16,500	19,500	23,400	28,400	33,000	40,000	41,000	49,500	48,000	57,500	67,800	81,000

Notes:

1. Flow rate is in lb/h at initial saturation pressures of 3.5 and 12 psig. Flow is based on Moody friction factor, where the flow of condensate does not inhibit the flow of steam.

2. The flow rates at 3.5 psig cover saturated pressure from 1 to 6 psig, and the rates at 12 psig cover saturated pressure from 8 to 16 psig with an error not exceeding 8%.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 22, Pipe Sizing, Table 18.

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6.3 Steam Tables

6.3.1 Properties of Saturated Water and Steam (Temperature)—I-P Units

Properties of Saturated Water and Steam (Temperature)—I-P Units

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
32.02	0.09	0.0160	3299.55	3299.56	0.00	1075.19	1075.19	-	2.1868	2.1868	32.02
34	0.10	0.0160	3059.90	3059.92	2.00	1074.06	1076.06	0.0042	2.1756	2.1797	34.00
36	0.10	0.0160	2837.52	2837.54	4.01	1072.95	1076.96	0.0091	2.1636	2.1728	36.00
38	0.11	0.0160	2632.98	2633.00	6.02	1071.80	1077.82	0.0122	2.1536	2.1658	38.00
40	0.12	0.0160	2444.73	2444.75	8.03	1070.66	1078.70	0.0162	2.1427	2.1589	40.00
42	0.13	0.0160	2271.35	2271.37	10.04	1069.54	1079.58	0.0202	2.1319	2.1522	42.00
44	0.14	0.0160	2111.58	2111.59	12.05	1068.39	1080.44	0.0242	2.1212	2.1454	44.00
46	0.15	0.0160	1964.23	1964.25	14.06	1067.28	1081.33	0.0282	2.1106	2.1388	46.00
48	0.17	0.0160	1828.28	1828.30	16.06	1066.14	1082.20	0.0321	2.1000	2.1322	48.00
50	0.18	0.0160	1702.75	1702.76	18.07	1065.00	1083.06	0.0363	2.0894	2.1257	50.00
52	0.19	0.0160	1587.57	1587.59	20.07	1063.86	1083.93	0.0402	2.0791	2.1192	52.00
54	0.21	0.0160	1481.05	1481.06	22.07	1062.75	1084.82	0.0449	2.0679	2.1128	54.00
56	0.22	0.0160	1382.45	1382.47	24.07	1061.61	1085.68	0.0478	2.0587	2.1065	56.00
58	0.24	0.0160	1291.15	1291.17	26.08	1060.47	1086.54	0.0517	2.0486	2.1002	58.00
60	0.26	0.0160	1206.55	1206.56	28.08	1059.35	1087.43	0.0555	2.0385	2.0940	60.00
62	0.28	0.0160	1128.12	1128.14	30.08	1058.23	1088.31	0.0594	2.0285	2.0879	62.00
64	0.30	0.0160	1055.37	1055.39	32.08	1057.09	1089.17	0.0632	2.0186	2.0818	64.00
66	0.33	0.0160	987.84	987.86	34.08	1055.95	1090.03	0.0670	2.0088	2.0758	66.00
68	0.34	0.0160	925.14	925.15	36.07	1054.81	1090.89	0.0708	1.9990	2.0698	68.00
70	0.36	0.0161	867.24	867.25	38.08	1053.71	1091.79	0.0760	1.9879	2.0639	70.00
72	0.39	0.0161	813.38	813.40	40.07	1052.58	1092.65	0.0784	1.9797	2.0581	72.00
74	0.42	0.0161	763.26	763.28	42.07	1051.44	1093.51	0.0822	1.9701	2.0523	74.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
76	0.44	0.0161	716.59	716.61	44.07	1050.30	1094.37	0.0858	1.9607	2.0466	76.00
78	0.48	0.0161	673.12	673.14	46.07	1049.16	1095.23	0.0896	1.9513	2.0409	78.00
80	0.51	0.0161	632.59	632.61	48.06	1048.02	1096.09	0.0933	1.9420	2.0353	80.00
82	0.54	0.0161	594.81	594.82	50.06	1046.89	1096.95	0.0971	1.9326	2.0297	82.00
84	0.58	0.0161	559.55	559.56	52.06	1045.75	1097.81	0.1007	1.9235	2.0242	84.00
86	0.62	0.0161	526.62	526.64	54.05	1044.61	1098.67	0.1043	1.9144	2.0187	86.00
88	0.66	0.0161	496.07	496.08	56.05	1043.48	1099.53	0.1090	1.9044	2.0133	88.00
90	0.70	0.0161	467.49	467.51	58.05	1042.38	1100.43	0.1116	1.8963	2.0079	90.00
92	0.74	0.0161	440.78	440.79	60.04	1041.25	1101.29	0.1152	1.8874	2.0026	92.00
94	0.79	0.0161	415.78	415.79	62.04	1040.09	1102.13	0.1188	1.8785	1.9974	94.00
96	0.84	0.0161	392.36	392.38	64.04	1038.93	1102.97	0.1224	1.8697	1.9922	96.00
98	0.89	0.0161	370.44	370.46	66.03	1037.79	1103.83	0.1260	1.8610	1.9870	98.00
100	0.95	0.0161	349.90	349.91	68.03	1036.66	1104.69	0.1296	1.8523	1.9819	100.00
102	1.01	0.0161	330.64	330.66	70.03	1035.52	1105.55	0.1332	1.8436	1.9768	102.00
104	1.07	0.0161	312.58	312.59	72.03	1034.38	1106.41	0.1367	1.8351	1.9718	104.00
106	1.14	0.0162	295.73	295.74	74.02	1033.24	1107.27	0.1403	1.8266	1.9668	106.00
108	1.20	0.0162	279.90	279.92	76.02	1032.11	1108.13	0.1438	1.8181	1.9619	108.00
110	1.28	0.0162	265.02	265.04	78.02	1030.96	1108.97	0.1473	1.8097	1.9570	110.00
112	1.35	0.0162	251.04	251.06	80.01	1029.79	1109.80	0.1508	1.8014	1.9522	112.00
114	1.43	0.0162	237.90	237.92	82.01	1028.65	1110.66	0.1543	1.7931	1.9474	114.00
116	1.52	0.0162	225.54	225.55	84.01	1027.51	1111.52	0.1577	1.7849	1.9426	116.00
118	1.60	0.0162	213.90	213.92	86.01	1026.38	1112.38	0.1612	1.7767	1.9379	118.00
120	1.70	0.0162	202.94	202.96	88.00	1025.20	1113.20	0.1663	1.7670	1.9333	120.00
122	1.79	0.0162	192.63	192.65	90.00	1024.06	1114.06	0.1681	1.7605	1.9286	122.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
124	1.89	0.0162	182.96	182.98	92.00	1022.92	1114.91	0.1715	1.7525	1.9241	124.00
126	2.00	0.0162	173.84	173.86	94.00	1021.74	1115.74	0.1749	1.7446	1.9195	126.00
128	2.11	0.0162	165.24	165.25	95.99	1020.59	1116.58	0.1784	1.7367	1.9150	128.00
130	2.23	0.0162	157.12	157.13	97.99	1019.42	1117.41	0.1817	1.7288	1.9106	130.00
132	2.35	0.0163	149.45	149.47	99.99	1018.26	1118.25	0.1851	1.7210	1.9061	132.00
134	2.48	0.0163	142.21	142.23	101.99	1017.10	1119.09	0.1885	1.7133	1.9018	134.00
136	2.61	0.0163	135.37	135.39	103.99	1015.93	1119.92	0.1919	1.7055	1.8974	136.00
138	2.75	0.0163	128.91	128.93	105.99	1014.78	1120.77	0.1952	1.6979	1.8931	138.00
140	2.89	0.0163	122.80	122.81	107.99	1013.60	1121.58	0.1986	1.6903	1.8888	140.00
142	3.05	0.0163	117.04	117.06	109.99	1012.45	1122.44	0.2019	1.6827	1.8846	142.00
144	3.20	0.0163	111.60	111.62	111.99	1011.26	1123.25	0.2052	1.6752	1.8804	144.00
146	3.37	0.0163	106.44	106.46	113.99	1010.09	1124.08	0.2085	1.6678	1.8763	146.00
148	3.54	0.0163	101.56	101.58	115.99	1008.93	1124.92	0.2118	1.6603	1.8721	148.00
150	3.72	0.0163	96.93	96.95	117.99	1007.74	1125.73	0.2151	1.6529	1.8680	150.00
152	3.91	0.0164	92.55	92.57	119.99	1006.58	1126.57	0.2184	1.6456	1.8640	152.00
154	4.11	0.0164	88.39	88.41	121.99	1005.41	1127.40	0.2216	1.6383	1.8600	154.00
156	4.31	0.0164	84.45	84.47	123.99	1004.22	1128.21	0.2249	1.6311	1.8560	156.00
158	4.53	0.0164	80.71	80.72	126.00	1003.02	1129.02	0.2281	1.6239	1.8520	158.00
160	4.75	0.0164	77.17	77.19	128.00	1001.83	1129.83	0.2314	1.6167	1.8481	160.00
162	4.98	0.0164	73.81	73.83	130.00	1000.64	1130.64	0.2346	1.6096	1.8442	162.00
164	5.22	0.0164	70.63	70.64	132.00	999.45	1131.46	0.2378	1.6025	1.8403	164.00
166	5.47	0.0164	67.59	67.61	134.01	998.26	1132.27	0.2410	1.5955	1.8365	166.00
168	5.73	0.0164	64.71	64.73	136.01	997.07	1133.08	0.2442	1.5885	1.8327	168.00
170	6.00	0.0164	61.97	61.99	138.01	995.88	1133.89	0.2474	1.5816	1.8290	170.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
172	6.28	0.0165	59.37	59.38	140.02	994.69	1134.71	0.2506	1.5747	1.8252	172.00
174	6.57	0.0165	56.89	56.90	142.02	993.46	1135.48	0.2537	1.5678	1.8215	174.00
176	6.88	0.0165	54.53	54.54	144.03	992.26	1136.29	0.2569	1.5610	1.8179	176.00
178	7.19	0.0165	52.29	52.31	146.03	991.06	1137.10	0.2600	1.5542	1.8142	178.00
180	7.52	0.0165	50.16	50.17	148.04	989.86	1137.90	0.2632	1.5474	1.8106	180.00
182	7.86	0.0165	48.13	48.14	150.05	988.63	1138.68	0.2663	1.5407	1.8070	182.00
184	8.21	0.0165	46.19	46.21	152.05	987.42	1139.47	0.2694	1.5340	1.8035	184.00
186	8.58	0.0165	44.34	44.36	154.06	986.20	1140.26	0.2725	1.5274	1.8000	186.00
188	8.96	0.0166	42.58	42.60	156.07	984.97	1141.04	0.2757	1.5208	1.7965	188.00
190	9.35	0.0166	40.90	40.92	158.08	983.76	1141.84	0.2787	1.5143	1.7930	190.00
192	9.76	0.0166	39.30	39.32	160.09	982.53	1142.62	0.2818	1.5077	1.7895	192.00
194	10.18	0.0166	37.77	37.79	162.10	981.28	1143.38	0.2849	1.5012	1.7861	194.00
196	10.62	0.0166	36.32	36.33	164.11	980.08	1144.19	0.2880	1.4947	1.7827	196.00
198	11.07	0.0166	34.93	34.94	166.12	978.83	1144.95	0.2910	1.4883	1.7794	198.00
200	11.54	0.0166	33.60	33.61	168.13	977.58	1145.72	0.2941	1.4819	1.7760	200.00
202	12.02	0.0166	32.33	32.34	170.14	976.34	1146.48	0.2971	1.4756	1.7727	202.00
204	12.53	0.0167	31.11	31.13	172.15	975.09	1147.24	0.3002	1.4693	1.7694	204.00
206	13.05	0.0167	29.95	29.97	174.17	973.84	1148.01	0.3032	1.4630	1.7661	206.00
208	13.58	0.0167	28.84	28.86	176.18	972.59	1148.77	0.3062	1.4567	1.7629	208.00
210	14.14	0.0167	27.78	27.80	178.19	971.34	1149.54	0.3092	1.4505	1.7597	210.00
212	14.71	0.0167	26.76	26.78	180.21	970.09	1150.30	0.3122	1.4443	1.7565	212.00
214	15.30	0.0167	25.79	25.81	182.23	968.80	1151.02	0.3152	1.4381	1.7533	214.00
216	15.92	0.0167	24.86	24.88	184.24	967.55	1151.79	0.3182	1.4320	1.7502	216.00
218	16.55	0.0168	23.97	23.99	186.26	966.28	1152.54	0.3212	1.4259	1.7471	218.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
220	17.20	0.0168	23.12	23.14	188.27	965.00	1153.27	0.3241	1.4198	1.7440	220.00
222	17.88	0.0168	22.30	22.32	190.29	963.72	1154.01	0.3271	1.4138	1.7409	222.00
224	18.57	0.0168	21.52	21.54	192.31	962.45	1154.76	0.3301	1.4078	1.7378	224.00
226	19.29	0.0168	20.77	20.78	194.33	961.16	1155.49	0.3330	1.4018	1.7348	226.00
228	20.03	0.0169	20.05	20.06	196.35	959.86	1156.21	0.3360	1.3958	1.7318	228.00
230	20.80	0.0168	19.35	19.37	198.38	958.59	1156.97	0.3389	1.3899	1.7288	230.00
232	21.58	0.0169	18.69	18.71	200.40	957.29	1157.68	0.3418	1.3840	1.7258	232.00
234	22.40	0.0169	18.06	18.07	202.42	955.98	1158.40	0.3447	1.3781	1.7229	234.00
236	23.24	0.0169	17.45	17.46	204.44	954.67	1159.12	0.3476	1.3723	1.7199	236.00
238	24.10	0.0169	16.86	16.88	206.46	953.37	1159.83	0.3505	1.3665	1.7170	238.00
240	24.99	0.0169	16.30	16.32	208.49	952.06	1160.55	0.3534	1.3607	1.7141	240.00
242	25.90	0.0169	15.76	15.78	210.52	950.72	1161.24	0.3563	1.3549	1.7113	242.00
244	26.85	0.0170	15.24	15.26	212.54	949.39	1161.94	0.3592	1.3492	1.7084	244.00
246	27.82	0.0170	14.74	14.76	214.57	948.09	1162.66	0.3621	1.3435	1.7056	246.00
248	28.81	0.0170	14.26	14.28	216.60	946.73	1163.33	0.3649	1.3378	1.7028	248.00
250	29.85	0.0170	13.80	13.81	218.63	945.41	1164.04	0.3678	1.3322	1.7000	250.00
252	30.90	0.0170	13.35	13.37	220.66	944.06	1164.72	0.3706	1.3265	1.6972	252.00
254	31.99	0.0170	12.93	12.95	222.69	942.73	1165.42	0.3735	1.3209	1.6944	254.00
256	33.11	0.0170	12.52	12.54	224.72	941.37	1166.09	0.3763	1.3153	1.6917	256.00
258	34.27	0.0171	12.12	12.14	226.76	940.00	1166.76	0.3792	1.3098	1.6890	258.00
260	35.45	0.0171	11.74	11.76	228.79	938.64	1167.43	0.3820	1.3043	1.6863	260.00
262	36.67	0.0171	11.38	11.39	230.83	937.27	1168.10	0.3848	1.2987	1.6836	262.00
264	37.92	0.0171	11.02	11.04	232.87	935.90	1168.76	0.3876	1.2933	1.6809	264.00
266	39.20	0.0171	10.68	10.70	234.90	934.53	1169.43	0.3904	1.2878	1.6782	266.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
268	40.52	0.0172	10.36	10.37	236.94	933.16	1170.10	0.3932	1.2824	1.6756	268.00
270	41.88	0.0172	10.04	10.06	238.98	931.75	1170.73	0.3960	1.2770	1.6730	270.00
272	43.27	0.0172	9.74	9.75	241.02	930.36	1171.38	0.3988	1.2716	1.6704	272.00
274	44.71	0.0172	9.44	9.46	243.06	928.96	1172.02	0.4016	1.2662	1.6678	274.00
276	46.17	0.0172	9.16	9.18	245.11	927.56	1172.67	0.4044	1.2608	1.6652	276.00
278	47.68	0.0172	8.89	8.91	247.15	926.14	1173.29	0.4071	1.2555	1.6626	278.00
280	49.22	0.0173	8.63	8.64	249.20	924.71	1173.91	0.4099	1.2502	1.6601	280.00
282	50.81	0.0173	8.37	8.39	251.24	923.29	1174.53	0.4127	1.2449	1.6576	282.00
284	52.44	0.0173	8.13	8.14	253.29	921.86	1175.15	0.4154	1.2396	1.6550	284.00
286	54.11	0.0173	7.89	7.91	255.34	920.43	1175.77	0.4182	1.2344	1.6525	286.00
288	55.82	0.0173	7.66	7.68	257.39	919.00	1176.39	0.4209	1.2292	1.6500	288.00
290	57.58	0.0174	7.44	7.46	259.45	917.55	1177.00	0.4236	1.2239	1.6476	290.00
292	59.38	0.0174	7.23	7.25	261.50	916.09	1177.59	0.4263	1.2188	1.6451	292.00
294	61.22	0.0174	7.02	7.04	263.56	914.63	1178.19	0.4291	1.2136	1.6427	294.00
296	63.11	0.0174	6.83	6.84	265.61	913.18	1178.79	0.4318	1.2084	1.6402	296.00
298	65.05	0.0174	6.63	6.65	267.67	911.71	1179.38	0.4345	1.2033	1.6378	298.00
300	67.03	0.0174	6.45	6.47	269.73	910.22	1179.95	0.4372	1.1982	1.6354	300.00
302	69.06	0.0175	6.27	6.29	271.79	908.74	1180.53	0.4399	1.1931	1.6330	302.00
304	71.15	0.0175	6.10	6.11	273.85	907.25	1181.10	0.4426	1.1880	1.6306	304.00
306	73.28	0.0175	5.93	5.95	275.91	905.76	1181.67	0.4453	1.1830	1.6283	306.00
308	75.46	0.0175	5.77	5.78	277.98	904.27	1182.25	0.4480	1.1779	1.6259	308.00
310	77.70	0.0175	5.61	5.63	280.05	902.75	1182.80	0.4507	1.1729	1.6236	310.00
312	79.98	0.0176	5.46	5.47	282.11	901.24	1183.35	0.4533	1.1679	1.6212	312.00
314	82.32	0.0176	5.31	5.33	284.18	899.71	1183.89	0.4560	1.1629	1.6189	314.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
316	84.72	0.0176	5.17	5.19	286.25	898.17	1184.42	0.4587	1.1579	1.6166	316.00
318	87.16	0.0176	5.03	5.05	288.33	896.62	1184.94	0.4613	1.1530	1.6143	318.00
320	89.67	0.0177	4.90	4.91	290.40	895.07	1185.47	0.4640	1.1480	1.6120	320.00
322	92.28	0.0177	4.77	4.78	292.48	893.52	1186.00	0.4666	1.1431	1.6097	322.00
324	95.19	0.0177	4.64	4.66	294.56	891.96	1186.52	0.4693	1.1382	1.6075	324.00
326	97.54	0.0177	4.52	4.54	296.64	890.41	1187.05	0.4719	1.1333	1.6052	326.00
328	100.28	0.0177	4.40	4.42	298.72	888.83	1187.55	0.4745	1.1284	1.6030	328.00
330	103.08	0.0178	4.29	4.31	300.80	887.25	1188.05	0.4772	1.1236	1.6007	330.00
332	105.94	0.0178	4.18	4.20	302.88	885.67	1188.55	0.4798	1.1187	1.5985	332.00
334	108.86	0.0178	4.07	4.09	304.97	884.06	1189.03	0.4824	1.1139	1.5963	334.00
336	111.85	0.0178	3.97	3.99	307.06	882.45	1189.51	0.4850	1.1091	1.5941	336.00
338	114.90	0.0178	3.87	3.89	309.15	880.83	1189.98	0.4877	1.1043	1.5919	338.00
340	118.02	0.0179	3.77	3.79	311.24	879.22	1190.46	0.4903	1.0995	1.5897	340.00
342	121.21	0.0179	3.68	3.69	313.34	877.59	1190.93	0.4929	1.0947	1.5875	342.00
344	124.46	0.0179	3.58	3.60	315.43	875.94	1191.37	0.4955	1.0899	1.5854	344.00
346	127.78	0.0179	3.50	3.51	317.53	874.30	1191.83	0.4980	1.0852	1.5832	346.00
348	131.17	0.0180	3.41	3.43	319.63	872.63	1192.26	0.5006	1.0804	1.5811	348.00
350	134.63	0.0180	3.32	3.34	321.73	870.96	1192.69	0.5032	1.0757	1.5789	350.00
352	138.16	0.0180	3.24	3.26	323.84	869.28	1193.12	0.5058	1.0710	1.5768	352.00
354	141.77	0.0180	3.16	3.18	325.95	867.61	1193.55	0.5084	1.0663	1.5747	354.00
356	145.44	0.0181	3.09	3.10	328.05	865.93	1193.98	0.5109	1.0616	1.5726	356.00
358	149.21	0.0181	3.01	3.03	330.16	864.24	1194.41	0.5135	1.0570	1.5705	358.00
360	153.04	0.0181	2.94	2.96	332.28	862.52	1194.80	0.5161	1.0523	1.5684	360.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
362	156.95	0.0181	2.87	2.89	334.39	860.82	1195.21	0.5187	1.0476	1.5663	362.00
364	160.94	0.0182	2.80	2.82	336.51	859.09	1195.60	0.5212	1.0430	1.5642	364.00
366	165.00	0.0182	2.73	2.75	338.63	857.35	1195.98	0.5237	1.0384	1.5621	366.00
368	169.14	0.0182	2.67	2.69	340.75	855.61	1196.36	0.5263	1.0338	1.5601	368.00
370	173.36	0.0182	2.61	2.63	342.88	853.87	1196.74	0.5288	1.0292	1.5580	370.00
372	177.67	0.0183	2.55	2.56	345.00	852.08	1197.09	0.5314	1.0246	1.5560	372.00
374	182.05	0.0183	2.49	2.50	347.13	850.33	1197.46	0.5339	1.0200	1.5539	374.00
376	186.54	0.0183	2.43	2.45	349.26	848.54	1197.80	0.5365	1.0154	1.5519	376.00
378	191.10	0.0183	2.37	2.39	351.40	846.73	1198.13	0.5390	1.0108	1.5499	378.00
380	195.75	0.0184	2.32	2.34	353.54	844.93	1198.47	0.5415	1.0063	1.5478	380.00
382	200.49	0.0184	2.26	2.28	355.68	843.13	1198.80	0.5441	1.0018	1.5458	382.00
384	205.31	0.0184	2.21	2.23	357.82	841.32	1199.14	0.5466	0.9972	1.5438	384.00
386	210.23	0.0184	2.16	2.18	359.96	839.48	1199.44	0.5491	0.9927	1.5418	386.00
388	215.23	0.0185	2.11	2.13	362.11	837.65	1199.76	0.5516	0.9882	1.5398	388.00
390	220.34	0.0185	2.07	2.08	364.26	835.80	1200.06	0.5541	0.9837	1.5378	390.00
392	225.52	0.0185	2.02	2.04	366.41	833.93	1200.35	0.5566	0.9792	1.5358	392.00
394	230.81	0.0186	1.97	1.99	368.57	832.07	1200.63	0.5591	0.9747	1.5338	394.00
396	236.20	0.0186	1.93	1.95	370.72	830.18	1200.91	0.5616	0.9702	1.5319	396.00
398	241.69	0.0186	1.89	1.91	372.89	828.28	1201.16	0.5641	0.9657	1.5299	398.00
400	247.27	0.0186	1.85	1.86	375.05	826.38	1201.43	0.5667	0.9613	1.5279	400.00
402	252.95	0.0187	1.80	1.82	377.22	824.45	1201.67	0.5692	0.9568	1.5260	402.00
404	258.73	0.0187	1.76	1.78	379.38	822.55	1201.94	0.5716	0.9524	1.5240	404.00
406	264.61	0.0187	1.73	1.74	381.56	820.60	1202.16	0.5741	0.9480	1.5221	406.00
408	270.59	0.0188	1.69	1.71	383.73	818.65	1202.38	0.5766	0.9435	1.5201	408.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
410	276.69	0.0188	1.65	1.67	385.91	816.71	1202.62	0.5791	0.9391	1.5182	410.00
412	282.89	0.0188	1.62	1.63	388.09	814.72	1202.81	0.5816	0.9347	1.5162	412.00
414	289.19	0.0188	1.58	1.60	390.28	812.73	1203.01	0.5840	0.9303	1.5143	414.00
416	295.61	0.0189	1.55	1.57	392.47	810.73	1203.20	0.5865	0.9259	1.5124	416.00
418	302.13	0.0189	1.51	1.53	394.66	808.73	1203.39	0.5890	0.9215	1.5105	418.00
420	308.76	0.0189	1.48	1.50	396.85	806.73	1203.58	0.5915	0.9171	1.5086	420.00
422	315.51	0.0190	1.45	1.47	399.05	804.69	1203.74	0.5939	0.9127	1.5066	422.00
424	322.37	0.0190	1.42	1.44	401.25	802.63	1203.88	0.5964	0.9083	1.5047	424.00
426	329.35	0.0190	1.39	1.41	403.46	800.61	1204.07	0.5989	0.9039	1.5028	426.00
428	336.43	0.0191	1.36	1.38	405.67	798.50	1204.17	0.6013	0.8996	1.5009	428.00
430	343.64	0.0191	1.33	1.35	407.88	796.44	1204.31	0.6038	0.8952	1.4990	430.00
432	350.97	0.0191	1.30	1.32	410.10	794.35	1204.45	0.6063	0.8909	1.4971	432.00
434	358.41	0.0192	1.28	1.30	412.31	792.23	1204.54	0.6087	0.8865	1.4952	434.00
436	365.98	0.0192	1.25	1.27	414.54	790.10	1204.64	0.6112	0.8822	1.4933	436.00
438	373.68	0.0192	1.22	1.24	416.76	787.97	1204.74	0.6136	0.8778	1.4914	438.00
440	381.50	0.0193	1.20	1.22	418.99	785.84	1204.83	0.6161	0.8735	1.4896	440.00
442	389.43	0.0193	1.17	1.19	421.23	783.70	1204.93	0.6185	0.8691	1.4877	442.00
444	397.49	0.0193	1.15	1.17	423.47	781.52	1204.98	0.6210	0.8648	1.4858	444.00
446	405.69	0.0194	1.13	1.15	425.71	779.33	1205.03	0.6234	0.8605	1.4839	446.00
448	414.01	0.0194	1.10	1.12	427.95	777.13	1205.08	0.6259	0.8562	1.4820	448.00
450	422.47	0.0194	1.08	1.10	430.20	774.92	1205.12	0.6283	0.8519	1.4802	450.00
452	431.06	0.0195	1.06	1.08	432.45	772.69	1205.13	0.6307	0.8475	1.4783	452.00
454	439.79	0.0195	1.04	1.06	434.71	770.45	1205.16	0.6332	0.8432	1.4764	454.00
456	448.64	0.0195	1.02	1.04	436.98	768.18	1205.16	0.6356	0.8389	1.4745	456.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
458	457.64	0.0196	1.00	1.02	439.25	765.88	1205.13	0.6381	0.8346	1.4727	458.00
460	466.76	0.0196	0.98	1.00	441.51	763.61	1205.12	0.6405	0.8303	1.4708	460.00
462	476.03	0.0197	0.96	0.98	443.80	761.28	1205.08	0.6429	0.8260	1.4689	462.00
464	485.43	0.0197	0.94	0.96	446.09	758.99	1205.07	0.6454	0.8217	1.4671	464.00
466	495.00	0.0197	0.92	0.94	448.34	756.68	1205.02	0.6478	0.8174	1.4652	466.00
468	504.69	0.0198	0.90	0.92	450.63	754.30	1204.94	0.6502	0.8131	1.4633	468.00
470	514.53	0.0198	0.88	0.90	452.92	751.95	1204.87	0.6527	0.8088	1.4615	470.00
472	524.53	0.0198	0.86	0.88	455.22	749.56	1204.78	0.6551	0.8045	1.4596	472.00
474	534.66	0.0199	0.85	0.87	457.53	747.15	1204.68	0.6575	0.8002	1.4578	474.00
476	544.94	0.0199	0.83	0.85	459.85	744.74	1204.59	0.6599	0.7959	1.4559	476.00
478	555.37	0.0200	0.81	0.83	462.17	742.29	1204.46	0.6624	0.7916	1.4540	478.00
480	565.96	0.0200	0.80	0.82	464.47	739.84	1204.31	0.6648	0.7874	1.4522	480.00
482	576.70	0.0201	0.78	0.80	466.81	737.36	1204.17	0.6672	0.7831	1.4503	482.00
484	587.61	0.0201	0.77	0.79	469.11	734.92	1204.03	0.6697	0.7788	1.4484	484.00
486	598.66	0.0201	0.75	0.77	471.45	732.43	1203.88	0.6721	0.7745	1.4466	486.00
488	609.88	0.0202	0.74	0.76	473.79	729.89	1203.68	0.6745	0.7702	1.4447	488.00
490	621.26	0.0202	0.72	0.74	476.13	727.36	1203.49	0.6769	0.7659	1.4428	490.00
492	632.79	0.0203	0.71	0.73	478.49	724.78	1203.28	0.6794	0.7616	1.4409	492.00
494	644.49	0.0203	0.69	0.72	480.85	722.21	1203.07	0.6818	0.7573	1.4391	494.00
496	656.34	0.0204	0.68	0.70	483.20	719.65	1202.84	0.6842	0.7530	1.4372	496.00
498	668.36	0.0204	0.67	0.69	485.57	716.99	1202.57	0.6866	0.7487	1.4353	498.00
500	680.56	0.0204	0.66	0.68	487.96	714.36	1202.32	0.6890	0.7444	1.4335	500.00
502	692.92	0.0205	0.64	0.66	490.31	711.73	1202.04	0.6915	0.7401	1.4316	502.00
504	705.47	0.0205	0.63	0.65	492.70	709.05	1201.75	0.6939	0.7358	1.4297	504.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
506	718.18	0.0206	0.62	0.64	495.08	706.38	1201.46	0.6963	0.7315	1.4278	506.00
508	731.07	0.0206	0.61	0.63	497.49	703.66	1201.16	0.6988	0.7272	1.4259	508.00
510	744.13	0.0207	0.59	0.61	499.90	700.92	1200.82	0.7012	0.7228	1.4240	510.00
512	757.37	0.0207	0.58	0.60	502.29	698.19	1200.49	0.7036	0.7185	1.4222	512.00
514	770.78	0.0208	0.57	0.59	504.72	695.41	1200.12	0.7061	0.7142	1.4202	514.00
516	784.37	0.0208	0.56	0.58	507.15	692.59	1199.74	0.7085	0.7099	1.4184	516.00
518	798.14	0.0209	0.55	0.57	509.59	689.77	1199.36	0.7109	0.7055	1.4165	518.00
520	812.12	0.0209	0.54	0.56	512.02	686.91	1198.93	0.7134	0.7012	1.4145	520.00
522	826.27	0.0210	0.53	0.55	514.46	684.08	1198.54	0.7158	0.6968	1.4126	522.00
524	840.61	0.0210	0.52	0.54	516.90	681.20	1198.10	0.7182	0.6925	1.4107	524.00
526	855.14	0.0211	0.51	0.53	519.35	678.28	1197.64	0.7207	0.6881	1.4088	526.00
528	869.86	0.0211	0.50	0.52	521.84	675.35	1197.18	0.7231	0.6838	1.4069	528.00
530	884.77	0.0212	0.49	0.51	524.32	672.36	1196.68	0.7256	0.6794	1.4049	530.00
532	899.86	0.0212	0.48	0.50	526.77	669.41	1196.18	0.7280	0.6750	1.4030	532.00
534	915.15	0.0213	0.47	0.49	529.28	666.39	1195.67	0.7304	0.6706	1.4011	534.00
536	930.65	0.0213	0.46	0.48	531.77	663.37	1195.14	0.7329	0.6662	1.3991	536.00
538	946.35	0.0214	0.45	0.47	534.26	660.31	1194.57	0.7353	0.6619	1.3972	538.00
540	962.26	0.0215	0.44	0.47	536.79	657.20	1194.00	0.7378	0.6574	1.3952	540.00
542	978.37	0.0215	0.44	0.46	539.31	654.10	1193.41	0.7402	0.6530	1.3933	542.00
544	994.68	0.0216	0.43	0.45	541.81	650.98	1192.79	0.7427	0.6486	1.3913	544.00
546	1011.19	0.0216	0.42	0.44	544.37	647.80	1192.17	0.7452	0.6441	1.3893	546.00
548	1027.92	0.0217	0.41	0.43	546.92	644.60	1191.52	0.7476	0.6397	1.3873	548.00
550	1044.85	0.0218	0.40	0.42	549.48	641.36	1190.85	0.7501	0.6352	1.3853	550.00

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Properties of Saturated Water and Steam (Temperature)—I-P Units (cont'd)

T, °F	Abs. Press. P, $\frac{lbf}{in^2}$	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			T, °F
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
552	1061.99	0.0218	0.40	0.42	552.03	638.15	1190.18	0.7526	0.6308	1.3833	552.00
554	1079.34	0.0219	0.39	0.41	554.60	634.87	1189.47	0.7550	0.6263	1.3813	554.00
556	1096.93	0.0219	0.38	0.40	557.18	631.56	1188.75	0.7575	0.6218	1.3793	556.00
558	1114.73	0.0220	0.37	0.39	559.80	628.18	1187.98	0.7600	0.6173	1.3773	558.00
560	1132.76	0.0221	0.37	0.39	562.40	624.82	1187.22	0.7625	0.6128	1.3753	560.00
562	1151.00	0.0221	0.36	0.38	565.02	621.41	1186.43	0.7650	0.6082	1.3732	562.00
564	1169.46	0.0222	0.35	0.37	567.65	617.97	1185.62	0.7675	0.6037	1.3712	564.00
566	1188.15	0.0223	0.34	0.37	570.28	614.50	1184.78	0.7700	0.5991	1.3691	566.00
568	1207.06	0.0224	0.34	0.36	572.91	611.02	1183.92	0.7725	0.5946	1.3670	568.00
570	1226.20	0.0224	0.33	0.35	575.57	607.45	1183.02	0.7750	0.5900	1.3649	570.00
572	1245.57	0.0225	0.32	0.35	578.25	603.87	1182.12	0.7775	0.5853	1.3628	572.00
574	1265.19	0.0226	0.32	0.34	580.93	600.28	1181.20	0.7800	0.5807	1.3607	574.00
576	1285.05	0.0226	0.31	0.33	583.64	596.61	1180.25	0.7825	0.5761	1.3586	576.00
578	1305.15	0.0227	0.31	0.33	586.33	592.95	1179.28	0.7851	0.5714	1.3565	578.00
580	1325.48	0.0228	0.30	0.32	589.05	589.20	1178.26	0.7876	0.5667	1.3543	580.00
582	1346.06	0.0229	0.29	0.32	591.77	585.43	1177.21	0.7901	0.5620	1.3521	582.00
584	1366.88	0.0229	0.29	0.31	594.53	581.63	1176.15	0.7927	0.5573	1.3500	584.00
586	1387.94	0.0230	0.28	0.30	597.30	577.77	1175.07	0.7952	0.5526	1.3478	586.00
588	1409.24	0.0231	0.28	0.30	600.07	573.90	1173.97	0.7978	0.5478	1.3456	588.00

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6.3.2 Properties of Saturated Water and Steam (Pressure)—I-P Units

Properties of Saturated Water and Steam (Pressure)—I-P Units

Psia, $\frac{lbf}{in^2}$	T, °F	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			Psia, $\frac{lbf}{in^2}$
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
0.09	32.02	0.0160	3299.54	3299.55	0.00	1075.19	1075.19	0.0000	2.1868	2.1868	0.09
0.25	59.25	0.0160	1238.86	1238.87	27.33	1059.78	1087.10	0.0541	2.0423	2.0964	0.25
0.50	79.50	0.0161	643.19	643.21	47.57	1048.32	1095.89	0.0924	1.9443	2.0367	0.50
1	101.68	0.0161	333.74	333.76	69.71	1035.71	1105.42	0.1326	1.8451	1.9776	1.00
2	126.01	0.0162	173.83	173.85	94.01	1021.74	1115.75	0.1750	1.7445	1.9195	2.00
3	141.33	0.0163	119.19	119.21	109.32	1012.82	1122.14	0.2008	1.6853	1.8860	3.00
4	152.88	0.0164	90.79	90.81	120.87	1006.04	1126.91	0.2198	1.6424	1.8622	4.00
5	162.13	0.0164	73.72	73.74	130.13	1000.57	1130.70	0.2348	1.6092	1.8440	5.00
6	169.95	0.0164	62.11	62.13	137.96	995.92	1133.88	0.2473	1.5818	1.8291	6.00
7	176.74	0.0165	53.75	53.77	144.78	991.81	1136.59	0.2581	1.5585	1.8165	7.00
8	182.80	0.0165	47.34	47.35	150.85	988.15	1139.00	0.2676	1.5380	1.8056	8.00
9	188.19	0.0166	42.44	42.46	156.27	984.88	1141.14	0.2759	1.5202	1.7961	9.00
10	193.14	0.0166	38.44	38.45	161.24	981.82	1143.06	0.2836	1.5040	1.7876	10.00
14.696	211.97	0.0167	26.76	26.78	180.18	970.07	1150.25	0.3122	1.4443	1.7565	14.70
20	227.90	0.0168	20.09	20.11	196.25	959.94	1156.19	0.3358	1.3962	1.7319	20.00
25	240.02	0.0169	16.30	16.31	208.51	952.03	1160.54	0.3535	1.3607	1.7141	25.00
30	250.29	0.0170	13.74	13.75	218.92	945.21	1164.13	0.3682	1.3314	1.6996	30.00
35	259.25	0.0171	11.88	11.90	228.03	939.15	1167.18	0.3809	1.3064	1.6873	35.00
40	267.21	0.0171	10.49	10.50	236.14	933.68	1169.81	0.3921	1.2845	1.6766	40.00
45	274.41	0.0172	9.38	9.40	243.48	928.67	1172.16	0.4022	1.2651	1.6672	45.00
50	280.98	0.0173	8.50	8.52	250.20	924.03	1174.23	0.4113	1.2476	1.6588	50.00
55	287.05	0.0173	7.77	7.79	256.42	919.68	1176.10	0.4196	1.2316	1.6512	55.00
60	292.67	0.0174	7.16	7.18	262.19	915.63	1177.82	0.4273	1.2170	1.6443	60.00

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Properties of Saturated Water and Steam (Pressure)—I-P Units (cont'd)

Psia, $\frac{lbf}{in^2}$	T, °F	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			Psia, $\frac{lbf}{in^2}$
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
65	297.94	0.0174	6.64	6.66	267.61	911.76	1179.37	0.4344	1.2035	1.6379	65.00
70	302.90	0.0175	6.19	6.21	272.72	908.08	1180.80	0.4411	1.1908	1.6319	70.00
75	307.58	0.0175	5.80	5.82	277.55	904.59	1182.13	0.4474	1.1790	1.6264	75.00
80	312.01	0.0176	5.46	5.47	282.13	901.21	1183.33	0.4533	1.1679	1.6212	80.00
85	316.23	0.0176	5.15	5.17	286.49	898.00	1184.49	0.4590	1.1574	1.6163	85.00
90	320.26	0.0177	4.88	4.90	290.67	894.90	1185.57	0.4643	1.1474	1.6117	90.00
95	324.11	0.0177	4.64	4.65	294.67	891.90	1186.57	0.4694	1.1379	1.6073	95.00
100	327.80	0.0177	4.42	4.43	298.51	888.99	1187.50	0.4743	1.1289	1.6032	100.00
110	334.77	0.0178	4.03	4.05	305.78	883.44	1189.22	0.4834	1.1120	1.5954	110.00
120	341.25	0.0179	3.71	3.73	312.55	878.20	1190.74	0.4919	1.0965	1.5884	120.00
130	347.31	0.0180	3.44	3.46	318.91	873.19	1192.11	0.4997	1.0821	1.5818	130.00
140	353.02	0.0180	3.20	3.22	324.92	868.43	1193.34	0.5071	1.0686	1.5757	140.00
150	358.40	0.0181	3.00	3.02	330.60	863.87	1194.47	0.5140	1.0560	1.5700	150.00
160	363.54	0.0182	2.82	2.83	336.02	859.47	1195.49	0.5206	1.0441	1.5647	160.00
170	368.40	0.0182	2.66	2.68	341.18	855.24	1196.42	0.5268	1.0328	1.5597	170.00
180	373.06	0.0183	2.51	2.53	346.13	851.14	1197.27	0.5327	1.0221	1.5549	180.00
190	377.52	0.0183	2.39	2.40	350.89	847.20	1198.08	0.5384	1.0119	1.5503	190.00
200	381.79	0.0184	2.27	2.29	355.45	843.32	1198.77	0.5438	1.0022	1.5460	200.00
210	385.91	0.0184	2.16	2.18	359.86	839.56	1199.42	0.5490	0.9929	1.5419	210.00
220	389.86	0.0185	2.07	2.09	364.11	835.93	1200.05	0.5540	0.9840	1.5379	220.00
230	393.69	0.0185	1.98	2.00	368.23	832.35	1200.58	0.5588	0.9754	1.5341	230.00
240	397.39	0.0186	1.90	1.92	372.22	828.88	1201.11	0.5634	0.9671	1.5305	240.00
250	400.96	0.0187	1.83	1.84	376.09	825.47	1201.56	0.5678	0.9591	1.5270	250.00
300	417.33	0.0189	1.53	1.54	393.93	809.42	1203.35	0.5882	0.9229	1.511	300.00

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Properties of Saturated Water and Steam (Pressure)—I-P Units (cont'd)

Psia, $\frac{lbf}{in^2}$	T, °F	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			Psia, $\frac{lbf}{in^2}$
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
350	431.73	0.0191	1.31	1.33	409.80	794.62	1204.41	0.6059	0.8914	1.4974	350.00
400	444.60	0.0193	1.14	1.16	424.14	780.85	1204.99	0.6217	0.8635	1.4852	400.00
450	456.31	0.0196	1.01	1.03	437.33	767.83	1205.16	0.6360	0.8383	1.4742	450.00
500	467.03	0.0198	0.91	0.93	449.52	755.45	1204.97	0.6490	0.8152	1.4642	500.00
550	476.97	0.0199	0.82	0.84	460.97	743.56	1204.53	0.6611	0.7938	1.4550	550.00
600	486.24	0.0201	0.75	0.77	471.75	732.09	1203.83	0.6724	0.7740	1.4463	600.00
650	494.93	0.0203	0.69	0.71	481.93	721.01	1202.94	0.6829	0.7553	1.4382	650.00
700	503.13	0.0205	0.64	0.66	491.65	710.23	1201.89	0.6929	0.7377	1.4305	700.00
750	510.89	0.0207	0.59	0.61	500.96	699.71	1200.67	0.7023	0.7209	1.4232	750.00
800	518.27	0.0209	0.55	0.57	509.90	689.39	1199.29	0.7113	0.7050	1.4162	800.00
850	525.29	0.0211	0.51	0.53	518.51	679.30	1197.81	0.7198	0.6897	1.4095	850.00
900	532.02	0.0212	0.48	0.50	526.82	669.37	1196.19	0.7280	0.6750	1.4030	900.00
950	538.46	0.0214	0.45	0.47	534.85	659.61	1194.46	0.7359	0.6608	1.3967	950.00
1000	544.65	0.0216	0.42	0.45	542.66	649.93	1192.59	0.7435	0.6471	1.3907	1000.00
1050	550.60	0.0218	0.40	0.42	550.25	640.40	1190.65	0.7508	0.6339	1.3847	1050.00
1100	556.35	0.0220	0.38	0.40	557.66	630.96	1188.62	0.7579	0.6210	1.3790	1100.00
1150	561.89	0.0221	0.36	0.38	564.87	621.62	1186.49	0.7648	0.6085	1.3733	1150.00
1200	567.26	0.0223	0.34	0.36	571.94	612.29	1184.23	0.7715	0.5963	1.3678	1200.00
1250	572.45	0.0225	0.32	0.35	578.87	603.03	1181.90	0.7780	0.5843	1.3624	1250.00
1300	577.49	0.0227	0.31	0.33	585.64	593.86	1179.50	0.7844	0.5726	1.3570	1300.00
1350	582.38	0.0229	0.29	0.32	592.33	584.70	1177.03	0.7906	0.5611	1.3517	1350.00
1400	587.13	0.0231	0.28	0.30	598.85	575.60	1174.44	0.7967	0.5499	1.3465	1400.00

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Properties of Saturated Water and Steam (Pressure)—I-P Units (cont'd)

Psia, $\frac{lbf}{in^2}$	T, °F	Specific Volume, $\frac{ft^3}{lbm}$			Enthalpy, $\frac{Btu}{lbm}$			Entropy, $\frac{Btu}{lbm \cdot °R}$			Psia, $\frac{lbf}{in^2}$
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	
1450	591.76	0.0233	0.2656	0.29	605.33	566.45	1171.78	0.8026	0.5388	1.3414	1450
1500	596.26	0.0235	0.2535	0.28	611.67	557.33	1169.00	0.8085	0.5278	1.3363	1500
1550	600.64	0.0237	0.2421	0.27	617.95	548.22	1166.17	0.8142	0.5171	1.3312	1550
1600	604.93	0.0239	0.2313	0.26	624.12	539.11	1163.23	0.8198	0.5064	1.3262	1600
1650	609.10	0.0241	0.2211	0.25	630.27	529.95	1160.23	0.8254	0.4958	1.3212	1650
1700	613.18	0.0243	0.2115	0.24	636.33	520.79	1157.12	0.8308	0.4854	1.3162	1700
1750	617.17	0.0245	0.2023	0.23	642.36	511.53	1153.89	0.8362	0.4751	1.3113	1750
1800	621.07	0.0247	0.1936	0.22	648.33	502.29	1150.63	0.8415	0.4648	1.3063	1800
1850	624.88	0.0249	0.1853	0.21	654.26	492.96	1147.22	0.8468	0.4546	1.3013	1850
1900	628.61	0.0252	0.1774	0.20	660.13	483.60	1143.72	0.8520	0.4444	1.2963	1900
1950	632.26	0.0254	0.1698	0.20	665.98	474.12	1140.10	0.8571	0.4342	1.2913	1950
2000	635.85	0.0256	0.1625	0.19	671.83	464.57	1136.40	0.8623	0.4241	1.2863	2000

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6.3.3 Properties of Superheated Steam—I-P Units

Pressure = 2.0 Psia T_s = 126.1 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.016	61.635	92.2	0.172	t_s(L)
173.7	0.006	1115.0	1.924	t_s(v)
177.960	0.006	1122.6	1.931	140
184.01	0.005	1131.4	1.952	160
190.04	0.005	1140.6	1.966	180
196.06	0.005	1149.7	1.981	200
202.10	0.005	1158.9	1.994	220
208.10	0.005	1168.0	2.007	240
214.10	0.005	1177.1	2.020	260
220.00	0.005	1186.3	2.033	280
226.00	0.004	1195.4	2.045	300
232.00	0.004	1204.7	2.057	320
238.00	0.004	1213.9	2.069	340
244.00	0.004	1223.1	2.080	360
249.90	0.004	1232.4	2.091	380
255.90	0.004	1241.7	2.102	400
261.90	0.004	1251.0	2.113	420
267.80	0.004	1260.3	2.123	440
273.80	0.004	1269.7	2.134	460
279.80	0.004	1279.1	2.144	480
285.70	0.004	1288.5	2.154	500
300.60	0.003	1312.2	2.178	550
315.50	0.003	1336.1	2.201	600
330.45	0.003	1360.3	2.223	650
345.40	0.003	1384.6	2.245	700
360.25	0.003	1409.1	2.265	750
375.10	0.003	1433.9	2.285	800
390.00	0.003	1458.9	2.305	850
404.90	0.002	1484.0	2.324	900
419.80	0.002	1509.5	2.342	950
434.70	0.002	1535.1	2.360	1,000
449.60	0.002	1561.0	2.377	1,050
464.50	0.002	1587.1	2.394	1,100
479.40	0.002	1613.4	2.411	1,150
494.30	0.002	1640.0	2.427	1,200
509.20	0.002	1666.8	2.443	1,250
524.10	0.002	1693.9	2.459	1,300
602.404	0.002	1721.2	2.474	1,350
619.050	0.002	1748.7	2.489	1,400

Pressure = 5.0 Psia T_s = 162.2 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.016	33.756	129.8	0.234	t_s(L)
74.899	0.007	1130.6	1.845	t_s(v)
77.280	0.013	1139.1	1.858	180
79.772	0.013	1148.5	1.873	200
82.255	0.012	1157.8	1.887	220
84.727	0.012	1167.1	1.900	240
87.194	0.012	1176.3	1.913	260
89.654	0.011	1185.6	1.926	280
92.109	0.011	1194.8	1.938	300
96.741	0.011	1204.1	1.950	320
97.015	0.010	1213.4	1.962	340
99.464	0.010	1222.6	1.973	360
101.912	0.010	1231.9	1.985	380
104.357	0.010	1241.3	1.996	400
106.801	0.009	1250.6	2.006	420
109.241	0.009	1260.0	2.017	440
111.223	0.009	1267.3	2.025	460
114.123	0.009	1278.8	2.037	480
116.563	0.009	1288.2	2.047	500
122.658	0.008	1312.0	2.071	550
128.754	0.008	1335.9	2.094	600
134.846	0.008	1360.1	2.117	650
140.932	0.007	1384.4	2.138	700
147.022	0.007	1409.0	2.159	750
153.109	0.007	1433.8	2.179	800
159.194	0.006	1458.7	2.198	850
165.277	0.006	1484.0	2.217	900
171.366	0.006	1509.4	2.236	950
177.449	0.006	1535.0	2.254	1,000
183.531	0.005	1560.9	2.271	1,050
189.613	0.005	1587.0	2.288	1,100
195.696	0.005	1613.4	2.305	1,150
201.779	0.005	1640.0	2.321	1,200
207.861	0.005	1666.8	2.337	1,250
213.943	0.005	1693.8	2.352	1,300
220.024	0.005	1721.1	2.368	1,350
226.106	0.004	1748.6	2.383	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 8.0 Psia T_s = 182.9 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.017	60.519	150.7	0.267	t_s(L)
47.701	0.021	1138.9	1.806	t_s(v)
49.085	0.021	1147.2	1.819	200
50.638	0.020	1156.7	1.833	220
52.181	0.019	1166.2	1.847	240
53.717	0.019	1175.5	1.860	260
55.126	0.018	1184.8	1.873	280
56.776	0.018	1194.2	1.885	300
58.300	0.017	1203.5	1.897	320
59.821	0.017	1212.8	1.909	340
61.340	0.016	1222.2	1.920	360
62.855	0.016	1231.5	1.932	380
64.371	0.016	1240.9	1.943	400
65.885	0.015	1250.2	1.953	420
67.397	0.015	1259.6	1.964	440
68.153	0.015	1264.3	1.969	460
70.418	0.014	1278.5	1.985	480
71.927	0.014	1288.0	1.995	500
75.698	0.013	1311.8	2.019	550
79.467	0.013	1335.7	2.042	600
83.234	0.012	1359.9	2.064	650
86.995	0.012	1384.3	2.086	700
90.758	0.011	1408.8	2.106	750
94.520	0.011	1433.6	2.126	800
98.280	0.010	1458.6	2.146	850
102.038	0.010	1483.8	2.165	900
105.797	0.010	1509.3	2.183	950
109.557	0.009	1534.9	2.201	1,000
113.315	0.009	1560.9	2.218	1,050
117.070	0.009	1587.0	2.236	1,100
120.829	0.008	1613.3	2.252	1,150
124.587	0.008	1639.9	2.268	1,200
128.342	0.008	1666.7	2.284	1,250
132.098	0.008	1693.8	2.300	1,300
135.855	0.007	1721.1	2.315	1,350
139.612	0.007	1748.6	2.330	1,400

Pressure = 10.0 Psia T_s = 193.2 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.017	60.282	161.2	0.284	t_s(L)
38.499	0.026	1143.0	1.788	t_s(v)
38.937	0.026	1146.4	1.793	200
40.183	0.025	1156.0	1.807	220
41.419	0.024	1165.5	1.821	240
42.649	0.024	1175.0	1.834	260
43.848	0.023	1184.4	1.847	280
45.093	0.022	1193.8	1.860	300
46.310	0.022	1203.1	1.872	320
47.522	0.021	1212.5	1.884	340
48.733	0.021	1221.8	1.895	360
50.420	0.020	1235.0	1.911	380
51.150	0.020	1240.6	1.918	400
52.356	0.019	1250.0	1.928	420
53.561	0.019	1259.4	1.939	440
54.692	0.018	1268.4	1.949	460
55.967	0.018	1278.3	1.959	480
57.169	0.018	1287.8	1.969	500
60.172	0.017	1311.6	1.994	550
62.756	0.016	1335.6	2.017	600
66.168	0.015	1359.8	2.039	650
69.163	0.014	1384.2	2.061	700
72.156	0.014	1408.7	2.081	750
75.148	0.013	1433.5	2.101	800
78.141	0.013	1458.6	2.121	850
81.130	0.012	1483.8	2.140	900
84.119	0.012	1509.2	2.158	950
87.107	0.012	1534.9	2.176	1,000
90.098	0.011	1560.8	2.194	1,050
93.088	0.011	1586.9	2.211	1,100
96.073	0.010	1613.3	2.227	1,150
99.062	0.010	1639.9	2.243	1,200
12.000	0.010	1666.7	2.259	1,250
105.036	0.010	1693.7	2.275	1,300
108.023	0.009	1721.1	2.290	1,350
111.010	0.009	1748.6	2.305	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 12.0 Psia T_s = 202.0 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	60.076	170.0	0.297	t_s(L)
32.477	0.031	1146.4	1.773	t_s(v)
33.423	0.030	1155.3	1.786	220
34.474	0.029	1164.9	1.800	240
35.505	0.028	1174.4	1.814	260
36.531	0.027	1183.9	1.827	280
37.550	0.027	1193.3	1.839	300
38.570	0.026	1202.7	1.851	320
39.586	0.025	1212.1	1.863	340
40.598	0.025	1221.5	1.875	360
42.062	0.024	1235.1	1.891	380
42.618	0.024	1240.3	1.897	400
43.625	0.023	1249.8	1.908	420
44.631	0.022	1259.2	1.919	440
45.637	0.022	1268.6	1.929	460
46.642	0.022	1278.1	1.939	480
47.645	0.021	1287.6	1.949	500
50.151	0.020	1311.5	1.973	550
52.654	0.019	1335.5	1.997	600
55.155	0.018	1359.7	2.019	650
57.653	0.017	1384.1	2.041	700
60.151	0.017	1408.7	2.061	750
62.475	0.016	1433.5	2.081	800
65.141	0.015	1458.5	2.101	850
67.635	0.015	1483.7	2.120	900
70.128	0.014	1509.2	2.138	950
72.621	0.014	1534.8	2.156	1,000
75.114	0.013	1560.7	2.173	1,050
77.606	0.013	1586.9	2.190	1,100
80.099	0.013	1613.2	2.207	1,150
82.589	0.012	1639.8	2.223	1,200
85.081	0.012	1666.7	2.239	1,250
87.574	0.011	1693.7	2.255	1,300
90.064	0.011	1721.0	2.270	1,350
92.553	0.011	1748.5	2.285	1,400

Pressure = 14.7 Psia T_s = 212.0 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	59.829	180.1	0.312	t_s(L)
26.828	0.037	1150.2	1.757	t_s(v)
27.178	0.037	1154.2	1.763	220
28.033	0.036	1164.0	1.777	240
28.882	0.035	1173.6	1.790	260
29.724	0.034	1183.2	1.803	280
30.562	0.033	1192.7	1.816	300
31.396	0.032	1202.2	1.828	320
32.227	0.031	1211.7	1.840	340
33.056	0.030	1221.1	1.852	360
34.254	0.029	1234.8	1.868	380
34.708	0.029	1240.0	1.874	400
35.531	0.028	1249.4	1.885	420
36.353	0.028	1258.9	1.896	440
37.174	0.027	1268.3	1.906	460
37.995	0.026	1277.8	1.917	480
38.815	0.026	1287.3	1.927	500
40.730	0.025	1311.2	1.951	550
42.903	0.023	1335.3	1.974	600
44.944	0.022	1359.5	1.996	650
46.982	0.021	1383.9	2.018	700
49.019	0.020	1408.5	2.039	750
51.055	0.020	1433.3	2.059	800
53.090	0.019	1458.4	2.078	850
55.125	0.018	1483.6	2.097	900
57.158	0.018	1509.1	2.116	950
59.191	0.017	1534.8	2.134	1,000
61.224	0.016	1560.7	2.151	1,050
63.255	0.016	1586.8	2.168	1,100
65.287	0.015	1613.2	2.185	1,150
67.318	0.015	1639.8	2.201	1,200
69.349	0.014	1666.6	2.217	1,250
71.380	0.014	1693.7	2.232	1,300
73.410	0.014	1721.0	2.248	1,350
75.442	0.013	1748.5	2.263	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 17.0 Psia T_s = 219.4 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	59.642	187.6	0.323	t_s(L)
23.421	0.043	1153.1	1.745	t_s(v)
24.195	0.041	1163.3	1.760	220
24.934	0.040	1173.0	1.774	240
25.667	0.039	1182.7	1.787	260
26.396	0.038	1192.2	1.800	280
27.120	0.037	1201.8	1.812	300
27.842	0.036	1211.3	1.824	320
28.561	0.035	1220.7	1.836	340
29.601	0.034	1234.5	1.852	360
29.994	0.033	1239.7	1.858	380
30.708	0.033	1249.1	1.869	400
31.421	0.032	1258.6	1.880	420
32.132	0.031	1268.1	1.890	440
32.843	0.030	1277.6	1.900	460
33.553	0.030	1287.1	1.910	480
35.325	0.028	1311.1	1.935	500
37.094	0.027	1335.1	1.958	550
38.860	0.026	1359.4	1.980	600
40.624	0.025	1383.8	2.002	650
42.387	0.024	1408.4	2.023	700
44.149	0.023	1433.3	2.043	750
45.910	0.022	1458.3	2.062	800
47.670	0.021	1483.6	2.081	850
49.429	0.020	1509.0	2.100	900
51.188	0.020	1534.7	2.117	950
52.947	0.019	1560.6	2.135	1,000
54.704	0.018	1586.8	2.152	1,050
56.463	0.018	1613.1	2.169	1,100
58.220	0.017	1639.7	2.185	1,150
59.976	0.017	1666.6	2.201	1,200
61.733	0.016	1693.7	2.216	1,250
63.490	0.016	1721.0	2.232	1,300
65.247	0.015	1748.5	2.247	1,350
111.010	0.009	1748.6	2.305	1,400

Pressure = 20.0 Psia T_s = 228.0 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	59.421	196.2	0.336	t_s(L)
20.107	0.050	1156.2	1.732	t_s(v)
				220
20.497	0.049	1162.3	1.741	240
21.131	0.047	1172.1	1.755	260
21.759	0.046	1181.9	1.768	280
22.382	0.045	1191.5	1.781	300
23.001	0.044	1201.2	1.793	320
23.617	0.042	1210.7	1.805	340
24.231	0.041	1220.2	1.817	360
25.118	0.040	1234.0	1.834	380
25.453	0.039	1239.3	1.840	400
26.061	0.038	1248.8	1.851	420
26.668	0.038	1258.3	1.861	440
27.274	0.037	1267.8	1.872	460
27.879	0.036	1277.3	1.882	480
28.484	0.035	1286.9	1.892	500
29.992	0.033	1310.8	1.917	550
31.496	0.032	1334.9	1.940	600
32.999	0.030	1359.2	1.962	650
34.499	0.029	1383.6	1.984	700
35.997	0.028	1408.3	2.005	750
37.495	0.027	1433.1	2.025	800
38.992	0.026	1458.2	2.044	850
40.488	0.025	1483.4	2.063	900
41.983	0.024	1508.9	2.082	950
43.478	0.023	1534.6	2.099	1,000
44.972	0.022	1560.5	2.117	1,050
46.466	0.022	1586.7	2.134	1,100
47.959	0.021	1613.1	2.151	1,150
49.452	0.020	1639.7	2.167	1,200
50.945	0.020	1666.5	2.183	1,250
52.439	0.019	1693.6	2.198	1,300
53.931	0.019	1720.9	2.214	1,350
55.424	0.018	1748.4	2.229	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 25.0 Psia T_s = 240.1 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	59.098	208.5	0.353	t_s(L)
16.354	0.061	1160.5	1.714	t_s(v)
16.877	0.059	1170.7	1.729	260
17.388	0.058	1180.6	1.742	280
17.893	0.056	1190.4	1.755	300
18.395	0.055	1200.1	1.768	320
18.893	0.053	1209.8	1.780	340
19.389	0.052	1219.4	1.792	360
20.105	0.050	1233.3	1.809	380
20.375	0.049	1238.6	1.815	400
20.865	0.048	1248.1	1.826	420
21.354	0.047	1257.7	1.837	440
21.842	0.046	1267.3	1.847	460
22.329	0.045	1276.8	1.857	480
22.816	0.044	1286.4	1.867	500
23.301	0.043	1296.0	1.877	520
23.786	0.042	1305.6	1.887	540
24.270	0.041	1315.3	1.897	560
24.754	0.041	1324.9	1.906	580
25.238	0.040	1334.6	1.915	600
26.445	0.038	1358.9	1.938	650
27.650	0.036	1383.4	1.959	700
28.853	0.035	1408.0	1.980	750
30.055	0.033	1432.9	2.000	800
31.257	0.032	1458.0	2.020	850
32.458	0.031	1483.3	2.039	900
33.658	0.030	1508.8	2.057	950
34.857	0.029	1534.5	2.075	1,000
36.056	0.028	1560.4	2.092	1,050
37.254	0.027	1586.6	2.109	1,100
38.452	0.026	1612.9	2.126	1,150
39.650	0.025	1639.6	2.142	1,200
40.848	0.025	1666.4	2.158	1,250
42.046	0.024	1693.5	2.174	1,300
43.243	0.023	1720.8	2.189	1,350
44.440	0.023	1748.3	2.204	1,400

Pressure = 30.0 Psia T_s = 250.3 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	58.813	218.9	0.368	t_s(L)
13.773	0.073	1164.1	1.700	t_s(v)
13.988	0.072	1169.1	1.707	260
14.420	0.069	1179.3	1.721	280
14.846	0.068	1189.3	1.734	300
15.268	0.066	1199.2	1.747	320
15.687	0.064	1208.9	1.759	340
16.103	0.062	1218.6	1.771	360
16.702	0.060	1232.6	1.788	380
16.928	0.059	1237.9	1.794	400
17.338	0.058	1247.5	1.805	420
17.747	0.056	1257.1	1.816	440
18.155	0.055	1266.7	1.826	460
18.562	0.054	1276.3	1.837	480
18.968	0.053	1285.9	1.847	500
19.139	0.052	1289.6	1.851	520
19.427	0.052	1296.3	1.857	540
19.714	0.051	1303.0	1.864	560
20.001	0.050	1309.7	1.871	580
20.990	0.048	1334.3	1.895	600
21.996	0.046	1358.6	1.917	650
23.001	0.044	1383.1	1.939	700
24.004	0.042	1407.8	1.960	750
25.006	0.040	1432.7	1.980	800
26.007	0.039	1457.8	1.999	850
27.007	0.037	1483.1	2.018	900
28.008	0.036	1508.6	2.037	950
29.006	0.035	1534.3	2.055	1,000
30.004	0.033	1560.3	2.072	1,050
31.002	0.032	1586.4	2.089	1,100
32.000	0.031	1612.8	2.106	1,150
32.997	0.030	1639.5	2.122	1,200
33.995	0.029	1666.3	2.138	1,250
34.992	0.029	1693.4	2.154	1,300
35.989	0.028	1720.7	2.169	1,350
36.985	0.027	1748.3	2.184	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 35.0 Psia T_s = 259.3 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.017	58.557	228.0	0.381	t_s(L)
11.903	0.084	1167.2	1.687	t_s(v)
11.911	0.084	1167.5	1.688	260
12.294	0.081	1178.0	1.702	280
12.664	0.079	1188.1	1.716	300
13.029	0.077	1198.1	1.729	320
13.390	0.075	1208.0	1.741	340
13.749	0.073	1217.8	1.753	360
14.264	0.070	1231.9	1.770	380
14.460	0.069	1237.2	1.776	400
14.813	0.068	1246.9	1.787	420
15.164	0.066	1256.5	1.798	440
15.514	0.064	1266.2	1.809	460
15.865	0.063	1275.8	1.819	480
16.214	0.062	1285.5	1.829	500
15.935	0.063	1277.8	1.821	520
15.970	0.063	1278.7	1.822	540
16.005	0.063	1279.7	1.823	560
16.039	0.062	1280.7	1.824	580
17.948	0.056	1333.9	1.877	600
18.811	0.053	1358.3	1.900	650
19.672	0.051	1382.9	1.922	700
20.532	0.049	1407.6	1.942	750
21.390	0.047	1432.5	1.963	800
22.245	0.045	1457.6	1.982	850
23.104	0.043	1482.9	2.001	900
23.960	0.042	1508.5	2.020	950
24.815	0.040	1534.2	2.038	1,000
25.670	0.039	1560.2	2.055	1,050
26.525	0.038	1586.3	2.072	1,100
27.379	0.037	1612.7	2.089	1,150
28.233	0.035	1639.4	2.105	1,200
29.087	0.034	1666.2	2.121	1,250
29.940	0.033	1693.3	2.137	1,300
30.794	0.032	1720.7	2.152	1,350
31.647	0.032	1748.2	2.167	1,400

Pressure = 40.0 Psia T_s = 267.3 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.017	58.325	236.1	0.392	t_s(L)
10.509	0.095	1169.8	1.677	t_s(v)
				260
10.723	0.093	1176.6	1.686	280
11.051	0.091	1186.9	1.700	300
11.374	0.088	1197.0	1.713	320
11.693	0.086	1207.0	1.725	340
12.010	0.083	1216.9	1.738	360
12.466	0.080	1231.1	1.755	380
12.636	0.079	1236.5	1.761	400
12.947	0.077	1246.2	1.772	420
13.256	0.076	1256.0	1.783	440
13.565	0.074	1265.7	1.794	460
13.872	0.072	1275.3	1.804	480
14.178	0.071	1285.0	1.814	500
14.361	0.070	1291.0	1.821	520
14.605	0.068	1298.9	1.829	540
14.848	0.067	1306.8	1.836	560
15.092	0.066	1314.7	1.844	580
15.701	0.064	1333.6	1.863	600
16.458	0.061	1358.0	1.885	650
17.213	0.058	1382.6	1.907	700
17.966	0.056	1407.4	1.928	750
18.719	0.053	1432.3	1.948	800
19.464	0.051	1457.4	1.967	850
20.221	0.050	1482.8	1.986	900
20.971	0.048	1508.3	2.005	950
21.720	0.046	1534.1	2.023	1,000
22.469	0.045	1560.0	2.040	1,050
23.218	0.043	1586.2	2.057	1,100
23.966	0.042	1612.6	2.074	1,150
24.714	0.041	1639.3	2.090	1,200
25.461	0.039	1666.1	2.106	1,250
26.209	0.038	1693.2	2.122	1,300
26.956	0.037	1720.6	2.137	1,350
27.703	0.036	1748.1	2.152	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 45.0 Psia T_s = 274.4 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	58.112	243.4	0.402	t_s(L)
9.435	0.106	1172.1	1.667	t_s(v)
9.484	0.105	1175.0	1.671	280
9.820	0.102	1185.7	1.686	300
10.112	0.099	1196.0	1.699	320
10.399	0.097	1206.1	1.712	340
10.683	0.094	1216.1	1.724	360
11.092	0.091	1230.4	1.741	380
11.246	0.089	1235.8	1.748	400
11.524	0.087	1245.6	1.759	420
11.802	0.085	1255.4	1.770	440
12.078	0.083	1265.1	1.781	460
12.352	0.081	1274.8	1.791	480
12.626	0.080	1284.6	1.801	500
12.900	0.078	1294.3	1.811	520
13.172	0.076	1304.0	1.821	540
13.444	0.075	1313.7	1.831	560
13.716	0.073	1323.5	1.840	580
13.987	0.072	1333.2	1.849	600
14.663	0.068	1357.7	1.872	650
15.338	0.065	1382.3	1.894	700
16.011	0.063	1407.1	1.915	750
16.682	0.060	1432.1	1.935	800
17.353	0.058	1457.2	1.954	850
18.022	0.056	1482.6	1.973	900
18.691	0.054	1508.2	1.992	950
19.360	0.052	1533.9	2.010	1,000
20.028	0.050	1559.9	2.027	1,050
20.696	0.049	1586.1	2.044	1,100
21.363	0.047	1612.5	2.061	1,150
22.030	0.046	1639.2	2.077	1,200
22.697	0.044	1666.0	2.093	1,250
23.364	0.043	1693.2	2.109	1,300
24.030	0.042	1720.5	2.124	1,350
24.697	0.041	1748.0	2.139	1,400

Pressure = 50.0 Psia T_s = 281.0 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	57.911	250.2	0.411	t_s(L)
8.534	0.117	1174.2	1.659	t_s(v)
8.794	0.114	1184.5	1.673	300
9.058	0.111	1194.9	1.686	320
9.319	0.108	1205.1	1.699	340
9.577	0.105	1215.2	1.712	360
9.947	0.101	1229.7	1.729	380
10.086	0.099	1235.1	1.735	400
10.337	0.097	1245.0	1.747	420
10.588	0.095	1254.8	1.758	440
10.837	0.092	1264.5	1.768	460
11.085	0.090	1274.3	1.779	480
11.332	0.088	1284.1	1.789	500
11.578	0.087	1293.8	1.799	520
11.824	0.085	1303.6	1.809	540
12.069	0.083	1313.3	1.819	560
12.314	0.081	1323.1	1.828	580
12.558	0.080	1332.9	1.838	600
13.167	0.076	1357.4	1.860	650
13.774	0.073	1382.1	1.882	700
14.380	0.070	1406.9	1.903	750
14.983	0.067	1431.9	1.923	800
15.587	0.064	1457.1	1.943	850
16.189	0.062	1482.4	1.962	900
16.791	0.060	1508.0	1.980	950
17.392	0.058	1533.8	1.998	1,000
17.992	0.056	1559.8	2.016	1,050
18.593	0.054	1586.0	2.033	1,100
19.193	0.052	1612.4	2.049	1,150
19.792	0.051	1639.1	2.066	1,200
20.392	0.049	1666.0	2.082	1,250
20.991	0.048	1693.1	2.097	1,300
21.590	0.046	1720.4	2.113	1,350
22.189	0.045	1748.0	2.128	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 55.0 Psia T_s = 287.1 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	57.725	256.3	0.419	t_s(L)
7.818	0.128	1176.1	1.651	t_s(v)
7.984	0.126	1183.2	1.661	300
8.228	0.122	1193.8	1.675	320
8.468	0.119	1204.2	1.688	340
8.705	0.115	1214.3	1.700	360
9.044	0.111	1228.9	1.718	380
9.172	0.110	1234.4	1.724	400
9.402	0.107	1244.3	1.736	420
9.631	0.104	1254.2	1.747	440
9.859	0.102	1264.0	1.758	460
10.086	0.100	1273.8	1.768	480
10.312	0.097	1283.6	1.778	500
10.537	0.095	1293.4	1.788	520
10.761	0.093	1303.2	1.798	540
10.985	0.091	1313.0	1.808	560
11.209	0.090	1322.7	1.818	580
11.432	0.088	1332.6	1.827	600
11.988	0.084	1357.1	1.850	650
12.541	0.080	1381.8	1.871	700
13.093	0.077	1406.7	1.892	750
13.645	0.074	1431.7	1.913	800
14.195	0.071	1456.9	1.932	850
14.744	0.068	1482.3	1.951	900
15.292	0.066	1507.9	1.970	950
15.840	0.063	1533.6	1.988	1,000
16.388	0.061	1559.6	2.005	1,050
16.935	0.059	1585.9	2.022	1,100
17.482	0.057	1612.3	2.039	1,150
18.028	0.056	1639.0	2.055	1,200
18.575	0.054	1665.9	2.071	1,250
19.121	0.053	1693.0	2.087	1,300
19.667	0.051	1720.3	2.102	1,350
20.212	0.050	1747.9	2.117	1,400

Pressure = 60.0 Psia T_s = 292.7 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	57.547	262.1	0.427	t_s(L)
7.194	0.139	1177.8	1.644	t_s(v)
7.259	0.138	1181.6	1.649	300
7.508	0.134	1192.7	1.664	320
7.730	0.130	1203.2	1.677	340
7.948	0.126	1213.5	1.690	360
8.261	0.121	1228.2	1.708	380
8.378	0.120	1233.7	1.714	400
8.590	0.117	1243.7	1.725	420
8.801	0.114	1253.6	1.737	440
9.011	0.111	1263.5	1.747	460
9.219	0.109	1273.3	1.758	480
9.427	0.106	1283.1	1.768	500
9.633	0.104	1292.9	1.778	520
9.840	0.102	1302.8	1.788	540
10.045	0.100	1312.6	1.798	560
10.250	0.098	1322.4	1.808	580
10.455	0.096	1332.2	1.817	600
10.964	0.091	1356.8	1.840	650
11.472	0.087	1381.6	1.861	700
11.978	0.084	1406.4	1.882	750
12.483	0.080	1431.5	1.903	800
12.987	0.077	1456.7	1.922	850
13.490	0.074	1482.1	1.941	900
13.993	0.072	1507.7	1.960	950
14.495	0.069	1533.5	1.978	1,000
14.996	0.067	1559.5	1.995	1,050
15.497	0.065	1585.7	2.013	1,100
15.997	0.063	1612.2	2.029	1,150
16.498	0.061	1638.9	2.046	1,200
16.998	0.059	1665.8	2.062	1,250
17.498	0.057	1692.9	2.077	1,300
17.998	0.056	1720.3	2.092	1,350
18.497	0.054	1747.8	2.108	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 70.1 Psia T_s = 302.9 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.017	57.219	272.7	0.441	t_s(L)
6.221	0.161	1180.8	1.632	t_s(v)
6.394	0.157	1190.4	1.644	320
6.588	0.152	1201.2	1.658	340
6.779	0.148	1211.7	1.671	360
7.051	0.142	1226.7	1.689	380
7.153	0.140	1232.2	1.696	400
7.337	0.137	1242.3	1.707	420
7.519	0.133	1252.4	1.719	440
7.700	0.130	1262.3	1.729	460
7.880	0.127	1272.3	1.740	480
8.060	0.124	1282.2	1.751	500
8.238	0.122	1292.1	1.761	520
8.416	0.119	1301.9	1.771	540
8.592	0.117	1311.8	1.781	560
8.769	0.114	1321.7	1.790	580
8.945	0.112	1331.5	1.799	600
9.384	0.107	1356.2	1.822	650
9.820	0.102	1381.1	1.844	700
10.255	0.098	1406.0	1.865	750
10.689	0.094	1431.1	1.886	800
11.122	0.090	1456.3	1.905	850
11.554	0.087	1481.8	1.924	900
11.985	0.084	1507.4	1.943	950
12.415	0.081	1533.2	1.961	1,000
12.845	0.078	1559.3	1.978	1,050
13.276	0.076	1585.5	1.995	1,100
13.705	0.073	1612.0	2.012	1,150
14.134	0.071	1638.7	2.028	1,200
14.563	0.069	1665.6	2.044	1,250
14.992	0.067	1692.7	2.060	1,300
15.420	0.065	1720.1	2.075	1,350
15.848	0.063	1747.7	2.090	1,400

Pressure = 80 Psia T_s = 312.03 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.018	56.919	282.1	0.453	t_s(L)
5.474	0.183	1183.3	1.621	t_s(v)
5.545	0.180	1187.9	1.627	320
5.719	0.175	1199.1	1.641	340
5.889	0.170	1209.9	1.655	360
6.130	0.163	1225.1	1.673	380
6.220	0.161	1230.7	1.679	400
6.383	0.157	1241.0	1.691	420
6.543	0.153	1251.1	1.703	440
6.703	0.149	1261.2	1.714	460
6.862	0.146	1271.2	1.724	480
7.019	0.142	1281.2	1.735	500
7.176	0.139	1291.2	1.745	520
7.332	0.136	1301.1	1.755	540
7.487	0.134	1311.0	1.765	560
7.642	0.131	1320.9	1.775	580
7.797	0.128	1330.8	1.784	600
8.181	0.122	1355.6	1.807	650
8.564	0.117	1380.5	1.829	700
8.944	0.112	1405.5	1.850	750
9.324	0.107	1430.6	1.870	800
9.702	0.103	1456.0	1.890	850
10.080	0.099	1481.4	1.909	900
10.457	0.096	1507.1	1.928	950
10.834	0.092	1532.9	1.946	1,000
11.210	0.089	1559.0	1.963	1,050
11.586	0.086	1585.3	1.980	1,100
11.961	0.084	1611.8	1.997	1,150
12.336	0.081	1638.5	2.013	1,200
12.711	0.079	1665.4	2.029	1,250
13.086	0.076	1692.6	2.045	1,300
13.460	0.074	1720.0	2.060	1,350
13.833	0.072	1747.5	2.076	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 90.0 Psia T_s = 320.3 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.018	56.643	290.6	0.464	t_s(L)
4.904	0.204	1185.5	1.612	t_s(v)
5.062	0.198	1196.9	1.626	340
5.216	0.192	1208.0	1.640	360
5.434	0.184	1223.5	1.658	380
5.515	0.182	1229.3	1.665	400
5.661	0.177	1239.6	1.677	420
5.806	0.173	1249.9	1.689	440
5.949	0.168	1260.1	1.700	460
6.092	0.164	1270.2	1.711	480
6.233	0.161	1280.2	1.721	500
6.373	0.157	1290.3	1.732	520
6.513	0.154	1300.2	1.742	540
6.652	0.151	1310.2	1.752	560
6.791	0.148	1320.2	1.761	580
6.929	0.145	1330.1	1.771	600
7.067	0.142	1340.1	1.775	620
7.204	0.139	1350.0	1.787	640
7.341	0.136	1360.0	1.798	660
7.478	0.134	1370.0	1.807	680
7.614	0.132	1380.0	1.816	700
7.954	0.126	1405.0	1.837	750
8.292	0.121	1430.2	1.857	800
8.630	0.116	1455.6	1.877	850
8.967	0.112	1481.1	1.896	900
9.303	0.108	1506.8	1.915	950
9.639	0.104	1532.7	1.933	1,000
9.974	0.100	1558.7	1.950	1,050
10.308	0.097	1585.0	1.967	1,100
10.643	0.094	1611.5	1.984	1,150
10.977	0.091	1638.3	2.000	1,200
11.311	0.089	1665.2	2.016	1,250
11.645	0.086	1692.4	2.032	1,300
11.978	0.084	1719.8	2.048	1,350
12.311	0.081	1747.4	2.063	1,400

Pressure = 100.0 Psia T_s = 327.8 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.018	56.456	296.3	0.471	t_s(L)
4.562	0.219	1187.0	1.606	t_s(v)
4.669	0.215	1195.3	1.616	340
4.814	0.208	1206.6	1.630	360
5.018	0.200	1222.4	1.649	380
5.094	0.197	1228.2	1.656	400
5.231	0.191	1238.7	1.668	420
5.366	0.187	1249.0	1.679	440
5.500	0.182	1259.3	1.691	460
5.632	0.178	1269.4	1.702	480
5.764	0.174	1279.5	1.712	500
5.895	0.170	1289.6	1.723	520
6.025	0.166	1299.7	1.733	540
6.154	0.163	1309.7	1.743	560
6.283	0.159	1319.6	1.752	580
6.411	0.156	1329.6	1.762	600
6.539	0.153	1339.6	1.771	620
6.667	0.150	1349.6	1.780	640
6.794	0.147	1359.6	1.789	660
6.921	0.145	1369.6	1.798	680
7.047	0.142	1379.6	1.807	700
7.363	0.136	1404.7	1.828	750
7.677	0.130	1429.9	1.849	800
7.990	0.125	1455.3	1.868	850
8.303	0.121	1480.8	1.888	900
8.614	0.116	1506.6	1.906	950
8.926	0.112	1532.5	1.924	1,000
9.236	0.108	1558.6	1.942	1,050
9.546	0.105	1584.9	1.959	1,100
9.857	0.102	1611.4	1.976	1,150
10.166	0.099	1638.1	1.992	1,200
10.476	0.096	1665.1	2.008	1,250
10.785	0.093	1692.2	2.024	1,300
11.094	0.090	1719.7	2.039	1,350
11.403	0.088	1747.3	2.054	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 150.0 Psia T_s = 358.4 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.018	55.285	330.5	0.514	t_s(L)
3.021	0.332	1194.5	1.570	t_s(v)
3.023	0.331	1195.0	1.571	360
3.176	0.315	1213.4	1.593	380
3.229	0.310	1219.7	1.600	400
3.324	0.302	1231.0	1.613	420
3.417	0.293	1242.1	1.626	440
3.509	0.286	1253.0	1.638	460
3.599	0.279	1263.7	1.649	480
3.688	0.272	1274.3	1.660	500
3.776	0.265	1284.7	1.671	520
3.863	0.259	1295.1	1.682	540
3.949	0.254	1305.4	1.692	560
4.035	0.248	1315.7	1.702	580
4.120	0.243	1325.9	1.711	600
4.205	0.238	1336.1	1.721	620
4.289	0.234	1346.3	1.730	640
4.374	0.229	1356.5	1.740	660
4.457	0.225	1366.6	1.749	680
4.541	0.221	1376.8	1.757	700
4.748	0.211	1402.2	1.779	750
4.954	0.202	1427.7	1.800	800
5.160	0.194	1453.3	1.819	850
5.364	0.187	1479.0	1.839	900
5.568	0.180	1504.9	1.857	950
5.771	0.174	1531.0	1.876	1,000
5.974	0.168	1557.2	1.893	1,050
6.176	0.162	1583.6	1.910	1,100
6.378	0.157	1610.2	1.927	1,150
6.579	0.152	1637.1	1.944	1,200
6.781	0.148	1664.1	1.960	1,250
6.982	0.144	1691.4	1.975	1,300
7.183	0.140	1718.8	1.991	1,350
7.384	0.136	1746.5	2.006	1,400

Pressure = 200.0 Psia T_s = 381.8 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.018	54.388	355.4	0.544	t_s(L)
2.290	0.437	1198.8	1.546	t_s(v)
				360
				380
2.363	0.424	1210.8	1.560	400
2.440	0.410	1223.2	1.574	420
2.515	0.398	1235.2	1.588	440
2.587	0.387	1246.7	1.601	460
2.658	0.377	1258.0	1.613	480
2.727	0.367	1269.0	1.624	500
2.796	0.358	1279.9	1.636	520
2.863	0.350	1290.6	1.646	540
2.930	0.342	1301.3	1.657	560
2.996	0.334	1311.8	1.667	580
3.061	0.327	1322.3	1.677	600
3.126	0.320	1332.7	1.687	620
3.191	0.314	1343.1	1.696	640
3.255	0.307	1353.4	1.706	660
3.319	0.302	1363.8	1.715	680
3.383	0.296	1374.1	1.724	700
3.540	0.283	1399.8	1.746	750
3.697	0.271	1425.6	1.766	800
3.852	0.260	1451.4	1.787	850
4.007	0.250	1477.3	1.806	900
4.161	0.241	1503.4	1.825	950
4.314	0.232	1529.6	1.843	1,000
4.467	0.224	1555.9	1.861	1,050
4.619	0.217	1582.4	1.878	1,100
4.771	0.210	1609.1	1.895	1,150
4.923	0.203	1636.1	1.911	1,200
5.074	0.197	1663.2	1.928	1,250
5.225	0.192	1690.5	1.943	1,300
5.376	0.186	1718.0	1.959	1,350
5.527	0.181	1745.7	1.974	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 300.0 Psia T_s = 417.3 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.019	52.921	393.9	0.588	t_s(L)
1.546	0.648	1203.3	1.511	t_s(v)
1.551	0.645	1204.8	1.513	420
1.613	0.622	1219.6	1.529	440
1.667	0.601	1232.9	1.544	460
1.720	0.583	1245.6	1.558	480
1.771	0.566	1257.9	1.571	500
1.820	0.551	1269.7	1.583	520
1.869	0.536	1281.2	1.595	540
1.916	0.523	1292.6	1.606	560
1.963	0.511	1303.8	1.617	580
2.009	0.499	1314.8	1.627	600
2.054	0.488	1325.7	1.637	620
2.099	0.477	1336.5	1.647	640
2.144	0.467	1347.3	1.657	660
2.188	0.458	1357.9	1.666	680
2.232	0.449	1368.6	1.676	700
2.276	0.440	1379.1	1.685	720
2.319	0.432	1389.7	1.694	740
2.362	0.424	1400.3	1.702	760
2.405	0.417	1410.8	1.711	780
2.447	0.409	1421.3	1.719	800
2.490	0.402	1431.8	1.728	820
2.532	0.396	1442.3	1.736	840
2.574	0.389	1452.8	1.744	860
2.617	0.383	1463.4	1.752	880
2.658	0.377	1473.9	1.759	900
2.763	0.363	1500.3	1.778	950
2.866	0.350	1526.7	1.797	1,000
2.990	0.335	1558.6	1.818	1,050
3.072	0.326	1580.1	1.832	1,100
3.175	0.316	1607.0	1.849	1,150
3.277	0.306	1634.0	1.866	1,200
3.379	0.297	1661.3	1.882	1,250
3.481	0.288	1688.8	1.898	1,300
3.582	0.280	1716.4	1.913	1,350
3.683	0.272	1744.2	1.929	1,400

Pressure = 400.0 Psia T_s = 444.6 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.019	51.709	423.8	0.621	t_s(L)
1.171	0.861	1204.9	1.486	t_s(v)
				420
				440
1.198	0.835	1216.5	1.498	460
1.254	0.806	1231.7	1.515	480
1.297	0.779	1245.5	1.529	500
1.338	0.755	1258.5	1.543	520
1.377	0.734	1271.1	1.555	540
1.415	0.714	1283.3	1.567	560
1.453	0.695	1295.2	1.579	580
1.490	0.678	1306.9	1.590	600
1.526	0.662	1318.3	1.601	620
1.561	0.647	1329.7	1.611	640
1.596	0.632	1340.8	1.621	660
1.631	0.619	1351.9	1.631	680
1.665	0.606	1362.9	1.641	700
1.699	0.594	1373.8	1.650	720
1.733	0.582	1384.6	1.659	740
1.766	0.571	1395.4	1.668	760
1.799	0.561	1406.2	1.677	780
1.832	0.551	1416.9	1.685	800
1.865	0.541	1427.6	1.694	820
1.898	0.532	1438.4	1.702	840
1.930	0.523	1449.0	1.710	860
1.962	0.514	1459.7	1.718	880
1.995	0.506	1470.4	1.726	900
2.075	0.486	1497.1	1.745	950
2.154	0.468	1523.9	1.764	1,000
2.249	0.448	1556.1	1.786	1,050
2.311	0.436	1577.7	1.800	1,100
2.389	0.422	1604.8	1.817	1,150
2.467	0.409	1632.0	1.834	1,200
2.545	0.396	1659.4	1.850	1,250
2.622	0.385	1687.0	1.866	1,300
2.699	0.374	1714.8	1.881	1,350
2.776	0.363	1742.7	1.897	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 500.0 Psia T_s = 467.0 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.020	50.630	449.5	0.649	t_s(L)
0.930	1.078	1204.9	1.464	t_s(v)
0.954	1.048	1215.4	1.475	480
0.996	1.008	1231.9	1.493	500
1.031	0.972	1246.5	1.508	520
1.066	0.941	1260.3	1.522	540
1.099	0.913	1273.5	1.535	560
1.131	0.887	1286.2	1.547	580
1.162	0.863	1298.6	1.559	600
1.192	0.841	1310.7	1.570	620
1.221	0.821	1322.5	1.581	640
1.251	0.802	1334.2	1.592	660
1.279	0.784	1345.7	1.602	680
1.307	0.767	1357.0	1.612	700
1.335	0.751	1368.3	1.621	720
1.363	0.736	1379.4	1.631	740
1.390	0.721	1390.5	1.640	760
1.417	0.707	1401.5	1.649	780
1.444	0.694	1412.5	1.658	800
1.471	0.681	1423.4	1.666	820
1.498	0.669	1434.3	1.675	840
1.524	0.658	1445.2	1.683	860
1.550	0.647	1456.1	1.691	880
1.576	0.636	1466.9	1.699	900
1.641	0.611	1493.9	1.719	950
1.705	0.588	1521.0	1.738	1,000
1.781	0.563	1553.5	1.760	1,050
1.831	0.547	1575.3	1.774	1,100
1.894	0.529	1602.6	1.791	1,150
1.957	0.512	1630.0	1.808	1,200
2.019	0.497	1657.5	1.824	1,250
2.081	0.482	1685.3	1.840	1,300
2.142	0.468	1713.2	1.856	1,350
2.204	0.455	1741.2	1.871	1,400

Pressure = 600.0 Psia T_s = 486.2 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.020	49.657	471.6	0.672	t_s(L)
0.772	1.299	1203.8	1.446	t_s(v)
0.798	1.259	1216.4	1.460	500
0.832	1.208	1233.1	1.477	520
0.863	1.164	1248.4	1.492	540
0.893	1.125	1262.9	1.507	560
0.921	1.090	1276.6	1.520	580
0.949	1.058	1289.8	1.533	600
0.976	1.029	1302.6	1.545	620
1.002	1.002	1315.1	1.556	640
1.027	0.977	1327.3	1.567	660
1.052	0.954	1339.2	1.578	680
1.076	0.932	1351.0	1.588	700
1.100	0.912	1362.6	1.598	720
1.124	0.892	1374.1	1.607	740
1.148	0.874	1385.5	1.617	760
1.171	0.857	1396.8	1.626	780
1.194	0.840	1408.0	1.635	800
1.217	0.825	1419.1	1.644	820
1.239	0.809	1430.2	1.652	840
1.262	0.795	1441.3	1.661	860
1.284	0.781	1452.3	1.669	880
1.306	0.768	1463.3	1.677	900
1.361	0.737	1490.7	1.697	950
1.415	0.709	1518.1	1.716	1,000
1.479	0.678	1550.9	1.738	1,050
1.522	0.659	1572.9	1.752	1,100
1.575	0.637	1600.4	1.770	1,150
1.627	0.616	1627.9	1.787	1,200
1.679	0.597	1655.7	1.803	1,250
1.731	0.579	1683.5	1.819	1,300
1.783	0.562	1711.6	1.835	1,350
1.835	0.547	1739.7	1.850	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 700.0 Psia T_s = 503.1 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.021	48.752	491.6	0.693	t_s(L)
0.658	1.525	1201.8	1.431	t_s(v)
0.686	1.465	1218.1	1.447	520
0.716	1.403	1235.5	1.465	540
0.744	1.350	1251.4	1.481	560
0.770	1.303	1266.4	1.495	580
0.795	1.262	1280.6	1.509	600
0.820	1.224	1294.2	1.521	620
0.843	1.190	1307.3	1.534	640
0.866	1.158	1320.1	1.545	660
0.888	1.129	1332.6	1.556	680
0.910	1.102	1344.8	1.567	700
0.932	1.077	1356.8	1.577	720
0.953	1.053	1368.6	1.587	740
0.973	1.031	1380.3	1.597	760
0.994	1.009	1391.9	1.606	780
1.014	0.989	1403.3	1.615	800
1.034	0.970	1414.7	1.624	820
1.054	0.952	1426.1	1.633	840
1.073	0.934	1437.3	1.642	860
1.093	0.918	1448.5	1.650	880
1.112	0.902	1459.7	1.658	900
1.160	0.865	1487.5	1.678	950
1.207	0.831	1515.2	1.698	1,000
1.263	0.794	1548.3	1.720	1,050
1.300	0.772	1570.4	1.734	1,100
1.345	0.745	1598.1	1.752	1,150
1.391	0.721	1625.9	1.769	1,200
1.436	0.698	1653.8	1.785	1,250
1.481	0.677	1681.8	1.801	1,300
1.525	0.657	1709.9	1.817	1,350
1.570	0.639	1738.2	1.833	1,400

Pressure = 800.0 Psia T_s = 518.2 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.021	47.896	509.9	0.711	t_s(L)
0.569	1.757	1199.3	1.416	t_s(v)
0.572	1.750	1200.5	1.417	520
0.602	1.662	1221.2	1.438	540
0.629	1.591	1239.1	1.456	560
0.654	1.529	1255.5	1.472	580
0.678	1.476	1270.8	1.487	600
0.701	1.428	1285.3	1.500	620
0.722	1.385	1299.2	1.513	640
0.743	1.346	1312.7	1.525	660
0.764	1.310	1325.7	1.537	680
0.783	1.277	1338.4	1.548	700
0.803	1.246	1350.8	1.558	720
0.822	1.217	1363.0	1.569	740
0.840	1.190	1375.0	1.578	760
0.859	1.165	1386.9	1.588	780
0.877	1.141	1398.7	1.598	800
0.895	1.118	1410.3	1.607	820
0.913	1.096	1421.8	1.616	840
0.930	1.075	1433.3	1.624	860
0.947	1.056	1444.7	1.633	880
0.965	1.037	1456.0	1.641	900
1.007	0.994	1484.2	1.662	950
1.049	0.954	1512.2	1.681	1,000
1.098	0.911	1545.7	1.704	1,050
1.130	0.885	1568.0	1.718	1,100
1.171	0.854	1595.9	1.736	1,150
1.211	0.826	1623.8	1.753	1,200
1.250	0.800	1651.9	1.770	1,250
1.290	0.775	1680.0	1.786	1,300
1.329	0.753	1708.3	1.802	1,350
1.368	0.731	1736.7	1.817	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 900.0 Psia T_s = 532.0 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.021	47.083	526.7	0.728	t_s(L)
0.502	1.996	1196.2	1.403	t_s(v)
0.512	1.952	1204.4	1.411	540
0.541	1.855	1225.4	1.432	560
0.566	1.773	1243.6	1.450	580
0.588	1.704	1260.3	1.466	600
0.610	1.644	1275.9	1.480	620
0.630	1.590	1290.7	1.494	640
0.650	1.542	1304.9	1.507	660
0.669	1.498	1318.5	1.519	680
0.687	1.458	1331.8	1.530	700
0.705	1.421	1344.6	1.541	720
0.723	1.386	1357.3	1.552	740
0.740	1.354	1369.6	1.562	760
0.757	1.324	1381.8	1.572	780
0.773	1.296	1393.9	1.582	800
0.790	1.269	1405.8	1.591	820
0.806	1.243	1417.5	1.600	840
0.822	1.219	1429.2	1.609	860
0.837	1.196	1440.8	1.618	880
0.853	1.175	1452.3	1.626	900
0.891	1.124	1480.9	1.647	950
0.929	1.078	1509.2	1.667	1,000
0.973	1.029	1543.0	1.690	1,050
1.003	0.999	1565.5	1.704	1,100
1.039	0.964	1593.6	1.722	1,150
1.075	0.932	1621.8	1.739	1,200
1.110	0.902	1650.0	1.756	1,250
1.146	0.874	1678.3	1.772	1,300
1.181	0.848	1706.6	1.788	1,350
1.216	0.824	1735.2	1.804	1,400

Pressure = 1000.0 Psia T_s = 544.6 °F				*t*, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	*h*, $\frac{Btu}{lb}$	*s*, $\frac{Btu}{lb\text{-}°R}$	
0.022	46.298	542.6	0.743	t_s(L)
0.446	2.242	1192.6	1.391	t_s(v)
				540
0.468	2.144	1210.2	1.408	560
0.492	2.036	1230.7	1.428	580
0.515	1.946	1249.1	1.446	600
0.536	1.870	1266.0	1.461	620
0.555	1.804	1281.8	1.476	640
0.574	1.745	1296.8	1.489	660
0.592	1.692	1311.1	1.502	680
0.609	1.644	1324.9	1.514	700
0.626	1.600	1338.3	1.525	720
0.642	1.559	1351.4	1.536	740
0.658	1.522	1364.1	1.547	760
0.674	1.486	1376.6	1.557	780
0.689	1.453	1389.0	1.567	800
0.704	1.422	1401.2	1.577	820
0.719	1.393	1413.2	1.586	840
0.733	1.365	1425.1	1.595	860
0.748	1.339	1436.9	1.604	880
0.762	1.314	1448.6	1.613	900
0.797	1.256	1477.5	1.634	950
0.832	1.204	1506.2	1.654	1,000
0.872	1.147	1540.4	1.677	1,050
0.899	1.114	1563.0	1.691	1,100
0.932	1.075	1591.4	1.709	1,150
0.964	1.038	1619.7	1.726	1,200
0.996	1.005	1648.0	1.743	1,250
1.029	0.973	1676.5	1.760	1,300
1.060	0.944	1705.0	1.776	1,350
1.092	0.917	1733.6	1.791	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 1100.0 Psia T_s = 556.3 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.022	45.536	557.6	0.758	t_s(L)
0.401	2.496	1188.6	1.379	t_s(v)
0.405	2.467	1192.6	1.383	560
0.431	2.324	1216.6	1.406	580
0.454	2.208	1237.0	1.426	600
0.474	2.111	1255.4	1.443	620
0.493	2.029	1272.4	1.458	640
0.511	1.958	1288.3	1.473	660
0.528	1.894	1303.4	1.486	680
0.545	1.837	1317.8	1.499	700
0.561	1.785	1331.8	1.511	720
0.576	1.738	1345.3	1.522	740
0.591	1.694	1358.5	1.533	760
0.606	1.653	1371.3	1.543	780
0.620	1.615	1384.0	1.554	800
0.634	1.579	1396.5	1.563	820
0.648	1.545	1408.8	1.573	840
0.661	1.513	1420.9	1.582	860
0.675	1.483	1432.9	1.591	880
0.688	1.455	1444.8	1.600	900
0.720	1.390	1474.2	1.621	950
0.752	1.331	1503.2	1.641	1,000
0.789	1.267	1537.7	1.665	1,050
0.814	1.230	1560.6	1.679	1,100
0.844	1.186	1589.1	1.697	1,150
0.874	1.145	1617.6	1.715	1,200
0.903	1.108	1646.1	1.732	1,250
0.933	1.073	1674.7	1.748	1,300
0.962	1.040	1703.4	1.764	1,350
0.991	1.010	1732.1	1.780	1,400

Pressure = 1200.0 Psia T_s = 567.2 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.022	44.794	571.8	0.771	t_s(L)
0.364	2.761	1184.2	1.368	t_s(v)
				560
0.379	2.641	1200.4	1.383	580
0.403	2.497	1223.6	1.406	600
0.424	2.373	1244.0	1.425	620
0.443	2.271	1262.3	1.442	640
0.460	2.183	1279.4	1.457	660
0.477	2.106	1295.3	1.471	680
0.493	2.039	1310.5	1.484	700
0.508	1.978	1325.0	1.497	720
0.522	1.922	1339.0	1.508	740
0.537	1.871	1352.6	1.520	760
0.550	1.824	1365.9	1.531	780
0.564	1.780	1378.9	1.541	800
0.577	1.739	1391.7	1.551	820
0.590	1.701	1404.2	1.561	840
0.603	1.664	1416.6	1.570	860
0.615	1.631	1428.8	1.579	880
0.628	1.598	1440.9	1.588	900
0.658	1.525	1470.7	1.610	950
0.688	1.459	1500.1	1.630	1,000
0.722	1.388	1535.0	1.654	1,050
0.745	1.347	1558.1	1.669	1,100
0.773	1.298	1586.8	1.687	1,150
0.801	1.253	1615.5	1.704	1,200
0.828	1.211	1644.2	1.721	1,250
0.855	1.173	1672.9	1.738	1,300
0.882	1.137	1701.7	1.754	1,350
0.909	1.103	1730.6	1.770	1,400

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Properties of Superheated Steam—I-P Units

Pressure = 1300.0 Psia T_s = 577.5 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.023	44.061	585.6	0.784	t_s(L)
0.330	3.032	1179.5	1.357	t_s(v)
0.333	3.005	1182.4	1.360	580
0.357	2.804	1209.4	1.385	600
0.378	2.648	1231.9	1.407	620
0.397	2.522	1251.9	1.425	640
0.414	2.416	1270.1	1.441	660
0.430	2.325	1287.0	1.456	680
0.446	2.245	1302.9	1.470	700
0.460	2.174	1318.1	1.483	720
0.474	2.110	1332.6	1.495	740
0.488	2.052	1346.7	1.507	760
0.501	1.998	1360.4	1.518	780
0.514	1.948	1373.7	1.529	800
0.526	1.901	1386.8	1.539	820
0.539	1.858	1399.7	1.549	840
0.551	1.817	1412.3	1.559	860
0.562	1.779	1424.8	1.568	880
0.574	1.743	1437.0	1.577	900
0.602	1.661	1467.3	1.599	950
0.630	1.588	1497.1	1.620	1,000
0.662	1.510	1532.3	1.644	1,050
0.684	1.464	1555.5	1.659	1,100
0.710	1.410	1584.5	1.677	1,150
0.735	1.361	1613.4	1.694	1,200
0.761	1.315	1642.3	1.712	1,250
0.786	1.273	1671.1	1.728	1,300
0.811	1.234	1700.1	1.744	1,350
0.836	1.197	1729.1	1.760	1,400

Pressure = 1400.0 Psia T_s = 591.7 °F				t, °F
v, $\frac{ft^3}{lb}$	ρ, $\frac{lb}{ft^3}$	h, $\frac{Btu}{lb}$	s, $\frac{Btu}{lb\text{-}°R}$	
0.023	43.340	598.8	0.797	t_s(L)
0.303	3.318	1174.4	1.347	t_s(v)
				580
0.317	3.151	1193.0	1.364	600
0.340	2.958	1218.4	1.388	620
0.359	2.798	1240.5	1.408	640
0.377	2.668	1260.1	1.426	660
0.393	2.558	1278.2	1.442	680
0.407	2.464	1295.0	1.457	700
0.422	2.381	1310.8	1.470	720
0.435	2.307	1326.0	1.483	740
0.448	2.239	1340.6	1.495	760
0.461	2.178	1354.7	1.506	780
0.473	2.121	1368.4	1.517	800
0.485	2.069	1381.8	1.528	820
0.497	2.020	1395.0	1.538	840
0.508	1.974	1407.9	1.548	860
0.519	1.931	1420.6	1.558	880
0.530	1.891	1433.1	1.567	900
0.557	1.800	1463.8	1.589	950
0.583	1.719	1494.0	1.610	1,000
0.614	1.633	1529.6	1.634	1,050
0.634	1.583	1553.0	1.649	1,100
0.658	1.523	1582.2	1.668	1,150
0.682	1.470	1611.3	1.685	1,200
0.706	1.420	1640.3	1.703	1,250
0.730	1.374	1669.4	1.719	1,300
0.753	1.331	1698.4	1.736	1,350
0.776	1.291	1727.5	1.752	1,400

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6.3.4 Properties of Saturated Water and Steam (Temperature)—SI Units

Properties of Saturated Water and Steam (Temperature)—SI Units
Pressures Are Absolute

		Specific Volume, $\frac{m^3}{kg}$			Enthalpy, $\frac{kJ}{kg}$			Entropy, $\frac{kJ}{kg \cdot K}$			
T, °C	Psia, MPa	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T, °C
0.01	0.0006	0.0010002	205.99	205.991	0	2500.9	2500.9	0	9.1555	9.1555	0.01
5	0.0009	1.0001×10^{-3}	147.0090	147.01	21.02	2489	2510.1	0.07625	8.9486	9.0248	5
10	0.0012	1.0003×10^{-3}	106.3010	106.302	42.02	2477.2	2519.2	0.1519	8.7487	8.8998	10
15	0.0017	1.0009×10^{-3}	77.830	77.8740	62.98	2465.4	2528.3	0.22446	8.5558	8.7803	15
20	0.0023	1.0018×10^{-3}	57.7550	57.7560	83.91	2453.5	2537.4	0.29648	8.3695	8.666	20
25	0.0032	1.0030×10^{-3}	43.3350	43.3360	104.83	2441.7	2546.5	0.36722	8.1894	8.5566	25
30	0.0042	1.0044×10^{-3}	32.8760	32.8770	125.73	2429.8	2555.5	0.43675	8.0152	8.452	30
35	0.0056	1.0061×10^{-3}	25.2030	25.2040	146.63	2417.9	2564.5	0.50513	7.8466	8.3517	35
40	0.0074	1.0079×10^{-3}	19.5130	19.5140	167.53	2406	2573.5	0.5724	7.6831	8.2555	40
45	0.0096	1.0099×10^{-3}	15.2500	15.2510	188.43	2394	2582.4	0.63861	7.5247	8.1633	45
50	0.0124	1.0122×10^{-3}	12.0250	12.0260	209.34	2381.9	2591.3	0.70381	7.371	8.0748	50
55	0.0158	0.0010	9.5633	9.5643	230.26	2369.8	2600.1	0.76802	7.2218	7.9898	55
60	0.0199	0.0010	7.6662	7.6672	251.18	2357.7	2608.8	0.83129	7.0769	7.9081	60
65	0.0250	0.0010	6.1925	6.1935	272.12	2345.4	2617.5	0.89365	6.9359	7.8296	65
70	0.0312	0.0010	5.0385	5.0395	293.07	2333	2626.1	0.95513	6.7989	7.754	70
75	0.0386	0.0010	4.1279	4.1289	314.03	2320.6	2634.6	1.0158	6.6654	7.6812	75
80	0.0474	0.0010	3.4042	3.4052	335.01	2308	2643	1.0756	6.5355	7.6111	80
85	0.0579	0.0010	2.8248	2.8258	356.01	2295.3	2651.3	1.1346	6.4088	7.5434	85
90	0.0702	0.0010	2.3581	2.3591	377.04	2282.5	2659.5	1.1929	6.2853	7.4781	90
95	0.0846	0.0010	1.9796	1.9806	398.09	2269.5	2667.6	1.2504	6.1647	7.4151	95
100	0.10	0.0010	1.6708	1.6718	419.17	2256.4	2675.6	1.3072	6.0469	7.3541	100
105	0.12	0.0010	1.4174	1.4184	440.27	2243.1	2683.4	1.3633	5.9318	7.2952	105
110	0.14	0.0011	1.2082	1.2093	461.42	2229.6	2691.1	1.4188	5.8193	7.2381	110

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Properties of Saturated Water and Steam (Temperature)—SI Units (cont'd)

Pressures Are Absolute

		Specific Volume, $\frac{m^3}{kg}$			Enthalpy, $\frac{kJ}{kg}$			Entropy, $\frac{kJ}{kg \cdot K}$			
T, °C	Psia, MPa	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T, °C
115	0.1692	0.0011	1.0347	1.0358	482.59	2216	2698.6	1.4737	5.7091	7.1828	115
120	0.1987	0.0011	0.8901	0.8912	503.81	2202.1	2705.9	1.5279	5.6012	7.1291	120
125	0.2322	0.0011	0.7690	0.7700	525.07	2188	2713.1	1.5816	5.4955	7.077	125
130	0.2703	0.0011	0.6669	0.6680	546.38	2173.7	2720.1	1.6346	5.3918	7.0264	130
135	0.3132	0.0011	0.5807	0.5817	567.74	2159.1	2726.9	1.6872	5.29	6.9772	135
140	0.3615	0.0011	0.5074	0.5085	589.16	2144.3	2733.4	1.7392	5.1901	6.9293	140
145	0.4157	0.0011	0.4449	0.4460	610.64	2129.2	2739.8	1.7907	5.0919	6.8826	145
150	0.4762	0.0011	0.3914	0.3925	632.18	2113.7	2745.9	1.8418	4.9953	6.8371	150
155	0.5435	0.0011	0.3454	0.3465	653.79	2098	2751.8	1.8924	4.9002	6.7926	155
160	0.6182	0.0011	0.3057	0.3068	675.47	2082	2757.4	1.9426	4.8066	6.7491	160
165	0.7009	0.0011	0.2713	0.2724	697.24	2065.6	2762.8	1.9923	4.7143	6.7066	165
170	0.7922	0.0011	0.2415	0.2425	719.08	2048.8	2767.9	2.0417	4.6233	6.665	170
175	0.8926	0.0011	0.2155	0.2166	741.02	2031.7	2772.7	2.0906	4.5335	6.6241	175
180	1.0028	0.0011	0.1927	0.1938	763.05	2014.2	2777.2	2.1392	4.4448	6.584	180
185	1.1235	0.0011	0.1728	0.1739	785.19	1996.2	2781.4	2.1875	4.3571	6.5447	185
190	1.2552	0.0011	0.1552	0.1564	807.43	1977.9	2785.3	2.2355	4.2704	6.5059	190
195	1.3988	0.0011	0.1397	0.1409	829.79	1959	2788.8	2.2832	4.1846	6.4678	195
200	1.5549	0.0012	0.1261	0.1272	852.27	1939.7	2792	2.3305	4.0996	6.4302	200
205	1.7243	0.0012	0.1139	0.1151	874.88	1919.9	2794.8	2.3777	4.0154	6.393	205
210	1.9077	0.0012	0.1031	0.1043	897.63	1899.6	2797.3	2.4245	3.9318	6.3563	210
215	2.1058	0.0012	0.0935	0.0947	920.53	1878.8	2799.3	2.4712	3.8488	6.32	215
220	2.3196	0.0012	0.0849	0.0861	943.58	1857.4	2800.9	2.5177	3.7663	6.284	220
225	2.5497	0.0012	0.0772	0.0784	966.8	1835.4	2802.1	2.564	3.6843	6.2483	225

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Properties of Saturated Water and Steam (Temperature)—SI Units (cont'd)

Pressures Are Absolute

		Specific Volume, $\frac{m^3}{kg}$			Enthalpy, $\frac{kJ}{kg}$			Entropy, $\frac{kJ}{kg \cdot K}$			
T, °C	Psia, MPa	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T, °C
230	2.7971	0.0012	0.0703	0.07150	990.19	1812.7	2802.9	2.6101	3.6027	6.2128	230
235	3.0625	0.0012	0.0641	0.0653	1013.8	1789.4	2803.2	2.6561	3.5214	6.1775	235
240	3.3469	0.0012	0.0585	0.0597	1037.6	1765.4	2803	2.702	3.4403	6.1423	240
245	3.6512	0.0012	0.0534	0.0547	1061.5	1740.7	2802.2	2.7478	3.3594	6.1072	245
250	3.9762	0.0013	0.0488	0.0501	1085.8	1715.2	2800.9	2.7935	3.2785	6.0721	250
255	4.3229	0.0013	0.0447	0.0460	1110.2	1688.8	2799.1	2.8392	3.1977	6.0369	255
260	4.6923	0.0013	0.0409	0.0422	1135	1661.6	2796.6	2.8849	3.1167	6.0016	260
265	5.0853	0.0013	0.0375	0.0387	1160	1633.5	2793.5	2.9307	3.0354	5.9661	265
270	5.503	0.0013	0.0343	0.0356	1185.3	1604.4	2789.7	2.9765	2.9539	5.9304	270
275	5.9464	0.0013	0.0315	0.0328	1210.9	1574.3	2785.2	3.0224	2.872	5.8944	275
280	6.4166	0.0013	0.0288	0.0302	1236.9	1543	2779.9	3.0685	2.7894	5.8579	280
285	6.9147	0.0013	0.0264	0.0278	1263.2	1510.5	2773.7	3.1147	2.7062	5.8209	285
290	7.4418	0.0014	0.0242	0.0256	1290	1476.7	2766.7	3.1612	2.6222	5.7834	290
295	7.9991	0.0014	0.0221	0.0235	1317.3	1441.4	2758.7	3.208	2.5371	5.7451	295
300	8.5879	0.0014	0.0203	0.0217	1345	1404.6	2749.6	3.2552	2.4507	5.7059	300
305	9.2094	0.0014	0.0185	0.0199	1373.3	1366.1	2739.4	3.3028	2.3629	5.6657	305
310	9.8651	0.0014	0.0169	0.0183	1402.2	1325.7	2727.9	3.351	2.2734	5.6244	310
311	10	0.0015	0.0166	0.0180	1408.1	1317.4	2725.5	3.3607	2.2553	5.6159	311

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6.3.5 Properties of Saturated Water and Steam (Pressure)—SI Units

Properties of Saturated Water and Steam (Pressure)—SI Units
Pressures Are Absolute

		Specific Volume, $\frac{m^3}{kg}$			Enthalpy, $\frac{kJ}{kg}$			Entropy, $\frac{kJ}{kg \cdot K}$			
Psia, MPa	***T*, °C**	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	**Psia, MPa**
611.7 Pa	0.01	0.0010	205.9900	205.9910	0.0	2,500.9	2,500.9	0.0000	9.1555	9.1555	611.7
0.0010	6.97	0.0010	129.1770	129.1780	29.3	2,484.4	2,513.7	0.1059	8.8690	8.9749	0.0010
0.0014	11.97	0.0010	93.8980	93.8990	50.3	2,472.5	2,522.8	0.1802	8.6719	8.8521	0.0014
0.0020	17.50	0.0010	66.9860	66.9870	73.4	2,459.4	2,532.9	0.2606	8.4620	8.7226	0.0020
0.0032	25.16	0.0010	42.9510	42.9520	105.5	2,441.3	2,546.8	0.3695	8.1838	8.5533	0.0032
0.0040	28.96	0.0010	34.7900	34.7910	121.4	2,432.3	2,553.7	0.4224	8.0510	8.4734	0.0040
0.0050	32.87	0.0010	28.1840	28.1850	137.8	2,423.0	2,560.7	0.4762	7.9176	8.3938	0.0050
0.0060	36.16	0.0010	23.7320	23.7330	151.5	2,415.2	2,566.6	0.5208	7.8082	8.3290	0.0060
0.0070	39.00	0.0010	20.5230	20.5240	163.4	2,408.4	2,571.7	0.5590	7.7154	8.2745	0.0070
0.0080	41.51	0.0010	18.0980	18.0990	173.8	2,402.4	2,576.2	0.5925	7.6348	8.2273	0.0080
0.0090	43.76	0.0010	16.1980	16.1990	183.3	2,397.0	2,580.2	0.6223	7.5635	8.1858	0.0090
0.010	45.81	0.0010	14.6690	14.6700	191.8	2,392.1	2,583.9	0.6492	7.4996	8.1488	0.010
0.016	55.31	0.0010	9.4296	9.4306	231.6	2,369.1	2,600.6	0.7720	7.2126	7.9846	0.016
0.020	60.06	0.0010	7.6470	7.6480	251.4	2,357.5	2,608.9	0.8320	7.0752	7.9072	0.020
0.032	70.59	0.0010	4.9205	4.9215	295.5	2,331.6	2,627.1	0.9623	6.7830	7.7453	0.032
0.040	75.86	0.0010	3.9920	3.9930	317.6	2,318.4	2,636.1	1.0261	6.6429	7.6690	0.040
0.050	81.32	0.0010	3.2390	3.2400	340.5	2,304.7	2,645.2	1.0912	6.5018	7.5930	0.050
0.060	85.93	0.0010	2.7307	2.7317	359.9	2,292.9	2,652.9	1.1454	6.3857	7.5311	0.060
0.065	87.99	0.0010	2.5336	2.5346	368.6	2,287.7	2,656.3	1.1696	6.3345	7.5040	0.065
0.070	89.93	0.0010	2.3638	2.3648	376.8	2,282.7	2,659.4	1.1921	6.2869	7.4790	0.070
0.075	91.76	0.0010	2.2160	2.2170	384.4	2,277.9	2,662.4	1.2132	6.2425	7.4557	0.075
0.080	93.49	0.0010	2.0861	2.0871	391.7	2,273.5	2,665.2	1.2330	6.2009	7.4339	0.080
0.085	95.13	0.0010	1.9710	1.9720	398.6	2,269.2	2,667.8	1.2518	6.1617	7.4135	0.085
0.090	96.69	0.0010	1.8684	1.8694	405.2	2,265.1	2,670.3	1.2696	6.1246	7.3943	0.090
0.095	98.18	0.0010	1.7762	1.7772	411.5	2,261.2	2,672.7	1.2866	6.0895	7.3761	0.095

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Properties of Saturated Water and Steam (Pressure)—SI Units (cont'd)
Pressures Are Absolute

		Specific Volume, $\frac{m^3}{kg}$			Enthalpy, $\frac{kJ}{kg}$			Entropy, $\frac{kJ}{kg \cdot K}$			
Psia, MPa	***T*, °C**	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	**Psia, MPa**
0.10	99.61	0.0010	1.6929	1.6939	417.5	2,257.4	2,674.9	1.3028	6.0561	7.3588	0.100
0.11	102.29	0.0010	1.5485	1.5495	428.8	2,250.3	2,679.2	1.3330	5.9938	7.3269	0.110
0.12	104.78	0.0010	1.4274	1.4284	439.4	2,243.7	2,683.1	1.3609	5.9367	7.2977	0.120
0.13	107.11	0.0010	1.3243	1.3253	449.2	2,237.5	2,686.6	1.3868	5.8840	7.2709	0.130
0.14	109.29	0.0011	1.2355	1.2366	458.4	2,231.6	2,690.0	1.4110	5.8351	7.2461	0.140
0.15	111.35	0.0011	1.1582	1.1593	467.1	2,226.0	2,693.1	1.4337	5.7893	7.2230	0.15
0.20	120.21	0.0011	0.8846	0.8857	504.7	2,201.5	2,706.2	1.5302	5.5967	7.1269	0.20
0.30	133.52	0.0011	0.6047	0.6058	561.4	2,163.5	2,724.9	1.6717	5.3199	6.9916	0.30
0.40	143.61	0.0011	0.4613	0.4624	604.7	2,133.4	2,738.1	1.7765	5.1190	6.8955	0.40
0.50	151.83	0.0011	0.3737	0.3748	640.1	2,108.0	2,748.1	1.8604	4.9603	6.8207	0.50
0.60	158.83	0.0011	0.3145	0.3156	670.4	2,085.8	2,756.1	1.9308	4.8284	6.7592	0.60
0.70	164.95	0.0011	0.2717	0.2728	697.0	2,065.8	2,762.8	1.9918	4.7153	6.7071	0.70
0.80	170.41	0.0011	0.2392	0.2403	720.9	2,047.4	2,768.3	2.0457	4.6160	6.6616	0.80
0.90	175.35	0.0011	0.2138	0.2149	742.6	2,030.5	2,773.0	2.0940	4.5272	6.6213	0.90
1.0	179.88	0.0011	0.1932	0.1944	762.5	2,014.6	2,777.1	2.1381	4.4470	6.5850	1.00
1.5	198.29	0.0012	0.1306	0.1317	844.6	1,946.4	2,791.0	2.3143	4.1286	6.4430	1.50
2.0	212.38	0.0012	0.0984	0.0996	908.5	1,889.8	2,798.3	2.4468	3.8923	6.3390	2.0
3.0	233.85	0.0012	0.0654	0.0667	1,008.3	1,794.8	2,803.2	2.6455	3.5400	6.1856	3.0
4.0	250.35	0.0013	0.0485	0.0498	1,087.5	1,713.3	2,800.8	2.7968	3.2728	6.0696	4.0
5.0	263.94	0.0013	0.0382	0.0394	1,154.6	1,639.6	2,794.2	2.9210	3.0527	5.9737	5.0
6.0	275.59	0.0013	0.0311	0.0324	1,213.9	1,570.7	2,784.6	3.0278	2.8623	5.8901	6.0
7.0	285.83	0.0014	0.0260	0.0274	1,267.7	1,505.0	2,772.6	3.1224	2.6924	5.8148	7.0
8.0	295.01	0.0014	0.0221	0.0235	1,317.3	1,441.4	2,758.7	3.2081	2.5369	5.7450	8.0
10.0	311.00	0.0015	0.0166	0.0180	1,408.1	1,317.4	2,725.5	3.3606	2.2553	5.6160	10.0

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6.3.6 Properties of Superheated Steam—SI Units

Properties of Superheated Steam—SI Units
Pressures Are Absolute

Pressure = 0.01 MPa T_s = 45.8 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	989.830	191.8	0.65	t_s(L)
14.670	0.068	2583.9	8.15	t_s(v)
14.867	0.067	2592.0	8.17	50
15.335	0.065	2611.2	8.23	60
15.802	0.063	2630.3	8.29	70
16.267	0.061	2649.3	8.34	80
16.732	0.060	2668.4	8.40	90
17.196	0.058	2687.5	8.45	100
17.660	0.057	2706.5	8.50	110
18.124	0.055	2725.6	8.55	120
18.587	0.054	2744.7	8.60	130
19.050	0.052	2763.9	8.64	140
19.513	0.051	2783.0	8.69	150
19.976	0.050	2802.3	8.73	160
20.439	0.049	2821.5	8.78	170
20.901	0.048	2840.8	8.82	180
21.363	0.047	2860.2	8.86	190
21.825	0.046	2879.6	8.90	200
22.288	0.045	2899.1	8.95	210
22.750	0.044	2918.6	8.99	220
23.212	0.043	2938.1	9.02	230
23.674	0.042	2957.8	9.06	240
24.136	0.041	2977.4	9.10	250
24.598	0.041	2997.2	9.14	260
25.060	0.040	3017.0	9.18	270
25.522	0.039	3036.8	9.21	280
25.983	0.038	3056.8	9.25	290
26.445	0.038	3076.7	9.28	300
26.908	0.037	3096.8	9.32	310
27.370	0.037	3116.9	9.35	320
27.831	0.036	3137.0	9.39	330
28.293	0.035	3157.3	9.42	340
28.755	0.035	3177.5	9.45	350
29.216	0.034	3197.9	9.48	360
29.678	0.034	3218.3	9.52	370
30.140	0.033	3238.8	9.55	380
30.602	0.033	3259.3	9.58	390

Pressure = 0.01 MPa T_s = 45.81 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
31.063	0.032	3279.9	9.61	400
31.525	0.032	3300.6	9.64	410
31.987	0.031	3321.4	9.67	420
32.449	0.031	3342.2	9.70	430
32.910	0.030	3363.0	9.73	440
33.371	0.030	3384.0	9.76	450
33.833	0.030	3405.0	9.79	460
34.295	0.029	3426.1	9.82	470
34.756	0.029	3447.2	9.84	480
35.217	0.028	3468.4	9.87	490
35.680	0.028	3489.7	9.90	500
36.603	0.027	3532.5	9.95	520
37.526	0.027	3575.5	10.01	540
38.450	0.026	3618.8	10.06	560
39.373	0.025	3662.4	10.11	580
40.295	0.025	3706.3	10.16	600
41.218	0.024	3750.4	10.21	620
42.143	0.024	3794.9	10.26	640
43.064	0.023	3839.6	10.31	660
43.989	0.023	3884.6	10.36	680
44.912	0.022	3929.9	10.41	700
45.834	0.022	3975.5	10.45	720
46.757	0.021	4021.3	10.50	740
47.680	0.021	4067.5	10.54	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.04 MPa T_s = 75.86 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	974.300	317.6	1.03	t_s(L)
3.993	0.250	2636.1	7.67	t_s(v)
4.043	0.247	2644.3	7.69	80
4.161	0.240	2664.1	7.75	90
4.280	0.234	2683.7	7.80	100
4.398	0.227	2703.2	7.85	110
4.515	0.221	2722.7	7.90	120
4.632	0.216	2742.1	7.95	130
4.749	0.211	2761.5	8.00	140
4.866	0.206	2780.9	8.05	150
4.983	0.201	2800.3	8.09	160
5.099	0.196	2819.8	8.14	170
5.216	0.192	2839.2	8.18	180
5.332	0.188	2858.7	8.22	190
5.448	0.184	2878.2	8.26	200
5.564	0.180	2897.8	8.30	210
5.680	0.176	2917.4	8.34	220
5.796	0.173	2937.0	8.38	230
5.912	0.169	2956.7	8.42	240
6.028	0.166	2976.5	8.46	250
6.144	0.163	2996.3	8.50	260
6.259	0.160	3016.1	8.53	270
6.375	0.157	3036.0	8.57	280
6.491	0.154	3056.0	8.61	290
6.607	0.151	3076.0	8.64	300
6.722	0.149	3096.1	8.68	310
6.838	0.146	3116.2	8.71	320
6.954	0.144	3136.4	8.74	330
7.069	0.141	3156.7	8.78	340
7.185	0.139	3177.0	8.81	350
7.300	0.137	3197.4	8.84	360
7.416	0.135	3217.8	8.88	370
7.532	0.133	3238.3	8.91	380
7.647	0.131	3258.9	8.94	390

Pressure = 0.04 MPa T_s = 75.86 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
7.763	0.129	3279.5	8.97	400
7.878	0.127	3300.2	9.00	410
7.994	0.125	3320.9	9.03	420
8.110	0.123	3341.8	9.06	430
8.225	0.122	3362.6	9.09	440
8.340	0.120	3383.6	9.12	450
8.456	0.118	3404.6	9.15	460
8.571	0.117	3425.7	9.18	470
8.687	0.115	3446.9	9.20	480
8.802	0.114	3468.1	9.23	490
8.918	0.112	3489.4	9.26	500
9.149	0.109	3532.2	9.31	520
9.380	0.107	3575.2	9.37	540
9.611	0.104	3618.5	9.42	560
9.842	0.102	3662.2	9.47	580
10.073	0.099	3706.0	9.52	600
10.303	0.097	3750.2	9.57	620
10.534	0.095	3794.7	9.62	640
10.765	0.093	3839.4	9.67	660
10.996	0.091	3884.4	9.72	680
11.227	0.089	3929.7	9.77	700
11.458	0.087	3975.3	9.81	720
11.689	0.086	4021.2	9.86	740
11.919	0.084	4067.3	9.90	760

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Properties of Superheated Steam—SI Units
Pressures Are Absolute

Pressure = 0.06 MPa T_s = 85.93 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	967.990	359.9	1.15	t_s(L)
2.732	0.366	2652.9	7.53	t_s(v)
2.764	0.362	2661.1	7.55	90
2.844	0.352	2681.1	7.61	100
2.924	0.342	2701.0	7.66	110
3.003	0.333	2720.7	7.71	120
3.082	0.324	2740.3	7.76	130
3.160	0.316	2759.9	7.81	140
3.239	0.309	2779.5	7.86	150
3.317	0.301	2799.0	7.90	160
3.395	0.295	2818.6	7.95	170
3.473	0.288	2838.1	7.99	180
3.551	0.282	2857.7	8.03	190
3.628	0.276	2877.3	8.07	200
3.706	0.270	2896.9	8.12	210
3.783	0.264	2916.6	8.16	220
3.861	0.259	2936.3	8.20	230
3.938	0.254	2956.0	8.23	240
4.016	0.249	2975.8	8.27	250
4.093	0.244	2995.7	8.31	260
4.170	0.240	3015.5	8.35	270
4.248	0.235	3035.5	8.38	280
4.325	0.231	3055.5	8.42	290
4.402	0.227	3075.5	8.45	300
4.479	0.223	3095.6	8.49	310
4.557	0.219	3115.8	8.52	320
4.634	0.216	3136.0	8.56	330
4.711	0.212	3156.3	8.59	340
4.788	0.209	3176.6	8.62	350
4.865	0.206	3197.0	8.66	360
4.942	0.202	3217.4	8.69	370
5.020	0.199	3238.0	8.72	380
5.097	0.196	3258.5	8.75	390

Pressure = 0.06 MPa T_s = 85.93 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
5.174	0.193	3279.2	8.78	400
5.251	0.190	3299.9	8.81	410
5.328	0.188	3320.7	8.84	420
5.405	0.185	3341.5	8.87	430
5.482	0.182	3362.4	8.90	440
5.559	0.180	3383.3	8.93	450
5.636	0.177	3404.4	8.96	460
5.713	0.175	3425.5	8.99	470
5.790	0.173	3446.6	9.02	480
5.867	0.170	3467.9	9.04	490
5.944	0.168	3489.2	9.07	500
6.098	0.164	3532.0	9.13	520
6.252	0.160	3575.0	9.18	540
6.407	0.156	3618.4	9.23	560
6.560	0.152	3662.0	9.29	580
6.715	0.149	3705.9	9.34	600
6.868	0.146	3750.1	9.39	620
7.022	0.142	3794.5	9.44	640
7.176	0.139	3839.3	9.48	660
7.330	0.136	3884.3	9.53	680
7.484	0.134	3929.6	9.58	700
7.638	0.131	3975.2	9.62	720
7.792	0.128	4021.1	9.67	740
7.946	0.126	4067.2	9.72	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.08 MPa T_s = 93.49 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	962.930	391.7	1.23	t_s(L)
2.087	0.479	2665.2	7.43	t_s(v)
2.118	0.472	2678.5	7.47	100
2.187	0.457	2698.7	7.52	110
2.247	0.445	2718.7	7.57	120
2.306	0.434	2738.6	7.62	130
2.366	0.423	2758.3	7.67	140
2.425	0.412	2778.1	7.72	150
2.484	0.403	2797.7	7.77	160
2.543	0.393	2817.4	7.81	170
2.601	0.384	2837.1	7.86	180
2.660	0.376	2856.7	7.90	190
2.718	0.368	2876.4	7.94	200
2.777	0.360	2896.1	7.98	210
2.835	0.353	2915.8	8.02	220
2.893	0.346	2935.5	8.06	230
2.952	0.339	2955.3	8.10	240
3.010	0.332	2975.2	8.14	250
3.068	0.326	2995.0	8.18	260
3.126	0.320	3015.0	8.21	270
3.184	0.314	3034.9	8.25	280
3.242	0.308	3055.0	8.29	290
3.300	0.303	3075.0	8.32	300
3.358	0.298	3095.1	8.36	310
3.416	0.293	3115.3	8.39	320
3.474	0.288	3135.6	8.42	330
3.532	0.283	3155.9	8.46	340
3.590	0.279	3176.2	8.49	350
3.648	0.274	3196.6	8.52	360
3.706	0.270	3217.1	8.55	370
3.764	0.266	3237.6	8.59	380
3.821	0.262	3258.2	8.62	390
3.879	0.258	3278.9	8.65	400
3.937	0.254	3299.6	8.68	410
3.951	0.253	3320.4	8.71	420
4.053	0.247	3341.2	8.74	430

Pressure = 0.08 MPa T_s = 93.49 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
4.111	0.243	3362.1	8.77	440
4.169	0.240	3383.1	8.80	450
4.226	0.237	3404.1	8.83	460
4.284	0.233	3425.2	8.86	470
4.342	0.230	3446.4	8.88	480
4.400	0.227	3467.6	8.91	490
4.458	0.224	3488.9	8.94	500
4.573	0.219	3531.8	8.99	520
4.689	0.213	3574.8	9.05	540
4.804	0.208	3618.2	9.10	560
4.920	0.203	3661.8	9.15	580
5.035	0.199	3705.7	9.20	600
5.151	0.194	3749.9	9.25	620
5.266	0.190	3794.4	9.30	640
5.382	0.186	3839.1	9.35	660
5.497	0.182	3884.2	9.40	680
5.613	0.178	3929.5	9.45	700
5.728	0.175	3975.1	9.49	720
5.844	0.171	4021.0	9.54	740
5.959	0.168	4067.1	9.58	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.10 MPa T_s = 99.61 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	958.630	417.5	1.30	t_s(L)
1.694	0.590	2674.9	7.36	t_s(v)
1.696	0.590	2675.8	7.36	100
1.745	0.573	2696.3	7.42	110
1.793	0.558	2716.6	7.47	120
1.841	0.543	2736.7	7.52	130
1.889	0.529	2756.7	7.57	140
1.937	0.516	2776.6	7.61	150
1.984	0.504	2796.4	7.66	160
2.031	0.492	2816.2	7.71	170
2.078	0.481	2836.0	7.75	180
2.125	0.470	2855.7	7.79	190
2.172	0.460	2875.5	7.84	200
2.219	0.451	2895.2	7.88	210
2.266	0.441	2915.0	7.92	220
2.313	0.432	2934.8	7.96	230
2.359	0.424	2954.6	8.00	240
2.406	0.416	2974.5	8.03	250
2.453	0.408	2994.4	8.07	260
2.499	0.400	3014.4	8.11	270
2.546	0.393	3034.4	8.15	280
2.580	0.388	3054.4	8.18	290
2.639	0.379	3074.5	8.22	300
2.685	0.372	3094.7	8.25	310
2.732	0.366	3114.9	8.29	320
2.778	0.360	3135.1	8.32	330
2.825	0.354	3155.5	8.35	340
2.871	0.348	3175.8	8.39	350
2.917	0.343	3196.3	8.42	360
2.964	0.337	3216.7	8.45	370
3.010	0.332	3237.3	8.48	380
3.056	0.327	3257.9	8.51	390
3.103	0.322	3278.6	8.55	400
3.149	0.318	3299.3	8.58	410
3.195	0.313	3320.1	8.61	420
3.242	0.308	3340.9	8.64	430

Pressure = 0.10 MPa T_s = 99.61 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
3.288	0.304	3361.9	8.67	440
3.334	0.300	3382.8	8.69	450
3.380	0.296	3403.9	8.72	460
3.427	0.292	3425.0	8.75	470
3.473	0.288	3446.2	8.78	480
3.519	0.284	3467.4	8.81	490
3.566	0.280	3488.7	8.84	500
3.658	0.273	3531.6	8.89	520
3.751	0.267	3574.7	8.94	540
3.843	0.260	3618.0	9.00	560
3.935	0.254	3661.7	9.05	580
4.028	0.248	3705.6	9.10	600
4.120	0.243	3749.8	9.15	620
4.213	0.237	3794.3	9.20	640
4.305	0.232	3839.0	9.25	660
4.398	0.227	3884.0	9.30	680
4.490	0.223	3929.4	9.34	700
4.582	0.218	3975.0	9.39	720
4.675	0.214	4020.9	9.43	740
4.767	0.210	4067.0	9.48	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.12 MPa T_s = 104.78 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	954.860	439.4	1.36	t_s(L)
1.428	0.700	2683.1	7.30	t_s(v)
1.450	0.690	2693.9	7.33	110
1.491	0.671	2714.6	7.38	120
1.531	0.653	2734.9	7.43	130
1.571	0.636	2755.1	7.48	140
1.611	0.621	2775.1	7.53	150
1.651	0.606	2795.1	7.57	160
1.690	0.592	2815.0	7.62	170
1.730	0.578	2834.9	7.66	180
1.769	0.565	2854.7	7.71	190
1.808	0.553	2874.5	7.75	200
1.848	0.541	2894.3	7.79	210
1.887	0.530	2914.2	7.83	220
1.926	0.519	2934.1	7.87	230
1.965	0.509	2953.9	7.91	240
2.004	0.499	2973.9	7.95	250
2.043	0.490	2993.8	7.99	260
2.082	0.480	3013.8	8.02	270
2.120	0.472	3033.8	8.06	280
2.159	0.463	3053.9	8.10	290
2.198	0.455	3074.0	8.13	300
2.237	0.447	3094.2	8.17	310
2.275	0.439	3114.4	8.20	320
2.314	0.432	3134.7	8.24	330
2.353	0.425	3155.1	8.27	340
2.392	0.418	3175.4	8.30	350
2.430	0.411	3195.9	8.33	360
2.469	0.405	3216.4	8.37	370
2.508	0.399	3237.0	8.40	380
2.546	0.393	3257.6	8.43	390
2.585	0.387	3278.3	8.46	400
2.624	0.381	3299.0	8.49	410
2.662	0.376	3319.8	8.52	420
2.701	0.370	3340.7	8.55	430

Pressure = 0.12 MPa T_s = 104.78 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
2.739	0.365	3361.6	8.58	440
2.778	0.360	3382.6	8.61	450
2.817	0.355	3403.6	8.64	460
2.855	0.350	3424.8	8.67	470
2.894	0.346	3446.0	8.70	480
2.932	0.341	3467.2	8.72	490
2.971	0.337	3488.5	8.75	500
3.048	0.328	3531.4	8.81	520
3.125	0.320	3574.5	8.86	540
3.202	0.312	3617.8	8.91	560
3.279	0.305	3661.5	8.96	580
3.356	0.298	3705.4	9.02	600
3.433	0.291	3749.6	9.07	620
3.510	0.285	3794.1	9.11	640
3.587	0.279	3838.9	9.16	660
3.664	0.273	3883.9	9.21	680
3.741	0.267	3929.3	9.26	700
3.818	0.262	3974.9	9.30	720
3.895	0.257	4020.8	9.35	740
3.973	0.252	4066.9	9.40	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.14 MPa T_s = 109.29 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	951.490	458.4	1.41	t_s(L)
1.237	0.809	2690.0	7.25	t_s(v)
1.239	0.807	2691.5	7.25	110
1.274	0.785	2712.4	7.30	120
1.309	0.764	2733.0	7.36	130
1.344	0.744	2753.4	7.41	140
1.379	0.725	2773.6	7.45	150
1.413	0.708	2793.8	7.50	160
1.447	0.691	2813.8	7.55	170
1.481	0.675	2833.7	7.59	180
1.515	0.660	2853.7	7.63	190
1.548	0.646	2873.6	7.68	200
1.582	0.632	2893.5	7.72	210
1.616	0.619	2913.4	7.76	220
1.649	0.606	2933.3	7.80	230
1.683	0.594	2953.2	7.84	240
1.716	0.583	2973.2	7.88	250
1.750	0.572	2993.2	7.92	260
1.783	0.561	3013.2	7.95	270
1.816	0.551	3033.3	7.99	280
1.850	0.541	3053.4	8.03	290
1.883	0.531	3073.5	8.06	300
1.916	0.522	3093.7	8.10	310
1.950	0.513	3114.0	8.13	320
1.983	0.504	3134.3	8.16	330
2.016	0.496	3154.7	8.20	340
2.049	0.488	3175.1	8.23	350
2.082	0.480	3195.5	8.26	360
2.116	0.473	3216.0	8.30	370
2.149	0.465	3236.6	8.33	380
2.182	0.458	3257.3	8.36	390
2.215	0.451	3277.9	8.39	400
2.248	0.445	3298.7	8.42	410
2.281	0.438	3319.5	8.45	420
2.314	0.432	3340.4	8.48	430
2.348	0.426	3361.3	8.51	440
2.381	0.420	3382.3	8.54	450

Pressure = 0.14 MPa T_s = 109.29 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
2.414	0.414	3403.4	8.57	460
2.447	0.409	3424.5	8.60	470
2.480	0.403	3445.7	8.62	480
2.513	0.398	3467.0	8.65	490
2.546	0.393	3488.3	8.68	500
2.612	0.383	3531.2	8.74	520
2.678	0.373	3574.3	8.79	540
2.744	0.364	3617.7	8.84	560
2.810	0.356	3661.3	8.89	580
2.877	0.348	3705.3	8.94	600
2.943	0.340	3749.5	8.99	620
3.009	0.332	3794.0	9.04	640
3.075	0.325	3838.7	9.09	660
3.141	0.318	3883.8	9.14	680
3.207	0.312	3929.1	9.19	700
3.273	0.306	3974.8	9.23	720
3.339	0.300	4020.6	9.28	740
3.405	0.294	4066.8	9.32	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.20 MPa T_s = 120.21 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	942.940	504.7	1.53	t_s(L)
0.886	1.129	2706.2	7.13	t_s(v)
0.910	1.099	2727.3	7.18	130
0.935	1.069	2748.3	7.23	140
0.960	1.042	2769.1	7.28	150
0.984	1.016	2789.7	7.33	160
1.009	0.992	2810.1	7.38	170
1.033	0.968	2830.4	7.42	180
1.057	0.946	2850.6	7.47	190
1.080	0.926	2870.7	7.51	200
1.104	0.906	2890.8	7.55	210
1.128	0.887	2910.9	7.59	220
1.152	0.868	2931.0	7.63	230
1.175	0.851	2951.1	7.67	240
1.199	0.834	2971.2	7.71	250
1.222	0.818	2991.3	7.75	260
1.246	0.803	3011.5	7.79	270
1.269	0.788	3031.6	7.82	280
1.293	0.774	3051.8	7.86	290
1.316	0.760	3072.1	7.89	300
1.340	0.746	3092.3	7.93	310
1.363	0.734	3112.7	7.96	320
1.386	0.721	3133.0	8.00	330
1.410	0.709	3153.4	8.03	340
1.433	0.698	3173.9	8.06	350
1.456	0.687	3194.4	8.10	360
1.480	0.676	3215.0	8.13	370
1.503	0.665	3235.6	8.16	380
1.526	0.655	3256.3	8.19	390
1.549	0.645	3277.0	8.22	400
1.573	0.636	3297.8	8.25	410
1.596	0.627	3318.7	8.28	420
1.619	0.618	3339.6	8.31	430
1.642	0.609	3360.5	8.34	440
1.665	0.600	3381.6	8.37	450

Pressure = 0.20 MPa T_s = 120.21 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
1.689	0.592	3402.7	8.40	460
1.712	0.584	3423.8	8.43	470
1.735	0.576	3445.0	8.46	480
1.758	0.569	3466.3	8.49	490
1.782	0.561	3487.7	8.52	500
1.828	0.547	3530.6	8.57	520
1.874	0.534	3573.7	8.62	540
1.920	0.521	3617.1	8.68	560
1.967	0.508	3660.8	8.73	580
2.013	0.497	3704.8	8.78	600
2.059	0.486	3749.0	8.83	620
2.106	0.475	3793.6	8.88	640
2.152	0.465	3838.4	8.93	660
2.198	0.455	3883.4	8.98	680
2.244	0.446	3928.8	9.02	700
2.291	0.437	3974.4	9.07	720
2.337	0.428	4020.3	9.11	740
2.383	0.420	4066.5	9.16	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.30 MPa T_s = 133.52 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	927.150	584.3	1.73	t_s(L)
0.524	1.908	2732.0	6.94	t_s(v)
0.617	1.621	2739.4	7.03	140
0.634	1.577	2761.2	7.08	150
0.651	1.537	2782.6	7.13	160
0.667	1.498	2803.7	7.18	170
0.684	1.462	2824.6	7.22	180
0.700	1.428	2845.3	7.27	190
0.716	1.396	2865.9	7.31	200
0.733	1.365	2886.4	7.36	210
0.749	1.336	2906.8	7.40	220
0.765	1.308	2927.2	7.44	230
0.781	1.281	2947.5	7.48	240
0.796	1.256	2967.9	7.52	250
0.812	1.231	2988.2	7.56	260
0.828	1.208	3008.5	7.59	270
0.844	1.185	3028.8	7.63	280
0.860	1.163	3049.2	7.67	290
0.875	1.142	3069.6	7.70	300
0.891	1.122	3090.0	7.74	310
0.907	1.103	3110.4	7.77	320
0.922	1.084	3130.9	7.81	330
0.938	1.066	3151.4	7.84	340
0.954	1.049	3172.0	7.88	350
0.969	1.032	3192.6	7.91	360
0.985	1.015	3213.2	7.94	370
1.000	1.000	3233.9	7.97	380
1.016	0.984	3254.7	8.00	390
1.032	0.969	3275.5	8.03	400
1.047	0.955	3296.3	8.07	410
1.063	0.941	3317.2	8.10	420
1.078	0.928	3338.2	8.13	430
1.094	0.914	3359.2	8.16	440
1.109	0.902	3380.3	8.18	450

Pressure = 0.30 MPa T_s = 133.52 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
1.125	0.889	3401.4	8.21	460
1.140	0.877	3422.6	8.24	470
1.156	0.865	3443.9	8.27	480
1.171	0.854	3465.2	8.30	490
1.187	0.843	3486.6	8.33	500
1.218	0.821	3529.6	8.38	520
1.249	0.801	3572.8	8.44	540
1.280	0.782	3616.3	8.49	560
1.310	0.763	3660.0	8.54	580
1.341	0.746	3704.0	8.59	600
1.372	0.729	3748.3	8.64	620
1.403	0.713	3792.9	8.69	640
1.434	0.697	3837.7	8.74	660
1.465	0.683	3882.8	8.79	680
1.496	0.669	3928.2	8.83	700
1.527	0.655	3973.9	8.88	720
1.558	0.642	4019.8	8.93	740
1.588	0.630	4066.0	8.97	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.40 MPa T_s = 143.61 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
6.000	922.890	604.7	1.78	t_s(L)
0.462	2.163	2738.1	6.90	t_s(v)
0.471	2.124	2752.8	6.93	150
0.484	2.066	2775.2	6.98	160
0.497	2.013	2797.1	7.03	170
0.509	1.963	2818.6	7.08	180
0.522	1.916	2839.9	7.13	190
0.534	1.872	2860.9	7.17	200
0.547	1.829	2881.8	7.22	210
0.559	1.789	2902.6	7.26	220
0.571	1.751	2923.3	7.30	230
0.583	1.715	2943.9	7.34	240
0.595	1.680	2964.5	7.38	250
0.607	1.647	2985.0	7.42	260
0.619	1.615	3005.5	7.46	270
0.631	1.585	3026.0	7.49	280
0.643	1.555	3046.6	7.53	290
0.655	1.527	3067.1	7.57	300
0.667	1.500	3087.6	7.60	310
0.679	1.474	3108.2	7.64	320
0.690	1.449	3128.8	7.67	330
0.702	1.424	3149.4	7.71	340
0.714	1.401	3170.0	7.74	350
0.726	1.378	3190.7	7.77	360
0.737	1.356	3211.5	7.81	370
0.749	1.335	3232.2	7.84	380
0.761	1.314	3253.0	7.87	390
0.773	1.294	3273.9	7.90	400
0.784	1.275	3294.8	7.93	410
0.796	1.256	3315.8	7.96	420
0.808	1.238	3336.8	7.99	430
0.819	1.220	3357.9	8.02	440
0.831	1.203	3379.0	8.05	450
0.843	1.187	3400.2	8.08	460
0.854	1.170	3421.4	8.11	470
0.866	1.155	3442.8	8.14	480
0.878	1.139	3464.1	8.17	490

Pressure = 0.40 MPa T_s = 143.61 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.889	1.124	3485.5	8.19	500
0.913	1.096	3528.6	8.25	520
0.936	1.069	3571.9	8.30	540
0.959	1.043	3615.4	8.36	560
0.982	1.018	3659.2	8.41	580
1.006	0.994	3703.2	8.46	600
1.029	0.972	3747.6	8.51	620
1.052	0.951	3792.2	8.56	640
1.075	0.930	3837.0	8.61	660
1.098	0.910	3882.2	8.65	680
1.122	0.892	3927.6	8.70	700
1.145	0.874	3973.3	8.75	720
1.168	0.856	4019.3	8.79	740
1.191	0.840	4065.5	8.84	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.50 MPa T_s = 151.83 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	915.290	640.1	1.86	t_s(L)
0.375	2.668	2748.1	6.82	t_s(v)
0.384	2.606	2767.4	6.87	160
0.394	2.536	2790.2	6.92	170
0.405	2.471	2812.4	6.97	180
0.415	2.410	2834.3	7.02	190
0.425	2.353	2855.8	7.06	200
0.435	2.299	2877.2	7.11	210
0.445	2.247	2898.3	7.15	220
0.455	2.198	2919.3	7.19	230
0.465	2.152	2940.2	7.23	240
0.474	2.108	2961.0	7.27	250
0.484	2.066	2981.8	7.31	260
0.494	2.025	3002.5	7.35	270
0.503	1.986	3023.2	7.39	280
0.513	1.949	3043.9	7.43	290
0.523	1.914	3064.6	7.46	300
0.532	1.879	3085.2	7.50	310
0.542	1.846	3105.9	7.53	320
0.551	1.814	3126.6	7.57	330
0.561	1.784	3147.3	7.60	340
0.570	1.754	3168.1	7.63	350
0.580	1.725	3188.9	7.67	360
0.589	1.698	3209.7	7.70	370
0.598	1.671	3230.5	7.73	380
0.608	1.645	3251.4	7.76	390
0.617	1.620	3272.3	7.80	400
0.627	1.596	3293.3	7.83	410
0.636	1.572	3314.4	7.86	420
0.645	1.549	3335.4	7.89	430
0.655	1.527	3356.6	7.92	440
0.664	1.506	3377.7	7.95	450
0.674	1.485	3399.0	7.98	460
0.683	1.464	3420.3	8.00	470
0.692	1.445	3441.6	8.03	480
0.702	1.425	3463.0	8.06	490

Pressure = 0.50 MPa T_s = 151.83 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.711	1.407	3484.5	8.09	500
0.730	1.371	3527.6	8.14	520
0.748	1.337	3570.9	8.20	540
0.767	1.304	3614.5	8.25	560
0.785	1.273	3658.4	8.30	580
0.804	1.244	3702.5	8.35	600
0.823	1.216	3746.8	8.40	620
0.841	1.189	3791.5	8.45	640
0.860	1.163	3836.4	8.50	660
0.878	1.138	3881.6	8.55	680
0.897	1.115	3927.0	8.60	700
0.915	1.092	3972.7	8.64	720
0.934	1.071	4018.7	8.69	740
0.953	1.050	4065.0	8.74	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.60 MPa T_s = 158.83 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	908.590	670.4	1.93	t_s(L)
0.316	3.169	2756.1	6.76	t_s(v)
0.317	3.158	2759.0	6.77	160
0.326	3.069	2783.0	6.82	170
0.335	2.987	2806.0	6.87	180
0.344	2.911	2828.5	6.92	190
0.352	2.840	2850.6	6.97	200
0.361	2.773	2872.4	7.01	210
0.369	2.710	2893.9	7.06	220
0.377	2.650	2915.3	7.10	230
0.386	2.593	2936.5	7.14	240
0.394	2.539	2957.6	7.18	250
0.402	2.487	2978.5	7.22	260
0.410	2.438	2999.5	7.26	270
0.418	2.391	3020.3	7.30	280
0.426	2.345	3041.2	7.34	290
0.434	2.302	3062.0	7.37	300
0.442	2.260	3082.8	7.41	310
0.450	2.220	3103.6	7.45	320
0.458	2.182	3124.4	7.48	330
0.466	2.144	3145.3	7.51	340
0.474	2.109	3166.1	7.55	350
0.482	2.074	3187.0	7.58	360
0.490	2.040	3207.9	7.61	370
0.498	2.008	3228.8	7.65	380
0.506	1.977	3249.8	7.68	390
0.514	1.947	3270.8	7.71	400
0.522	1.917	3291.8	7.74	410
0.529	1.889	3312.9	7.77	420
0.537	1.861	3334.0	7.80	430
0.545	1.834	3355.2	7.83	440
0.553	1.809	3376.5	7.86	450
0.561	1.783	3397.7	7.89	460
0.569	1.759	3419.1	7.92	470
0.576	1.735	3440.5	7.95	480
0.584	1.712	3461.9	7.98	490

Pressure = 0.60 MPa T_s = 158.83 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.592	1.689	3483.4	8.00	500
0.608	1.646	3526.6	8.06	520
0.623	1.605	3570.0	8.11	540
0.639	1.566	3613.6	8.17	560
0.654	1.529	3657.5	8.22	580
0.670	1.493	3701.7	8.27	600
0.685	1.459	3746.1	8.32	620
0.701	1.427	3790.8	8.37	640
0.716	1.396	3835.7	8.42	660
0.732	1.367	3880.9	8.47	680
0.747	1.338	3926.4	8.51	700
0.763	1.311	3972.2	8.56	720
0.778	1.285	4018.2	8.61	740
0.794	1.260	4064.5	8.65	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.70 MPa T_s = 164.95 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	902.560	697.0	1.99	t_s(L)
0.273	3.666	2762.8	6.71	t_s(v)
0.277	3.612	2775.4	6.74	170
0.285	3.512	2799.4	6.79	180
0.292	3.419	2822.6	6.84	190
0.300	3.333	2845.3	6.89	200
0.307	3.253	2867.5	6.93	210
0.315	3.177	2889.5	6.98	220
0.322	3.105	2911.2	7.02	230
0.329	3.037	2932.7	7.07	240
0.336	2.973	2954.0	7.11	250
0.343	2.912	2975.2	7.15	260
0.350	2.853	2996.4	7.19	270
0.358	2.797	3017.5	7.22	280
0.364	2.744	3038.5	7.26	290
0.371	2.692	3059.4	7.30	300
0.378	2.643	3080.4	7.34	310
0.385	2.596	3101.3	7.37	320
0.392	2.550	3122.3	7.41	330
0.399	2.507	3143.2	7.44	340
0.406	2.464	3164.2	7.47	350
0.413	2.424	3185.1	7.51	360
0.419	2.384	3206.1	7.54	370
0.426	2.346	3227.1	7.57	380
0.433	2.310	3248.1	7.61	390
0.440	2.274	3269.2	7.64	400
0.447	2.240	3290.3	7.67	410
0.453	2.206	3311.5	7.70	420
0.460	2.174	3332.7	7.73	430
0.467	2.142	3353.9	7.76	440
0.473	2.112	3375.2	7.79	450
0.480	2.082	3396.5	7.82	460
0.487	2.054	3417.9	7.85	470
0.494	2.026	3439.3	7.88	480
0.500	1.999	3460.8	7.90	490
0.507	1.972	3482.3	7.93	500
0.520	1.922	3525.6	7.99	520

Pressure = 0.70 MPa T_s = 164.95 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.534	1.873	3569.0	8.04	540
0.547	1.828	3612.8	8.09	560
0.560	1.784	3656.7	8.15	580
0.574	1.743	3700.9	8.20	600
0.587	1.703	3745.4	8.25	620
0.600	1.666	3790.1	8.30	640
0.614	1.629	3835.1	8.35	660
0.627	1.595	3880.3	8.39	680
0.640	1.562	3925.8	8.44	700
0.654	1.530	3971.6	8.49	720
0.667	1.500	4017.7	8.53	740
0.680	1.470	4064.0	8.58	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.80 MPa T_s = 170.41 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	897.040	720.9	2.05	t_s(L)
0.240	4.161	2768.3	6.66	t_s(v)
0.247	4.045	2792.4	6.72	180
0.254	3.935	2816.5	6.77	190
0.261	3.833	2839.7	6.82	200
0.268	3.738	2862.5	6.87	210
0.274	3.649	2884.9	6.91	220
0.281	3.565	2907.0	6.96	230
0.287	3.486	2928.8	7.00	240
0.293	3.411	2950.4	7.04	250
0.299	3.339	2971.9	7.08	260
0.306	3.271	2993.3	7.12	270
0.312	3.206	3014.5	7.16	280
0.318	3.144	3035.7	7.20	290
0.324	3.085	3056.9	7.23	300
0.330	3.028	3078.0	7.27	310
0.336	2.973	3099.0	7.31	320
0.342	2.921	3120.1	7.34	330
0.348	2.870	3141.1	7.38	340
0.354	2.822	3162.2	7.41	350
0.360	2.775	3183.2	7.44	360
0.366	2.729	3204.3	7.48	370
0.372	2.686	3225.4	7.51	380
0.378	2.643	3246.5	7.54	390
0.384	2.602	3267.6	7.57	400
0.390	2.563	3288.8	7.60	410
0.396	2.524	3310.0	7.64	420
0.402	2.487	3331.3	7.67	430
0.408	2.451	3352.6	7.70	440
0.414	2.416	3373.9	7.73	450
0.420	2.382	3395.3	7.76	460
0.426	2.349	3416.7	7.78	470
0.432	2.317	3438.2	7.81	480
0.437	2.286	3459.7	7.84	490
0.443	2.256	3481.3	7.87	500
0.455	2.198	3524.6	7.92	520

Pressure = 0.80 MPa T_s = 170.41 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.467	2.142	3568.1	7.98	540
0.478	2.090	3611.9	8.03	560
0.490	2.040	3655.9	8.08	580
0.502	1.993	3700.1	8.14	600
0.514	1.947	3744.6	8.19	620
0.525	1.904	3789.4	8.24	640
0.537	1.863	3834.4	8.28	660
0.548	1.823	3879.7	8.33	680
0.560	1.785	3925.3	8.38	700
0.572	1.749	3971.1	8.43	720
0.583	1.714	4017.2	8.47	740
0.595	1.681	4063.5	8.52	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 0.90 MPa T_s = 175.35 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	891.920	742.6	2.09	t_s(L)
0.215	4.654	2773.0	6.62	t_s(v)
0.218	4.589	2785.2	6.65	180
0.224	4.459	2810.1	6.70	190
0.230	4.340	2834.1	6.75	200
0.236	4.229	2857.4	6.80	210
0.242	4.126	2880.3	6.85	220
0.248	4.029	2902.7	6.89	230
0.254	3.938	2924.9	6.94	240
0.260	3.852	2946.8	6.98	250
0.265	3.770	2968.5	7.02	260
0.271	3.692	2990.1	7.06	270
0.276	3.618	3011.6	7.10	280
0.282	3.547	3033.0	7.14	290
0.287	3.480	3054.3	7.18	300
0.293	3.415	3075.5	7.21	310
0.298	3.352	3096.7	7.25	320
0.304	3.293	3117.9	7.28	330
0.309	3.235	3139.0	7.32	340
0.314	3.180	3160.2	7.35	350
0.320	3.127	3181.3	7.39	360
0.325	3.075	3202.5	7.42	370
0.331	3.026	3223.7	7.45	380
0.336	2.978	3244.8	7.49	390
0.341	2.931	3266.1	7.52	400
0.346	2.887	3287.3	7.55	410
0.352	2.843	3308.6	7.58	420
0.357	2.801	3329.9	7.61	430
0.362	2.760	3351.2	7.64	440
0.368	2.721	3372.6	7.67	450
0.373	2.683	3394.0	7.70	460
0.378	2.645	3415.5	7.73	470
0.383	2.609	3437.0	7.76	480
0.389	2.574	3458.6	7.79	490
0.394	2.540	3480.2	7.81	500
0.404	2.474	3523.6	7.87	520

Pressure = 0.90 MPa T_s = 175.35 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.415	2.412	3567.2	7.92	540
0.425	2.353	3611.0	7.98	560
0.435	2.296	3655.1	8.03	580
0.446	2.243	3699.4	8.08	600
0.456	2.192	3743.9	8.13	620
0.467	2.143	3788.7	8.18	640
0.477	2.096	3833.8	8.23	660
0.487	2.052	3879.1	8.28	680
0.498	2.009	3924.7	8.32	700
0.508	1.968	3970.5	8.37	720
0.518	1.929	4016.6	8.42	740
0.529	1.891	4063.0	8.46	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 1.00 MPa T_s = 179.88 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	887.130	762.5	2.14	t_s(L)
0.194	5.145	2777.1	6.59	t_s(v)
0.194	5.143	2777.4	6.59	180
0.200	4.992	2803.5	6.64	190
0.206	4.854	2828.3	6.70	200
0.212	4.727	2852.2	6.75	210
0.217	4.609	2875.5	6.79	220
0.222	4.498	2898.4	6.84	230
0.228	4.394	2920.9	6.88	240
0.233	4.297	2943.1	6.93	250
0.238	4.204	2965.1	6.97	260
0.243	4.116	2986.9	7.01	270
0.248	4.032	3008.6	7.05	280
0.253	3.952	3030.2	7.09	290
0.258	3.876	3051.6	7.12	300
0.263	3.803	3073.0	7.16	310
0.268	3.733	3094.4	7.20	320
0.273	3.666	3115.7	7.23	330
0.278	3.602	3136.9	7.27	340
0.283	3.540	3158.2	7.30	350
0.287	3.480	3179.4	7.34	360
0.292	3.423	3200.7	7.37	370
0.297	3.367	3221.9	7.40	380
0.302	3.313	3243.2	7.44	390
0.307	3.262	3264.5	7.47	400
0.311	3.211	3285.8	7.50	410
0.316	3.163	3307.1	7.53	420
0.321	3.116	3328.5	7.56	430
0.326	3.070	3349.9	7.59	440
0.330	3.026	3371.3	7.62	450
0.335	2.983	3392.8	7.65	460
0.340	2.942	3414.3	7.68	470
0.345	2.901	3435.8	7.71	480
0.349	2.862	3457.4	7.74	490
0.354	2.824	3479.1	7.76	500
0.364	2.751	3522.6	7.82	520
0.373	2.681	3566.2	7.87	540

Pressure = 1.00 MPa T_s = 179.88 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.382	2.615	3610.1	7.93	560
0.392	2.553	3654.2	7.98	580
0.401	2.493	3698.6	8.03	600
0.410	2.436	3743.2	8.08	620
0.420	2.382	3788.0	8.13	640
0.429	2.330	3833.1	8.18	660
0.439	2.281	3878.5	8.23	680
0.448	2.233	3924.1	8.28	700
0.457	2.188	3970.0	8.32	720
0.466	2.144	4016.1	8.37	740
0.476	2.102	4062.5	8.41	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 1.50 MPa T_s = 198.29 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	866.650	844.6	2.31	t_s(L)
0.132	7.592	2791.0	6.44	t_s(v)
0.132	7.550	2796.0	6.45	200
0.137	7.319	2823.9	6.51	210
0.141	7.110	2850.2	6.57	220
0.145	6.919	2875.5	6.62	230
0.148	6.743	2900.0	6.66	240
0.152	6.579	2923.9	6.71	250
0.156	6.425	2947.4	6.76	260
0.159	6.280	2970.5	6.80	270
0.163	6.144	2993.3	6.84	280
0.166	6.015	3015.8	6.88	290
0.170	5.893	3038.2	6.92	300
0.173	5.776	3060.4	6.96	310
0.177	5.665	3082.4	7.00	320
0.180	5.559	3104.4	7.03	330
0.183	5.457	3126.2	7.07	340
0.187	5.359	3148.0	7.10	350
0.190	5.266	3169.8	7.14	360
0.193	5.176	3191.5	7.17	370
0.196	5.089	3213.2	7.21	380
0.200	5.006	3234.8	7.24	390
0.203	4.926	3256.5	7.27	400
0.206	4.848	3278.1	7.30	410
0.210	4.773	3299.8	7.33	420
0.213	4.701	3321.4	7.37	430
0.216	4.630	3343.1	7.40	440
0.219	4.562	3364.8	7.43	450
0.222	4.497	3386.5	7.46	460
0.226	4.433	3408.3	7.49	470
0.229	4.371	3430.0	7.51	480
0.232	4.311	3451.8	7.54	490
0.235	4.252	3473.7	7.57	500
0.242	4.141	3517.5	7.63	520
0.248	4.035	3561.5	7.68	540

Pressure = 1.50 MPa T_s = 198.29 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.254	3.934	3605.7	7.74	560
0.260	3.839	3650.1	7.79	580
0.267	3.748	3694.7	7.84	600
0.273	3.662	3739.5	7.89	620
0.279	3.580	3784.5	7.94	640
0.286	3.501	3829.8	7.99	660
0.292	3.426	3875.4	8.04	680
0.298	3.354	3921.1	8.09	700
0.304	3.286	3967.2	8.13	720
0.311	3.220	4013.4	8.18	740
0.317	3.156	4060.0	8.22	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 2.00 MPa T_s = 212.38 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	849.800	908.5	2.45	t_s(L)
0.100	10.042	2798.3	6.34	t_s(v)
0.102	9.787	2821.6	6.39	220
0.105	9.487	2850.2	6.44	230
0.109	9.217	2877.2	6.50	240
0.111	8.969	2903.2	6.55	250
0.114	8.740	2928.5	6.60	260
0.117	8.528	2953.1	6.64	270
0.120	8.330	2977.1	6.68	280
0.123	8.143	3000.8	6.73	290
0.126	7.968	3024.2	6.77	300
0.128	7.802	3047.3	6.81	310
0.131	7.644	3070.1	6.85	320
0.133	7.494	3092.8	6.89	330
0.136	7.351	3115.3	6.92	340
0.139	7.215	3137.7	6.96	350
0.141	7.085	3159.9	6.99	360
0.144	6.959	3182.1	7.03	370
0.146	6.839	3204.2	7.06	380
0.149	6.724	3226.3	7.10	390
0.151	6.613	3248.3	7.13	400
0.154	6.506	3270.3	7.16	410
0.156	6.403	3292.3	7.19	420
0.159	6.304	3314.3	7.23	430
0.161	6.208	3336.3	7.26	440
0.164	6.115	3358.2	7.29	450
0.166	6.025	3380.2	7.32	460
0.168	5.938	3402.2	7.35	470
0.171	5.853	3424.2	7.38	480
0.173	5.771	3446.2	7.41	490
0.176	5.692	3468.2	7.43	500
0.181	5.540	3512.4	7.49	520
0.185	5.397	3556.7	7.55	540

Pressure = 2.00 MPa T_s = 212.38 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.190	5.261	3601.2	7.60	560
0.195	5.132	3645.9	7.65	580
0.200	5.010	3690.7	7.70	600
0.204	4.893	3735.8	7.76	620
0.209	4.782	3781.0	7.81	640
0.214	4.677	3826.5	7.85	660
0.219	4.576	3872.2	7.90	680
0.223	4.479	3918.2	7.95	700
0.228	4.387	3964.3	8.00	720
0.233	4.298	4010.8	8.04	740
0.237	4.213	4057.4	8.09	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 3.00 MPa T_s = 233.85 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	821.900	1008.3	2.65	t_s(L)
0.067	15.001	2803.2	6.19	t_s(v)
0.068	14.656	2824.5	6.23	240
0.071	14.159	2856.5	6.29	250
0.073	13.718	2886.4	6.35	260
0.075	13.322	2914.9	6.40	270
0.077	12.960	2942.2	6.45	280
0.079	12.627	2968.6	6.50	290
0.081	12.318	2994.3	6.54	300
0.083	12.031	3019.5	6.58	310
0.085	11.762	3044.2	6.63	320
0.087	11.508	3068.4	6.67	330
0.089	11.269	3092.4	6.71	340
0.091	11.043	3116.1	6.74	350
0.092	10.828	3139.5	6.78	360
0.094	10.623	3162.8	6.82	370
0.096	10.428	3185.9	6.85	380
0.098	10.241	3208.8	6.89	390
0.099	10.062	3231.7	6.92	400
0.101	9.891	3254.4	6.96	410
0.103	9.727	3277.1	6.99	420
0.105	9.568	3299.7	7.02	430
0.106	9.416	3322.3	7.05	440
0.108	9.269	3344.8	7.09	450
0.110	9.127	3367.3	7.12	460
0.111	8.990	3389.8	7.15	470
0.113	8.858	3412.3	7.18	480
0.115	8.730	3434.8	7.21	490
0.116	8.606	3457.2	7.24	500
0.119	8.370	3502.2	7.29	520
0.123	8.147	3547.2	7.35	540
0.126	7.937	3592.3	7.40	560

Pressure = 3.00 MPa T_s = 233.85 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.129	7.739	3637.5	7.46	580
0.132	7.550	3682.8	7.51	600
0.136	7.372	3728.3	7.56	620
0.139	7.202	3774.0	7.61	640
0.142	7.040	3819.9	7.66	660
0.145	6.886	3866.0	7.71	680
0.148	6.738	3912.2	7.76	700
0.152	6.597	3958.7	7.81	720
0.155	6.463	4005.4	7.85	740
0.158	6.333	4052.4	7.90	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 4.00 MPa T_s = 250.35 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	798.370	1087.5	2.80	t_s(L)
0.050	20.090	2800.8	6.07	t_s(v)
0.052	19.314	2837.1	6.14	260
0.054	18.624	2871.2	6.20	270
0.055	18.019	2902.9	6.26	280
0.057	17.477	2933.0	6.31	290
0.059	16.987	2961.7	6.36	300
0.060	16.538	2989.4	6.41	310
0.062	16.123	3016.3	6.46	320
0.064	15.739	3042.5	6.50	330
0.065	15.380	3068.1	6.54	340
0.066	15.044	3093.3	6.58	350
0.068	14.727	3118.1	6.62	360
0.069	14.428	3142.6	6.66	370
0.071	14.144	3166.8	6.70	380
0.072	13.875	3190.7	6.74	390
0.073	13.618	3214.5	6.77	400
0.075	13.373	3238.1	6.81	410
0.076	13.139	3261.5	6.84	420
0.077	12.915	3284.8	6.87	430
0.079	12.700	3308.0	6.91	440
0.080	12.493	3331.2	6.94	450
0.081	12.295	3354.2	6.97	460
0.083	12.103	3377.2	7.00	470
0.084	11.919	3400.2	7.03	480
0.085	11.741	3423.1	7.06	490
0.086	11.568	3446.0	7.09	500
0.089	11.241	3491.8	7.15	520
0.091	10.934	3537.5	7.21	540
0.094	10.645	3583.2	7.26	560

Pressure = 4.00 MPa T_s = 250.35 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.096	10.373	3629.0	7.32	580
0.099	10.115	3674.9	7.37	600
0.101	9.872	3720.9	7.42	620
0.104	9.640	3767.0	7.47	640
0.106	9.420	3813.2	7.52	660
0.109	9.211	3859.7	7.57	680
0.111	9.011	3906.3	7.62	700
0.113	8.820	3953.1	7.67	720
0.116	8.638	4000.1	7.72	740
0.118	8.463	4047.3	7.76	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 5.00 MPa T_s = 263.94 °C				*t*, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	*h*, $\frac{kJ}{kg}$	*s*, $\frac{kJ}{kg \cdot K}$	
0.001	777.370	1154.6	2.92	t_s(L)
0.039	25.351	2794.2	5.97	t_s(v)
0.041	24.651	2819.8	6.02	270
0.042	23.655	2858.1	6.09	280
0.044	22.802	2893.0	6.15	290
0.045	22.053	2925.7	6.21	300
0.047	21.383	2956.6	6.26	310
0.048	20.777	2986.2	6.31	320
0.049	20.224	3014.7	6.36	330
0.051	19.714	3042.4	6.41	340
0.052	19.242	3069.3	6.45	350
0.053	18.802	3095.6	6.49	360
0.054	18.390	3121.5	6.53	370
0.056	18.002	3146.9	6.57	380
0.057	17.636	3171.9	6.61	390
0.058	17.290	3196.7	6.65	400
0.059	16.961	3221.2	6.68	410
0.060	16.648	3245.4	6.72	420
0.061	16.350	3269.5	6.75	430
0.062	16.065	3293.4	6.79	440
0.063	15.792	3317.2	6.82	450
0.064	15.530	3340.9	6.85	460
0.065	15.279	3364.4	6.89	470
0.066	15.038	3387.9	6.92	480
0.068	14.805	3411.3	6.95	490
0.069	14.581	3434.7	6.98	500
0.071	14.156	3481.2	7.04	520
0.073	13.759	3527.7	7.10	540
0.075	13.386	3574.1	7.15	560

Pressure = 5.00 MPa T_s = 263.94 °C				*t*, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	*h*, $\frac{kJ}{kg}$	*s*, $\frac{kJ}{kg \cdot K}$	
0.077	13.036	3620.4	7.21	580
0.079	12.706	3666.8	7.26	600
0.081	12.394	3713.3	7.31	620
0.083	12.098	3759.9	7.36	640
0.085	11.818	3806.5	7.42	660
0.087	11.551	3853.3	7.46	680
0.089	11.297	3900.3	7.51	700
0.090	11.055	3947.4	7.56	720
0.092	10.824	3994.7	7.61	740
0.094	10.602	4042.2	7.66	760

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Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 7.00 MPa T_s = 285.83 °C				*t*, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	*h*, $\frac{kJ}{kg}$	*s*, $\frac{kJ}{kg \cdot K}$	
0.001	739.720	1267.7	3.12	t_s(L)
0.027	36.525	2772.6	5.81	t_s(v)
0.028	35.659	2794.1	5.85	290
0.029	33.907	2839.9	5.93	300
0.031	32.466	2880.6	6.00	310
0.032	31.238	2917.9	6.07	320
0.033	30.166	2952.7	6.13	330
0.034	29.215	2985.6	6.18	340
0.035	28.359	3016.9	6.23	350
0.036	27.581	3047.0	6.28	360
0.037	26.868	3076.2	6.32	370
0.038	26.209	3104.5	6.37	380
0.039	25.597	3132.1	6.41	390
0.040	25.026	3159.2	6.45	400
0.041	24.491	3185.7	6.49	410
0.042	23.987	3211.8	6.53	420
0.043	23.510	3237.6	6.56	430
0.043	23.060	3263.1	6.60	440
0.044	22.631	3288.3	6.64	450
0.045	22.224	3313.3	6.67	460
0.046	21.835	3338.0	6.70	470
0.047	21.463	3362.6	6.74	480
0.047	21.107	3387.1	6.77	490
0.048	20.765	3411.4	6.80	500
0.050	20.122	3459.7	6.86	520
0.051	19.526	3507.7	6.92	540
0.053	18.971	3555.5	6.98	560
0.054	18.452	3603.1	7.04	580
0.056	17.965	3650.6	7.09	600
0.057	17.507	3698.1	7.14	620
0.059	17.074	3745.5	7.20	640
0.060	16.666	3793.0	7.25	660
0.061	16.279	3840.6	7.30	680
0.063	15.911	3888.2	7.35	700
0.064	15.561	3936.0	7.40	720
0.066	15.228	3983.9	7.45	740
0.067	14.910	4031.9	7.49	760

Pressure = 8.00 MPa T_s = 295.01 °C				*t*, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	*h*, $\frac{kJ}{kg}$	*s*, $\frac{kJ}{kg \cdot K}$	
0.001	722.200	1317.3	3.21	t_s(L)
0.024	42.507	2758.7	5.75	t_s(v)
				290
0.024	41.188	2786.5	5.79	300
0.026	39.016	2835.4	5.88	310
0.027	37.258	2878.4	5.95	320
0.028	35.775	2917.6	6.02	330
0.029	34.493	2953.9	6.08	340
0.030	33.361	2988.1	6.13	350
0.031	32.350	3020.6	6.18	360
0.032	31.434	3051.8	6.23	370
0.033	30.599	3081.8	6.28	380
0.034	29.830	3111.0	6.32	390
0.034	29.117	3139.4	6.37	400
0.035	28.454	3167.1	6.41	410
0.036	27.834	3194.3	6.45	420
0.037	27.251	3221.0	6.48	430
0.037	26.702	3247.3	6.52	440
0.038	26.182	3273.3	6.56	450
0.039	25.690	3299.0	6.59	460
0.040	25.222	3324.4	6.63	470
0.040	24.776	3349.6	6.66	480
0.041	24.350	3374.7	6.69	490
0.042	23.942	3399.5	6.73	500
0.043	23.177	3448.7	6.79	520
0.045	22.471	3497.6	6.85	540
0.046	21.816	3546.0	6.91	560
0.047	21.205	3594.3	6.97	580
0.048	20.634	3642.4	7.02	600
0.050	20.098	3690.4	7.08	620
0.051	19.593	3738.3	7.13	640
0.052	19.117	3786.2	7.18	660
0.054	18.666	3834.2	7.23	680
0.055	18.239	3882.2	7.28	700
0.056	17.833	3930.3	7.33	720
0.057	17.446	3978.5	7.38	740
0.059	17.078	4026.8	7.43	760

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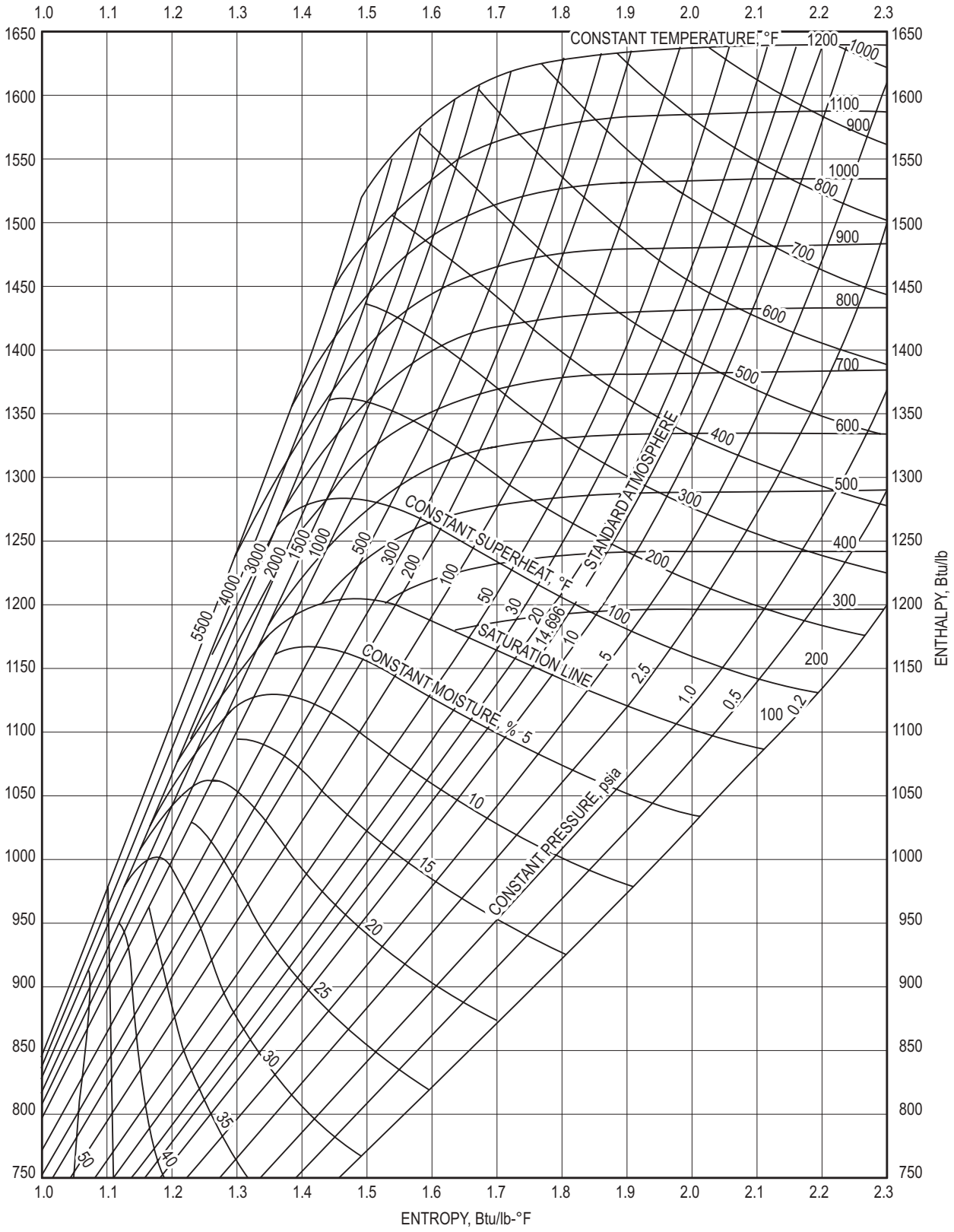
Properties of Superheated Steam—SI Units (cont'd)
Pressures Are Absolute

Pressure = 9.00 MPa T_s = 303.35 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	705.160	1363.9	3.29	t_s(L)
0.020	48.804	2742.9	5.68	t_s(v)
0.021	46.625	2782.7	5.75	310
0.023	44.036	2834.0	5.84	320
0.024	41.962	2879.0	5.91	330
0.025	40.228	2919.7	5.98	340
0.026	38.736	2957.3	6.04	350
0.027	37.428	2992.6	6.09	360
0.028	36.263	3026.1	6.15	370
0.028	35.212	3058.1	6.20	380
0.029	34.256	3089.0	6.24	390
0.030	33.378	3118.8	6.29	400
0.031	32.567	3147.9	6.33	410
0.031	31.813	3176.2	6.37	420
0.032	31.110	3203.9	6.41	430
0.033	30.450	3231.2	6.45	440
0.034	29.829	3258.0	6.49	450
0.034	29.243	3284.5	6.52	460
0.035	28.687	3310.6	6.56	470
0.036	28.160	3336.4	6.59	480
0.036	27.658	3362.0	6.63	490
0.037	27.179	3387.4	6.66	500
0.038	26.283	3437.6	6.72	520
0.039	25.460	3487.3	6.79	540
0.040	24.698	3536.5	6.85	560
0.042	23.991	3585.4	6.90	580
0.043	23.331	3634.1	6.96	600
0.044	22.713	3682.6	7.02	620
0.045	22.133	3731.0	7.07	640
0.046	21.586	3779.4	7.12	660
0.047	21.070	3827.7	7.17	680
0.049	20.581	3876.1	7.22	700
0.050	20.117	3924.5	7.27	720
0.051	19.676	3973.0	7.32	740
0.052	19.256	4021.6	7.37	760

Pressure = 10.00 MPa T_s = 311.00 °C				t, °C
v, $\frac{m^3}{kg}$	ρ, $\frac{kg}{m^3}$	h, $\frac{kJ}{kg}$	s, $\frac{kJ}{kg \cdot K}$	
0.001	688.420	1408.1	3.36	t_s(L)
0.018	55.463	2725.5	5.62	t_s(v)
				310
0.019	51.894	2782.8	5.71	320
0.020	48.913	2835.8	5.80	330
0.021	46.539	2882.1	5.88	340
0.022	44.564	2924.0	5.95	350
0.023	42.873	2962.7	6.01	360
0.024	41.394	2998.9	6.06	370
0.025	40.081	3033.2	6.12	380
0.026	38.900	3065.9	6.17	390
0.026	37.827	3097.4	6.21	400
0.027	36.844	3127.9	6.26	410
0.028	35.937	3157.5	6.30	420
0.028	35.096	3186.4	6.34	430
0.029	34.312	3214.6	6.38	440
0.030	33.578	3242.3	6.42	450
0.030	32.887	3269.6	6.46	460
0.031	32.236	3296.5	6.50	470
0.032	31.619	3323.0	6.53	480
0.032	31.034	3349.2	6.57	490
0.033	30.478	3375.1	6.60	500
0.034	29.441	3426.4	6.66	520
0.035	28.493	3476.9	6.73	540
0.036	27.619	3526.9	6.79	560
0.037	26.809	3576.5	6.85	580
0.038	26.057	3625.8	6.90	600
0.039	25.353	3674.8	6.96	620
0.040	24.694	3723.7	7.01	640
0.042	24.074	3772.5	7.07	660
0.043	23.490	3821.3	7.12	680
0.044	22.937	3870.0	7.17	700
0.045	22.414	3918.7	7.22	720
0.046	21.917	3967.6	7.27	740
0.047	21.444	4016.4	7.32	760

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Mollier (h, s) Diagram for Steam



Source: ©ASHRAE, www.ashrae.org., Howell, Ronald, L., William J. Coad, Harry J. Sauer Jr., *Principles of Heating, Ventilating, and Air Conditioning*, 6th ed., 2010, Chapter 2, Thermodynamics and Psychrometrics, Fig. 2-4.

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7 PSYCHROMETRICS

7.1 Psychrometric Properties

Humidity ratio W is the ratio of the mass of water vapor to the mass of dry air:

$$W = \frac{M_w}{M_{da}}$$

W equals the mole fraction ratio $\frac{x_w}{x_{da}}$ multiplied by the ratio of molecular masses $\left(\frac{18.01528}{28.9645} = 0.62198\right)$:

$$W = 0.62198\frac{x_w}{x_{da}}$$

Specific humidity γ is the ratio of the mass of water vapor to the total mass of the moist air sample:

$$\gamma = \frac{M_w}{\left(M_w + M_{da}\right)}$$

In terms of humidity ratio:

$$\gamma = \frac{W}{(1 + W)}$$

Absolute humidity d_v , or water vapor density, is the ratio of the mass of the water vapor to the total volume of the sample:

$$d_v = \frac{M_w}{V}$$

Density ρ of a moist air mixture is the ratio of total mass to total volume:

$$\rho = \frac{\left(M_{da} + M_w\right)}{V} = \left(\frac{1}{v}\right)(1 + W)$$

where v = moist air specific volume $\left(\frac{\text{ft}^3}{\text{lb}_{da}}\right)$

Saturation humidity W_s (t, p) is the humidity ratio of moist air saturated with respect to water (or ice) at a specified temperature t and pressure p.

Degree of saturation μ is the ratio of the air humidity ratio W to the humidity ratio of saturated moist air W_s at the same temperature and pressure:

$$\mu = \left.\frac{W}{W_s}\right|_{t,p}$$

where the saturation humidity ratio W_s is

$$W_s = 0.622\frac{p_{ws}}{p - p_{ws}}$$

p_{ws} = saturation pressure of water (psia) in the absence of air, at the given temperature t.

Relative humidity ϕ is the ratio of the mole fraction of water vapor x_w to the mole fraction x_{ws} in an air sample saturated at the same temperature and pressure:

$$\phi = \left.\frac{x_w}{x_{ws}}\right|_{t,p} \qquad \phi = \left.\frac{p_w}{p_{ws}}\right|_{t,p}$$

$$\mu = \frac{\phi}{\left[\frac{1 + (1 - \phi)W_s}{0.622}\right]} \qquad \phi = \frac{\mu}{1 - (1 - \mu)(p_{ws}/p)}$$

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Dew-point temperature t_d is the temperature of moist air saturated at pressure p with the same humidity ratio:

$$W_s(p, t_d) = W$$

Thermodynamic wet-bulb temperature t^* is the temperature at which water (liquid or solid), by evaporating into moist air at dry-bulb temperature t and humidity ratio W, can bring air to saturation adiabatically at the same temperature t^*, while the total pressure is held constant.

Perfect gas (ideal gas) relationships for dry and moist air can be expressed as

Dry air: $p_{da} V = n_{da} RT$

Water vapor: $p_w V = n_w RT$

where

p_{da} = partial pressure of dry air (psia)

p_w = partial pressure of water vapor (psia)

V = total mixture volume

n_{da} = number of moles of dry air

n_w = number of moles of water vapor

R = universal gas constant

T = absolute temperature (°R)

Perfect gas equation:

$$pV = nRT$$

or

$$(p_{da} + p_w)V = (n_{da} + n_w)RT$$

where

p = total mixture pressure = $p_{da} + p_w$

n = total moles in the mixture = $n_{da} + n_w$

The mole fractions of dry air and water vapor are:

$$x_{da} = \frac{p_{da}}{(p_{da} + p_w)} = \frac{p_{da}}{p}$$

$$x_w = \frac{p_w}{(p_{da} + p_w)} = \frac{p_w}{p}$$

Humidity ratio W is

$$W = \frac{0.622 p_w}{(p - p_w)}$$

The specific volume v of a moist-air mixture in terms of unit mass of dry air is

$$v = \frac{V}{M_{da}} = \frac{V}{28.97 n_{da}}$$

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where

V = total volume of the mixture
M_{da} = total mass of dry air
n_{da} = number of moles of dry air

$$v = \frac{RT}{\left[28.97\left(p - p_w\right)\right]} = \frac{R_{da}T}{\left(p - p_w\right)}$$

$$v = \frac{RT\left(1 + 1.608W\right)}{28.97p} = \frac{R_{da}T\left(1 + 1.608W\right)}{p}$$

In specific units:

$$v = \frac{0.370\left(t + 459.67\right)\left(1 + 1.608W\right)}{p}$$

where

v = specific volume (ft^3/lb_{da})

t = dry-bulb temperature (°F)

W = humidity ratio (lb_w/lb_{da})

p = total pressure (psia)

The enthalpy of a mixture of perfect gases equals the same of the individual partial enthalpies

$$h = h_{da} + Wh_g$$

As an approximation:

$$h_{da} \cong 0.240\ t$$

$$h_g \cong 1061 + 0.444\ t \quad \text{for water vapor}$$

The moist air specific enthalpy in Btu/lb_{da} becomes

$$h = 0.240\ t + W(1061 + 0.444\ t)$$

The sensible heat ratio (SHR) of a space is:

$$\text{SHR} = \frac{\text{sensible heat gain}}{\text{total heat gain}}$$

where total heat gain = sensible heat gain + latent heat gain

Grains of moisture: the moisture content of air can be in pounds of water per pounds of dry air (lb_w/lb_{da}) or in grains of water per pound of dry air (gr/lb_{da}).

7,000 grains = 1 lb_w

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7.2 Temperature and Altitude Corrections for Air

Assuming air at standard conditions at sea level (70°F and 29.92 inches Hg):

Pressure as a function of altitude is

$$p = 14.696\ (1 - 6.8754 \bullet 10^{-6}\ Z)^{\ 5.2559}$$

Temperature as a function of altitude is

$$t = 59 - 0.00356620Z$$

where

Z = altitude (ft)

p = barometric pressure (psia)

t = temperature (°F)

Temperature and Altitude Corrections for Air

Temperature - Density*			Altitude - Density**		
Temperature	Air Density	Density Factor	Elevation	Air Density	Density Factor
°F	$\frac{lb}{ft^3}$		ft	$\frac{lb}{ft^3}$	
0	0.0864	1.152	0	0.0750	1.000
70	0.0749	1.000	500	0.0736	0.982
100	0.0709	0.946	1,000	0.0723	0.964
150	0.0651	0.869	1,500	0.0710	0.947
200	0.0602	0.803	2,000	0.0697	0.930
250	0.0560	0.747	2,500	0.0684	0.913
300	0.0522	0.697	3,000	0.0672	0.896
350	0.0490	0.654	3,500	0.0659	0.880
400	0.0462	0.616	4,000	0.0647	0.864
450	0.0436	0.582	4,500	0.0635	0.848
500	0.0414	0.552	5,000	0.0623	0.832
550	0.0393	0.525	5,500	0.0612	0.817
600	0.0375	0.500	6,000	0.0600	0.801
650	0.0358	0.477	6,500	0.0589	0.786
700	0.0342	0.457	7,000	0.0578	0.772
760	0.0328	0.438	7,500	0.0567	0.757
800	0.0315	0.421	8,000	0.0557	0.743
850	0.0303	0.404	8,500	0.0546	0.729
900	0.0292	0.390	9,000	0.0536	0.715
950	0.0282	0.376	9,500	0.0525	0.701
1,000	0.0272	0.363	10,000	0.0515	0.688

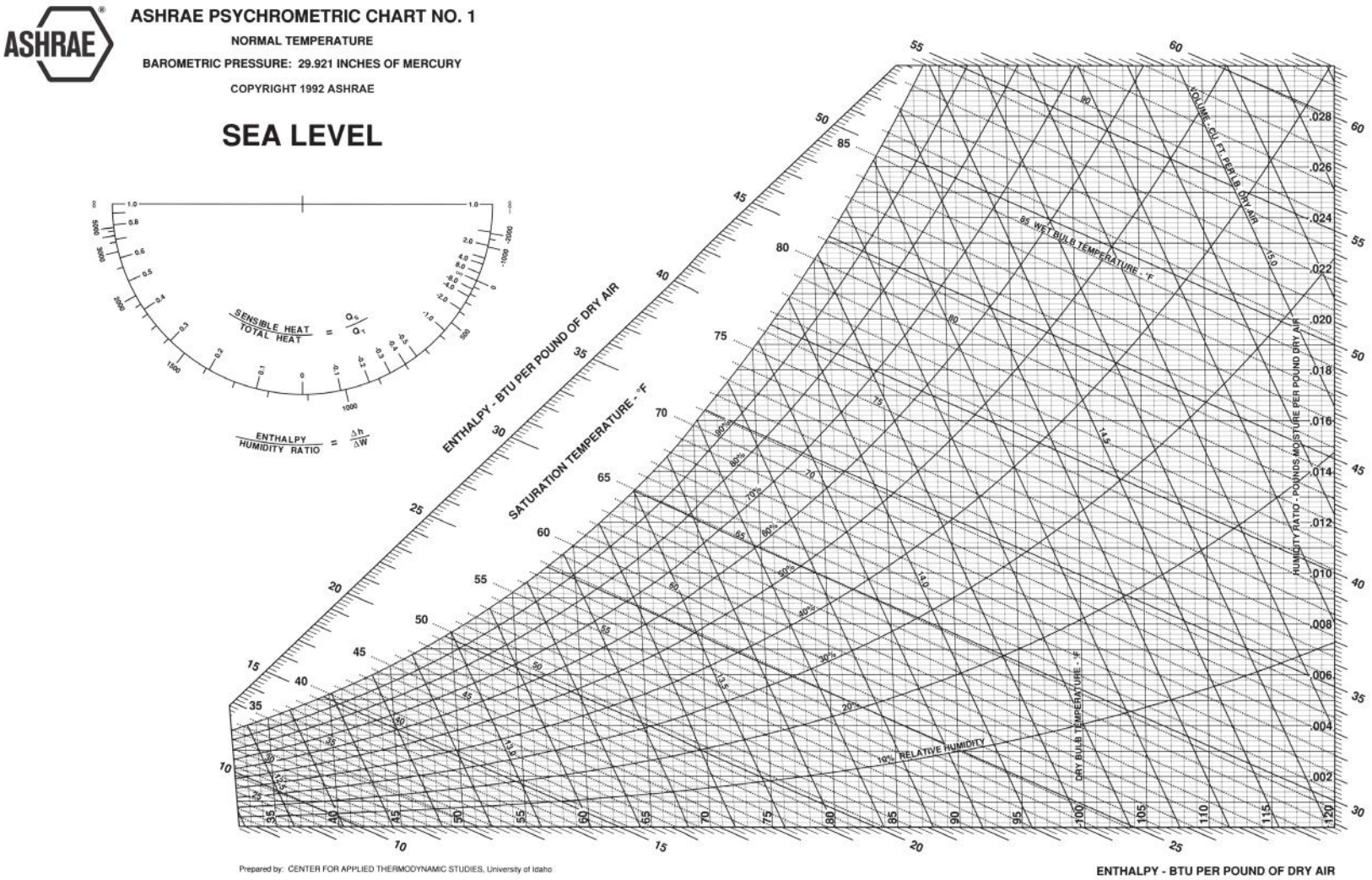
* Tables based on 29.92 inches Hg

** Dry air at 70°F

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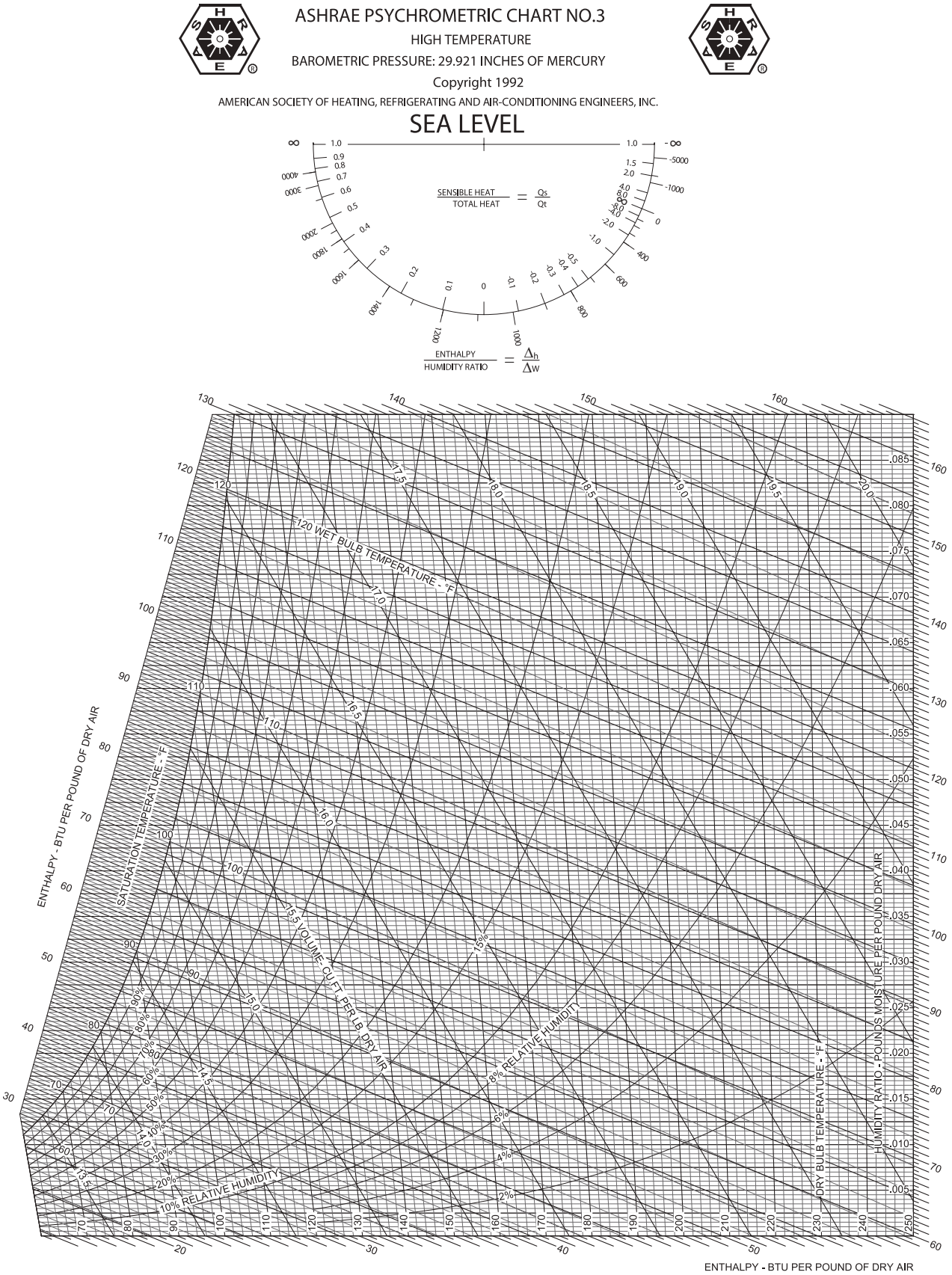
7.3 Psychrometric Charts

ASHRAE Psychrometric Chart No. 1 - Sea Level



Source: ©ASHRAE, www.ashrae.org., Psychrometric Chart, No. 1.

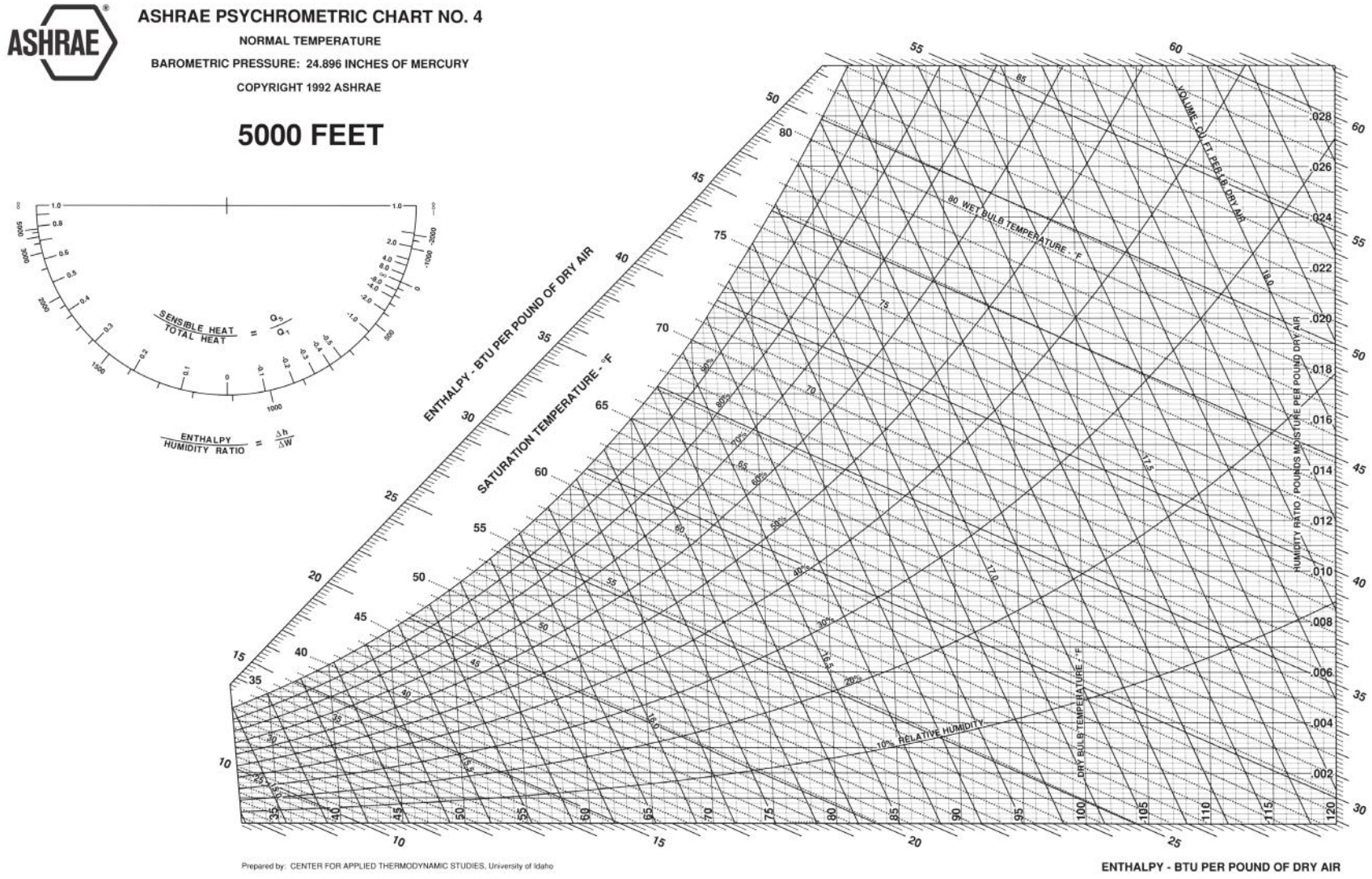
ASHRAE Psychrometric Chart No. 3 - High Temperature



Source: ©ASHRAE, www.ashrae.org., Psychrometric Chart, No. 3.

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ASHRAE Psychrometric Chart No. 4 - 5,000 Feet



Source: ©ASHRAE, www.ashrae.org., Psychrometric Chart, No. 4.

7.4 Thermodynamic Properties of Moist Air

Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 Psia

Temp., °F	Humidity Ratio at Saturation, $\frac{lb_w}{lb_{da}}$	Specific Volume, $\frac{ft^3}{lb_{da}}$			Specific Enthalpy, $\frac{Btu}{lb_{da}}$			Specific Entropy, $\frac{Btu}{lb_{da}\text{-}°F}$		Temp., °F
T	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	T
–20	0.000263	11.073	0.005	11.078	–4.804	0.277	–4.527	–0.01069	–0.01002	–20
–19	0.000279	11.098	0.005	11.103	–4.564	0.293	–4.271	–0.01014	–0.00943	–19
–18	0.000295	11.124	0.005	11.129	–4.324	0.311	–4.013	–0.00960	–0.00885	–18
–17	0.000312	11.149	0.006	11.155	–4.084	0.329	–3.754	–0.00905	–0.00826	–17
–16	0.000330	11.174	0.006	11.180	–3.843	0.348	–3.495	–0.00851	–0.00768	–16
–15	0.000349	11.200	0.006	11.206	–3.603	0.368	–3.235	–0.00797	–0.00709	–15
–14	0.000369	11.225	0.007	11.232	–3.363	0.390	–2.973	–0.00743	–0.00650	–14
–13	0.000391	11.250	0.007	11.257	–3.123	0.412	–2.710	–0.00689	–0.00591	–13
–12	0.000413	11.276	0.007	11.283	–2.882	0.436	–2.447	–0.00635	–0.00532	–12
–11	0.000436	11.301	0.008	11.309	–2.642	0.460	–2.182	–0.00582	–0.00473	–11
–10	0.000461	11.326	0.008	11.335	–2.402	0.487	–1.915	–0.00528	–0.00414	–10
–9	0.000487	11.351	0.009	11.360	–2.162	0.514	–1.647	–0.00475	–0.00354	–9
–8	0.000514	11.377	0.009	11.386	–1.922	0.543	–1.378	–0.00422	–0.00294	–8
–7	0.000543	11.402	0.010	11.412	–1.681	0.574	–1.108	–0.00369	–0.00234	–7
–6	0.000573	11.427	0.010	11.438	–1.441	0.606	–0.835	–0.00316	–0.00174	–6
–5	0.000604	11.453	0.011	11.464	–1.201	0.640	–0.561	–0.00263	–0.00114	–5
–4	0.000637	11.478	0.012	11.490	–0.961	0.675	–0.286	–0.00210	–0.00053	–4
–3	0.000672	11.503	0.012	11.516	–0.721	0.712	–0.008	–0.00157	0.00008	–3
–2	0.000709	11.529	0.013	11.542	–0.480	0.751	0.271	–0.00105	0.00069	–2
–1	0.000747	11.554	0.014	11.568	–0.240	0.792	0.552	–0.00052	0.00130	–1
0	0.000788	11.579	0.015	11.594	0.000	0.835	0.835	0.00000	0.00192	0
Subscripts da = dry air, s = moist air at saturation, as = difference										

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Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 Psia (cont'd)

Temp., °F	Humidity Ratio at Saturation, $\frac{lb_w}{lb_{da}}$	Specific Volume, $\frac{ft^3}{lb_{da}}$			Specific Enthalpy, $\frac{Btu}{lb_{da}}$			Specific Entropy, $\frac{Btu}{lb_{da}\text{-}°F}$		Temp., °F
T	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	T
1	0.000830	11.604	0.015	11.620	0.240	0.880	1.121	0.00052	0.00254	1
2	0.000874	11.630	0.016	11.646	0.480	0.928	1.408	0.00104	0.00317	2
3	0.000921	11.655	0.017	11.672	0.721	0.978	1.699	0.00156	0.00380	3
4	0.000970	11.680	0.018	11.699	0.961	1.030	1.991	0.00208	0.00443	4
5	0.001021	11.706	0.019	11.725	1.201	1.085	2.286	0.00260	0.00506	5
6	0.001074	11.731	0.020	11.751	1.441	1.143	2.584	0.00311	0.00570	6
7	0.001131	11.756	0.021	11.778	1.681	1.203	2.884	0.00363	0.00272	7
8	0.001190	11.782	0.022	11.804	1.922	1.266	3.188	0.00414	0.00700	8
9	0.001251	11.807	0.024	11.831	2.162	1.332	3.494	0.00466	0.00766	9
10	0.001316	11.832	0.025	11.857	2.402	1.402	3.804	0.00517	0.00832	10
11	0.001384	11.857	0.026	11.884	2.642	1.474	4.117	0.00568	0.00898	11
12	0.001454	11.883	0.028	11.910	2.882	1.550	4.433	0.00619	0.00966	12
13	0.001529	11.908	0.029	11.937	3.123	1.630	4.753	0.00670	0.01033	13
14	0.001606	11.933	0.031	11.964	3.363	1.714	5.077	0.00721	0.01102	14
15	0.001687	11.959	0.032	11.991	3.603	1.801	5.404	0.00771	0.01171	15
16	0.001772	11.984	0.034	12.018	3.843	1.892	5.736	0.00822	0.01241	16
17	0.001861	12.009	0.036	12.045	4.084	1.988	6.072	0.00872	0.01312	17
18	0.001954	12.035	0.038	12.072	4.324	2.088	6.412	0.00923	0.01383	18
19	0.002052	12.060	0.040	12.099	4.564	2.193	6.757	0.00973	0.01455	19
20	0.002153	12.085	0.042	12.127	4.804	2.303	7.107	0.01023	0.01528	20
21	0.002259	12.110	0.044	12.154	5.044	2.417	7.462	0.01073	0.01602	21
22	0.002370	12.136	0.046	12.182	5.285	2.537	7.822	0.01123	0.01677	22
23	0.002486	12.161	0.048	12.209	5.525	2.662	8.187	0.01173	0.01753	23
Subscripts da = dry air, s = moist air at saturation, as = difference										

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Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 Psia (cont'd)

Temp., °F	Humidity Ratio at Saturation, $\frac{lb_w}{lb_{da}}$	Specific Volume, $\frac{ft^3}{lb_{da}}$			Specific Enthalpy, $\frac{Btu}{lb_{da}}$			Specific Entropy, $\frac{Btu}{lb_{da}\text{-}°F}$		Temp., °F
T	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	T
24	0.002607	12.186	0.051	12.237	5.765	2.793	8.558	0.01223	0.01830	24
25	0.002734	12.212	0.054	12.265	6.005	2.930	8.935	0.01272	0.01908	25
26	0.002866	12.237	0.056	12.293	6.246	3.073	9.318	0.01322	0.01987	26
27	0.003004	12.262	0.059	12.321	6.486	3.222	9.708	0.01371	0.02067	27
28	0.003148	12.287	0.062	12.349	6.726	3.378	10.104	0.01420	0.02148	28
29	0.003298	12.313	0.065	12.378	6.966	3.541	10.507	0.01470	0.02231	29
30	0.003455	12.338	0.068	12.406	7.206	3.711	10.917	0.01519	0.02315	30
31	0.003619	12.363	0.072	12.435	7.447	3.888	11.335	0.01568	0.02400	31
32	0.003790	12.389	0.075	12.464	7.687	4.073	11.760	0.01617	0.02487	32
32*	0.003790	12.389	0.075	12.464	7.687	4.073	11.760	0.01617	0.02487	32*
33	0.003947	12.414	0.079	12.492	7.927	4.243	12.170	0.01665	0.02570	33
34	0.004109	12.439	0.082	12.521	8.167	4.420	12.587	0.01714	0.02655	34
35	0.004277	12.464	0.085	12.550	8.408	4.603	13.010	0.01763	0.02740	35
36	0.004452	12.490	0.089	12.579	8.648	4.793	13.441	0.01811	0.02827	36
37	0.004633	12.515	0.093	12.608	8.888	4.990	13.878	0.01860	0.02915	37
38	0.004820	12.540	0.097	12.637	9.128	5.194	14.322	0.01908	0.03004	38
39	0.005014	12.566	0.101	12.667	9.369	5.405	14.773	0.01956	0.03095	39
40	0.005216	12.591	0.105	12.696	9.609	5.624	15.233	0.02004	0.03187	40
41	0.005424	12.616	0.110	12.726	9.849	5.851	15.700	0.02052	0.03281	41
42	0.005640	12.641	0.114	12.756	10.089	6.086	16.175	0.02100	0.03375	42
43	0.005863	12.667	0.119	12.786	10.330	6.330	16.660	0.02148	0.03472	43
44	0.006094	12.692	0.124	12.816	10.570	6.582	17.152	0.02196	0.03570	44
45	0.006334	12.717	0.129	12.846	10.810	6.843	17.653	0.02244	0.03669	45
Subscripts da = dry air, s = moist air at saturation, as = difference										

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Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 Psia (cont'd)

Temp., °F	Humidity Ratio at Saturation, $\frac{lb_w}{lb_{da}}$	Specific Volume, $\frac{ft^3}{lb_{da}}$			Specific Enthalpy, $\frac{Btu}{lb_{da}}$			Specific Entropy, $\frac{Btu}{lb_{da}\text{-}°F}$		Temp., °F
T	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	T
46	0.006581	12.743	0.134	12.877	11.050	7.114	18.164	0.02291	0.03770	46
47	0.006838	12.768	0.140	12.908	11.291	7.394	18.685	0.02339	0.03873	47
48	0.007103	12.793	0.146	12.939	11.531	7.684	19.215	0.02386	0.03978	48
49	0.007378	12.818	0.152	12.970	11.771	7.984	19.756	0.02433	0.04084	49
50	0.007661	12.844	0.158	13.001	12.012	8.295	20.306	0.02480	0.04192	50
51	0.007955	12.869	0.164	13.033	12.252	8.616	20.868	0.02528	0.04302	51
52	0.008259	12.894	0.171	13.065	12.492	8.949	21.441	0.02575	0.04415	52
53	0.008573	12.920	0.178	13.097	12.732	9.293	22.025	0.02622	0.04529	53
54	0.008897	12.945	0.185	13.129	12.973	9.648	22.621	0.02668	0.04645	54
55	0.009233	12.970	0.192	13.162	13.213	10.016	23.229	0.02715	0.04763	55
56	0.009580	12.995	0.200	13.195	13.453	10.397	23.850	0.02762	0.04884	56
57	0.009938	13.021	0.207	13.228	13.694	10.790	24.484	0.02808	0.05006	57
58	0.010309	13.046	0.216	13.262	13.934	11.197	25.131	0.02855	0.05132	58
59	0.010692	13.071	0.224	13.295	14.174	11.618	25.792	0.02901	0.05259	59
60	0.011087	13.096	0.233	13.329	14.415	12.052	26.467	0.02947	0.05389	60
61	0.011496	13.122	0.242	13.364	14.655	12.502	27.157	0.02994	0.05522	61
62	0.011919	13.147	0.251	13.398	14.895	12.966	27.862	0.03040	0.05657	62
63	0.012355	13.172	0.261	13.433	15.135	13.446	28.582	0.03086	0.05795	63
64	0.012805	13.198	0.271	13.468	15.376	13.942	29.318	0.03132	0.05936	64
65	0.013270	13.223	0.281	13.504	15.616	14.454	30.071	0.03178	0.06080	65
66	0.013750	13.248	0.292	13.540	15.856	14.983	30.840	0.03223	0.06226	66
67	0.014246	13.273	0.303	13.577	16.097	15.530	31.626	0.03269	0.06376	67
68	0.014758	13.299	0.315	13.613	16.337	16.094	32.431	0.03315	0.06529	68
69	0.015286	13.324	0.326	13.650	16.577	16.677	33.254	0.03360	0.06685	69

Subscripts da = dry air, s = moist air at saturation, as = difference

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Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 Psia (cont'd)

Temp., °F	Humidity Ratio at Saturation, $\frac{lb_w}{lb_{da}}$	Specific Volume, $\frac{ft^3}{lb_{da}}$			Specific Enthalpy, $\frac{Btu}{lb_{da}}$			Specific Entropy, $\frac{Btu}{lb_{da}\text{-}°F}$		Temp., °F
T	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	T
70	0.015832	13.349	0.339	13.688	16.818	17.279	34.097	0.03406	0.06844	70
71	0.016395	13.375	0.351	13.726	17.058	17.901	34.959	0.03451	0.07007	71
72	0.016976	13.400	0.365	13.764	17.299	18.543	35.841	0.03496	0.07173	72
73	0.017575	13.425	0.378	13.803	17.539	19.204	36.743	0.03541	0.07343	73
74	0.018194	13.450	0.392	13.843	17.779	19.889	37.668	0.03586	0.07516	74
75	0.018833	13.476	0.407	13.882	18.020	20.595	38.615	0.03631	0.07694	75
76	0.019491	13.501	0.422	13.923	18.260	21.323	39.583	0.03676	0.07875	76
77	0.020170	13.526	0.437	13.963	18.500	22.075	40.576	0.03721	0.08060	77
78	0.020871	13.551	0.453	14.005	18.741	22.851	41.592	0.03766	0.08250	78
79	0.021594	13.577	0.470	14.046	18.981	23.652	42.633	0.03811	0.08444	79
80	0.022340	13.602	0.487	14.089	19.222	24.479	43.701	0.03855	0.08642	80
81	0.023109	13.627	0.505	14.132	19.462	25.332	44.794	0.03900	0.08844	81
82	0.023902	13.653	0.523	14.175	19.702	26.211	45.913	0.03944	0.09052	82
83	0.024720	13.678	0.542	14.220	19.943	27.120	47.062	0.03988	0.09264	83
84	0.025563	13.703	0.561	14.264	20.183	28.055	48.238	0.04033	0.09481	84
85	0.026433	13.728	0.581	14.310	20.424	29.021	49.445	0.04077	0.09703	85
86	0.027329	13.754	0.602	14.356	20.664	30.017	50.681	0.04121	0.09930	86
87	0.028254	13.779	0.624	14.403	20.905	31.045	51.949	0.04165	0.10163	87
88	0.029208	13.804	0.646	14.450	21.145	32.105	53.250	0.04209	0.10401	88
89	0.030189	13.829	0.669	14.498	21.385	33.197	54.582	0.04253	0.10645	89
90	0.031203	13.855	0.692	14.547	21.626	34.325	55.951	0.04297	0.10895	90
Subscripts da = dry air, s = moist air at saturation, as = difference										

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Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 14.696 Psia (cont'd)

Temp., °F	Humidity Ratio at Saturation, $\frac{lb_w}{lb_{da}}$	Specific Volume, $\frac{ft^3}{lb_{da}}$			Specific Enthalpy, $\frac{Btu}{lb_{da}}$			Specific Entropy, $\frac{Btu}{lb_{da}-°F}$		Temp., °F
T	W_s	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	T
91	0.032247	13.880	0.717	14.597	21.866	35.489	57.355	0.04340	0.11150	91
92	0.033323	13.905	0.742	14.647	22.107	36.687	58.794	0.04384	0.11412	92
93	0.034433	13.930	0.768	14.699	22.347	37.924	60.271	0.04427	0.11680	93
94	0.035577	13.956	0.795	14.751	22.588	39.199	61.787	0.04471	0.11955	94
95	0.036757	13.981	0.823	14.804	22.828	40.515	63.343	0.04514	0.12237	95
96	0.037972	14.006	0.852	14.858	23.069	41.871	64.940	0.04558	0.12525	96
97	0.039225	14.032	0.881	14.913	23.309	43.269	66.578	0.04601	0.12821	97
98	0.040516	14.057	0.912	14.969	23.550	44.711	68.260	0.04644	0.13124	98
99	0.041848	14.082	0.944	15.026	23.790	46.198	69.988	0.04687	0.13434	99
100	0.043219	14.107	0.976	15.084	24.031	47.730	71.761	0.04730	0.13752	100
101	0.044634	14.133	1.010	15.143	24.271	49.312	73.583	0.04773	0.14079	101
102	0.046090	14.158	1.045	15.203	24.512	50.940	75.452	0.04816	0.14413	102
103	0.047592	14.183	1.081	15.264	24.752	52.621	77.373	0.04859	0.14756	103
104	0.049140	14.208	1.118	15.326	24.993	54.354	79.346	0.04901	0.15108	104
105	0.050737	14.234	1.156	15.390	25.233	56.142	81.375	0.04944	0.15469	105
106	0.052383	14.259	1.196	15.455	25.474	57.986	83.460	0.04987	0.15839	106
107	0.054077	14.284	1.236	15.521	25.714	59.884	85.599	0.05029	0.16218	107
108	0.055826	14.309	1.279	15.588	25.955	61.844	87.799	0.05071	0.16608	108
109	0.057628	14.335	1.322	15.657	26.195	63.866	90.061	0.05114	0.17008	109
110	0.059486	14.360	1.367	15.727	26.436	65.950	92.386	0.05156	0.17418	110
Subscripts da = dry air, s = moist air at saturation, as = difference										

* Extrapolated to represent metastable equilibrium with undercooled liquid

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 1, Psychrometrics, Table 2.

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7.5 Thermodynamic Properties of Water

Thermodynamic Properties of Water at Saturation up to 32°F

Temp., °F	Absolute Pressure, psia	Specific Volume, $\frac{ft^3}{lb_w}$			Specific Enthalpy, $\frac{Btu}{lb_w}$			Specific Entropy, $\frac{Btu}{lb_w\text{-}°F}$			Temp., °F
T	p_{ws}	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T
−20	0.0062	0.0174	42,333.00	42,333.00	−168.16	1220.39	1052.22	−0.3448	2.7757	2.4309	−20
−19	0.0066	0.0174	40,073.00	40,073.00	−167.71	1220.38	1052.67	−0.3438	2.7694	2.4256	−19
−18	0.0069	0.0174	37,943.00	37,943.00	−167.26	1220.37	1053.11	−0.3428	2.7631	2.4203	−18
−17	0.0073	0.0174	35,934.00	35,934.00	−166.81	1220.36	1053.55	−0.3418	2.7568	2.4151	−17
−16	0.0078	0.0174	34,041.00	34,041.00	−166.35	1220.34	1053.99	−0.3407	2.7506	2.4098	−16
−15	0.0082	0.0174	32,256.00	32,256.00	−165.90	1220.33	1054.43	−0.3397	2.7444	2.4046	−15
−14	0.0087	0.0174	30,572.00	30,572.00	−165.44	1220.31	1054.87	−0.3387	2.7382	2.3995	−14
−13	0.0092	0.0174	28,983.00	28,983.00	−164.98	1220.30	1055.32	−0.3377	2.7320	2.3943	−13
−12	0.0097	0.0174	27,483.00	27,483.00	−164.52	1220.28	1055.76	−0.3366	2.7259	2.3892	−12
−11	0.0103	0.0174	26,067.00	26,067.00	−164.06	1220.26	1056.20	−0.3356	2.7197	2.3841	−11
−10	0.0108	0.0174	24,730.00	24,730.00	−163.60	1220.24	1056.64	−0.3346	2.7136	2.3791	−10
−9	0.0114	0.0174	23,467.00	23,467.00	−163.14	1220.22	1057.08	−0.3335	2.7076	2.3740	−9
−8	0.0121	0.0174	22,274.00	22,274.00	−162.68	1220.20	1057.53	−0.3325	2.7015	2.3690	−8
−7	0.0127	0.0174	21,147.00	21,147.00	−162.21	1220.18	1057.97	−0.3315	2.6955	2.3640	−7
−6	0.0135	0.0174	20,081.00	20,081.00	−161.75	1220.16	1058.41	−0.3305	2.6895	2.3591	−6
−5	0.0142	0.0174	19,074.00	19,074.00	−161.28	1220.13	1058.85	−0.3294	2.6836	2.3541	−5
−4	0.0150	0.0174	18,121.00	18,121.00	−160.82	1220.11	1059.29	−0.3284	2.6776	2.3492	−4
−3	0.0158	0.0174	17,220.00	17,220.00	−160.35	1220.08	1059.73	−0.3274	2.6717	2.3443	−3
−2	0.0167	0.0174	16,367.00	16,367.00	−159.88	1220.05	1060.17	−0.3264	2.6658	2.3394	−2
−1	0.0176	0.0174	15,561.00	15,561.00	−159.41	1220.02	1060.62	−0.3253	2.6599	2.3346	−1
0	0.0185	0.0174	14,797.00	14,797.00	−158.94	1220.00	1061.06	−0.3243	2.6541	2.3298	0
1	0.0195	0.0174	14,073.00	14,073.00	−158.47	1219.96	1061.50	−0.3233	2.6482	2.3249	1
2	0.0205	0.0174	13,388.00	13,388.00	−157.99	1219.93	1061.94	−0.3223	2.6424	2.3202	2

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Thermodynamic Properties of Water at Saturation up to 32°F (cont'd)

Temp., °F	Absolute Pressure, psia	Specific Volume, $\frac{ft^3}{lb_w}$			Specific Enthalpy, $\frac{Btu}{lb_w}$			Specific Entropy, $\frac{Btu}{lb_w\text{-}°F}$			Temp., °F
T	p_{ws}	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T
3	0.0216	0.0174	12,740.00	12,740.00	−157.52	1219.90	1062.38	−0.3212	2.6367	2.3154	3
4	0.0228	0.0174	12,125.00	12,125.00	−157.05	1219.87	1062.82	−0.3202	2.6309	2.3107	4
5	0.0240	0.0174	11,543.00	11,543.00	−156.57	1219.83	1063.26	−0.3192	2.6252	2.3060	5
6	0.0252	0.0174	10,991.00	10,991.00	−156.09	1219.80	1063.70	−0.3182	2.6194	2.3013	6
7	0.0266	0.0174	10,468.00	10,468.00	−155.62	1219.76	1064.14	−0.3171	2.6138	2.2966	7
8	0.0279	0.0174	9971.00	9971.00	−155.14	1219.72	1064.58	−0.3161	2.6081	2.2920	8
9	0.0294	0.0174	9500.00	9500.00	−154.66	1219.68	1065.03	−0.3151	2.6024	2.2873	9
10	0.0309	0.0174	9054.00	9054.00	−154.18	1219.64	1065.47	−0.3141	2.5968	2.2827	10
11	0.0325	0.0174	8630.00	8630.00	−153.70	1219.60	1065.91	−0.3130	2.5912	2.2782	11
12	0.0341	0.0174	8228.00	8228.00	−153.21	1219.56	1066.35	−0.3120	2.5856	2.2736	12
13	0.0359	0.0175	7846.00	7846.00	−152.73	1219.52	1066.79	−0.3110	2.5801	2.2691	13
14	0.0377	0.0175	7483.00	7483.00	−152.24	1219.47	1067.23	−0.3100	2.5745	2.2645	14
15	0.0396	0.0175	7139.00	7139.00	−151.76	1219.43	1067.67	−0.3089	2.5690	2.2600	15
16	0.0416	0.0175	6811.00	6811.00	−151.27	1219.38	1068.11	−0.3079	2.5635	2.2556	16
17	0.0437	0.0175	6501.00	6501.00	−150.78	1219.33	1068.55	−0.3069	2.5580	2.2511	17
18	0.0458	0.0175	6205.00	6205.00	−150.30	1219.28	1068.99	−0.3059	2.5526	2.2467	18
19	0.0481	0.0175	5924.00	5924.00	−149.81	1219.23	1069.43	−0.3049	2.5471	2.2423	19
20	0.0505	0.0175	5657.00	5657.00	−149.32	1219.18	1069.87	−0.3038	2.5417	2.2379	20
21	0.0530	0.0175	5404.00	5404.00	−148.82	1219.13	1070.31	−0.3028	2.5363	2.2335	21
22	0.0556	0.0175	5162.00	5162.00	−148.33	1219.08	1070.75	−0.3018	2.5309	2.2292	22
23	0.0583	0.0175	4932.00	4932.00	−147.84	1219.02	1071.19	−0.3008	2.5256	2.2248	23
24	0.0611	0.0175	4714.00	4714.00	−147.34	1218.97	1071.63	−0.2997	2.5203	2.2205	24
25	0.0641	0.0175	4506.00	4506.00	−146.85	1218.91	1072.07	−0.2987	2.5149	2.2162	25

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Thermodynamic Properties of Water at Saturation up to 32°F (cont'd)

Temp., °F	Absolute Pressure, psia	Specific Volume, $\frac{ft^3}{lb_w}$			Specific Enthalpy, $\frac{Btu}{lb_w}$			Specific Entropy, $\frac{Btu}{lb_w\text{-}°F}$			Temp., °F
T	p_{ws}	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	T
26	0.0671	0.0175	4308.00	4308.00	−146.35	1218.85	1072.50	−0.2977	2.5096	2.2119	26
27	0.0703	0.0175	4119.00	4119.00	−145.85	1218.80	1072.94	−0.2967	2.5044	2.2077	27
28	0.0737	0.0175	3940.00	3940.00	−145.35	1218.74	1073.38	−0.2956	2.4991	2.2035	28
29	0.0772	0.0175	3769.00	3769.00	−144.85	1218.68	1073.82	−0.2946	2.4939	2.1992	29
30	0.0809	0.0175	3606.00	3606.00	−144.35	1218.61	1074.26	−0.2936	2.4886	2.1951	30
31	0.0847	0.0175	3450.00	3450.00	−143.85	1218.55	1074.70	−0.2926	2.4834	2.1909	31
32	0.0886	0.0175	3302.00	3302.00	−143.35	1218.49	1075.14	−0.2915	2.4783	2.1867	32
Transitions from saturated solid to saturated liquid. Difference in enthalpy h_f between these two states is referred to as the latent heat of fusion.											
32*	0.0887	0.0160	3302.02	3302.04	−0.02	1075.15	1075.14	0.0000	2.1867	2.1867	32*

For temperatures greater than 32°F, refer to "Flow Rate of Steam in Schedule 40 Pipe" in Chapter 6.

*Extrapolated to represent metastable equilibrium with undercooled liquid

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 1, Psychrometrics, Table 3.

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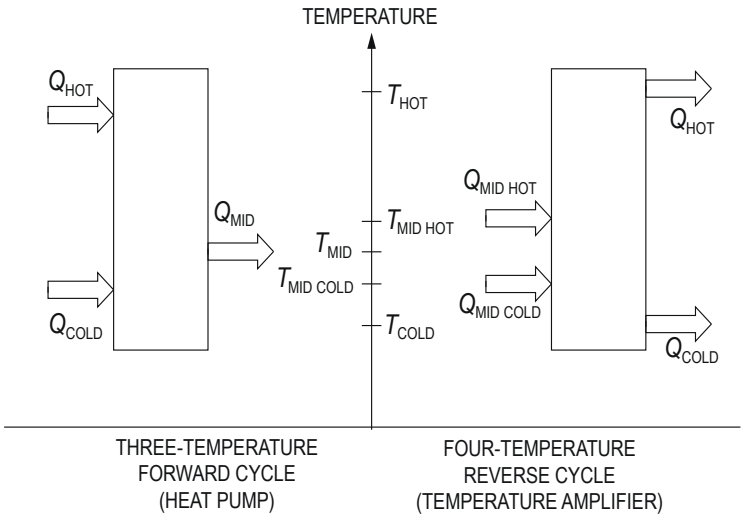
8 REFRIGERATION

8.1 Compression Refrigeration Cycles

Refer to Chapter 4, Thermodynamics, for additional information on compression refrigeration cycles.

8.2 Absorption Refrigeration Cycles

8.2.1 Thermal Cycles



Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 2, Thermodynamics and Refrigeration Cycles, Fig. 16.

All absorption cycles include at least three energy exchanges with their surroundings:

1. Highest to lowest temperature heat flows are in one direction and the mid-temperature (one or two) is in the opposite direction.
2. In a *forward cycle*, the extreme (hottest to coldest) heat flows are *into* the cycle. This cycle is also called the heat amplifier heat pump, conventional cycle, or Type I cycle.
3. A *reverse cycle*, heat transformer, temperature amplifier, temperature booster, or Type II cycle is when extreme temperature heat flows are *out of* the cycle.

By the first law of thermodynamics (at steady state):

$$Q_{hot} + Q_{cold} = -Q_{mid}$$ Positive heat quantities are into the cycle.

The second law of thermodynamics requires that

$$\frac{Q_{hot}}{T_{hot}} + \frac{Q_{cold}}{T_{cold}} + \frac{Q_{mid}}{T_{mid}} \geq 0$$ with equality holding in the ideal case

The ideal forward cycles becomes

$$\text{COP}_{\text{ideal}} = \frac{Q_{\text{cold}}}{Q_{\text{hot}}} = \frac{T_{\text{hot}} - T_{\text{mid}}}{T_{\text{hot}}} \times \frac{T_{\text{cold}}}{T_{\text{mid}} - T_{\text{cold}}}$$

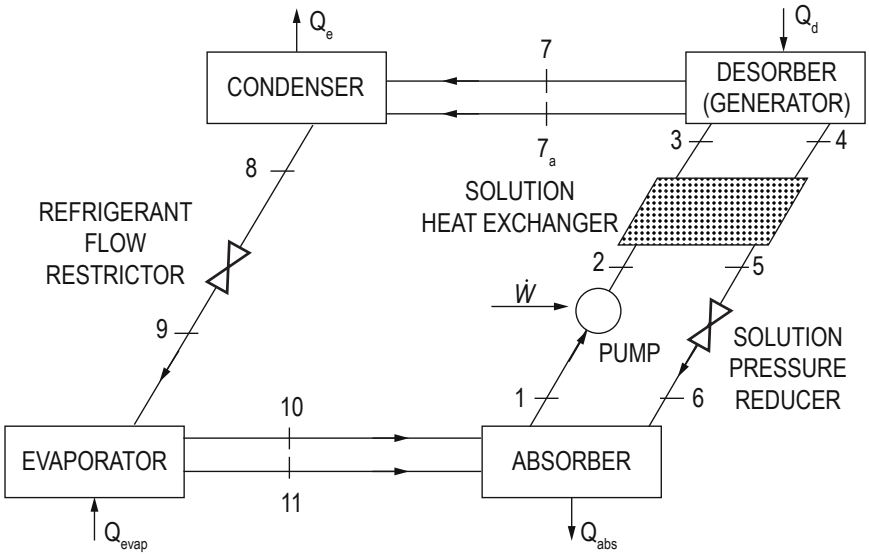
Heat rejected to ambient may be at two different temperatures, creating a *four-temperature cycle*. The $\text{COP}_{\text{ideal}}$ for a four-temperature cycle is calculated with T_{mid} as follows

$$T_{\text{mid}} = \frac{Q_{\text{mid hot}} + Q_{\text{mid cold}}}{\frac{Q_{\text{mid hot}}}{T_{\text{mid hot}}} + \frac{Q_{\text{mid cold}}}{T_{\text{mid cold}}}}$$

For a four-temperature cycle, assuming $Q_{\text{cold}} = Q_{\text{mid cold}}$ and $Q_{\text{hot}} = Q_{\text{mid hot}}$ the result is

$$\text{COP}_{\text{ideal}} = \frac{T_{\text{hot}} - T_{\text{mid hot}}}{T_{\text{hot}}} \times \frac{T_{\text{cold}}}{T_{\text{mid cold}}} \times \frac{T_{\text{cold}}}{T_{\text{mid hot}}}$$

8.2.2 Single-Effect Absorption Cycle



Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 2, Thermodynamics and Refrigeration Cycles, Fig. 17.

Absorption cycles require at least two working substances: a sorbent and a fluid refrigerant. These substances undergo phase changes.

For the *forward absorption cycle*, the highest-temperature heat is always supplied to the generator

$$Q_{\text{hot}} \equiv Q_{\text{gen}}$$

and the coldest heat is supplied to the evaporator

$$Q_{\text{cold}} \equiv Q_{\text{evap}}$$

For the *reverse absorption cycle* (also called heat transformer or Type II absorption cycle), the highest-temperature heat is rejected from the absorber, and the lowest-temperature heat is rejected from the condenser.

For all known refrigerants and sorbents over pressure ranges of interest:

$$Q_{\text{evap}} \approx Q_{\text{cond}} \quad \text{and} \quad Q_{\text{gen}} \approx Q_{\text{abs}}$$

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The ideal, single-effect, forward-cycle COP expression is

$$\text{COP}_{\text{ideal}} \le \frac{T_{\text{gen}} - T_{\text{abs}}}{T_{\text{gen}}} \times \frac{T_{\text{evap}}}{T_{\text{cond}} - T_{\text{evap}}} \times \frac{T_{\text{cond}}}{T_{\text{abs}}}$$

$$\text{Lift} = (T_{\text{cond}} - T_{\text{evap}})$$

$$\text{Drop} = (T_{\text{gen}} - T_{\text{abs}})$$

For most absorbents,

$$\frac{Q_{\text{abs}}}{Q_{\text{cond}}} \approx 1.2 \text{ to } 1.3 \quad \text{and} \quad T_{\text{gen}} - T_{\text{abs}} = 1.2\left(T_{\text{cond}} - T_{\text{evap}}\right)$$

Applying approximations and constraints, the ideal cycle COP for the single-effect forward cycle is

$$\text{COP}_{\text{ideal}} \approx 1.2\frac{T_{\text{evap}}\,T_{\text{cond}}}{T_{\text{gen}}\,T_{\text{abs}}} \approx \frac{Q_{\text{cond}}}{Q_{\text{abs}}} \approx 0.8$$

Another useful result is

$$T_{\text{gen min}} = T_{\text{cond}} + T_{\text{abs}} - T_{\text{evap}}$$

where $T_{\text{gen min}}$ = minimum generator temperature necessary to achieve the given evaporator temperature

Another expression for $\text{COP}_{\text{ideal}}$ is

$$\text{COP}_{\text{ideal}} \le \frac{T_{\text{evap}}}{T_{\text{abs}}} = \frac{T_{\text{cond}}}{T_{\text{gen}}}$$

8.3 Condensers

8.3.1 Water-Cooled Condensers

The volumetric flow rate of condensing water required can be calculated from

$$Q = \frac{q_o}{\rho c_{\text{p}}\left(t_2 - t_1\right)}$$

where

Q = volumetric flow rate of water $\left(\frac{\text{ft}^3}{\text{hr}}\right)$ (multiply $\frac{\text{ft}^3}{\text{hr}}$ by 0.125 to obtain gpm)

q_{o} = heat rejection rate $\left(\frac{\text{Btu}}{\text{hr}}\right)$

ρ = density of water $\left(\frac{\text{lb}}{\text{ft}^3}\right)$

c_{p} = specific heat of water at constant pressure $\left(\frac{\text{Btu}}{\text{lb-°F}}\right)$

t_1 = temperature of water entering condenser (°F)

t_2 = temperature of water leaving condenser (°F)

The pressure drop through tubes can be calculated from a modified Darcy-Weisbach equation

$$\Delta p = N_{\text{p}}\left(K_{\text{h}} + f\frac{L}{D}\right)\frac{\rho v^2}{2g_c}$$

where

Δp = pressure drop (lbf/ft^2)

N_{p} = number of tube passes

K_{h} = entrance and exit flow resistance and flow reversal coefficient, number of velocity heads $\left(\frac{v^2}{2g_c}\right)$

f = friction factor

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L = length of tube (ft)

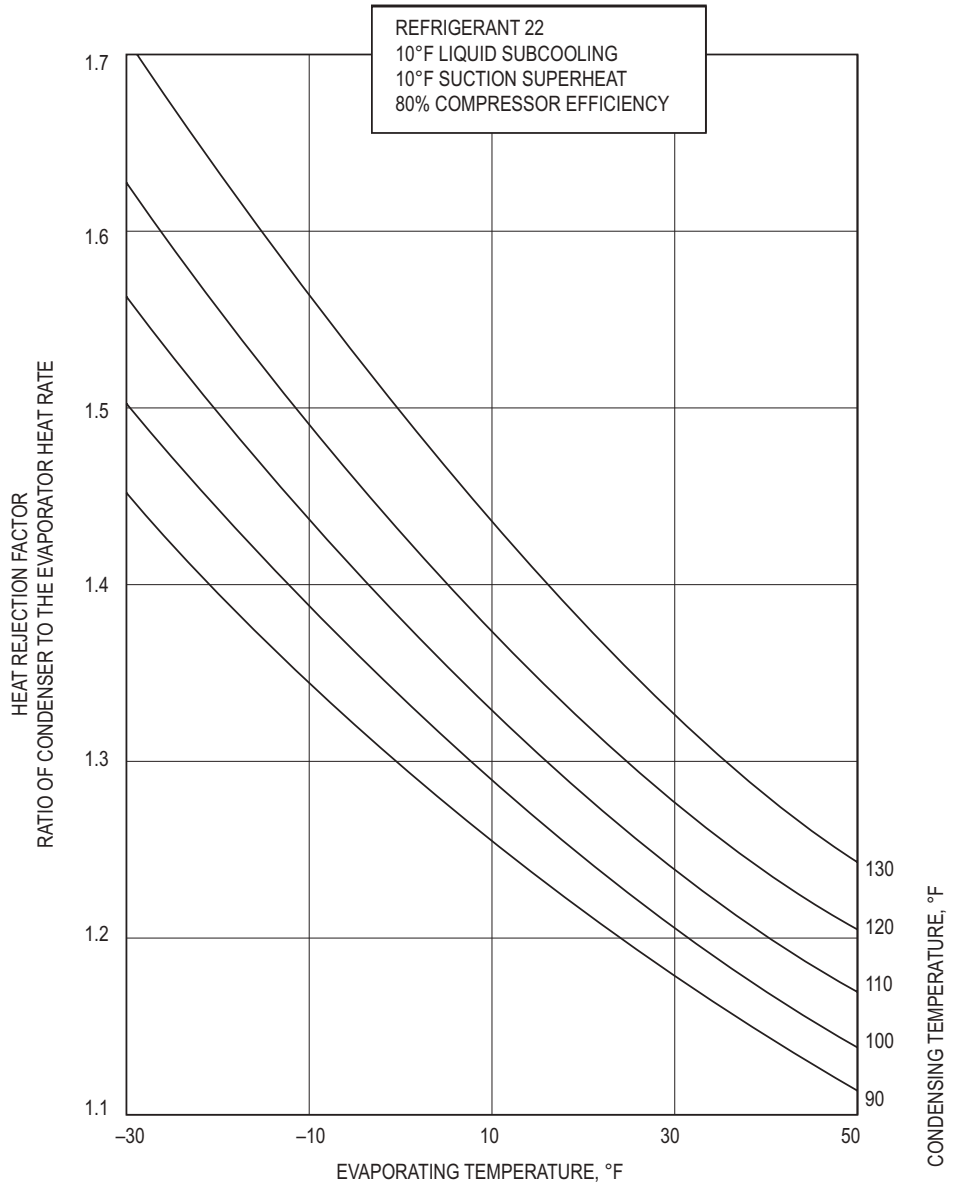
D = inside tube diameter (ft)

ρ = fluid density (lb/ft^3)

v = fluid velocity (fps)

g_c = gravitational constant = $32.174 \frac{\text{lbm-ft}}{\text{lbf-sec}^2}$

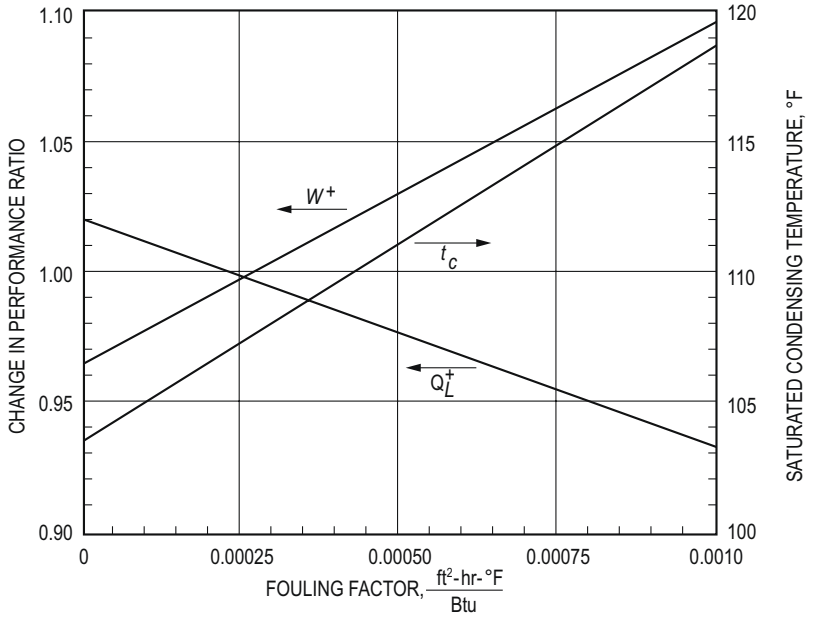
Heat Removed in R-22 Condenser



Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 39, Condensers, Fig. 1.

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Effect of Condenser Fouling on Chiller Performance



Q_L^+ = chiller actual capacity/chiller design capacity

W^+ = compressor actual kW/compressor design kW

t_c = saturated condensing temperature (°F)

Design condenser fouling factor = 0.00025 ft²-hr-°F/Btu

Cooler leaving-water temperature = 44°F

Condenser entering-water temperature = 85°F

Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 39, Condensers, Fig. 5.

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8.4 Refrigeration Evaporator: Top-Feed Versus Bottom-Feed

Advantages of top-feed:

1. Smaller refrigerant charge
2. Possible absence of static pressure penalty
3. Better oil return
4. Quicker, simpler defrost arrangement

Advantages of bottom-feed:

1. Less critical distribution considerations
2. Less important relative locations of evaporators and low-pressure receivers
3. Simpler systems design and layout

Source: ©ASHRAE, www.ashrae.org., *2010 ASHRAE Handbook—Refrigeration, Chapter 4*, Liquid Overfeed Systems, Section 4.6.

Recommended Minimum Refrigerant Circulating Rate

Refrigerant	Circulating Rate*
Ammonia (R-717)	
Topfeed (large-diameter tubes)	6 to 7
Bottomfeed (small-diameter tubes)	2 to 4
R-22, upfeed	3
R-134a	2

*Circulating rate of 1 equals evaporating rate

Source: ©ASHRAE, www.ashrae.org., *2010 ASHRAE Handbook—Refrigeration*, Chapter 4, Liquid Overfeed Systems, Table 1.

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8.5 Liquid Refrigerant Flow

8.5.1 Liquid Overfeed Systems

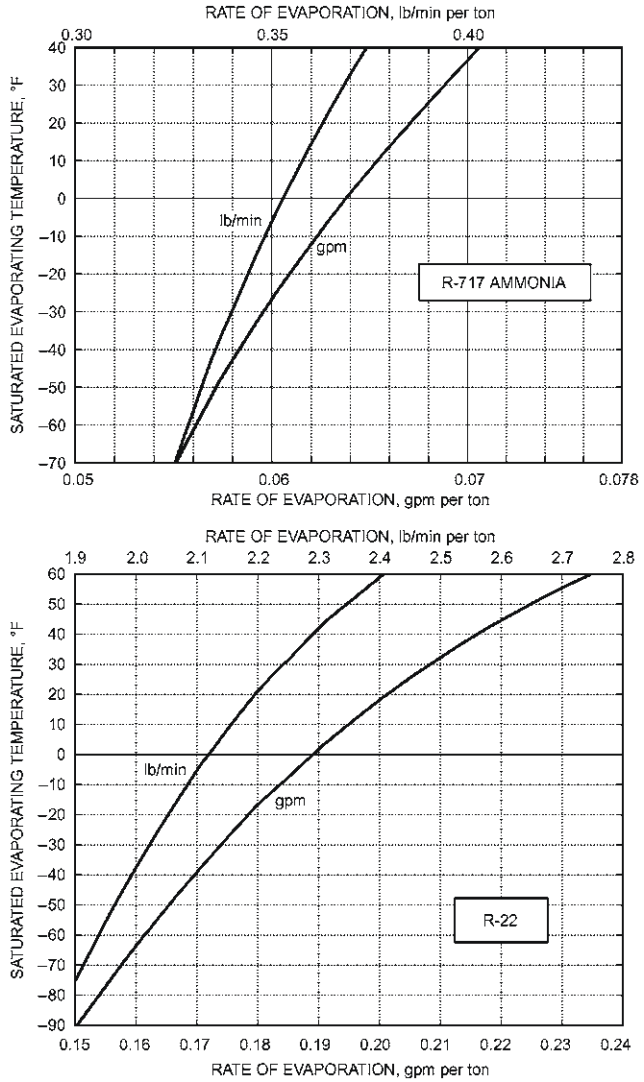


Fig. 7 Charts for Determining Rate of Refrigerant Feed (No Flash Gas)

Source: ©ASHRAE, www.ashrae.org., *2010 ASHRAE Handbook—Refrigeration*, Chapter 4, Liquid Overfeed Systems, Fig. 7.

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8.6 Comparative Refrigerant Performance per Ton of Refrigeration

Comparative Refrigerant Performance per Ton of Refrigeration

Refrigerant No.	Chemical Name or Composition (% by Mass)	Evaporator Pressure, psia	Condenser Pressure, psia	Compression Ratio	Net Refrigerating Effect, $\frac{Btu}{lb}$	Refrigerant Circulated, $\frac{lb}{min}$	Liquid Circulated, $\frac{gal}{min}$	Specific Vol. of Suction Gas, $\frac{ft^3}{lb}$	Compressor Displacement, $\frac{ft^3}{min}$	Power Consumption, hp	Coeff. of Performance	Compressor Discharge Temp., °F
Evaporator – 25°F/Condenser 86°F												
744	Carbon dioxide	195.7	1046.2	5.35	56.8	3.52	0.711	0.457	1.61	2.779	1.698	196.3
170	Ethane	146.8	675.1	4.60	66.0	3.03	1.314	0.878	2.66	2.805	1.681	136.2
502	R-22/115 (48.8/51.2)	26.5	189.2	7.14	42.1	4.76	0.480	1.480	7.06	1.722	2.739	106.3
22	Chlorodifluoromethane	22.1	172.9	7.81	66.8	3.00	0.307	2.320	6.95	1.589	2.967	149.8
717	Ammonia	16.0	169.3	10.61	463.9	0.43	0.087	16.700	7.19	1.569	3.007	285.6
Evaporator 20°F/Condenser 86°F												
744	Carbon dioxide	421.9	1046.2	2.48	55.7	3.59	0.726	0.203	0.73	1.342	3.514	142.3
170	Ethane	293.6	675.1	2.30	70.1	2.85	1.238	0.421	1.20	1.314	3.588	115.8
410A	R-32/125 (50/50)	93.2	273.6	2.94	73.5	2.72	0.316	0.651	1.77	0.815	5.780	115.8
1270	Propylene	69.1	189.3	2.74	126.6	1.58	0.381	1.580	2.50	0.790	5.975	102.8
502	R-22/115 (48.8/51.2)	66.3	189.2	2.86	47.1	4.25	0.429	0.619	2.63	0.813	5.799	95.8
22	Chlorodifluoromethane	57.8	172.9	2.99	71.3	2.80	0.287	0.935	2.62	0.772	6.105	118.0
407c	R-32/125/134a (23/25/52)	57.5	183.7	3.19	71.9	2.78	0.296	0.942	2.62	0.795	5.930	111.0
290	Propane	55.8	156.5	2.80	124.1	1.61	0.399	1.890	3.05	0.787	5.987	94.8
717	Ammonia	48.2	169.3	3.51	478.5	0.42	0.084	5.910	2.47	0.754	6.254	179.8
1234yf	2,3,3,3-tetrafluoropropene*	36.3	113.6	3.13	51.8	3.86	0.430	1.150	4.44	0.809	5.835	86.0
134a	Tetrafluoroethane	33.1	111.7	3.37	65.8	3.04	0.307	1.410	4.28	0.778	6.063	94.7
1234ze(E)	Trans-1,3,3,3-tetrafluoropropene	24.4	83.9	3.44	60.0	3.33	0.349	1.740	5.81	0.782	6.030	86.0
600a	Isobutane*	17.9	58.7	3.29	119.5	1.67	0.368	4.780	7.99	0.764	6.171	86.0
Evaporator 45°F/Condenser 86°F												
32	Difluoromethane	147.7	279.6	1.89	112.2	1.78	0.223	0.577	1.03	0.445	10.602	116.4
410A	R-32/125 (50/50)	145.0	273.6	1.89	75.2	2.66	0.308	0.416	1.11	0.455	10.379	103.7

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Comparative Refrigerant Performance per Ton of Refrigeration (cont'd)

Refrigerant No.	Chemical Name or Composition (% by Mass)	Evaporator Pressure, psia	Condenser Pressure, psia	Compression Ratio	Net Refrigerating Effect, $\frac{\text{Btu}}{\text{lb}}$	Refrigerant Circulated, $\frac{\text{lb}}{\text{min}}$	Liquid Circulated, $\frac{\text{gal}}{\text{min}}$	Specific Vol. of Suction Gas, $\frac{\text{ft}^3}{\text{lb}}$	Compressor Displacement, $\frac{\text{ft}^3}{\text{min}}$	Power Consumption., hp	Coeff. of Performance	Compressor Discharge Temp., °F
407c	R-32/125/134a (23/25/52)	92.8	183.7	1.98	74.7	2.68	0.284	0.588	1.57	0.443	10.655	102.7
22	Chlorodifluoromethane	90.8	172.9	1.90	73.5	2.72	0.279	0.604	1.64	0.433	10.885	104.5
290	Propane	85.3	156.5	1.84	130.7	1.53	0.379	1.260	1.92	0.439	10.743	90.7
717	Ammonia	81.0	169.3	2.09	484.9	0.41	0.083	3.610	1.49	0.421	11.186	137.4
1234yf	2,3,3,3-tetrafluoropropene*	58.1	113.6	1.96	55.5	3.61	0.402	0.726	2.62	0.444	10.623	86.0
12	Dichlorodifluoromethane	56.3	107.9	1.92	54.6	3.67	0.340	0.719	2.64	0.429	11.004	91.6
134a	Tetrafluoroethane	54.7	111.7	2.04	69.2	2.89	0.292	0.868	2.51	0.433	10.903	90.6
1234ze(E)	Trans-1,3,3,3-tetrafluoropropene	40.6	83.9	2.06	64.1	3.12	0.327	1.070	3.34	0.433	10.899	86.0
600a	Isobutane*	29.2	58.7	2.01	127.4	1.57	0.345	3.010	4.72	0.425	11.084	86.0
600	Butane*	19.5	41.1	2.11	140.5	1.42	0.301	4.570	6.50	0.420	11.226	86.0

* Superheat required
Source: Data from NIST CYCLE_D4.0, zero subcool, zero superheat unless noted, no line losses, 100% efficiencies, average temperatures.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 29, Refrigerants, Table 8.

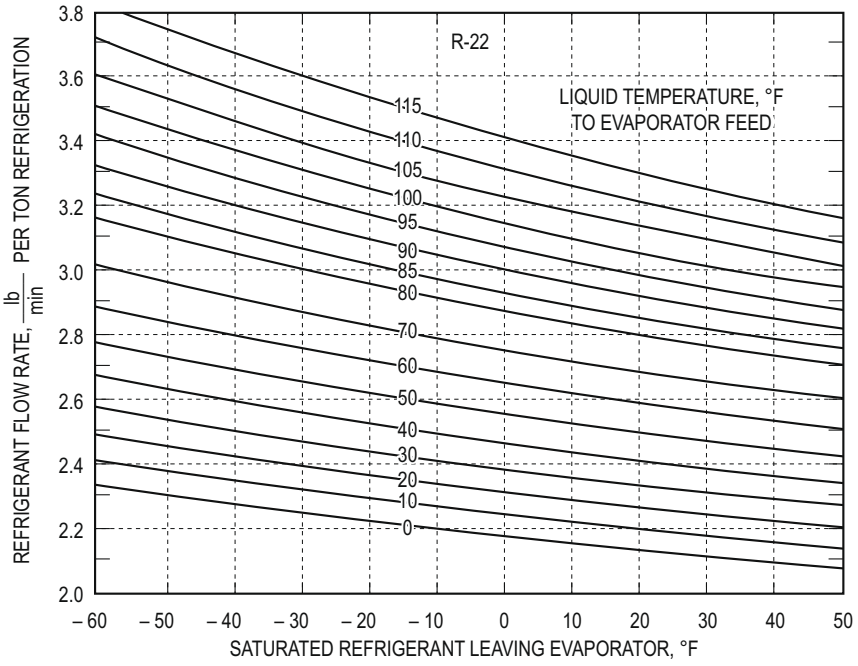
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8.7 Halocarbon Refrigeration Systems

8.7.1 Refrigerant R-22

Refrigerant flow rates for saturated evaporator temperatures are:

Flow Rate Per Ton of Refrigeration for Refrigerant 22



Source: ©ASHRAE, www.ashrae.org., *2014 ASHRAE Handbook—Refrigeration*, Chapter 1, Halocarbon Refrigeration Systems, Fig. 1.

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Suction Line Capacities, in Tons, for Refrigerant 22 (Single- or High-Stage Applications)

Line Size		Suction Lines (Δt = 2°F)				
		Saturated Suction Temperature, °F				
		–40	–20	0	20	40
Type L Copper, OD		Corresponding Δp, psi/100 feet				
		0.79	1.15	1.6	2.22	2.91
1/2		—	—	—	0.4	0.6
5/8		—	0.32	0.51	0.76	1.1
7/8		0.52	0.86	1.3	2	2.9
1-1/8		1.1	1.7	2.7	4	5.8
1-3/8		1.9	3.1	4.7	7	10.1
1-5/8		3	4.8	7.5	11.1	16
2-1/2		6.2	10	15.6	23.1	33.1
2-5/8		10.9	17.8	27.5	40.8	58.3
Steel		Corresponding Δp, psi/100 feet				
IPS	SCH	0.79	1.15	1.6	2.22	2.91
1/2	40	—	0.38	0.58	0.85	1.2
3/4	40	0.5	0.8	1.2	1.8	2.5
1	40	0.95	1.5	2.3	3.4	4.8
1-1/4	40	2	3.2	4.8	7	9.9
1-1/2	40	3	4.7	7.2	10.5	14.8
2	40	5.7	9.1	13.9	20.2	28.5
2-1/2	40	9.2	14.6	22.1	32.2	45.4

Notes for above and next table:

1. Table capacities are in tons of refrigeration.
   Δp = pressure drop from line friction, psi per 100 feet of equivalent line length
   Δt = corresponding change in saturation temperature, °F per 100 feet
2. Line capacity for other saturation temperature Δt and equivalent length L_e:

$$\text{Line Capacity} = \text{Table Capacity} \left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t} \right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent length L_e:

$$\Delta t = \text{Table } \Delta t \left(\frac{\text{Actual } L_e}{\text{Table } L_e} \right) \times \left(\frac{\text{Actual Capacity}}{\text{Table Capacity}} \right)^{1.8}$$

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4. Values based on 105°F condensing temperature. Multiply table capacities by the following factors for other condensing temperatures:

Condensing Temperature, °F	Suction Line	Discharge Line
80	1.11	0.79
90	1.07	0.88
100	1.03	0.95
110	0.97	1.04
120	0.90	1.10
130	0.86	1.18
140	0.80	1.26

Sizing shown is recommended where any gas generated in receiver must return up condensate line to condenser without restricting condensate flow. Water-cooled condensers, where receiver ambient temperature may be higher than refrigerant condensing temperature, fall into this category.

e. Line pressure drop Δp is conservative; if subcooling is substantial or line is short, a smaller size line may be used. Applications with very little subcooling or very long lines may require a larger line.

Discharge and Liquid Line Capacities, in Tons, for Refrigerant 22 (Single- or High-Stage Applications)

Line Size		Discharge Lines (Δt = 1°F, Δp = 3.05 psi)		Liquid Lines (See notes a and b)	
		Saturated Suction Temperature, °F			
Type L Copper, OD		–40	40	Velocity = 100 fpm	Δt = 1°F, Δp = 3.05 psi
1/2		0.75	0.85	2.3	3.6
5/8		1.4	1.6	3.7	6.7
7/8		3.7	4.2	7.8	18.2
1-1/8		7.5	8.5	13.2	37
1-3/8		13.1	14.8	20.2	64.7
1-5/8		20.7	23.4	28.5	102.5
2-1/2		42.8	48.5	49.6	213
2-5/8		75.4	85.4	76.5	376.9
Steel					
IPS	SCH				
1/2	80	1.5	1.7	3.8	5.7
3/4	80	3.3	3.7	6.9	12.8
1	80	6.1	6.9	11.5	25.2
1-1/4	80	12.6	14.3	20.6	54.1
1-1/2	80	19	21.5	28.3	82.6
2	80	36.6	41.4	53.8	192
2-1/2	80	58.1	65.9	76.7	305.8

Refer to previous table for notes.

Source: ©ASHRAE, www.ashrae.org., *2010 ASHRAE Handbook—Refrigeration*, Chapter 1, Halocarbon Refrigeration Systems,Table 1.

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Suction, Discharge, and Liquid Line Capacities, in Tons, for Refrigerant 22 (Intermediate or Low-Stage Duty)

Line Size	Suction Lines (Δt = 2°F)							Discharge Lines (Δt = 2°F)*	Liquid Lines (See notes a and b)	
Type L Copper, OD	Saturated Suction Temperature, °F									
	–90	–80	–70	–60	–50	–40	–30		Velocity = 100 fpm	Δt = 1°F, Δp = 3.05 psi
5/8								0.7	3.7	6.7
7/8	0.18	0.25	0.34	0.46	0.61	0.79	1.0	1.9	7.8	18.2
1-1/8	0.36	0.51	0.70	0.94	1.20	1.6	2.1	3.8	13.2	37.0
1-3/8	0.60	0.90	1.20	1.60	2.20	2.8	3.6	6.6	20.2	64.7
1-5/8	1.00	1.40	1.90	2.60	3.40	4.5	5.7	10.5	28.5	102.5
2-1/2	2.10	3.00	4.10	5.50	7.20	9.3	11.9	21.7	49.6	213.0
2-5/8	3.80	5.30	7.20	9.70	12.70	16.5	21.1	38.4	76.5	376.9

Notes:

1. Table capacities are in tons of refrigeration.
   Δp = pressure drop from line friction, psi per 100 feet of equivalent line length
   Δt = corresponding change in saturation temperature, °F per 100 feet
2. Line capacity for other saturation temperature Δt and equivalent length L_e:

$$\text{Line Capacity} = \text{Table Capacity}\left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t}\right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent length L_e:

$$\Delta t = \text{Table } \Delta t \left(\frac{\text{Actual } L_e}{\text{Table } L_e}\right) \times \left(\frac{\text{Actual Capacity}}{\text{Table Capacity}}\right)^{1.8}$$

4. Refer to refrigerant thermodynamic property tables for pressure drop corresponding to Δt.
5. Values based on 0°F condensing temperature. Multiply table capacities by the following factors for other condensing temperatures. Flow rates for discharge lines are based on –50 °F evaporating temperature.

Condensing Temperature, °F	Suction Line	Discharge Line
–30	1.09	0.58
–20	1.06	0.71
–10	1.03	0.85
0	1.00	1.00
10	0.97	1.20
20	0.94	1.45
30	0.90	1.80

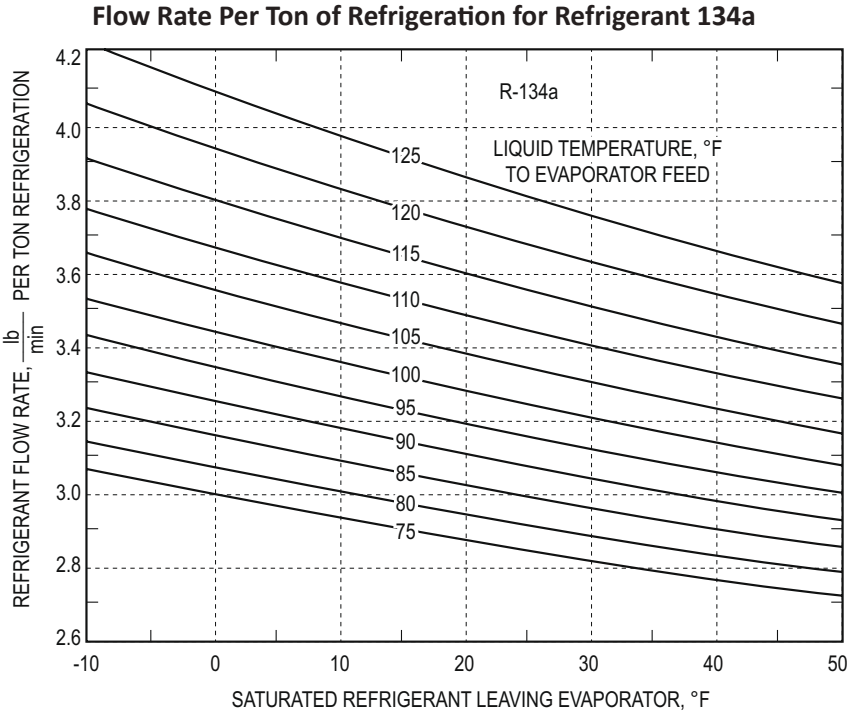
a. Sizing shown is recommended where any gas generated in receiver must return up condensate line to condenser without restricting condensate flow. Water-cooled condensers, where receiver ambient temperature may be higher than refrigerant condensing temperature, fall into this category.

b. Line pressure drop Δp is conservative; if subcooling is substantial or line is short, a smaller size line may be used. Applications with very little subcooling or very long lines may require a larger line.

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8.7.2 Refrigerant R-134a



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Suction Line Capacities in Tons for Refrigerant 134a (Single- or High-Stage Applications)

Line Size		Suction Lines (Δt = 2°F)				
		Saturated Suction Temperature, °F				
Type L Copper, OD		0	10	20	30	40
		Corresponding Δp, psi/100 feet				
		1.00	1.19	1.41	1.66	1.93
1/2		0.14	0.18	0.23	0.29	0.35
5/8		0.27	0.34	0.43	0.54	0.66
7/8		0.71	0.91	1.14	1.42	1.75
1-1/8		1.45	1.84	2.32	2.88	3.54
1-3/8		2.53	3.22	4.04	5.02	6.17
1-5/8		4.02	5.10	6.39	7.94	9.77
2-1/8		8.34	10.60	13.30	16.50	20.20
2-5/8		14.80	18.80	23.50	29.10	35.80
Steel						
IPS	SCH					
1/2	80	0.22	0.28	0.35	0.43	0.53
3/4	80	0.51	0.64	0.79	0.98	1.19
1	80	1.00	1.25	1.56	1.92	2.33
1-1/4	40	2.62	3.30	4.09	5.03	6.12
1-1/2	40	3.94	4.95	6.14	7.54	9.18
2	40	7.60	9.56	11.90	14.60	17.70
2-1/2	40	12.10	15.20	18.90	23.10	28.20

Notes for above and next table:

1. Table capacities are in tons of refrigeration.
   Δp = pressure drop from line friction, psi per 100 feet of equivalent line length
   Δt = corresponding change in saturation temperature, °F per 100 feet
2. Line capacity for other saturation temperature Δt and equivalent length L_e:

$$\text{Line Capacity} = \text{Table Capacity} \left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t} \right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent length L_e:

$$\Delta t = \text{Table } \Delta t \left(\frac{\text{Actual } L_e}{\text{Table } L_e} \right) \times \left(\frac{\text{Actual Capacity}}{\text{Table Capacity}} \right)^{1.8}$$

(Notes continued on next page)

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Discharge and Liquid Line Capacities in Tons for Refrigerant 134a (Single- or High-Stage Applications)

Line Size		Discharge Lines (Δt = 1°F, Δp = 2.2 psi/100 feet)			Liquid Lines (See notes a and b)	
		Saturated Suction Temperature, °F				
Type L Copper, OD		0	20	40	Velocity = 100 fpm	Δt = 1°F, Δp = 2.2 psi
1/2		0.54	0.57	0.59	2.13	2.79
5/8		1.01	1.07	1.12	3.42	5.27
7/8		2.67	2.81	2.94	7.09	14.00
1-1/8		5.4	5.68	5.95	12.10	28.40
1-3/8		9.42	9.91	10.4	18.40	50.00
1-5/8		14.9	15.7	16.4	26.10	78.60
2-1/8		30.8	32.4	34	45.30	163.00
2-5/8		54.4	57.2	59.9	69.90	290.00
Steel						
IPS	SCH					
1/2	80	0.79	0.84	0.88	3.43	4.38
3/4	80	1.79	1.88	1.97	6.34	9.91
1	80	3.51	3.69	3.86	10.50	19.50
1-1/4	80	9.20	9.68	10.10	18.80	41.80
1-1/2	80	13.80	14.50	15.20	25.90	63.70
2	40	26.60	28.00	29.30	49.20	148.00
2-1/2	40	42.40	44.60	46.70	70.10	236.00

4. Values based on 105°F condensing temperature. Multiply table capacities by the following factors for other condensing temperatures:

Condensing Temperature, °F	Suction Line	Discharge Line
80	1.158	0.804
90	1.095	0.882
100	1.032	0.961
110	0.968	1.026
120	0.902	1.078
130	0.834	1.156

a. Sizing shown is recommended where any gas generated in receiver must return up condensate line to condenser without restricting condensate flow. Water-cooled condensers, where receiver ambient temperature may be higher than refrigerant condensing temperature, fall into this category.

b. Line pressure drop Δp is conservative; if subcooling is substantial or line is short, a smaller size line may be used. Applications with very little subcooling or very long lines may require a larger line.

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8.7.3 Refrigerant R-717

Ammonia Refrigeration Systems

Suction Line Capacities in Tons for Ammonia with Pressure Drops of 0.25 and 0.50°F per 100 ft Equivalent

Steel Line Size		Saturated Suction Temperature, °F					
		–60		–40		–20	
IPS	SCH	Δt = 0.25°F Δp = 0.046	Δt = 0.50°F Δp = 0.092	Δt = 0.25°F Δp = 0.077	Δt = 0.50°F Δp = 0.155	Δt = 0.25°F Δp = 0.123	Δt = 0.50°F Δp = 0.245
3/8	80	0.03	0.05	0.06	0.09	0.11	0.16
1/2	80	0.06	0.10	0.12	0.18	0.22	0.32
3/4	80	0.15	0.22	0.28	0.42	0.50	0.73
1	80	0.30	0.45	0.57	0.84	0.99	1.44
1 1/4	80	0.68	1.09	1.26	1.84	2.18	3.17
1 1/2	80	1.05	1.54	1.95	2.83	3.35	4.86
2	40	2.43	3.57	4.54	6.59	7.79	11.26
2 1/2	40	3.94	5.78	7.23	10.56	12.50	18.03
3	40	7.10	10.30	13.00	18.81	22.23	32.09
4	40	14.77	21.21	26.81	38.62	45.66	65.81
5	40	26.66	38.65	48.68	70.07	82.70	119.60
6	40	43.48	62.83	79.18	114.26	134.37	193.44
8	40	90.07	129.79	163.48	235.38	277.80	397.55
10	40	164.26	236.39	297.51	427.71	504.98	721.08
12	ID*	264.07	379.88	477.55	686.10	808.93	1157.59
Steel Line Size		**Saturated Suction Temperature, °F**					
		0		**20**		**40**	
IPS	**SCH**	Δt = 0.25°F Δp = 0.184	Δt = 0.50°F Δp = 0.368	Δt = 0.25°F Δp = 0.265	Δt = 0.50°F Δp = 0.530	Δt = 0.25°F Δp = 0.366	Δt = 0.50°F Δp = 0.582
3/8	80	0.18	0.26	0.28	0.40	0.41	0.53
1/2	80	0.36	0.52	0.55	0.80	0.82	1.05
3/4	80	0.82	1.18	1.26	1.83	1.87	2.38
1	80	1.62	2.34	2.50	3.60	3.68	4.69
1 1/4	80	3.55	5.13	5.47	8.16	8.06	10.25
1 1/2	80	5.43	7.82	8.38	12.01	12.03	15.62
2	40	12.57	18.12	19.35	27.74	28.45	36.08
2 1/2	40	20.19	28.94	30.98	44.30	45.37	57.51
3	40	35.87	51.35	54.98	78.50	80.40	101.93
4	40	73.56	105.17	112.34	160.57	164.44	208.34
5	40	133.12	190.55	203.53	289.97	296.88	376.18
6	40	216.05	308.62	329.59	469.07	480.96	609.57
8	40	444.56	633.82	676.99	962.47	985.55	1250.34
10	40	806.47	1148.72	1226.96	1744.84	1786.55	2263.99
12	ID*	1290.92	1839.28	1964.56	2790.37	2862.23	3613.23

Note: Capacities are in tons of refrigeration resulting in a line friction loss (Δp in psi per 100 ft equivalent pipe length), with corresponding change (Δt in °F per 100 ft) in saturation temperature.

*The inside diameter of the pipe is the same as the nominal pipe size.

Source: ©ASHRAE, www.ashrae.org., *2014 ASHRAE Handbook—Refrigeration*, Chapter 2, Ammonia Refrigeration Systems, Table 1.

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Suction, Discharge, and Liquid Line Capacities in Tons for Ammonia (Single- or High-Stage Applications)

Steel Line Size		Suction Lines (Δt = 1°F) Saturated Suction Temperature, °F					Discharge Lines	Steel Line Size		Liquid Lines	
IPS	SCH	–40 Δp = 0.31	–20 Δp = 0.49	0 Δp = 0.73	20 Δp = 1.06	40 Δp = 1.46	Δt = 1°F Δp = 2.95	IPS	SCH	Velocity = 100 fpm	Δp =2.0 psi Δt = 0.7°F
3/8	80	—	—	—	—	—	—	3/8	80	8.6	12.1
1/2	80	—	—	—	—	—	3.1	1/2	80	14.2	24.0
3/4	80	—	—	—	2.6	3.8	7.1	3/4	80	26.3	54.2
1	80	—	2.1	3.4	5.2	7.6	13.9	1	80	43.8	106.4
1 1/4	80	2.7	4.6	7.3	11.2	16.4	29.9	1 1/4	80	78.1	228.6
1 1/2	80	4.1	7.0	11.2	17.2	25.1	45.8	1 1/2	80	107.5	349.2
2	40	9.5	16.2	26.0	39.6	57.8	105.7	2	40	204.2	811.4
2 1/2	40	15.3	25.9	41.5	63.2	92.1	168.5	2 1/2	40	291.1	1292.6
3	40	27.1	46.1	73.5	111.9	163.0	297.6	3	40	449.6	2287.8
4	40	55.7	94.2	150.1	228.7	333.0	606.2	4	40	774.7	4662.1
5	40	101.1	170.4	271.1	412.4	600.9	1095.2	5	40	—	—
6	40	164.0	276.4	439.2	667.5	971.6	1771.2	6	40	—	—
8	40	337.2	566.8	901.1	1366.6	1989.4	3623.0	8	40	—	—
10	40	611.6	1027.2	1634.3	2474.5	3598.0	—	10	40	—	—
12	ID*	981.6	1644.5	2612.4	3963.5	5764.6	—	12	ID*	—	—

Notes:

1. Table capacities are in tons of refrigeration.
   Δp = pressure drop due to line friction, psi per 100 ft of equivalent line length
   Δt = corresponding change in saturation temperature, °F per 100 ft
2. Line capacity for other saturation temperatures Δt and equivalent lengths L_e

$$\text{Line capacity} = \text{Table capacity}\left(\frac{\text{Table } L_e}{\text{Actual } L_e} \times \frac{\text{Actual } \Delta t}{\text{Table } \Delta t}\right)^{0.55}$$

3. Saturation temperature Δt for other capacities and equivalent lengths L_e

$$\Delta t = \text{Table } \Delta t \left(\frac{\text{Actual } L_e}{\text{Table } L_e}\right)\left(\frac{\text{Actual capacity}}{\text{Table capacity}}\right)^{1.8}$$

4. Values based on 90°F condensing temperature. Multiply table capacities by the following factors for other condensing temperatures:

Condensing Temperature, °F	Suction Lines	Discharge Lines
70	1.05	0.78
80	1.02	0.89
90	1.00	1.00
100	0.98	1.11

5. Discharge and liquid line capacities based on 20°F suction. Evaporator temperature is 0°F. The capacity is affected less than 3% when applied from –40 to +40°F extremes.

*The inside diameter of the pipe is the same as the nominal pipe size.

Liquid Ammonia Line Capacities

(Capacity in tons of refrigeration, except as noted)

Nominal Size, in.	Pumped Liquid Overfeed Ratio 3:1	4:1	5:1	High-Pressure Liquid at 3 psi[a]	Hot-Gas Defrost[a]	Equalizer High Side[b]	Thermosiphon Lubricant Cooling Lines Gravity Flow,[c] 1000 Btu/h Supply	Return	Vent
1/2	10	7.5	6	30	—	—	—	—	—
3/4	22	16.5	13	69	9-15	50	—	—	—
1	43	32.5	26	134	16-27	100	—	—	—
1 1/4	93.5	70	56	286	28-38	150	—	—	—
1 1/2	146	110	87.5	439	39-64	225	200	120	203
2	334	250	200	1016	65-107	300	470	300	362
2 1/2	533	400	320	1616	108-152	500	850	530	638
3	768	576	461	2886	153-246	1000	1312	870	1102
4	1365	1024	819	—	247-411	2000	2261	1410	2000
5	—	—	—	—	—	—	3550	2214	3624
6	—	—	—	—	—	—	5130	3200	6378
8	—	—	—	—	—	—	8874	5533	11596

Source: Wile (1977).

[a]Rating for hot-gas branch lines under 100 ft with minimum inlet pressure of 105 psig, defrost pressure of 70 psig, and –20°F evaporators designed for a 10°F temperature differential.

[b] Line sizes based on experience using total system evaporator tons.

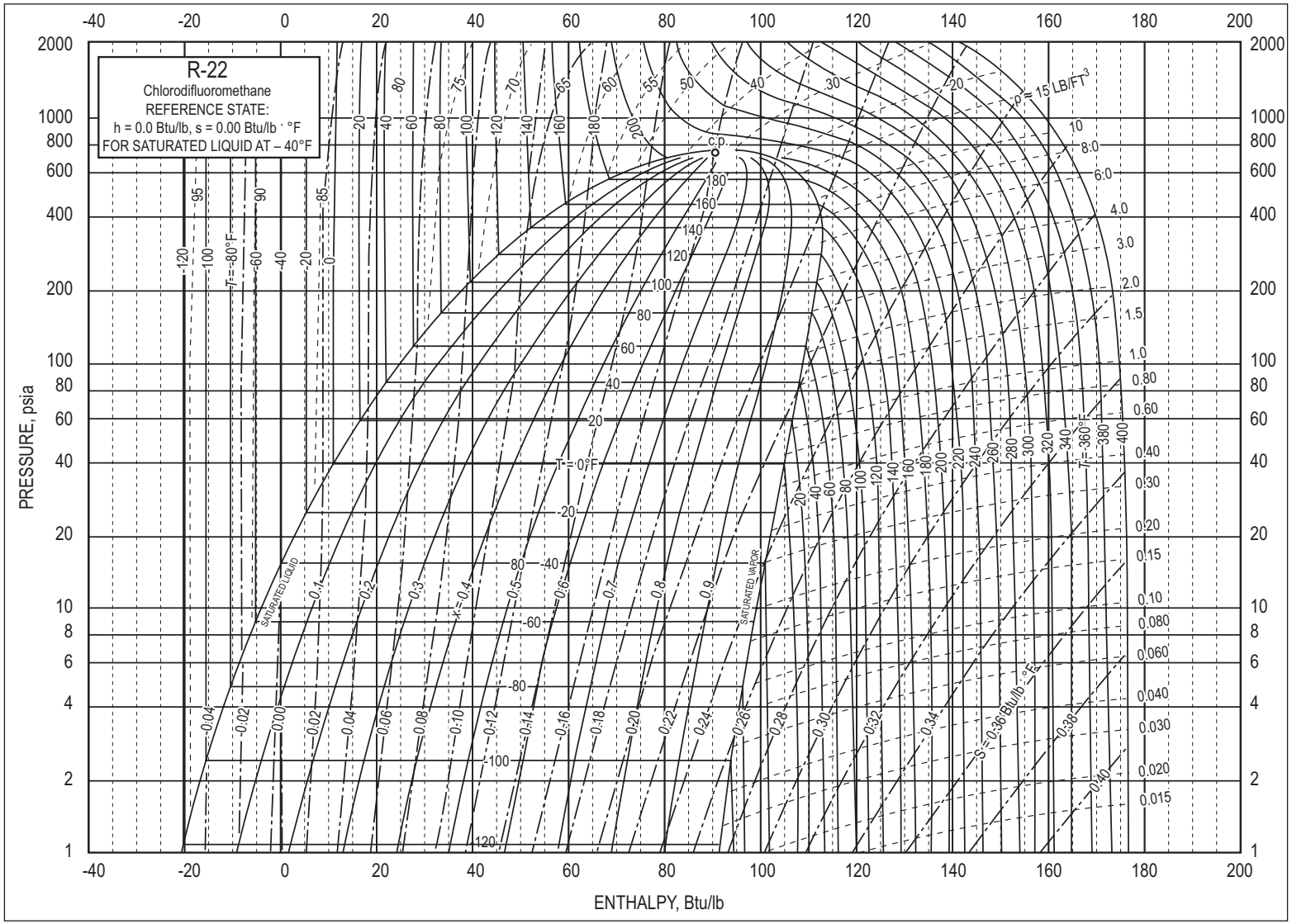
[c] From Frick Co. (1995). Values for line sizes above 4 in. are extrapolated.

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8.8 Thermophysical Properties of Refrigerants

Pressure Versus Enthalpy Curves for Refrigerant 22



Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 30, Thermophysical Properties of Refrigerants, Fig. 2.

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Refrigerant 22 (Chlorodifluoromethane) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
–150.00	0.263	98.28	146.060	–28.119	87.566	–0.07757	0.29600	0.2536	0.1185	1.2437	0.0831	0.00255	–150.00
–140.00	0.436	97.36	90.759	–25.583	88.729	–0.06951	0.28808	0.2536	0.1204	1.2404	0.0814	0.00267	–140.00
–130.00	0.698	96.44	58.384	–23.046	89.899	–0.06170	0.28090	0.2536	0.1223	1.2375	0.0797	0.00280	–130.00
–120.00	1.082	95.52	38.745	–20.509	91.074	–0.05412	0.27439	0.2537	0.1244	1.2350	0.0780	0.00293	–120.00
–110.00	1.629	94.59	26.444	–17.970	92.252	–0.04675	0.26846	0.2540	0.1265	1.2330	0.0763	0.00306	–110.00
–100.00	2.388	93.66	18.511	–15.427	93.430	–0.03959	0.26307	0.2543	0.1288	1.2315	0.0747	0.00320	–100.00
–95.00	2.865	93.19	15.623	–14.154	94.018	–0.03608	0.26055	0.2546	0.1300	1.2310	0.0739	0.00327	–95.00
–90.00	3.417	92.71	13.258	–12.880	94.605	–0.03261	0.25815	0.2549	0.1312	1.2307	0.0731	0.00334	–90.00
–85.00	4.053	92.24	11.309	–11.604	95.191	–0.02918	0.25585	0.2552	0.1324	1.2305	0.0723	0.00341	–85.00
–80.00	4.782	91.76	9.694	–10.326	95.775	–0.02580	0.25366	0.2556	0.1337	1.2304	0.0715	0.00348	–80.00
–75.00	5.615	91.28	8.3487	–9.046	96.357	–0.02245	0.25155	0.2561	0.1350	1.2305	0.0708	0.00355	–75.00
–70.00	6.561	90.79	7.2222	–7.763	96.937	–0.01915	0.24954	0.2566	0.1363	1.2308	0.0700	0.00363	–70.00
–65.00	7.631	90.31	6.2744	–6.477	97.514	–0.01587	0.24761	0.2571	0.1377	1.2313	0.0692	0.00370	–65.00
–60.00	8.836	89.82	5.4730	–5.189	98.087	–0.01264	0.24577	0.2577	0.1392	1.2320	0.0684	0.00378	–60.00
–55.00	10.190	89.33	4.7924	–3.897	98.657	–0.00943	0.24400	0.2583	0.1406	1.2328	0.0677	0.00386	–55.00
–50.00	11.703	88.83	4.2119	–2.602	99.224	–0.00626	0.24230	0.2591	0.1422	1.2339	0.0669	0.00394	–50.00
–45.00	13.390	88.33	3.7147	–1.303	99.786	–0.00311	0.24067	0.2598	0.1438	1.2352	0.0661	0.00402	–45.00
–41.46[b]	14.696	87.97	3.4054	–0.381	100.181	–0.00091	0.23955	0.2604	0.1449	1.2362	0.0656	0.00407	–41.46[b]
–40.00	15.262	87.82	3.2872	0.000	100.343	0.00000	0.23910	0.2606	0.1454	1.2367	0.0654	0.00410	–40.00
–35.00	17.336	87.32	2.9181	1.308	100.896	0.00309	0.23759	0.2615	0.1471	1.2384	0.0646	0.00418	–35.00
–30.00	19.624	86.80	2.5984	2.620	101.443	0.00615	0.23615	0.2625	0.1488	1.2404	0.0639	0.00426	–30.00
–25.00	22.142	86.29	2.3204	3.937	101.984	0.00918	0.23475	0.2635	0.1506	1.2426	0.0631	0.00435	–25.00
–20.00	24.906	85.76	2.0778	5.260	102.519	0.01220	0.23341	0.2645	0.1525	1.2451	0.0624	0.00444	–20.00
–15.00	27.929	85.24	1.8656	6.588	103.048	0.01519	0.23211	0.2656	0.1544	1.2479	0.0617	0.00452	–15.00
–10.00	31.230	84.71	1.6792	7.923	103.570	0.01815	0.23086	0.2668	0.1564	1.2510	0.0609	0.00461	–10.00

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Refrigerant 22 (Chlorodifluoromethane) Properties of Saturated Liquid and Saturated Vapor (cont'd)

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
–5.00	34.824	84.17	1.5150	9.263	104.085	0.02110	0.22965	0.2681	0.1585	1.2544	0.0602	0.00471	–5.00
0.00	38.728	83.63	1.3701	10.610	104.591	0.02403	0.22848	0.2694	0.1607	1.2581	0.0595	0.00480	0.00
5.00	42.960	83.08	1.2417	11.964	105.090	0.02694	0.22735	0.2708	0.1629	1.2622	0.0587	0.00489	5.00
10.00	47.536	82.52	1.1276	13.325	105.580	0.02983	0.22625	0.2722	0.1652	1.2666	0.0580	0.00499	10.00
15.00	52.475	81.96	1.0261	14.694	106.061	0.03270	0.22519	0.2737	0.1676	1.2714	0.0573	0.00509	15.00
20.00	57.795	81.39	0.9354	16.070	106.532	0.03556	0.22415	0.2753	0.1702	1.2767	0.0566	0.00519	20.00
25.00	63.514	80.82	0.8543	17.455	106.994	0.03841	0.22315	0.2770	0.1728	1.2824	0.0558	0.00530	25.00
30.00	69.651	80.24	0.7815	18.848	107.445	0.04124	0.22217	0.2787	0.1755	1.2886	0.0551	0.00540	30.00
35.00	76.225	79.65	0.7161	20.250	107.884	0.04406	0.22121	0.2806	0.1783	1.2953	0.0544	0.00551	35.00
40.00	83.255	79.05	0.6572	21.662	108.313	0.04686	0.22028	0.2825	0.1813	1.3026	0.0537	0.00562	40.00
45.00	90.761	78.44	0.6040	23.083	108.729	0.04966	0.21936	0.2845	0.1844	1.3105	0.0530	0.00574	45.00
50.00	98.763	77.83	0.5558	24.514	109.132	0.05244	0.21847	0.2866	0.1877	1.3191	0.0522	0.00586	50.00
55.00	107.280	77.20	0.5122	25.956	109.521	0.05522	0.21758	0.2889	0.1911	1.3284	0.0515	0.00598	55.00
60.00	116.330	76.57	0.4725	27.409	109.897	0.05798	0.21672	0.2913	0.1947	1.3385	0.0508	0.00611	60.00
65.00	125.940	75.92	0.4364	28.874	110.257	0.06074	0.21586	0.2938	0.1985	1.3495	0.0501	0.00625	65.00
70.00	136.130	75.27	0.4035	30.350	110.602	0.06350	0.21501	0.2964	0.2025	1.3615	0.0494	0.00638	70.00
75.00	146.920	74.60	0.3734	31.839	110.929	0.06625	0.21417	0.2992	0.2067	1.3746	0.0487	0.00653	75.00
80.00	158.330	73.92	0.3459	33.342	111.239	0.06899	0.21333	0.3022	0.2112	1.3889	0.0479	0.00668	80.00
85.00	170.380	73.23	0.3207	34.859	111.530	0.07173	0.21250	0.3054	0.2160	1.4046	0.0472	0.00684	85.00
90.00	183.090	72.52	0.2975	36.391	111.801	0.07447	0.21166	0.3089	0.2212	1.4218	0.0465	0.00701	90.00
95.00	196.500	71.80	0.2762	37.938	112.050	0.07721	0.21083	0.3126	0.2267	1.4407	0.0458	0.00718	95.00
100.00	210.610	71.06	0.2566	39.502	112.276	0.07996	0.20998	0.3166	0.2327	1.4616	0.0450	0.00737	100.00
105.00	225.460	70.30	0.2385	41.084	112.478	0.08270	0.20913	0.3209	0.2391	1.4849	0.0443	0.00757	105.00
110.00	241.060	69.52	0.2217	42.686	112.653	0.08545	0.20827	0.3257	0.2461	1.5107	0.0436	0.00778	110.00
115.00	257.450	68.72	0.2062	44.308	112.799	0.08821	0.20739	0.3309	0.2538	1.5396	0.0428	0.00801	115.00

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Refrigerant 22 (Chlorodifluoromethane) Properties of Saturated Liquid and Saturated Vapor (cont'd)

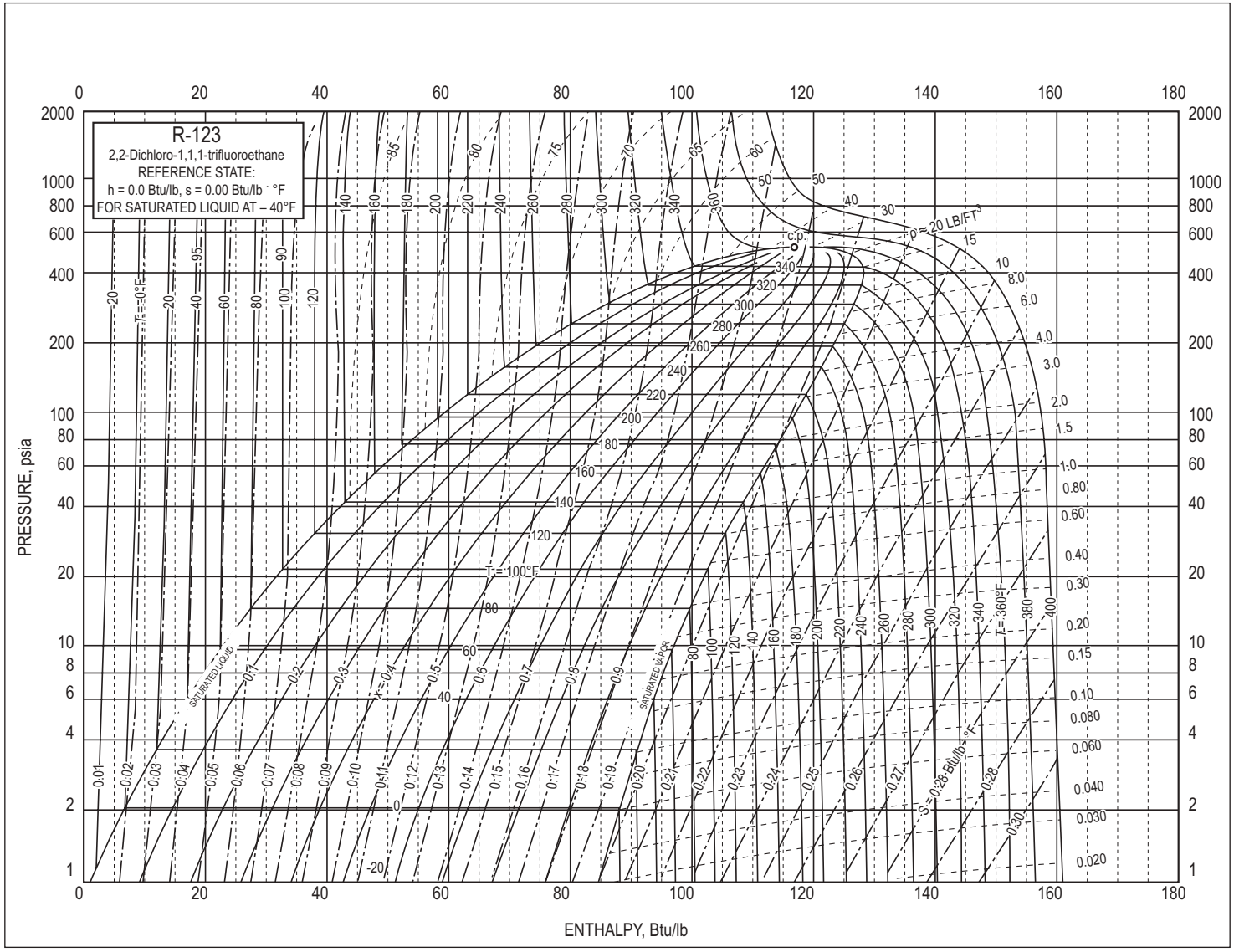
Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
120.00	274.650	67.90	0.1918	45.952	112.914	0.09098	0.20649	0.3367	0.2623	1.5722	0.0421	0.00825	120.00
125.00	292.690	67.05	0.1785	47.621	112.996	0.09376	0.20557	0.3431	0.2717	1.6090	0.0413	0.00851	125.00
130.00	311.580	66.18	0.1660	49.316	113.040	0.09656	0.20462	0.3504	0.2822	1.6509	0.0406	0.00880	130.00
135.00	331.370	65.27	0.1544	51.041	113.043	0.09937	0.20364	0.3585	0.2941	1.6990	0.0399	0.00911	135.00
140.00	352.080	64.32	0.1435	52.798	113.000	0.10222	0.20261	0.3679	0.3076	1.7548	0.0391	0.00946	140.00
145.00	373.740	63.34	0.1334	54.591	112.907	0.10509	0.20153	0.3787	0.3233	1.8201	0.0383	0.00984	145.00
150.00	396.380	62.31	0.1238	56.425	112.756	0.10800	0.20040	0.3913	0.3416	1.8976	0.0376	0.01027	150.00
155.00	420.040	61.22	0.1149	58.305	112.539	0.11096	0.19919	0.4063	0.3633	1.9907	0.0368	0.01076	155.00
160.00	444.750	60.07	0.1064	60.240	112.247	0.11397	0.19790	0.4243	0.3897	2.1047	0.0361	0.01131	160.00
165.00	470.560	58.84	0.0984	62.237	111.866	0.11705	0.19650	0.4467	0.4225	2.2474	0.0353	0.01195	165.00
170.00	497.500	57.53	0.0907	64.309	111.378	0.12022	0.19497	0.4750	0.4643	2.4310	0.0346	0.01270	170.00
175.00	525.620	56.10	0.0834	66.474	110.760	0.12350	0.19328	0.5124	0.5198	2.6759	0.0340	0.01360	175.00
180.00	554.980	54.52	0.0764	68.757	109.976	0.12693	0.19136	0.5641	0.5972	3.0184	0.0335	0.01470	180.00
185.00	585.630	52.74	0.0695	71.196	108.972	0.13056	0.18916	0.6410	0.7132	3.5317	0.0332	0.01609	185.00
190.00	617.640	50.67	0.0626	73.859	107.654	0.13450	0.18651	0.7681	0.9067	4.3857	0.0334	0.01793	190.00
195.00	651.120	48.14	0.0556	76.875	105.835	0.13893	0.18316	1.0200	1.2950	6.0900	0.0347	0.02061	195.00
200.00	686.200	44.68	0.0479	80.593	103.010	0.14437	0.17835	1.7780	2.4720	11.1900	0.0395	0.02574	200.00
205.06[c]	723.740	32.70	0.0306	91.208	91.208	0.16012	0.16012	∞	∞	∞	∞	∞	205.06[c]

* Temperature on ITS-90 scale [b] Normal boiling point [c] Critical point

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Pressure Versus Enthalpy Curves for Refrigerant 123



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Refrigerant 123 (2,2-Dichloro-1,1,1-trifluoroethane) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
–140.00	0.003	108.90	7431.6	–22.241	71.783	–0.06050	0.23363	0.2210	0.1181	1.1237	0.0645	0.00135	–140.00
–130.00	0.006	108.12	3871.0	–20.033	72.974	–0.05370	0.22843	0.2207	0.1203	1.1212	0.0636	0.00153	–130.00
–120.00	0.011	107.35	2111.6	–17.826	74.187	–0.04710	0.22379	0.2206	0.1226	1.1187	0.0628	0.00171	–120.00
–110.00	0.02	106.57	1201.0	–15.619	75.421	–0.04070	0.21966	0.2208	0.1248	1.1165	0.0619	0.00190	–110.00
–100.00	0.036	105.80	709.460	–13.410	76.676	–0.03447	0.21600	0.2211	0.1270	1.1144	0.0611	0.00208	–100.00
–90.00	0.06	105.03	433.830	–11.195	77.950	–0.02840	0.21275	0.2217	0.1291	1.1124	0.0602	0.00226	–90.00
–80.00	0.097	104.26	273.770	–8.975	79.244	–0.02247	0.20989	0.2224	0.1313	1.1106	0.0593	0.00244	–80.00
–70.00	0.154	103.48	177.810	–6.746	80.556	–0.01668	0.20737	0.2233	0.1334	1.1090	0.0584	0.00263	–70.00
–60.00	0.236	102.70	118.570	–4.509	81.885	–0.01101	0.20516	0.2243	0.1356	1.1075	0.0575	0.00281	–60.00
–50.00	0.354	101.92	80.999	–2.260	83.231	–0.00545	0.20323	0.2254	0.1377	1.1061	0.0565	0.00299	–50.00
–40.00	0.519	101.13	56.576	0.000	84.592	0.00000	0.20157	0.2266	0.1398	1.1050	0.0555	0.00317	–40.00
–30.00	0.744	100.34	40.333	2.272	85.967	0.00535	0.20014	0.2279	0.1420	1.1040	0.0546	0.00335	–30.00
–20.00	1.046	99.54	29.299	4.558	87.355	0.01061	0.19892	0.2292	0.1441	1.1032	0.0536	0.00353	–20.00
–10.00	1.445	98.73	21.655	6.857	88.754	0.01578	0.19790	0.2306	0.1463	1.1026	0.0526	0.00371	–10.00
0.00	1.963	97.92	16.264	9.170	90.163	0.02086	0.19706	0.2320	0.1484	1.1022	0.0515	0.00390	0.00
5.00	2.274	97.51	14.174	10.332	90.871	0.02337	0.19670	0.2327	0.1495	1.1021	0.0510	0.00399	5.00
10.00	2.625	97.10	12.396	11.498	91.582	0.02587	0.19638	0.2334	0.1506	1.1020	0.0505	0.00408	10.00
15.00	3.019	96.69	10.878	12.667	92.294	0.02834	0.19609	0.2341	0.1517	1.1020	0.0501	0.00417	15.00
20.00	3.46	96.28	9.578	13.840	93.008	0.03080	0.19585	0.2349	0.1528	1.1020	0.0496	0.00426	20.00
25.00	3.952	95.86	8.460	15.017	93.723	0.03324	0.19563	0.2356	0.1540	1.1021	0.0491	0.00435	25.00
30.00	4.499	95.44	7.4943	16.198	94.440	0.03566	0.19544	0.2364	0.1551	1.1023	0.0486	0.00444	30.00
35.00	5.106	95.02	6.6586	17.382	95.158	0.03806	0.19529	0.2371	0.1562	1.1025	0.0481	0.00453	35.00
40.00	5.778	94.60	5.9327	18.570	95.877	0.04045	0.19517	0.2379	0.1574	1.1028	0.0476	0.00462	40.00
45.00	6.519	94.17	5.3002	19.762	96.597	0.04282	0.19507	0.2387	0.1585	1.1031	0.0471	0.00471	45.00
50.00	7.334	93.74	4.7474	20.958	97.317	0.04518	0.19500	0.2394	0.1597	1.1035	0.0467	0.00481	50.00

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Refrigerant 123 (2,2-Dichloro-1,1,1-trifluoroethane) Properties of Saturated Liquid and Saturated Vapor (cont'd)

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
55.00	8.229	93.31	4.2629	22.158	98.038	0.04752	0.19495	0.2402	0.1609	1.1040	0.0462	0.00490	55.00
60.00	9.208	92.88	3.8371	23.362	98.760	0.04984	0.19493	0.2410	0.1621	1.1046	0.0457	0.00499	60.00
65.00	10.278	92.44	3.4617	24.570	99.481	0.05215	0.19493	0.2418	0.1633	1.1052	0.0453	0.00508	65.00
70.00	11.445	92.01	3.1301	25.782	100.203	0.05444	0.19495	0.2426	0.1645	1.1059	0.0448	0.00518	70.00
75.00	12.713	91.56	2.8362	26.998	100.924	0.05673	0.19499	0.2434	0.1657	1.1067	0.0444	0.00527	75.00
80.00	14.09	91.12	2.5753	28.218	101.645	0.05899	0.19505	0.2442	0.1669	1.1075	0.0439	0.00537	80.00
82.08[b]	14.696	90.94	2.4753	28.728	101.945	0.05993	0.19508	0.2445	0.1675	1.1079	0.0437	0.00540	82.08[b]
85.00	15.58	90.67	2.3429	29.443	102.365	0.06124	0.19513	0.2450	0.1682	1.1085	0.0435	0.00546	85.00
90.00	17.192	90.22	2.1356	30.671	103.085	0.06348	0.19522	0.2458	0.1695	1.1095	0.0430	0.00556	90.00
95.00	18.931	89.77	1.9503	31.904	103.804	0.06571	0.19534	0.2467	0.1707	1.1106	0.0426	0.00565	95.00
100.00	20.804	89.31	1.7841	33.141	104.521	0.06792	0.19546	0.2475	0.1720	1.1119	0.0422	0.00575	100.00
105.00	22.819	88.85	1.6349	34.383	105.238	0.07012	0.19560	0.2484	0.1734	1.1132	0.0418	0.00585	105.00
110.00	24.98	88.39	1.5006	35.628	105.953	0.07231	0.19576	0.2492	0.1747	1.1146	0.0413	0.00595	110.00
115.00	27.297	87.92	1.3795	36.879	106.666	0.07449	0.19593	0.2501	0.1761	1.1162	0.0409	0.00604	115.00
120.00	29.776	87.45	1.2701	38.134	107.377	0.07665	0.19611	0.2510	0.1775	1.1178	0.0405	0.00614	120.00
125.00	32.425	86.98	1.1710	39.393	108.086	0.07881	0.19630	0.2520	0.1789	1.1196	0.0401	0.00625	125.00
130.00	35.251	86.50	1.0812	40.657	108.792	0.08095	0.19650	0.2529	0.1803	1.1215	0.0397	0.00635	130.00
135.00	38.261	86.01	0.9996	41.926	109.497	0.08308	0.19671	0.2539	0.1818	1.1236	0.0393	0.00645	135.00
140.00	41.464	85.52	0.9253	43.200	110.198	0.08520	0.19693	0.2548	0.1833	1.1258	0.0389	0.00656	140.00
145.00	44.868	85.03	0.8577	44.479	110.896	0.08732	0.19716	0.2559	0.1848	1.1281	0.0385	0.00666	145.00
150.00	48.479	84.53	0.7959	45.763	111.591	0.08942	0.19739	0.2569	0.1863	1.1306	0.0381	0.00677	150.00
160.00	56.36	83.52	0.6876	48.347	112.970	0.09359	0.19788	0.2591	0.1896	1.1362	0.0374	0.00699	160.00
170.00	65.173	82.49	0.5965	50.953	114.333	0.09773	0.19839	0.2614	0.1929	1.1426	0.0366	0.00722	170.00
180.00	74.986	81.43	0.5195	53.583	115.678	0.10184	0.19892	0.2638	0.1965	1.1499	0.0359	0.00745	180.00
190.00	85.868	80.34	0.4539	56.237	117.001	0.10592	0.19945	0.2665	0.2004	1.1583	0.0352	0.00769	190.00

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Refrigerant 123 (2,2-Dichloro-1,1,1-trifluoroethane) Properties of Saturated Liquid and Saturated Vapor (cont'd)

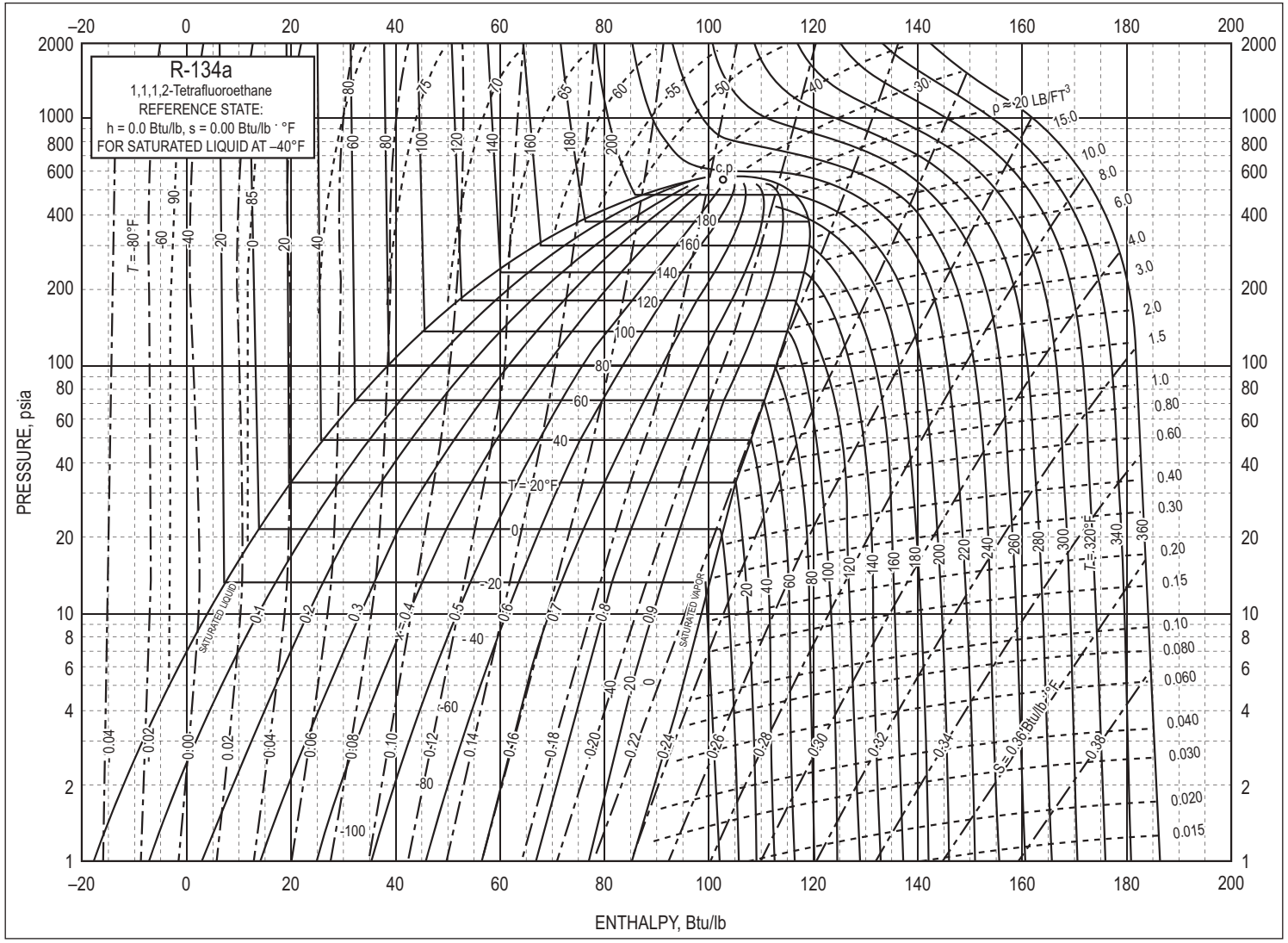
Temp.,* °F	Pressure, psia	Density, lb/ft³	Volume, ft³/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
200.00	97.892	79.23	0.3979	58.918	118.300	0.10997	0.19999	0.2694	0.2045	1.1681	0.0345	0.00795	200.00
210.00	111.13	78.08	0.3497	61.627	119.572	0.11400	0.20053	0.2726	0.2089	1.1793	0.0338	0.00821	210.00
220.00	125.66	76.89	0.3080	64.367	120.813	0.11801	0.20106	0.2761	0.2138	1.1925	0.0331	0.00849	220.00
230.00	141.56	75.66	0.2719	67.141	122.019	0.12201	0.20158	0.2800	0.2191	1.2079	0.0324	0.00877	230.00
240.00	158.91	74.38	0.2404	69.952	123.184	0.12599	0.20207	0.2845	0.2251	1.2262	0.0317	0.00908	240.00
250.00	177.8	73.04	0.2128	72.805	124.303	0.12997	0.20254	0.2896	0.2319	1.2482	0.0310	0.00940	250.00
260.00	198.31	71.64	0.1885	75.704	125.367	0.13396	0.20296	0.2956	0.2398	1.2749	0.0303	0.00974	260.00
270.00	220.53	70.16	0.1670	78.655	126.368	0.13795	0.20334	0.3026	0.2490	1.3079	0.0296	0.01010	270.00
280.00	244.58	68.60	0.1479	81.666	127.294	0.14196	0.20365	0.3110	0.2603	1.3496	0.0289	0.01050	280.00
290.00	270.54	66.92	0.1309	84.749	128.128	0.14600	0.20387	0.3215	0.2742	1.4035	0.0282	0.01092	290.00
300.00	298.53	65.11	0.1155	87.916	128.851	0.15010	0.20398	0.3349	0.2922	1.4755	0.0275	0.01139	300.00
310.00	328.69	63.12	0.1016	91.188	129.431	0.15426	0.20395	0.3529	0.3166	1.5762	0.0267	0.01191	310.00
320.00	361.16	60.91	0.0889	94.594	129.822	0.15853	0.20372	0.3785	0.3520	1.7258	0.0259	0.01251	320.00
330.00	396.11	58.37	0.0770	98.186	129.950	0.16297	0.20320	0.4186	0.4084	1.9693	0.0251	0.01321	330.00
340.00	433.76	55.33	0.0658	102.059	129.670	0.16769	0.20222	0.4925	0.5138	2.4318	0.0243	0.01411	340.00
350.00	474.41	51.32	0.0544	106.459	128.628	0.17298	0.20036	0.6830	0.7861	3.6383	0.0234	0.01539	350.00
360.00	518.66	43.97	0.0403	112.667	125.064	0.18039	0.19551	2.5070	3.2630	14.6330	0.0227	0.01819	360.00
362.63[c]	531.1	34.34	0.0291	118.800	118.800	0.18779	0.18779	∞	∞	∞	∞	∞	362.63[c]

* Temperature on ITS-90 scale [b] Normal boiling point [c] Critical point

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Pressure Versus Enthalpy Curves for Refrigerant 134a



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Refrigerant 134a (1,1,1,2-Tetrafluoroethane) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
–153.94[a]	0.057	99.33	568.59	–32.992	80.362	–0.09154	0.27923	0.2829	0.1399	1.1637	0.0840	0.00178	–153.94[a]
–150.00	0.072	98.97	452.12	–31.878	80.907	–0.08791	0.27629	0.2830	0.1411	1.1623	0.0832	0.00188	–150.00
–140.00	0.129	98.05	260.63	–29.046	82.304	–0.07891	0.26941	0.2834	0.1443	1.1589	0.0813	0.00214	–140.00
–130.00	0.221	97.13	156.50	–26.208	83.725	–0.07017	0.26329	0.2842	0.1475	1.1559	0.0794	0.00240	–130.00
–120.00	0.365	96.20	97.48	–23.360	85.168	–0.06166	0.25784	0.2853	0.1508	1.1532	0.0775	0.00265	–120.00
–110.00	0.583	95.27	62.763	–20.500	86.629	–0.05337	0.25300	0.2866	0.1540	1.1509	0.0757	0.00291	–110.00
–100.00	0.903	94.33	41.637	–17.626	88.107	–0.04527	0.24871	0.2881	0.1573	1.1490	0.0739	0.00317	–100.00
–90.00	1.359	93.38	28.381	–14.736	89.599	–0.03734	0.24490	0.2898	0.1607	1.1475	0.0722	0.00343	–90.00
–80.00	1.993	92.42	19.825	–11.829	91.103	–0.02959	0.24152	0.2916	0.1641	1.1465	0.0705	0.00369	–80.00
–75.00	2.392	91.94	16.711	–10.368	91.858	–0.02577	0.23998	0.2925	0.1658	1.1462	0.0696	0.00382	–75.00
–70.00	2.854	91.46	14.161	–8.903	92.614	–0.02198	0.23854	0.2935	0.1676	1.1460	0.0688	0.00395	–70.00
–65.00	3.389	90.97	12.060	–7.432	93.372	–0.01824	0.23718	0.2945	0.1694	1.1459	0.0680	0.00408	–65.00
–60.00	4.002	90.49	10.321	–5.957	94.131	–0.01452	0.23590	0.2955	0.1713	1.1460	0.0671	0.00420	–60.00
–55.00	4.703	90.00	8.873	–4.476	94.890	–0.01085	0.23470	0.2965	0.1731	1.1462	0.0663	0.00433	–55.00
–50.00	5.501	89.50	7.662	–2.989	95.650	–0.00720	0.23358	0.2976	0.1751	1.1466	0.0655	0.00446	–50.00
–45.00	6.406	89.00	6.6438	–1.498	96.409	–0.00358	0.23252	0.2987	0.1770	1.1471	0.0647	0.00460	–45.00
–40.00	7.427	88.50	5.7839	0.000	97.167	0.00000	0.23153	0.2999	0.1790	1.1478	0.0639	0.00473	–40.00
–35.00	8.576	88.00	5.0544	1.503	97.924	0.00356	0.23060	0.3010	0.1811	1.1486	0.0632	0.00486	–35.00
–30.00	9.862	87.49	4.4330	3.013	98.679	0.00708	0.22973	0.3022	0.1832	1.1496	0.0624	0.00499	–30.00
–25.00	11.299	86.98	3.9014	4.529	99.433	0.01058	0.22892	0.3035	0.1853	1.1508	0.0616	0.00512	–25.00
–20.00	12.898	86.47	3.4449	6.051	100.184	0.01406	0.22816	0.3047	0.1875	1.1521	0.0608	0.00525	–20.00
–15.00	14.671	85.95	3.0514	7.580	100.932	0.01751	0.22744	0.3060	0.1898	1.1537	0.0601	0.00538	–15.00
–14.93[b]	14.696	85.94	3.0465	7.600	100.942	0.01755	0.22743	0.3061	0.1898	1.1537	0.0601	0.00538	–14.93[b]
–10.00	16.632	85.43	2.7109	9.115	101.677	0.02093	0.22678	0.3074	0.1921	1.1554	0.0593	0.00552	–10.00
–5.00	18.794	84.90	2.4154	10.657	102.419	0.02433	0.22615	0.3088	0.1945	1.1573	0.0586	0.00565	–5.00

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Refrigerant 134a (1,1,1,2-Tetrafluoroethane) Properties of Saturated Liquid and Saturated Vapor (cont'd)

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
0.00	21.171	84.37	2.1579	12.207	103.156	0.02771	0.22557	0.3102	0.1969	1.1595	0.0578	0.00578	0.00
5.00	23.777	83.83	1.9330	13.764	103.889	0.03107	0.22502	0.3117	0.1995	1.1619	0.0571	0.00592	5.00
10.00	26.628	83.29	1.7357	15.328	104.617	0.03440	0.22451	0.3132	0.2021	1.1645	0.0564	0.00605	10.00
15.00	29.739	82.74	1.5623	16.901	105.339	0.03772	0.22403	0.3147	0.2047	1.1674	0.0556	0.00619	15.00
20.00	33.124	82.19	1.4094	18.481	106.056	0.04101	0.22359	0.3164	0.2075	1.1705	0.0549	0.00632	20.00
25.00	36.800	81.63	1.2742	20.070	106.767	0.04429	0.22317	0.3181	0.2103	1.1740	0.0542	0.00646	25.00
30.00	40.784	81.06	1.1543	21.667	107.471	0.04755	0.22278	0.3198	0.2132	1.1777	0.0535	0.00660	30.00
35.00	45.092	80.49	1.0478	23.274	108.167	0.05079	0.22241	0.3216	0.2163	1.1818	0.0528	0.00674	35.00
40.00	49.741	79.90	0.9528	24.890	108.856	0.05402	0.22207	0.3235	0.2194	1.1862	0.0521	0.00688	40.00
45.00	54.749	79.32	0.8680	26.515	109.537	0.05724	0.22174	0.3255	0.2226	1.1910	0.0514	0.00703	45.00
50.00	60.134	78.72	0.7920	28.150	110.209	0.06044	0.22144	0.3275	0.2260	1.1961	0.0507	0.00717	50.00
55.00	65.913	78.11	0.7238	29.796	110.871	0.06362	0.22115	0.3297	0.2294	1.2018	0.0500	0.00732	55.00
60.00	72.105	77.50	0.6625	31.452	111.524	0.06680	0.22088	0.3319	0.2331	1.2079	0.0493	0.00747	60.00
65.00	78.729	76.87	0.6072	33.120	112.165	0.06996	0.22062	0.3343	0.2368	1.2145	0.0486	0.00762	65.00
70.00	85.805	76.24	0.5572	34.799	112.796	0.07311	0.22037	0.3368	0.2408	1.2217	0.0479	0.00777	70.00
75.00	93.351	75.59	0.5120	36.491	113.414	0.07626	0.22013	0.3394	0.2449	1.2296	0.0472	0.00793	75.00
80.00	101.390	74.94	0.4710	38.195	114.019	0.07939	0.21989	0.3422	0.2492	1.2382	0.0465	0.00809	80.00
85.00	109.930	74.27	0.4338	39.913	114.610	0.08252	0.21966	0.3451	0.2537	1.2475	0.0458	0.00825	85.00
90.00	119.010	73.58	0.3999	41.645	115.186	0.08565	0.21944	0.3482	0.2585	1.2578	0.0451	0.00842	90.00
95.00	128.650	72.88	0.3690	43.392	115.746	0.08877	0.21921	0.3515	0.2636	1.2690	0.0444	0.00860	95.00
100.00	138.850	72.17	0.3407	45.155	116.289	0.09188	0.21898	0.3551	0.2690	1.2813	0.0437	0.00878	100.00
105.00	149.650	71.44	0.3148	46.934	116.813	0.09500	0.21875	0.3589	0.2747	1.2950	0.0431	0.00897	105.00
110.00	161.070	70.69	0.2911	48.731	117.317	0.09811	0.21851	0.3630	0.2809	1.3101	0.0424	0.00916	110.00
115.00	173.140	69.93	0.2693	50.546	117.799	0.10123	0.21826	0.3675	0.2875	1.3268	0.0417	0.00936	115.00
120.00	185.860	69.14	0.2493	52.382	118.258	0.10435	0.21800	0.3723	0.2948	1.3456	0.0410	0.00958	120.00

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Refrigerant 134a (1,1,1,2-Tetrafluoroethane) Properties of Saturated Liquid and Saturated Vapor (cont'd)

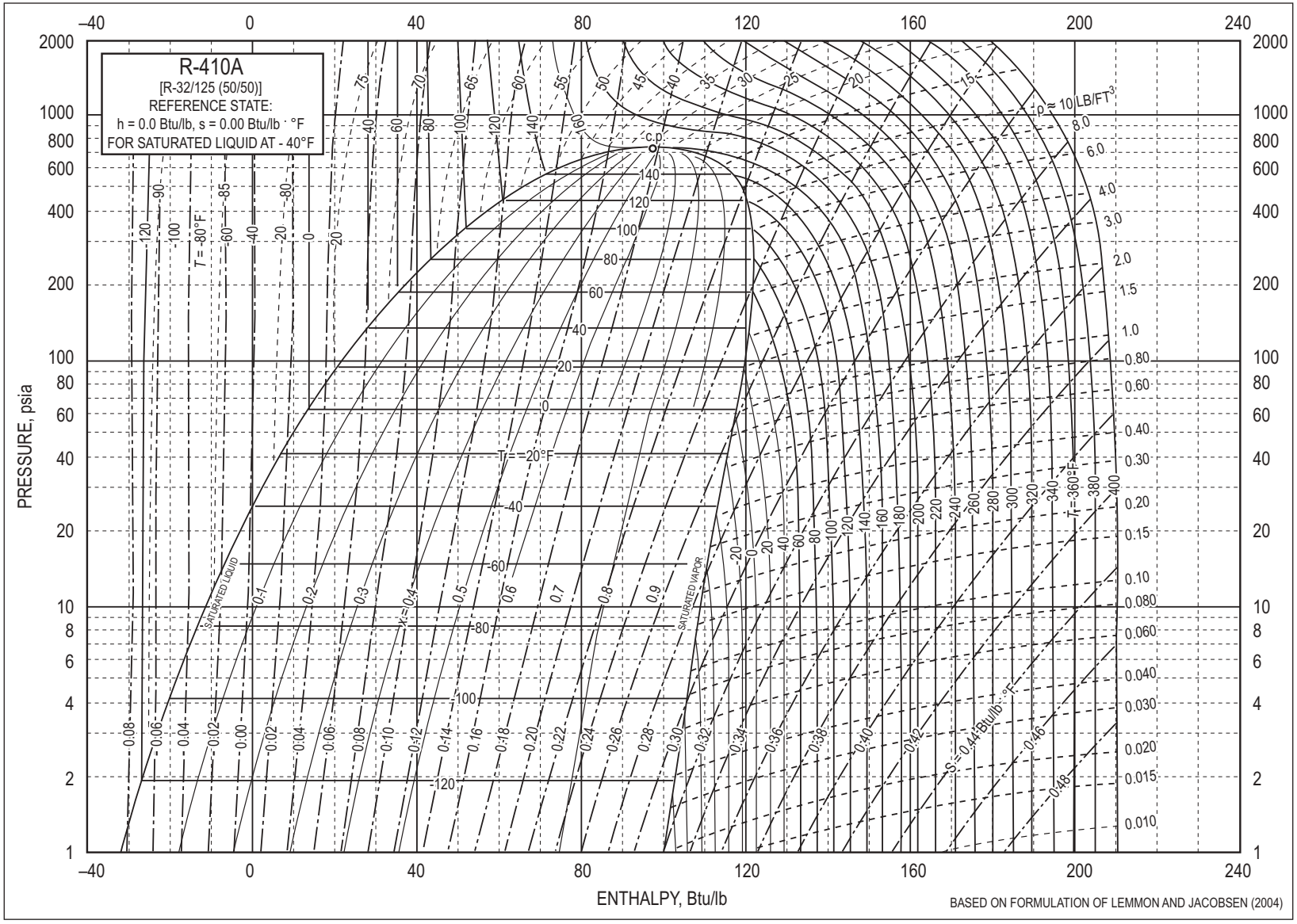
Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
125.00	199.280	68.32	0.2308	54.239	118.690	0.10748	0.21772	0.3775	0.3026	1.3666	0.0403	0.00981	125.00
130.00	213.410	67.49	0.2137	56.119	119.095	0.11062	0.21742	0.3833	0.3112	1.3903	0.0396	0.01005	130.00
135.00	228.280	66.62	0.1980	58.023	119.468	0.11376	0.21709	0.3897	0.3208	1.4173	0.0389	0.01031	135.00
140.00	243.920	65.73	0.1833	59.954	119.807	0.11692	0.21673	0.3968	0.3315	1.4481	0.0382	0.01058	140.00
145.00	260.360	64.80	0.1697	61.915	120.108	0.12010	0.21634	0.4048	0.3435	1.4837	0.0375	0.01089	145.00
150.00	277.610	63.83	0.1571	63.908	120.366	0.12330	0.21591	0.4138	0.3571	1.5250	0.0368	0.01122	150.00
155.00	295.730	62.82	0.1453	65.936	120.576	0.12653	0.21542	0.4242	0.3729	1.5738	0.0361	0.01158	155.00
160.00	314.730	61.76	0.1343	68.005	120.731	0.12979	0.21488	0.4362	0.3914	1.6318	0.0354	0.01199	160.00
165.00	334.650	60.65	0.1239	70.118	120.823	0.13309	0.21426	0.4504	0.4133	1.7022	0.0346	0.01245	165.00
170.00	355.530	59.47	0.1142	72.283	120.842	0.13644	0.21356	0.4675	0.4400	1.7889	0.0339	0.01297	170.00
175.00	377.410	58.21	0.1051	74.509	120.773	0.13985	0.21274	0.4887	0.4733	1.8984	0.0332	0.01358	175.00
180.00	400.340	56.86	0.0964	76.807	120.598	0.14334	0.21180	0.5156	0.5159	2.0405	0.0325	0.01430	180.00
185.00	424.360	55.38	0.0881	79.193	120.294	0.14693	0.21069	0.5512	0.5729	2.2321	0.0318	0.01516	185.00
190.00	449.520	53.76	0.0801	81.692	119.822	0.15066	0.20935	0.6012	0.6532	2.5041	0.0311	0.01623	190.00
195.00	475.910	51.91	0.0724	84.343	119.123	0.15459	0.20771	0.6768	0.7751	2.9192	0.0304	0.01760	195.00
200.00	503.590	49.76	0.0647	87.214	118.097	0.15880	0.20562	0.8062	0.9835	3.6309	0.0300	0.01949	200.00
205.00	532.680	47.08	0.0567	90.454	116.526	0.16353	0.20275	1.0830	1.4250	5.1360	0.0300	0.02240	205.00
210.00	563.350	43.20	0.0477	94.530	113.746	0.16945	0.19814	2.1130	3.0080	10.5120	0.0316	0.02848	210.00
213.91[c]	588.750	31.96	0.0313	103.894	103.894	0.18320	0.18320	∞	∞	∞	∞	∞	213.91c

* Temperature on ITS-90 scale [a] Triple point [b] Normal boiling point [c] Critical point

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Pressure Versus Enthalpy Curves for Refrigerant 410A



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Refrigerant 410A [R-32/125 (50/50)] Properties of Liquid on Bubble Line and Vapor on Dew Line

Pressure, psia	Temp.,* °F		Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Pressure, psia
	Bubble	Dew	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
1	–135.16	–134.98	92.02	47.6458	–30.90	100.62	–0.08330	0.32188	0.3215	0.1568	1.228	0.1043	0.00421	1
1.5	–126.03	–125.87	91.10	32.5774	–27.97	101.90	–0.07439	0.31477	0.3212	0.1600	1.227	0.1023	0.00431	1.5
2	–119.18	–119.02	90.41	24.8810	–25.76	102.86	–0.06786	0.30981	0.3213	0.1626	1.227	0.1008	0.00439	2
2.5	–113.63	–113.48	89.84	20.1891	–23.98	103.63	–0.06267	0.30602	0.3214	0.1648	1.228	0.0996	0.00446	2.5
3	–108.94	–108.78	89.36	17.0211	–22.47	104.27	–0.05834	0.30296	0.3216	0.1668	1.228	0.0985	0.00451	3
4	–101.22	–101.07	88.57	13.0027	–19.98	105.33	–0.05133	0.29820	0.3221	0.1703	1.229	0.0968	0.00461	4
5	–94.94	–94.80	87.92	10.5514	–17.96	106.18	–0.04574	0.29455	0.3226	0.1733	1.230	0.0954	0.00469	5
6	–89.63	–89.48	87.36	8.8953	–16.24	106.89	–0.04107	0.29162	0.3231	0.1760	1.232	0.0942	0.00476	6
7	–84.98	–84.84	86.87	7.6992	–14.74	107.50	–0.03704	0.28916	0.3236	0.1785	1.233	0.0931	0.00482	7
8	–80.85	–80.71	86.44	6.7935	–13.40	108.05	–0.03349	0.28705	0.3241	0.1807	1.234	0.0922	0.00488	8
10	–73.70	–73.56	85.67	5.5105	–11.08	108.97	–0.02743	0.28356	0.3251	0.1848	1.237	0.0905	0.00498	10
12	–67.62	–67.48	85.02	4.6434	–9.10	109.75	–0.02235	0.28075	0.3261	0.1884	1.240	0.0891	0.00507	12
14	–62.31	–62.16	84.44	4.0168	–7.36	110.42	–0.01795	0.27840	0.3270	0.1917	1.243	0.0879	0.00515	14
14.70[b]	–60.60	–60.46	84.26	3.8375	–6.80	110.63	–0.01655	0.27766	0.3274	0.1928	1.244	0.0875	0.00517	14.70[b]
16	–57.56	–57.42	83.93	3.5423	–5.80	111.01	–0.01407	0.27638	0.3279	0.1947	1.245	0.0868	0.00522	16
18	–53.27	–53.13	83.45	3.1699	–4.39	111.54	–0.01059	0.27461	0.3288	0.1975	1.248	0.0858	0.00528	18
20	–49.34	–49.19	83.02	2.8698	–3.09	112.01	–0.00743	0.27305	0.3297	0.2002	1.251	0.0849	0.00535	20
22	–45.70	–45.56	82.61	2.6225	–1.89	112.45	–0.00452	0.27164	0.3305	0.2027	1.254	0.0841	0.00540	22
24	–42.32	–42.18	82.23	2.4151	–0.77	112.85	–0.00184	0.27036	0.3313	0.2050	1.256	0.0833	0.00546	24
26	–39.15	–39.01	81.87	2.2386	0.28	113.22	0.0007	0.26919	0.3321	0.2073	1.259	0.0826	0.00551	26
28	–36.17	–36.02	81.54	2.0865	1.27	113.56	0.0030	0.26811	0.3329	0.2094	1.261	0.0819	0.00556	28
30	–33.35	–33.20	81.21	1.9540	2.22	113.88	0.0052	0.26711	0.3337	0.2115	1.264	0.0813	0.00561	30
32	–30.68	–30.53	80.90	1.8375	3.11	114.19	0.0073	0.26617	0.3345	0.2135	1.267	0.0806	0.00565	32
34	–28.13	–27.98	80.61	1.7343	3.97	114.47	0.0093	0.26530	0.3352	0.2154	1.269	0.0801	0.00570	34
36	–25.69	–25.54	80.33	1.6422	4.79	114.74	0.0112	0.26448	0.3360	0.2173	1.272	0.0795	0.00574	36

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Refrigerant 410A [R-32/125 (50/50)] Properties of Liquid on Bubble Line and Vapor on Dew Line (cont'd)

Pressure, psia	Temp.,* °F		Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Pressure, psia
	Bubble	Dew	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
38	–23.36	–23.20	80.05	1.5594	5.57	115.00	0.0130	0.26371	0.3367	0.2191	1.274	0.0790	0.00578	38
40	–21.12	–20.96	79.79	1.4847	6.33	115.24	0.0147	0.26297	0.3374	0.2208	1.277	0.0785	0.00582	40
42	–18.96	–18.81	79.54	1.4168	7.06	115.47	0.0163	0.26228	0.3382	0.2226	1.279	0.0780	0.00586	42
44	–16.89	–16.73	79.29	1.3549	7.76	115.69	0.0179	0.26162	0.3389	0.2242	1.282	0.0775	0.00589	44
46	–14.88	–14.73	79.05	1.2982	8.45	115.90	0.0194	0.26098	0.3396	0.2259	1.284	0.0771	0.00593	46
48	–12.94	–12.79	78.82	1.2460	9.11	116.10	0.0209	0.26038	0.3403	0.2275	1.287	0.0766	0.00597	48
50	–11.07	–10.91	78.59	1.1979	9.75	116.30	0.0223	0.25980	0.3410	0.2290	1.289	0.0762	0.00600	50
55	–6.62	–6.45	78.05	1.0925	11.27	116.75	0.0257	0.25845	0.3427	0.2328	1.295	0.0752	0.00610	55
60	–2.46	–2.30	77.54	1.0040	12.70	117.16	0.0288	0.25722	0.3445	0.2365	1.301	0.0743	0.00619	60
65	1.43	1.60	77.06	0.9287	14.05	117.53	0.0317	0.25610	0.3462	0.2400	1.308	0.0734	0.00628	65
70	5.10	5.27	76.60	0.8638	15.33	117.88	0.0344	0.25505	0.3478	0.2434	1.314	0.0726	0.00636	70
75	8.58	8.75	76.15	0.8073	16.54	118.20	0.0370	0.25408	0.3495	0.2467	1.320	0.0719	0.00645	75
80	11.88	12.06	75.73	0.7576	17.70	118.49	0.0395	0.25316	0.3512	0.2499	1.326	0.0711	0.00653	80
85	15.03	15.21	75.32	0.7135	18.81	118.77	0.0418	0.25231	0.3528	0.2531	1.333	0.0704	0.00661	85
90	18.05	18.22	74.93	0.6742	19.88	119.02	0.0440	0.25149	0.3545	0.2562	1.339	0.0698	0.00669	90
95	20.93	21.11	74.54	0.6389	20.91	119.26	0.0461	0.25072	0.3561	0.2592	1.345	0.0692	0.00677	95
100	23.71	23.89	74.17	0.6070	21.90	119.48	0.0482	0.24999	0.3578	0.2622	1.352	0.0685	0.00684	100
110	28.96	29.14	73.46	0.5515	23.79	119.89	0.0520	0.24862	0.3611	0.2681	1.365	0.0674	0.00700	110
120	33.86	34.05	72.78	0.5051	25.57	120.24	0.0556	0.24736	0.3644	0.2738	1.378	0.0664	0.00715	120
130	38.46	38.65	72.13	0.4655	27.25	120.56	0.0589	0.24618	0.3678	0.2795	1.392	0.0654	0.00730	130
140	42.80	42.99	71.51	0.4314	28.85	120.83	0.0621	0.24508	0.3712	0.2852	1.406	0.0645	0.00745	140
150	46.91	47.11	70.90	0.4016	30.38	121.08	0.0650	0.24403	0.3746	0.2908	1.420	0.0636	0.00760	150
160	50.82	51.02	70.32	0.3755	31.85	121.29	0.0679	0.24304	0.3781	0.2965	1.435	0.0628	0.00775	160
170	54.56	54.76	69.75	0.3523	33.27	121.48	0.0706	0.24210	0.3816	0.3022	1.451	0.0620	0.00791	170
180	58.13	58.33	69.20	0.3316	34.63	121.65	0.0732	0.24119	0.3851	0.3080	1.467	0.0612	0.00807	180

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Refrigerant 410A [R-32/125 (50/50)] Properties of Liquid on Bubble Line and Vapor on Dew Line (cont'd)

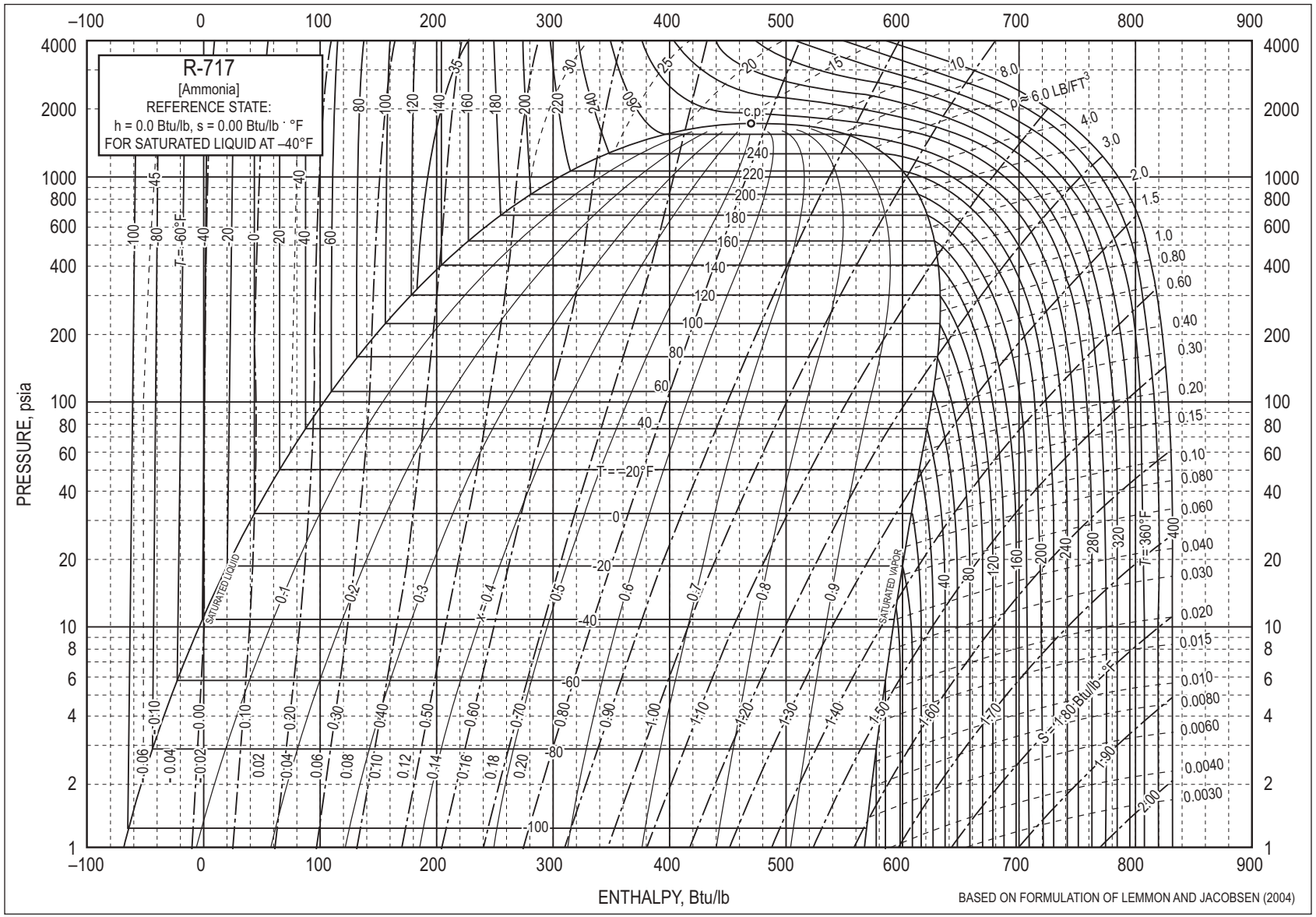
Pressure, psia	Temp.,* °F		Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Pressure, psia
	Bubble	Dew	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
190	61.55	61.76	68.66	0.3130	35.95	121.79	0.0757	0.24031	0.3888	0.3139	1.483	0.0605	0.00823	190
200	64.84	65.05	68.13	0.2962	37.22	121.91	0.0780	0.23946	0.3925	0.3200	1.500	0.0598	0.00839	200
220	71.07	71.28	67.10	0.2669	39.67	122.09	0.0826	0.23783	0.4001	0.3325	1.537	0.0585	0.00873	220
240	76.89	77.10	66.11	0.2424	41.99	122.20	0.0868	0.23628	0.4081	0.3457	1.576	0.0573	0.00908	240
260	82.35	82.57	65.14	0.2215	44.21	122.25	0.0908	0.23478	0.4165	0.3599	1.619	0.0562	0.00945	260
280	87.51	87.73	64.19	0.2034	46.34	122.24	0.0946	0.23333	0.4255	0.3751	1.665	0.0552	0.00983	280
300	92.40	92.61	63.26	0.1876	48.40	122.18	0.0983	0.23190	0.4350	0.3915	1.716	0.0542	0.01024	300
320	97.04	97.26	62.34	0.1736	50.38	122.07	0.1018	0.23049	0.4452	0.4094	1.772	0.0533	0.01067	320
340	101.48	101.69	61.42	0.1613	52.31	121.91	0.1051	0.22909	0.4564	0.4290	1.833	0.0524	0.01113	340
360	105.71	105.93	60.52	0.1501	54.19	121.70	0.1083	0.22769	0.4685	0.4507	1.901	0.0515	0.01162	360
380	109.78	109.99	59.61	0.1401	56.03	121.44	0.1115	0.22629	0.4820	0.4747	1.977	0.0507	0.01214	380
400	113.68	113.89	58.70	0.1310	57.83	121.13	0.1145	0.22488	0.4971	0.5016	2.063	0.0499	0.01271	400
450	122.82	123.01	56.39	0.1114	62.23	120.14	0.1218	0.22124	0.5443	0.5857	2.333	0.0481	0.01433	450
500	131.19	131.38	53.97	0.0952	66.54	118.80	0.1289	0.21732	0.6143	0.7083	2.728	0.0465	0.01636	500
550	138.93	139.09	51.32	0.0814	70.89	117.02	0.1359	0.21295	0.7303	0.9059	3.367	0.0451	0.01902	550
600	146.12	146.25	48.24	0.0690	75.47	114.59	0.1432	0.20777	0.9603	1.2829	4.579	0.0440	0.02275	600
692.78[c]	158.40	158.40	34.18	0.0293	90.97	90.97	0.1678	0.16781	—	—	—	—	—	692.78[c]

* Temperature on ITS-90 scale [b] Bubble and dew point at one standard atmosphere [c] Critical point

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Pressure Versus Enthalpy Curves for Refrigerant 717 (Ammonia)



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Refrigerant 717 (Ammonia) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
–107.78[a]	0.883	45.75	249.92	–69.830	568.765	–0.18124	1.63351	1.0044	0.4930	1.3252	0.4735	0.01135	–107.78[a]
–100.00	1.237	45.47	182.19	–61.994	572.260	–0.15922	1.60421	1.0100	0.4959	1.3262	0.4647	0.01138	–100.00
–90.00	1.864	45.09	124.12	–51.854	576.688	–0.13142	1.56886	1.0176	0.5003	1.3278	0.4534	0.01143	–90.00
–80.00	2.739	44.71	86.55	–41.637	581.035	–0.10416	1.53587	1.0254	0.5056	1.3296	0.4422	0.01149	–80.00
–70.00	3.937	44.31	61.65	–31.341	585.288	–0.07741	1.50503	1.0331	0.5118	1.3319	0.4310	0.01158	–70.00
–60.00	5.544	43.91	44.774	–20.969	589.439	–0.05114	1.47614	1.0406	0.5190	1.3346	0.4198	0.01168	–60.00
–50.00	7.659	43.50	33.105	–10.521	593.476	–0.02534	1.44900	1.0478	0.5271	1.3379	0.4088	0.01180	–50.00
–40.00	10.398	43.08	24.881	0.000	597.387	0.0000	1.42347	1.0549	0.5364	1.3419	0.3978	0.01193	–40.00
–30.00	13.890	42.66	18.983	10.592	601.162	0.0249	1.39938	1.0617	0.5467	1.3465	0.3870	0.01209	–30.00
–27.99[b]	14.696	42.57	18.007	12.732	601.904	0.0299	1.39470	1.0631	0.5490	1.3475	0.3849	0.01212	–27.99[b]
–25.00	15.962	42.45	16.668	15.914	602.995	0.0372	1.38784	1.0651	0.5524	1.3491	0.3817	0.01217	–25.00
–20.00	18.279	42.23	14.684	21.253	604.789	0.0494	1.37660	1.0684	0.5583	1.3520	0.3764	0.01226	–20.00
–15.00	20.858	42.01	12.976	26.609	606.544	0.0615	1.36567	1.0716	0.5646	1.3550	0.3711	0.01236	–15.00
–10.00	23.723	41.79	11.502	31.982	608.257	0.0735	1.35502	1.0749	0.5711	1.3584	0.3658	0.01246	–10.00
–5.00	26.895	41.57	10.226	37.372	609.928	0.0854	1.34463	1.0782	0.5781	1.3619	0.3606	0.01256	–5.00
0.00	30.397	41.34	9.1159	42.779	611.554	0.0972	1.33450	1.0814	0.5853	1.3657	0.3555	0.01267	0.00
5.00	34.253	41.12	8.1483	48.203	613.135	0.1089	1.32462	1.0847	0.5929	1.3698	0.3503	0.01279	5.00
10.00	38.487	40.89	7.3020	53.644	614.669	0.1205	1.31496	1.0880	0.6009	1.3742	0.3453	0.01291	10.00
15.00	43.126	40.66	6.5597	59.103	616.154	0.1320	1.30552	1.0914	0.6092	1.3789	0.3402	0.01304	15.00
20.00	48.194	40.43	5.9067	64.579	617.590	0.1434	1.29629	1.0948	0.6179	1.3840	0.3352	0.01317	20.00
25.00	53.720	40.20	5.3307	70.072	618.974	0.1547	1.28726	1.0983	0.6271	1.3894	0.3302	0.01331	25.00
30.00	59.730	39.96	4.8213	75.585	620.305	0.1660	1.27842	1.1019	0.6366	1.3951	0.3253	0.01345	30.00
35.00	66.255	39.72	4.3695	81.116	621.582	0.1772	1.26975	1.1056	0.6465	1.4012	0.3204	0.01360	35.00
40.00	73.322	39.48	3.9680	86.666	622.803	0.1883	1.26125	1.1094	0.6569	1.4078	0.3155	0.01376	40.00
45.00	80.962	39.24	3.6102	92.237	623.967	0.1993	1.25291	1.1134	0.6678	1.4147	0.3107	0.01392	45.00

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Refrigerant 717 (Ammonia) Properties of Saturated Liquid and Saturated Vapor (cont'd)

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
50.00	89.205	38.99	3.2906	97.828	625.072	0.2102	1.24472	1.1175	0.6791	1.4222	0.3059	0.01409	50.00
55.00	98.083	38.75	3.0045	103.441	626.115	0.2211	1.23667	1.1218	0.6909	1.4301	0.3012	0.01426	55.00
60.00	107.630	38.50	2.7479	109.076	627.097	0.2319	1.22875	1.1260	0.7030	1.4380	0.2965	0.01445	60.00
65.00	117.870	38.25	2.5172	114.734	628.013	0.2427	1.22095	1.1310	0.7160	1.4470	0.2918	0.01464	65.00
70.00	128.850	37.99	2.3094	120.417	628.864	0.2533	1.21327	1.1360	0.7300	1.4570	0.2872	0.01483	70.00
75.00	140.590	37.73	2.1217	126.126	629.647	0.2640	1.20570	1.1410	0.7440	1.4670	0.2825	0.01504	75.00
80.00	153.130	37.47	1.9521	131.861	630.359	0.2745	1.19823	1.1470	0.7580	1.4780	0.2780	0.01525	80.00
85.00	166.510	37.21	1.7983	137.624	630.999	0.2850	1.19085	1.1530	0.7740	1.4900	0.2734	0.01548	85.00
90.00	180.760	36.94	1.6588	143.417	631.564	0.2955	1.18356	1.1590	0.7900	1.5020	0.2689	0.01571	90.00
95.00	195.910	36.67	1.5319	149.241	632.052	0.3059	1.17634	1.1660	0.8070	1.5150	0.2644	0.01595	95.00
100.00	212.010	36.40	1.4163	155.098	632.460	0.3163	1.16920	1.1730	0.8240	1.5290	0.2600	0.01620	100.00
105.00	229.090	36.12	1.3108	160.990	632.785	0.3266	1.16211	1.1800	0.8430	1.5440	0.2556	0.01646	105.00
110.00	247.190	35.83	1.2144	166.919	633.025	0.3369	1.15508	1.1880	0.8620	1.5610	0.2512	0.01673	110.00
115.00	266.340	35.55	1.1262	172.887	633.175	0.3471	1.14809	1.1970	0.8830	1.5780	0.2468	0.01702	115.00
120.00	286.600	35.26	1.0452	178.896	633.232	0.3574	1.14115	1.2060	0.9050	1.5970	0.2424	0.01732	120.00
125.00	307.980	34.96	0.9710	184.949	633.193	0.3676	1.13423	1.2160	0.9280	1.6170	0.2381	0.01763	125.00
130.00	330.540	34.66	0.9026	191.049	633.053	0.3778	1.12733	1.2270	0.9520	1.6380	0.2338	0.01795	130.00
135.00	354.320	34.35	0.8397	197.199	632.807	0.3879	1.12044	1.2390	0.9780	1.6620	0.2295	0.01829	135.00
140.00	379.360	34.04	0.7817	203.403	632.451	0.3981	1.11356	1.2510	1.0060	1.6870	0.2253	0.01865	140.00
145.00	405.700	33.72	0.7280	209.663	631.978	0.4082	1.10666	1.2650	1.0350	1.7150	0.2210	0.01903	145.00
150.00	433.380	33.39	0.6785	215.984	631.383	0.4184	1.09975	1.2800	1.0670	1.7450	0.2168	0.01943	150.00
155.00	462.450	33.06	0.6325	222.370	630.659	0.4286	1.09281	1.2960	1.1010	1.7780	0.2125	0.01986	155.00
160.00	492.950	32.72	0.5899	228.827	629.798	0.4388	1.08582	1.3130	1.1380	1.8130	0.2083	0.02031	160.00
165.00	524.940	32.37	0.5504	235.359	628.791	0.4490	1.07878	1.3330	1.1780	1.8530	0.2041	0.02079	165.00
170.00	558.450	32.01	0.5136	241.973	627.630	0.4592	1.07167	1.3540	1.2220	1.8960	0.1999	0.02130	170.00

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Refrigerant 717 (Ammonia) Properties of Saturated Liquid and Saturated Vapor (cont'd)

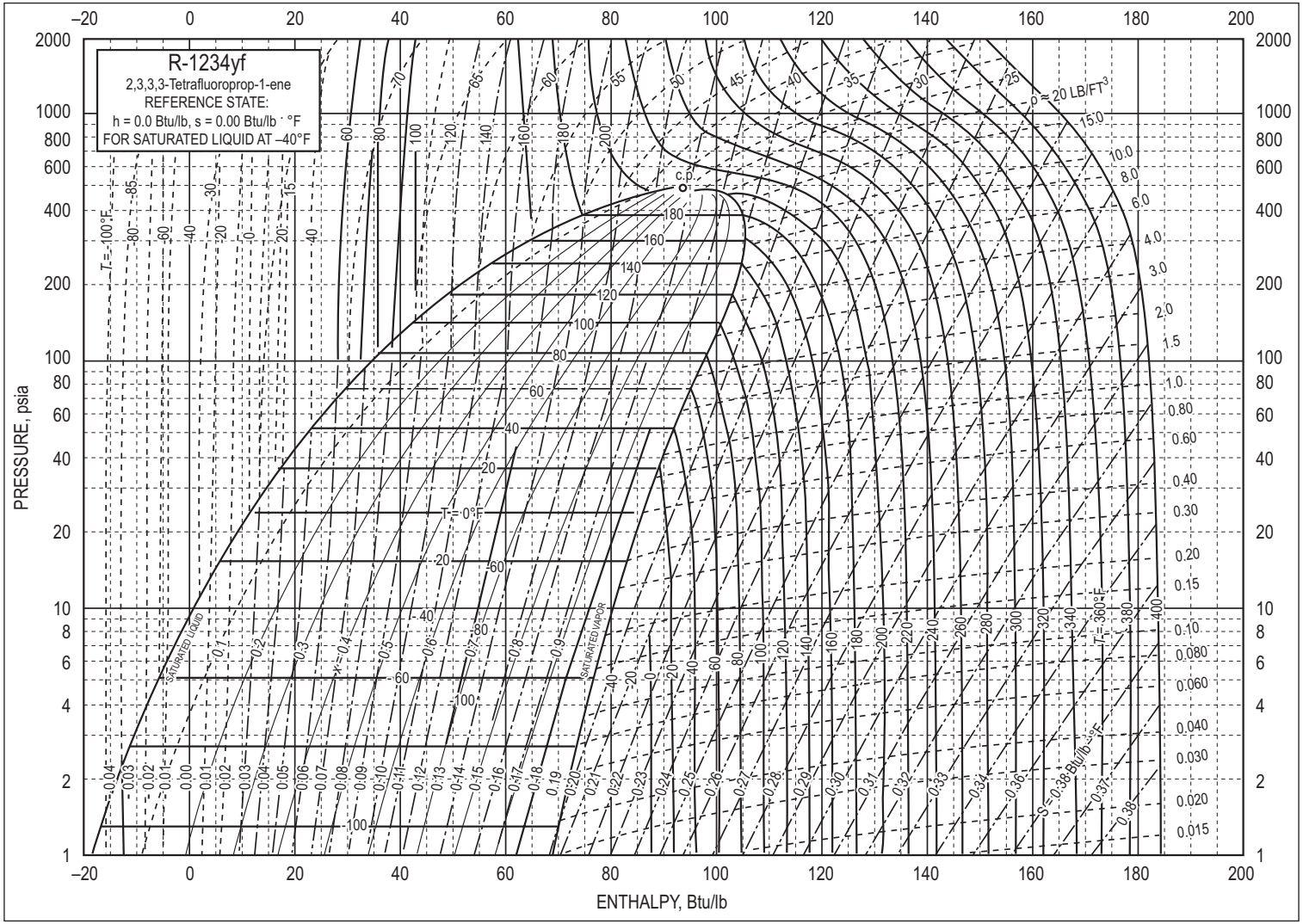
Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
175.00	593.530	31.64	0.4793	248.675	626.302	0.4695	1.06447	1.3770	1.2700	1.9440	0.1957	0.02185	175.00
180.00	630.240	31.26	0.4473	255.472	624.797	0.4798	1.05717	1.4030	1.3220	1.9980	0.1916	0.02245	180.00
185.00	668.630	30.87	0.4174	262.374	623.100	0.4902	1.04974	1.4320	1.3810	2.0580	0.1874	0.02310	185.00
190.00	708.740	30.47	0.3895	269.390	621.195	0.5007	1.04217	1.4650	1.4460	2.1260	0.1832	0.02381	190.00
195.00	750.640	30.05	0.3633	276.530	619.064	0.5112	1.03443	1.5020	1.5190	2.2030	0.1790	0.02458	195.00
200.00	794.380	29.62	0.3387	283.809	616.686	0.5219	1.02649	1.5430	1.6020	2.2900	0.1748	0.02545	200.00
205.00	840.030	29.17	0.3156	291.240	614.035	0.5327	1.01831	1.5910	1.6970	2.3920	0.1706	0.02641	205.00
210.00	887.640	28.70	0.2938	298.842	611.081	0.5436	1.00986	1.6460	1.8060	2.5090	0.1663	0.02749	210.00
215.00	937.280	28.21	0.2733	306.637	607.788	0.5547	1.00109	1.7110	1.9350	2.6480	0.1621	0.02872	215.00
220.00	989.030	27.69	0.2538	314.651	604.112	0.5661	0.99193	1.7880	2.0880	2.8140	0.1578	0.03013	220.00
225.00	1042.960	27.15	0.2354	322.918	599.996	0.5776	0.98232	1.8820	2.2720	3.0150	0.1536	0.03178	225.00
230.00	1099.140	26.57	0.2178	331.483	595.371	0.5895	0.97216	1.9990	2.5010	3.2650	0.1492	0.03372	230.00
235.00	1157.690	25.95	0.2010	340.404	590.142	0.6018	0.96133	2.1480	2.7900	3.5820	0.1449	0.03607	235.00
240.00	1218.680	25.28	0.1849	349.766	584.183	0.6146	0.94966	2.3460	3.1710	4.0000	0.1406	0.03895	240.00
245.00	1282.240	24.55	0.1693	359.695	577.309	0.6281	0.93690	2.6240	3.6930	4.5750	0.1363	0.04261	245.00
250.00	1348.490	23.72	0.1540	370.391	569.240	0.6425	0.92269	3.0470	4.4600	5.4200	0.1320	0.04744	250.00
260.00	1489.710	21.60	0.1233	395.943	547.139	0.6766	0.88671	5.2730	8.1060	9.4390	0.1250	0.06473	260.00
270.05[c]	1643.710	14.05	0.0712	473.253	473.253	0.7809	0.78093	∞	∞	∞	∞	∞	270.05[c]

* Temperature on ITS-90 scale [a] Triple point [b] Normal boiling point [c] Critical point

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Pressure Versus Enthalpy Curves for Refrigerant 1234yf



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Refrigerant 1234yf (2,3,3,3-Tetrafluoroprop-1-ene) Properties of Saturated Liquid and Saturated Vapor

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
–60	5.111	82.49	7.1955	–5.458	76.593	–0.10330	0.19200	0.2688	0.1776	1.1241	0.0528	0.00426	–60
–55	5.932	82.03	6.2622	–4.109	77.395	–0.00995	0.19146	0.2707	0.1796	1.1243	0.0522	0.00449	–55
–50	6.855	81.58	5.4710	–2.749	78.198	–0.00662	0.19097	0.2727	0.1817	1.1247	0.0517	0.00462	–50
–45	7.889	81.11	4.7974	–1.380	79.002	–0.00330	0.19055	0.2746	0.1838	1.1252	0.0511	0.00475	–45
–40	9.046	80.65	4.2215	0.000	79.808	0.00000	0.19017	0.2766	0.1859	1.1258	0.0506	0.00487	–40
–35	10.333	80.18	3.7271	1.390	80.614	0.00328	0.18984	0.2787	0.1880	1.1265	0.0501	0.00500	–35
–30	11.761	79.71	3.3012	2.790	81.420	0.00655	0.18956	0.2807	0.1903	1.1274	0.0496	0.00513	–30
–25	13.341	79.23	2.9329	4.200	82.226	0.00981	0.18932	0.2828	0.1925	1.1285	0.0490	0.00526	–25
–21.07[b]	14.696	78.85	2.6781	5.315	82.859	0.01236	0.18916	0.2844	0.1943	1.1294	0.0486	0.00536	–21.07[b]
–20	15.084	78.75	2.6132	5.621	83.032	0.01305	0.18912	0.2828	0.1948	1.1297	0.0485	0.00538	–20
–15	17.001	78.26	2.3349	7.053	83.837	0.01628	0.18896	0.2870	0.1971	1.1310	0.0480	0.00551	–15
–10	19.104	77.77	2.0917	8.495	84.641	0.01949	0.18883	0.2891	0.1995	1.1325	0.0475	0.00564	–10
–5	21.404	77.28	1.8786	9.948	85.444	0.02269	0.18874	0.2912	0.2019	1.1342	0.0470	0.00576	–5
0	23.914	76.78	1.6913	11.412	86.244	0.02588	0.18868	0.2934	0.2043	1.1361	0.0465	0.00589	0
5	26.647	76.27	1.5262	12.887	87.043	0.02906	0.18865	0.2956	0.2068	1.1381	0.0459	0.00602	5
10	29.615	75.76	1.3802	14.374	87.839	0.03223	0.18865	0.2979	0.2094	1.1404	0.0454	0.00615	10
15	32.831	75.24	1.2508	15.871	88.632	0.03538	0.18867	0.3001	0.2120	1.1429	0.0450	0.00628	15
20	36.309	74.72	1.1357	17.381	89.422	0.03895	0.18872	0.3024	0.2147	1.1457	0.0445	0.00641	20
25	40.062	74.19	1.0332	18.902	90.208	0.04166	0.18878	0.3048	0.2174	1.1486	0.0440	0.00654	25
30	44.105	73.65	0.9416	20.434	90.989	0.04479	0.18887	0.3072	0.2202	1.1519	0.0435	0.00667	30
35	48.451	73.11	0.8596	21.979	91.765	0.04790	0.18898	0.3096	0.2231	1.1555	0.0430	0.00680	35
40	53.116	72.55	0.7860	23.536	92.536	0.05101	0.18910	0.3121	0.2261	1.1594	0.0425	0.00694	40
45	58.113	71.99	0.7198	25.106	93.301	0.05411	0.18924	0.3147	0.2291	1.1637	0.0421	0.00707	45
50	63.459	71.42	0.6601	26.688	94.059	0.05720	0.18939	0.3173	0.2323	1.1685	0.0416	0.00721	50
55	69.167	70.84	0.6062	28.283	94.810	0.06029	0.18955	0.3199	0.2355	1.1736	0.0412	0.00735	55

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Refrigerant 1234yf (2,3,3,3-Tetrafluoroprop-1-ene) Properties of Saturated Liquid and Saturated Vapor (cont'd)

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
60	75.255	70.25	0.5573	29.891	95.552	0.06337	0.18972	0.3227	0.2389	1.1793	0.0407	0.00749	60
65	81.737	69.65	0.5130	31.513	96.285	0.06644	0.18989	0.3255	0.2425	1.1856	0.0403	0.00764	65
70	88.629	69.04	0.4728	33.149	97.008	0.06951	0.19007	0.3285	0.2462	1.1926	0.0398	0.00779	70
75	95.949	68.42	0.4361	34.799	97.720	0.07257	0.19025	0.3315	0.2501	1.2002	0.0394	0.00794	75
80	103.710	67.78	0.4027	36.463	98.420	0.07563	0.19044	0.3346	0.2543	1.2087	0.0390	0.00810	80
85	111.940	67.14	0.3721	38.142	99.106	0.07869	0.19062	0.3379	0.2587	1.2181	0.0385	0.00826	85
90	120.640	66.47	0.3441	39.837	99.779	0.08174	0.19079	0.3413	0.2635	1.2286	0.0381	0.00843	90
95	129.840	65.80	0.3185	41.548	100.435	0.08479	0.19096	0.3450	0.2686	1.2402	0.0377	0.00861	95
100	139.550	65.10	0.2949	43.275	101.076	0.08784	0.19112	0.3488	0.2742	1.2533	0.0373	0.00879	100
105	149.800	64.39	0.2732	45.021	101.696	0.09090	0.19126	0.3530	0.2802	1.2679	0.0369	0.00899	105
110	160.600	63.66	0.2532	46.784	102.296	0.09395	0.19140	0.3574	0.2867	1.2843	0.0365	0.00919	110
115	171.970	62.92	0.2347	48.568	102.874	0.09701	0.19151	0.3623	0.2940	1.3028	0.0361	0.00941	115
120	183.930	62.14	0.2176	50.373	103.428	0.10008	0.19160	0.3676	0.3019	1.3239	0.0358	0.00964	120
125	196.510	61.35	0.2017	52.201	103.955	0.10315	0.19167	0.3735	0.3107	1.3479	0.0354	0.00989	125
130	209.720	60.52	0.1870	54.054	104.452	0.10624	0.19171	0.3801	0.3206	1.3756	0.0350	0.01016	130
135	223.590	59.66	0.1733	55.935	104.916	0.10934	0.19171	0.3875	0.3318	1.4077	0.0347	0.01045	135
140	238.130	58.77	0.1606	57.845	105.342	0.11246	0.19167	0.3959	0.3446	1.4453	0.0344	0.01077	140
145	253.390	57.83	0.1487	59.789	105.726	0.11561	0.19158	0.4055	0.3594	1.4898	0.0340	0.01113	145
150	269.370	56.84	0.1375	61.769	106.061	0.11879	0.19144	0.4167	0.3767	1.5432	0.0338	0.01153	150
155	286.110	55.80	0.1270	63.792	106.340	0.12200	0.19122	0.4300	0.3974	1.6082	0.0335	0.01199	155
160	303.640	54.68	0.1172	65.861	106.554	0.12526	0.19093	0.4459	0.4227	1.6891	0.0332	0.01252	160
165	321.990	53.49	0.1078	67.986	106.690	0.12857	0.19053	0.4655	0.4544	1.7922	0.0331	0.01314	165
170	341.190	52.21	0.0990	70.175	106.731	0.13196	0.19001	0.4906	0.4956	1.9275	0.0329	0.01389	170
175	361.280	50.80	0.0905	72.445	106.653	0.13543	0.18933	0.5241	0.5513	2.1127	0.0329	0.01481	175
180	382.320	49.24	0.0823	74.816	106.421	0.13903	0.18844	0.5717	0.6314	2.3809	0.0330	0.01601	180

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Refrigerant 1234yf (2,3,3,3-Tetrafluoroprop-1-ene) Properties of Saturated Liquid and Saturated Vapor (cont'd)

Temp.,* °F	Pressure, psia	Density, lb/ft^3	Volume, ft^3/lb	Enthalpy, Btu/lb		Entropy, Btu/lb-°F		Specific Heat c_p Btu/lb-°F		C_p/C_v	Thermal Conductivity Btu/hr-ft-°F		Temp.,* °F
		Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Liquid	Vapor	Vapor	Liquid	Vapor	
185	404.350	47.47	0.0743	77.328	105.976	0.14281	0.18725	0.6458	0.7571	2.8031	0.0335	0.01763	185
190	427.450	45.39	0.0662	80.050	105.213	0.14688	0.18561	0.7788	0.9837	3.5641	0.0346	0.02004	190
195	451.720	42.73	0.0578	83.145	103.888	0.15147	0.18315	1.0940	1.5170	5.3442	0.0373	0.02428	195
200	477.330	38.53	0.0475	87.241	101.103	0.15752	0.17853	—	—	—	—	—	200
202.46[c]	490.550	29.69	0.0337	93.995	93.995	0.16763	0.16763	∞	∞	∞	∞	∞	202.46[c]

* Temperature on ITS-90 scale [b] Normal boiling point [c] Critical point

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8.9 Refrigerant Safety

Refrigerant Data and Safety Classifications

Refrigerant Number	Chemical Name	Chemical Formula	Molecular Mass	Normal Boiling °F	Safety Group
Methane Series					
11	Trichlorofluoromethane	CCl_3F	137.4	75	A1
12	Dichlorofluoromethane	CCl_2F_2	120.9	–20	A1
22	Chlorodifluoromethane	$CHCl_2F$	86.5	–41	A1
32	Difluoromethane	CH_2F_2	52.0	–62	A2L
Ethane Series					
123	2,2-dichloro-1,1,1-trifluorethane	$CHCl_2CF_3$	153.0	81	B1
134a	1,1,1,2-tetrafluoroethane	CH_3FCF_3	102.0	–15	A1
Propane Series					
290	Propane	$CH_3CH_2CH_3$	44.0	–44	A3
Hydrocarbons					
600	Butane	$CH_3CH_2CH_2CH_3$	58.1	31	A3
600a	Isobutane	$CH(CH_3)_2CH_3$	58.1	11	A3
601	Pentane	$CH_3(CH_2)_3CH_3$	72.2	97	A3
Inorganic Compounds					
717	Ammonia	NH_3	17.0	–28	B2
718	Water	H_2O	18.0	212	A1
744	Carbon dioxide	CO_2	44.0	–109	A1
Unsaturated Organic Compounds					
1234yf	2,3,3,3-tetrafluoro-1-propene	$CF_3CF{=}CH_2$	114.0	–20.9	A2L
1234ze(E)	Trans-1,3,3,3-tetrafluoro-1-propene	$CF_3CH{=}CHF$	114.0	–2.2	A2L
Zeotropes					
407C	R-32/125/134a (23.0/25.0/52.0)		86.2	–46.8	A1
410A	R-332/125 (50.0/50.0)		72.6	–60.9	A1
454A	R-32/1234yf (35/65)		80.47	–55.1	A2L
454B	R-32/1234yf (68.9/31.1)		62.61	–59.6	A2L

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 29, Refrigerants, Table 1.

Toxicity and flammability classifications yield six safety groups (A1, A2, A3, B1, B2, and B3) for refrigerants. Each capital letter designates a toxicity class based on allowable exposure.

Class A: Refrigerants that have an occupational exposure limit (OEL) of 400 ppm or greater

Class B: Refrigerants that have an OEL of less than 400 ppm

The numeral denotes a flammability class.

Class 1: No flame propagation in air at 140°F and 14.7 psia

Class 2: Exhibits flame propagation in air at 140°F and 14.7 psia, a lower flammability limit (LFL) greater than 0.0062 $\frac{lb}{ft^3}$ at 73.4°F and 14.7 psia, and heat of combustion less than 8,169 $\frac{Btu}{lb}$

Class 2L (Optional): Exhibits a maximum burning velocity of no more than 3.9 $\frac{in}{s}$ at 73.4°F and 14.7 psia

Class 3: Exhibits flame propagation in air at 140°F and 14.7 psia, with an LFL less than or equal to 0.0062 $\frac{lb}{ft^3}$ at 73.4°F and 14.7 psia, or heat of combustion greater than or equal to 8,169 $\frac{Btu}{lb}$

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8.10 Refrigeration Properties of Foods

Unfrozen Composition Data, Initial Freezing Point, and Specific Heats of Foods

Food Item	Initial Freezing Point, °F	Specific Heat Above Freezing, Btu/lb-°F	Specific Heat Below Freezing, Btu/lb-°F	Latent Heat of Fusion, Btu/lb
Vegetables:				
Beans, snap	30.7	0.95	0.44	130
Carrots	29.5	0.94	0.48	126
Corn	30.9	0.86	0.47	109
Peas, green	30.9	0.9	0.47	113
Brussels sprouts	30.6	0.93	0.46	123
Fruits:				
Apples, fresh	30.0	0.91	0.47	120
Apricots	30.0	0.92	0.47	124
Bananas	30.6	0.85	0.48	107
Blackberries	30.6	0.93	0.46	123
Blueberries	29.1	0.91	0.49	122
Cherries, sour	28.9	0.92	0.49	124
sweet	28.8	0.89	0.51	116
Cranberries	30.4	0.93	0.46	124
Oranges	30.6	0.91	0.47	118
Peaches, fresh	30.4	0.93	0.45	126
Pears	29.1	0.91	0.49	120
Raspberries	30.9	0.95	0.46	124
Strawberries	30.6	0.96	0.44	132
Whole Fish:				
Cod	28.0	0.9	0.51	117
Haddock	28.0	0.9	0.51	115
Halibut	28.0	0.89	0.52	112
Herring, kippered	28.0	0.78	0.54	86
Mackerel, Atlantic	28.0	0.8	0.53	91
Perch	28.0	0.89	0.51	113
Pollock, Atlantic	28.0	0.88	0.51	112
Salmon, pink	28.0	0.88	0.52	110
Beef:				
Carcass, choice	28.0	0.77	0.55	82
Round, full cut, lean	—	0.84	0.51	102
Sirloin, lean	28.9	0.84	0.5	103
T-bone steak, lean	—	0.83	0.51	100
Tenderloin, lean	—	0.82	0.51	98

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Unfrozen Composition Data, Initial Freezing Point, and Specific Heats of Foods (cont'd)

Food Item	Initial Freezing Point, °F	Specific Heat Above Freezing, Btu/lb-°F	Specific Heat Below Freezing, Btu/lb-°F	Latent Heat of Fusion, Btu/lb
Pork:				
Bacon	—	0.64	0.64	45
Carcass	—	0.74	0.74	71
Ham, cured, whole, lean	—	0.83	0.53	98
Smoked sausage links	—	0.67	0.59	56
Shoulder, whole, lean	28.0	0.86	0.53	104
Poultry Products:				
Chicken	27.0	0.79	0.42	95
Turkey	—	0.84	0.54	101
Ice Cream:				
Chocolate	21.9	0.74	0.66	80
Strawberry	21.9	0.76	0.65	86
Vanilla	21.9	0.77	0.65	88
Juice and Beverages:				
Apple juice, unsweetened	—	0.92	0.43	126
Grapefruit juice, sweetened	—	0.92	0.43	126
Grape juice, unsweetened	—	0.9	0.43	121
Lime juice, unsweetened	—	0.95	0.41	133
Orange juice	31.3	0.93	0.42	128
Pineapple juice, unsweetened	—	0.91	0.43	123

Source: ©ASHRAE, www.ashrae.org., *2014 ASHRAE Handbook—Refrigeration*, Chapter 19, Thermal Properties of Food, Table 3.

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9 HEATING, VENTILATION, AND AIR CONDITIONING

9.1 Heating and Cooling Load Calculations

9.1.1 Human Cooling Loads

Representative Rates at Which Heat and Moisture Are Given Off by People in Different States of Activity

Degree of Activity	Location	Total Heat, Btu/hr		Sensible Heat	Latent Heat	% Sensible Heat That Is Radiant[b]	
		Adult Male	Adjusted M/F[a]	Btu/hr	Btu/hr	Low V	High V
Seated at theater	Theater, matinee	390	330	225	105		
Seated at theater, night	Theater, night	390	350	245	105	60	27
Seated, very light work	Offices, hotels, apartments	450	400	245	155		
Moderately active office work	Offices, hotels, apartments	475	450	250	200	58	38
Standing, light work; walking	Department store; retail store	550	450	250	200		
Walking, standing	Drug store, bank	550	500	250	250		
Sedentary work	Restaurant[c]	490	550	275	275		
Light bench work	Factory	800	750	275	475		
Moderate dancing	Dance hall	900	850	305	545	49	35
Walking 3 mph; light machine work	Factory	1,000	1,000	375	625		
Bowling[d]	Bowling alley	1,500	1,450	580	870		
Heavy work	Factory	1,500	1,450	580	870	54	19
Heavy machine work; lifting	Factory	1,600	1,600	635	965		
Athletics	Gymnasium	2,000	1,800	710	1,090		

Note: Tabulated values are based on 75°F room dry-bulb temperature. For 80°F room dry bulb, the total heat remains the same, but the latent heat values increase accordingly.

a. Adjusted heat gain is based on normal percentage of men, women, and children for the application listed, with the postulate that the heat gain from an adult female is 85% of that for an adult male, and that the heat gain from a child is 75% of that for an adult male.

b. Values are approximated where V is air velocity in fpm.

c. Adjusted heat gain includes 60 $\frac{\text{Btu}}{\text{hr}}$ for food per individual (30 $\frac{\text{Btu}}{\text{hr}}$ sensible and 30 $\frac{\text{Btu}}{\text{hr}}$ latent).

d. Figure one person per alley actually bowling, all others sitting (400 $\frac{\text{Btu}}{\text{hr}}$) or standing or walking slowly (550 $\frac{\text{Btu}}{\text{hr}}$).

Source: ©ASHRAE, www.ashrae.org, *2013 ASHRAE Handbook—Fundamentals*, Chapter 18, Nonresidential Cooling and Heating Load Calculations, Table 1.

9.1.2 Human Oxygen Consumption

Heart Rate and Oxygen Consumption at Different Activity Levels

Level of Exertion	Heart Rate	Oxygen Consumed
	Beats per Minute	$\frac{ft^3}{hr}$
Light work	<90	<1
Moderate work	90 to 110	1 to 2
Heavy work	110 to 130	2 to 3
Very heavy work	130 to 150	3 to 4
Extremely heavy work	150 to 170	>4

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 9, Thermal Comfort, Table 5.

9.1.3 Electric Lighting

Instantaneous sensible heat gain from electric lighting:

$$q_{el} = 3.412 W F_{ul} F_{sa}$$

where

q_{el} = heat gain $\left(\frac{Btu}{hr}\right)$

W = total lighting wattage (W)

F_{ul} = lighting use factor, 1.0 or decimal fraction <1.0

F_{sa} = lighting special allowance factor, ratio of lighting fixtures' power consumption (including lamps and ballasts) to nominal power consumption of the lamps

3.412 = conversion factor $\left(\frac{Btu/hr}{W}\right)$

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9.1.4 Electric Motors

Instantaneous sensible heat gain from equipment operated by electric motors in a conditioned space:

$$q_{em} = 2,545 \frac{P}{E_M} F_{UM} F_{LM}$$

where

q_{em} = heat equivalent of equipment operation $\left(\frac{\text{Btu}}{\text{hr}}\right)$

P = motor power rating (hp)

E_M = motor efficiency, decimal fraction < 1.0

F_{UM} = motor use factor, 1.0 or decimal fraction < 1.0

F_{LM} = motor load factor, 1.0 or decimal fraction < 1.0

2,545 = conversion factor $\left(\frac{\text{Btu}}{\text{hr - hp}}\right)$

If the motor is outside the conditioned space or air stream:

$$q_{em} = 2,545 P F_{UM} F_{LM}$$

If the motor is inside the conditioned space or air stream, but the driven machine is outside or a fan or pump inside the space exhausts air or pumps fluid outside the space:

$$q_{em} = 2,545 P F_{UM} F_{LM} \left[\frac{(1.0 - E_M)}{E_M}\right]$$

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9.1.4.1 Average Efficiencies Representing Typical Electric Motors

Average Efficiencies and Related Data Representative of Typical Electric Motors

Motor	Nominal	Full Load	Location of Motor and Driven Equipment With Respect to Conditioned Space or Airstream—100% Load Factor		
			Motor In, Driven Equipment In	Motor Out, Driven Equipment In	Motor In, Driven Equipment Out
Horsepower	RPM	Efficiency, %	$\frac{\text{Btu}}{\text{hr}}$	$\frac{\text{Btu}}{\text{hr}}$	$\frac{\text{Btu}}{\text{hr}}$
1	1750	85.5%	2,977	2,545	432
1.5	1750	86.5%	4,413	3,818	596
2	1750	86.5%	5,884	5,090	794
3	1750	89.5%	8,531	7,635	896
5	1750	89.5%	14,218	12,725	1,493
7.5	1750	91.0%	20,975	19,088	1,888
10	1750	91.7%	27,754	25,450	2,304
15	1750	93.0%	41,048	38,175	2,873
20	1750	93.0%	54,731	50,900	3,831
25	1750	93.6%	67,975	63,625	4,350
30	1750	94.1%	81,137	76,350	4,787
40	1750	94.1%	108,183	101,800	6,383
50	1750	94.5%	134,656	127,250	7,406
60	1750	95.0%	160,737	152,700	8,037
75	1750	95.0%	200,921	190,875	10,046
100	1750	95.4%	266,771	254,500	12,271
125	1750	95.4%	333,464	318,125	15,339
150	1750	95.8%	398,486	381,750	16,736
200	1750	95.8%	531,315	509,000	22,315

Nominal efficiencies established in accordance with NEMA Standard MG1.

9.1.5 Heat Gain for Generic Appliances

The sensible heat gain for generic electric, steam, and gas appliances installed under a hood can be estimated from

$$q_s = q_{input} F_U F_R \quad \text{or} \quad q_s = q_{input} F_L$$

where

q_s = sensible heat gain

q_{input} = nameplate or rated energy input

F_U = usage factor

F_R = radiation factor

F_L = ratio of sensible heat gain to the manufacturer's rated energy input

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9.1.6 Heat Gain from Kitchen Equipment

Recommended Rates of Radiant and Convective Heat Gain

Unhooded Appliances During Idle (Ready-to-Cook) Conditions

Appliance	Energy Rate, $\frac{Btu}{hr}$		Rate of Heat Gain, $\frac{Btu}{hr}$				Usage Factor	Radiation Factor
	Rated	Standby	Sensible Radiant	Sensible Convective	Latent	Total	F_U	F_R
Cabinet: hot serving (large), insulated*	6,800	1,200	400	800	0	1,200	0.18	0.33
hot serving (large), uninsulated	6,800	3,500	700	2,800	0	3,500	0.51	0.20
proofing (large)*	17,400	1,400	1,200	0	200	1,400	0.08	0.86
proofing (small 15-shelf)	14,300	3,900	0	900	3,000	3,900	0.27	0.00
Coffee brewing urn	13,000	1,200	200	300	700	1,200	0.09	0.17
Drawer warmers, 2-drawer (moist holding)*	4,100	500	0	0	200	200	0.12	0.00
Egg cooker	10,900	700	300	400	0	700	0.06	0.43
Espresso machine*	8,200	1,200	400	800	0	1,200	0.15	0.33
Food warmer: steam table (2-well type)	5,100	3,500	300	600	2,600	3,500	0.69	0.09
Freezer (small)	2,700	1,100	500	600	0	1,100	0.41	0.45
Hot dog roller*	3,400	2,400	900	1,500	0	2,400	0.71	0.38
Hot plate: single-burner, high speed	3,800	3,000	900	2,100	0	3,000	0.79	0.30
Hot-food case (dry holding)*	31,100	2,500	900	1,600	0	2,500	0.08	0.36
Hot-food case (moist holding)*	31,100	3,300	900	1,800	600	3,300	0.11	0.27
Microwave oven: commercial (heavy duty)	10,900	0	0	0	0	0	0.00	0.00
Oven: countertop conveyorized bake/finishing*	20,500	12,600	2,200	10,400	0	12,600	0.61	0.17
Panini*	5,800	3,200	1,200	2,000	0	3,200	0.55	0.38
Popcorn popper*	2,000	200	100	100	0	200	0.10	0.50
Rapid-cook oven (quartz-halogen)*	41,000	0	0	0	0	0	0.00	0.00
Rapid-cook oven (microwave/convection)*	24,900	4,100	1,000	3,100	0	1,000	0.16	0.24
Reach-in refrigerator*	4,800	1,200	300	900	0	1,200	0.25	0.25
Refrigerated prep table*	2,000	900	600	300	0	900	0.45	0.67
Steamer (bun)	5,100	700	600	100	0	700	0.14	0.86
Toaster: 4-slice pop-up (large): cooking	6,100	3,000	200	1,400	1,000	2,600	0.49	0.07
contact (vertical)	11,300	5,300	2,700	2,600	0	5,300	0.47	0.51
conveyor (large)	32,800	10,300	3,000	7,300	0	10,300	0.31	0.29
conveyor (small)	5,800	3,700	400	3,300	0	3,700	0.64	0.11
Waffle iron	3,100	1,200	800	400	0	1,200	0.39	0.67

* Items with an asterisk appear only in Swierczyna et al. (2009). All others appear in both Swierczyna et al. (2008) and (2009).

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Recommended Rates of Radiant Heat Gain

Hooded Appliances During Idle (Ready-to-Cook) Conditions

Appliance	Energy Rate, $\frac{Btu}{hr}$		Rate of Heat Gain, $\frac{Btu}{hr}$	Usage Factor	Radiation Factor
	Rated	Standby	Sensible Radiant	F_U	F_R
Broiler: underfired 3 ft	39,900	30,900	10,800	0.84	0.35
Cheese melter*	12,300	11,900	4,600	0.97	0.39
Fryer: kettle	99,000	1,800	500	0.02	0.28
open deep-fat, 1-vat	47,800	2,800	1,000	0.06	0.36
pressure	46,100	2,700	500	0.06	0.19
Griddle: double-sided 3 ft (clamshell down)*	72,400	6,900	1,400	0.10	0.20
double-sided 3 ft (clamshell up)*	72,400	11,500	3,600	0.16	0.31
flat 3 ft	58,400	11,500	4,500	0.20	0.39
small 3 ft*	30,700	6,100	2,700	0.20	0.44
Induction cooktop*	71,700	0	0	0.00	0.00
Induction wok*	11,900	0	0	0.00	0.00
Oven: combi: combi-mode*	56,000	5,500	800	0.10	0.15
convection mode	56,000	5,500	1,400	0.10	0.25
Oven: convection full-sized	41,300	6,700	1,500	0.16	0.22
half-sized*	18,800	3,700	500	0.20	0.14
Pasta cooker*	75,100	8,500	0	0.11	0.00
Range top: top off/oven on*	16,600	4,000	1,000	0.24	0.25
3 elements on/oven off	51,200	15,400	6,300	0.30	0.41
6 elements on/oven off	51,200	33,200	13,900	0.65	0.42
6 elements on/oven on	67,800	36,400	14,500	0.54	0.40
Range: hot-top	54,000	51,300	11,800	0.95	0.23
Rotisserie*	37,900	13,800	4,500	0.36	0.33
Salamander*	23,900	23,300	7,000	0.97	0.30
Steam kettle: large (60 gal) simmer lid down*	110,600	2,600	100	0.02	0.04
Steam kettle: small (40 gal) simmer lid down*	73,700	1,800	300	0.02	0.17
Steamer: compartment: atmospheric*	33,400	15,300	200	0.46	0.01
Tilting skillet/braising pan	32,900	5,300	0	0.16	0.00

* Items with an asterisk appear only in Swierczyna et al. (2009). All others appear in both Swierczyna et al. (2008) and (2009).

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Recommended Rates of Radiant Heat Gain

Hooded Gas Appliances During Idle (Ready-to-Cook) Conditions

Appliance	Energy Rate, $\frac{Btu}{hr}$		Rate of Heat Gain, $\frac{Btu}{hr}$	Usage Factor	Radiation Factor
	Rated	Standby	Sensible Radiant	F_U	F_R
Broiler: batch*	95,000	69,200	8,100	0.73	0.12
chain (conveyor)	132,000	96,700	13,200	0.73	0.14
overfired (upright)*	100,000	87,900	2,500	0.88	0.03
underfired 3 ft	96,000	73,900	9,000	0.77	0.12
Fryer: doughnut	44,000	12,400	2,900	0.28	0.23
open deep-fat, 1 vat	80,000	4,700	1,100	0.06	0.23
pressure	80,000	9,000	800	0.11	0.09
Griddle: double-sided 3 ft (clamshell down)*	108,200	8,000	1,800	0.07	0.23
double-sided 3 ft (clamshell up)*	108,200	14,700	4,900	0.14	0.33
flat 3 ft	90,000	20,400	3,700	0.23	0.18
Oven: combi: combi-mode*	75,700	6,000	400	0.08	0.07
convection mode	75,700	5,800	1,000	0.08	0.17
convection full-sized	44,000	11,900	1,000	0.27	0.08
conveyor (pizza)	170,000	68,300	7,800	0.40	0.11
deck	105,000	20,500	3,500	0.20	0.17
rack mini-rotating*	56,300	4,500	1,100	0.08	0.24
Pasta cooker*	80,000	23,700	0	0.30	0.00
Range top: top off/oven on*	25,000	7,400	2,000	0.30	0.27
3 burners on/oven off	120,000	60,100	7,100	0.50	0.12
6 burners on/oven off	120,000	120,800	11,500	1.01	0.10
6 burners on/oven on	145,000	122,900	13,600	0.85	0.11
Range: wok*	99,000	87,400	5,200	0.88	0.06
Rethermalizer*	90,000	23,300	11,500	0.26	0.49
Rice cooker*	35,000	500	300	0.01	0.60
Salamander*	35,000	33,300	5,300	0.95	0.16
Steam kettle: large (60 gal) simmer lid down*	145,000	5,400	0	0.04	0.00
Steam kettle: small (10 gal) simmer lid down*	52,000	3,300	300	0.06	0.09
Steam kettle: small (40 gal) simmer lid down	100,000	4,300	0	0.04	0.00
Steamer: compartment: atmospheric*	26,000	8,300	0	0.32	0.00
Tilting skillet/braising pan	104,000	10,400	400	0.10	0.04

* Items with an asterisk appear only in Swierczyna et al. (2009). All others appear in both Swierczyna et al. (2008) and (2009).

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Recommended Rates of Radiant Heat Gain

Hooded, Solid Fuel Appliances During Idle (Ready-to-Cook) Conditions

Appliance	Energy Rate, $\frac{Btu}{hr}$	Rate of Heat Gain, $\frac{Btu}{hr}$		Usage Factor	Radiation Factor
	Rated	Standby	Sensible	F_U	F_R
Broiler: solid fuel: charcoal	40 lb	42,000	6,200	n/a	0.15
wood (mesquite)*	40 lb	49,600	7,000	n/a	0.14

* Items with an asterisk appear only in Swierczyna et al. (2009). All others appear in both Swierczyna et al. (2008) and (2009).

Source: ©ASHRAE, www.ashrae.org, *2013 ASHRAE Handbook—Fundamentals*, Chapter 18, Nonresidential Cooling and Heating Load Calculations, Table 5D.

Recommended Rates of Radiant and Convective Heat Gain

Warewashing Equipment During Idle (Standby) Conditions

Appliance	Energy Rate, $\frac{Btu}{hr}$		Rate of Heat Gain, $\frac{Btu}{hr}$					Usage Factor	Radiation Factor
			Unhooded				Hooded		
	Rated	Standby/ Washing	Sensible Radiant	Sensible Convective	Latent	Total	Sensible Radiant	F_U	F_R
Dishwasher (conveyor type, chemical sanitizing)	46,800	5,700/43,600	0	4,450	13,490	17,940	0	0.36	0
(conveyor type, hot-water sanitizing) standby	46,800	5,700/n/a	0	4,750	16,970	21,720	0	n/a	0
(door-type, chemical sanitizing) washing	18,400	1,200/13,300	0	1,980	2,790	4,770	0	0.26	0
(door-type, hot-water sanitizing) washing	18,400	1,200/13,300	0	1,980	2,790	4,770	0	0.26	0
(under-counter type, chemical sanitizing) standby	26,600	1,200/18,700	0	2,280	4,170	6,450	0	0.35	0.00
(under-counter type, hot-water sanitizing) standby	26,600	1,700/19,700	800	1,040	3,010	4,850	800	0.27	0.34
Booster heater*	130,000	0	500	0	0	0	500	0	n/a

Heat load values are prorated for 30° washing and 70° standby.

* Items with an asterisk appear only in Swierczyna et al. (2009). All others appear in both Swierczyna et al. (2008) and (2009).

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9.1.7 Heat Gain Calculations Using Standard Air and Water Values

Total heat gain is calculated as

$$q_t = 60 \times 0.075\, Q_s \Delta h = 4.5 Q_s \Delta h$$

where

Q_s = standard flow rate (cfm)

$60 = \frac{\text{min}}{\text{hr}}$

$0.075 = \frac{\text{lb}_{da}}{\text{ft}^3}$

$q_t = \frac{\text{Btu}}{\text{hr}}$, latent plus sensible

Total heat gain can also be expressed as

$$q_t = C_t Q_s \Delta h$$

For air at sea level and normal temperatures:

$$C_t = 4.5$$

For air at 5,000 feet:

$$C_t = 3.74$$

Sensible heat gain:

$$q_s = 60 \times 0.075 \left(0.24 + 0.45W\right) Q_s \Delta t$$

where

0.24 = specific heat of dry air $\left(\frac{\text{Btu}}{\text{lb-°F}}\right)$

W = humidity ratio $\left(\frac{\text{lb}_w}{\text{lb}_{da}}\right)$

0.45 = specific heat of water vapor $\left(\frac{\text{Btu}}{\text{lb-°F}}\right)$

For air at or near sea level, this can be simplified to

$$q_s = 1.10\, Q_s \Delta t$$

Sensible heat gain can also be expressed as

$$q_s = C_s Q_s \Delta t$$

For air at sea level:

C_s = 1.10, the sensible heat factor for standard air $\left(\frac{\text{Btu}}{\text{hr-cfm-°F}}\right)$

For air at 5,000 ft:

$$C_s = 0.92$$

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Latent heat gain:

$$q_l = 60 \times 0.075 \times 1{,}076\, Q_s \Delta W = 4{,}840\, Q_s \Delta W$$

where

$1{,}076\ \frac{\text{Btu}}{\text{lb}}$ = approximate heat content of 50% RH vapor at 75°F less the heat content of water at 50°F.

Latent heat gain can also be expressed as

$$q_l = C_t Q_s \Delta W$$

For air at or near sea level:

C_t = 4,840, the air latent heat factor for standard air $\left(\frac{\text{Btu}}{\text{hr-cfm}}\right)$

For air at 5,000 ft:

C_t = 4,027

The rate of heat transfer to or from water can be calculated by:

$$q_w = \dot{m} c_p \Delta t$$

where

q_w = heat transfer rate to or from water (Btu/hr)

$\dot{m}$ = mass flow rate of water (lb/hr)

c_p = specific heat of water (Btu/lb-°F)

Δt = water temperature increase or decrease across unit (°F)

Expressing the flow rate as volumetric flow, the equation becomes:

$$q_w = 8.02 \rho_w c_p Q_w \Delta t$$

where

Q_w = water flow rate (gpm)

ρ_w = density of water (lb/ft^3)

For standard water conditions in which the density is 62.4 lb/ft^3 and specific heat is 1 Btu/lb-°F, the equation becomes:

$$q_w = 500 Q_w \Delta t$$

This can be rearranged to:

$$Q_w = q_w / (500\ \Delta t)$$

q_w is called the heat carrying capacity. In systems with glycol solutions, the above equation needs to be adjusted to reflect the actual density and specific heat of the solution.

Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 18, Nonresidential Cooling and Heating Load Calculations, and *2020 ASHRAE Handbook—HVAC Systems and Equipment,* Chapter 13, Hydronic Heating and Cooling.

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9.1.8 Elevation Corrections for Total, Sensible, and Latent Heat Equations

The above constants 4.5, 1.10, and 4,840 apply to sea level. At 5,000 feet, the factors are 3.74, 0.92, and 4,027. For other elevations, the factors can be derived from

$$C_{x,alt} = \frac{C_{x,0}\,P}{P_0}$$

where

$C_{x,0}$ = any of the sea-level C values

$\frac{P}{P_0} = \left[1 - \left(\text{elevation} \times 6.875 \times 10^{-6}\right)\right]^{5.256}$, where elevation is in feet above sea level

9.1.9 Heat Gain Through Interior Surfaces

$$q = UA\left(t_b - t_i\right)$$

where

q = heat-transfer rate $\left(\frac{\text{Btu}}{\text{hr}}\right)$

U = coefficient of overall heat transfer between adjacent and conditioned space $\left(\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}\right)$

A = area of separating section concerned (ft^2)

t_b = average air temperature in adjacent space (°F)

t_i = air temperature in conditioned space (°F)

9.1.10 Fenestration

The basic equation for the steady-state energy flow through a fenestration is

$$q = UA_{pf}\left(t_{out} - t_{in}\right) + \left(SHGC\right)A_{pf}\,E_t + C\left(AL\right)A_{pf}\,\rho C_p\left(t_{out} - t_{in}\right)$$

where

q = instantaneous energy flow $\left(\frac{\text{Btu}}{\text{hr}}\right)$

U = overall coefficient of heat transfer (U-factor) $\left(\frac{\text{Btu}}{\text{hr - ft}^2\text{-°F}}\right)$

A_{pf} = total projected area of fenestration (product's rough opening in wall or roof minus installation clearances) (ft^2)

t_{in} = indoor air temperature (°F)

t_{out} = outdoor air temperature (°F)

$SHGC$ = *solar heat gain coefficient*, dimensionless

E_t = incident total irradiance $\left(\frac{\text{Btu}}{\text{hr - ft}^2}\right)$

C = constant, 60 $\frac{\text{min}}{\text{hr}}$

AL = air leakage at current conditions $\left(\frac{\text{cfm}}{\text{ft}^2}\right)$

ρ = air density $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

C_p = specific heat of air $\left(\frac{\text{Btu}}{\text{lbm-°F}}\right)$

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The overall U-factor through a fenestration system using area weighted U-factors for each contribution is

$$U = \frac{U_{cg} A_{cg} + U_{eg} A_{eg} + U_f A_f}{A_{pf}}$$

where

cg = center of glass

eg = edge of glass

f = frame

9.1.10.1 Condensation Resistance Factor (CRF) or Temperature Index (I)

The condensation resistance factor (*CRF)* or temperature index (*I)* for fenestration glass or frame is calculated from

$$CRF \text{ or } I = \frac{t - t_c}{t_h - t_c}$$

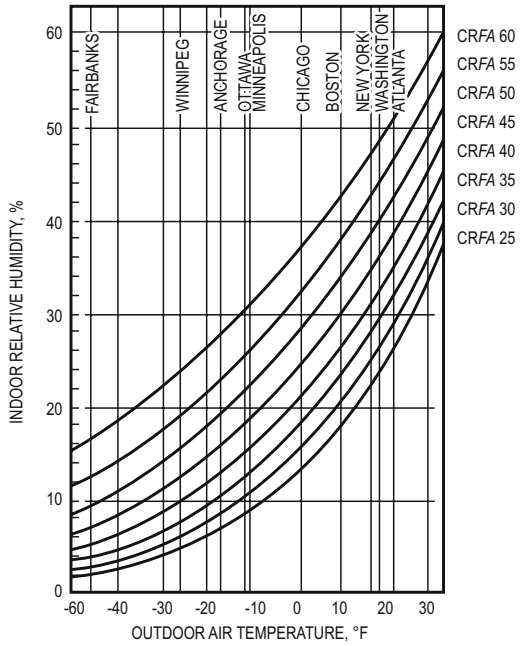
where

t_h = warm side temperature

t_c = cold side temperature

t = glass or frame temperature

Minimum Condensation Resistance Requirements (t_h= 68°F)



Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 15, Fenestration, Fig. 28.

9.1.11 Thermal Resistance Properties

Surface Film Coefficients/Resistances for Air

Position of Surface	Direction of Heat Flow	Surface Emittance, ε					
		Nonreflective		Reflective			
		ε = 0.90		ε = 0.20		ε = 0.05	
		h_i	R_i	h_i	R_i	h_i	R_i
Indoor							
Horizontal	Upward	1.63	0.61	0.91	1.1	0.76	1.32
Sloping 45°	Upward	1.6	0.62	0.88	1.14	0.73	1.37
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.7
Sloping 45°	Downward	1.32	0.76	0.6	1.67	0.45	2.22
Horizontal	Downward	1.08	0.92	0.37	2.7	0.22	4.55
Outdoor (any position)		h_o	R_o				
15 mph wind (for winter)	Any	6.00	0.17	—	—	—	—
7.5 mph wind (for summer)	Any	4.00	0.25	—	—	—	—

Notes:

1. Surface conductance h_i and h_o measured in $\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$; resistance R_i and R_o, in $\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}$.
2. No surface has both an air-space resistance value and a surface resistance value.
3. Conductances are for surfaces of the stated emittance that face virtual black body surroundings at the same temperature as the ambient air. Values are based on a surface-air temperature difference of 10°F and surface temperatures of 70°F.
4. For additional information on emissivity of various surfaces and effective emittances of facing air spaces, refer to Heat Transfer chapter.

Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 26, Heat, Air, and Moisture Control in Building Assemblies—Material Properties, Table 10.

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Thermal Resistances of Plane Air Spaces, in $\frac{ft^2\text{-}°F\text{-}hr}{Btu}$

Position of Air Space	Direction of Heat Flow	Air Space		0.5 in. Air Space					0.75 in. Air Space				
		Mean Temp.	Temp. Diff.	Effective Emittance ε_{eff}					Effective Emittance ε_{eff}				
		°F	°F	0.03	0.05	0.20	0.50	0.82	0.03	0.05	0.20	0.50	0.82
Horizontal	Up ↑	90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
		0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		−50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		−50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
45° Slope	Up ↗	90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
		0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		−50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		−50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
Vertical	Horizontal →	90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
		0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		−50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		−50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
45° Slope	Down ↘	90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
		0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		−50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		−50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66
Horizontal	Down ↓	90	10	2.48	2.34	1.67	1.06	0.77	3.55	3.29	2.10	1.22	0.85
		50	30	2.66	2.54	1.88	1.24	0.91	3.77	3.52	2.38	1.44	1.02
		50	10	2.67	2.55	1.89	1.25	0.92	3.84	3.59	2.41	1.45	1.02
		0	20	2.94	2.83	2.20	1.53	1.15	4.18	3.96	2.83	1.81	1.30
		0	10	2.96	2.85	2.22	1.53	1.16	4.25	4.02	2.87	1.82	1.31
		−50	20	3.25	3.15	2.58	1.89	1.47	4.60	4.41	3.36	2.28	1.69
		−50	10	3.28	3.18	2.60	1.90	1.47	4.71	4.51	3.42	2.30	1.71

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Thermal Resistances of Plane Air Spaces, in $\frac{ft^2\text{-}°F\text{-}hr}{Btu}$ (cont'd)

Position of Air Space	Direction of Heat Flow	Air Space		1.5 in. Air Space					3.5 in. Air Space				
		Mean Temp.	Temp. Diff.	Effective Emittance ε_{eff}					Effective Emittance ε_{eff}				
		°F	°F	0.03	0.05	0.20	0.50	0.82	0.03	0.05	0.20	0.50	0.82
Horizontal	Up ↑	90	10	2.55	2.41	1.71	1.08	0.77	2.84	2.66	1.83	1.13	0.80
		50	30	1.87	1.81	1.45	1.04	0.80	2.09	2.01	1.58	1.10	0.84
		50	10	2.50	2.40	1.81	1.21	0.89	2.80	2.66	1.95	1.28	0.93
		0	20	2.01	1.95	1.63	1.23	0.97	2.25	2.18	1.79	1.32	1.03
		0	10	2.43	2.35	1.90	1.38	1.06	2.71	2.62	2.07	1.47	1.12
		−50	20	1.94	1.91	1.68	1.36	1.13	2.19	2.14	1.86	1.47	1.20
		−50	10	2.37	2.31	1.99	1.55	1.26	2.65	2.58	2.18	1.67	1.33
45° Slope	Up ↗	90	10	2.92	2.73	1.86	1.14	0.80	3.18	2.96	1.97	1.18	0.82
		50	30	2.14	2.06	1.61	1.12	0.84	2.26	2.17	1.67	1.15	0.86
		50	10	2.88	2.74	1.99	1.29	0.94	3.12	2.95	2.10	1.34	0.96
		0	20	2.30	2.23	1.82	1.34	1.04	2.42	2.35	1.90	1.38	1.06
		0	10	2.79	2.69	2.12	1.49	1.13	2.98	2.87	2.23	1.54	1.16
		−50	20	2.22	2.17	1.88	1.49	1.21	2.34	2.29	1.97	1.54	1.25
		−50	10	2.71	2.64	2.23	1.69	1.35	2.87	2.79	2.33	1.75	1.39
Vertical	Horizontal →	90	10	3.99	3.66	2.25	1.27	0.87	3.69	3.40	2.15	1.24	0.85
		50	30	2.58	2.46	1.84	1.23	0.90	2.67	2.55	1.89	1.25	0.91
		50	10	3.79	3.55	2.39	1.45	1.02	3.63	3.40	2.32	1.42	1.01
		0	20	2.76	2.66	2.10	1.48	1.12	2.88	2.78	2.17	1.51	1.14
		0	10	3.51	3.35	2.51	1.67	1.23	3.49	3.33	2.50	1.67	1.23
		−50	20	2.64	2.58	2.18	1.66	1.33	2.82	2.75	2.30	1.73	1.37
		−50	10	3.31	3.21	2.62	1.91	1.48	3.40	3.30	2.67	1.94	1.50
45° Slope	Down ↘	90	10	5.07	4.55	2.56	1.36	0.91	4.81	4.33	2.49	1.34	0.90
		50	30	3.58	3.36	2.31	1.42	1.00	3.51	3.30	2.28	1.40	1.00
		50	10	5.10	4.66	2.85	1.60	1.09	4.74	4.36	2.73	1.57	1.08
		0	20	3.85	3.66	2.68	1.74	1.27	3.81	3.63	2.66	1.74	1.27
		0	10	4.92	4.62	3.16	1.94	1.37	4.59	4.32	3.02	1.88	1.34
		−50	20	3.62	3.50	2.80	2.01	1.54	3.77	3.64	2.90	2.05	1.57
		−50	10	4.67	4.47	3.40	2.29	1.70	4.50	4.32	3.31	2.25	1.68
Horizontal	Down ↓	90	10	6.09	5.35	2.79	1.43	0.94	10.07	8.19	3.41	1.57	1.00
		50	30	6.27	5.63	3.18	1.70	1.14	9.60	8.17	3.86	1.88	1.22
		50	10	6.61	5.90	3.27	1.73	1.15	11.15	9.27	4.09	1.93	1.24
		0	20	7.03	6.43	3.91	2.19	1.49	10.90	9.52	4.87	2.47	1.62
		0	10	7.31	6.66	4.00	2.22	1.51	11.97	10.32	5.08	2.52	1.64
		−50	20	7.73	7.20	4.77	2.85	1.99	11.64	10.49	6.02	3.25	2.18
		−50	10	8.09	7.52	4.91	2.89	2.01	12.98	11.56	6.36	3.34	2.22

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Thermal Resistance of Building Materials

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
BUILDING BOARD							
Gypsum or plaster board	0.375 in.	50	—	3.10	—	0.32	0.26
Gypsum or plaster board	0.5 in.	50	—	2.22	—	0.45	
Gypsum or plaster board	0.625 in.	50	—	1.78	—	0.56	
Plywood (Douglas fir)		34	0.80	—	1.25	—	0.29
Plywood (Douglas fir)	0.25 in.	34	—	3.20	—	0.31	
Plywood (Douglas fir)	0.375 in.	34	—	2.13	—	0.47	
Plywood (Douglas fir)	0.5 in.	34	—	1.60	—	0.62	
Plywood (Douglas fir)	0.625 in.	34	—	1.29	—	0.77	
Plywood or wood panels	0.75 in.	34	—	1.07	—	0.93	0.29
Vegetable fiber board							
Sheathing, regular density	0.5 in.	18	—	0.76	—	1.32	0.31
	0.78125 in.	18	—	0.49	—	2.06	
Sheathing intermediate density	0.5 in.	22	—	0.92	—	1.09	0.31
Nail-base sheathing	0.5 in.	25	—	0.94	—	1.06	0.31
Shingle backer	0.375 in.	18	—	1.06	—	0.94	0.31
Shingle backer	0.3125 in.	18	—	1.28	—	0.78	
Sound deadening board	0.5 in.	15	—	0.74	—	1.35	0.30
Tile and lay-in panels, plain or acoustic		18	0.40	—	2.50	—	0.14
	0.5 in.	18	—	0.80	—	1.25	
	0.75 in.	18	—	0.53	—	1.89	
Laminated paperboard		30	0.50	—	2.00	—	0.33
Homogeneous board from repulped paper		30	0.50	—	2.00	—	0.28
Hardboard							
Medium density		50	0.73	—	1.37	—	0.31
High density, service-tempered grade and service grade		55	0.82	—	1.22	—	0.32
High density, standard tempered grade		63	1.00	—	1.00	—	0.32

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Particleboard							
Low density		37	0.71	—	1.41	—	0.31
Medium density		50	0.94	—	1.06	—	0.31
High density		62	0.50	1.18	—	0.85	—
Underlayment	0.625 in.	40	—	1.22	—	0.82	0.29
Waferboard		37	0.63	—	1.59	—	—
Wood subfloor	0.75 in.	—	—	1.06	—	0.94	0.33
BUILDING MEMBRANE							
Vapor—permeable felt		—	—	16.7	—	0.06	
Vapor—seal, 2 layers of mopped 15 lb felt		—	—	8.35	—	0.12	
Vapor—seal, plastic film		—	—	—	—	Negl.	
FINISH FLOORING MATERIALS							
Carpet and fibrous pad		—	—	0.48	—	2.08	0.34
Carpet and rubber pad		—	—	0.81	—	1.23	0.33
Cork tile	0.125 in.	—	—	3.60	—	0.28	0.48
Terrazzo	1 in.	—	—	12.50	—	0.08	0.19
Tile—asphalt, linoleum, vinyl, rubber		—	—	20.00	—	0.05	0.30
ceramic							0.19
Wood, hardwood finish	0.75 in.	—	—	1.47	—	0.68	—
INSULATING MATERIALS							
Blanket and Batt							
Mineral fiber, fibrous form processed from rock, slag, or fiberglass							
Nominal 3.5 in.		0.4 - 2.0	—	0.077	—	13	
Nominal 6 inches in.		0.4 - 2.0	—	0.053	—	19	
Nominal 9 inches in.		0.4 - 2.0	—	0.033	—	30	
Nominal 12 inches		0.4 - 2.0	—	0.026	—	38	

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Board and Slabs							
Cellular glass		8.0	0.33	—	3.03	—	0.18
Glass fiber, organic bonded		4.0 - 9.0	0.25	—	4.00	—	0.23
Expanded perlite, organic bonded		1.0	0.36	—	2.78	—	0.30
Expanded rubber (rigid)		4.5	0.22	—	4.55	—	0.40
Expanded polystyrene, extruded (smooth skin surface)		1.8 - 3.5	0.20	—	5.00	—	0.29
Expanded polystyrene, molded beads		1	0.26	—	3.85	—	—
		1.25	0.25	—	4	—	—
		1.5	0.24	—	4.17	—	—
		1.75	0.24	—	4.17	—	—
		2	0.23	—	4.35	—	—
Cellular polyurethane/polyisocyanurate with foil faces				—	6.5	—	—
Cellular phenolic (closed cell)		3	0.12	—	8.2	—	—
Cellular phenolic (open cell)		1.8-2.2	0.23	—	4.4	—	—
Mineral fiber with resin binder		15	0.29	—	3.45	—	0.17
Mineral fiberboard, wet felted							
Core or roof insulation		16-17	0.34	—	2.94	—	—
Acoustical tile		18	0.35	—	2.86	—	0.19
Acoustical tile		21	0.37	—	2.7	—	—
Mineral fiberboard, wet molded							
Acoustical tile		23	0.42	—	2.38	—	0.14

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Wood or cane fiberboard							
Acoustical tile	0.5 in.	—	—	0.8	—	1.25	0.31
Acoustical tile	0.75 in.	—	—	0.53	—	1.89	—
Interior finish (plank, tile)		15	0.35	—	2.86	—	0.32
Cement fiber slabs (shredded wood with Portland cement binder			25–27.0	0.50–0.53	2.0–1.89		
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)		22	0.57	—	1.75	—	0.31
Loose fill							
Cellulosic insulation (milled paper or wood pulp)		2.3-3.2	0.27–0.32	—	3.70–3.13	—	0.33
Perlite, expanded		2.0-4.1	0.27–0.31	—	3.7–3.3	—	0.26
		4.1–7.4	0.31–0.36	—	3.3–2.8	—	—
		7.4–11.0	0.36–0.42	—	2.8–2.4	—	—
Mineral fiber (rock, slag, or glass)							
approx. 3.75–5 in.		0.6–2.0	—	—	—	11	0.17
approx. 6.5–8.75 in.		0.6–2.0	—	—	—	19	—
approx. 7.5–10 in .		0.6–2.0	—	—	—	22	—
approx. 10.25–13.75 in.		0.6–2.0	—	—	—	30	—
Mineral fiber (rock, slag, or glass)							
approx. 3.5 in. (closed sidewall application)		2.0–3.5	—	—	—	12.0–14.0	—
Vermiculite		7.0–8.2	0.47	—	2.13	—	0.32
		4.0–6.0	0.44	—	2.27	—	—
Reflective Insulation							
Reflective material ($\varepsilon < 0.5$) in center of 3/4 in. cavity forms		—	—	0.31	—	3.2	—

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
ROOFING							
Asbestos-cement shingles		120	—	4.76	—	0.21	0.24
Asphalt roll roofing		70	—	6.5	—	0.15	0.36
Asphalt shingles		70	—	2.27	—	0.44	0.3
Built-up roofing	0.375 in.	70	—	3	—	0.33	0.35
Slate	0.5 in.	—	—	20	—	0.05	0.3
Wood shingles, plain and plastic film faced		—	—	1.06	—	0.94	0.31
PLASTERING MATERIALS							
Cement plaster, sand aggregate		116	5	—	0.2	—	0.2
Sand aggregate	0.375 in.	—	—	13.3	—	0.08	0.2
Sand aggregate	0.75 in.	—	—	6.66	—	0.15	0.2
Gypsum plaster:							
Lightweight aggregate		45	—	3.12	—	0.32	—
Lightweight aggregate		45	—	2.67	—	0.39	—
Lightweight aggregate		—	—	2.13	—	0.47	—
Perlite aggregate		45	1.5	—	0.67	—	0.32
Sand aggregate		105	5.6	—	0.18	—	0.2
Sand aggregate	0.5 in.	105	—	11.1	—	0.09	—
Sand aggregate	0.625 in.	105	—	9.1	—	0.11	—
Sand aggregate on metal lathe	0.75 in.	—	—	7.7	—	0.13	—
Vermiculite aggregate		45	1.7	—	0.59	—	—

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
MASONRY MATERIALS							
Masonry Units							
Brick, fired clay		150	8.4–10.2	—	0.12–0.10	—	—
		140	7.4–9.0	—	0.14–0.11	—	—
		130	6.4–7.8	—	0.16–0.12	—	—
		120	5.6–6.8	—	0.18–0.15	—	0.19
		110	4.9–5.9	—	0.20–0.17	—	—
		100	4.2–5.1	—	0.24–0.20	—	—
		90	3.6–4.3	—	0.28–0.24	—	—
		80	3.0–3.7	—	0.33–0.27	—	—
		70	2.5–3.1	—	0.40–0.33	—	—
Clay tile, hollow							
1 cell deep	3 in.	—	—	1.25	—	0.8	0.21
1 cell deep	4 in.	—	—	0.9	—	1.11	—
2 cells deep	6 in.	—	—	0.66	—	1.52	—
2 cells deep	8 in.	—	—	0.54	—	1.85	—
2 cells deep	10 in.	—	—	0.45	—	2.22	—
3 cells deep	12 in.	—	—	0.4	—	2.5	—
Concrete blocks							
Limestone aggregate							
8 in., 36 lb, 138 lb/ft3 concrete, 2 cores		—	—	—	—	—	—
Same with perlite filled cores		—	—	0.48	—	2.1	—
12 in., 55 lb, 138 lb/ft3 concrete, 2 cores		—	—	—	—	—	—
Same with perlite filled core		—	—	0.27	—	3.7	—
Normal weight aggregate (sand and gravel)							
8 in., 33–36 lb, 126–136 lb/ft3 concrete, 2 or 3 cores		—	—	0.90–1.03	—	1.11–0.97	0.22

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Same with perlite filled core		—	—	0.5	—	2	—
Same with vermiculate filled core		—	—	0.52–0.73	—	1.92–1.37	—
12 in., 50 lb, 125 lb/ft3 concrete, 2 cores		—	—	0.81	—	1.23	0.22
Medium weight aggregate (combinations of normal weight and lightweight aggregate)							
8 in., 26–29 lb, 97–112 lb/ft3 concrete, 2 or 3 cores		—	—	0.58–0.78	—	1.71–1.28	—
Same with perlite filled cores		—	—	0.27–0.44	—	3.7–2.3	—
Same with vermiculate filled cores		—	0.3	—	3.3	—	
Same with molded EPS (beads) filled cores		—	—	0.32	—	3.2	—
Same with molded EPS inserts in cores		—	—	0.37	—	2.7	—
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)							
6 in., 16–17 lb 85–87 lb/ft3 concrete, 2 or 3 cores		—	—	0.52–0.61	—	1.93–1.65	—
Same with perlite filled cores		—	—	0.24	—	4.2	—
Same with vermiculite filled cores		—	—	0.33	—	3	—
8 in., 19–22 lb, 72–86 lb/ft3 concrete		—	—	0.32–0.54	—	3.2–1.90	0.21
Same with perlite filled cores		—	—	0.15–0.23	—	6.8–4.4	—
Same with vermiculite filled cores		—	—	0.19–0.26	—	5.3–3.9	—
Same with molded EPS (beads) filled cores		—	—	0.21	—	4.8	—
Same with UF foam filled cores		—	—	0.22	—	4.5	—
Same with molded EPS inserts in core		—	—	0.29	—	3.5	—
12 in., 23–26 lb, 80–90 lb/ft3 concrete, 2 or 3 cores		—	—	0.38–0.44	—	2.6–2.3	—
Same with perlite filled cores		—	—	0.11–0.16	—	9.2–6.3	—
Same with vermiculite filled cores		—	—	0.17	—	5.8	—
Stone, lime or sand		180	72	—	0.01	—	—

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Quartzitic and sandstone		160	43	—	0.02	—	—
		140	24	—	0.04	—	—
		120	13	—	0.08	—	0.19
Calcitic, dolomitic, limestone, marble, and granite		180	30	—	0.03	—	—
		160	22	—	0.05	—	—
		140	16	—	0.06	—	—
		120	11	—	0.09	—	0.19
		100	8	—	0.13	—	—
Gypsum partition tile							
3 by 12 by 30 in., solid		—	—	0.79	—	1.26	0.19
3 by 12 by 30 in., 4 cells		—	—	0.74	—	1.35	—
4 by 12 by 30 in., 3 cells		—	—	0.6	—	1.67	—
Concretes							
Sand and gravel or stone aggregate concretes (Concretes with more than 50% quartz or quartzite sand have conductivities in the higher end of the range.)		150	10.0–20.0	—	0.10–0.05	—	—
		140	9.0–18.0	—	0.11–0.06	—	0.19–0.24
		130	7.0–13.0	—	0.14–0.08	—	—
Limestone concretes		140	11.1	—	0.09	—	—
		120	7.9	—	0.13	—	—
		100	5.5	—	0.18	—	—
Gypsum-fiber concrete (87.5% gypsum, 12.5% wood chips)		51	1.66	—	0.6	—	0.21
Cement/lime, mortar, and stucco		120	9.7	—	0.1	—	—
		100	6.7	—	0.15	—	—
		80	4.5	—	0.22	—	—

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Lightweight aggregate concretes							
Expanded shale, clay, or slate; expanded slags; cinders; pumice (with density up to 100 lb ft^3); and scoria (Sanded concretes have conductivities in the higher end of the range.)		120	6.4–9.1	—	0.16–0.11	—	—
		100	4.7–6.2	—	0.21–0.16	—	0.2
		80	3.3–4.1	—	0.30–0.24	—	0.2
		60	2.1–2.5	—	0.48–0.40	—	—
		40	1.3	—	0.78	—	—
Perlite, vermiculite, and polystyrene beads		50	1.8–1.9	—	0.55–0.53	—	—
		40	1.4–1.5	—	0.71–0.67	—	0.15–0.23
		30	1.1	—	0.91	—	—
		20	0.8	—	1.25	—	—
Foam concretes		120	5.4	—	0.19	—	—
		100	4.1	—	0.24	—	—
		80	3	—	0.33	—	—
		70	2.5	—	0.4	—	—
Foam concretes and cellular concretes		60	2.1	—	0.48	—	—
		40	1.4	—	0.71	—	—
		20	0.8	—	1.25	—	—
SIDING MATERIALS (on flat surface)							
Shingles							
Asbestos-cement		120	—	4.75	—	0.21	—
Wood, 16 in., 7.5 exposure		—	—	1.15	—	0.87	0.31
Wood, double, 16 in., 12 in. exposure		—	—	0.84	—	1.19	0.28
Wood, plus ins. Backer board, 0.312 in.		—	—	0.71	—	1.4	0.31

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Siding							
Asbestos-cement, 0.25 in., lapped		—	—	4.76	—	0.21	0.24
Asphalt roll siding		—	—	6.5	—	0.15	0.35
Asphalt insulating siding (0.5 in. bed)		—	—	0.69	—	1.46	0.35
Hardboard siding, 0.4375 in.		—	—	1.49	—	0.67	0.28
Wood, drop, 1 by 8 in.		—	—	1.27	—	0.79	0.28
Wood, bevel, 0.5 by 8 in., lapped		—	—	1.23	—	0.81	0.28
Wood, bevel, 0.75 by 10 in., lapped		—	—	0.95	—	1.05	0.28
Wood, plywood, 0.375 in., lapped		—	—	1.69	—	0.59	0.29
Aluminum, steel or vinyl, over sheathing							
Hollow-backed		—	—	1.64	—	0.61	0.29
Insulating-board backed nominal 0.375 in		—	—	0.55	—	1.82	0.32
Insulating-board backed nominal 0.375 in foil backed		—	—	0.34	—	2.96	—
Architectural (soda-lime float) glass		158	6.9	—	—	—	0.21
WOODS (12% moisture content)							
Hardwoods							0.39
Oak		41.2–46.8	1.12–1.25	—	0.89–0.80	—	
Birch		42.6–45.4	1.16–1.22	—	0.87–0.82	—	
Maple		39.8–44.0	1.09–1.19	—	0.92–0.84	—	
Ash		38.4–41.9	1.06–1.14	—	0.94–0.88	—	

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Thermal Resistance of Building Materials (cont'd)

Material	Thickness	Density	Conductivity k	Conductance C	Resistance (R)		Specific Heat
					Per Inch Thickness $\left(\frac{1}{k}\right)$	For Thickness Listed $\left(\frac{1}{C}\right)$	
		$\frac{lb}{ft^3}$	$\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}°F}$	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu\text{-}in}$	$\frac{hr\text{-}ft^2\text{-}°F}{Btu}$	$\frac{Btu}{lb\text{-}°F}$
Softwoods							0.39
Southern pine		35.6–41.2	1.00–1.12	—	1.00–0.89	—	
Douglas fir-larch		33.5–36.3	0.95–1.01	—	1.06–0.99	—	
Southern cypress		31.4–32.1	0.90–0.92	—	1.11–1.09	—	
Hem-Fir, Spruce-Pine-Fir		24.5–31.4	0.74–0.90	—	1.35–1.11	—	
West coast woods, cedar		21.7–31.4	0.68–0.90	—	1.48–1.11	—	
California redwood		24.5–28.0	0.74–0.82	—	1.35–1.22	—	

Source: Compiled from ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 26, Heat, Air, and Moisture Control in Building Assemblies—Material Properties, and manufacturers' data.

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9.1.12 Thermal Conductivity of Soils

Typical Apparent Thermal Conductivity Values for Soils, in $\frac{\text{Btu-in}}{\text{hr-ft}^2\text{-°F}}$

	Normal Range	Recommended Values for Design[a]	
		Low[b]	High[c]
Sands	4.2 to 17.4	5.4	15.6
Silts	6 to 17.4	11.4	15.6
Clays	6 to 11.4	7.8	10.8
Loams	6 to 17.4	6.6	15.6

a. Reasonable values for use when no site- or soil-specific data are available.

b. Moderately conservative values for minimum heat loss through soil (e.g., use in soil heat exchanger or earth-contact cooling calculations). Values are from Salomone and Marlowe (1989).

c. Moderately conservative values for maximum heat loss through soil (e.g., use in peak winter heat loss calculations). Values are from Salomone and Marlowe (1989).

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 26, Heat, Air, and Moisture Control in Building Assemblies—Material Properties, Table 8.

Typical Apparent Thermal Conductivity Values for Rocks, in $\frac{\text{Btu-in}}{\text{hr-ft}^2\text{-°F}}$

	Normal Range
Pumice, tuff, obsidian	3.6 to 15.6
Basalt	3.6 to 18.0
Shale	6 to 27.6
Granite	12 to 30
Limestone, dolomite, marble	8.4 to 30
Quartzose sandstone	9.6 to 54

Notes:

1. *k* increases with moisture content.
2. *k* increases with increasing dry density of a soil.
3. *k* decreases with increasing organic content of a soil.
4. *k* tends to decrease for soils with uniform gradations and rounded soil grains, because the grain-to-grain contacts are reduced.
5. *k* of a frozen soil may be higher or lower than that of the same unfrozen soil, because the conductivity of ice is higher than that of water but lower than that of the typical soil grains. Differences in *k* below moisture contents of 7 to 8% are quite small. At approximately 15% moisture content, differences in *k*-factors may vary up to 30% from unfrozen values.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 26, Heat, Air, and Moisture Control in Building Assemblies—Material Properties, Table 9.

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9.1.13 U-Factors for Fenestration

U-Factors for Various Fenestration Products, in $\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$, Table 1

Product Type		Glass Only		Vertical Installation									
				Operable (incl. sliding and swinging glass doors)					Fixed				
Frame Type		Center of Glass	Edge of Glass	Aluminum w/o Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum w/o Thermal Break	Aluminum w/ Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
ID	Glazing Type												
	Single Glazing												
1	1/8 in. glass	1.04	1.04	1.23	1.07	0.93	0.91	0.85	1.12	1.07	0.98	0.98	1.04
2	1/4 in. acrylic/polycarbonate	0.88	0.88	1.10	0.94	0.81	0.80	0.74	0.98	0.92	0.84	0.84	0.88
3	1/8 in. acrylic/polycarbonate	0.96	0.96	1.17	1.01	0.87	0.86	0.79	1.05	0.99	0.91	0.91	0.96
	Double Glazing												
4	1/4 in. air space	0.55	0.64	0.81	0.64	0.57	0.55	0.50	0.68	0.62	0.56	0.56	0.55
5	1/2 in. air space	0.48	0.59	0.76	0.58	0.52	0.50	0.45	0.62	0.56	0.50	0.50	0.48
6	1/4 in. argon space	0.51	0.61	0.78	0.61	0.54	0.52	0.47	0.65	0.59	0.53	0.52	0.51
7	1/2 in. argon space	0.45	0.57	0.73	0.56	0.50	0.48	0.43	0.60	0.53	0.48	0.47	0.45
	Double Glazing e = 0.60 on surface 2 or 3												
8	1/4 in. air space	0.52	0.62	0.79	0.61	0.55	0.53	0.48	0.66	0.59	0.54	0.53	0.52
9	1/2 in. air space	0.44	0.56	0.72	0.55	0.49	0.48	0.43	0.59	0.53	0.47	0.47	0.44
10	1/4 in. argon space	0.47	0.58	0.75	0.57	0.51	0.50	0.45	0.61	0.55	0.49	0.49	0.47
11	1/2 in. argon space	0.41	0.54	0.70	0.53	0.47	0.45	0.41	0.56	0.50	0.44	0.44	0.41
	Double Glazing e = 0.40 on surface 2 or 3												
12	1/4 in. air space	0.49	0.60	0.76	0.59	0.53	0.51	0.46	0.63	0.57	0.51	0.51	0.49
13	1/2 in. air space	0.40	0.54	0.69	0.52	0.47	0.45	0.40	0.55	0.49	0.44	0.43	0.40
14	1/4 in. argon space	0.43	0.56	0.72	0.54	0.49	0.47	0.42	0.58	0.52	0.46	0.46	0.43
15	1/2 in. argon space	0.36	0.51	0.66	0.49	0.44	0.42	0.37	0.52	0.46	0.40	0.40	0.36
	Double Glazing e = 0.20 on surface 2 or 3												
16	1/4 in. air space	0.45	0.57	0.73	0.56	0.50	0.48	0.43	0.60	0.53	0.48	0.47	0.45
17	1/2 in. air space	0.35	0.50	0.65	0.48	0.43	0.41	0.37	0.51	0.45	0.39	0.39	0.35
18	1/4 in. argon space	0.38	0.52	0.68	0.51	0.45	0.43	0.39	0.54	0.47	0.42	0.42	0.38
19	1/2 in. argon space	0.30	0.46	0.61	0.45	0.39	0.38	0.33	0.47	0.41	0.35	0.35	0.30
	Double Glazing e = 0.10 on surface 2 or 3												
20	1/4 in. air space	0.42	0.55	0.71	0.54	0.48	0.46	0.41	0.57	0.51	0.45	0.45	0.42

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U-Factors for Various Fenestration Products, in $\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$, Table 1 (cont'd)

Product Type		Glass Only		Vertical Installation									
				Operable (incl. sliding and swinging glass doors)					Fixed				
Frame Type													
ID	Glazing Type	Center of Glass	Edge of Glass	Aluminum w/o Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum w/o Thermal Break	Aluminum w/ Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
21	1/2 in. air space	0.32	0.48	0.63	0.46	0.43	0.39	0.34	0.49	0.42	0.37	0.37	0.32
22	1/4 in. argon space	0.35	0.50	0.65	0.48	0.43	0.41	0.37	0.51	0.45	0.39	0.39	0.35
23	1/2 in. argon space	0.27	0.44	0.59	0.42	0.37	0.36	0.31	0.44	0.38	0.33	0.32	0.27
	Double Glazing e = 0.05 on surface 2 or 3												
24	1/4 in. air space	0.41	0.54	0.70	0.53	0.47	0.45	0.41	0.50	0.50	0.44	0.44	0.41
25	1/2 in. air space	0.30	0.46	0.61	0.45	0.39	0.38	0.33	0.47	0.41	0.35	0.35	0.30
26	1/4 in. argon space	0.33	0.48	0.64	0.47	0.42	0.40	0.35	0.49	0.43	0.38	0.37	0.33
27	1/2 in. argon space	0.25	0.42	0.57	0.41	0.36	0.34	0.30	0.43	0.36	0.31	0.31	0.25

1. All heat transmission coefficients in this table include film resistances and are based on winter conditions of 0°F outdoor air temperature and 70°F indoor air temperature, with 15 mph outdoor air velocity and zero solar flux. Except for single glazing, small charges in indoor and outdoor temperatures do not significantly affect overall U-factors. Coefficients are for vertical position except skylight values, which are for 20° from horizontal with heat flow up.
2. Glazing layer surfaces are numbered from outdoor to indoor. Double, triple, and quadruple refer to number of glazing panels. All data are based on 1/4 in. glass, unless otherwise noted. Thermal conductivities are

   0.53 $\frac{\text{Btu}}{\text{hr-ft-°F}}$ for glass and 0.11 $\frac{\text{Btu}}{\text{hr-ft-°F}}$ for acrylic and polycarbonate.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 15, Fenestration, Table 4.

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9.1.14 Design U-Factors of Swinging Doors

Design U-Factors of Swinging Doors, in $\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$

Door Type (Rough Opening = 38 × 82 in.)	No Glazing	Single Glazing	Double Glazing With 1/2-in. Air Space	Double Glazing With e = 0.10, 1/2-in. Argon
Slab Doors				
Wood slab in wood frame[a]	0.46			
6% glazing (22 × 8 in. lite)		0.48	0.46	0.44
25% glazing (22 × 36 in. lite)		0.58	0.46	0.42
45% glazing (22 × 64 in. lite)		0.69	0.46	0.39
More than 50% glazing		Use fenestration table for operable		
Insulated steel slab with wood edge in wood frame[b]	0.16			
6% glazing (22 × 8 in. lite)		0.21	0.19	0.18
25% glazing (22 × 36 in. lite)		0.39	0.26	0.23
45% glazing (22 × 64 in. lite)		0.58	0.35	0.26
More than 50% glazing		Use fenestration table for operable		
Foam insulated steel slab with metal edge in steel frame[c]	0.37			
6% glazing (22 × 8 in. lite)		0.44	0.41	0.39
25% glazing (22 × 36 in. lite)		0.55	0.48	0.44
45% glazing (22 × 64 in. lite)		0.71	0.56	0.48
More than 50% glazing		Use fenestration table for operable		
Cardboard honeycomb slab with metal edge in steel frame				
Stile-and-Rail Doors				
Sliding glass doors/French doors		Use fenestration table for operable		
Site-Assembled Stile-and-Rail Doors				
Aluminum in aluminum frame		1.32	0.93	0.79
Aluminum in aluminum frame with thermal break		1.13	0.74	0.63

a. Thermally broken sill; add 0.03 $\frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$ for nonthermally broken sill.

b. Nonthermally broken sill.

c. Nominal U-factors are through center of insulated panel before consideration of thermal bridges around edges of door sections and because of frame.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 15, Fenestration, Table 6.

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9.1.15 Pipe and Duct Insulation

Minimum Pipe Insulation Thickness[a]

Fluid Design Operating Temp. Range, °F	Insulation Conductivity		Nominal Pipe or Tube Size, in.				
	Conductivity, $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$	Mean Rating Temp., °F	< 1	1 to < 1-1/2	1-1/2 to < 4	4 to < 8	> 8
Heating Systems (Steam, Steam Condensate, Hot Water, and Domestic Hot Water)[bc]							
> 350	0.32 to 0.34	250	4.5	5.0	5.0	5.0	5.0
251 to 350	0.29 to 0.32	200	3.5	4.0	4.5	4.5	4.5
201 to 250	0.27 to 0.30	150	2.5	2.5	3.0	3.0	3.0
141 to 200	0.25 to 0.29	125	1.5	1.5	2.0	2.0	2.0
105 to 140	0.22 to 0.28	100	1.0	1.0	1.5	1.5	1.5
Cooling Systems (Chilled Water, Brine, and Refrigerant)[d]							
40 to 60	0.22 to 0.28	75	0.5	0.5	1.0	1.0	1.0
< 40	0.22 to 0.28	50	0.5	1.0	1.0	1.0	1.5

a. For insulation outside stated conductivity range, determine minimum thickness T as follows:

$$T = r\left[\left(1 + \frac{t}{r}\right)^{\frac{K}{k}} - 1\right]$$

where T = minimum insulation thickness, in inches
r = actual outside radius of pipe, in inches
t = insulation thickness listed in this table for applicable fluid temperature and pipe size
K = conductivity of alternative material at mean rating temperature indicated for applicable fluid temperature, in $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$
k = upper value of conductivity range listed in this table for the applicable fluid temperature

b. These thicknesses are based on energy *efficiency* considerations only. Additional insulation is sometimes required relative to safety issues/surface temperature.

c. Piping insulation is not required between control valve and coil on run-outs when control valve is located within 4 ft of coil and pipe size is 1 in. or less.

d. These thicknesses are based on energy *efficiency* considerations only. Issues such as water vapor permeability or surface condensation sometimes require vapor retarders or additional insulation.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 23, Insulation for Mechanical Systems, Table 2.

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Minimum Duct Insulation R-Value of Cooling-Only and Heating-Only Supply Ducts and Return Ducts

Climate Zone[a]	Duct Location						
	Exterior	Ventilated Attic	Unvented Attic Above Insulated Ceiling	Unvented Attic With Roof Insulation[b]	Unconditioned Space[c]	Indirectly Conditioned Space[d]	Buried
Heating-Only Ducts							
1, 2	none	none	none	none	none	none	none
3	R-3.5	none	none	none	none	none	none
4	R-3.5	none	none	none	none	none	none
5	R-6	R-3.5	none	none	none	none	R-3.5
6	R-6	R-6	R-3.5	none	none	none	R-3.5
7	R-8	R-6	R-6	none	R-3.5	none	R-3.5
8	R-8	R-8	R-6	none	R-6	none	R-6
Cooling-Only Ducts							
1	R-6	R-6		R-3.5	R-3.5	none	R-3.5
2	R-6	R-6	R-6	R-3.5	R-3.5	none	R-3.5
3	R-6	R-6	R-6	R-3.5	R-1.9	none	none
4	R-3.5	R-3.5	R-6	R-1.9	R-1.9	none	none
5, 6	R-3.5	R-1.9	R-3.5	R-1.9	R-1.9	none	none
7, 8	R-1.9	R-1.9	R-1.9	R-1.9	R-1.9	none	none
Return Ducts							
1 to 8	R-3.5	R-3.5	R-3.5	none	none	none	none

a. Climate zones for the continental United States defined in ASHRAE *Standard* 90.1-2010.

b. Insulation R-values, measured in $\frac{\text{hr-ft}^2\text{-°F}}{\text{Btu}}$, are for the insulation as installed and do not include film resistance. The required minimum thicknesses do not consider water vapor transmission and possible surface condensation. Where exterior wall are used as plenum walls, wall insulation must be as required by the most restrictive condition of Section 6.4.4.2 or Section 5 of ASHRAE *Standard* 90.1-2010. Insulation resistance measured on a horizontal plane in accordance with ASTM C518 at a mean temperature of 75°F at the installed thickness.

c. Includes crawl spaces, both ventilated and nonventilated.

d. Includes return air plenums with or without exposed roofs above.

Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 23, Insulation for Mechanical Systems, Table 1.

9.1.16 Residential Infiltration

Using the effective air leakage rate area at 0.016 in. of water, the airflow rate from infiltration is:

$$Q = A_L\sqrt{C_s|\Delta T| + C_w U^2}$$

where

Q = airflow rate (cfm)

A_L = effective air leakage area (in^2)

C_s = stack coefficient (cfm^2/in^4-°F)

ΔT = average indoor-outdoor temperature difference for time interval of calculation (°F)

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C_w = wind coefficient (cfm^2/in^4-mph^2)

U = average wind speed measured at local weather station for time interval of calculation (mph)

Table 1 shows values of C_s for one-, two-, and three-story houses. The value of wind coefficient C_w depends on the local shelter class of the building (Table 2) and the building height. Table 3 shows values of C_w for one-, two-, and three-story houses in shelter classes 1 to 5. In calculating values in Tables 1 and 3, the following assumptions were made:

Terrain used for converting meteorological to local wind speeds is that of a rural area with scattered obstacles.

R = 0.5 (half the building leakage in the walls)

Table 1 Basic Model Stack Coefficient, C_s

	House Height (Stories)		
	One	**Two**	**Three**
Stack coefficient	0.0150	0.0299	0.0449

Table 2 Local Shelter Classes

Shelter Class	Description
1	No obstructions or local shielding
2	Typical shelter for an isolated rural house
3	Typical shelter caused by other buildings across street from building under study
4	Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away
5	Typical shelter produced by buildings or other structures immediately adjacent (closer than one house height: e.g., neighboring houses on same side of street, trees, bushes)

X = 0 (equal amounts of leakage in the floor and ceiling)

Heights of one-, two-, and three-story buildings = 8, 16, and 24 ft, respectively

Table 3 Basic Model Wind Coefficient, C_w

	House Height (Stories)		
Shelter Class	**One**	**Two**	**Three**
1	0.0119	0.0157	0.0184
2	0.0092	0.0121	0.0143
3	0.0065	0.0086	0.0101
4	0.0039	0.0051	0.0060
5	0.0012	0.0016	0.0018

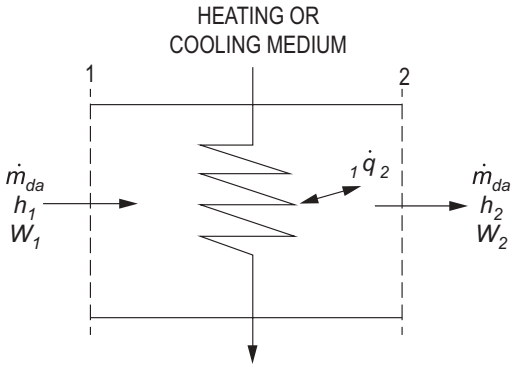
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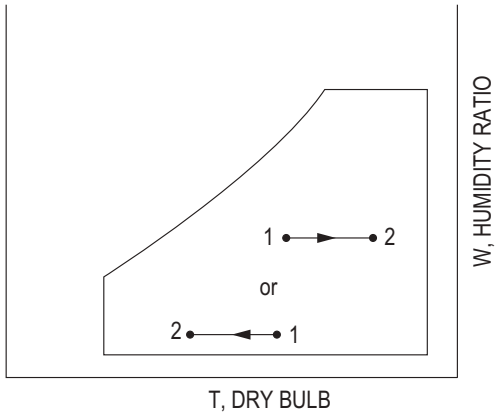
9.2 Typical Air-Conditioning Processes

9.2.1 Moist-Air Sensible Heating or Cooling

Device for Heating or Cooling Moist Air
(No Dehumidification)



SCHEMATIC OF DEVICE FOR HEATING OR COOLING (NO DEHUMIDIFICATION) MOIST AIR



For steady flow conditions, the required rate of sensible heat addition or removal is

$$_1\dot{q}_2 = \dot{m}_{da}\left(h_2 - h_1\right)$$

where

$\dot{q}$ = rate of heat addition (Btu/hr)

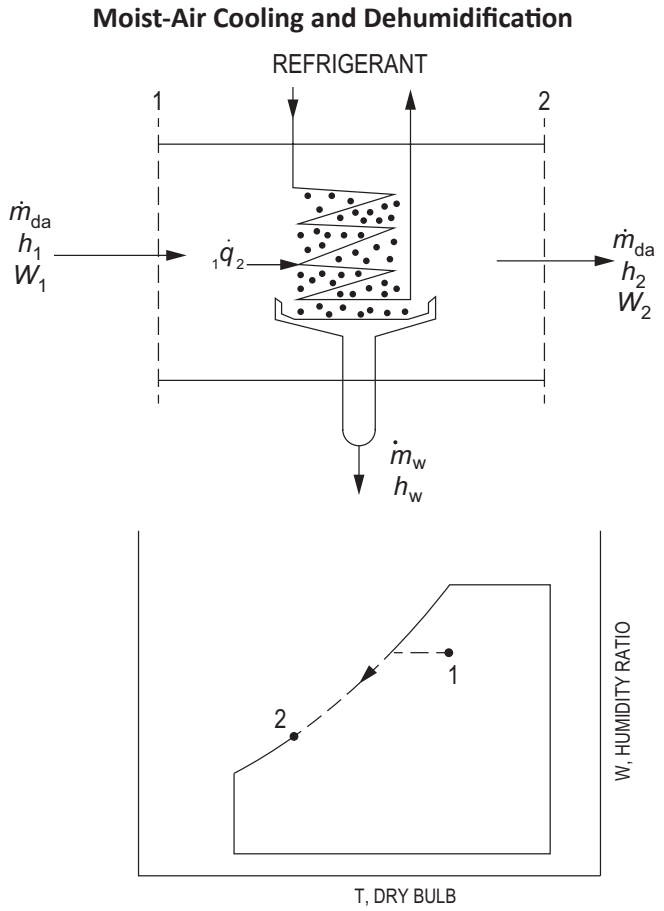
da = dry air

W = humidity ratio $\left(\frac{\text{lb}_\text{w}}{\text{lb}_\text{a}}\right)$

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9.2.2 Moist-Air Cooling and Dehumidification



The steady flow energy and material balance equations are

$$\dot{m}_w = \dot{m}_{da}\left(W_1 - W_2\right)$$
$$_1\dot{q}_2 = \dot{m}_{da}\left[\left(h_1 - h_2\right) - \left(W_1 - W_2\right)h_{w2}\right]$$

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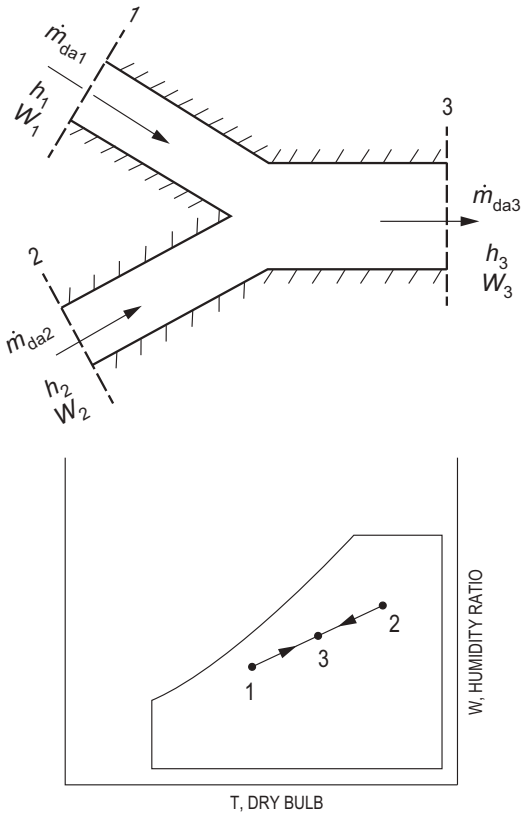
9.2.3 Adiabatic Mixing of Two Moist Airstreams

Adiabatic mixing is governed by three equations:

$$\dot{m}_{da1} h_1 + \dot{m}_{da2} h_2 = \dot{m}_{da3} h_3$$
$$\dot{m}_{da1} + \dot{m}_{da2} = \dot{m}_{da3}$$
$$\dot{m}_{da1} W_1 + \dot{m}_{da2} W_2 = \dot{m}_{da3} W_3$$

Eliminating $\dot{m}_{da3}$ results in

$$\frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1} = \frac{\dot{m}_{da1}}{\dot{m}_{da2}}$$



Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 1, Psychrometrics, Fig. 6.

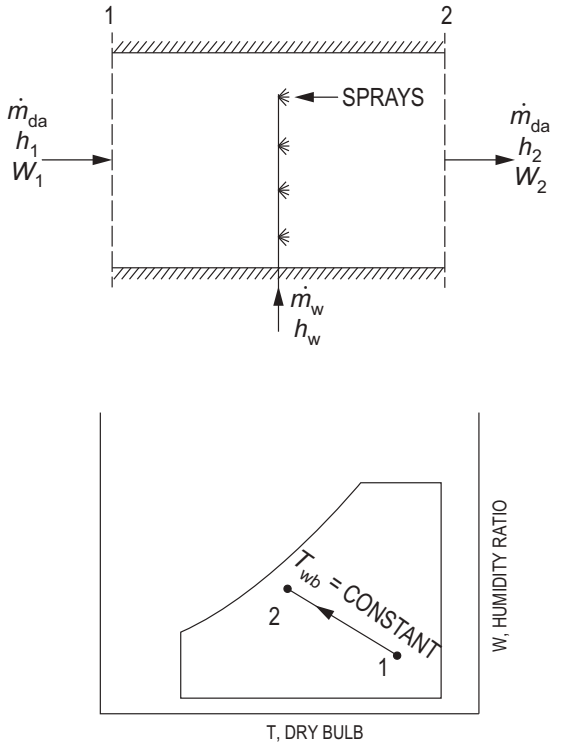
9.2.4 Adiabatic Mixing of Water Injected Into Moist Air (Evaporative Cooling)

If mixing is adiabatic, then:

$$\dot{m}_{da} h_1 + \dot{m}_w h_w = \dot{m}_{da} h_2$$
$$\dot{m}_{da} W_1 + \dot{m}_w = \dot{m}_{da} W_2$$

Therefore,

$$\frac{h_2 - h_1}{W_2 - W_1} = \frac{\Delta h}{\Delta W} = h_w$$



Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 1, Psychrometrics, Fig. 8.

9.2.5 Space Heat Absorption and Moist-Air Moisture Gains

If mixing is adiabatic, then:

$$\dot{m}_{da} h_1 + \dot{q}_s + \sum \left(\dot{m}_w h_w \right) = \dot{m}_{da} h_2$$

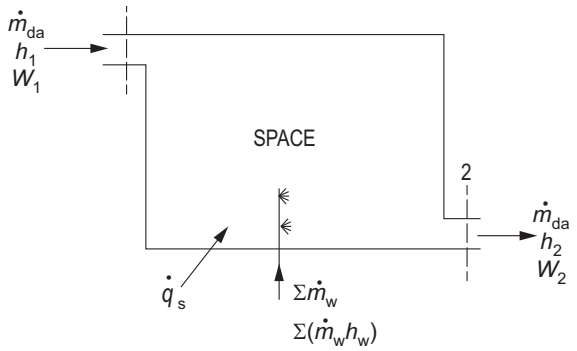
$$\dot{m}_{da} W_1 + \sum \dot{m}_w = \dot{m}_{da} W_2$$

or

$$\dot{q}_s + \sum \left(\dot{m}_w h_w \right) = \dot{m}_{da} \left(h_2 - h_1 \right)$$

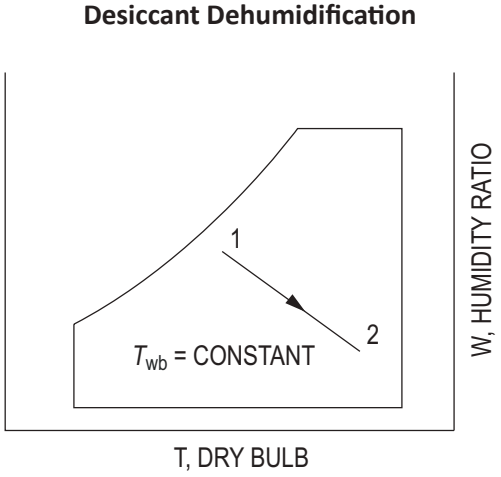
Therefore,

$$\frac{h_2 - h_1}{W_2 - W_1} = \frac{\Delta h}{\Delta W} = \frac{\dot{q}_s + \sum \left(\dot{m}_w h_w \right)}{\sum \dot{m}_w}$$

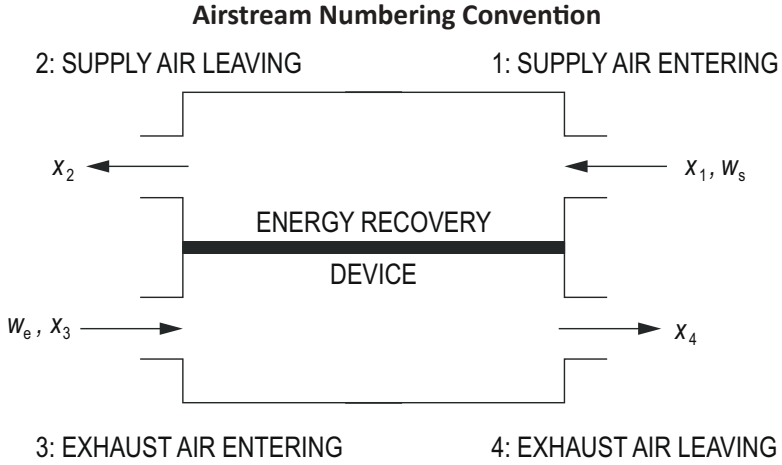


Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 1, Psychrometrics, Fig. 10.

9.2.6 Desiccant Dehumidification



9.2.7 Heat-Recovery Ventilator (HRV)—Sensible Energy Recovery



Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 26, Air-to-Air Energy Recovery Equipment, Fig. 1.

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The sensible effectiveness ε_s of a *heat-recovery ventilator* (HRV) is

$$\varepsilon_s = \frac{\dot{q}_s}{\dot{q}_{s,max}} = \frac{\dot{m}_s c_{ps}(t_2 - t_1)}{C_{min}(t_3 - t_1)} = \frac{\dot{m}_e c_{pe}(t_3 - t_4)}{C_{min}(t_3 - t_1)}$$

where

$\dot{q}_s$ = sensible heat-transfer rate $\left(\frac{\text{Btu}}{\text{hr}}\right) = \varepsilon_s \dot{q}_{s,max}$

$\dot{q}_{s,max}$ = maximum sensible heat-transfer rate $\left(\frac{\text{Btu}}{\text{hr}}\right) = 60 C_{min}(t_3 - t_1)$

ε_s = sensible effectiveness

t_1 = dry-bulb temperature at Location 1 (°F)

$\dot{m}_s$ = supply dry air-mass flow rate $\left(\frac{\text{lb}}{\text{min}}\right)$

$\dot{m}_e$ = exhaust dry air-mass flow rate $\left(\frac{\text{lb}}{\text{min}}\right)$

C_{min} = smaller of $c_{ps}\dot{m}_s$ and $c_{pe}\dot{m}_e$

c_{ps} = supply moist-air specific heat at constant pressure $\left(\frac{\text{Btu}}{\text{lb-°F}}\right)$

c_{pe} = exhaust moist-air specific heat at constant pressure $\left(\frac{\text{Btu}}{\text{lb-°F}}\right)$

Assuming no water vapor condensation in the HRV, the leaving supply-air condition is

$$t_2 = t_1 - \varepsilon_s \frac{C_{min}}{\dot{m}_s c_{ps}}(t_1 - t_3)$$

The leaving exhaust-air condition is

$$t_4 = t_3 + \varepsilon_s \frac{C_{min}}{\dot{m}_e c_{pe}}(t_1 - t_3)$$

The sensible heat-energy transfer $\dot{q}_s$ from the heat recovery ventilator can be estimated from

$$\dot{q}_s = 60\dot{m}_s c_{ps}(t_2 - t_1) = 60 Q_s \rho_s c_{ps}(t_2 - t_1)$$

$$\dot{q}_s = 60\dot{m}_e c_{pe}(t_4 - t_3) = 60 Q_e \rho_e c_{pe}(t_4 - t_3)$$

$$\dot{q}_s = 60\varepsilon_s \dot{m}_{min} c_p(t_1 - t_3)$$

where

Q_s = volume flow rate of supply air (cfm)

Q_e = volume flow rate of exhaust air (cfm)

ρ_s = density of dry supply air $\left(\frac{\text{lb}}{\text{ft}^3}\right)$

ρ_e = density of dry exhaust air $\left(\frac{\text{lb}}{\text{ft}^3}\right)$

t_1, t_2, t_3, t_4 = inlet and exit temperatures of supply and exhaust airstreams, respectively

$\dot{m}_{min}$ = smaller of $\dot{m}_s$ and $\dot{m}_e$

c_{ps} and c_{pe} are nearly equal and can be noted as c_p.

Source: ©ASHRAE, www.ashrae.org., *2012 ASHRAE Handbook—HVAC Systems and Equipment,* Chapter 26, Air-to-Air Energy Recovery Equipment, p. 26.2.

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9.2.8 Energy-Recovery Ventilator (ERV)

Refer to airstream figure for Heat-Recovery Ventilation (HRV) in Section 9.2.7

Provides sensible and latent energy recovery

$$\varepsilon_L = \frac{\dot{q}_L}{\dot{q}_{L,\,max}} = \frac{\dot{m}_s h_{fg}\left(w_1 - w_2\right)}{\dot{m}_{min} h_{fg}\left(w_1 - w_3\right)} = \frac{\dot{m}_e h_{fg}\left(w_4 - w_3\right)}{\dot{m}_{min} h_{fg}\left(w_1 - w_3\right)}$$

where

$\dot{q}_L$ = actual latent heat-transfer rate = $\varepsilon_L\ \dot{q}_{L,max}$

$\dot{q}_{L,max}$ = maximum latent heat-transfer rate = $60\dot{m}_{min}\ h_{fg}\,(w_1 - w_3)$

ε_L = latent effectiveness

h_{fg} = enthalpy of vaporization $\left(\frac{\text{Btu}}{\text{lb}}\right)$

w = humidity ratios at locations indicated in the airstream figure

$\dot{m}_s$ = supply dry air-mass flow rate $\left(\frac{\text{lb}}{\text{min}}\right)$

$\dot{m}_e$ = exhaust dry air-mass flow rate $\left(\frac{\text{lb}}{\text{min}}\right)$

$\dot{m}_{min}$ = the smaller value of $\dot{m}_s$ and $\dot{m}_e$

$$\varepsilon_m = \frac{\dot{m}_w}{\dot{m}_{w,max}} = \frac{\dot{m}_s\left(w_1 - w_2\right)}{\dot{m}_{min}\left(w_1 - w_3\right)} = \frac{\dot{m}_e\left(w_4 - w_3\right)}{\dot{m}_{min}\left(w_1 - w_3\right)}$$

where ε_m is the moisture effectiveness

The actual moisture transfer rate is

$$\dot{m}_w = \varepsilon_m \dot{m}_{w,max}$$

where $\dot{m}_{w,max}$ = the maximum moisture transfer = $\dot{m}_{w,min}\left(w_1 - w_3\right)$

Assuming no water condensation in the *energy-recovery ventilator* (ERV), the supply-air-leaving humidity ratio is

$$w_2 = w_1 - \varepsilon_L \frac{\dot{m}_{w,min}}{\dot{m}_s}\left(w_1 - w_3\right)$$

and the leaving exhaust-air humidity ratio is

$$w_4 = w_3 + \varepsilon_L \frac{\dot{m}_{w,min}}{\dot{m}_s}\left(w_1 - w_3\right)$$

The total effectiveness ε_t of an ERV is

$$\varepsilon_t = \frac{\dot{q}_t}{\dot{q}_{t,max}} = \frac{\dot{m}_s\left(h_2 - h_1\right)}{\dot{m}_{min}\left(h_3 - h_1\right)} = \frac{\dot{m}_e\left(h_3 - h_4\right)}{\dot{m}_{min}\left(h_3 - h_1\right)}$$

where

$\dot{q}_t$ = the actual total energy-transfer rate = $\varepsilon_t \dot{q}_{t,max}$

$\dot{q}_{t,max}$ = the maximum total energy-transfer rate = $60\dot{m}_{min}\left(h_1 - h_3\right)$

ε_t = total effectiveness

h = enthalpy at locations indicated in the airstream figure $\left(\frac{\text{Btu}}{\text{lb}}\right)$

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$\dot{m}_s$ = supply dry-air mass flow rate $\left(\frac{\text{lb}}{\text{min}}\right)$

$\dot{m}_e$ = exhaust dry-air mass flow rate $\left(\frac{\text{lb}}{\text{min}}\right)$

$\dot{m}_{min}$ = smaller of $\dot{m}_s$ and $\dot{m}_e$

The leaving supply-air condition is $h_2 = h_1 - \varepsilon_t \frac{\dot{m}_{min}}{\dot{m}_s}(h_1 - h_3)$.

The leaving exhaust-air condition is $h_4 = h_3 + \varepsilon_t \frac{\dot{m}_{min}}{\dot{m}_e}(h_1 - h_3)$.

Assuming the stream at State 1 is of higher humidity, the latent heat recovery $\dot{q}_L$ from the ERV can be estimated from

$$\dot{q}_L = 60\dot{m}_s h_{fg}(w_1 - w_2) = 60Q_s \rho_s h_{fg}(w_1 - w_2)$$

$$\dot{q}_L = 60\dot{m}_e h_{fg}(w_4 - w_3) = 60Q_e \rho_e h_{fg}(w_4 - w_3)$$

where $\dot{q}_L = 60\varepsilon_L \dot{m}_{min} h_{fg}(w_1 - w_3)$

h_{fg} = enthalpy of vaporization or heat of vaporization of water vapor $\left(\frac{\text{Btu}}{\text{lb}}\right)$

w_1, w_2, w_3, w_4 = inlet and exit humidity ratios of supply and exhaust airstreams, respectively

The total energy transfer $\dot{q}_t$ between the streams is

$$\dot{q}_t = \dot{q}_s + \dot{q}_L = 60\dot{m}_s(h_{1s} - h_{2s}) = 60Q_s \rho_s(h_{1s} - h_{2s}) = 60\left[\dot{m}_s c_{ps}(t_1 - t_2) + \dot{m}_s h_{fg}(w_1 - w_2)\right]$$

$$\dot{q}_t = \dot{q}_s + \dot{q}_L = 60\dot{m}_e(h_{4e} - h_{3e}) = 60Q_e \rho_e(h_{4e} - h_{3e}) = 60\left[\dot{m}_e c_{pe}(t_4 - t_3) + \dot{m}_e h_{fg}(w_4 - w_3)\right]$$

$$\dot{q}_t = 60\varepsilon_t \dot{m}_{min}(h_{1s} - h_{3e})$$

where

h_{1s} = enthalpy of supply air at inlet $\left(\frac{\text{Btu}}{\text{lb}}\right)$

h_{3e} = enthalpy of exhaust air at inlet $\left(\frac{\text{Btu}}{\text{lb}}\right)$

h_{2s} = enthalpy of supply air at outlet $\left(\frac{\text{Btu}}{\text{lb}}\right)$

h_{4e} = enthalpy of exhaust air at outlet $\left(\frac{\text{Btu}}{\text{lb}}\right)$

The fan power, P_s, required by the supply air is estimated from

$$P_s = Q_s \Delta p_s / 6{,}356\ \eta_f$$

The fan power, P_e, required by the exhaust air is estimated from

$$P_e = Q_e \Delta p_e / 6{,}356\ \eta_f$$

where

P_s = fan power for supply fan (hp)

P_e = fan power for exhaust fan (hp)

Δp_s = pressure drop of supply air (in. of water)

Δp_e = pressure drop of exhaust air (in. of water)

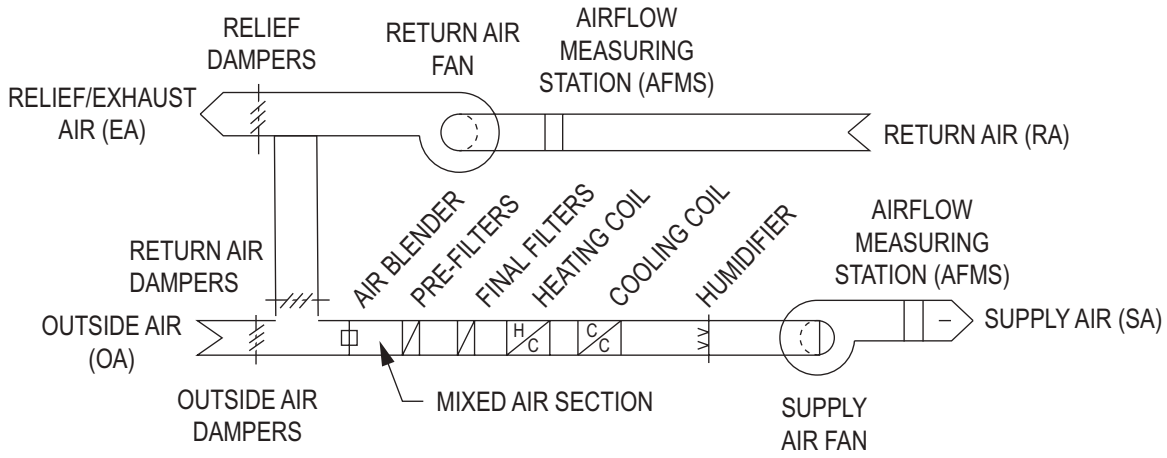
η_f = overall efficiency of fan and motor, or product of fan and motor efficiency

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9.3 HVAC Systems

9.3.1 HVAC System Components

Components in a Common Central HVAC System



Components used in the assembly of an air-handling unit.

Unit configuration (arrangement):

1. **Draw-through:** Cooling coil located upstream of supply fan. Fan motor heat will be added to conditioned air leaving the air-handling unit.
2. **Blow-through:** Cooling coil located downstream of supply fan. Fan motor heat is added ahead of cooling coil and not added to conditioned air leaving the air-handling unit.

Air-handling unit systems and components:

1. **Return air (RA):** Air from the conditioned space. Return air may be fully ducted, or partially ducted with connections to ceiling return air plenums. Return air grilles are connected to the return-air ductwork, or to provide a path from conditioned space to the return air plenum.
2. **Airflow measuring station (AFMS):** Measures airflow volume. Used as an input to provide supply and return fan tracking to assure proper building pressurization. AFMS can consist of a duct-mounted velocity pressure grid, or a piezo ring sensor located in the fan volute.
3. **Return fan:** Moves air from conditioned space to air-handling unit. Overcomes static pressure drop of return-air ductwork and accessories. Assists in removal of relief/exhaust air from the system.
4. **Variable frequency drive (VFD):** Adjusts power input to motor to reduce from constant full speed.
5. **Economizer mode:** Uses outside air to condition the space. Return air is directed through the EA system and discharged outside.
6. **Relief/exhaust air (EA):** Excess return air that is offset by outside air.
7. **EA damper:** Dampers that modulate to control amount of EA airflow.
8. **RA damper:** Dampers that modulate to control amount of RA airflow.
9. **Outside air (OA):** Air used for occupant ventilation air or makeup air. Used to provide space conditioning during economizer operation.
10. **OA damper:** Dampers that modulate to control amount of OA airflow.
11. **Air blender:** Blends mixed air stream to mitigate cold air stratification. Proper air blender sizing and downstream distance is necessary to ensure good mixing. Can result in pressure drops of 0.35 inches of water or greater.
12. **Pre-filters:** Lower-efficiency filters to capture most particulate in the mixed airstream. Typically MERV 8.
13. **Final filters:** Higher-efficiency filters to provider better filtration of the mixed air. Typically MERV 13 or greater.

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14. **Heating section:** Increases conditioned air temperature. Typical heating section can be:
    a. Electric coil
    b. Gas-fired furnace
    c. Steam coils
    d. Hot water coils
15. **Cooling section:** Decreases conditioned air temperature sensible and/or latent condition. Typical cooling section:
    a. Direct expansion coils
    b. Chilled water coils
16. **Humidifier:** Adds moisture to conditioned air.
17. **Supply fan:** The supply fan overcomes the static pressure drop of the supply-air ductwork, system components, and the return-air ductwork where a return fan is not used.
18. **Supply Air:** Conditioned air delivered to the conditioned space.

9.3.2 Air-Handling Unit Mixed-Air Plenums

When the difference between outdoor- and return-air temperatures is greater than 20°F, the temperature of the mixture can be calculated as

$$Q_t t_m = Q_o t_o + Q_r t_r \qquad t_m = \frac{Q_o}{Q_t} t_o + \frac{Q_r}{Q_t} t_r \qquad t_m = (\text{fraction outdoor air}) t_o + (\text{fraction return air}) t_r$$

where

Q_t = total measured air quantity (cfm)

Q_o = outdoor-air quantity (cfm)

Q_r = return-air quantity (cfm)

t_m = temperature of outdoor- and return-air mixture (°F)

t_o = outdoor-air temperature (°F)

t_r = return-air temperature (°F)

9.3.3 In-Room Terminal Systems

Changeover Temperature: Outdoor temperature at which the heat gain to every space can be satisfied by the combination of cold primary air and transmission loss.

$$t_{co} = t_r - \frac{q_{is} + q_{es} - 1.1 Q_p (t_r - t_p)}{\Delta q_{td}}$$

where

t_{co} = temperature of changeover point (°F)

t_r = room temperature at time of changeover, normally 72°F

t_p = primary-air temperature at unit after system is changed over, normally 56°F

Q_p = primary-air quantity (cfm)

q_{is} = internal sensible heat gain $\left(\frac{\text{Btu}}{\text{hr}}\right)$

q_{es} = external sensible heat gain $\left(\frac{\text{Btu}}{\text{hr}}\right)$

Δq_{td} = heat transmission per degree of temperature difference between room and outdoor air

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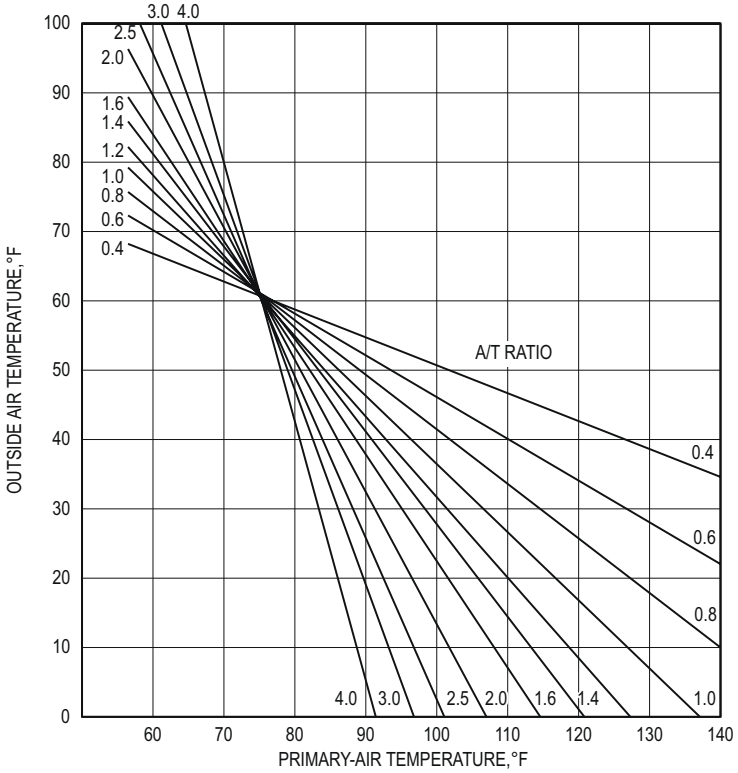
9.3.4 Transmission of Heat in a Space

Transmission Per Degree: The transmission heat flow of a space per degree temperature difference between the space temperature and the outdoor temperature, assuming steady-state heat transfer.

Air-to-Transmission (A-T) Ratio: The ratio of the primary airflow to a given space, divided by the transmission per degree of that space:

$$\frac{A}{T} = \frac{\text{Primary airflow}}{\text{Transmission per degree}}$$

Primary-Air Temperature Versus Outdoor Air Temperature



Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 5, In-Room Terminal Systems, Fig. 6.

Note: These temperatures are required at the units, and thermostat settings must be adjusted to allow for duct heat gains or losses. Temperatures are based on:

1. Minimum average load in this space, equivalent to 10°F multiplied by the transmission per degree.
2. Preventing the room temperature from dropping below 72°F. These values compensate for the radiation and convection effect of the cold outside walls.

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9.3.5 Chilled Beam Systems

Chilled beam systems can be either passive or active.

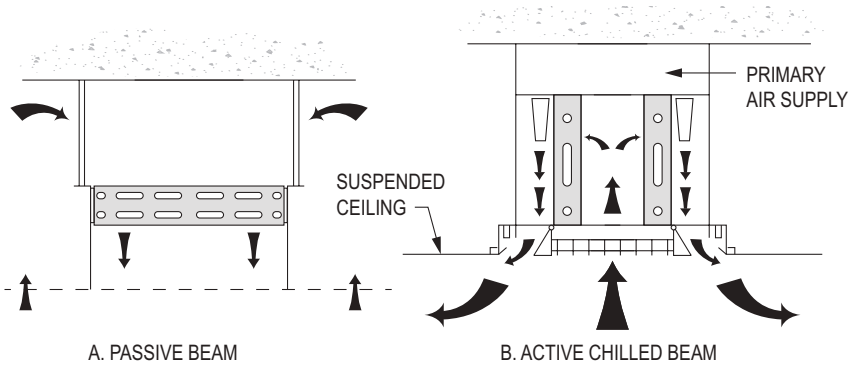
A *passive chilled beam system* consists of a chilled water coil mounted inside a housing. The chilled water supply temperature is between 58 and 60°F, with about a 6°F temperature rise. Passive beams use convective currents to provide cooling to the space. They provide about 400 Btu/hr per linear feet.

An *active chilled beam system* operates with induction nozzles that entrain room air and mix it with primary or ventilation air. The chilled water supply temperature is between 55 and 60°F, with about a 10°F temperature rise. Primary air is typically ducted to the beam at 55°F to provide dehumidification. Typical induction ratios are 2:1 or 3:1 room air to primary air. They provide about 800 Btu/hr per linear feet.

Chilled beams are designed to operated as sensible cooling units only with no condensate, although condensate drain pans are available on some models. Active chilled beams can be two-pipe (cooling only or two-pipe changeover) or four-pipe (cooling and heating) systems. Active beams can provide heat to the space, but typically both types of beams use some other source of heat, such as fin tube radiation.

When installing either type of chilled beam system, ensure that the building's dewpoint is low enough so that humidity is controlled without causing condensation at the chilled beams.

Passive and Active Chilled-Beam Operation



9.3.6 Duct Design

9.3.6.1 Bernoulli Equation

Assuming constant fluid density:

$$\frac{v^2}{2g_c} + \frac{p}{\rho} + \frac{gz}{g_c} = \text{constant}\left(\frac{\text{ft-lbf}}{\text{lbm}}\right)$$

where

v = streamline (local) velocity (fps)

g_c = dimensional constant = $32.2\frac{\text{lbm-ft}}{\text{lbf-sec}^2}$

p = absolute pressure $\left(\frac{\text{lbf}}{\text{ft}^2}\right)$

ρ = density $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

g = acceleration caused by gravity $\left(\frac{\text{ft}}{\text{sec}^2}\right)$

z = elevation (ft)

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Head: The height of a fluid column supported by fluid flow

Pressure: The normal force per unit area

Static pressure:

$\frac{pg_c}{\rho g}$ = static head

p = static pressure

where

p = pressure $\left(\frac{\text{lbf}}{\text{ft}^2}\right)$

g_c = dimensional constant = $32.2\frac{\text{lbm-ft}}{\text{lbf-sec}^2}$

ρ = density $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

g = acceleration caused by gravity $\left(\frac{\text{ft}}{\text{sec}^2}\right)$

Velocity pressure:

$$p_v = \rho\left(\frac{V}{1{,}097}\right)^2$$

where

p_v = velocity pressure (inches of water)

V = fluid mean velocity (fpm)

1,097 = conversion factor to inches of water

For air at standard conditions:

$$p_v = \left(\frac{V}{4{,}005}\right)^2$$

Velocity is calculated from

$$V = \frac{Q}{A}$$

where

Q = airflow rate (cfm)

A = cross-sectional area of duct (ft^2)

Total pressure:

$$p_t = p_s + \rho\left(\frac{V}{1{,}097}\right)^2 \quad \text{or} \quad p_t = p_s + p_v$$

where:

p_t = total pressure (inches of water)

p_s = static pressure (inches of water)

p_v = velocity pressure (inches of water)

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Darcy equation for fluid flow friction loss in conduits:

$$\Delta p_f = \frac{12fL}{D_h}\rho\left(\frac{V}{1{,}097}\right)^2$$

where

Δp_f = friction losses in terms of total pressure (inches of water)

f = friction factor (dimensionless)

L = duct length (ft)

D_h = hydraulic diameter (inches)

V = velocity (fpm)

ρ = density $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

9.3.6.2 Hydraulic Diameter

For noncircular ducts:

$$D_h = \frac{4A}{P}$$

where

D_h = hydraulic diameter

A = duct area (in^2)

P = perimeter of cross-section (inches)

9.3.6.3 Rectangular Ducts

To determine size equivalency based on equal airflow, resistance, and length, the relationship between rectangular and round ducts is:

$$D_e = \frac{1.30(ab)^{0.625}}{(a+b)^{0.250}}$$

where

D_e = circular equivalent of rectangular duct for equal length, fluid resistance, and airflow, in inches

a = length of one side of duct (inches)

b = length of adjacent side of duct (inches)

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9.3.6.4 Pressure Loss Coefficients

The ratio of total pressure loss to velocity pressure loss at a referenced cross-section is

$$C = \frac{\Delta p_t}{\rho\left(\frac{V}{1,097}\right)^2} = \frac{\Delta p_t}{p_v}$$

where

C = local loss coefficient (dimensionless)

Δp_t = total pressure loss (inches of water)

ρ = density $\left(\frac{\text{lbm}}{\text{ft}^3}\right)$

V = velocity (fpm)

p_v = velocity pressure (inches of water)

For all fittings except junctions, the total pressure loss is calculated from

$$\Delta p_t = C_0 p_{v,o}$$

where

Δp_t = total pressure loss of fitting (inches of water)

C_0 = local loss coefficient of fitting (dimensionless)

$p_{v,o}$ = velocity pressure at section o of fitting (inches of water)

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9.3.6.5 Duct Pressure Losses

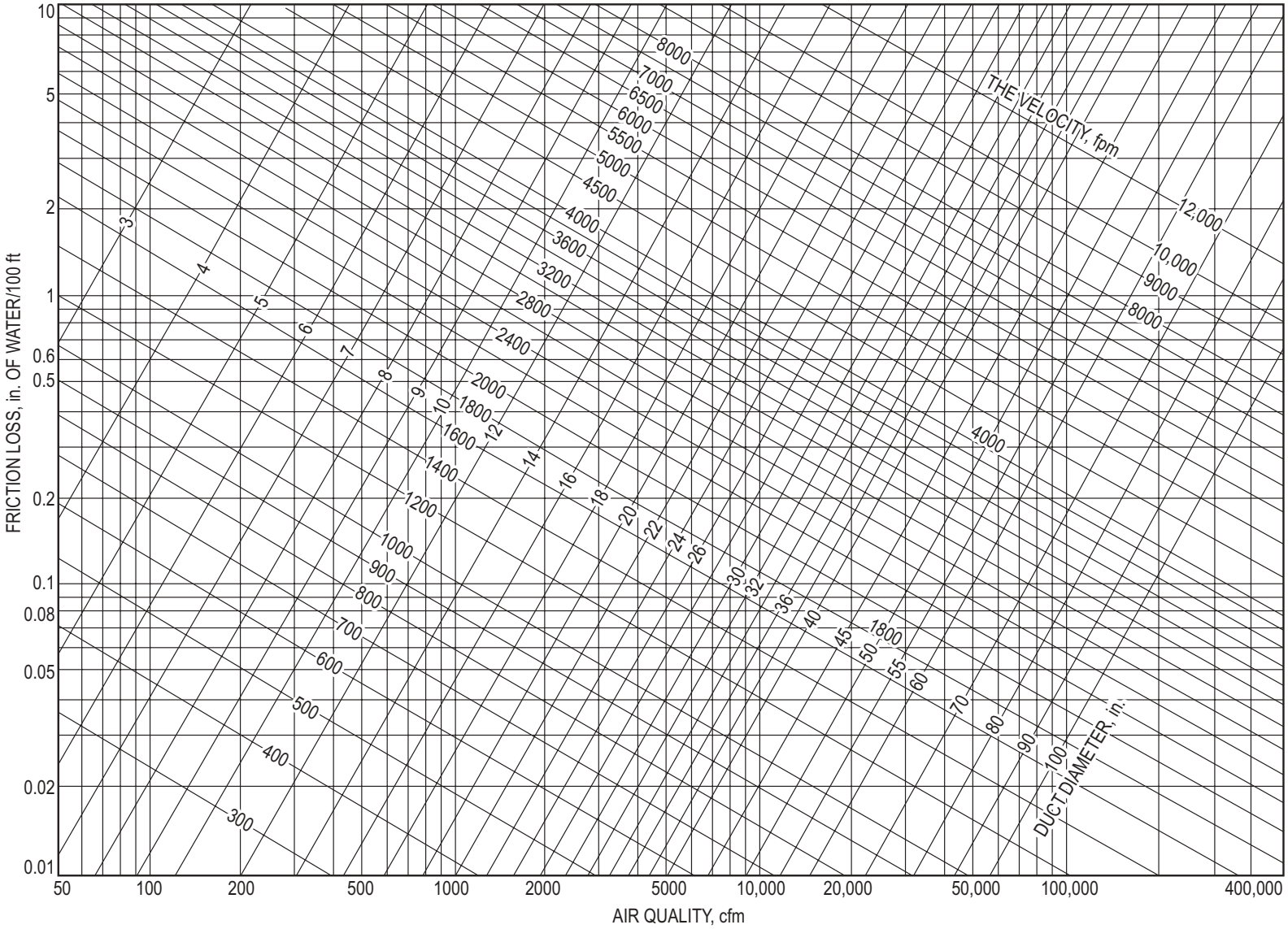


Fig. 9 FRICTION CHART FOR ROUND DUCT (ρ = 0.075 lb_m/ft^3 and ε = 0.0003 ft)

Source: ©ASHRAE, www.ashrae.org., *2009 ASHRAE Handbook—Fundamentals*, Chapter 21, Duct Design, Fig. 9.

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Circular Duct Diameter, in.	Length of One Side of Rectangular Duct *a*, in.																
	4	5	6	7	8	9	10	12	14	16	18	20	22	24	26	28	30
	Length Adjacent Side of Rectangular Duct *b*, in.																
5	5																
5.5	6	5															
6	8	6															
6.5	9	7	6														
7	11	8	7														
7.5	13	10	8	7													
8	15	11	9	8													
8.5	17	13	10	9													
9	20	15	12	10	8												
9.5	22	17	13	11	9												
10	25	19	15	12	10	9											
10.5	29	21	16	14	12	10											
11	32	23	18	15	13	11	10										
11.5		26	20	17	14	12	11										
12		29	22	18	15	13	12										
12.5		32	24	20	17	15	13										
13		35	27	22	18	16	14	12									
13.5		38	29	24	20	17	15	13									
14			32	26	22	19	17	14									
14.5			35	28	24	20	18	15									
15			38	30	25	22	19	16	14								
16			45	36	30	25	22	18	15								
17				41	34	29	25	20	17	16							
18				47	39	33	29	23	19	17							
19				54	44	38	33	26	22	19	18						
20					50	43	37	29	24	21	19						
21					57	48	41	33	27	23	20						
22					64	54	46	36	30	26	23	20					
23						60	51	40	33	28	25	22					
24						66	57	44	36	31	27	24	22				
25							63	49	40	34	29	26	24				
26							69	54	44	37	32	28	26	24			
27							76	59	48	40	35	31	28	25			
28								64	52	43	38	33	30	27	26		
29								70	56	47	41	36	32	29	27		
30								76	61	51	44	39	35	31	29	28	
31								82	66	55	47	41	37	34	31	29	
32								89	71	59	51	44	40	36	33	31	
33								96	76	64	54	48	42	38	35	33	30

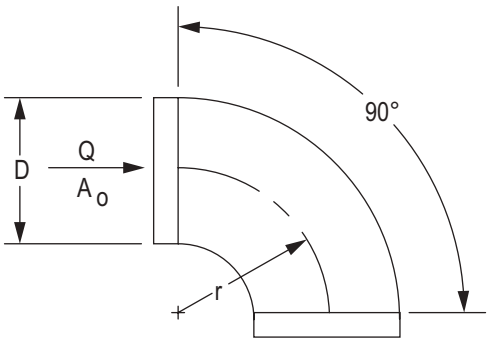
Source: ©ASHRAE, www.ashrae.org., *2009 ASHRAE Handbook—Fundamentals*, Chapter 21, Duct Design, Table 2.

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Round Fittings

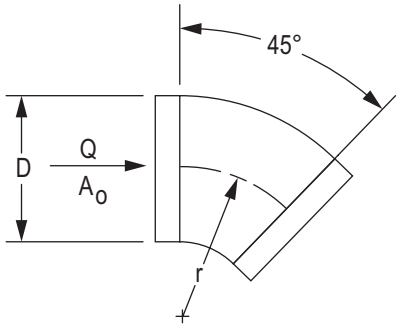
CD3-1 Elbow, Die Stamped, 90 Degree, *r/D* = 1.5

***D*, in.**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C_o	0.30	0.21	0.16	0.14	0.12	0.11	0.11	0.11



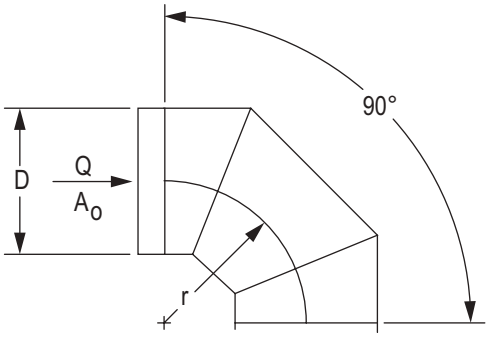
CD3-3 Elbow, Die Stamped, 45 Degree, *r/D* = 1.5

***D*, in.**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
C_o	0.18	0.13	0.10	0.08	0.07	0.07	0.07	0.07



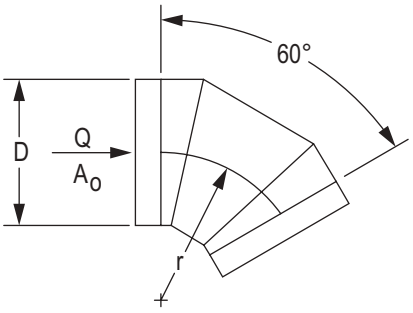
CD3-12 Elbow, 3 Gore, 90 Degree, *r/D* = 0.75 to 2.0

r/D	**0.75**	**1.00**	**1.50**	**2.00**
C_o	0.54	0.42	0.34	0.33



CD3-13 Elbow, 3 Gore, 60 Degree, *r/D* = 1.5

***D*, in.**	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**60**
C_o	0.40	0.21	0.16	0.14	0.12	0.12	0.11	0.10	0.09	0.09	0.09

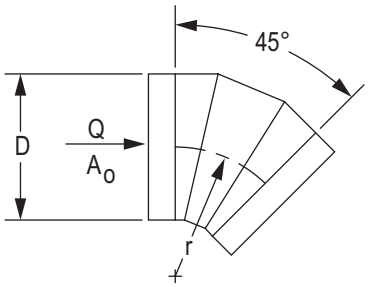


Source: ©ASHRAE, www.ashrae.org., *2009 ASHRAE Handbook—Fundamentals*, Chapter 21, Duct Design, Round Fittings, pp. 21.26 and 21.27.

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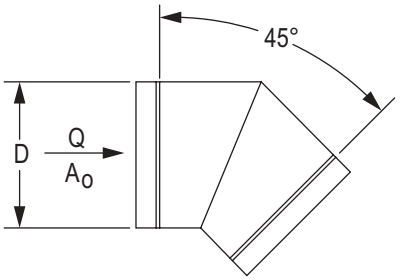
CD3-14 Elbow, 3 Gore, 45 Degree, *r/D* = 1.5

***D*, in.**	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**60**
C_o	0.31	0.17	0.13	0.11	0.11	0.09	0.08	0.08	0.07	0.07	0.07



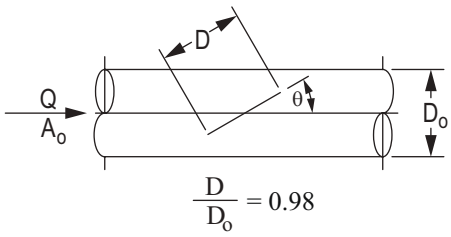
CD3-17 Elbow, Mitered, 45 Degree

***D*, in.**	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**60**
C_o	0.87	0.79	0.74	0.72	0.71	0.70	0.69	0.68	0.68	0.67



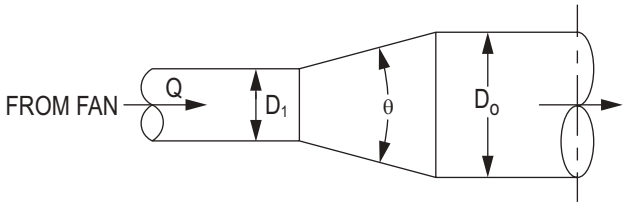
CD9-1 Damper, Butterfly

θ	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**	**90**
C_o	0.60	0.85	1.70	4.0	9.4	24	67	215	400	9999



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SD4-1 Transition, Round to Round, Supply Air Systems

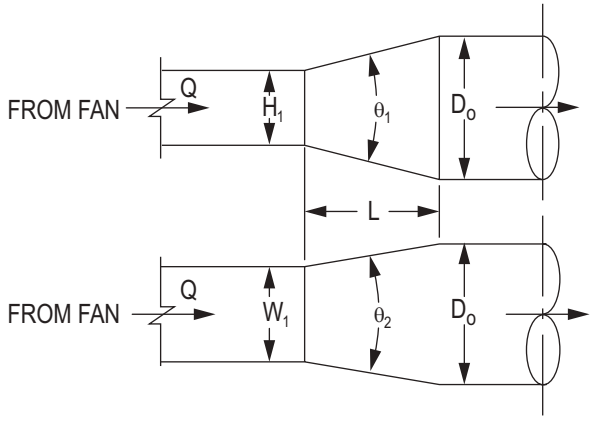


	C_o **Values**							
	θ							
A_o/A_1	**0**	**3**	**5**	**10**	**15**	**20**	**30**	**45**
0.10	0.0	0.12	0.09	0.05	0.05	0.05	0.05	0.06
0.167	0.0	0.11	0.08	0.05	0.04	0.04	0.04	0.06
0.25	0.0	0.10	0.07	0.05	0.04	0.04	0.04	0.06
0.39	0.0	0.10	0.07	0.05	0.05	0.05	0.05	0.06
0.50	0.0	0.07	0.06	0.05	0.05	0.05	0.05	0.06
0.64	0.0	0.07	0.07	0.05	0.04	0.04	0.04	0.05
1.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.0	0.0	0.59	0.51	0.43	0.52	0.76	1.26	1.32
4.0	0.0	3.15	2.78	2.51	3.38	4.77	7.38	9.70

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SD4-2 Transition, Rectangular to Round, Supply Air Systems



C_o Values

	θ							
A_o/A_1	0	3	5	10	15	20	30	45
0.10	0.0	0.12	0.09	0.05	0.05	0.05	0.05	0.06
0.167	0.0	0.11	0.08	0.05	0.05	0.05	0.05	0.06
0.25	0.0	0.10	0.07	0.05	0.05	0.05	0.05	0.06
0.50	0.0	0.08	0.07	0.06	0.07	0.06	0.05	0.06
1.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.0	0.0	0.57	0.55	0.61	0.87	1.00	1.20	1.30
4.0	0.0	2.60	2.84	3.92	5.72	7.20	8.32	9.28

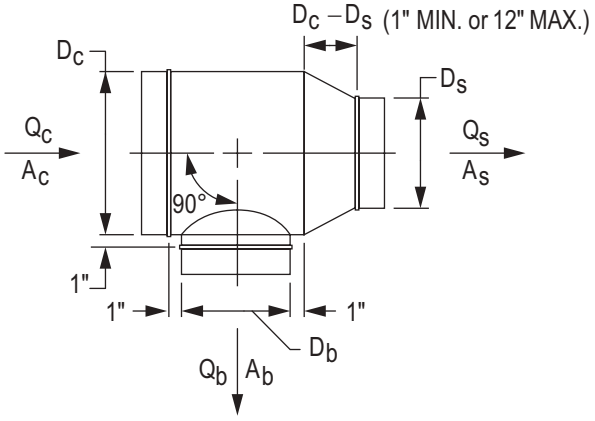
SD5-9 Tee, Diverging

C_b Values

	Q_b/Q_c				
A_b/A_c	0.1	0.2	0.3	0.4	0.5
0.1	1.20	0.62	0.80	1.28	1.99
0.2	4.10	1.20	0.72	0.62	0.66
0.3	8.99	2.40	1.20	0.81	0.66
0.4	15.89	4.10	1.94	1.20	0.88
0.5	24.80	6.29	2.91	1.74	1.20
0.6	35.73	8.99	4.10	2.40	1.62
0.7	48.67	12.19	5.51	3.19	2.12
0.8	63.63	15.89	7.14	4.10	2.70

C_s Values

	Q_s/Q_c				
A_s/A_c	0.1	0.2	0.3	0.4	0.5
0.1	0.13	0.24	0.57	0.74	0.74
0.2	0.20	0.13	0.15	0.16	0.28
0.3	0.90	0.14	0.13	0.14	0.15
0.4	2.88	0.20	0.14	0.13	0.14
0.5	6.25	0.38	0.17	0.14	0.13
0.6	11.88	0.90	0.20	0.14	0.14
0.7	18.62	1.72	0.33	0.18	0.16
0.8	26.88	2.88	0.50	0.20	0.15



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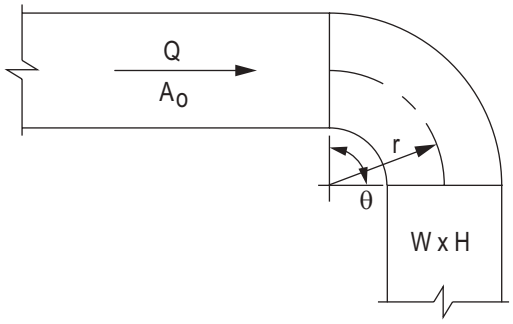
Rectangular Fittings

CR3-1 Elbow, Smooth Radius, Without Vanes

	C_p Values										
	H/W										
r/W	**0.25**	**0.50**	**0.75**	**1.0**	**1.50**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**
0.50	1.53	1.38	1.29	1.18	1.06	1.00	1.00	1.06	1.12	1.16	1.18
0.75	0.57	0.52	0.48	0.44	0.40	0.39	0.39	0.40	0.42	0.43	0.44
1.00	0.27	0.25	0.23	0.21	0.19	0.18	0.18	0.19	0.20	0.21	0.21
1.50	0.22	0.20	0.19	0.17	0.15	0.14	0.14	0.15	0.16	0.17	0.17
2.00	0.20	0.18	0.16	0.15	0.14	0.13	0.13	0.14	0.14	0.15	0.15

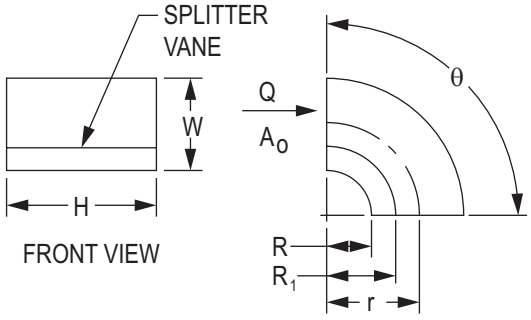
	Angle Factor K										
θ	**0**	**20**	**30**	**45**	**60**	**75**	**90**	**110**	**130**	**150**	**180**
K	0.00	0.31	0.45	0.60	0.78	0.90	1.00	1.13	1.20	1.28	1.40

$C_o = KC_p$ where K = angle factor



CR3-3 Elbow, Smooth Radius, One Splitter Vane

	C_p Values						
	H/W						
r/W	**0.25**	**0.50**	**1.0**	**1.50**	**2.0**	**3.0**	**4.0**
0.55	0.52	0.40	0.43	0.49	0.55	0.66	0.75
0.60	0.36	0.27	0.25	0.28	0.30	0.35	0.39
0.65	0.28	0.21	0.18	0.19	0.20	0.22	0.25
0.70	0.22	0.16	0.14	0.14	0.15	0.16	0.17
0.75	0.18	0.13	0.11	0.11	0.11	0.12	0.13
0.80	0.15	0.11	0.09	0.09	0.09	0.09	0.10
0.85	0.13	0.09	0.08	0.07	0.07	0.08	0.08
0.90	0.11	0.08	0.07	0.06	0.06	0.06	0.06
0.95	0.10	0.07	0.06	0.05	0.05	0.05	0.05
1.00	0.09	0.06	0.05	0.05	0.04	0.04	0.04



$C_o = KC_p$

$R_1 = R/CR$

where

R = THROAT RADIUS

R_1 = SPLITTER VANE RADIUS

CR = CURVE RATIO

K = ANGLE FACTOR

	Angle Factor K				
θ	**0**	**30**	**45**	**60**	**90**
K	0.00	0.45	0.60	0.78	1.00

	Curve Ratio CR									
r/W	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**	**1.0**
CR	0.218	0.302	0.361	0.408	0.447	0.480	0.509	0.535	0.557	0.577

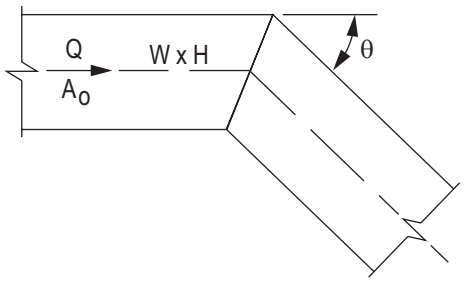
	Throat Radius/Width Ratio (R/W)									
r/W	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**	**1.0**
R/W	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50

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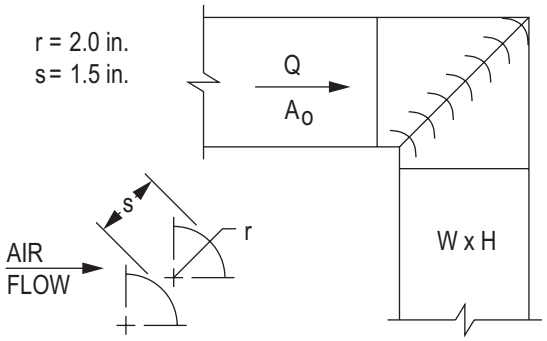
CR3-6 Elbow, Mitered

	C_o Values										
	H/W										
θ	**0.25**	**0.50**	**0.75**	**1.00**	**1.50**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**
20	0.08	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.05	0.05
30	0.18	0.17	0.17	0.16	0.15	0.15	0.13	0.13	0.12	0.12	0.11
45	0.38	0.37	0.36	0.34	0.33	0.31	0.28	0.27	0.26	0.25	0.24
60	0.60	0.59	0.57	0.55	0.52	0.49	0.46	0.43	0.41	0.39	0.38
75	0.89	0.87	0.84	0.81	0.77	0.73	0.67	0.63	0.61	0.58	0.57
90	1.30	1.27	1.23	1.18	1.13	1.07	0.98	0.92	0.89	0.85	0.83



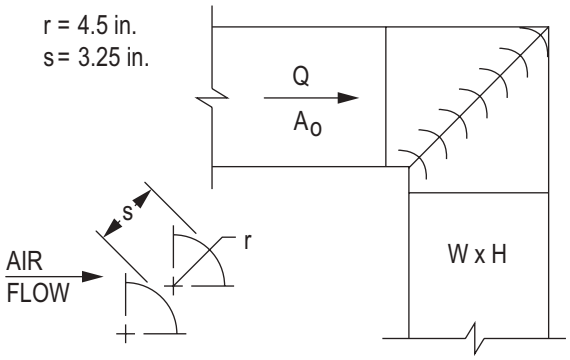
CR3-9 Elbow, Mitered, 90 Degree, Single-Thickness Vanes (1.5 in. Vane Spacing)

$C_o = 0.11$



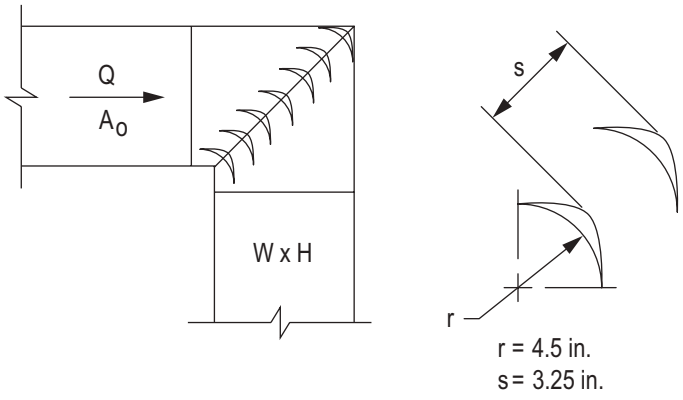
CR3-12 Elbow, Mitered, 90 Degree, Single-Thickness Vanes (3.25 in. Vane Spacing)

$C_O = 0.33$



CR3-16 Elbow, Mitered, 90 Degree, Double-Thickness Vanes (3.25 in. Vane Spacing)

$C_O = 0.41$

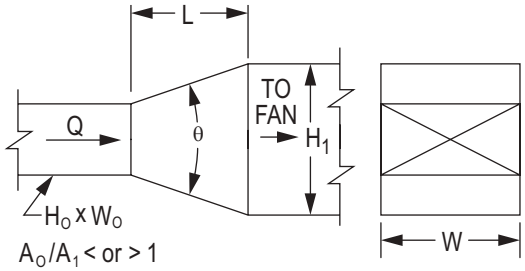


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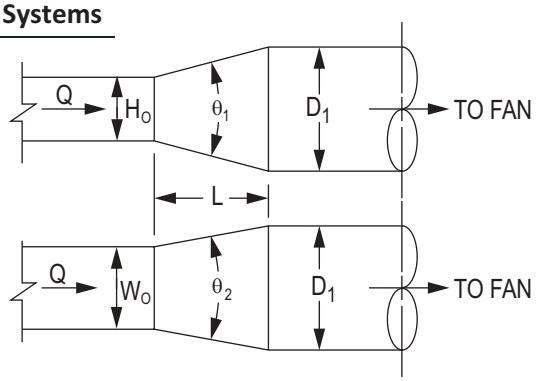
ER4-1 Transition, Rectangular, Two Sides Parallel, Symmetrical, Exhaust/Return Systems

	C_o Values							
	θ							
A_o/A_1	0	3	5	10	15	20	30	45
0.063	0.0	0.44	0.27	0.25	0.27	0.36	0.56	0.71
0.10	0.0	0.41	0.27	0.23	0.25	0.34	0.53	0.69
0.167	0.0	0.34	0.28	0.21	0.23	0.30	0.48	0.65
0.25	0.0	0.26	0.29	0.17	0.19	0.25	0.42	0.60
0.50	0.0	0.16	0.24	0.14	0.13	0.15	0.24	0.35
1.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.0	0.30	0.38	0.25	0.17	0.17	0.17	0.23
4.00	0.0	1.66	1.25	0.77	0.70	0.70	0.70	0.90



ER4-3 Transition, Rectangular to Round, Exhaust/Return Systems

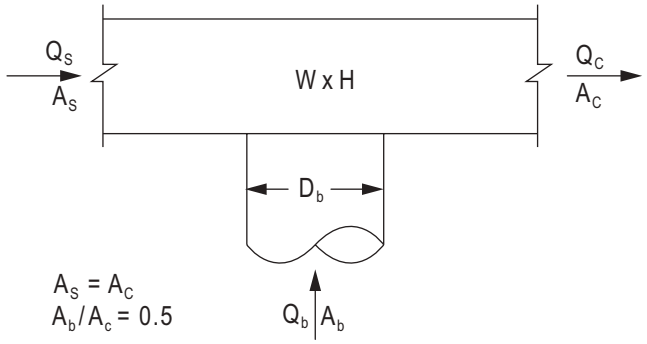
	C_o Values							
	θ							
A_o/A_1	0	3	5	10	15	20	30	45
0.063	0.0	0.17	0.19	0.30	0.46	0.53	0.64	0.77
0.10	0.0	0.17	0.19	0.30	0.45	0.53	0.64	0.75
0.167	0.0	0.18	0.19	0.30	0.44	0.53	0.63	0.72
0.25	0.0	0.16	0.18	0.25	0.36	0.45	0.52	0.58
0.50	0.0	0.14	0.14	0.15	0.22	0.25	0.30	0.33
1.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.0	0.30	0.27	0.26	0.28	0.25	0.19	0.23
4.00	0.0	1.60	1.14	0.84	0.85	0.86	0.76	0.90



ER5-2 Tee, Round Tap to Rectangular Main, Converging

Q_b/Q_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
C_b	–14.00	–2.38	0.50	0.65	1.03	1.17	1.19	1.33	1.51	1.44

Q_s/Q_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
C_s	22.15	11.91	6.54	3.74	2.23	1.33	0.76	0.38	0.10	0.0



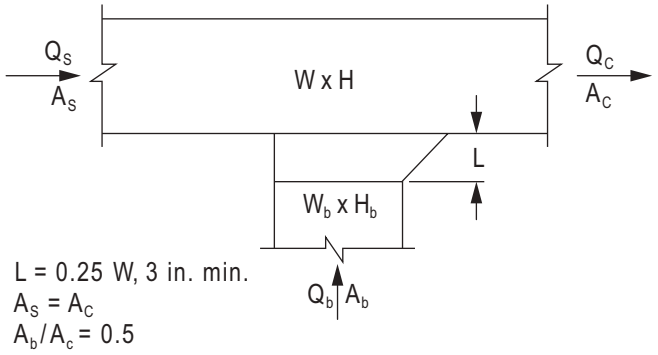
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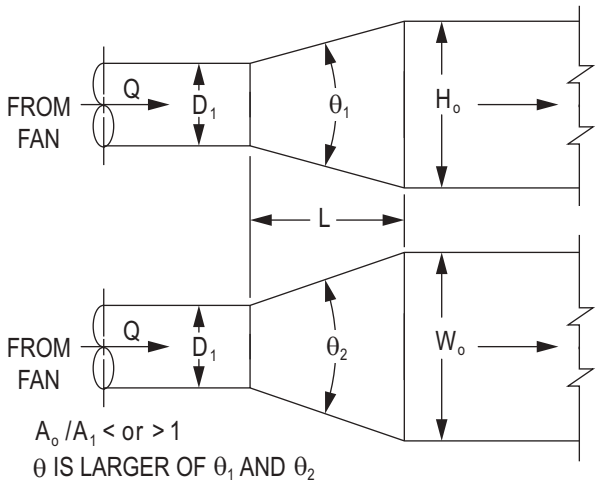
ER5-3 Tee, 45 Degree Entry Branch, Converging

Q_b/Q_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
C_b	–19.38	–3.75	–0.74	0.48	0.66	0.75	0.85	0.77	0.83	0.83

Q_s/Q_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
C_s	22.15	11.91	6.54	3.74	2.23	1.33	0.76	0.38	0.10	0.0



SR4-3 Transition, Round to Rectangular, Supply Air Systems



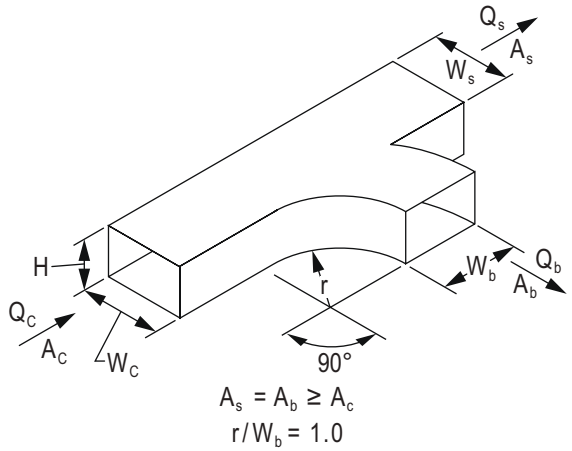
	C_o Values							
	θ							
A_o/A_1	0	3	5	10	15	20	30	45
0.10	0.0	0.12	0.09	0.05	0.05	0.05	0.05	0.06
0.167	0.0	0.11	0.08	0.05	0.05	0.05	0.05	0.06
0.25	0.0	0.10	0.07	0.05	0.05	0.05	0.05	0.06
0.50	0.0	0.08	0.07	0.06	0.07	0.06	0.05	0.06
1.00	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.0	0.57	0.55	0.61	0.87	1.00	1.20	1.30
4.00	0.0	2.60	2.84	3.92	5.72	7.20	8.32	9.28

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SR5-1 Smooth Wye of Type $A_S + A_b \geq A_C$, Branch 90° to Main, Diverging

		C_b Values								
		Q_b/Q_c								
A_s/A_c	A_b/A_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.50	0.25	2.25	0.48	0.25	0.18	0.17	0.16	0.17	0.17	0.17
	0.50	11.00	2.38	1.06	0.64	0.52	0.47	0.47	0.47	0.48
	1.00	60.00	13.00	4.78	2.06	0.96	0.47	0.31	0.27	0.26
0.75	0.25	2.19	0.55	0.35	0.31	0.33	0.35	0.36	0.37	0.39
	0.50	13.00	2.50	0.89	0.47	0.34	0.31	0.32	0.36	0.43
	1.00	70.00	15.00	5.67	2.63	1.36	0.78	0.53	0.41	0.36
1.00	0.25	3.44	0.78	0.42	0.33	0.30	0.31	0.40	0.42	0.46
	0.50	15.50	3.00	1.11	0.63	0.48	0.42	0.40	0.42	0.46
	1.00	67.00	13.75	5.11	2.31	1.28	0.81	0.59	0.47	0.46
		C_s Values								
		Q_s/Q_c								
A_s/A_c	A_b/A_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.50	0.25	8.65	1.12	0.21	0.05	0.06	0.10	0.15	0.19	0.24
	0.50	7.50	0.98	0.19	0.06	0.06	0.10	0.14	0.18	0.22
	1.00	5.21	0.68	0.15	0.06	0.07	0.10	0.13	0.16	0.19
0.75	0.25	19.62	3.25	0.86	0.23	0.05	0.02	0.00	0.00	0.05
	0.50	20.62	3.24	0.76	0.14	–0.03	–0.07	–0.05	–0.01	0.03
	1.00	17.01	2.55	0.55	0.07	–0.05	–0.05	–0.02	0.02	0.06
1.00	0.25	46.00	9.50	3.22	1.31	0.52	0.14	–0.02	–0.05	–0.01
	0.50	35.34	6.49	1.98	0.69	0.22	0.00	–0.04	–0.05	–0.05
	1.00	38.95	7.10	2.15	0.74	0.23	0.03	–0.04	–0.05	–0.04

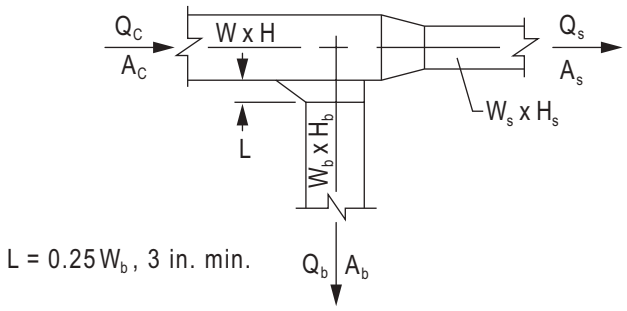


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SR5-13 Tee, 45 Degree Entry Branch, Diverging

	C_b Values								
	Q_b/Q_c								
A_b/A_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.32	0.33	0.32	0.34	0.32	0.37	0.38	0.39	0.40
0.2	0.31	0.32	0.41	0.34	0.32	0.32	0.33	0.34	0.35
0.3	1.86	1.65	0.73	0.47	0.37	0.34	0.32	0.32	0.32
0.4	3.56	3.10	1.28	0.73	0.51	0.41	0.36	0.34	0.32
0.5	5.74	4.93	2.07	1.12	0.73	0.54	0.44	0.38	0.35
0.6	8.48	7.24	3.10	1.65	1.03	0.73	0.56	0.47	0.41
0.7	11.75	10.00	4.32	3.31	1.42	0.98	0.73	0.58	0.49
0.8	15.57	13.22	5.74	3.10	1.90	1.28	0.94	0.73	0.60
0.9	19.92	16.90	7.38	4.02	2.46	1.65	1.19	0.91	0.73
	C_s Values								
	Q_s/Q_c								
A_s/A_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.2	0.98	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.3	3.48	0.31	0.04	0.01	0.00	0.00	0.00	0.00	0.00
0.4	7.55	0.98	0.18	0.04	0.02	0.00	0.00	0.00	0.00
0.5	13.18	2.03	0.49	0.13	0.04	0.00	0.01	0.00	0.00
0.6	20.38	3.48	0.98	0.31	0.10	0.04	0.02	0.01	0.00
0.7	29.15	5.32	1.64	0.60	0.23	0.09	0.04	0.02	0.01
0.8	39.48	7.55	2.47	0.98	0.42	0.18	0.08	0.04	0.02
0.9	51.37	10.17	3.48	1.46	0.67	0.31	0.15	0.07	0.04

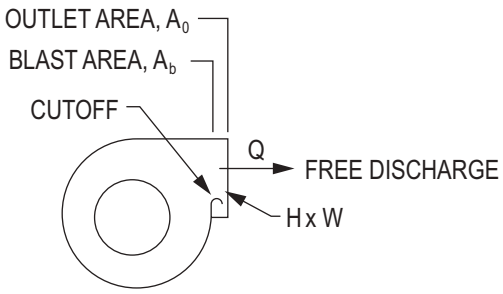


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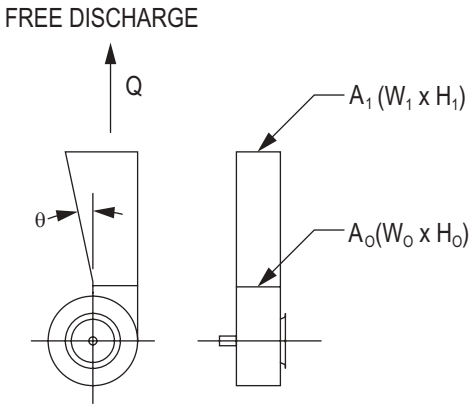
SR7-1 Fan, Centrifugal, Without Outlet Diffuser, Free Discharge

A_b/A_o	0.4	0.5	0.6	0.7	0.8	0.9	1.0
C_o	2.00	2.00	1.00	0.80	0.47	0.22	0.00



SR7-2 Plane Asymmetric Diffuser at Centrifugal Fan Outlet, Free Discharge

	C_o Values					
	A_1/A_o					
θ	1.5	2.0	2.5	3.0	3.5	4.0
10	0.51	0.34	0.25	0.21	0.18	0.17
15	0.54	0.36	0.27	0.24	0.22	0.20
20	0.55	0.38	0.31	0.27	0.25	0.24
25	0.59	0.43	0.37	0.35	0.33	0.33
30	0.63	0.50	0.46	0.44	0.43	0.42
35	0.65	0.56	0.53	0.52	0.51	0.50



SR7-5 Fan Outlet, Centrifugal, SWSI, with Elbow (Position A)

	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	3.20	2.50	1.80	0.80	0.0	0.0
0.5	2.20	1.80	1.20	0.53	0.0	0.0
0.6	1.60	1.40	0.80	0.40	0.0	0.0
0.7	1.00	0.80	0.53	0.26	0.0	0.0
0.8	0.80	0.67	0.47	0.18	0.0	0.0
0.9	0.53	0.47	0.33	0.18	0.0	0.0
1.0	0.53	0.47	0.33	0.18	0.0	0.0

$$V_o > 2{,}500 \text{ fpm: } L_e = \frac{V_o\sqrt{A_o}}{10{,}600}$$

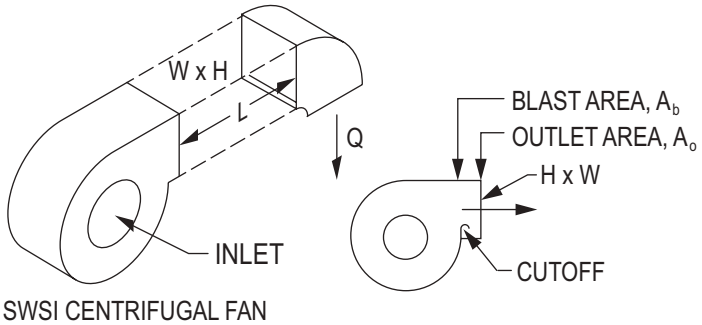
$$V_o \le 2{,}500 \text{ fpm: } L_e = \frac{\sqrt{A_o}}{4.3}$$

where

V_o = duct velocity, fpm

L_e = effective duct lenght, ft

A_o = duct area, in.^{2}



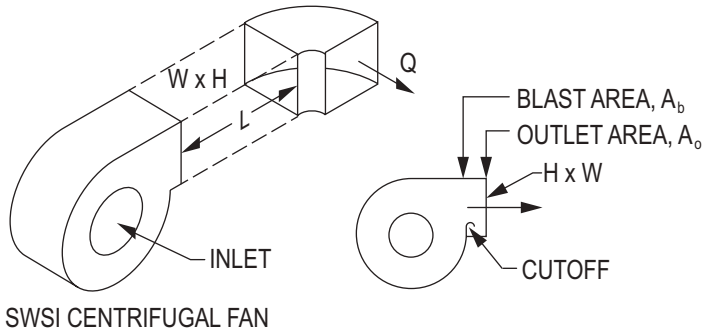
SWSI CENTRIFUGAL FAN

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SR7-6 Fan Outlet, Centrifugal, SWSI, with Elbow (Position B)

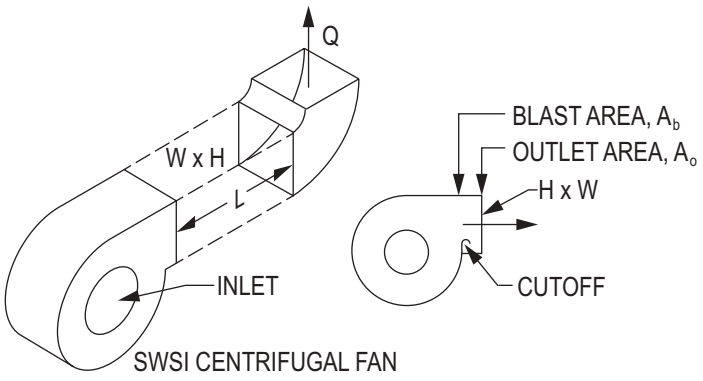
	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	3.80	3.20	2.20	1.00	0.0	0.0
0.5	2.90	2.20	1.60	0.67	0.0	0.0
0.6	2.00	1.60	1.20	0.53	0.0	0.0
0.7	1.40	1.00	0.67	0.33	0.0	0.0
0.8	1.00	0.80	0.53	0.26	0.0	0.0
0.9	0.80	0.67	0.47	0.18	0.0	0.0
1.0	0.67	0.53	0.40	0.18	0.0	0.0



To calculate L_e, see Fitting SR7-5.

SR7-7 Fan Outlet, Centrifugal, SWSI, with Elbow (Position C)

	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	5.50	4.50	3.20	1.60	0.0	0.0
0.5	3.80	3.20	2.20	1.00	0.0	0.0
0.6	2.90	2.50	1.60	0.80	0.0	0.0
0.7	2.00	1.60	1.00	0.53	0.0	0.0
0.8	1.40	1.20	0.80	0.33	0.0	0.0
0.9	1.20	0.80	0.67	0.26	0.0	0.0
1.0	1.00	0.80	0.53	0.26	0.0	0.0



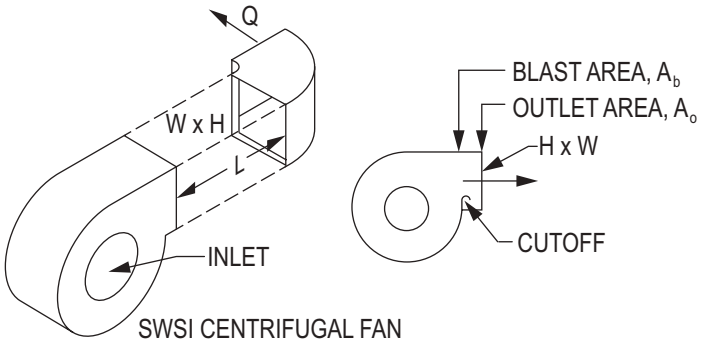
To calculate L_e, see Fitting SR7-5.

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SR7-8 Fan Outlet, Centrifugal, SWSI, with Elbow (Position D)

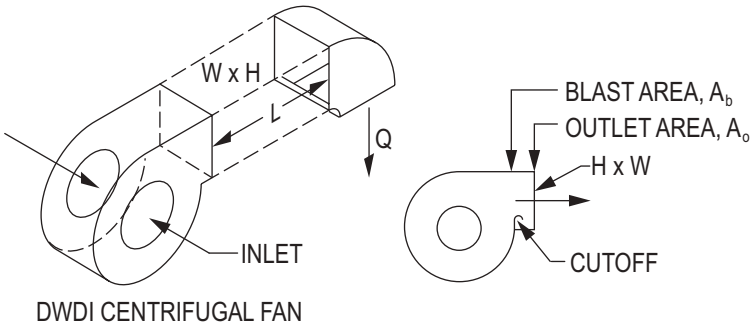
	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	5.50	4.50	3.20	1.60	0.0	0.0
0.5	3.80	3.20	2.20	1.00	0.0	0.0
0.6	2.90	2.50	1.60	0.80	0.0	0.0
0.7	2.00	1.60	1.00	0.53	0.0	0.0
0.8	1.40	1.20	0.80	0.33	0.0	0.0
0.9	1.20	0.80	0.67	0.26	0.0	0.0
1.0	1.00	0.80	0.53	0.26	0.0	0.0



To calculate L_e, see Fitting SR7-5.

SR7-9 Fan Outlet, Centrifugal, DWDI, with Elbow (Position A)

	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	3.20	2.50	1.80	0.80	0.0	0.0
0.5	2.20	1.80	1.20	0.53	0.0	0.0
0.6	1.60	1.40	0.80	0.40	0.0	0.0
0.7	1.00	0.80	0.53	0.26	0.0	0.0
0.8	0.80	0.67	0.47	0.18	0.0	0.0
0.9	0.53	0.47	0.33	0.18	0.0	0.0
1.0	0.53	0.47	0.33	0.18	0.0	0.0



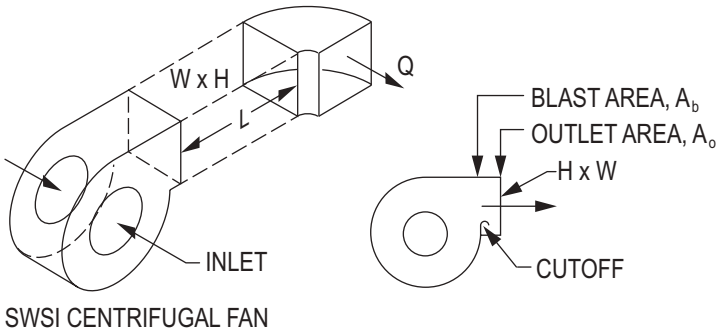
To calculate L_e, see Fitting SR7-5.

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SR7-10 Fan Outlet, Centrifugal, DWDI, with Elbow (Position B)

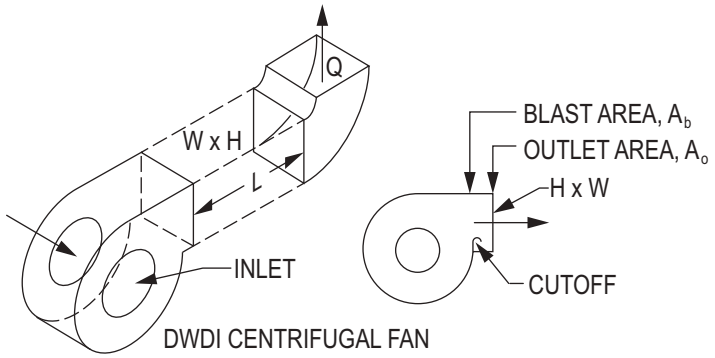
	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	4.80	4.00	2.90	1.30	0.0	0.0
0.5	3.60	2.90	2.00	0.84	0.0	0.0
0.6	2.50	2.00	1.50	0.66	0.0	0.0
0.7	1.80	1.30	0.84	0.41	0.0	0.0
0.8	1.25	1.00	0.66	0.33	0.0	0.0
0.9	1.00	0.84	0.59	0.23	0.0	0.0
1.0	0.84	0.66	0.50	0.23	0.0	0.0



To calculate L_e, see Fitting SR7-5.

SR7-11 Fan Outlet, Centrifugal, DWDI, with Elbow (Position C)

	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	5.50	4.50	3.20	1.60	0.0	0.0
0.5	3.80	3.20	2.20	1.00	0.0	0.0
0.6	2.90	2.50	1.60	0.80	0.0	0.0
0.7	2.00	1.60	1.00	0.53	0.0	0.0
0.8	1.40	1.20	0.80	0.33	0.0	0.0
0.9	1.20	0.80	0.67	0.26	0.0	0.0
1.0	1.00	0.80	0.53	0.26	0.0	0.0



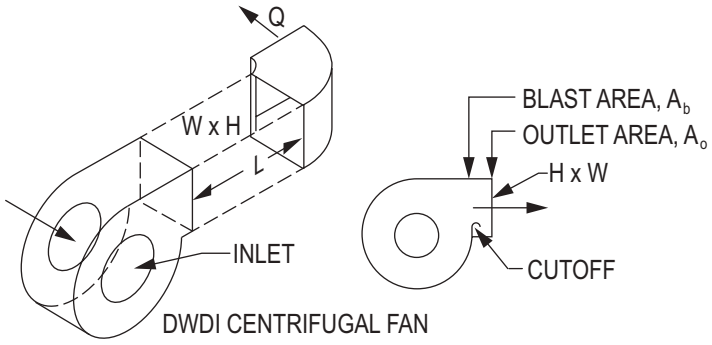
To calculate L_e, see Fitting SR7-5.

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SR7-12 Fan Outlet, Centrifugal, DWDI, with Elbow (Position D)

	C_o Values					
	L/L_e					
A_b/A_o	0.00	0.12	0.25	0.50	1.0	10.0
0.4	4.70	3.80	2.70	1.40	0.0	0.0
0.5	3.20	2.70	1.90	0.85	0.0	0.0
0.6	2.50	2.10	1.40	0.68	0.0	0.0
0.7	1.70	1.40	0.85	0.45	0.0	0.0
0.8	1.20	1.00	0.68	0.26	0.0	0.0
0.9	1.00	0.68	0.57	0.22	0.0	0.0
1.0	0.85	0.68	0.45	0.22	0.0	0.0

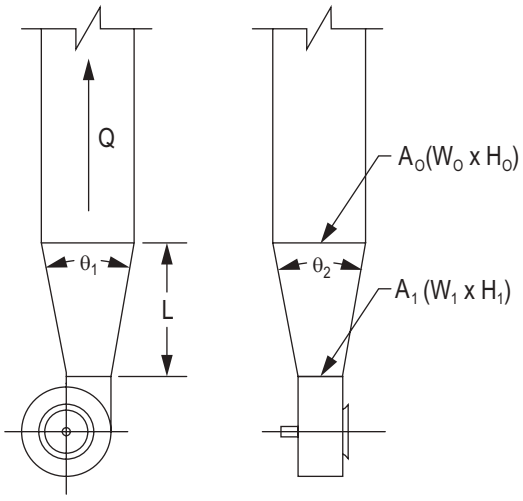


To calculate L_e, see Fitting SR7-5.

SR7-17 Pyramidal Diffuser at Centrifugal Fan Outlet with Ductwork

	C_1 Values						
	A_o/A_1						
θ	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.10	0.18	0.21	0.23	0.24	0.25
15	0.00	0.23	0.33	0.38	0.40	0.42	0.44
20	0.00	0.31	0.43	0.48	0.53	0.56	0.58
25	0.00	0.36	0.49	0.55	0.58	0.62	0.64
30	0.00	0.42	0.53	0.59	0.64	0.67	0.69

$$C_o = C_1\left(\frac{A_o}{A_1}\right)^2$$



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9.3.6.6 Darcy-Weisbach Equation

Total pressure loss in a duct section is calculated by

$$\Delta p_f = \left(\frac{12f\,L}{D_h} + \sum C\right)\rho\left(\frac{V}{1{,}097}\right)^2$$

where $\sum C$ = summation of local loss coefficient on the duct section

Each fitting loss coefficient must be referenced to that section's velocity pressure.

HVAC systems generally follow this law: $\frac{\Delta P_2}{\Delta P_1} = \left(\frac{Q_2}{Q_1}\right)^2$

9.3.6.7 Fan Outlet Conditions

For 100% recovery, the duct length including transition must meet the requirements for 100% effective duct length, calculated as follows:

For $V_o > 2{,}500$ fpm: $L_e = \frac{V_o\sqrt{A_o}}{10{,}600}$

For $V_o < 2{,}500$ fpm: $L_e = \frac{\sqrt{A_o}}{4.3}$

where

V_o = duct velocity (fpm)

L_e = effective duct length (ft)

A_o = duct area (in^2)

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9.3.6.8 Duct Heat Gain or Loss

Duct air exit temperatures for an uninsulated duct can be estimated using the following:

$$t_{drop} \text{ or } t_{gain} = 0.2\left(\frac{qPL}{VC_p\rho A}\right)$$

For warm air ducts:

$$t_{exit} = t_{enter} - t_{drop}$$

For cold air ducts:

$$t_{exit} = t_{enter} - t_{gain}$$

where

t_{drop} = temperature loss for warm air ducts (°F)

t_{enter} = entering air temperature (°F)

t_{gain} = temperature rise for cool air ducts (°F)

t_{exit} = exit temperature for either warm or cool air ducts (°F)

q = heat loss through duct wall $\left(\frac{\text{Btu}}{\text{hr-ft}^2}\right)$

P = duct perimeter (inches)

L = length of duct run (ft)

V = air velocity in duct $\left(\frac{\text{ft}}{\text{min}}\right)$

C_p = specific heat of air $\left(\frac{\text{Btu}}{\text{lbm-°F}}\right)$

ρ = density of air, 0.075 $\frac{\text{lb}}{\text{ft}^3}$

A = area of duct (in^2)

0.2 = conversion factor for length, in time units

9.3.7 Air Distribution

9.3.7.1 Characteristic Room Length for Diffusers

Characteristic Room Length for Several Diffusers

Diffuser Type	Characteristic Length *L*
High sidewall grille	Distance to wall perpendicular to jet
Circular ceiling pattern diffuser	Distance to closest wall or intersecting air jet
Sill grille	Length of room in direction of jet flow
Ceiling slot diffuser	Distance to wall or midplane between outlets
Light troffer diffusers	Distance to midplane between outlets, plus distance from ceiling to top of occupied zone
Cross-flow pattern ceiling diffusers	Distance to wall or midplane between outlets

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 57, Room Air Distribution, Table 3.

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9.3.7.2 Air Diffusion Performance Index

Air Diffusion Performance Index (ADPI) Selection Guide

Terminal Device	Room Load $\frac{Btu}{h\text{-}ft^2}$	$\frac{T_{50}}{L}$ for Maximum ADPI	Maximum ADPI	For ADPI Greater Than	Range of $\frac{T_{50}}{L}$
High sidewall grilles	80	1.8	68	—	—
	60	1.8	72	70	1.5 to 2.2
	40	1.6	78	70	1.2 to 2.3
	20	1.5	85	80	1 to 1.9
Circular ceiling diffusers	80	0.8	76	70	0.7 to 1.3
	60	0.8	83	80	0.7 to 1.2
	40	0.8	88	80	0.5 to 1.5
	20	0.8	93	90	0.7 to 1.3
Sill grille, straight vanes	80	1.7	61	60	1.5 to 1.7
	60	1.7	72	70	1.4 to 1.7
	40	1.3	86	80	1.2 to 1.8
	20	0.9	95	90	0.8 to 1.3
Sill grille, spread vanes	80	0.7	94	90	0.6 to 1.5
	60	0.7	94	80	0.6 to 1.7
	40	0.7	94	—	—
	20	0.7	94	—	—
Ceiling slot diffusers for $\frac{T_{100}}{L}$	80	0.3	85	80	0.3 to 0.7
	60	0.3	88	80	0.3 to 0.8
	40	0.3	91	80	0.3 to 1.1
	20	0.3	92	80	0.3 to 1.5
Light troffer diffusers	60	2.5	86	80	<3.8
	40	1.0	92	90	<3.0
	20	1.0	95	90	<4.5
Perforated, louvered ceiling diffusers	11 to 50	2.0	96	90	1.4 to 2.7
				80	1.0 to 3.4

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 57, Room Air Distribution, Table 4.

9.3.7.3 Recommended Return Inlet Face Velocity

Recommended Return Inlet Face Velocity

Inlet Location	Velocity Across Gross Area, fpm
Above occupied zone	>800
In occupied zone, not near seats	600 to 800
In occupied zone, near seats	400 to 600
Door or wall louvers	200 to 300
Through undercut areas of doors	200 to 300

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 57, Room Air Distribution, Table 1.

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9.3.7.4 Air Intake Minimum Separation Distances

Air Intake Minimum Separation Distance, Based on ANSI/ASHRAE Standard 62.1-2007

Object	Minimum Distance, ft (m)
Significantly contaminated exhaust (Note 1)	15 (5)
Noxious or dangerous exhaust (Notes 2 and 3)	30 (10)
Vents, chimneys, and flues from combustion appliances and equipment (Note 4)	15 (5)
Garage entry, automobile loading area, or drive-in queue (Note 5)	15 (5)
Truck loading area or dock, bus parking/idling area (Note 5)	25 (7.5)
Driveway, street, or parking place (Note 5)	5 (1.5)
Thoroughfare with high traffic volume	25 (7.5)
Roof, landscaped grade, or other surface directly below intake (Notes 6 and 7)	1 (.3)
Garbage storage/pick-up area, dumpsters	15 (5)
Cooling tower intake or basin	15 (5)
Cooling tower exhaust	25 (7.5)

1. Significantly contaminated exhaust is exhaust air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.
2. Laboratory fumehood exhaust air outlets shall be in compliance with NFPA 45-1991 and ANSI/AIHA Z9.5-1992.
3. Noxious or dangerous exhaust is exhaust air with highly objectionable fumes or gases and/or exhaust air with potentially dangerous particles, bioaerosols,or gases at concentrations high enough to be considered harmful.
4. Shorter separation distances are permitted when determined in accordance with (a) Chapter 7 of ANSI Z223/NFPA 54-2002 for fuel gas burning appliances and equipment, (b) Chapter 6 of NFPA 31-2001 for oil burning appliancesand equipment, or (c) Chapter 7 of NFPA 211-2003 for other combustion appliances and equipment.
5. Distance measured to closest place that vehicle exhaust is likely to be located.
6. No minimum separation distance applies to surfaces that are sloped more than 45 degrees from horizontal or that are less than 1 inch (3 cm) wide.
7. Where snow accumulation is expected, distance listed shall be increased by the expected average snow depth.

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9.3.7.5 Minimum Ventilation Rates

Minimum Ventilation Rates in the Breathing Zone, Based on ANSI/ASHRAE Standard 62.1-2022

Occupancy Category	People Outdoor Air Rate, R_p cfm/person	Area Outdoor Air Rate, R_a cfm/ft^2	Default Values #/1,000 ft^2	Air Class
Educational Facilities				
Art classroom	10	0.18	20	2
Daycare (through age 4)	10	0.18	25	2
Classrooms (ages 5–8)	10	0.12	25	1
Classrooms (ages 9 plus)	10	0.12	35	1
Lecture classroom	7.5	0.06	65	1
Multi-use assembly	7.5	0.06	100	1
Science laboratories	10	0.18	25	2
University/college laboratories	10	0.18	25	2
Wood/metal shop	10	0.18	20	2
Office Buildings				
Main entry lobbies	5	0.06	10	1
Office space	5	0.06	5	1
Reception areas	5	0.06	30	1
Miscellaneous Spaces				
Shipping/receiving	10	0.12	0.6	1
Warehouses	10	0.06	0.3	2
Public Assembly Spaces				
Auditorium seating area	5	0.06	150	1
Libraries	5	0.12	10	1
Museums (children's)	7.5	0.12	40	1
Museums/galleries	7.5	0.06	40	1
Retail				
Sales (except as below)	7.5	0.12	15	2
Beauty and nail salons	20	0.12	25	2
Mall common areas	7.5	0.06	40	1
Sports and Entertainment				
Spectator areas	7.5	0.06	150	1
Health club/aerobics room	20	0.06	40	2
Gambling casinos	7.5	0.18	120	1

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9.3.7.6 Healthcare Ventilation Requirements

Ventilation Requirements for Areas Affecting Patient Care in Hospitals and Outpatient Facilities

Function Space	Pressure Relationship to Adjacent Areas	Minimum Air Changes of Outside Air per Hour	Minimum Total Air Changes per Hour	All Air Exhausted Directly to Outside	Air Recirculated Within Room Units	Relative Humidity, %	Design Temperature, °F
Surgery and Critical Care							
Operating room (class B and positive C surgical)	Positive	4	20	—	No	30 to 60	62 to 80
Operating/surgical cystoscopic rooms	Positive	4	20	—	No	30 to 60	68 to 73
Delivery room	Positive	4	20	—	No	30 to 60	68 to 73
Recovery room	—	2	6	—	No	30 to 60	75 ± 2
Critical or intensive care (burn or intermediate)	Positive	2	6	—	No	30 to 60	70 to 75
Treatment room	—	2	6	—	—	30 to 60	70 to 75
Trauma room	Positive	5	12	—	No	30 to 60	70 to 75
Emergency waiting rooms	Negative	2	12	Yes	—	30 to 60	70 to 75
Triage areas	Negative	2	12	Yes	—	—	70 to 75
Procedure room (class A surgical)	Positive	3	15	—	No	30 to 60	70 to 75
Nursing							
Patient room	—	2	6	—	—	30 (W), 50 (S)	70 to 75
Toilet room	Negative	Optional	10	Yes	No	—	—
Airborne infection isolation room	Negative	—	12	Yes	No	30 to 60	70 to 75
Isolation alcove or anteroom	Pos./Neg.	2	10	Yes	No	—	—
Public corridor	Negative	2	2	—	—	—	—
Patient corridor	—	2	4	—	—	—	—
Ancillary							
Radiology (diagnostic and treatment)	—	2	6	—	—	40 (W), 50 (S)	78 to 80
Laboratory, general	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, nuclear medicine	Negative	2	6	Yes	No	30 to 60	70 to 75
Laboratory, pathology	Negative	2	6	Yes	No	30 to 60	70 to 75
Autopsy room	Negative	2	12	Yes	No	—	—
Nonrefrigerated body-holding room	Negative	Optional	10	Yes	No	—	70 to 75
Pharmacy	Positive	2	4	—	—	30 to 60	70 to 75
Diagnostic and Treatment							
Examination room	—	2	6	—	—	30 to 60	70 to 75
Medication room	Positive	2	4	—	—	30 to 60	70 to 75
Treatment room	—	2	6	—	—	30 (W), 50 (S)	75 ± 2
Physical therapy and hydrotherapy	Negative	2	6	—	—	30 to 60	72 to 78 up to 80
Soiled workroom or soiled holding	Negative	2	10	Yes	No	30 to 60	72 to 78
Clean workroom or clean holding	Positive	2	4	—	—	—	—
Sterilizing and Supply							
ETO-sterilizer room	Negative	—	10	Yes	No	30 to 60	72 to 78
Sterilizer equipment room	Negative	—	10	Yes	No	30 to 60	74 ± 2
Central medical and surgical supply							
Soiled or decontamination room	Negative	2	6	Yes	No	30 to 60	72 to 78
Clean workroom	Positive	2	4	—	No	30 to 60	72 to 78
Sterile storage	Positive	2	4	—	—	Under 50	74 ± 2

Source: ©ASHRAE, www.ashrae.org., *2007 ASHRAE Handbook—HVAC Applications*, Chapter 7, Health Care Facilities, Table 3.

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9.3.7.7 Zone Air Distribution Effectiveness

Air Distribution Configuration	E_z
Ceiling supply of cool air	1.0
Ceiling supply of warm air and floor return	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above space temperature and ceiling return provided that the 150 fpm (0.8 m/s) supply air jet reaches to within 4.5 ft (1.4 m) of floor level (See Note 6)	1.0
Floor supply of cool air and ceiling return, provided that the vertical throw is greater than 50 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) or more above the floor	1.0
Floor supply of cool air and ceiling return, provided low-velocity displacement ventilation achieves unidirectional flow and thermal stratification, or underfloor air distribution systems where the vertical throw is less than or equal to 50 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor	1.2
Floor supply of warm air and floor return	1.0
Floor supply of warm air and ceiling return	0.7
Makeup supply drawn in on the opposite side of the room from the exhaust, return, or both.	0.8
Makeup supply drawn in near to the exhaust, return, or both locations.	0.5

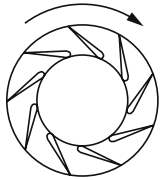
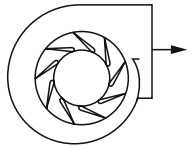
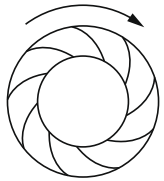
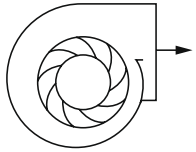
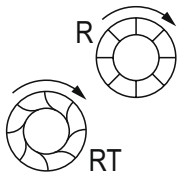
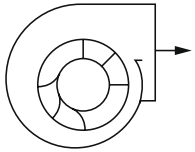
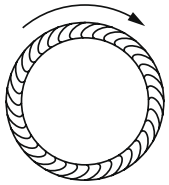
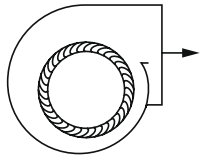
Notes:
1. "Cool air" is air cooler than space temperature.
2. "Warm air" is air warmer than space temperature.
3. "Ceiling supply" includes any point above the breathing zone.
4. "Floor supply" includes any point below the breathing zone.
5. As an alternative to using the above values, E_z may be regarded as equal to air-change effectiveness determined in accordance with ASHRAE Standard 129[16] for air distribution configurations except unidirectional flow.
6. For lower velocity supply air, $E_z = 0.8$.

Source: ©ASHRAE, www.ashrae.org., *ANSI/ASHRAE Standard 62.1-2016*, *Ventilation for Acceptable Indoor Air Quality*, Table 6.2.2.2.

9.3.8 Fans

9.3.8.1 Types of Fans

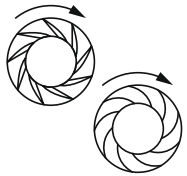
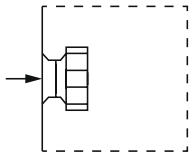
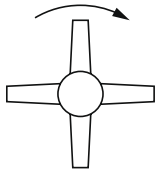
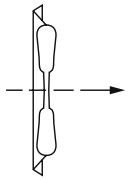
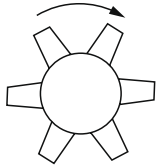
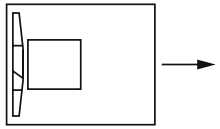
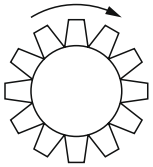
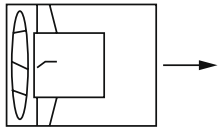
Types of Fans

	Type	Impeller Design		Housing Design	
Centrifugal Fans	**Airfoil**		Blades of airfoil contour curved away from direction of rotation. Deep blades allow efficient expansion within passages. Air leaves impeller at velocity less than tip speed. For a given duty, has highest speed of centrifugal fan designs.		Scroll design for efficient conversion of velocity pressure to static pressure Maximum efficiency requires close clearance and alignment between wheel and inlet
	Backward-Inclined Backward-Curved		Single-thickness blades curved or inclined away from direction of rotation Efficient for same reasons as airfoil fan		Uses same housing configuration as airfoil design
	Radial (R), Radial Tip (Rt)		Higher pressure characteristics than airfoil, backward-curved, or backward-inclined fans Curve may have a break to left of peak pressure		Scroll similar to and often identical to other centrifugal fan designs Fit between wheel and inlet is not as critical as for airfoil and backward-inclined fans
	Forward-curved		Flatter pressure curve and lower peak efficiency than the airfoil, backward-curved, or backward-inclined		Scroll similar to and often identical to other centrifugal fan designs Fit between wheel and inlet is not as critical as for airfoil and backward-inclined fans

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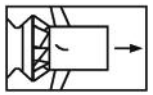
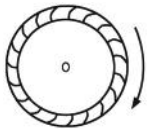
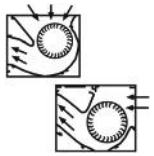
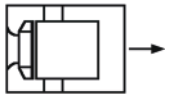
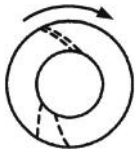
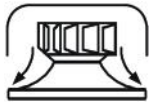
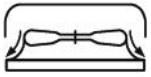
Types of Fans (cont'd)

	Type	Impeller Design		Housing Design	
Centrifugal Fans	Plenum/ Plug		Plenum and plug fans typically use airfoil, backward inclined, or backward curved impellers in a single inlet configuration Relative benefits of each impeller are the same as those for scroll-housed fans		Plenum and plug fans are unique in that they operate with no housing. The equivalent of a housing, or plenum chamber (dashed line), depends on the application. The components of the drive system for the plug fan are located outside the airstream.
Axial Fans	Propeller		Low efficiency Limited to low-pressure applications Usually low-cost impellers have two or more blades of a single thickness attached to a relatively small hub Primary energy transfer by velocity pressure		Simple circular ring, orifice plate, or venturi Optimum design is close to blade tips and forms smooth airfoil into wheel
	Tube axial		Somewhat more efficient and capable of developing more useful static pressure than propeller fan Usually has 4 to 8 blades with airfoil or single-thickness cross section Hub is usually less than half the fan-tip diameter		Cylindrical tube with close clearance to blade tips
	Vane axial		Good blade design gives medium- to high-pressure capability at good efficiency The most efficient have airfoil blades Blades may have fixed, adjustable, or controllable pitch Hub is usually greater than half the fan-tip diameter		Cylindrical tube with close clearance to blade tips The guide vanes upstream or downstream from impeller increase pressure capability and efficiency.

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Types of Fans (cont'd)

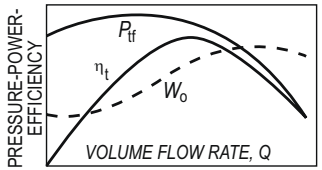
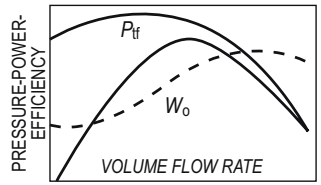
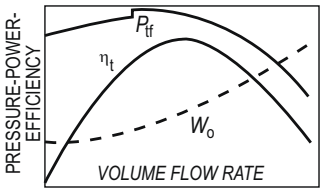
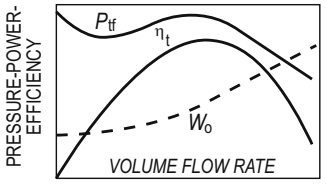
	Type		Impeller Design		Housing Design	
Mixed-Flow	Mixed-Flow			Combination of axial and centrifugal characteristics. Ideally suited in applications in which the air has to flow in or out axially. Higher pressure characteristic than axial fans.		The majority of mixed-flow fans are in a tubular housing and include outlet turning vanes. Can operate without housing or in a pipe and duct.
Cross-flow	Cross-flow (Tangential)			Impeller with forward-curved blades. During rotation the flow of air passes through part of the rotor blades into the rotor. This creates an area of turbulence which, working with the guide system, deflects the airflow through another section of the rotor into the discharge duct of the fan casing. Lowest efficiency of any type of fan.		Special designed housing for 90° or straight through airflow.
Other Designs	Tubular Centrifugal			Performance similar to backward-curved fan except capacity and pressure are lower. Lower efficiency than backward-curved fan. Performance curve may have a dip to the left of peak pressure.		Cylindrical tube similar to vane axial fan, except clearance to wheel is not as close. Air discharges radially from wheel and turns 90° to flow through guide vanes.
	Power Roof Ventilators	Centrifugal		Low-pressure exhaust systems such as general factory, kitchen, warehouse, and some commercial installations. Provides positive exhaust ventilation, which is an advantage over gravity-type exhaust units. Centrifugal units are slightly quieter than axial units.		Normal housing not used, because air discharges from impeller in full circle. Usually does not include configuration to recover velocity pressure component.
		Axial		Low-pressure exhaust systems such as general factory, kitchen, warehouse, and some commercial installations. Provides positive exhaust ventilation, which is an advantage over gravity-type exhaust units. Hood protects fan from weather and acts as safety guard.		Essentially a propeller fan mounted in a supporting structure. Air discharges from annular space at bottom of weather hood.

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9.3.8.2 Performance of Fans

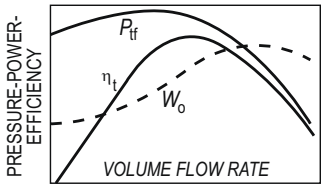
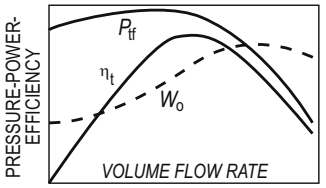
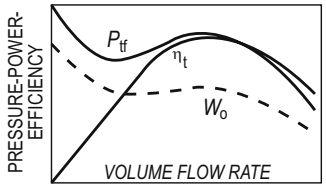
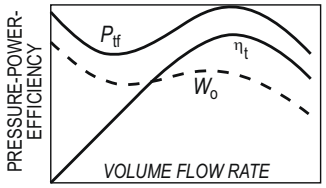
Fan Performance

	Type	Performance Curves*	Performance Characteristics	Applications
Centrifugal Fans	**Airfoil**		Highest efficiency of all centrifugal fan designs: peak efficiencies occur at 50% to 60% wide-open volume Fan has a non-overloading characteristic, which means power reaches maximum near peak efficiency and becomes lower, or self-limiting, toward free delivery	General heating, ventilating, and air-conditioning applications Usually only applied to large systems, which may be low-, medium-, or high-pressure applications Applied to large, clean-air industrial applications for significant energy savings
	Backward-Inclined, Backward-Curved		Similar to airfoil fan, except peak efficiency is slightly lower Curved blades are slightly more efficient than straight blades	Same heating, ventilating, and air-conditioning applications as airfoil fan Used in some industrial applications where environment may corrode or erode airfoil blade
	Radial (R) Radial Tip (Rt)		Higher pressure characteristics than airfoil or backward-curved fans Pressure may drop suddenly at left of peak pressure, but this is usually due to free delivery, which is an overloading characteristic Curved blades are slightly more efficient than straight blades	Primarily for materials handling in industrial plants Also for some high-pressure industrial requirements Rugged wheel is simple to repair in the field Wheel is sometimes coated with special material Not common for HVAC applications
	Forward-curved		Pressure curve less steep than that of backward-curved fans. Curve dips to the left of peak pressure. Highest efficiency occurs at 40% to 50% of wide-open volume. Operate fan to the right of peak pressure. Use caution when selecting left of peak pressure, because instability is possible Power rises continually to free delivery, which is an overloading characteristic	Primarily for low-pressure HVAC applications, such as residential furnaces, central station units, and packaged air conditioners

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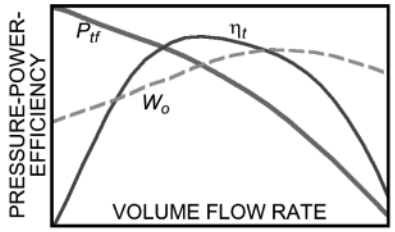
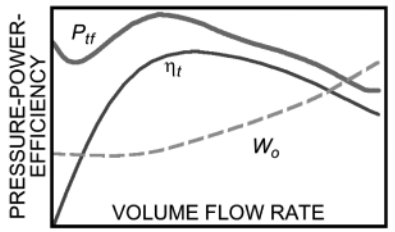
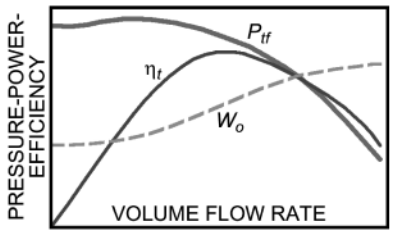
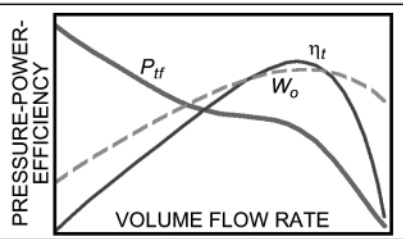
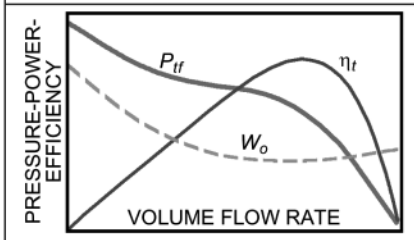
Fan Performance (cont'd)

	Type	Performance Curves*	Performance Characteristics	Applications
Centrifugal Fans	**Plenum/ Plug**		Plenum and plug fans are similar to comparable housed airfoil/backward-curved fans but are generally less efficient because of inefficient conversion of kinetic energy in discharge airstream They are more susceptible to performance degradation caused by poor installation	Plenum and plug fans are used in a variety of HVAC applications such as air handlers, especially where direct-drive arrangements are desirable. Other advantages of these fans are discharge configuration flexibility and potential for smaller footprint units.
Axial Fans	**Propeller**		High flow rate, but very low pressure capabilities Maximum efficiency reached near free delivery Discharge pattern circular and airstream rotates or swirls	For low-pressure, high-volume air-moving applications, such as air circulation in a space or ventilation through a wall without duct work Used for make-up air applications
	Tube axial		High flow rate, medium pressure capabilities Pressure curve dips to left of peak pressure Avoid operating fan in this region Discharge pattern circular and airstream rotates or swirls	Low- and medium-pressure ducted HVAC applications where air distribution downstream is not critical Used in some industrial applications, such as drying ovens, paint spray booths, and fume exhausts
	Vane axial		High-pressure characteristics with medium-volume flow capabilities Pressure curve dips left of peak pressure. Avoid operating fan in this region Guide vanes correct the circular motion imparted by impeller and improve pressure characteristics and efficiency of fan	For general HVAC systems in low-, medium-, and high-pressure applications where straight-through flow and compact installation are required Has good downstream air distribution Used in industrial applications in place of tube axial fans More compact than centrifugal fans for same duty

Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 21, Fans, Table 1.

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Fan Performance (cont'd)

	Performance Curves*	Performance Characteristics	Applications
MIXED FLOW		Characteristic pressure curve between axial fans and centrifugal fans. Higher pressure than axial fans and higher volume flow than centrifugal fans.	Similar HVAC applications to centrifugal fans or in applications where an axial fan cannot generate sufficient pressure rise.
CROSS FLOW		Similar to forward-curved fans. Power rises continually to free delivery, which is an overloading characteristic. Unlike all other fans, performance curves include motor characteristics. Lowest efficiency of any fan type.	Low-pressure HVAC systems such as fan heaters, fireplace inserts, electronic cooling, and air curtains.
TABLE AXIAL		Performance similar to backward-curved fan, except capacity and pressure are lower. Lower efficiency than backward-curved fan because air turns 90°. Performance curve of some designs is similar to axial flow fan and dips to left of peak pressure.	Primarily for low-pressure, return air systems in HVAC applications. Has straight-through flow.
OTHER DESIGNS		Usually operated without ductwork; therefore, operates at very low pressure and high volume.	Centrifugal units are somewhat quieter than axial flow units. Low-pressure exhaust systems, such as general factory, kitchen, warehouse, and some commercial installations. Low first cost and low operating cost give an advantage over gravity-flow exhaust systems.
		Usually operated without ductwork; therefore, operates at very low pressure and high volume.	Low-pressure exhaust systems, such as general factory, kitchen, warehouse, and some commercial installations. Low first cost and low operating cost give an advantage over gravity-flow exhaust systems.

*These performance curves reflect general characteristics of various fans as commonly applied. They are not intended to provide complete selection criteria, because other parameters, such as diameter and speed, are not defined.

Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 21, Fans, Table 1.

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9.3.8.3 Fan Affinity Laws

Fan Laws

Law No.	Dependent Variable	Independent Variable
1a	$Q_1 = Q_2 \times \left(\frac{D_1}{D_2}\right)^3 \left(\frac{N_1}{N_2}\right)$	
1b	$P_1 = P_2 \times \left(\frac{D_1}{D_2}\right)^2 \left(\frac{N_1}{N_2}\right)^2 \left(\frac{\rho_1}{\rho_2}\right)$	
1c	$W_1 = W_2 \times \left(\frac{D_1}{D_2}\right)^5 \left(\frac{N_1}{N_2}\right)^3 \left(\frac{\rho_1}{\rho_2}\right)$	
2a	$Q_1 = Q_2 \times \left(\frac{D_1}{D_2}\right)^2 \left(\frac{P_1}{P_2}\right)^{\frac{1}{2}} \left(\frac{\rho_2}{\rho_1}\right)^{\frac{1}{2}}$	
2b	$N_1 = N_2 \times \left(\frac{D_2}{D_1}\right) \left(\frac{P_1}{P_2}\right)^{\frac{1}{2}} \left(\frac{\rho_2}{\rho_1}\right)^{\frac{1}{2}}$	
2c	$W_1 = W_2 \times \left(\frac{D_1}{D_2}\right)^2 \left(\frac{P_1}{P_2}\right)^{\frac{3}{2}} \left(\frac{\rho_2}{\rho_1}\right)^{\frac{1}{2}}$	
3a	$N_1 = N_2 \times \left(\frac{D_2}{D_1}\right)^3 \left(\frac{Q_1}{Q_2}\right)$	
3b	$P_1 = P_2 \times \left(\frac{D_2}{D_1}\right)^4 \left(\frac{Q_1}{Q_2}\right)^2 \left(\frac{\rho_1}{\rho_2}\right)$	
3c	$W_1 = W_2 \times \left(\frac{D_2}{D_1}\right)^4 \left(\frac{Q_1}{Q_2}\right)^3 \left(\frac{\rho_1}{\rho_2}\right)$	

a. The subscript 1 denotes fan under consideration.
b. The subscript 2 denotes tested fan.
c. P equals P_{vf}, P_{tf}, or P_{sf}
d. Unless otherwise identified, fan performance data is based on dry standard air conditions,

14.696 psia and 70°F $\left(\frac{0.075 \text{ lbm}}{\text{ft}^3}\right)$

Variables: Fan size D (diameter of wheel)
Rotational speed N
Gas density ρ
Volume airflow rate Q
Pressure P_{vf}, P_{tf}, or P_{sf}
Power W

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9.3.8.4 Fan Power Requirements

Power required to provide airflow and static pressure at standard conditions:

$$HP_A = 0.000157\ Vp$$

where

HP_A = air power (hp)

V = flow rate (cfm)

p = total pressure (inches of water)

Power necessary at the fan motor input to account for fan inefficiencies is calculated by

$$P_F = \frac{HP_A}{\eta_F}$$

where

P_F = power required at fan shaft

η_F = fan efficiency (dimensionless)

Power necessary at the fan motor input to account for both fan motor inefficiencies and drive losses is calculated by

$$HP_M = \frac{(1 + DL)\,P_F}{E_M\,E_D}$$

where

HP_M = power required at input to motor (hp)

E_M = fan motor efficiency (dimensionless)

E_D = belt drive efficiency (dimensionless)

P_F = power required at fan shaft (hp)

DL = drive loss (dimensionless)

9.3.8.5 Temperature Rise Across Fans

$$\Delta T = \frac{\Delta P\,C_p}{\rho c_p J \eta}$$

where

ΔT = temperature rise across fan (°F)

ΔP = pressure rise across fan (inches of water)

C_p = conversion factor = $5.193\ \frac{\text{lbf}}{\text{ft}^2\text{-inches of water}}$

ρ = density $\left(\frac{1\text{bm}}{\text{ft}^3}\right)$

c_p = specific heat = $0.24\ \frac{\text{Btu}}{\text{lbm-°F}}$

J = mechanical equivalent of heat = $778.2\ \frac{\text{ft-lbf}}{\text{Btu}}$

η = efficiency, in decimal

If the motor is not in the airstream, the efficiency is the fan total efficiency. If the motor is in the airstream, the efficiency is the combined efficiency of the motor and fan.

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9.3.9 Cooling Towers and Fluid Coolers

9.3.9.1 Cooling Ponds

Cooling ponds are used to dissipate heat. Heat rejection can be estimated as:

$$w_p = \frac{A(95 + 0.425v)}{h_{fg}}(p_w - p_a)$$

where

w_p = evaporation rate of water $\left(\frac{\text{lb}}{\text{hr}}\right)$

A = area of pool surface (ft^2)

v = air velocity over water surface (fpm)

h_{fg} = latent heat required to change water to vapor at temperature of surface water $\left(\frac{\text{Btu}}{\text{lb}}\right)$

p_w = saturation vapor pressure at temperature of surface water (inches of Hg)

p_a = saturation vapor pressure at dew point temperature of ambient air (inches of Hg)

9.3.9.2 Evaporative Cooling Tower Makeup Water

Range: The difference between the entering hot water temperature and leaving cold water temperature of the cooling tower

Approach: The difference between the leaving condenser water temperature and the ambient air wet-bulb temperature

Cooling tower ton: Industry term using 15,000 Btu/hr per ton accounting for the chiller cooling heat rejection and the heat of compression at a 0.88-kW/T chiller efficiency

The cooling tower makeup water requirements, excluding drift (windage) losses and blowdown (draw-off), can be calculated as:

$$\dot{W}_{lb/hr} = \frac{\dot{Q}}{h_{fg}} = \frac{500 \text{ gpm}(T_{ent} - T_{lvg})}{h_{fg}}$$

where

500 is derived from $\rho_w C_p$ and has units of $\frac{\text{Btu - min}}{^\circ\text{F - hr - gal}}$

$\dot{Q}$ = total heat rejection rate of cooling tower (Btu/hr)

h_{fg} = average latent heat of evaporation of condenser water (Btu/lb)

$\dot{W}_{lb/hr}$ = makeup in lb of water evaporated per hour

gpm = total cooling tower condenser water flow

T_{ent} = hot water entering condition (°F)

T_{lvg} = cold water leaving condition (°F)

Blowdown can be between 0–100% of the water makeup rate.

The cooling tower makeup in gpm can be calculated from:

$$\dot{W}_{gpm} = \frac{\dot{W}_{lb/hr}}{8.34 \text{ lb/gal} \times 60 \text{ min/hr}}$$

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Typically, drift (windage) losses are negligible (about 0.001% or less of total flow) and blowdown (draw-off) is dependent on the cycles of concentration.

$$\text{blowdown} = \frac{\dot{W}}{(\text{cycles of concentration} - 1)}$$

9.3.10 Humidifiers

The humidification load H can be calculated from the equations below.

For ventilation systems with natural infiltration:

$$H = \rho VR(W_i - W_o) - S + L$$

For mechanical ventilation systems having a fixed quantity of outdoor air:

$$H = 60\rho Q_o(W_i - W_o) - S + L$$

For mechanical systems having a variable quantity of outdoor air:

$$H = 60\rho Q_t(W_i - W_o)\left[\frac{(t_i - t_m)}{(t_i - t_o)}\right] - S + L$$

where

H = humidification load $\left(\frac{\text{lb of water}}{\text{hr}}\right)$

V = volume of space to be humidified (ft^3)

R = infiltration rate, in air changes per hour

Q_o = volumetric flow rate of outdoor air (cfm)

Q_i = total volumetric flow rate of air (outside air plus return air) (cfm)

t_i = design indoor air temperature (°F)

t_m = design mixed air temperature (°F)

t_o = design outdoor air temperature (°F)

W_i = humidity ratio at indoor design conditions $\left(\frac{\text{lb of water}}{\text{lb of dry air}}\right)$

W_o = humidity ratio at outdoor design conditions $\left(\frac{\text{lb of water}}{\text{lb of dry air}}\right)$

S = contribution of internal moisture sources $\left(\frac{\text{lb of water}}{\text{hr}}\right)$

L = other moisture losses $\left(\frac{\text{lb of water}}{\text{hr}}\right)$

ρ = density of air at sea level, $0.074\frac{\text{lb}}{\text{ft}^3}$

Source: ©ASHRAE, www.ashrae.org., *2012 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 22, Humidifiers, p. 22.4.

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9.3.11 Evaporative Air-Cooling Equipment

9.3.11.1 Direct Evaporative Air Coolers

Direct saturation efficiency ε_e is the extent to which the air temperature leaving a direct evaporative cooler approaches the wet-bulb temperature of the air entering the cooler.

$$\varepsilon_e = 100\frac{(t_1 - t_2)}{(t_1 - t'_s)}$$

where

ε_e = direct evaporative cooling saturation efficiency (%)

t_1 = dry bulb temperature of air entering (°F)

t_2 = dry bulb temperature of air leaving (°F)

t'_s = thermodynamic wet-bulb temperature of air entering (°F)

Cooling tower approach: the difference between the cooling tower leaving water temperature and the entering air wet-bulb temperature.

9.3.11.2 Evaporative Dehumidifiers

An evaporative dehumidifier has a performance factor of 1.0 if it can cool and dehumidify the air entering to a wet-bulb temperature equal to the temperature of the water leaving. The performance factor F_p of any evaporative dehumidifier is calculated by dividing the actual air enthalpy change by the maximum air enthalpy change.

$$F_p = \frac{h_1 - h_2}{h_1 - h_3}$$

where

h_1 = enthalpy at wet-bulb temperature of air entering $\left(\frac{\text{Btu}}{\text{lb}}\right)$

h_2 = enthalpy at wet-bulb temperature of air leaving at actual condition $\left(\frac{\text{Btu}}{\text{lb}}\right)$

h_3 = enthalpy at wet-bulb temperature of air leaving a dehumidifier with $F_p = 1.0$ $\frac{\text{Btu}}{\text{lb}}$

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9.3.12 Filtration

ASHRAE Standard 52.2-2017 Minimum Efficiency Reporting Value (MERV) Filter Ratings

ASHRAE Standard 52.2 MERV	Approx. ASHRAE Std 52.1 (1) Dust-Spot Efficiency	Approx. ASHRAE Std 52.1 (1) Average Arrestance, %	Composite Average Particle Size Efficiency (PSE), % Group E_1: 0.3 to 1 µm	Group E_2: 1 to 3 µm	Group E_3: 3 to 10 µm	Min. final resistance (in. WG)	Typical controlled contaminant	Typical Application	Typical Filter type
> 10µm Particle Size									
1	<20%	A_{avg}<65	N/A	N/A	E_3<20%	0.3	Textile fibers, carpet fibers	Minimum filtration	Throwaway
2	<20%	65≤A_{avg}	N/A	N/A	E_3<20%	0.3	Sanding dust, spray paint dust	Residential	Washable
3	<20%	70≤A_{avg}	N/A	N/A	E_3<20%	0.3	Spanish moss, dust mites	Window air conditioners	Electrostatic
4	<20%	75≤A_{avg}	N/A	N/A	E_3<20%	0.3	Pollen		Inertial separators
3.0 to 10.0 µm Particle Size									
5	<20%	N/A	N/A	N/A	20≤E_3	0.6	Cement dust, pudding mix, snuff, powdered milk	Commercial buildings	Pleated filters Cartridge filters Throwaway
6	<20%	N/A	N/A	N/A	35≤E_3	0.6	Fabric protector, dusting aids	Better residential	
7	25 to 30%	N/A	N/A	N/A	50≤E_3	0.6	Spores, hair spray	Industrial workplaces	
8	30 to 35%	N/A	N/A	20≤E_2	70≤E_3	0.6	Mold	Paint booth inlet air	
1.0 to 3.0 µm Particle Size									
9	40 to 45%	N/A	N/A	35≤E_2	75≤E_3	1	Nebulizer drops, welding fumes	Superior residential	Box filters Bag filters
10	50 to 55%	N/A	N/A	50≤E_2	80≤E_3	1	Coal dust, milled flour	Better commercial	
11	60 to 65%	N/A	20≤E_1	65≤E_2	85≤E_3	1	Humidifier dust, lead dust	buildings	
12	70 to 75%	N/A	35≤E_1	80≤E_2	90≤E_3	1	Legionella	Hospital laboratories	
0.30 to 1.0 µm Particle Size									
13	80 to 90%	N/A	50≤E_1	85≤E_2	90≤E_3	1.4	Insecticide dust, Copier toner, most face powder, most paint pigment	Hospital inpatient care	Box filters Bag filters
14	90 to 95%	N/A	75≤E_1	90≤E_2	95≤E_3	1.4	Cooking oil, most smoke	General surgery	
15	>95%	N/A	85≤E_1	90≤E_2	95≤E_3	1.4	Droplet nuclei (sneezing), most tobacco smoke	Superior commercial buildings	
16	N/A	N/A	95≤E_1	95≤E_2	95≤E_3	1.4	All bacteria	Smoking lounges	

ASHRAE Standard 52.2 testing does not apply to MERV 17 to 20, which are HEPA/ULPA filters. Refer to ISO or IEST classification system for these products.
(1) ANSI/ASHRAE 52.1 Standard discontinued January 2009 and is shown for reference only.

Note: Minimum final resistance typically twice the initial resistance.

Source: ©ASHRAE, www.ashrae.org., *ASHRAE Standard 52.2-2017—Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size.*

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9.4 Heat Losses from Pipes

9.4.1 Heat Loss from Bare Steel Pipe

Heat Loss from Bare Steel Pipe in Still Air at 80°F, $\frac{\text{Btu}}{\text{hr-ft}}$

Nominal Pipe Size, inches	Pipe Inside Temperature, °F				
	180	280	380	480	580
0.5	56.3	138	243	377	545
0.75	68.1	167	296	459	665
1	82.5	203	360	560	813
1.25	102	251	446	695	1,010
1.5	115	283	504	787	1,150
2	141	350	623	974	1,420
2.5	168	416	743	1,160	1,700
3	201	499	891	1,400	2,040
4	254	631	1,130	1,770	2,590
5	313	777	1,390	2,180	3,190
6	368	915	1,640	2,580	3,770
8	473	1,180	2,110	3,320	4,860
10	583	1,450	2,610	4,100	6,000
12	686	1,710	3,070	4,830	7,090

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 23, Insulation for Mechanical Systems, Table 17.

9.4.2 Heat Loss from Bare Copper Tubing

Heat Loss from Bare Copper Tubing in Still Air at 80°F, in $\frac{\text{Btu}}{\text{hr-ft}}$

Nominal Tube Size, inches	Pipe Inside Temperature, °F				
	120	150	180	210	240
0.5	12.7	24.7	38.2	53.1	69.2
0.75	16.7	32.7	50.7	70.4	91.9
1	20.7	40.5	62.9	87.5	114
1.25	24.6	48.3	74.9	104	136
1.5	28.5	55.9	86.9	121	158
2	36.1	71	110	154	201
2.5	43.7	86	134	187	244
3	51.2	101	157	219	287

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 23, Insulation for Mechanical Systems, Table 18.

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9.4.3 Heat Loss from Piping

Approximate Heat Loss from Piping at 140°F Inlet, 70°F Ambient

Nominal Tube Size, inches	Bare Copper Tubing, $\frac{\text{Btu}}{\text{hr-ft}}$	Bare Copper Tubing UA $\frac{\text{Btu}}{\text{hr-ft-°F}}$	0.5 in. Glass Fiber Insulated Copper Tubing $\frac{\text{Btu}}{\text{hr-ft}}$	0.5 in. Glass Fiber Insulated Copper Tubing UA $\frac{\text{Btu}}{\text{hr-ft-°F}}$
0.75	30	0.43	17.7	0.25
1	38	0.54	20.3	0.29
1.25	45	0.64	23.4	0.33
1.5	53	0.76	25.4	0.36
2	66	0.94	29.6	0.42
2.5	80	1.14	33.8	0.48
3	94	1.34	39.5	0.56
4	120	1.71	48.4	0.69

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 50, Service Water Heating, Table 2.

9.4.4 Time Needed to Freeze Water

Time Needed to Freeze Water, in Hours

Nominal Pipe Size, NPS	Insulation Thickness, in Inches					
	0.5	1	1.5	2	3	4
$\frac{1}{2}$	0.1	0.2	0.2	0.3	—	—
1	0.3	0.4	0.5	0.6	0.8	—
$1\frac{1}{2}$	0.4	0.8	1.0	1.3	1.5	—
2	0.6	1.1	1.4	1.7	2.2	2.5
3	0.9	1.7	2.3	2.9	3.7	4.5
4	1.3	2.4	3.3	4.1	5.5	6.6
5	1.6	3.0	4.3	5.4	7.4	9.1
6	1.9	3.7	5.3	6.9	9.4	11.7
8	—	5.3	7.6	9.6	13.7	16.9
10	—	6.5	10.2	12.9	17.9	22.3
12	—	8.8	12.5	15.8	22.1	27.7

Note: Assumes initial temperature = 42°F, ambient air temperature = –18°F, and insulation thermal conductivity $= 0.30 \frac{\text{Btu-in}}{\text{hr-ft}^2\text{-°F}}$. Thermal resistance of pipe and air film are neglected.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 23, Insulation for Mechanical Systems, Table 6.

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9.4.5 Domestic Hot-Water Recirculation Loops and Return Piping

The required recirculation flow in a domestic hot-water piping system for a given temperature drop can be calculated:

$$Q_p = \frac{q}{500\Delta t}$$

where

Q_p = recirculation pump capacity (gpm)

q = piping heat loss $\left(\frac{\text{Btu}}{\text{hr}}\right)$

Δt = allowable temperature drop (°F)

9.5 Pipe Expansion and Contraction

9.5.1 Thermal Expansion of Metal Pipe

Thermal Expansion of Metal Pipe

Saturated Steam Pressure, psig		Temperature, °F	Linear Thermal Expansion, $\frac{\text{in.}}{\text{100 ft}}$		
			Carbon Steel	Type 304 Stainless Steel	Copper
Vacuum		–30	–0.19	–0.30	–0.32
		–20	–0.12	–0.20	–0.21
		–10	–0.06	–0.10	–0.11
		0	0	0	0
		10	0.08	0.11	0.12
		20	0.15	0.22	0.24
	–14.6	32	0.24	0.36	0.37
	–14.6	40	0.3	0.45	0.45
	–14.5	50	0.38	0.56	0.57
	–14.4	60	0.46	0.67	0.68
	–14.3	70	0.53	0.78	0.79
	–14.2	80	0.61	0.9	0.9
	–14.0	90	0.68	1.01	1.02
	–13.7	100	0.76	1.12	1.13
	–13.0	120	0.91	1.35	1.37
	–11.8	140	1.06	1.57	1.59
	–10.0	160	1.22	1.79	1.8
	–7.2	180	1.37	2.02	2.05
	–3.2	200	1.52	2.24	2.3
	0	212	1.62	2.38	2.43
	2.5	220	1.69	2.48	2.52
	10.3	240	1.85	2.71	2.76
	20.7	260	2.02	2.94	2.99
	34.6	280	2.18	3.17	3.22
	52.3	300	2.35	3.4	3.46
	75.0	320	2.53	3.64	3.7
	103.3	340	2.7	3.88	3.94

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Thermal Expansion of Metal Pipe (cont'd)

Saturated Steam Pressure, psig	Temperature, °F	Linear Thermal Expansion, $\frac{\text{in.}}{100\text{ ft}}$		
		Carbon Steel	Type 304 Stainless Steel	Copper
138.3	360	2.88	4.11	4.18
181.1	380	3.05	4.35	4.42
232.6	400	3.23	4.59	4.87
666.1	500	4.15	5.8	5.91
1,528	600	5.13	7.03	7.18
3,079	700	6.16	8.29	8.47
	800	7.23	9.59	9.79
	900	8.34	10.91	11.16
	1,000	9.42	12.27	12.54

Source: ©ASHRAE, www.ashrae.org., *2012 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 46, Pipes, Tubes, and Fittings, Table 10.

9.5.2 L-Bends

For continuous (butt) welded, seamless, and ERW pipe, and B88 drawn copper tubing, the length of the leg of an L-bend is calculated from

$$L = 6.225\sqrt{\Delta D}$$

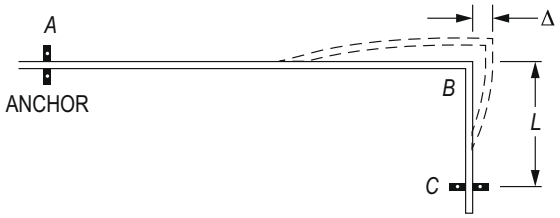
where

L = length of leg BC required to accommodate thermal expansion of long leg AB (ft)

Δ = thermal expansion or contraction of leg AB (inches)

D = actual pipe outside diameter (inches)

Guided Cantilever Beam



$$F = \frac{12E_c I\Delta}{\left(1{,}728\text{ in}^3/\text{ft}^3\right)L^3}$$

where

F = force (lb)

E_c = modulus of elasticity (psi)

I = moment of inertia (in^4)

L = length of offset leg (ft)

Δ = deflection of offset leg (in.)

Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 46, Pipes, Tubes, and Fittings, Fig. 1.

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9.5.3 Z-Bends

For A53 continuous (butt) welded, seamless, and ERW pipe, and B88 drawn copper tubing, the length of the leg of a Z-bend is calculated from

$$L = 4\sqrt{\Delta D}$$

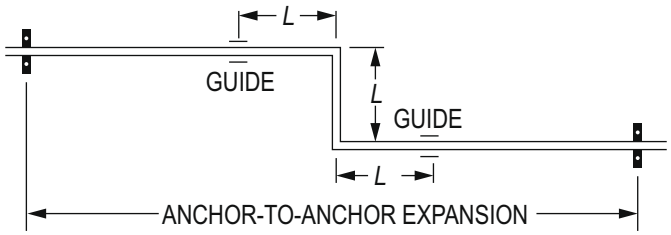
where

L = length of offset leg (ft)

Δ = anchor-to-anchor expansion (inches)

D = actual pipe outside diameter (inches)

Z-Bend in Pipe



The force developed in the Z-bend can be calculated from:

$$F = C_1\Delta(D/L)^2$$

where

C_1 = 4,000 lb/in.

F = force (lb)

D = pipe outside diameter (in.)

L = length of offset leg (ft)

Δ = anchor to anchor expansion (in.)

Distance from guide to offsets, if used, should equal or exceed length of offset.

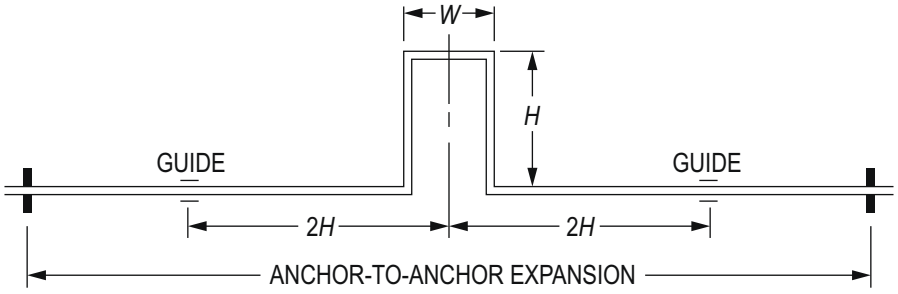
Offset piping must be support with hangers, slide plates, and spring hangers similar to those for L-bends.

Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 46, Pipes, Tubes, and Fittings, Fig. 2.

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9.5.4 U-Bends and Pipe Loops

Pipe Loop Design for A53 Grade B Carbon Steel Pipe Through 400°F



Anchor-to-Anchor Expansion, in Inches

Pipe Size, in	2		4		6		8		10		12	
	W	*H*	*W*	*H*	*W*	*H*	*W*	*H*	*W*	*H*	*W*	*H*
1	2	4	3	6	3.5	7	4	8	4.5	9	5	10
2	3	6	4	8	5	10	5.5	11	6	12	7	14
3	3.5	7	5	10	6	12	6.5	13	7.5	15	8	16
4	4	8	5.5	11	6.5	13	7.5	15	8.5	17	9	18
6	5	10	6.5	13	8	16	9	18	10	20	11	22
8	5.5	11	7.5	15	9	18	10.5	21	12	24	13	26
10	6	12	8.5	17	10	20	11.5	23	13	26	14	28
12	6.5	13	9	18	11	22	12.5	25	14	28	15.5	31
14	7	14	9.5	19	11.5	23	13	26	15	30	16	32
16	7.5	15	10	20	12.5	25	14	28	16	32	17.5	35
18	8	16	11	22	13	26	15	30	17	34	18.5	37
20	8.5	17	11.5	23	14	28	16	32	18	36	19.5	39
24	9	18	12.5	25	14.5	29	17.5	35	19.5	39	21	42

W and *H* dimensions are in feet.
L is the necessary length to accommodate the anchor-to-anchor expansion.

$$W = \frac{L}{5} \quad H = 2W \quad 2H + W = L$$

Approximate force to deflect loop = 200 lb per diameter inch of pipe. For example, 8-in. pipe creates 1,600 lb of force.

Source: ©ASHRAE, www.ashrae.org., *2016 ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 46, Pipes, Tubes, and Fittings, Table 11.

9.6 Mechanical Energy

9.6.1 Mechanical Energy Equation in Terms of Energy per Unit Mass

The *mechanical energy equation* for a pump or fan can be written in terms of energy per unit mass:

$$\frac{p_{in}}{\rho} + \frac{v_{in}^2}{2} + g h_{in} + w_{shaft} = \frac{p_{out}}{\rho} + \frac{v_{out}^2}{2} + g h_{out} + w_{loss}$$

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where

p = static pressure

ρ = density

v = flow velocity

g = acceleration of gravity

h = elevation height

w_{shaft} = net shaft energy per unit mass for a pump, fan, or similar device

w_{loss} = loss due to friction

The energy equation is often used for incompressible flow problems and is called the *mechanical energy equation* or the *extended Bernoulli equation*.

The mechanical energy equation for a *turbine* can be written:

$$\frac{p_{in}}{\rho} + \frac{v_{in}^2}{2} + g h_{in} = \frac{p_{out}}{\rho} + \frac{v_{out}^2}{2} + g h_{out} + w_{shaft} + w_{loss}$$

where

w_{shaft} = net shaft energy output per unit mass for a turbine or similar device

The units used in the mechanical energy equations are

$$\text{energy per unit mass} \left(\frac{\text{ft}^2}{\text{sec}^2} = \frac{\text{ft-lb}}{\text{slug}} \text{ or } \frac{\text{m}^2}{\text{s}^2} = \frac{\text{N} \cdot \text{m}}{\text{kg}} \right)$$

9.6.2 Efficiency

According to the mechanical energy equation above, a higher amount of loss (w_{loss}) requires more shaft work for the same rise of output energy.

The efficiency of a pump or fan process can be expressed as

$$\eta = \frac{\left(w_{shaft} - w_{loss} \right)}{w_{shaft}}$$

The efficiency of a turbine process can be expressed as

$$\eta = \frac{w_{shaft}}{\left(w_{shaft} + w_{loss} \right)}$$

Energy Efficiency Ratio (EER—generally for cooling)

$$\text{EER} = \frac{\text{output cooling energy (Btu/hr)}}{\text{input electrical energy (W)}}$$

Seasonal Energy Efficiency Ratio (SEER—generally for cooling)

$$\text{SEER} = \frac{\text{total seasonal cooling output (Btu)}}{\text{total seasonal input energy (W-hr)}}$$

Coefficient of Performance (COP—generally for heating)

$$\text{COP} = \frac{\text{capacity in Btu/hr}}{\text{input in watts} \times 3.412} = \frac{\text{capacity in Btu/hr}}{\text{input energy in Btu/hr}}$$

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9.6.3 Mechanical Energy Equation in Terms of Energy per Unit Volume

The mechanical energy equation for a pump or a fan can also be written in terms of *energy per unit volume* by multiplying with fluid density (ρ).

$$p_{in} + \frac{\rho v_{in}^2}{2} + \gamma h_{in} + \rho w_{shaft} = p_{out} + \frac{\rho v_{out}^2}{2} + \gamma h_{out} + \rho w_{loss}$$

where

$\gamma = \rho g$ = specific weight

The dimensions used are energy per unit volume $\left(\frac{\text{ft-lb}}{\text{ft}^3} = \frac{\text{lb}}{\text{ft}^2} \text{ or } \frac{\text{N} \cdot \text{m}}{\text{m}^3} = \frac{\text{N}}{\text{m}^2}\right)$.

9.6.4 Mechanical Energy Equation in Terms of Energy per Unit Weight Involving Heads

The mechanical energy equation for a pump or a fan can also be written in terms of energy per unit weight by dividing with gravity, g.

$$\frac{p_{in}}{\gamma} + \frac{v_{in}^2}{2g} + h_{in} + h_{shaft} = \frac{p_{out}}{\gamma} + \frac{v_{out}^2}{2g} + h_{out} + h_{loss}$$

where

$\gamma = \rho g$ = specific weight

$h_{shaft} = \frac{w_{shaft}}{g}$ = net shaft energy head per unit mass for a pump, fan, or similar device

$h_{loss} = \frac{w_{loss}}{g}$ = loss head due to friction

The dimensions used are energy per unit weight $\left(\frac{\text{ft-lb}}{\text{lb}} = \text{ft} \text{ or } \frac{\text{N} \cdot \text{m}}{\text{N}} = \text{m}\right)$.

Head is the energy per unit weight.

h_{shaft} can also be expressed as $h_{shaft} = \frac{w_{shaft}}{g} = \frac{W_{shaft}}{mg} = \frac{W_{shaft}}{\gamma Q}$

where

W_{shaft} = shaft power

m = mass flow rate

Q = volume flow rate

The head equation yields

$$h_{shaft} = \frac{W_{shaft}}{\gamma Q}$$

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9.7 Acoustics and Noise Control

9.7.1 Sound Power

Examples of Sound Power Outputs and Sound Power Levels

Source	Sound Power, W	Sound Power Level, dB re 10^{-12} W
Space shuttle launch	10^{8}	200
Jet aircraft at take-off	10^{4}	160
Large pipe organ playing	10	130
Small aircraft engine running	1	120
Large HVAC fan running	0.1	110
Heavy truck at highway speed	0.01	100
Voice shouting	0.0001	90
Garbage disposal unit running	10^{-4}	80
Voice, at conversation level	10^{-5}	70
Electronic equipment ventilation fan	10^{-6}	60
Office air diffuser	10^{-7}	50
Small electric clock	10^{-8}	40
Voice, at soft whisper	10^{-9}	30
Rustling leaves	10^{-10}	20
Human breath	10^{-11}	10

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 8, Sound and Vibration, Table 2.

9.7.2 Multiple Sound Sources

Combining Two Sound Levels

Difference Between Levels to be Combined, dB	0 to 1	2 to 4	5 to 9	10 or more
No. of decibels to be added to highest level to obtain combined level	3	2	1	0

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 8, Sound and Vibration, Table 3.

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9.7.3 Sound Rating Methods

Comparison of Sound Rating Methods

Method	Overview	Considers Speech Interference Effects	Evaluates Sound Quality	Components Presently Rated by Each Method
dBA	No quality assessment Frequently used for outdoor noise ordinances	Yes	No	Cooling towers Water chillers Condensing units
NC	Can rate components Limited quality assessment Does not evaluate low-frequency rumble	Yes	Somewhat	Air terminals Diffusers
RC Mark II	Used to evaluate systems Should not be used to evaluate components Evaluates sound quality Provides improved diagnostics capability	Yes	Yes	Not used for component rating
NCB	Can rate components Some quality assessment	Yes	Somewhat	See NC
RNC	Some quality assessment Attempts to quantify fluctuations	Yes	Somewhat	Not used for component rating

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 48, Noise and Vibration Control, Table 4.

Table 8 Maximum Recommended Duct Airflow Velocities to Achieve Specified Acoustic Design Criteria

		Maximum Airflow Velocity, fpm	
Main Duct Location	Design RC(N)	Rectangular Duct	Circular Duct
In shaft or above drywall ceiling	45	3500	5000
	35	2500	3500
	25	1700	2500
Above suspended acoustic ceiling	45	2500	4500
	35	1750	3000
	25	1200	2000
Duct located within occupied space	45	2000	3900
	35	1450	2600
	25	950	1700

Notes:
1. Branch ducts should have airflow velocities of about 80% of values listed.
2. Velocities in final runouts to outlets should be 50% of values or less.
3. Elbows and other fittings can increase airflow noise substantially, depending on type. Thus, duct airflow velocities should be reduced accordingly.

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 48, Noise and Vibration Control, Table 8.

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Insertion Loss for Rectangular Sheet Metal Ducts with 1-in. Fiberglass Lining						
	Insertion Loss, dB/foot Octave Midband Frequency, Hz					
Dimensions, in.	125	250	500	1,000	2,000	4,000
6 × 6	0.6	1.5	2.7	5.8	7.4	4.3
6 × 10	0.5	1.2	2.4	5.1	6.1	3.7
6 × 12	0.5	1.2	2.3	5.0	5.8	3.6
6 × 18	0.5	1.0	2.2	4.7	5.2	3.3
8 × 8	0.5	1.2	2.3	5.0	5.8	3.6
8 × 12	0.4	1.0	2.1	4.5	4.9	3.2
8 × 16	0.4	0.9	2.0	4.3	4.5	3.0
8 × 24	0.4	0.8	1.9	4.0	4.1	2.8
10 × 10	0.4	1.0	2.1	4.4	4.7	3.1
10 × 16	0.4	0.8	1.9	4.0	4.0	2.7
10 × 20	0.3	0.8	1.8	3.8	3.7	2.6
10 × 30	0.3	0.7	1.7	3.6	3.3	2.4
12 × 12	0.4	0.8	1.9	4.0	4.1	2.8
12 × 18	0.3	0.7	1.7	3.7	3.5	2.5
12 × 24	0.3	0.6	1.7	3.5	3.2	2.3
12 × 36	0.3	0.6	1.6	3.3	2.9	2.2
15 × 15	0.3	0.7	1.7	3.6	3.3	2.4
15 × 22	0.3	0.6	1.6	3.3	2.9	2.2
15 × 30	0.3	0.5	1.5	3.1	2.6	2.0
15 × 45	0.2	0.5	1.4	2.9	2.4	1.9
18 × 18	0.3	0.6	1.6	3.3	2.9	2.2
18 × 28	0.2	0.5	1.4	3.0	2.4	1.9
18 × 36	0.2	0.5	1.4	2.8	2.2	1.8
18 × 54	0.2	0.4	1.3	2.7	2.0	1.7
24 × 24	0.2	0.5	1.4	2.8	2.2	1.8
24 × 36	0.2	0.4	1.2	2.6	1.9	1.6
24 × 48	0.2	0.4	1.2	2.4	1.7	1.5
24 × 72	0.2	0.3	1.1	2.3	1.6	1.4
30 × 30	0.2	0.4	1.2	2.5	1.8	1.6
30 × 45	0.2	0.3	1.1	2.3	1.6	1.4
30 × 60	0.2	0.3	1.1	2.2	1.4	1.3
30 × 90	0.1	0.3	1.0	2.1	1.3	1.2
36 × 36	0.2	0.3	1.1	2.3	1.6	1.4
36 × 54	0.1	0.3	1.0	2.1	1.3	1.2
36 × 72	0.1	0.3	1.0	2.0	1.2	1.2
36 × 108	0.1	0.2	0.9	1.9	1.1	1.1
42 × 42	0.2	0.3	1.0	2.1	1.4	1.3
42 × 64	0.1	0.3	0.9	1.9	1.2	1.1
42 × 84	0.1	0.2	0.9	1.8	1.1	1.1
42 × 126	0.1	0.2	0.9	1.7	1.0	1.0
48 × 48	0.1	0.3	1.0	2.0	1.2	1.2
48 × 72	0.1	0.2	0.9	1.8	1.0	1.0
48 × 96	0.1	0.2	0.8	1.7	1.0	1.0
48 × 144	0.1	0.2	0.8	1.6	0.9	0.9

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Table 40 Sound Transmission Class (STC) and Transmission Loss Values of Typical Mechanical Equipment Room Wall, Floor, and Ceiling Types, dB

Room Construction Type	STC	Octave Midband Frequency, Hz						
		63	125	250	500	1000	2000	4000
8 in. CMU*	50	35	35	41	44	50	57	64
8 in. CMU with 5/8 in. GWB* on furring strips	53	33	32	44	50	56	59	65
5/8 in. GWB on both sides of 3 5/8 in. metal studs	38	18	16	33	47	55	43	47
5/8 in. GWB on both sides of 3 5/8 in. metal studs with fiberglass insulation in cavity	49	16	23	44	58	64	52	53
2 layers of 5/8 in. GWB on both sides of 3 5/8 in. metal studs with fiberglass insulation in cavity	56	19	32	50	62	67	58	63
Double row of 3 5/8 in. metal studs, 1 in. apart, each with 2 layers of 5/8 in. GWB and fiberglass insulation in cavity	64	23	40	54	62	71	69	74
6 in. solid concrete floor/ceiling	53	40	40	40	49	58	67	76
6 in. solid concrete floor with 4 in. isolated concrete slab and fiberglass insulation in cavity	72	44	52	58	73	87	97	100
6 in. solid concrete floor with two layers of 5/8 in. GWB hung on spring isolators with fiberglass insulation in cavity	84	53	63	70	84	93	104	105

Note: Actual material composition (e.g., density, porosity, stiffness) affects transmission loss and STC values.
*CMU = concrete masonry unit; GWB = gypsum wallboard.

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 48, Noise and Vibration Control, Table 40.

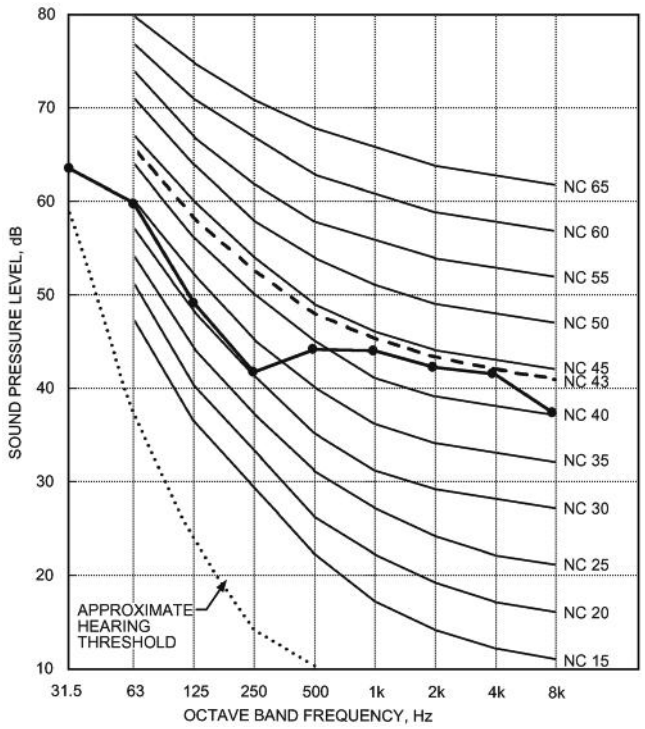
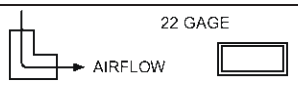
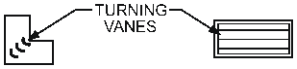
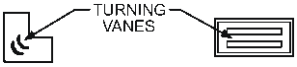
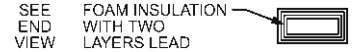
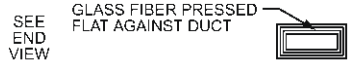
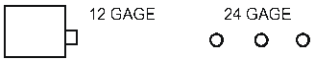
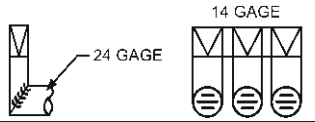
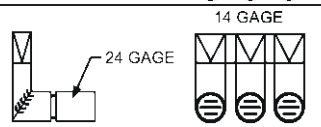
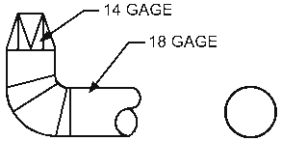


Fig. 7 NC (Noise Criteria) Curves and Sample Spectrum (Curve with Symbols)

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Table 7 Duct Breakout Insertion Loss—Potential Low-Frequency Improvement over Bare Duct and Elbow

Discharge Duct Configuration, 12 ft of Horizontal Supply Duct	Duct Breakout Insertion Loss at Low Frequencies, dB			Side View	End View
	63 Hz	125 Hz	250 Hz		
Rectangular duct: no turning vanes (reference)	0	0	0		
Rectangular duct: one-dimensional turning vanes	0	1	1		
Rectangular duct: two-dimensional turning vanes	0	1	1		
Rectangular duct: wrapped with foam insulation and two layers of lead	4	3	5		
Rectangular duct: wrapped with glass fiber and one layer 5/8 in. gypsum board	4	7	6		
Rectangular duct: wrapped with glass fiber and two layers 5/8 in. gypsum board	7	9	9		
Rectangular plenum drop (12 ga.): three parallel rectangular supply ducts (22 ga.)	1	2	4		
Rectangular plenum drop (12 ga.): one round supply duct (18 ga.)	8	10	6		
Rectangular plenum drop (12 ga.): three parallel round supply ducts (24 ga.)	11	14	8		
Rectangular (14 ga.) to multiple drop: round mitered elbows with turning vanes, three parallel round supply ducts (24 ga.)	18	12	13		
Rectangular (14 ga.) to multiple drop: round mitered elbows with turning vanes, three parallel round lined double-wall, 22 in. OD supply ducts (24 ga.)	18	13	16		
Round drop: radiused elbow (14 ga.), single 37 in. diameter supply duct	15	17	10		

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9.7.4 Background Noise

Design Guidelines for HVAC-Related Background Sound in Rooms

Room Types		Octave Band Analysis[a]	Approximate Overall Sound Pressure Level[a]	
		NC/RC[b]	dBA[c]	dBC[c]
Rooms With Intrusion From Outdoor Noise Sources[d]	Traffic noise	N/A	45	70
	Aircraft fly overs	N/A	45	70
Residences, Apartments, and Condominiums	Living areas	30	35	60
	Bathrooms, kitchens, utility rooms	35	40	60
Hotels and Motels	Individual rooms or suites	30	35	60
	Meeting/banquet rooms	30	35	60
	Corridors and lobbies	40	45	65
	Service/support areas	40	45	65
Office Buildings	Executive and private offices	30	35	60
	Conference rooms	30	35	60
	Teleconference rooms	25	30	55
	Open-plan offices	40	45	65
	Corridors and lobbies	40	45	65
Courtrooms	Unamplified speech	30	35	60
	Amplified speech	35	40	60
Performing Arts Spaces	Drama theaters, concert and recital halls	20	25	50
	Music teaching studios	25	30	55
	Music practice rooms	30	35	60
Hospitals and Clinics	Patient rooms	30	35	60
	Wards	35	40	60
	Operating and procedure rooms	35	40	60
	Corridors and lobbies	40	45	65
Laboratories	Testing/research with minimal speech communication	50	55	75
	Extensive phone use and speech communication	45	50	70
	Group teaching	35	40	60
Churches, Mosques, and Synagogues	General assembly with critical music programs[e]	25	30	55

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Design Guidelines for HVAC-Related Background Sound in Rooms (cont'd)

Room Types		Octave Band Analysis[a]	Approximate Overall Sound Pressure Level[a]	
		NC/RC[b]	dBA[c]	dBC[c]
Schools[f]	Classrooms	30	35	60
	Large lecture rooms with speech amplification	30	35	60
	Large lecture rooms without speech amplification	25	30	55
Libraries	Libraries	30	35	60
Indoor Stadiums, Gymnasiums	Gymnasiums and natatoriums[g]	45	50	70
	Large-seating-capacity spaces with speech amplification[g]	50	55	75

N/A = Not applicable

[a] Values and ranges are based on judgment and experience, and represent general limits of acceptability for typical building occupancies.

[b] NC: This metric plots octave band sound levels against a family of reference curves, with the number rating equal to the highest tangent line value.
RC: When sound quality in the space is important, the RC metric provides a diagnostic tool to quantify both the speech interference level and spectral imbalance.

[c] dBA and dBC: These are overall sound pressure-level measurements with A- and C-weighting, and serve as good references for a fast, single-number measurement. They are also appropriate for specification in cases where no octave band sound data are available for design.

[d] Intrusive noise is addressed here for use in evaluating possible non-HVAC noise that is likely to contribute to background noise levels.

[e] An experienced acoustical consultant should be retained for guidance on acoustically critical spaces (below RC 30) and for all performing arts spaces.

[f] Some educators and others believe that HVAC-related sound criteria for schools, as listed in previous editions of this table, are too high and impede learning for affected groups of all ages. See ANSI/ASA *Standard* S12.60 for classroom acoustics and a justification for lower sound criteria in schools. The HVAC component of total noise meets the background noise requirement of that standard if HVAC-related background sound is approximately NC/RC 25. Within this category, designs for K–8 schools should be quieter than those for high schools and colleges.

[g] RC or NC criteria for these spaces need only be selected for the desired speech and hearing conditions.

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 48, Noise and Vibration Control, Table 1.

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9.8 Vibration Control

Selection Guide for Vibration Isolation

Equipment Type	Horsepower and Other	RPM	Equipment Location											
			Slab on Grade			Floor Span								
						Up to 20 feet			20 to 30 feet			30 to 40 feet		
			Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches
Refrigeration Machines and Chillers														
Water-cooled reciprocating	All	All	A	2	0.25	A	4	0.75	A	4	1.5	A	4	2.5
Water-cooled centrifugal, scroll	All	All	A	1	0.25	A	4	0.75	A	4	1.5	A	4	1.5
Water-cooled screw	All	All	A	1	1	A	4	1.5	A	4	2.5	A	4	2.5
Absorption	All	All	A	4	0.25	A	4	0.75	A	4	1.5	A	4	1.5
Air-cooled reciprocating, scroll	All	All	A	1	0.25	A	4	1.5	A	4	1.5	A	4	2.5
Air-cooled screw	All	All	A	4	1	A	4	1.5	B	4	2.5	B	4	2.5
Air Compressors and Vacuum Pumps														
Tank-mounted horizontal	≤ 10	All	A	3	0.75	A	3	0.75	A	3	1.5	A	3	1.5
	≥ 10	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	1.5
Tank-mounted vertical	All	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	1.5
Base-mounted	All	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	1.5
Large reciprocating	All	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	1.5
Pumps														
Close-coupled	≤ 7.5	All	B	2	0.25	C	3	0.75	C	3	0.75	C	3	0.75
	≥ 7.5	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	1.5
In-line	5 to 25	All	A	3	0.75	A	3	1.5	A	3	1.5	A	3	1.5
	≥ 25	All	A	3	1.5	A	3	1.5	A	3	1.5	A	3	2.5
End suction and double suction/	≤ 40	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	1.5
split case	50 to 125	All	C	3	0.75	C	3	0.75	C	3	1.5	C	3	2.5
	≥ 150	All	C	3	0.75	C	3	1.5	C	3	2.5	C	3	3.5
Packaged pump systems	All	All	A	3	0.75	A	3	0.75	A	3	1.5	C	3	2.5
Cooling Towers														
	All	Up to 300	A	1	0.25	A	4	3.5	A	4	3.5	A	4	3.5
		301 to 500	A	1	0.25	A	4	2.5	A	4	2.5	A	4	2.5
		501 and up	A	1	0.25	A	4	0.75	A	4	0.75	A	4	0.75

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Selection Guide for Vibration Isolation (cont'd)

Equipment Type	Horsepower and Other	RPM	Equipment Location											
			Slab on Grade			Floor Span								
						Up to 20 feet			20 to 30 feet			30 to 40 feet		
			Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches
Boilers														
Fire-tube	All	All	A	1	0.25	B	4	0.75	B	4	1.5	B	4	2.5
Water-tube, copper fin	All	All	A	1	0.12	A	1	0.12	A	1	0.12	B	4	0.25
Axial Fans, Plenum Fans, Cabinet Fans, Fan Sections, Centrifugal In-line Fans														
Up to 22 in. diameter	All	All	A	2	0.25	A	3	0.75	A	3	0.75	C	3	0.75
42 in. diameter and up	≤ 2 in. SP	Up to 300	B	3	2.5	C	3	3.5	C	3	3.5	C	3	3.5
		301 to 500	B	3	0.75	B	3	1.5	C	3	2.5	C	3	2.5
		501 and up	B	3	0.75	B	3	1.5	B	3	1.5	B	3	1.5
	≥ 2.1 in. SP	Up to 300	C	3	2.5	C	3	3.5	C	3	3.5	C	3	3.5
		301 to 500	C	3	1.5	C	3	1.5	C	3	2.5	C	3	2.5
		501 and up	C	3	0.75	C	3	1.5	C	3	1.5	C	3	2.5
Centrifugal Fans														
Up to 22 in. diameter	All	All	B	2	0.25	B	3	0.75	B	3	0.75	B	3	1.5
24 in. diameter and up	≤ 40	Up to 300	B	3	2.5	B	3	3.5	B	3	3.5	B	3	3.5
		301 TO 500	B	3	1.5	B	3	1.5	B	3	2.5	B	3	2.5
		501 and up	B	3	0.75	B	3	0.75	B	3	0.75	B	3	1.5
	≥ 50	Up to 300	C	3	2.5	C	3	3.5	C	3	3.5	C	3	3.5
		301 to 500	C	3	1.5	C	3	1.5	C	3	2.5	C	3	2.5
		501 and up	C	3	1	C	3	1.5	C	3	1.5	C	3	2.5
Propeller Fans														
Wall-mounted	All	All	A	1	0.25	A	1	0.25	A	1	0.25	A	1	0.25
Roof-mounted	All	All	A	1	0.25	A	1	0.25	B	4	1.5	D	4	1.5
Heat Pumps, Fan-Coils, Computer Room Units														
	All	All	A	3	0.75	A	3	0.75	A	3	0.75	A/D	3	1.5
Condensing Units														
	All	All	A	1	0.25	A	4	0.75	A	4	1.5	A/D	4	1.5

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Selection Guide for Vibration Isolation (cont'd)

Equipment Type	Horsepower and Other	RPM	Equipment Location											
			Slab on Grade			Floor Span								
						Up to 20 feet			20 to 30 feet			30 to 40 feet		
			Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches	Base Type	Isolator Type	Minimum Deflection, inches
Packaged AH, AC, H and V Units														
All	≤ 10	All	A	3	0.75	A	3	0.75	A	3	0.75	A	3	0.75
	≤ 15	Up to 300	A	3	0.75	A	3	3.5	A	3	3.5	C	3	3.5
		301 to 500	A	3	0.75	A	3	2.5	A	3	2.5	A	3	2.5
	≤ 4 in. SP	501 and up	A	3	0.75	A	3	1.5	A	3	1.5	A	3	1.5
	> 15,	Up to 300	B	3	0.75	C	3	3.5	C	3	3.5	C	3	3.5
	> 4 in. SP	301 to 500	B	3	0.75	C	3	1.5	C	3	2.5	C	3	2.5
		501 and up	B	3	0.75	C	3	1.5	C	3	1.5	C	3	2.5
Packaged Rooftop Equipment														
	All	All	A/D	1	0.25	D	3	0.75						
Ducted Rotating Equipment														
Small fans, fan powered boxes	≤ 600 cfm		A	3	0.5	A	3	0.5	A	3	0.5	A	3	0.5
	≥ 601 cfm		A	3	0.75	A	3	0.75	A	3	0.75	A	3	0.75
Engine-Driven Generators														
	All	All	A	3	0.75	C	3	1.5	C	3	2.5	C	3	3.5

Base Types:

A. No base, isolators attached directly to equipment

B. Structural steel rails or base

C. Concrete inertia base

D. Curb-mounted base

Isolator Types:

1. Pad, rubber, or glass fiber
2. Rubber floor isolator or hanger
3. Spring floor isolator or hanger
4. Restrained spring isolator

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 48, Noise and Vibration Control, Table 47.

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Recommended Live Lengths[a] of Flexible Rubber and Metal Hose

Nominal Diameter, in.	Length[b], in.	Nominal Diameter, in.	Length[b], in.
0.75	12	4	18
1	12	5	24
1.5	12	6	24
2	12	8	24
2.5	12	10	24
3	18	12	36

a. Live length is end-to-end length for integral flanged rubber hose and is end-to-end less total fittings length for all other types.
b. Per recommendations of Rubber Expansion Division, Fluid Sealing Association

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 48, Noise and Vibration Control, Table 48.

9.9 Building Energy Usage

9.9.1 Energy Utilization Index (EUI)

The total energy usage of a building per unit area per year. Typically expressed as $\frac{\text{Btu}}{\text{ft}^2\text{-yr}}$

$$\text{EUI} = \frac{\sum \text{Annual energy usage from all sources in common units}}{\text{Building total area}}$$

The EUI can be determined based on site energy usage or source energy usage.

9.9.2 Cost Utilization Index (CUI)

The total energy usage costs of a building per unit area per year. Typically expressed as $\frac{\$}{\text{ft}^2\text{-yr}}$

$$\text{CUI} = \frac{\sum \text{Annual energy usage costs from all sources}}{\text{Building total area}}$$

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10 COMBUSTION AND FUELS

10.1 General Information

The quantity of heat generated by complete combustion of a specific fuel is called the *heating value*, *heat of combustion*, or *caloric value* of that fuel.

Higher heating value (HHV), gross heating value, or *total heating value* includes the latent heat of vaporization.

Lower heating value (LHV) or *net heating value* does not include the latent heat of vaporization.

Heating Values of Substances Occurring in Common Fuels

Substance	Molecular Formula	Higher Heating Values[a] $\frac{Btu}{ft^3}$	Higher Heating Values[a] $\frac{Btu}{lb}$	Lower Heating Values[a] $\frac{Btu}{lb}$	Specific Volume[b] $\frac{ft^3}{lb}$
Carbon (to CO)	C	--	3,950	3,950	--
Carbon (to CO_2)	C	--	14,093	14,093	--
Carbon monoxide	CO	321	4,347	4,347	13.5
Hydrogen	H_2	325	61,095	51,623	188.0
Methane	CH_4	1,012	23,875	21,495	23.6
Ethane	C_2H_6	1,773	22,323	20,418	12.5
Propane	C_3H_8	2,524	21,669	19,937	8.36
Butane	C_4H_{10}	3,271	21,321	19,678	6.32
Ethylene	C_2H_4	1,604[c]	21,636	20,275	--
Propylene	C_3H_6	2,340[c]	21,048	19,687	9.01
Acetylene	C_2H_2	1,477	21,502	20,769	14.3
Sulfur (to SO_2)	S	--	3,980	3,980	--
Sulfur (to SO3)	S	--	5,940	5,940	--
Hydrogen sulfide	H_2S	646	7,097	6,537	11.0

a All values corrected to 60 °F, 30 in. Hg, dry. For gases saturated with water at 60 °F, deduct 1.74% of value to adjust gas volume displaced by water vapor.

b At 32 °F and 29.92 in. Hg

c North American Combustion Handbook, 1986.

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 28, Combustion and Fuels, Table 3.

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Typical Density and Higher Heating Value of Standard Grades of Fuel Oil

Grade No.	Density (kg/m^3)	Higher Heating Value (GJ/m^3)
1	833 to 800	38.2 to 37.0
2	874 to 834	39.5 to 38.2
4	933 to 886	41.3 to 39.9
5L	951 to 921	41.8 to 40.9
5H	968 to 945	42.4 to 41.6
6	1012 to 965	43.5 to 42.2

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, SI ed., Chapter 28, Combustion and Fuels, Table 6.

Combustion Reactions	Dry Air Volumetric Analysis
$C + O_2 \rightarrow CO_2$	O_2 21%
$H_2 + 0.5\,O_2 \rightarrow H_2O$	N_2 79%
	100%

To adjust fuel gas heat content for local barometric pressure instead of standard pressure, refer to "Automatic Fuel-Burning Systems."

10.2 Excess Air Supplied to Ensure Complete Combustion

$$\text{Excess air, in \%} = \frac{\text{Air supplied} - \text{Theoretical air}}{\text{Theoretical air}}$$

10.3 Stoichiometric Combustion of Fuels

Approximate Air Requirements for Stoichiometric Combustion of Fuels

Type of Fuel	Air Required		Approximate Precision, %	Exceptions
	$\frac{\text{lb}}{\text{lb Fuel}}$	$\frac{\text{ft}^3}{\text{Unit Fuel}}$ *		
Solid	$\frac{\text{Btu}}{\text{lb}} \times 0.00073$	$\frac{\text{Btu}}{\text{lb}} \times 0.0097$	3	Fuels containing more than 30% water
Liquid	$\frac{\text{Btu}}{\text{lb}} \times 0.00071$	$\frac{\text{Btu}}{\text{lb}} \times 0.0094$	3	Results low for gasoline and kerosene
Gas	$\frac{\text{Btu}}{\text{lb}} \times 0.00067$	$\frac{\text{Btu}}{\text{lb}} \times 0.0089$	5	$300\ \frac{\text{Btu}}{\text{ft}^3}$ or less

Source: Data based on Shnidman, 1954.

* Unit fuel for solid and liquid fuels in lb, for gas in ft^3

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 28, Combustion and Fuels, Table 9.

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Approximate Air Requirements for Stoichiometric Combustion of Various Fuels

Type of Fuel	Theoretical Air Required for Combustion
Solid fuels	$\frac{\text{lb}}{\text{lb of fuel}}$
Anthracite	9.6
Semibituminous	11.2
Bituminous	10.3
Lignite	6.2
Coke	11.2
Liquid fuels	$\frac{\text{lb}}{\text{gallon of fuel}}$
No. 1 fuel oil	103
No. 2 fuel oil	106
No. 5 fuel oil	112
No. 6 fuel oil	114
Gaseous fuels	$\frac{\text{ft}^3}{\text{ft}^3 \text{ of fuel}}$
Natural gas	9.6
Butane	31.1
Propane	24.0

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 28, Combustion and Fuels, Table 10.

Approximate Maximum Theoretical (Stoichiometric) CO_2 Values, and CO_2 Values of Various Fuels With Different Percentages of Excess Air

Type of Fuel	Theoretical or Maximum	Percent CO_2 at Given Excess Air Values		
	CO_2, %	20%	40%	60%
Gaseous Fuels				
Natural gas	12.1	9.9	8.4	7.3
Propane gas (commercial)	13.9	11.4	9.6	8.4
Butane gas (commercial)	14.1	11.6	9.8	8.5
Mixed gas (natural and carbureted water gas)	11.2	12.5	10.5	9.1
Carbureted water gas	17.2	14.2	12.1	10.6
Coke oven gas	11.2	9.2	7.8	6.8
Liquid Fuels				
No. 1 and 2 fuel oil	15.0	12.3	10.5	9.1
No. 6 fuel oil	16.5	13.6	11.6	10.1
Solid Fuels				
Bituminous coal	18.2	15.1	12.9	11.3
Anthracite	20.2	16.8	14.4	12.6
Coke	21.0	17.5	15.0	13.0

Source: ©ASHRAE, www.ashrae.org., *2013 ASHRAE Handbook—Fundamentals*, Chapter 28, Combustion and Fuels, Table 11.

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Theoretical CO_2 values can be calculated for combustion with excess air present from the flue gas analysis:

$$\text{Theoretical } CO_2\text{, in \%} = U = \frac{CO_2}{1 - \left(\frac{O_2}{20.95}\right)}$$

where:

CO_2 and O_2 = percentages by volume from the flue gas analysis, dry basis

Thermal efficiency:

$$\text{Thermal efficiency, in \%} = 100 \times \frac{\text{Useful heat}}{\text{Heating value of fuel}}$$

or

$$\eta = 100\frac{\left(Q_h - Q_{fl}\right)}{Q_h}$$

where

η = thermal efficiency (%)

Q_h = higher heating value of fuel gas per unit volume

Q_{fl} = flue gas losses per unit volume of fuel gas

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Combustion Reactions of Common Fuel Constituents

Constituent	Molecular Formula	Combustion Reactions	Stoichiometric Oxygen and Air Requirements: lb/lb Fuel[a] O_2	lb/lb Fuel[a] Air	ft³/ft³ Fuel O_2	ft³/ft³ Fuel Air	Flue Gas from Stoichiometric Combustion with Air: Ultimate CO_2, %	Dew Point, °F	ft³/ft³ Fuel CO_2	ft³/ft³ Fuel H_2O	lb/lb Fuel CO_2	lb/lb Fuel H_2O
Carbon (to CO)	C	$C + 0.5O_2 \rightarrow CO$	1.33	5.75	[b]	[b]	—	—	—	—	—	—
Carbon (to CO_2)	C	$C + O_2 \rightarrow CO_2$	2.66	11.51	[b]	[b]	29.30	—	—	—	3.664	—
Carbon monoxide	CO	$CO + 0.5O_2 \rightarrow CO_2$	0.57	2.47	0.50	2.39	34.70	—	1.0	—	1.571	—
Hydrogen	H_2	$H_2 + 0.5O_2 \rightarrow H_2O$	7.94	34.28	0.50	2.39	—	162	—	1.0	—	8.937
Methane	CH_4	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	3.99	17.24	2.00	9.57	11.73	139	1.0	2.0	2.744	2.246
Ethane	C_2H_6	$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$	3.72	16.09	3.50	16.75	13.18	134	2.0	3.0	2.927	1.798
Propane	C_3H_8	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	3.63	15.68	5.00	23.95	13.75	131	3.0	4.0	2.994	1.634
Butane	C_4H_{10}	$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$	3.58	15.47	6.50	31.14	14.05	129	4.0	5.0	3.029	1.550
Alkanes	C_nH_{2n+2}	$C_nH_{2n+2} + (1.5n + 0.5)O_2 \rightarrow nCO_2 + (n+1)H_2O$	—	—	$1.5n + 0.5$	$7.18n + 2.39$	—	128 to 127	n	$n+1$	$44.01n$ / $14.026n + 2.016$	$18.01(n+1)$ / $14.026n + 2.016$
Ethylene	C_2H_4	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	3.42	14.78	3.00	14.38	15.05	125	2.0	2.0	3.138	1.285
Propylene	C_3H_6	$C_3H_6 + 4.5O_2 \rightarrow 3CO_2 + 3H_2O$	3.42	14.78	4.50	21.53	15.05	125	3.0	3.0	3.138	1.285
Alkenes	C_nH_{2n}	$C_nH_{2n} + 1.5nO_2 \rightarrow nCO_2 + nH_2O$	3.42	14.78	$1.50n$	$7.18n$	15.05	125	n	n	3.138	1.285
Acetylene	C_2H_2	$C_2H_2 + 2.5O_2 \rightarrow 2CO_2 + H_2O$	3.07	13.27	2.50	11.96	17.53	103	2.0	1.0	3.834	0.692
Alkynes	C_nH_{2m}	$C_nH_{2m} + (n + 0.5m)O_2 \rightarrow nCO_2 + mH_2O$	—	—	$n + 0.5m$	$4.78n + 2.39m$	—	—	n	m	$22.005n$ / $6.005n + 1.008m$	$9.008m$ / $6.005n + 1.008m$
									SO_x	H_2O	SO_x	H_2O
Sulfur (to SO_2)	S	$S + O_2 \rightarrow SO_2$	1.00	4.31	[b]	[b]	—	—	$1.0SO_2$	—	1.998 (SO_2)	—
Sulfur (to SO_3)	S	$S + 1.5O_2 \rightarrow SO_3$	1.50	6.47	[b]	[b]	—	—	$1.0SO_3$	—	2.497 (SO_3)	—
Hydrogen sulfide	H_2S	$H_2S + 1.5O_2 \rightarrow SO_2 + H_2O$	1.41	6.08	1.50	7.18	—	125	$1.0SO_2$	1.0	1.880 (SO_2)	0.528

Adapted, in part, from *Gas Engineers Handbook* (1965).
[a]Atomic masses: H = 1.008, C = 12.01, O = 16.00, S = 32.06.
[b]Volume ratios are not given for fuels that do not exist in vapor form at reasonable temperatures or pressure.

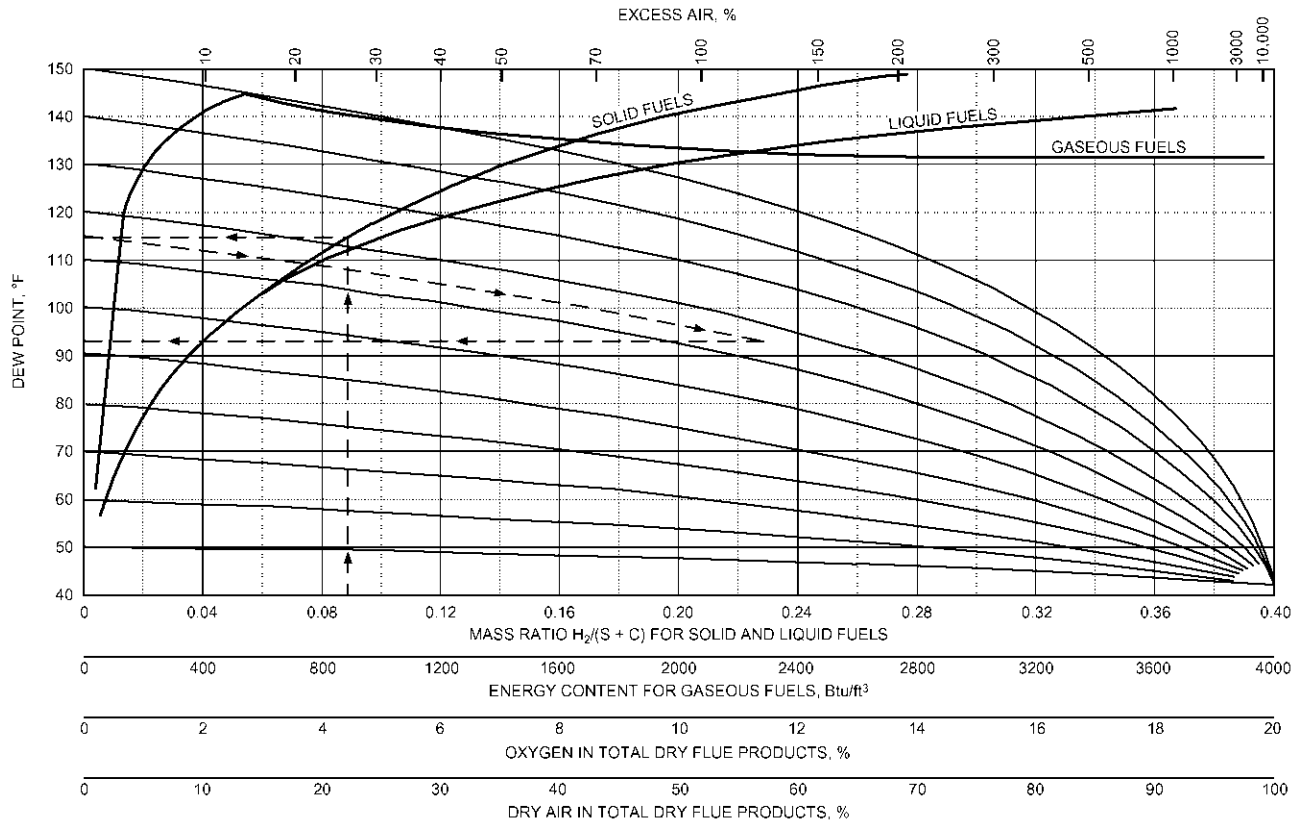
Flammability Limits and Ignition Temperatures of Common Fuels in Fuel/Air Mixtures

Substance	Molecular Formula	Lower Flammability Limit, %	Upper Flammability Limit, %	Ignition Temperature, °F	References
Carbon	C	—	—	1220	Hartman (1958)
Carbon monoxide	CO	12.5	74	1128	Scott et al. (1948)
Hydrogen	H_2	4.0	75.0	968	Zabetakis (1956)
Methane	CH_4	5.0	15.0	1301	*Gas Engineers Handbook* (1965)
Ethane	C_2H_6	3.0	12.5	968 to 1166	Trinks (1947)
Propane	C_3H_8	2.1	10.1	871	NFPA (1962)
n-Butane	C_4H_{10}	1.86	8.41	761	NFPA (1962)
Ethylene	C_2H_4	2.75	28.6	914	Scott et al. (1948)
Propylene	C_3H_6	2.00	11.1	856	Scott et al. (1948)
Acetylene	C_2H_2	2.50	81	763 to 824	Trinks (1947)
Sulfur	S	—	—	374	Hartman (1958)
Hydrogen sulfide	H_2S	4.3	45.50	558	Scott et al. (1948)

Flammability limits adapted from Coward and Jones (1952). All values corrected to 60°F, 30 in. Hg, dry.

Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 28, Combustion and Fuels, Tables 1 and 2.

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Theoretical Dew Points of Combustion Products of Industrial Fuels
Adapted from *Gas Engineers Handbook* (1965). Printed with permission of Industrial Press and American Gas Association.

Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 28, Combustion and Fuels, Fig. 4.

10.4 Heats of Reaction

For a chemical reaction the associated energy can be defined in terms of heats of formation of the individual species ΔH_f° at the standard state.

$$\left(\Delta H_r^\circ\right) = \sum_{\text{products}} \nu_i \left(\Delta H_f^\circ\right)_i - \sum_{\text{reactants}} \nu_i \left(\Delta H_f^\circ\right)_i$$

where ν_i = stoichiometric coefficient for species i

The standard state is 25°C and 1 bar.

The heat of formation is defined as the enthalpy change associated with the formation of a compound from its atomic species as they normally occur in nature (i.e., O_2 as a gas, H_2 as a gas, C as a solid, etc.).

The heat of reaction varies with the temperature:

$$\Delta H_r^\circ(T) = \Delta H_r^\circ\left(T_{ref}\right) + \int_{T_{ref}}^{T} \Delta c_p dT$$

where

T_{ref} = some reference temperature (typically 25°C or 298 K)

$$\Delta c_p = \sum_{\text{products}} \nu_i c_{p,i} - \sum_{\text{reactants}} \nu_i c_{p,i}$$

$c_{p,i}$ = molar heat capacity of component i

The heat of reaction for a combustion process using oxygen is also known as the *heat of combustion*. The principal products are CO_2(g) and H_2O(l).

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10.5 Combustion Processes

First, the combustion equation should be written and balanced. For example, the stoichiometric combustion of methane in oxygen is expressed as:

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$$

10.5.1 Combustion in Air

For each mole of oxygen, there will be 3.76 moles of nitrogen. For stoichiometric combustion of methane in air:

$$CH_4 + 2\ O_2 + 2(3.76)\ N_2 \rightarrow CO_2 + 2\ H_2O + 7.52\ N_2$$

The excess oxygen appears as oxygen on the right side of the combustion equation.

In the condition of incomplete combustion, some carbon is burned to create carbon monoxide (CO).

Molar Air-Fuel Ratio:

$$\overline{A/F} = \frac{\text{No. of moles of air}}{\text{No. of moles of fuel}}$$

Air-Fuel Ratio:

$$A/F = \frac{\text{Mass of air}}{\text{Mass of fuel}} = \left(\overline{A/F}\right)\left(\frac{M_{air}}{M_{fuel}}\right)$$

The stoichiometric (theoretical) air-fuel ratio is the air-fuel ratio calculated from the stoichiometric combustion equation:

$$\text{Percent Theoretical Air} = \frac{(A/F)_{actual}}{(A/F)_{stoichiometric}} \times 100$$

$$\text{Percent Excess Air} = \frac{(A/F)_{actual} - (A/F)_{stoichiometric}}{(A/F)_{stoichiometric}} \times 100$$

10.6 Automatic Fuel-Burning Systems

Gas input rate:

$$Q = HHV \times VFR \frac{(T_s \times P)}{(T \times P_s)}$$

where

Q = gas input $\left(\frac{\text{Btu}}{\text{hr}}\right)$

HHV = gas higher heating value as standard temperature and pressure $\left(\frac{\text{Btu}}{\text{ft}^3}\right)$

VFR = fuel as volumetric flow rate at meter temperature and pressure $\left(\frac{\text{ft}^3}{\text{hr}}\right)$

T_s = standard temperature, 520°R (60°F + 460°F)

P = fuel gas pressure in gas meter (psia)

T = absolute temperature of fuel gas in meter, in °R (fuel gas temperature in °F + 460°F)

P_s = standard pressure, at 14.735 psia

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Local gas heat content:

$$HC = HHV \times \frac{B}{P_s}$$

where

HC = local gas heat content at local barometric pressure and standard temperature conditions $\left(\frac{\text{Btu}}{\text{ft}^3}\right)$

HHV = gas higher heating value at standard temperature and pressure of 520°R (60°F + 460°F) and 14.735 psia $\left(\frac{\text{Btu}}{\text{ft}^3}\right)$

B = local barometric pressure, in psia (not corrected to sea level; not barometric pressure as reported by weather forecasters, which *is* corrected to sea level)

P_s = standard pressure = 14.735 psia

10.7 Flue Gas Condensation

In noncondensing type of boilers, the return hot water temperature must be maintained at 140°F minimum to avoid flue gases from condensing in the boiler and causing damage.

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11 TEMPERATURE CONTROLS

11.1 Terminology

Algorithm: A calculation method that produces a control output by operating on an error signal or a time series

Analog: Continuously variable

Analog input (AI): A continuous variable that is transmitted to a controller from a sensor or other control device

Analog output (AO): A continuous variable that is transmitted from a controller to an actuator or other control device

Automatic control system: A system that reacts to a change or imbalance in the variable it controls by adjusting other variables to restore the system to the desired balance

Binary (digital) point: A point that uses an on/off value to provide input to the control system or building management system (BMS)

Binary input (BI), digital input (DI): An on/off variable that is transmitted to a controller from a sensor or other control device

Binary output (BO), digital output (DO): An on/off variable that is transmitted from a controller to an actuator or other control device

Compensation control or *reset control*: A process of automatically adjusting the set point of a given controller to compensate for changes in a second measured variable (e.g., outdoor air temperature)

Control point: The value of a controlled variable maintained by a controller

Controlled medium: The medium, such as air, water or steam, manipulated by a controlled device

Controlled variable: The quantity or condition of a controlled medium that is measured and controlled; typical examples: air temperature, water temperature, relative humidity

Controller: A device that takes the controlled variable information from the sensor and provides a signal to the controlled device

Cycling: A periodic change in the controlled variable from one value to another. Out-of-control analog cycling is called "hunting." Too-frequent on-off cycling is called "short cycling."

Deadband: A range of the controlled variable in which no corrective action is taken by the controlled system

Deviation or *offset*: The difference between the set point and the value of the controlled variable

Direct digital control (DDC): Uses digital controllers to sense variables and control actuators or other devices

Digital point: See *Binary (digital) point*

Digital input (DI): See *Binary input (BI), digital input (DI)*

Digital output (DO): See *Binary output (BO), digital output (DO)*

Feedback: Information from a controlled device that is used to adjust the control signal to the controlled device

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Gain or *amplification*: the ratio of the output signal of a measured variable to the input signal of the measured variable; also represented as:

$$\text{Gain} = \frac{\%\text{ change in control signal}}{\%\text{ change in control variable}}$$

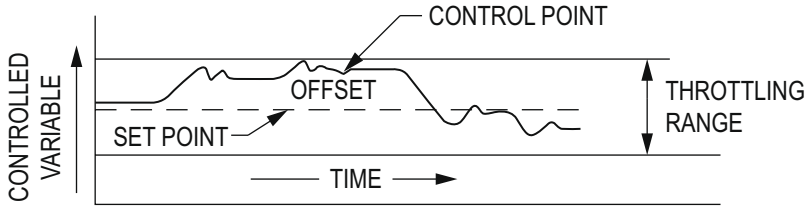
Manipulated variable: The quantity or condition regulated by an automatic control system to cause the desired change in the controlled variable

Measured variable: A variable that is measured and may be controlled

Proportional band: The change in the controlled variable required to drive the loop output from 0 to 100%. The same as throttling range

Proportional control or *modulating control*: A control algorithm or method in which the controlled device moves to a position proportional to the deviation from set point of the controlled variable

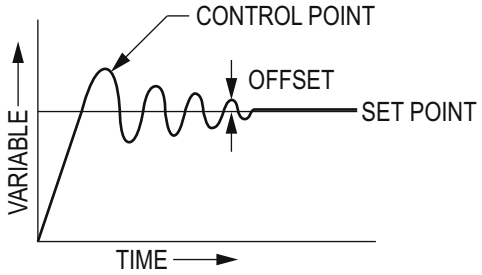
Proportional Control Showing Variations in Controlled Variable as Load Changes



Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 7, Fundamentals of Control, Fig. 5.

Proportional-integral (PI) *control*: A control algorithm that combines the proportional (proportional response) and integral (reset response) control algorithms. Reset response tends to correct the offset resulting from proportional control.

Proportional Plus Integral (PI) Control

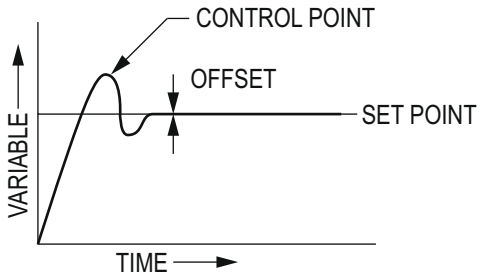


Source: Adapted from *2017 ASHRAE Handbook—Fundamentals*, Chapter 7, Fundamentals of Control, Fig. 6.

Proportional-integral-derivative (PID) *control*: A control algorithm that enhances the PI control algorithm by adding a component that is proportional to the rate of change (derivative) of the deviation of the controlled variable; compensates for system dynamics and allows faster control response; varies with the value of the derivative of the error

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Proportional-Integral-Derivative (PID) Control



Source: Adapted from *2017 ASHRAE Handbook—Fundamentals*, Chapter 7, Fundamentals of Control, Fig. 6.

Rangeability: The ratio of the maximum flow to the minimum controllable flow at a specified flow characteristic; higher values desirable for better control

Sensor: A device or component that measures the value of a variable and sends a signal to the controller

Set point: The desired value of the controlled variable

Step control: Control method in which a multiple-switch assembly sequentially switches equipment as the controller input varies through the proportional band

Throttling range: The change in the controlled variable required to move the controlled device from one extreme to the other; the same as proportional band, and inversely proportional to proportional gain

11.2 Control System Types

Control systems can be pneumatic, electric, electronic, or direct digital.

Two types of control loops are used in HVAC applications: open loop and closed loop.

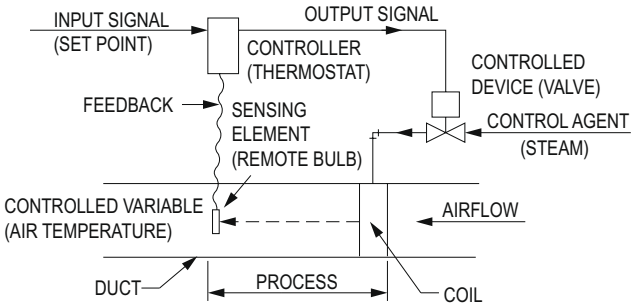
An open-loop control has no feedback between the controlled variable and the controller. This can result in overheating or underheating, and is not commonly used in commercial applications.

A closed-loop control system, also called a feedback control system, uses the measured variable to provide input to the controller. This feedback control reduces the magnitude of the deviation from set point and provides system stability. A closed-loop control must include:

- Sensor, which measures the controlled variable (e.g., temperature, humidity, pressure, or other condition)
- Controller, which compares the output from the sensor to the set point
- Controlled device (e.g., valve, dampers, heating element, or variable speed drive), which receives a signal from the controller and adjusts to maintain the set point. An example of a closed-loop control is shown below.

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Example of Feedback Control: Discharge Air Temperature Control



Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 7, Fundamentals of Control, Fig. 1.

A two-position controlled device has two operating states (e.g., on-off, open-closed). A modulating controlled device has a continuous range of operating states (e.g., 0–100% open).

11.3 Control Valves

11.3.1 Control-Valve Flow Characteristics

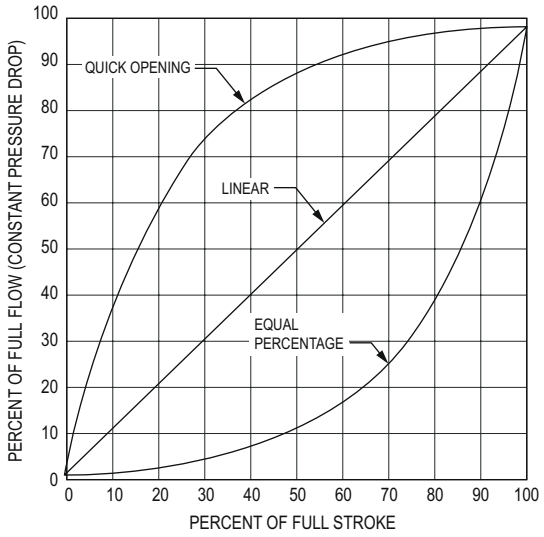
As the valve operates through its stroke, it has three common control-valve flow characteristics:

Quick opening: Maximum flow is reached very quickly as the valve opens.

Linear: Valve opening and flow are directly proportional.

Equal percentage: Each equal increment of valve opening increases the flow by an equal percentage over the previous value. This provides better control at partial load. When used with coils, whose output is not linear, equal percentage can provide linear heat transfer from the coil with respect to the control signal.

Typical Flow Characteristics of Valve



Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 7, Fundamentals of Control, Fig. 10.

11.3.2 Valve Authority

Authority is the ratio of the control valve pressure drop at full flow to the total branch pressure drop at full flow. The total branch pressure drop includes the fully open control valve, the piping, and the coil.

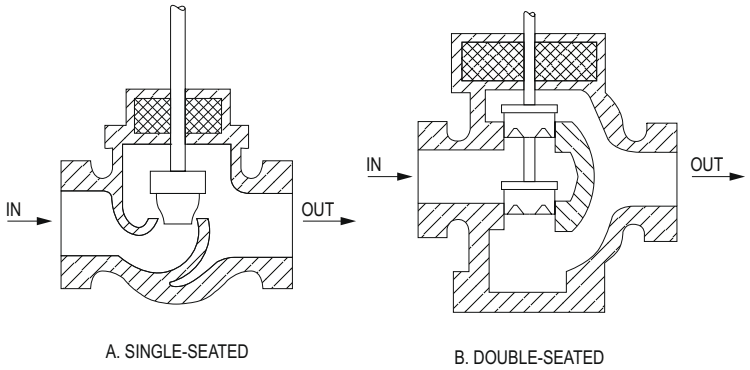
$$\text{Valve Authority \%} = \frac{\text{Open Valve Resistance}}{\text{Total System Resistance}} \times 100$$

11.3.3 Two-Way Control Valves

A two-way globe control valve can be either single-seated or double-seated. A single-seated valve is designed for tight shutoff. A double-seated or balanced valve reduces the actuator force required by balancing the media pressure acting on the valve.

Butterfly and ball valves may also be used as control valves. Butterfly and standard ball valves should be used for two-position (not modulating) applications. Characterized ball valves can be used for modulating applications. A pressure-independent control valve includes an integral pressure regulator to maintain a constant flow proportional to the given load, regardless of the differential pressure across the valve.

Typical Single- and Double-Seated Two-Way Globe Valves

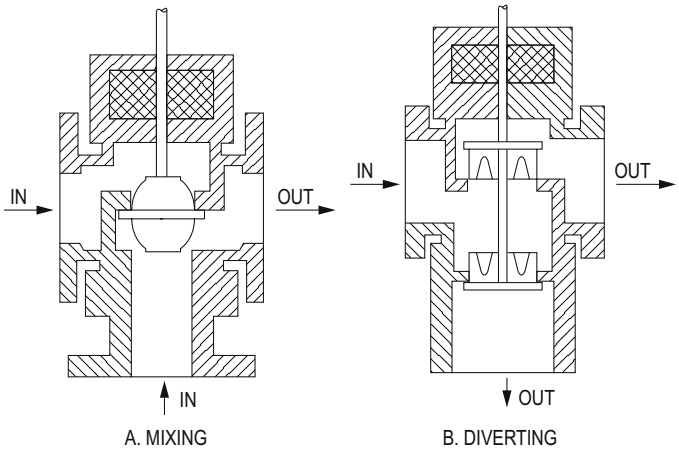


Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals,* Chapter 7, Fundamentals of Control, Fig. 9.

11.3.4 Three-Way Control Valves

A three-way mixing valve has two inlet connections and one outlet connection. Two fluid flows are mixed and exit through the common outlet. A three-way diverting valve has a single inlet connection and two outlet connections. It is used to divert flow to either outlet, or proportion the flow to both outlets. They are more expensive than mixing valves, and generally not used in HVAC applications.

Typical Three-Way Mixing and Diverting Globe Valves



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11.3.5 Valve Gain

Valve gain is the incremental change in flow resulting from an incremental change in the valve stroke. At any location along the valve flow curve, the gain is the slope of the curve, which can be calculated from:

$$\text{Slope} = \frac{\text{Change \% Flow Rate}}{\text{Change \% Valve Stroke}}$$

11.3.6 Valve Rangeability

The rangeability of a valve is the ratio between the maximum and minimum controllable flow through the valve. A larger range allows for control across a larger portion of the valve stroke.

11.3.7 Valve Cavitation

Cavitation can be damaging to a control valve. At the point where this occurs, the flow through the valve becomes choked, resulting in no change in flow regardless of increases in pressure drop. This point can be calculated from the following:

$$\Delta P_{\text{allowable}} = K_M (P_i - P_v)$$

where

$\Delta P_{\text{allowable}}$ = maximum allowable pressure drop (psi)

K_M = valve recovery coefficient:

0.7 for 1/2- to 2-inch valves

0.5 for 2-1/2- to 6-inch valves

P_i = absolute inlet pressure (psia)

P_v = absolute vapor pressure (psia)

11.3.8 Valve Flow Coefficient

The flow coefficient of a valve C_v is the flow, in gpm, of 60°F water though a fully open valve that results in a 1 psi pressure drop. It is a useful property when sizing control valves.

$$C_v = \frac{Q}{\sqrt{\Delta P}}$$

where

C_v = valve flow coefficient

Q = flow in gallons per minute (gpm)

ΔP = difference in pressure between the inlet and outlet (psi)

For fluids other than water, corrections must be made for the specific gravity. The revised formula becomes

$$C_v = Q\sqrt{\frac{S_g}{\Delta P}}$$

where

S_g = specific gravity of fluid

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When sizing steam control valves, if the steam pressure is 15 psig or below, the steam valve is sized based on a pressure drop equal to the supply pressure. The required coefficient of flow is calculated from:

$$C_v = \frac{Q}{2.11\sqrt{P_i^2 - P_o^2}}$$

where

C_v = valve flow coefficient

Q = flow (pounds of steam per hour)

P_i = absolute inlet pressure (psia)

P_o = absolute outlet pressure (psia)

When the inlet pressure in greater than 15 psig, the critical pressure drop is used for the pressure drop, which is equal to 42% of the absolute inlet pressure. The equation becomes:

$$C_v = \frac{Q}{[1.6P_i]}$$

where

C_v = valve flow coefficient

Q = flow (pounds of steam per hour)

P_i = absolute inlet pressure (psia)

11.3.9 Valve Normal Position

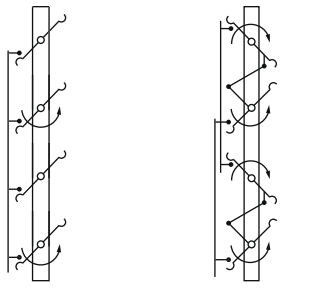
Valve operation can have a normal position if the control signal goes to zero or if the device actuator loses power. It can be "fail open," "fail closed," or "fail in last position." The valve actuators can use a spring to close the device on loss of signal or power (fail closed) or open on loss of signal or power (fail open). Sometimes, electric actuators use capacitors to drive the actuator to the fail-safe condition. The design of any system needs to determine whether a fail-safe condition exists if the power is lost, such as fail open for heating valves. If not, allowing the valve actuator to "fail in last position" may be an option for an electronic actuator.

11.4 Control Dampers

11.4.1 Damper Types

Control dampers can be two-position or modulating control. Multiblade dampers are available as parallel blades, where the blades open parallel to each other, or opposed blades, where the blades open in opposition to each other. The parallel blade dampers in the mixing section of an air-handling unit can be used to direct the outdoor-air and return-air flow toward each other to promote better mixing.

Typical Multiblade Dampers



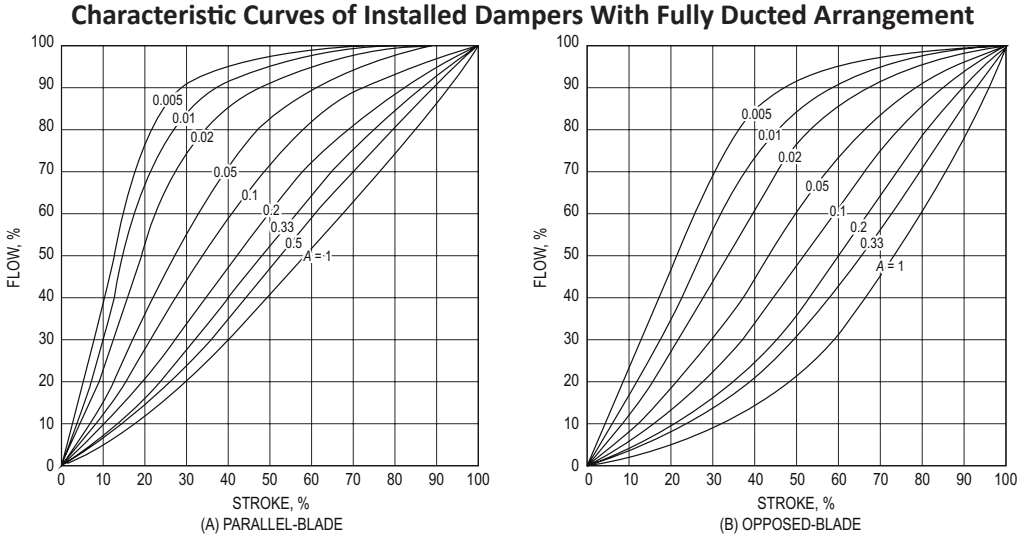
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11.4.2 Damper Authority

Authority is the ratio of the control damper pressure drop at full flow to the total branch pressure drop at full flow, including the fully open control damper. Typical authority curves are shown below for a fully ducted arrangement with long sections of ductwork before and after the damper. Similar curves are available for other arrangements. Dampers with low authority will not provide good controllability.

$$\text{Damper Authority \%} = \frac{\text{Open Damper Resistance}}{\text{Total System Resistance}} \times 100$$



Source: ©ASHRAE, www.ashrae.org., *2017 ASHRAE Handbook—Fundamentals*, Chapter 7, Fundamentals of Control, Fig. 13.

11.4.3 Damper Normal Position

Damper operation can have a normal position if the control signal goes to zero, or if the device actuator loses power. It can be "fail open," "fail closed," or "fail in last position." The damper actuators can use a spring to close the device on loss of signal or power (fail closed) or open on loss of signal or power (fail open). Sometimes, electric actuators use capacitors to drive the actuator to the fail-safe conditions. The design of any system needs to determine whether a fail-safe condition exists if the power is lost, such as fail closed for outdoor air dampers. If not, allowing the damper actuator to "fail in last position" may be an option for an electronic actuators.

11.5 Sensors and Transmitters

A transmitter takes the output of a sensor and converts the signal to an industry standard signal, such as 4–20 mA, 0–10v, or the DDC network protocol. A transducer can convert between mA and volts.

The sensor must be able to provide an adequate change in its output signal (operating range) over the expected input range.

Sensitivity is the ratio of a change in output magnitude to the change of input after steady state has been reached.

Repeatability is the ability to provide similar repeated measurements of the same variable under the same conditions.

The *sensor response time* describes the response of the sensor output to change in the controlled variable.

11.6 Digital Controllers

Digital controllers use microprocessors to execute software programs, which can be standardized programs or customized programs for the specific installation. Digital controls can be standalone or integrated with the building management system (BMS).

The advantages of digital controls include:

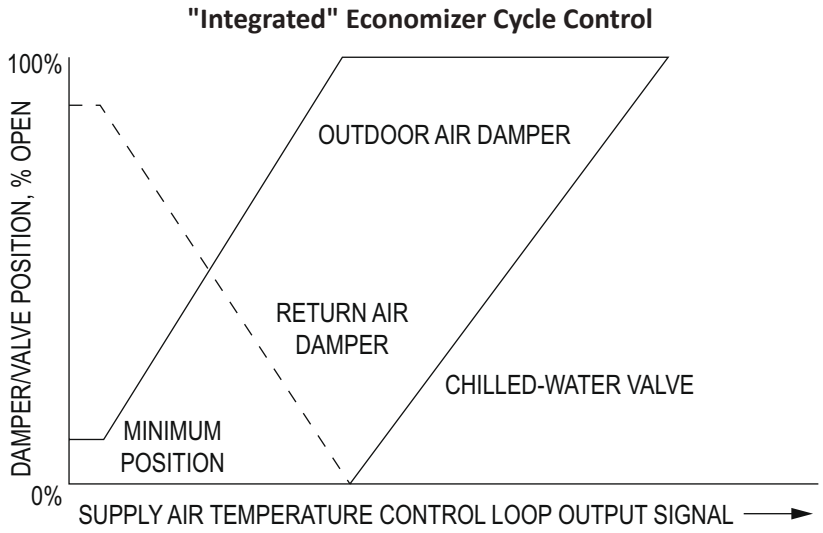
- Sequences or equipment can be modified with software changes, making it easier to modify a control sequence without the addition of hardware.
- Demand setback, reset, data logging, diagnostics, and time-clock integration are easy to add at minimal cost.
- Precise, accurate control can be implemented with high-resolution sensors and with analog-to-digital (A/D) and digital-to-analog (D/A) conversion processes. Control algorithms can be implemented mathematically and tuned to provide the desired results.
- Controls can communicate with other controls through an open or proprietary network standard.

11.7 Electric Heaters

An electric heater must include a minimum airflow switch and two high-limit sensors, one with manual reset and one with automatic reset. If the airflow is too low, the coil will not be activated on a call for heat. Low airflow can be caused by a variable air volume (VAV) box setting being too low, a duct fire/smoke damper closing, or duct blockage.

11.8 Air-Side Economizer Cycle

When outdoor conditions are below a high-limit setting, the air-side economizer system is activated to reduce cooling costs by bring in more outdoor air. Return air dampers and outdoor air dampers modulate to maintain the desired supply-air temperature in sequence with mechanical cooling. Some method of relieving the excess air must be included, such as gravity relief dampers, relief dampers with powered exhaust, or separate variable-volume exhaust fans. The operations of the outdoor air damper, return air damper, and chilled water valve are shown below.



Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Fig. 22.

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Economizer Damper Type and Sizing

Relief System	Damper	Blade Type	Face Velocity, in fpm
Return Fan	Relief/exhaust	Opposed	1000 to 1500
	Outdoor air	Parallel	400 to 1000
	Return air	Parallel	Per ΔP across damper ~1500
Relief Fan or Barometric	Outdoor air	Parallel	400 to 1000
	Return air	Parallel	800 to 1000

Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Table 1.

11.8.1 Economizer High-Limit Controls

High-limit controls disable the air-side economizer cycle if using outdoor air will use more energy than mechanically cooling the return air. Common high-limit controls include:

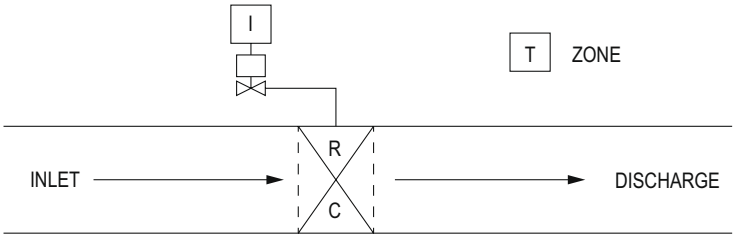
- Fixed dry-bulb temperature (compares the outdoor air dry-bulb temperature to a fixed set-point dry-bulb temperature)
- Differential dry-bulb temperature (compares the outdoor air dry-bulb temperature to the return air dry-bulb temperature)
- Fixed enthalpy (compares the outdoor air enthalpy to a fixed enthalpy set point)
- Differential enthalpy (compares the outdoor air enthalpy to the return air enthalpy)
- Electronic enthalpy (compares the outdoor air temperature and humidity to a set point that is a curve on the psychrometric chart)
- Combination of these controls

11.9 Terminal Units

11.9.1 Single-Duct, Constant Volume Reheat

This type of terminal unit provides constant air volume with reheat coil controlled by a space thermostat.

Single-Duct, Constant-Volume Zone Reheat

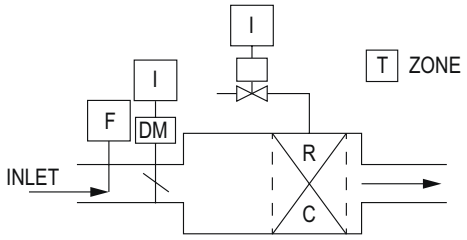


Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Fig. 24.

11.9.2 Single-Duct, Variable Air Volume (VAV)

This terminal includes an inlet damper that varies the airflow. Typically, it is a pressure-independent control with a control loop that resets the damper position between an adjustable minimum and maximum airflow in response to the space thermostat. Where zone heating is required, a reheat coil can be installed in the unit.

Throttling VAV Terminal Unit

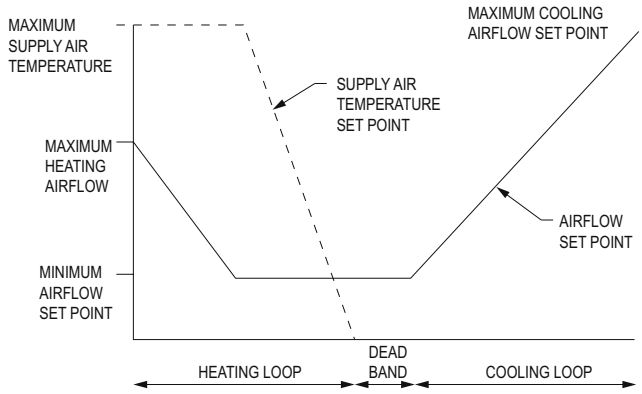


Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Fig. 25.

11.9.3 Variable Air Volume, Dual-Maximum

In perimeter spaces with high heating requirements, a dual-maximum control increases the air flow above the minimum to provide additional heating capacity and space air exchange. As the reheat coil valve opens, the air flow increases.

Throttling VAV Terminal Unit: Dual-Maximum Control Sequence

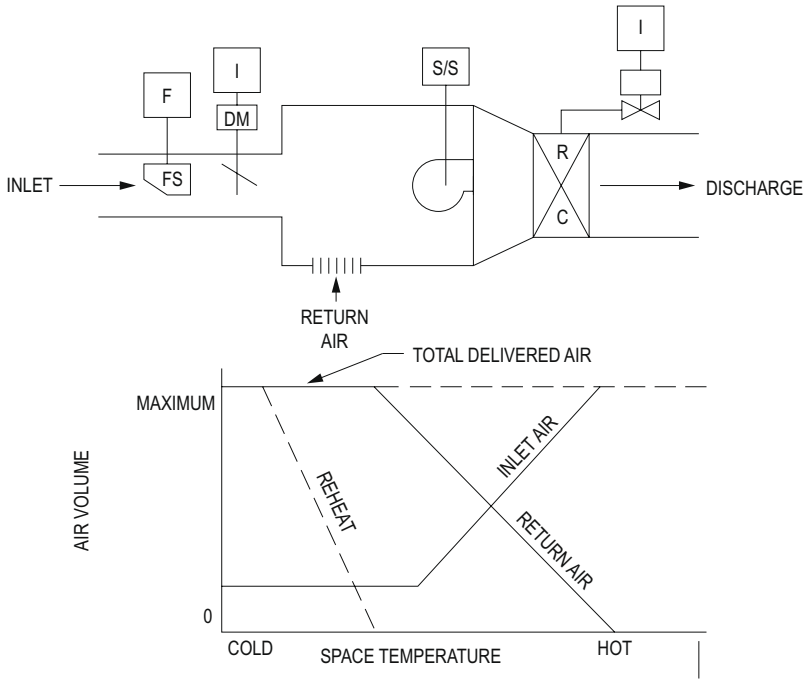


Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Fig. 26.

11.9.4 Series Fan-Powered VAV Terminal Unit

A series fan-powered VAV box includes an integral fan in series with the primary supply-air VAV damper to provide a constant air volume to the space. A reheat coil can be installed to provide heat, whether the central air-handling unit is turned on or off.

Series Fan-Powered VAV Terminal Unit Diagram

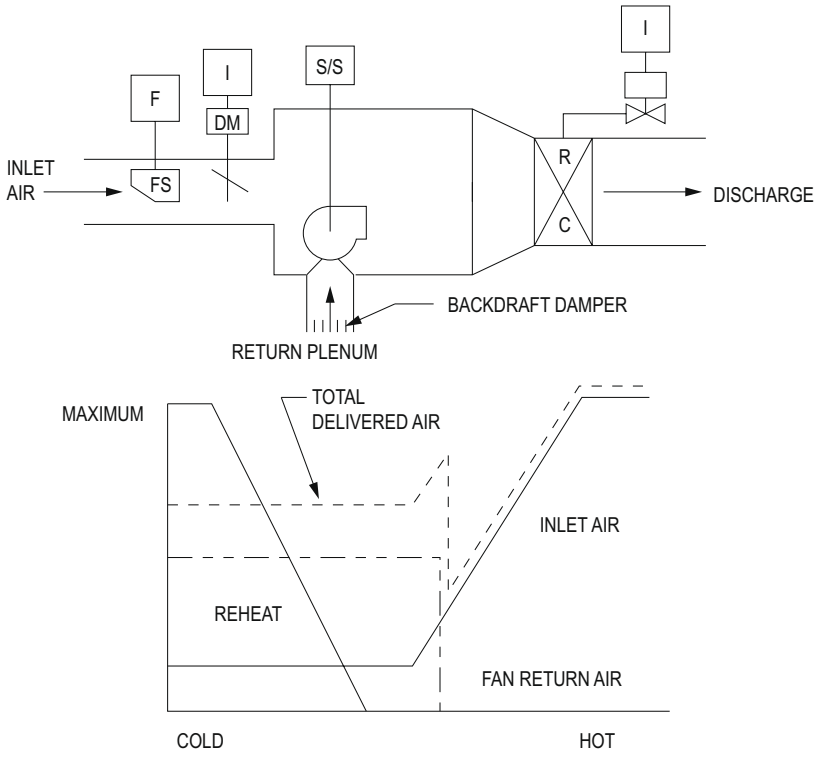


Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Fig. 28.

11.9.5 Parallel Fan-Powered VAV Terminal Unit

A parallel fan-powered VAV box is similar to a series fan terminal, except that the fan is in parallel with the primary supply-air VAV damper. The fan typically operates primarily during heating, but can also provide a minimum air exchange rate to the occupied space. Total airflow is the sum of the primary air plus the fan output. A reheat coil can be installed to provide heat, whether the central air-handling unit is turned on or off.

Parallel Fan-Powered VAV Terminal Unit Diagram



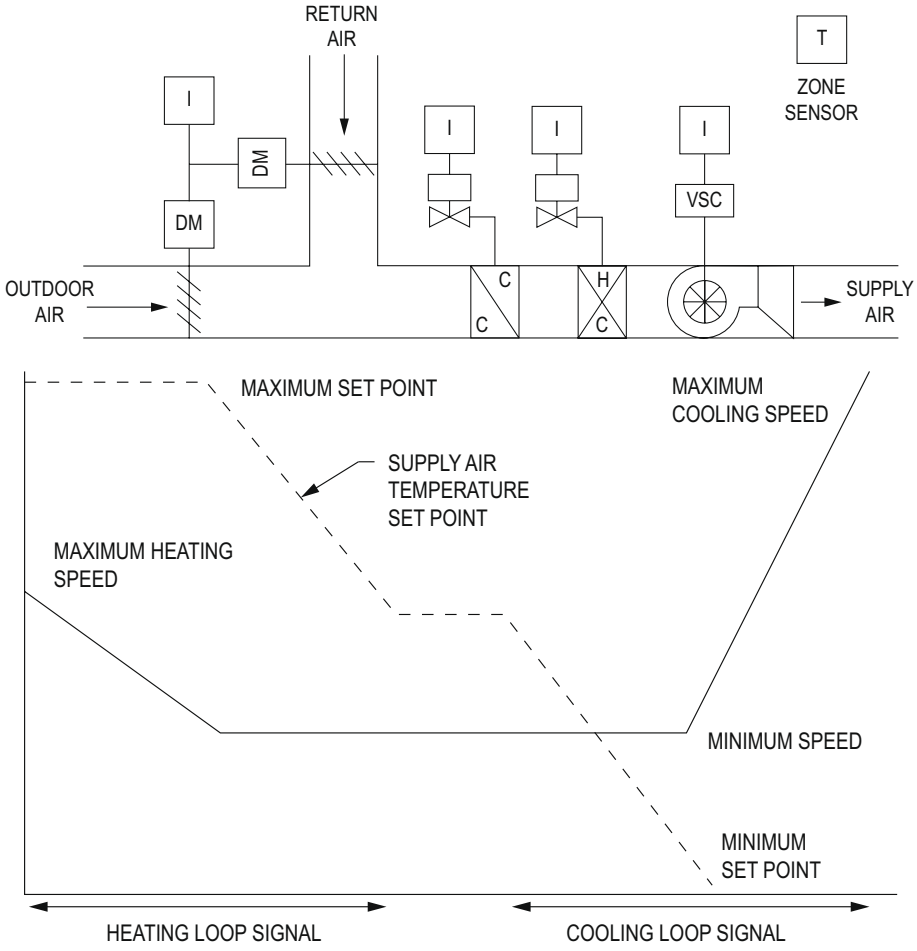
Source: ©ASHRAE, www.ashrae.org., *2015 ASHRAE Handbook—HVAC Applications*, Chapter 47, Design and Application of Controls, Fig. 29.

11.10 Air-Handling Units

11.10.1 Typical Single-Zone Air-Handling Unit

A typical single-zone air-handling unit control arrangement is shown below. The heating coil can be located in front of the cooling coil to provide freeze protection and preheat the air before it reaches the cooling coil. Locating the heating coil after the cooling coil provides dehumidification with reheat to prevent overcooling the supply air. If the cooling coil is a DX coil, freezing is not a concern.

Single-Zone VAV Fan System Diagram



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