APPENDIX A.1

Fundamental Constants and Conversion Factors

A.1-1 Gas Law Constant R

Numerical Value	*Units*
1.9872	g cal/g mol · K
1.9872	btu/lb mol · °R
82.057	cm^3 · atm/g mol · K
8314.34	J/kg mol · K
82.057×10^{-3}	m^3 · atm/kg mol · K
8314.34	kg · m^2/s^2 · kg mol · K
10.731	$ft^3 \cdot lb_f/in.^2$ · lb mol · °R
0.7302	ft^3 · atm/lb mol · °R
1545.3	ft · lb_f/lb mol · °R
8314.34	m^3 · Pa/kg mol · K

A.1-2 Volume and Density

1 g mol ideal gas at 0°C, 760 mm Hg = 22.4140 liters = 22 414 cm^3
1 lb mol ideal gas at 0°C, 760 mm Hg = 359.05 ft^3
1 kg mol ideal gas at 0°C, 760 mm Hg = 22.414 m^3
Density of dry air at 0°C, 760 mm Hg = 1.2929 g/liter
= 0.080711 lb_m/ft^3
Molecular weight of air = 28.97 lb_m/lb mol = 28.97 g/g mol
1 g/cm^3 = 62.43 lb_m/ft^3 = 1000 kg/m^3
1 g/cm^3 = 8.345 lb_m/U.S. gal
1 lb_m/ft^3 = 16.0185 kg/m^3

A.1-3 Length

1 in. = 2.540 cm
100 cm = 1 m (meter)

$1 \text{ micron} = 10^{-6} \text{ m} = 10^{-4} \text{ cm} = 10^{-3} \text{ mm} = 1 \mu\text{m}$ (micrometer)
1 Å (angstrom) $= 10^{-10} \text{ m} = 10^{-4} \mu\text{m}$
$1 \text{ mile} = 5280 \text{ ft}$
$1 \text{ m} = 3.2808 \text{ ft} = 39.37 \text{ in.}$

A.1-4 Mass

$1 \text{ lb}_m = 453.59 \text{ g} = 0.45359 \text{ kg}$
$1 \text{ lb}_m = 16 \text{ oz} = 7000 \text{ grains}$
$1 \text{ kg} = 1000 \text{ g} = 2.2046 \text{ lb}_m$
$1 \text{ ton (short)} = 2000 \text{ lb}_m$
$1 \text{ ton (long)} = 2240 \text{ lb}_m$
$1 \text{ ton (metric)} = 1000 \text{ kg}$

A.1-5 Standard Acceleration of Gravity

$g = 9.80665 \text{ m/s}^2$
$g = 980.665 \text{ cm/s}^2$
$g = 32.174 \text{ ft/s}^2$
g_c (gravitational conversion factor) $= 32.1740 \text{ lb}_m \cdot \text{ft/lb}_f \cdot \text{s}^2$
$= 980.665 \text{ g}_m \cdot \text{cm/g}_f \cdot \text{s}^2$

A.1-6 Volume

$1 \text{ L (liter)} = 1000 \text{ cm}^3$	$1 \text{ m}^3 = 1000 \text{ L (liter)}$
$1 \text{ in.}^3 = 16.387 \text{ cm}^3$	$1 \text{ U.S. gal} = 4 \text{ qt}$
$1 \text{ ft}^3 = 28.317 \text{ L (liter)}$	$1 \text{ U.S. gal} = 3.7854 \text{ L (liter)}$
$1 \text{ ft}^3 = 0.028317 \text{ m}^3$	$1 \text{ U.S. gal} = 3785.4 \text{ cm}^3$
$1 \text{ ft}^3 = 7.481 \text{ U.S. gal}$	$1 \text{ British gal} = 1.20094 \text{ U.S. gal}$
$1 \text{ m}^3 = 264.17 \text{ U.S. gal}$	$1 \text{ m}^3 = 35.313 \text{ ft}^3$

A.1-7 Force

$1 \text{ g} \cdot \text{cm/s}^2 \text{ (dyn)} = 10^{-5} \text{ kg} \cdot \text{m/s}^2 = 10^{-5} \text{ N (newton)}$
$1 \text{ g} \cdot \text{cm/s}^2 = 7.2330 \times 10^{-5} \text{ lb}_m \cdot \text{ft/s}^2 \text{ (poundal)}$
$1 \text{ kg} \cdot \text{m/s}^2 = 1 \text{ N (newton)}$
$1 \text{ lb}_f = 4.4482 \text{ N}$
$1 \text{ g} \cdot \text{cm/s}^2 = 2.2481 \times 10^{-6} \text{ lb}_f$

A.1-8 Pressure

$1 \text{ bar} = 1 \times 10^5 \text{ Pa (pascal)} = 1 \times 10^5 \text{ N/m}^2$
$1 \text{ psia} = 1 \text{ lb}_f/\text{in.}^2$
$1 \text{ psia} = 2.0360 \text{ in. Hg at } 0°\text{C}$
$1 \text{ psia} = 2.311 \text{ ft } H_2O \text{ at } 70°\text{F}$
$1 \text{ psia} = 51.715 \text{ mm Hg at } 0°\text{C} \ (\rho_{Hg} = 13.5955 \text{ g/cm}^3)$
$1 \text{ atm} = 14.696 \text{ psia} = 1.01325 \times 10^5 \text{ N/m}^2 = 1.01325 \text{ bar}$
$1 \text{ atm} = 760 \text{ mm Hg at } 0°\text{C} = 1.01325 \times 10^5 \text{ Pa}$
$1 \text{ atm} = 29.921 \text{ in. Hg at } 0°\text{C}$
$1 \text{ atm} = 33.90 \text{ ft } H_2O \text{ at } 4°\text{C}$

$1 \text{ psia} = 6.89476 \times 10^4 \text{ g/cm} \cdot \text{s}^2$
$1 \text{ psia} = 6.89476 \times 10^4 \text{ dyn/cm}^2$
$1 \text{ dyn/cm}^2 = 2.0886 \times 10^{-3} \text{ lb}_f/\text{ft}^2$
$1 \text{ psia} = 6.89476 \times 10^3 \text{ N/m}^2 = 6.89476 \times 10^3 \text{ Pa}$
$1 \text{ lb}_f/\text{ft}^2 = 4.7880 \times 10^2 \text{ dyn/cm}^2 = 47.880 \text{ N/m}^2$
$1 \text{ mm Hg (0°C)} = 1.333224 \times 10^2 \text{ N/m}^2 = 0.1333224 \text{ kPa}$

A.1-9 Power

$1 \text{ hp} = 0.74570 \text{ kW}$
$1 \text{ hp} = 550 \text{ ft} \cdot \text{lb}_f/\text{s}$
$1 \text{ hp} = 0.7068 \text{ btu/s}$
$1 \text{ watt (W)} = 14.340 \text{ cal/min}$
$1 \text{ btu/h} = 0.29307 \text{ W (watt)}$
$1 \text{ J/s (joule/s)} = 1 \text{ W}$

A.1-10 Heat, Energy, Work

$1 \text{ J} = 1 \text{ N} \cdot \text{m} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^2$
$1 \text{ kg} \cdot \text{m}^2/\text{s}^2 = 1 \text{ J (joule)} = 10^7 \text{ g} \cdot \text{cm}^2/\text{s}^2 \text{ (erg)}$
$1 \text{ btu} = 1055.06 \text{ J} = 1.05506 \text{ kJ}$
$1 \text{ btu} = 252.16 \text{ cal (thermochemical)}$
$1 \text{ kcal (thermochemical)} = 1000 \text{ cal} = 4.1840 \text{ kJ}$
$1 \text{ cal (thermochemical)} = 4.1840 \text{ J}$
$1 \text{ cal (IT)} = 4.1868 \text{ J}$
$1 \text{ btu} = 251.996 \text{ cal (IT)}$
$1 \text{ btu} = 778.17 \text{ ft} \cdot \text{lb}_f$
$1 \text{ hp} \cdot \text{h} = 0.7457 \text{ kW} \cdot \text{h}$
$1 \text{ hp} \cdot \text{h} = 2544.5 \text{ btu}$
$1 \text{ ft} \cdot \text{lb}_f = 1.35582 \text{ J}$
$1 \text{ ft} \cdot \text{lb}_f/\text{lb}_m = 2.9890 \text{ J/kg}$

A.1-11 Thermal Conductivity

$1 \text{ btu/h} \cdot \text{ft} \cdot °\text{F} = 4.1365 \times 10^{-3} \text{ cal/s} \cdot \text{cm} \cdot °\text{C}$
$1 \text{ btu/h} \cdot \text{ft} \cdot °\text{F} = 1.73073 \text{ W/m} \cdot \text{K}$

A.1-12 Heat-Transfer Coefficient

$1 \text{ btu/h} \cdot \text{ft}^2 \cdot °\text{F} = 1.3571 \times 10^{-4} \text{ cal/s} \cdot \text{cm}^2 \cdot °\text{C}$
$1 \text{ btu/h} \cdot \text{ft}^2 \cdot °\text{F} = 5.6783 \times 10^{-4} \text{ W/cm}^2 \cdot °\text{C}$
$1 \text{ btu/h} \cdot \text{ft}^2 \cdot °\text{F} = 5.6783 \text{ W/m}^2 \cdot \text{K}$
$1 \text{ kcal/h} \cdot \text{m}^2 \cdot °\text{F} = 0.2048 \text{ btu/h} \cdot \text{ft}^2 \cdot °\text{F}$

A.1-13 Viscosity

$1 \text{ cp} = 10^{-2} \text{ g/cm} \cdot \text{s (poise)}$
$1 \text{ cp} = 2.4191 \text{ lb}_m/\text{ft} \cdot \text{h}$
$1 \text{ cp} = 6.7197 \times 10^{-4} \text{ lb}_m/\text{ft} \cdot \text{s}$
$1 \text{ cp} = 10^{-3} \text{ Pa} \cdot \text{s} = 10^{-3} \text{ kg/m} \cdot \text{s} = 10^{-3} \text{ N} \cdot \text{s/m}^2$
$1 \text{ cp} = 2.0886 \times 10^{-5} \text{ lb}_f \cdot \text{s/ft}^2$
$1 \text{ Pa} \cdot \text{s} = 1 \text{ N} \cdot \text{s/m}^2 = 1 \text{ kg/m} \cdot \text{s} = 1000 \text{ cp} = 0.67197 \text{ lb}_m/\text{ft} \cdot \text{s}$

A.1-14 Diffusivity

$1\ \text{cm}^2/\text{s} = 3.875\ \text{ft}^2/\text{h}$ $\quad$ $1\ \text{m}^2/\text{s} = 3.875 \times 10^4\ \text{ft}^2/\text{h}$
$1\ \text{cm}^2/\text{s} = 10^{-4}\ \text{m}^2/\text{s}$ $\quad$ $1\ \text{centistoke} = 10^{-2}\ \text{cm}^2/\text{s}$
$1\ \text{m}^2/\text{h} = 10.764\ \text{ft}^2/\text{h}$

A.1-15 Mass Flux and Molar Flux

$1\ \text{g/s} \cdot \text{cm}^2 = 7.3734 \times 10^3\ \text{lb}_m/\text{h} \cdot \text{ft}^2$
$1\ \text{g mol/s} \cdot \text{cm}^2 = 7.3734 \times 10^3\ \text{lb mol/h} \cdot \text{ft}^2$
$1\ \text{g mol/s} \cdot \text{cm}^2 = 10\ \text{kg mol/s} \cdot \text{m}^2 = 1 \times 10^4\ \text{g mol/s} \cdot \text{m}^2$
$1\ \text{lb mol/h} \cdot \text{ft}^2 = 1.3562 \times 10^{-3}\ \text{kg mol/s} \cdot \text{m}^2$

A.1-16 Heat Flux and Heat Flow

$1\ \text{btu/h} \cdot \text{ft}^2 = 3.1546\ \text{W/m}^2$
$1\ \text{btu/h} = 0.29307\ \text{W}$
$1\ \text{cal/h} = 1.1622 \times 10^{-3}\ \text{W}$

A.1-17 Heat Capacity and Enthalpy

$1\ \text{btu/lb}_m \cdot {}^\circ\text{F} = 4.1868\ \text{kJ/kg} \cdot \text{K}$
$1\ \text{btu/lb}_m \cdot {}^\circ\text{F} = 1.000\ \text{cal/g} \cdot {}^\circ\text{C}$
$1\ \text{btu/lb}_m = 2326.0\ \text{J/kg}$
$1\ \text{ft} \cdot \text{lb}_f/\text{lb}_m = 2.9890\ \text{J/kg}$
$1\ \text{cal (IT)/g} \cdot {}^\circ\text{C} = 4.1868\ \text{kJ/kg} \cdot \text{K}$
$1\ \text{kcal/g mol} = 4.1840 \times 10^3\ \text{kJ/kg mol}$

A.1-18 Mass-Transfer Coefficient

$1\ k_c\ \text{cm/s} = 10^{-2}\ \text{m/s}$
$1\ k_c\ \text{ft/h} = 8.4668 \times 10^{-5}\ \text{m/s}$
$1\ k_x\ \text{g mol/s} \cdot \text{cm}^2 \cdot \text{mol frac} = 10\ \text{kg mol/s} \cdot \text{m}^2 \cdot \text{mol frac}$
$1\ k_x\ \text{g mol/s} \cdot \text{cm}^2 \cdot \text{mol frac} = 1 \times 10^4\ \text{g mol/s} \cdot \text{m}^2 \cdot \text{mol frac}$
$1\ k_x\ \text{lb mol/h} \cdot \text{ft}^2 \cdot \text{mol frac} = 1.3562 \times 10^{-3}\ \text{kg mol/s} \cdot \text{m}^2 \cdot \text{mol frac}$
$1\ k_x a\ \text{lb mol/h} \cdot \text{ft}^3 \cdot \text{mol frac} = 4.449 \times 10^{-3}\ \text{kg mol/s} \cdot \text{m}^3 \cdot \text{mol frac}$
$1\ k_G\ \text{kg mol/s} \cdot \text{m}^2 \cdot \text{atm} = 0.98692 \times 10^{-5}\ \text{kg mol/s} \cdot \text{m}^2 \cdot \text{Pa}$
$1\ k_G a\ \text{kg mol/s} \cdot \text{m}^3 \cdot \text{atm} = 0.98692 \times 10^{-5}\ \text{kg mol/s} \cdot \text{m}^3 \cdot \text{Pa}$

APPENDIX A.2

Physical Properties of Water

A.2-1 Latent Heat of Water at 273.15 K (0°C)

Latent heat of fusion = 1436.3 cal/g mol

= 79.724 cal/g

= 2585.3 btu/lb mol

= 6013.4 kJ/kg mol

Source: O. A. Hougen, K. M. Watson, and R. A. Ragatz, *Chemical Process Principles*, Part I, 2nd ed. New York: John Wiley & Sons, Inc., 1954.

Latent heat of vaporization at 298.15 K (25°C)

Pressure (mm Hg)	*Latent Heat*
23.75	44 020 kJ/kg mol, 10.514 kcal/g mol, 18 925 btu/lb mol
760	44 045 kJ/kg mol, 10.520 kcal/g mol, 18 936 btu/lb mol

Source: National Bureau of Standards, *Circular 500*.

A.2-2 Vapor Pressure of Water

Temperature		*Vapor Pressure*		*Temperature*		*Vapor Pressure*	
K	*°C*	*kPa*	*mm Hg*	*K*	*°C*	*kPa*	*mm Hg*
273.15	0	0.611	4.58	323.15	50	12.333	92.51
283.15	10	1.228	9.21	333.15	60	19.92	149.4
293.15	20	2.338	17.54	343.15	70	31.16	233.7
298.15	25	3.168	23.76	353.15	80	47.34	355.1
303.15	30	4.242	31.82	363.15	90	70.10	525.8
313.15	40	7.375	55.32	373.15	100	101.325	760.0

Source: Physikalish-technishe, Reichsansalt, Holborn, Scheel, and Henning, *Warmetabellen*. Brunswick, Germany: Friedrich Viewig and Son, 1909.

A.2-3 Density of Liquid Water

Temperature		Density		Temperature		Density	
K	°C	g/cm^3	kg/m^3	K	°C	g/cm^3	kg/m^3
273.15	0	0.99987	999.87	323.15	50	0.98807	988.07
277.15	4	1.00000	1000.00	333.15	60	0.98324	983.24
283.15	10	0.99973	999.73	343.15	70	0.97781	977.81
293.15	20	0.99823	998.23	353.15	80	0.97183	971.83
298.15	25	0.99708	997.08	363.15	90	0.96534	965.34
303.15	30	0.99568	995.68	373.15	100	0.95838	958.38
313.15	40	0.99225	992.25				

Source: R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973. With permission.

A.2-4 Viscosity of Liquid Water

Temperature		Viscosity $[(Pa \cdot s)\ 10^3$, $(kg/m \cdot s)\ 10^3$, or cp]	Temperature		Viscosity $[(Pa \cdot s)\ 10^3$, $(kg/m \cdot s)\ 10^3$, or cp]
K	°C		K	°C	
273.15	0	1.7921	323.15	50	0.5494
275.15	2	1.6728	325.15	52	0.5315
277.15	4	1.5674	327.15	54	0.5146
279.15	6	1.4728	329.15	56	0.4985
281.15	8	1.3860	331.15	58	0.4832
283.15	10	1.3077	333.15	60	0.4688
285.15	12	1.2363	335.15	62	0.4550
287.15	14	1.1709	337.15	64	0.4418
289.15	16	1.1111	339.15	66	0.4293
291.15	18	1.0559	341.15	68	0.4174
293.15	20	1.0050	343.15	70	0.4061
293.35	20.2	1.0000	345.15	72	0.3952
295.15	22	0.9579	347.15	74	0.3849
297.15	24	0.9142	349.15	76	0.3750
298.15	25	0.8937	351.15	78	0.3655
299.15	26	0.8737	353.15	80	0.3565
301.15	28	0.8360	355.15	82	0.3478
303.15	30	0.8007	357.15	84	0.3395
305.15	32	0.7679	359.15	86	0.3315
307.15	34	0.7371	361.15	88	0.3239
309.15	36	0.7085	363.15	90	0.3165
311.15	38	0.6814	365.15	92	0.3095
313.15	40	0.6560	367.15	94	0.3027
315.15	42	0.6321	369.15	96	0.2962
317.15	44	0.6097	371.15	98	0.2899
319.15	46	0.5883	373.15	100	0.2838
321.15	48	0.5683			

Source: Bingham, *Fluidity and Plasticity*. New York: McGraw-Hill Book Company, 1922. With permission.

A.2-5 Heat Capacity of Liquid Water at 101.325 kPa (1 Atm)

Temperature		Heat Capacity, c_p		Temperature		Heat Capacity, c_p	
°C	K	cal/g·°C	kJ/kg·K	°C	K	cal/g·°C	kJ/kg·K
0	273.15	1.0080	4.220	50	323.15	0.9992	4.183
10	283.15	1.0019	4.195	60	333.15	1.0001	4.187
20	293.15	0.9995	4.185	70	343.15	1.0013	4.192
25	298.15	0.9989	4.182	80	353.15	1.0029	4.199
30	303.15	0.9987	4.181	90	363.15	1.0050	4.208
40	313.15	0.9987	4.181	100	373.15	1.0076	4.219

Source: N. S. Osborne, H. F. Stimson, and D. C. Ginnings, *Bur. Standards J. Res.*, **23**, 197 (1939).

A.2-6 Thermal Conductivity of Liquid Water

Temperature			Thermal Conductivity	
°C	°F	K	btu/h·ft·°F	W/m·K
0	32	273.15	0.329	0.569
37.8	100	311.0	0.363	0.628
93.3	200	366.5	0.393	0.680
148.9	300	422.1	0.395	0.684
215.6	420	588.8	0.376	0.651
326.7	620	599.9	0.275	0.476

Source: D. L. Timrot and N. B. Vargaftik, *J. Tech. Phys.* (*U.S.S.R.*), 10, 1063 (1940); 6th International Conference on the Properties of Steam, Paris, 1964.

A.2-7 Vapor Pressure of Saturated Ice–Water Vapor and Heat of Sublimation

Temperature			Vapor Pressure			Heat of Sublimation	
K	°F	°C	kPa	psia	mm Hg	btu/lb_m	kJ/kg
273.2	32	0	6.107×10^{-1}	8.858×10^{-2}	4.581	1218.6	2834.5
266.5	20	−6.7	3.478×10^{-1}	5.045×10^{-2}	2.609	1219.3	2836.1
261.0	10	−12.2	2.128×10^{-1}	3.087×10^{-2}	1.596	1219.7	2837.0
255.4	0	−17.8	1.275×10^{-1}	1.849×10^{-2}	0.9562	1220.1	2838.0
249.9	−10	−23.3	7.411×10^{-2}	1.082×10^{-2}	0.5596	1220.3	2838.4
244.3	−20	−28.9	3.820×10^{-2}	6.181×10^{-3}	0.3197	1220.5	2838.9
238.8	−30	−34.4	2.372×10^{-2}	3.440×10^{-3}	0.1779	1220.5	2838.9
233.2	−40	−40.0	1.283×10^{-2}	1.861×10^{-3}	0.09624	1220.5	2838.9

Source: ASHRAE, *Handbook of Fundamentals*. New York: ASHRAE, 1972.

A.2-8 Heat Capacity of Ice

Temperature		c_p		Temperature		c_p	
°F	K	btu/lb$_m$ · °F	kJ/kg · K	°F	K	btu/lb$_m$ · °F	kJ/kg · K
32	273.15	0.500	2.093	−10	249.85	0.461	1.930
20	266.45	0.490	2.052	−20	244.25	0.452	1.892
10	260.95	0.481	2.014	−30	238.75	0.442	1.850
0	255.35	0.472	1.976	−40	233.15	0.433	1.813

Source: Adapted from ASHRAE, *Handbook of Fundamentals*. New York: ASHRAE, 1972.

A.2-9 Properties of Saturated Steam and Water (Steam Table), SI Units

Temperature (°C)	Vapor Pressure (kPa)	Specific Volume (m^3/kg)		Enthalpy (kJ/kg)		Entropy (kJ/kg · K)	
		Liquid	Sat'd Vapor	Liquid	Sat'd Vapor	Liquid	Sat'd Vapor
0.01	0.6113	0.0010002	206.136	0.00	2501.4	0.0000	9.1562
3	0.7577	0.0010001	168.132	12.57	2506.9	0.0457	9.0773
6	0.9349	0.0010001	137.734	25.20	2512.4	0.0912	9.0003
9	1.1477	0.0010003	113.386	37.80	2517.9	0.1362	8.9253
12	1.4022	0.0010005	93.784	50.41	2523.4	0.1806	8.8524
15	1.7051	0.0010009	77.926	62.99	2528.9	0.2245	8.7814
18	2.0640	0.0010014	65.038	75.58	2534.4	0.2679	8.7123
21	2.487	0.0010020	54.514	88.14	2539.9	0.3109	8.6450
24	2.985	0.0010027	45.883	100.70	2545.4	0.3534	8.5794
25	3.169	0.0010029	43.360	104.89	2547.2	0.3674	8.5580
27	3.567	0.0010035	38.774	113.25	2550.8	0.3954	8.5156
30	4.246	0.0010043	32.894	125.79	2556.3	0.4369	8.4533
33	5.034	0.0010053	28.011	138.33	2561.7	0.4781	8.3927
36	5.947	0.0010063	23.940	150.86	2567.1	0.5188	8.3336
40	7.384	0.0010078	19.523	167.57	2574.3	0.5725	8.2570
45	9.593	0.0010099	15.258	188.45	2583.2	0.6387	8.1648
50	12.349	0.0010121	12.032	209.33	2592.1	0.7038	8.0763
55	15.758	0.0010146	9.568	230.23	2600.9	0.7679	7.9913
60	19.940	0.0010172	7.671	251.13	2609.6	0.8312	7.9096
65	25.03	0.0010199	6.197	272.06	2618.3	0.8935	7.8310
70	31.19	0.0010228	5.042	292.98	2626.8	0.9549	7.7553
75	38.58	0.0010259	4.131	313.93	2635.3	1.0155	7.6824
80	47.39	0.0010291	3.407	334.91	2643.7	1.0753	7.6122
85	57.83	0.0010325	2.828	355.90	2651.9	1.1343	7.5445
90	70.14	0.0010360	2.361	376.92	2660.1	1.1925	7.4791
95	84.55	0.0010397	1.9819	397.96	2668.1	1.2500	7.4159
100	101.35	0.0010435	1.6729	419.04	2676.1	1.3069	7.3549

A.2-9 SI Units, *Continued*

Temperature (°C)	Vapor Pressure (kPa)	Specific Volume (m³/kg)		Enthalpy (kJ/kg)		Entropy (kJ/kg · K)	
		Liquid	Sat'd Vapor	Liquid	Sat'd Vapor	Liquid	Sat'd Vapor
105	120.82	0.0010475	1.4194	440.15	2683.8	1.3630	7.2958
110	143.27	0.0010516	1.2102	461.30	2691.5	1.4185	7.2387
115	169.06	0.0010559	1.0366	482.48	2699.0	1.4734	7.1833
120	198.53	0.0010603	0.8919	503.71	2706.3	1.5276	7.1296
125	232.1	0.0010649	0.7706	524.99	2713.5	1.5813	7.0775
130	270.1	0.0010697	0.6685	546.31	2720.5	1.6344	7.0269
135	313.0	0.0010746	0.5822	567.69	2727.3	1.6870	6.9777
140	316.3	0.0010797	0.5089	589.13	2733.9	1.7391	6.9299
145	415.4	0.0010850	0.4463	610.63	2740.3	1.7907	6.8833
150	475.8	0.0010905	0.3928	632.20	2746.5	1.8418	6.8379
155	543.1	0.0010961	0.3468	653.84	2752.4	1.8925	6.7935
160	617.8	0.0011020	0.3071	675.55	2758.1	1.9427	6.7502
165	700.5	0.0011080	0.2727	697.34	2763.5	1.9925	6.7078
170	791.7	0.0011143	0.2428	719.21	2768.7	2.0419	6.6663
175	892.0	0.0011207	0.2168	741.17	2773.6	2.0909	6.6256
180	1002.1	0.0011274	0.19405	763.22	2778.2	2.1396	6.5857
190	1254.4	0.0011414	0.15654	807.62	2786.4	2.2359	6.5079
200	1553.8	0.0011565	0.12736	852.45	2793.2	2.3309	6.4323
225	2548	0.0011992	0.07849	966.78	2803.3	2.5639	6.2503
250	3973	0.0012512	0.05013	1085.36	2801.5	2.7927	6.0730
275	5942	0.0013168	0.03279	1210.07	2785.0	3.0208	5.8938
300	8581	0.0010436	0.02167	1344.0	2749.0	3.2534	5.7045

Source: Abridged from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables—Metric Units*. New New York: John Wiley & Sons, Inc., 1969. Reprinted by permission of John Wiley & Sons, Inc.

A.2-9 Properties of Saturated Steam and Water (Steam Table), English Units

Temperature (°F)	Vapor Pressure (psia)	Specific Volume (ft^3/lb_m)		Enthalpy (btu/lb_m)		Entropy ($btu/lb_m \cdot °F$)	
		Liquid	Sat'd Vapor	Liquid	Sat'd Vapor	Liquid	Sat'd Vapor
32.02	0.08866	0.016022	3302	0.00	1075.4	0.000	2.1869
35	0.09992	0.016021	2948	3.00	1076.7	0.00607	2.1764
40	0.12166	0.016020	2445	8.02	1078.9	0.01617	2.1592
45	0.14748	0.016021	2037	13.04	1081.1	0.02618	2.1423
50	0.17803	0.016024	1704.2	18.06	1083.3	0.03607	2.1259
55	0.2140	0.016029	1431.4	23.07	1085.5	0.04586	2.1099

Temperature (°F)	Vapor Pressure (psia)	Specific Volume (ft^3/lb_m)		Enthalpy (btu/lb_m)		Entropy ($btu/lb_m \cdot °F$)	
		Liquid	Sat'd Vapor	Liquid	Sat'd Vapor	Liquid	Sat'd Vapor
60	0.2563	0.016035	1206.9	28.08	1087.7	0.05555	2.0943
65	0.3057	0.016042	1021.5	33.09	1089.9	0.06514	2.0791
70	0.3622	0.016051	867.7	38.09	1092.0	0.07463	2.0642
75	0.4300	0.016061	739.7	43.09	1094.2	0.08402	2.0497
80	0.5073	0.016073	632.8	48.09	1096.4	0.09332	2.0356
85	0.5964	0.016085	543.1	53.08	1098.6	0.10252	2.0218
90	0.6988	0.016099	467.7	58.07	1100.7	0.11165	2.0083
95	0.8162	0.016114	404.0	63.06	1102.9	0.12068	1.9951
100	0.9503	0.016130	350.0	68.05	1105.0	0.12963	1.9822
110	1.2763	0.016166	265.1	78.02	1109.3	0.14730	1.9574
120	1.6945	0.016205	203.0	88.00	1113.5	0.16465	1.9336
130	2.225	0.016247	157.17	97.98	1117.8	0.18172	1.9109
140	2.892	0.016293	122.88	107.96	1121.9	0.19851	1.8892
150	3.722	0.016343	96.99	117.96	1126.1	0.21503	1.8684
160	4.745	0.016395	77.23	127.96	1130.1	0.23130	1.8484
170	5.996	0.016450	62.02	137.97	1134.2	0.24732	1.8293
180	7.515	0.016509	50.20	147.99	1138.2	0.26311	1.8109
190	9.343	0.016570	40.95	158.03	1142.1	0.27866	1.7932
200	11.529	0.016634	33.63	168.07	1145.9	0.29400	1.7762
210	14.125	0.016702	27.82	178.14	1149.7	0.30913	1.7599
212	14.698	0.016716	26.80	180.16	1150.5	0.31213	1.7567
220	17.188	0.016772	23.15	188.22	1153.5	0.32406	1.7441
230	20.78	0.016845	19.386	198.32	1157.1	0.33880	1.7289
240	24.97	0.016922	16.327	208.44	1160.7	0.35335	1.7143
250	29.82	0.017001	13.826	218.59	1164.2	0.36772	1.7001
260	35.42	0.017084	11.768	228.76	1167.6	0.38193	1.6864
270	41.85	0.017170	10.066	238.95	1170.9	0.39597	1.6731
280	49.18	0.017259	8.650	249.18	1174.1	0.40986	1.6602
290	57.33	0.017352	7.467	259.44	1177.2	0.42360	1.6477
300	66.98	0.017448	6.472	269.73	1180.2	0.43720	1.6356
310	77.64	0.017548	5.632	280.06	1183.0	0.45067	1.6238
320	89.60	0.017652	4.919	290.43	1185.8	0.46400	1.6123
330	103.00	0.017760	4.312	300.84	1188.4	0.47722	1.6010
340	117.93	0.017872	3.792	311.30	1190.8	0.49031	1.5901
350	134.53	0.017988	3.346	321.80	1193.1	0.50329	1.5793
360	152.92	0.018108	2.961	332.35	1195.2	0.51617	1.5688
370	173.23	0.018233	2.628	342.96	1197.2	0.52894	1.5585
380	195.60	0.018363	2.339	353.62	1199.0	0.54163	1.5483
390	220.2	0.018498	2.087	364.34	1200.6	0.55422	1.5383
400	247.1	0.018638	1.8661	375.12	1202.0	0.56672	1.5284
410	276.5	0.018784	1.6726	385.97	1203.1	0.57916	1.5187
450	422.1	0.019433	1.1011	430.2	1205.6	0.6282	1.4806

Source: Abridged from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables—English Units.* New York: John Wiley & Sons, Inc., 1969. Reprinted by permission of John Wiley & Sons, Inc.

A.2-10 Properties of Superheated Steam (Steam Table), SI Units (v, specific volume, m^3/kg; H, enthalpy, kJ/kg; s, entropy, kJ/kg · K)

Absolute Pressure, kPa (Sat. Temp., °C)		*Temperature (°C)*							
		100	*150*	*200*	*250*	*300*	*360*	*420*	*500*
	v	17.196	19.512	21.825	24.136	26.445	29.216	31.986	35.679
10	H	2687.5	2783.0	2879.5	2977.3	3076.5	3197.6	3320.9	3489.1
(45.81)	s	8.4479	8.6882	8.9038	9.1002	9.2813	9.4821	9.6682	9.8978
	v	3.418	3.889	4.356	4.820	5.284	5.839	6.394	7.134
50	H	2682.5	2780.1	2877.7	2976.0	3075.5	3196.8	3320.4	3488.7
(81.33)	s	7.6947	7.9401	8.1580	8.3556	8.5373	8.7385	8.9249	9.1546
	v	2.270	2.587	2.900	3.211	3.520	3.891	4.262	4.755
75	H	2679.4	2778.2	2876.5	2975.2	3074.9	3196.4	3320.0	3488.4
(91.78)	s	7.5009	7.7496	7.9690	8.1673	8.3493	8.5508	8.7374	8.9672
	v	1.6958	1.9364	2.172	2.406	2.639	2.917	3.195	3.565
100	H	2672.2	2776.4	2875.3	2974.3	3074.3	3195.9	3319.6	3488.1
(99.63)	s	7.3614	7.6134	7.8343	8.0333	8.2158	8.4175	8.6042	8.8342
	v		1.2853	1.4443	1.6012	1.7570	1.9432	2.129	2.376
150	H		2772.6	2872.9	2972.7	3073.1	3195.0	3318.9	3487.6
(111.37)	s		7.4193	7.6433	7.8438	8.0720	8.2293	8.4163	8.6466
	v		0.4708	0.5342	0.5951	0.6548	0.7257	0.7960	0.8893
400	H		2752.8	2860.5	2964.2	3066.8	3190.3	3315.3	3484.9
(143.63)	s		6.9299	7.1706	7.3789	7.5662	7.7712	7.9598	8.1913
	v			0.2999	0.3363	0.3714	0.4126	0.4533	0.5070
700	H			2844.8	2953.6	3059.1	3184.7	3310.9	3481.7
(164.97)	s			6.8865	7.1053	7.2979	7.5063	7.6968	7.9299
	v			0.2060	0.2327	0.2579	0.2873	0.3162	0.3541
1000	H			2827.9	2942.6	3051.2	3178.9	3306.5	3478.5
(179.91)	s			6.6940	6.9247	7.1229	7.3349	7.5275	7.7622
	v			0.13248	0.15195	0.16966	0.18988	0.2095	0.2352
1500	H			2796.8	2923.3	3037.6	3.1692	3299.1	3473.1
(198.32)	s			6.4546	6.7090	6.9179	7.1363	7.3323	7.5698
	v				0.11144	0.12547	0.14113	0.15616	0.17568
2000	H				2902.5	3023.5	3159.3	3291.6	3467.6
(212.42)	s				6.5453	6.7664	6.9917	7.1915	7.4317
	v				0.08700	0.09890	0.11186	0.12414	0.13998
2500	H				2880.1	3008.8	3149.1	3284.0	3462.1
(223.99)	s				6.4085	6.6438	6.8767	7.0803	7.3234
	v				0.07058	0.08114	0.09233	0.10279	0.11619
3000	H				2855.8	2993.5	3138.7	3276.3	3456.5
(233.90)	s				6.2872	6.5390	6.7801	6.9878	7.2338

Source: Abridged from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables—Metric Units*. New York: John Wiley & Sons, Inc., 1969. Reprinted by permission of John Wiley & Sons, Inc.

A.2-10 **Properties of Superheated Steam (Steam Table), English Units (v, specific volume, ft^3/lb_m; H, enthalpy, btu/lb_m; s, entropy, $btu/lb_m \cdot °F$)**

Absolute Pressure, psia (Sat. Temp., °F)		*Temperature (°F)*								
		200	*300*	*400*	*500*	*600*	*700*	*800*	*900*	*1000*
	v	392.5	452.3	511.9	571.5	631.1	690.7	750.3	809.9	869.5
1.0	H	1150.1	1195.7	1241.8	1288.5	1336.1	1384.5	1433.7	1483.8	1534.8
(101.70)	s	2.0508	2.1150	2.1720	2.2235	2.2706	2.3142	2.3550	2.3932	2.4294
	v	78.15	90.24	102.24	114.20	126.15	138.08	150.01	161.94	173.86
5.0	H	1148.6	1194.8	1241.2	1288.2	1335.8	1384.3	1433.5	1483.7	1534.7
(162.21)	s	1.8715	1.9367	1.9941	2.0458	2.0930	2.1367	2.1775	2.2158	2.2520
	v	38.85	44.99	51.03	57.04	63.03	69.01	74.98	80.95	86.91
10.0	H	1146.6	1193.7	1240.5	1287.7	1335.5	1384.0	1433.3	1483.5	1534.6
(193.19)	s	1.7927	1.8592	1.9171	1.9690	2.0164	2.0601	2.1009	2.1393	2.1755
	v		30.52	34.67	38.77	42.86	46.93	51.00	55.07	59.13
14.696	H		1192.6	1239.9	1287.3	1335.2	1383.8	1433.1	1483.4	1534.5
(211.99)	s		1.8157	1.8741	1.9263	1.9737	2.0175	2.0584	2.0967	2.1330
	v		22.36	25.43	28.46	31.47	34.77	37.46	40.45	43.44
20.0	H		1191.5	1239.2	1286.8	1334.8	1383.5	1432.9	1483.2	1534.3
(227.96)	s		1.7805	1.8395	1.8919	1.9395	1.9834	2.0243	2.0627	2.0989
	v		7.260	8.353	9.399	10.425	11.440	12.448	13.452	14.454
60.0	H		1181.9	1233.5	1283.0	1332.1	1381.4	1431.2	1481.8	1533.2
(292.73)	s		1.6496	1.7134	1.7678	1.8165	1.8609	1.9022	1.9408	1.9773
	v			4.934	5.587	6.216	6.834	7.445	8.053	8.657
100.0	H			1227.5	1279.1	1329.3	1379.2	1429.6	1480.5	1532.1
(327.86)	s			1.6517	1.7085	1.7582	1.8033	1.8449	1.8838	1.9204
	v			3.221	3.679	4.111	4.531	4.944	5.353	5.759
150.0	H			1219.5	1274.1	1325.7	1376.6	1427.5	1478.8	1530.7
(358.48)	s			1.5997	1.6598	1.7110	1.7568	1.7989	1.8381	1.8750
	v			2.361	2.724	3.058	3.379	3.693	4.003	4.310
200.0	H			1210.8	1268.8	1322.1	1373.8	1425.3	1477.1	1529.3
(381.86)	s			1.5600	1.6239	1.6767	1.7234	1.7660	1.8055	1.8425
	v				2.150	2.426	2.688	2.943	3.193	3.440
250.0	H				1263.3	1318.3	1371.1	1423.2	1475.3	1527.9
(401.04)	s				1.5948	1.6494	1.6970	1.7401	1.7799	1.8172
	v				1.766	2.004	2.227	2.442	2.653	2.860
300.0	H				1257.5	1314.5	1368.3	1421.0	1473.6	1526.5
(417.43)	s				1.5701	1.6266	1.6751	1.7187	1.7589	1.7964
	v				1.2843	1.4760	1.6503	1.8163	1.9776	2.136
400	H				1245.2	1306.6	1362.5	1416.6	1470.1	1523.6
(444.70)	s				1.5282	1.5892	1.6397	1.6884	1.7252	1.7632

Source: Abridged from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables—Metric Units*. New York: John Wiley & Sons, Inc., 1969. Reprinted by permission of John Wiley & Sons, Inc.

A.2-11 Heat-Transfer Properties of Liquid Water, SI Units

T (°C)	T (K)	ρ (kg/m³)	c_p (kJ/kg·K)	$\mu \times 10^3$ (Pa·s, or kg/m·s)	k (W/m·K)	N_{Pr}	$\beta \times 10^4$ (1/K)	$(g\beta\rho^2/\mu^2) \times 10^{-8}$ (1/K·m³)
0	273.2	999.6	4.229	1.786	0.5694	13.3	−0.630	
15.6	288.8	998.0	4.187	1.131	0.5884	8.07	1.44	10.93
26.7	299.9	996.4	4.183	0.860	0.6109	5.89	2.34	30.70
37.8	311.0	994.7	4.183	0.682	0.6283	4.51	3.24	68.0
65.6	338.8	981.9	4.187	0.432	0.6629	2.72	5.04	256.2
93.3	366.5	962.7	4.229	0.3066	0.6802	1.91	6.66	642
121.1	394.3	943.5	4.271	0.2381	0.6836	1.49	8.46	1300
148.9	422.1	917.9	4.312	0.1935	0.6836	1.22	10.08	2231
204.4	477.6	858.6	4.522	0.1384	0.6611	0.950	14.04	5308
260.0	533.2	784.9	4.982	0.1042	0.6040	0.859	19.8	11 030
315.6	588.8	679.2	6.322	0.0862	0.5071	1.07	31.5	19 260

A.2-11 Heat-Transfer Properties of Liquid Water, English Units

T (°F)	ρ $\left(\frac{lb_m}{ft^3}\right)$	c_p $\left(\frac{btu}{lb_m \cdot °F}\right)$	$\mu \times 10^3$ $\left(\frac{lb_m}{ft \cdot s}\right)$	k $\left(\frac{btu}{h \cdot ft \cdot °F}\right)$	N_{Pr}	$\beta \times 10^4$ (1/°R)	$(g\beta\rho^2/\mu^2) \times 10^{-6}$ (1/°R·ft³)
32	62.4	1.01	1.20	0.329	13.3	−0.350	
60	62.3	1.00	0.760	0.340	8.07	0.800	17.2
80	62.2	0.999	0.578	0.353	5.89	1.30	48.3
100	62.1	0.999	0.458	0.363	4.51	1.80	107
150	61.3	1.00	0.290	0.383	2.72	2.80	403
200	60.1	1.01	0.206	0.393	1.91	3.70	1010
250	58.9	1.02	0.160	0.395	1.49	4.70	2045
300	57.3	1.03	0.130	0.395	1.22	5.60	3510
400	53.6	1.08	0.0930	0.382	0.950	7.80	8350
500	49.0	1.19	0.0700	0.349	0.859	11.0	17 350
600	42.4	1.51	0.0579	0.293	1.07	17.5	30 300

A.2-12 Heat-Transfer Properties of Water Vapor (Steam) at 101.32 kPa (1 Atm Abs), SI Units

T (°C)	T (K)	ρ (kg/m^3)	c_p ($kJ/kg \cdot K$)	$\mu \times 10^5$ ($Pa \cdot s$, or $kg/m \cdot s$)	k ($W/m \cdot K$)	N_{Pr}	$\beta \times 10^3$ ($1/K$)	$g\beta\rho^2/\mu^2$ ($1/K \cdot m^3$)
100.0	373.2	0.596	1.888	1.295	0.02510	0.96	2.68	0.557×10^8
148.9	422.1	0.525	1.909	1.488	0.02960	0.95	2.38	0.292×10^8
204.4	477.6	0.461	1.934	1.682	0.03462	0.94	2.09	0.154×10^8
260.0	533.2	0.413	1.968	1.883	0.03946	0.94	1.87	0.0883×10^8
315.6	588.8	0.373	1.997	2.113	0.04448	0.94	1.70	52.1×10^5
371.1	644.3	0.341	2.030	2.314	0.04985	0.93	1.55	33.1×10^5
426.7	699.9	0.314	2.068	2.529	0.05556	0.92	1.43	21.6×10^5

A.2-12 Heat-Transfer Properties of Water Vapor (Steam) at 101.32 kPa (1 Atm Abs), English Units

T (°F)	ρ $\left(\frac{lb_m}{ft^3}\right)$	c_p $\left(\frac{btu}{lb_m \cdot °F}\right)$	$\mu \times 10^5$ $\left(\frac{lb_m}{ft \cdot s}\right)$	k $\left(\frac{btu}{h \cdot ft \cdot °F}\right)$	N_{Pr}	$\beta \times 10^3$ ($1/°R$)	$g\beta\rho^2/\mu^2$ ($1/°R \cdot ft^3$)
212	0.0372	0.451	0.870	0.0145	0.96	1.49	0.877×10^6
300	0.0328	0.456	1.000	0.0171	0.95	1.32	0.459×10^6
400	0.0288	0.462	1.130	0.0200	0.94	1.16	0.243×10^6
500	0.0258	0.470	1.265	0.0228	0.94	1.04	0.139×10^6
600	0.0233	0.477	1.420	0.0257	0.94	0.943	82×10^3
700	0.0213	0.485	1.555	0.0288	0.93	0.862	52.1×10^3
800	0.0196	0.494	1.700	0.0321	0.92	0.794	34.0×10^3

Source: D. L. Timrot and N. B. Vargaftik, *J. Tech. Phys. (U.S.S.R.)*, **10**, 1063 (1940); R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables*. New York: John Wiley & Sons, Inc., 1969; National Research Council, *International Critical Tables*. New York: McGraw-Hill Book Company, 1929; L. S. Marks, *Mechanical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1951.

APPENDIX A.3

Physical Properties of Inorganic and Organic Compounds

A.3-1 **Standard Heats of Formation at 298.15 K (25°C) and 101.325 kPa (1 Atm Abs), (*c*) = crystalline, (*g*) = gas, (*l*) = liquid**

	ΔH_f°			ΔH_f°	
Compound	*(kJ/kg mol)10⁻³*	*kcal/g mol*	*Compound*	*(kJ/kg mol)10⁻³*	*kcal/g mol*
$NH_3(g)$	−46.19	−11.04	$CaCO_3(c)$	−1206.87	−288.45
$NO(g)$	+90.374	+21.600	$CaO(c)$	−635.5	−151.9
$H_2O(l)$	−285.840	−68.3174	$CO(g)$	−110.523	−26.4157
$H_2O(g)$	−241.826	−57.7979	$CO_2(g)$	−393.513	−94.0518
$HCN(g)$	+130.1	+31.1	$CH_4(g)$	−74.848	−17.889
$HCl(g)$	−92.312	−22.063	$C_2H_6(g)$	−84.667	−20.236
$H_2SO_4(l)$	−811.32	−193.91	$C_3H_8(g)$	−103.847	−24.820
$H_3PO_4(c)$	−1281.1	−306.2	$CH_3OH(l)$	−238.66	−57.04
$NaCl(c)$	−411.003	−98.232	$CH_3CH_3OH(l)$	−277.61	−66.35
$NH_4Cl(c)$	−315.39	−75.38			

Source: J. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; and O. A. Hougen, K. M. Watson, and R. A. Ragatz, *Chemical Process Principles*, Part I, 2nd ed. New York: John Wiley & Sons, Inc., 1954.

A.3-2 Standard Heats of Combustion at 298.15 K (25°C) and 101.325 kPa (1 Atm Abs)
(g) = gas, (l) = liquid, (s) = solid

Compound	Combustion Reaction	ΔH_c° kcal/g mol	ΔH_c° (kJ/kg mol)10^{-3}
$C(s)$	$C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g)$	−26.4157	−110.523
$CO(g)$	$CO(g) + \frac{1}{2}O_2(g) \rightarrow CO_2(g)$	−67.6361	−282.989
$C(s)$	$C(s) + O_2(g) \rightarrow CO_2(g)$	−94.0518	−393.513
$H_2(g)$	$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)$	−68.3174	−285.840
$H_2(g)$	$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(g)$	−57.7979	−241.826
$CH_4(g)$	$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$	−212.798	−890.346
$C_2H_6(g)$	$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$	−372.820	−1559.879
$C_3H_8(g)$	$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$	−530.605	−2220.051
d-Glucose (dextrose) $C_6H_{12}O_6(s)$	$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$	−673	−2816
Lactose (anhydrous) $C_{12}H_{22}O_{11}(s)$	$C_{12}H_{22}O_{11}(s) + 12O_2(g) \rightarrow 12CO_2(g) + 11H_2O(l)$	−1350.1	−5648.8
Sucrose $C_{12}H_{22}O_{11}(s)$	$C_{12}H_{22}O_{11}(s) + 12O_2(g) \rightarrow 12CO_2(g) + 11H_2O(l)$	−1348.9	−5643.8

Source: R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; and O. A. Hougen, K. M. Watson, and R. A. Ragatz, *Chemical Process Principles*, Part I, 2nd ed. New York: John Wiley & Sons, Inc., 1954.

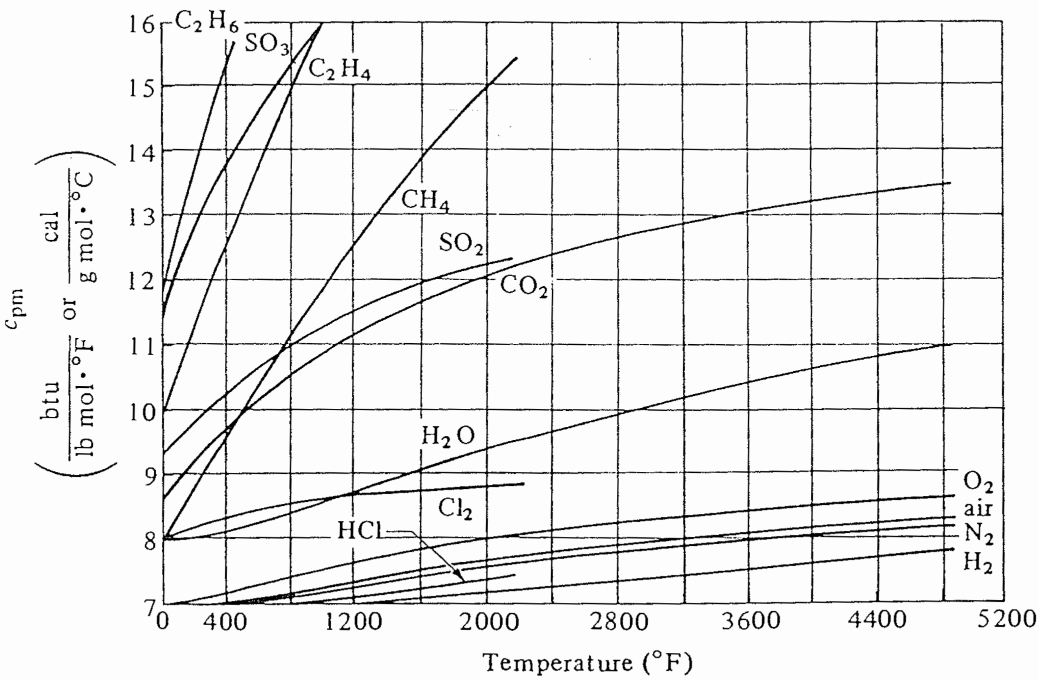


FIGURE A.3-1. *Mean molar heat capacities from 77°F (25°C) to t°F at constant pressure of 101.325 kPa (1 atm abs). (From O. A. Hougen, K. M. Watson, and R. A. Ragatz, Chemical Process Principles, Part I, 2nd ed. New York: John Wiley & Sons, Inc., 1954. With permission.)*

A.3-3 Physical Properties of Air at 101.325 kPa (1 Atm Abs), SI Units

T (°C)	T (K)	ρ (kg/m^3)	c_p ($kJ/kg \cdot K$)	$\mu \times 10^5$ ($Pa \cdot s$, or $kg/m \cdot s$)	k ($W/m \cdot K$)	N_{Pr}	$\beta \times 10^3$ ($1/K$)	$g\beta\rho^2/\mu^2$ ($1/K \cdot m^3$)
−17.8	255.4	1.379	1.0048	1.62	0.02250	0.720	3.92	2.79×10^8
0	273.2	1.293	1.0048	1.72	0.02423	0.715	3.65	2.04×10^8
10.0	283.2	1.246	1.0048	1.78	0.02492	0.713	3.53	1.72×10^8
37.8	311.0	1.137	1.0048	1.90	0.02700	0.705	3.22	1.12×10^8
65.6	338.8	1.043	1.0090	2.03	0.02925	0.702	2.95	0.775×10^8
93.3	366.5	0.964	1.0090	2.15	0.03115	0.694	2.74	0.534×10^8
121.1	394.3	0.895	1.0132	2.27	0.03323	0.692	2.54	0.386×10^8
148.9	422.1	0.838	1.0174	2.37	0.03531	0.689	2.38	0.289×10^8
176.7	449.9	0.785	1.0216	2.50	0.03721	0.687	2.21	0.214×10^8
204.4	477.6	0.740	1.0258	2.60	0.03894	0.686	2.09	0.168×10^8
232.2	505.4	0.700	1.0300	2.71	0.04084	0.684	1.98	0.130×10^8
260.0	533.2	0.662	1.0341	2.80	0.04258	0.680	1.87	0.104×10^8

A.3-3 Physical Properties of Air at 101.325 kPa (1 Atm Abs), English Units

T (°F)	ρ $\left(\frac{lb_m}{ft^3}\right)$	c_p $\left(\frac{btu}{lb_m \cdot °F}\right)$	μ (centipoise)	k $\left(\frac{btu}{h \cdot ft \cdot °F}\right)$	N_{Pr}	$\beta \times 10^3$ ($1/°R$)	$g\beta\rho^2/\mu^2$ ($1/°R \cdot ft^3$)
0	0.0861	0.240	0.0162	0.0130	0.720	2.18	4.39×10^6
32	0.0807	0.240	0.0172	0.0140	0.715	2.03	3.21×10^6
50	0.0778	0.240	0.0178	0.0144	0.713	1.96	2.70×10^6
100	0.0710	0.240	0.0190	0.0156	0.705	1.79	1.76×10^6
150	0.0651	0.241	0.0203	0.0169	0.702	1.64	1.22×10^6
200	0.0602	0.241	0.0215	0.0180	0.694	1.52	0.840×10^6
250	0.0559	0.242	0.0227	0.0192	0.692	1.41	0.607×10^6
300	0.0523	0.243	0.0237	0.0204	0.689	1.32	0.454×10^6
350	0.0490	0.244	0.0250	0.0215	0.687	1.23	0.336×10^6
400	0.0462	0.245	0.0260	0.0225	0.686	1.16	0.264×10^6
450	0.0437	0.246	0.0271	0.0236	0.674	1.10	0.204×10^6
500	0.0413	0.247	0.0280	0.0246	0.680	1.04	0.163×10^6

Source: National Bureau of Standards, *Circular* **461C**, 1947; **564**, 1955; NBS–NACA, *Tables of Thermal Properties of Gases*, 1949; F. G. Keyes, *Trans. A.S.M.E.*, **73**, 590, 597 (1951); **74**, 1303 (1952); D. D. Wagman, *Selected Values of Chemical Thermodynamic Properties*. Washington, D.C.: National Bureau of Standards, 1953.

A.3-4 Viscosity of Gases at 101.325 kPa (1 Atm Abs) [Viscosity in (Pa · s) 10^3, (kg/m · s) 10^3, or cp]

Temperature							
K	*°F*	*°C*	H_2	O_2	N_2	*CO*	CO_2
255.4	0	−17.8	0.00800	0.0181	0.0158	0.0156	0.0128
273.2	32	0	0.00840	0.0192	0.0166	0.0165	0.0137
283.2	50	10.0	0.00862	0.0197	0.0171	0.0169	0.0141
311.0	100	37.8	0.00915	0.0213	0.0183	0.0183	0.0154
338.8	150	65.6	0.00960	0.0228	0.0196	0.0195	0.0167
366.5	200	93.3	0.0101	0.0241	0.0208	0.0208	0.0179
394.3	250	121.1	0.0106	0.0256	0.0220	0.0220	0.0191
422.1	300	148.9	0.0111	0.0267	0.0230	0.0231	0.0203
449.9	350	176.7	0.0115	0.0282	0.0240	0.0242	0.0215
477.6	400	204.4	0.0119	0.0293	0.0250	0.0251	0.0225
505.4	450	232.2	0.0124	0.0307	0.0260	0.0264	0.0236
533.2	500	260.0	0.0128	0.0315	0.0273	0.0276	0.0247

Source: National Bureau of Standards, *Circular* 461C, 1947; 564, 1955; NBS–NACA, *Tables of Thermal Properties of Gases*, 1949; F. G. Keyes, *Trans. A.S.M.E.*, 73, 590, 597 (1951); 74, 1303 (1952); D. D. Wagman, *Selected Values of Chemical Thermodynamic Properties*. Washington, D.C.: National Bureau of Standards, 1953.

A.3-5 Thermal Conductivity of Gases at 101.325 kPa (1 Atm Abs)

Temperature			H_2		O_2		N_2		CO		CO_2	
K	°C	°F	W/m·K	btu/h·ft·°F	W/m·K	btu/h·ft·°F	W/m·K	btu/h·ft·°F	W/m·K	btu/h·ft·°F	W/m·K	btu/h·ft·°F
255.4	−17.8	0	0.1592	0.0920	0.0228	0.0132	0.0228	0.0132	0.0222	0.0128	0.0132	0.0076
273.2	0	32	0.1667	0.0963	0.0246	0.0142	0.0239	0.0138	0.0233	0.0135	0.0145	0.0084
283.2	10.0	50	0.1720	0.0994	0.0253	0.0146	0.0248	0.0143	0.0239	0.0138	0.0152	0.0088
311.0	37.8	100	0.1852	0.107	0.0277	0.0160	0.0267	0.0154	0.0260	0.0150	0.0173	0.0100
338.8	65.6	150	0.1990	0.115	0.0299	0.0173	0.0287	0.0166	0.0279	0.0161	0.0190	0.0110
366.5	93.3	200	0.2111	0.122	0.0320	0.0185	0.0303	0.0175	0.0296	0.0171	0.0216	0.0125
394.3	121.1	250	0.2233	0.129	0.0343	0.0198	0.0329	0.0190	0.0318	0.0184	0.0239	0.0138
422.1	148.9	300	0.2353	0.136	0.0363	0.0210	0.0348	0.0201	0.0338	0.0195	0.0260	0.0150
449.9	176.7	350	0.2458	0.142	0.0382	0.0221	0.0365	0.0211	0.0355	0.0205	0.0286	0.0165
477.6	204.4	400	0.2579	0.149	0.0398	0.0230	0.0382	0.0221	0.0369	0.0213	0.0308	0.0178
505.4	232.2	450	0.2683	0.155	0.0422	0.0244	0.0400	0.0231	0.0384	0.0222	0.0334	0.0193
533.2	260.0	500	0.2786	0.161	0.0438	0.0253	0.0419	0.0242	0.0407	0.0235	0.0355	0.0205

Source: National Bureau of Standards, *Circular* 461C, 1947; **564**, 1955; NBS–NACA, *Table of Thermal Properties of Gases*, 1949; F. G. Keyes, *Trans. A.S.M.E.*, **73**, 590, 597 (1951); **74**, 1303 (1952); D. D. Wagman, *Selected Values of Chemical Thermodynamic Properties*. Washington, D.C.: National Bureau of Standards, 1953.

A.3-6 Heat Capacity of Gases at Constant Pressure at 101.325 kPa (1 Atm Abs)

Temperature			H_2		O_2		N_2		CO		CO_2	
K	$°C$	$°F$	$kJ/kg \cdot K$	$btu/lb_m \cdot °F$	$kJ/kg \cdot K$	$btu/lb_m \cdot °F$	$kJ/kg \cdot K$	$btu/lb_m \cdot °F$	$kJ/kg \cdot K$	$btu/lb_m \cdot °F$	$kJ/kg \cdot K$	$btu/lb_m \cdot °F$
255.4	−17.8	0	14.07	3.36	0.909	0.217	1.034	0.247	1.034	0.247	0.800	0.191
273.2	0	32	14.19	3.39	0.913	0.218	1.038	0.248	1.038	0.248	0.816	0.195
283.2	10.0	50	14.19	3.39	0.917	0.219	1.038	0.248	1.038	0.248	0.825	0.197
311.0	37.8	100	14.32	3.42	0.921	0.220	1.038	0.248	1.043	0.249	0.854	0.204
338.8	65.6	150	14.36	3.43	0.925	0.221	1.038	0.248	1.043	0.249	0.883	0.211
366.5	93.3	200	14.40	3.44	0.929	0.222	1.043	0.249	1.047	0.250	0.904	0.216
394.3	121.1	250	14.44	3.45	0.938	0.224	1.043	0.249	1.047	0.250	0.929	0.222
422.1	148.9	300	14.49	3.46	0.946	0.226	1.047	0.250	1.051	0.251	0.950	0.227
449.9	176.7	350	14.49	3.46	0.955	0.228	1.047	0.250	1.055	0.252	0.976	0.233
477.6	204.4	400	14.49	3.46	0.963	0.230	1.051	0.251	1.059	0.253	0.996	0.238
505.4	232.2	450	14.52	3.47	0.971	0.232	1.055	0.252	1.063	0.254	1.017	0.243
533.2	260.0	500	14.52	3.47	0.976	0.233	1.059	0.253	1.068	0.255	1.030	0.246

Source: National Bureau of Standards, *Circular* **461**C, 1947; **564**, 1955; NBS–NACA, *Tables of Thermal Properties of Gases*, 1949; F. G. Keyes, *Trans. A.S.M.E.*, 73, 590, 597 (1951); 74, 1303 (1952); D. D. Wagman, *Selected Values of Chemical Thermodynamic Properties*. Washington, D.C.: National Bureau of Standards, 1953.

A.3-7 Prandtl Number of Gases at 101.325 kPa (1 Atm Abs)

Temperature							
°C	°F	K	H_2	O_2	N_2	CO	CO_2
−17.8	0	255.4	0.720	0.720	0.720	0.740	0.775
0	32	273.2	0.715	0.711	0.720	0.738	0.770
10.0	50	283.2	0.710	0.710	0.717	0.735	0.769
37.8	100	311.0	0.700	0.707	0.710	0.731	0.764
65.6	150	338.8	0.700	0.706	0.700	0.727	0.755
93.3	200	366.5	0.694	0.703	0.700	0.724	0.752
121.1	250	394.3	0.688	0.703	0.696	0.720	0.746
148.9	300	422.1	0.683	0.703	0.690	0.720	0.738
176.6	350	449.9	0.677	0.704	0.689	0.720	0.734
204.4	400	477.6	0.670	0.706	0.688	0.720	0.725
232.2	450	505.4	0.668	0.702	0.688	0.720	0.716
260.0	500	533.2	0.666	0.700	0.688	0.720	0.702

Source: National Bureau of Standards, *Circular* 461C, 1947; 564, 1955; NBS–NACA, *Tables of Thermal Properties of Gases*, 1949; F. G. Keyes, *Trans. A.S.M.E.*, 73, 590, 597 (1951); 74, 1303 (1952); D. D. Wagman, *Selected Values of Chemical Thermodynamic Properties*. Washington, D.C.: National Bureau of Standards, 1953.

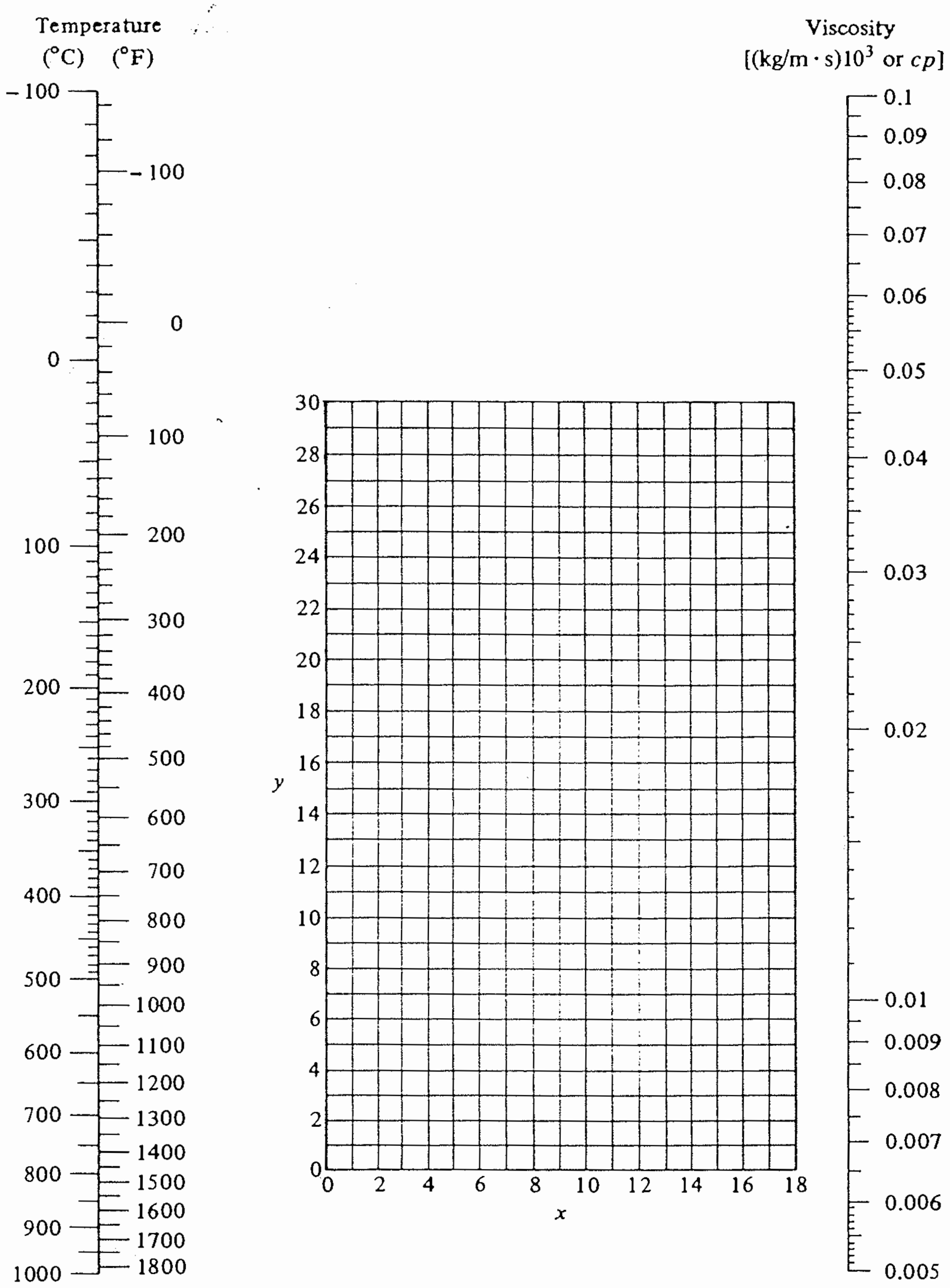


FIGURE A.3-2. *Viscosities of gases at 101.325 kPa (1 atm abs). (From R. H. Perry and C. H. Chilton, Chemical Engineers' Handbook, 5th ed. New York: McGraw-Hill Book Company, 1973. With permission.) See Table A.3-8 for coordinates for use with Fig. A.3-2.*

A.3-8 Viscosities of Gases (Coordinates for Use with Fig. A.3-2)

No.	Gas	X	Y	No.	Gas	X	Y
1	Acetic acid	7.7	14.3	29	Freon-113	11.3	14.0
2	Acetone	8.9	13.0	30	Helium	10.9	20.5
3	Acetylene	9.8	14.9	31	Hexane	8.6	11.8
4	Air	11.0	20.0	32	Hydrogen	11.2	12.4
5	Ammonia	8.4	16.0	33	$3H_2 + 1N_2$	11.2	17.2
6	Argon	10.5	22.4	34	Hydrogen bromide	8.8	20.9
7	Benzene	8.5	13.2	35	Hydrogen chloride	8.8	18.7
8	Bromine	8.9	19.2	36	Hydrogen cyanide	9.8	14.9
9	Butene	9.2	13.7	37	Hydrogen iodide	9.0	21.3
10	Butylene	8.9	13.0	38	Hydrogen sulfide	8.6	18.0
11	Carbon dioxide	9.5	18.7	39	Iodine	9.0	18.4
12	Carbon disulfide	8.0	16.0	40	Mercury	5.3	22.9
13	Carbon monoxide	11.0	20.0	41	Methane	9.9	15.5
14	Chlorine	9.0	18.4	42	Methyl alcohol	8.5	15.6
15	Chloroform	8.9	15.7	43	Nitric oxide	10.9	20.5
16	Cyanogen	9.2	15.2	44	Nitrogen	10.6	20.0
17	Cyclohexane	9.2	12.0	45	Nitrosyl chloride	8.0	17.6
18	Ethane	9.1	14.5	46	Nitrous oxide	8.8	19.0
19	Ethyl acetate	8.5	13.2	47	Oxygen	11.0	21.3
20	Ethyl alcohol	9.2	14.2	48	Pentane	7.0	12.8
21	Ethyl chloride	8.5	15.6	49	Propane	9.7	12.9
22	Ethyl ether	8.9	13.0	50	Propyl alcohol	8.4	13.4
23	Ethylene	9.5	15.1	51	Propylene	9.0	13.8
24	Fluorine	7.3	23.8	52	Sulfur dioxide	9.6	17.0
25	Freon-11	10.6	15.1	53	Toluene	8.6	12.4
26	Freon-12	11.1	16.0	54	2,3,3-Trimethylbutane	9.5	10.5
27	Freon-21	10.8	15.3	55	Water	8.0	16.0
28	Freon-22	10.1	17.0	56	Xenon	9.3	23.0

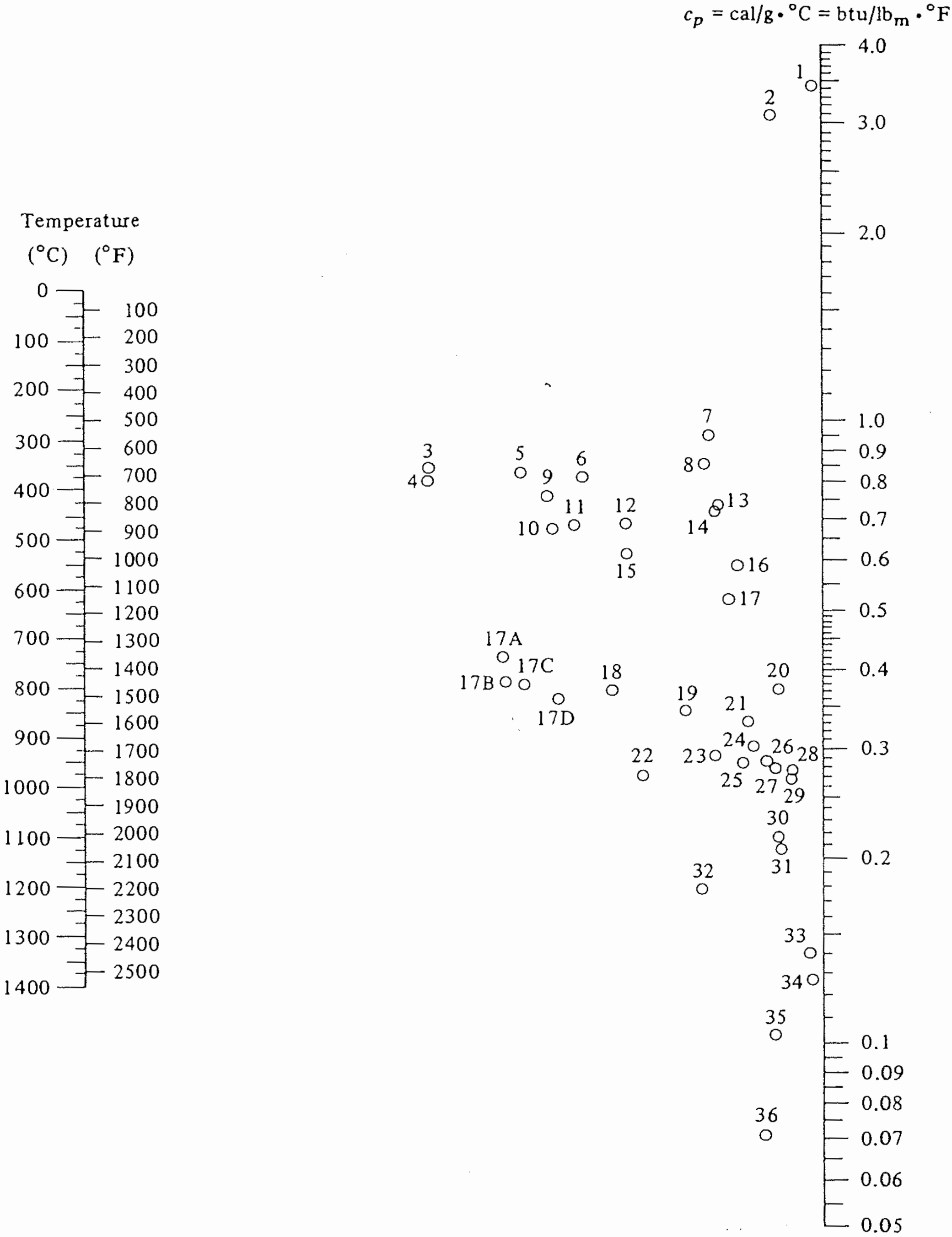


FIGURE A.3-3. *Heat capacity of gases at constant pressure at 101.325 kPa (1 atm abs). (From R. H. Perry and C. H. Chilton, Chemical Engineers' Handbook, 5th ed. New York: McGraw-Hill Book Company, 1973. With permission.) See Table A.3-9 for use with Fig. A.3-3.*

A.3-9 Heat Capacity of Gases at Constant Pressure (for Use with Fig. A.3-3)

No.	*Gas*	*Range (°C)*
10	Acetylene	0–200
15	Acetylene	200–400
16	Acetylene	400–1400
27	Air	0–1400
12	Ammonia	0–600
14	Ammonia	600–1400
18	Carbon dioxide	0–400
24	Carbon dioxide	400–1400
26	Carbon monoxide	0–1400
32	Chlorine	0–200
34	Chlorine	200–1400
3	Ethane	0–200
9	Ethane	200–600
8	Ethane	600–1400
4	Ethylene	0–200
11	Ethylene	200–600
13	Ethylene	600–1400
17B	Freon-11 (CCl_3F)	0–150
17C	Freon-21 ($CHCl_2F$)	0–150
17A	Freon-22 ($CHClF_2$)	0–150
17D	Freon-113 (CCl_2F–$CClF_2$)	0–150
1	Hydrogen	0–600
2	Hydrogen	600–1400
35	Hydrogen bromide	0–1400
30	Hydrogen chloride	0–1400
20	Hydrogen fluoride	0–1400
36	Hydrogen iodide	0–1400
19	Hydrogen sulfide	0–700
21	Hydrogen sulfide	700–1400
5	Methane	0–300
6	Methane	300–700
7	Methane	700–1400
25	Nitric oxide	0–700
28	Nitric oxide	700–1400
26	Nitrogen	0–1400
23	Oxygen	0–500
29	Oxygen	500–1400
33	Sulfur	300–1400
22	Sulfur dioxide	0–400
31	Sulfur dioxide	400–1400
17	Water	0–1400

A.3-10 Thermal Conductivities of Gases and Vapors at 101.325 kPa (1 Atm Abs); $k = W/m \cdot K$)

Gas or Vapor	*K*	*k*	*Gas or Vapor*	*K*	*k*
Acetone[1]	273	0.0099	Ethane[5,6]	239	0.0149
	319	0.0130		273	0.0183
	373	0.0171		373	0.0303
	457	0.0254	Ethyl alcohol[1]	293	0.0154
Ammonia[2]	273	0.0218		373	0.0215
	373	0.0332	Ethyl ether[1]	273	0.0133
	473	0.0484		319	0.0171
Butane[3]	273	0.0135		373	0.0227
	373	0.0234	Ethylene[6]	273	0.0175
Carbon monoxide[2]	173	0.0152		323	0.0227
	273	0.0232		373	0.0279
	373	0.0305	*n*-Hexane[3]	273	0.0125
Chlorine[4]	273	0.00744		293	0.0138
			Sulfur dioxide[7]	273	0.0087
				373	0.0119

Source: (1) Moser, dissertation, Berlin, 1913; (2) F. G. Keyes, *Tech. Rept.* 37, Project Squid, Apr. 1, 1952; (3) W. B. Mann and B. G. Dickens, *Proc. Roy. Soc.* (*London*), **A134**, 77 (1931); (4) *International Critical Tables*. New York: McGraw-Hill Book Company, 1929; (5) T. H. Chilton and R. P. Genereaux, personal communication, 1946; (6) A. Eucken, *Physik, Z.*, **12**, 1101 (1911); **14**, 324 (1913); (7) B. G. Dickens, *Proc. Roy. Soc.* (*London*), **A143**, 517 (1934).

A.3-11 Heat Capacities of Liquids ($c_p = kJ/kg \cdot K$)

Liquid	*K*	c_p	*Liquid*	*K*	c_p
Acetic acid	273	1.959	Hydrochloric acid (20 mol %)	273	2.43
	311	2.240		293	2.474
Acetone	273	2.119	Mercury	293	0.01390
	293	2.210	Methyl alcohol	293	2.512
Aniline	273	2.001		313	2.583
	323	2.181	Nitrobenzene	283	1.499
Benzene	293	1.700		303	1.419
	333	1.859		363	1.436
Butane	273	2.300	Sodium chloride (9.1 mol %)	293	3.39
i-Butyl alcohol	303	2.525		330	3.43
Ethyl alcohol	273	2.240	Sulfuric acid (100%)	293	1.403
	298	2.433	Toluene	273	1.616
Formic acid	273	1.825		323	1.763
	289	2.131	*o*-Xylene	303	1.721
Glycerol	288	2.324			
	305	2.412			

Source: N. A. Lange, *Handbook of Chemistry*, 10th ed. New York: McGraw-Hill Book Company, 1967; National Research Council, *International Critical Tables*, Vol. V. New York: McGraw-Hill Book Company, 1929; R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973.

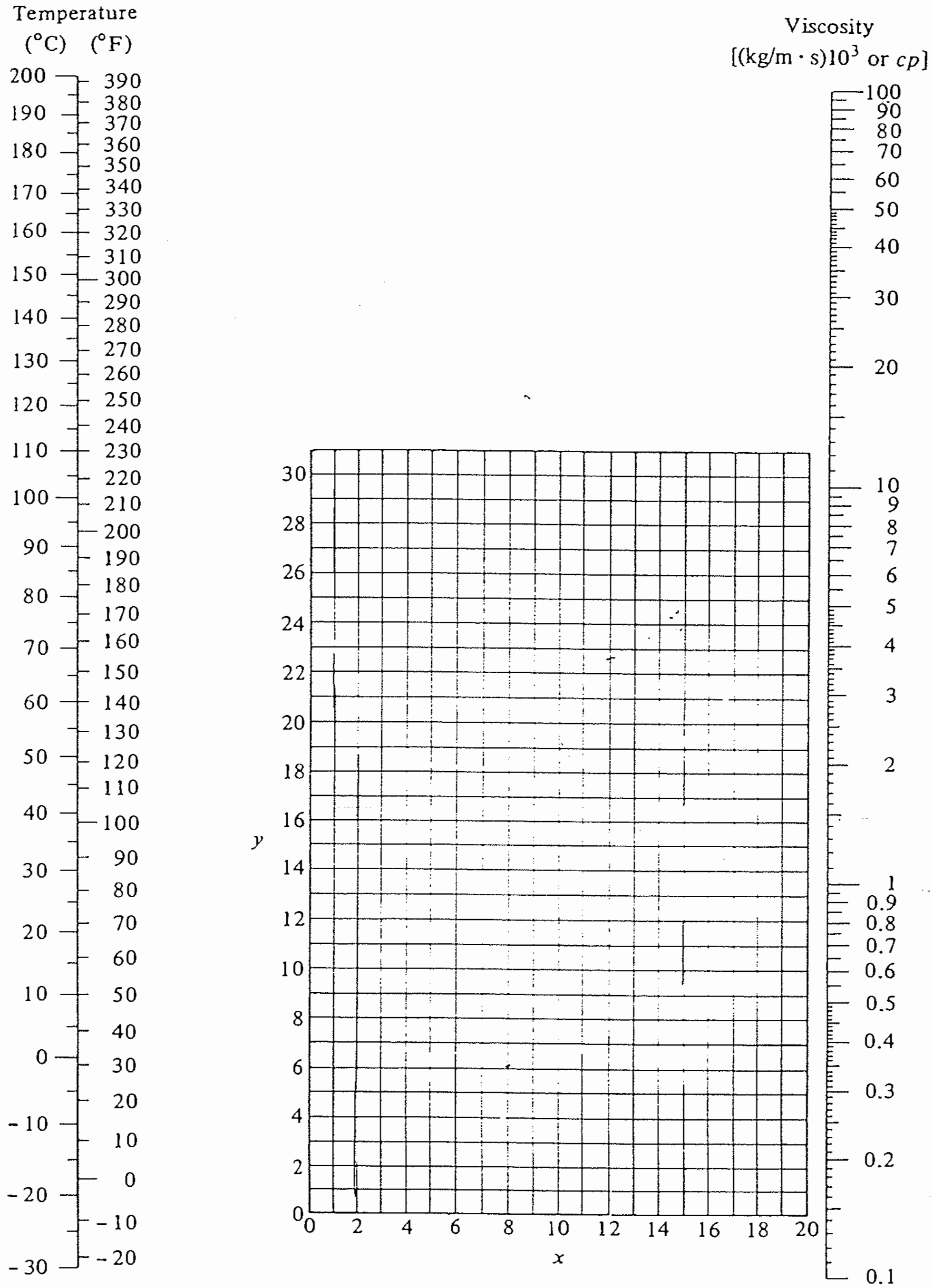


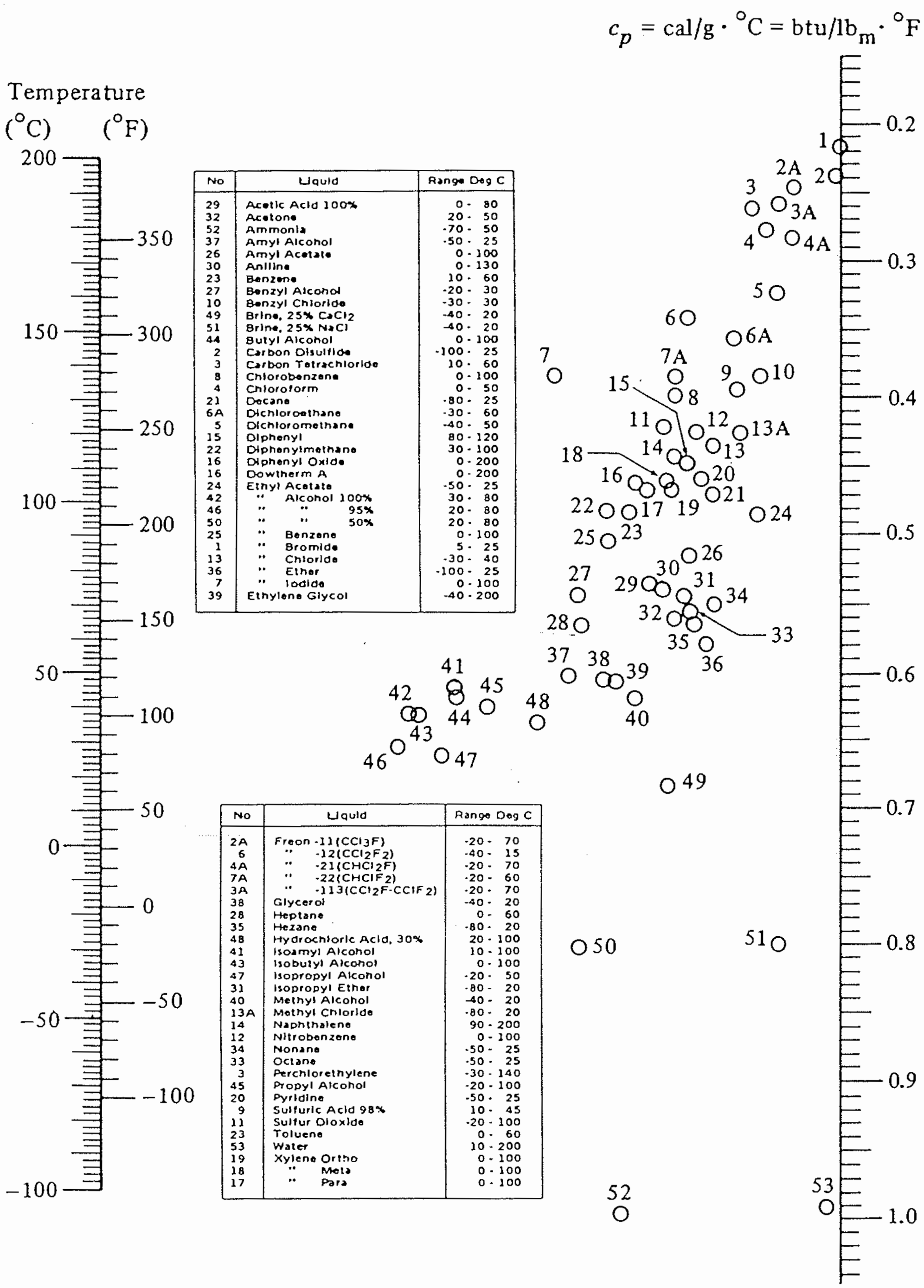
FIGURE A.3-4. *Viscosities of liquids. (From R. H. Perry and C. H. Chilton, Chemical Engineers' Handbook, 5th ed. New York: McGraw-Hill Book Company, 1973. With permission.) See Table A.3-12 for use with Fig. A.3-4.*

A.3-12 Viscosities of Liquids (Coordinates for Use with Fig. A.3-4)

Liquid	*X*	*Y*	*Liquid*	*X*	*Y*
Acetaldehyde	15.2	4.8	Cyclohexanol	2.9	24.3
Acetic acid, 100%	12.1	14.2	Cyclohexane	9.8	12.9
Acetic acid, 70%	9.5	17.0	Dibromomethane	12.7	15.8
Acetic anhydride	12.7	12.8	Dichloroethane	13.2	12.2
Acetone, 100%	14.5	7.2	Dichloromethane	14.6	8.9
Acetone, 35%	7.9	15.0	Diethyl ketone	13.5	9.2
Acetonitrile	14.4	7.4	Diethyl oxalate	11.0	16.4
Acrylic acid	12.3	13.9	Diethylene glycol	5.0	24.7
Allyl alcohol	10.2	14.3	Diphenyl	12.0	18.3
Allyl bromide	14.4	9.6	Dipropyl ether	13.2	8.6
Allyl iodide	14.0	11.7	Dipropyl oxalate	10.3	17.7
Ammonia, 100%	12.6	2.0	Ethyl acetate	13.7	9.1
Ammonia, 26%	10.1	13.9	Ethyl acrylate	12.7	10.4
Amyl acetate	11.8	12.5	Ethyl alcohol, 100%	10.5	13.8
Amyl alcohol	7.5	18.4	Ethyl alcohol, 95%	9.8	14.3
Aniline	8.1	18.7	Ethyl alcohol, 40%	6.5	16.6
Anisole	12.3	13.5	Ethyl benzene	13.2	11.5
Arsenic trichloride	13.9	14.5	Ethyl bromide	14.5	8.1
Benzene	12.5	10.9	2-Ethyl butyl acrylate	11.2	14.0
Brine, $CaCL_2$, 25%	6.6	15.9	Ethyl chloride	14.8	6.0
Brine, NaCl, 25%	10.2	16.6	Ethyl ether	14.5	5.3
Bromine	14.2	13.2	Ethyl formate	14.2	8.4
Bromotoluene	20.0	15.9	2-Ethyl hexyl acrylate	9.0	15.0
Butyl acetate	12.3	11.0	Ethyl iodide	14.7	10.3
Butyl acrylate	11.5	12.6	Ethyl propionate	13.2	9.9
Butyl alcohol	8.6	17.2	Ethyl propyl ether	14.0	7.0
Butyric acid	12.1	15.3	Ethyl sulfide	13.8	8.9
Carbon dioxide	11.6	0.3	Ethylene bromide	11.9	15.7
Carbon disulfide	16.1	7.5	Ethylene chloride	12.7	12.2
Carbon tetrachloride	12.7	13.1	Ethylene glycol	6.0	23.6
Chlorobenzene	12.3	12.4	Ethylidene chloride	14.1	8.7
Chloroform	14.4	10.2	Fluorobenzene	13.7	10.4
Chlorosulfonic acid	11.2	18.1	Formic acid	10.7	15.8
Chlorotoluene, ortho	13.0	13.3	Freon-11	14.4	9.0
Chlorotoluene, meta	13.3	12.5	Freon-12	16.8	15.6
Chlorotoluene, para	13.3	12.5	Freon-21	15.7	7.5
Cresol, meta	2.5	20.8	Freon-22	17.2	4.7

A.3-12 Viscosities of Liquids, *Continued*

Liquid	X	Y	Liquid	X	Y
Freon-113	12.5	11.4	Octyl alcohol	6.6	21.1
Glycerol, 100%	2.0	30.0	Pentachloroethane	10.9	17.3
Glycerol, 50%	6.9	19.6	Pentane	14.9	5.2
Heptane	14.1	8.4	Phenol	6.9	20.8
Hexane	14.7	7.0	Phosphorus tribromide	13.8	16.7
Hydrochloric acid, 31.5%	13.0	16.6	Phosphorus trichloride	16.2	10.9
Iodobenzene	12.8	15.9	Propionic acid	12.8	13.8
Isobutyl alcohol	7.1	18.0	Propyl acetate	13.1	10.3
Isobutyric acid	12.2	14.4	Propyl alcohol	9.1	16.5
Isopropyl alcohol	8.2	16.0	Propyl bromide	14.5	9.6
Isopropyl bromide	14.1	9.2	Propyl chloride	14.4	7.5
Isopropyl chloride	13.9	7.1	Propyl formate	13.1	9.7
Isopropyl iodide	13.7	11.2	Propyl iodide	14.1	11.6
Kerosene	10.2	16.9	Sodium	16.4	13.9
Linseed oil, raw	7.5	27.2	Sodium hydroxide, 50%	3.2	25.8
Mercury	18.4	16.4	Stannic chloride	13.5	12.8
Methanol, 100%	12.4	10.5	Succinonitrile	10.1	20.8
Methanol, 90%	12.3	11.8	Sulfur dioxide	15.2	7.1
Methanol, 40%	7.8	15.5	Sulfuric acid, 110%	7.2	27.4
Methyl acetate	14.2	8.2	Sulfuric acid, 100%	8.0	25.1
Methyl acrylate	13.0	9.5	Sulfuric acid, 98%	7.0	24.8
Methyl *i*-butyrate	12.3	9.7	Sulfuric acid, 60%	10.2	21.3
Methyl *n*-butyrate	13.2	10.3	Sulfuryl chloride	15.2	12.4
Methyl chloride	15.0	3.8	Tetrachloroethane	11.9	15.7
Methyl ethyl ketone	13.9	8.6	Thiophene	13.2	11.0
Methyl formate	14.2	7.5	Titanium tetrachloride	14.4	12.3
Methyl iodide	14.3	9.3	Toluene	13.7	10.4
Methyl propionate	13.5	9.0	Trichloroethylene	14.8	10.5
Methyl propyl ketone	14.3	9.5	Triethylene glycol	4.7	24.8
Methyl sulfide	15.3	6.4	Turpentine	11.5	14.9
Naphthalene	7.9	18.1	Vinyl acetate	14.0	8.8
Nitric acid, 95%	12.8	13.8	Vinyl toluene	13.4	12.0
Nitric acid, 60%	10.8	17.0	Water	10.2	13.0
Nitrobenzene	10.6	16.2	Xylene, ortho	13.5	12.1
Nitrogen dioxide	12.9	8.6	Xylene, meta	13.9	10.6
Nitrotoluene	11.0	17.0	Xylene, para	13.9	10.9
Octane	13.7	10.0			



No	Liquid	Range Deg C
29	Acetic Acid 100%	0 - 80
32	Acetone	20 - 50
52	Ammonia	-70 - 50
37	Amyl Alcohol	-50 - 25
26	Amyl Acetate	0 - 100
30	Aniline	0 - 130
23	Benzene	10 - 60
27	Benzyl Alcohol	-20 - 30
10	Benzyl Chloride	-30 - 30
49	Brine, 25% $CaCl_2$	-40 - 20
51	Brine, 25% NaCl	-40 - 20
44	Butyl Alcohol	0 - 100
2	Carbon Disulfide	-100 - 25
3	Carbon Tetrachloride	10 - 60
8	Chlorobenzene	0 - 100
4	Chloroform	0 - 50
21	Decane	-80 - 25
6A	Dichloroethane	-30 - 60
5	Dichloromethane	-40 - 50
15	Diphenyl	80 - 120
22	Diphenylmethane	30 - 100
16	Diphenyl Oxide	0 - 200
16	Dowtherm A	0 - 200
24	Ethyl Acetate	-50 - 25
42	" Alcohol 100%	30 - 80
46	" " 95%	20 - 80
50	" " 50%	20 - 80
25	" Benzene	0 - 100
1	" Bromide	5 - 25
13	" Chloride	-30 - 40
36	" Ether	-100 - 25
7	" Iodide	0 - 100
39	Ethylene Glycol	-40 - 200

No	Liquid	Range Deg C
2A	Freon -11(CCl_3F)	-20 - 70
6	" -12(CCl_2F_2)	-40 - 15
4A	" -21($CHCl_2F$)	-20 - 70
7A	" -22($CHClF_2$)	-20 - 60
3A	" -113(CCl_2F-$CClF_2$)	-20 - 70
38	Glycerol	-40 - 20
28	Heptane	0 - 60
35	Hezane	-80 - 20
48	Hydrochloric Acid, 30%	20 - 100
41	Isoamyl Alcohol	10 - 100
43	Isobutyl Alcohol	0 - 100
47	Isopropyl Alcohol	-20 - 50
31	Isopropyl Ether	-80 - 20
40	Methyl Alcohol	-40 - 20
13A	Methyl Chloride	-80 - 20
14	Naphthalene	90 - 200
12	Nitrobenzene	0 - 100
34	Nonane	-50 - 25
33	Octane	-50 - 25
3	Perchlorethylene	-30 - 140
45	Propyl Alcohol	-20 - 100
20	Pyridine	-50 - 25
9	Sulfuric Acid 98%	10 - 45
11	Sulfur Dioxide	-20 - 100
23	Toluene	0 - 60
53	Water	10 - 200
19	Xylene Ortho	0 - 100
18	" Meta	0 - 100
17	" Para	0 - 100

FIGURE A.3-5. *Heat capacity of liquids. (From R. H. Perry and C. H. Chilton, Chemical Engineers' Handbook, 5th ed. New York: McGraw-Hill Book Company, 1973. With permission.)*

A.3-13 Thermal Conductivities of Liquids (k = W/m · K)*

Liquid	*K*	*k*	*Liquid*	*K*	*k*
Acetic acid			Ethylene glycol	273	0.265
100%	293	0.171	Glycerol, 100%	293	0.284
50%	293	0.346	*n*-Hexane	303	0.138
Ammonia	243–258	0.502		333	0.135
n-Amyl alcohol	303	0.163	Kerosene	293	0.149
	373	0.154		348	0.140
Benzene	303	0.159	Methyl alcohol		
	333	0.151	100%	293	0.215
Carbon tetrachloride	273	0.185	60%	293	0.329
	341	0.163	20%	293	0.492
n-Decane	303	0.147	100%	323	0.197
	333	0.144	*n*-Octane	303	0.144
Ethyl acetate	293	0.175		333	0.140
Ethyl alcohol			NaCl brine		
100%	293	0.182	25%	303	0.571
60%	293	0.305	12.5%	303	0.589
20%	293	0.486	Sulfuric acid		
100%	323	0.151	90%	303	0.364
			60%	303	0.433
			Vaseline	332	0.183

* A linear variation with temperature may be assumed between the temperature limits given.
Source: R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973. With permission.

A.3-14 Heat Capacities of Solids ($c_p = kJ/kg \cdot K$)

Solid	*K*	c_p	*Solid*	*K*	c_p
Alumina	373	0.84	Benzene	273	1.570
	1773	1.147	Benzoic acid	293	1.243
Asbestos		1.05	Camphene	308	1.591
Asphalt		0.92	Caprylic acid	271	2.629
Brick, fireclay	373	0.829	Dextrin	273	1.218
	1773	1.248	Formic acid	273	1.800
Cement, portland		0.779	Glycerol	273	1.382
Clay		0.938	Lactose	293	1.202
Concrete		0.63	Oxalic acid	323	1.612
Corkboard	303	0.167	Tartaric acid	309	1.202
Glass		0.84	Urea	293	1.340
Magnesia	373	0.980			
	1773	0.787			
Oak		2.39			
Pine, yellow	298	2.81			
Porcelain	293–373	0.775			
Rubber, vulcanized		2.01			
Steel		0.50			
Wool		1.361			

Source: R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; National Research Council, *International Critical Tables*, Vol. V. New York: McGraw-Hill Book Company, 1929; L. S. Marks, *Mechanical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1951; F. Kreith, *Principles of Heat Transfer*, 2nd ed. Scranton, Pa.: International Textbook Co., 1965.

A.3-15 Thermal Conductivities of Building and Insulating Materials

Material	ρ $\left(\frac{kg}{m^3}\right)$	t^* (°C)	$k(W/m \cdot K)$		
Asbestos	577		0.151 (0°C)	0.168 (37.8°C)	0.190 (93.3°C)
Asbestos sheets	889	51	0.166		
Brick, building		20	0.69		
Brick, fireclay			1.00 (200°C)	1.47 (600°C)	1.64 (1000°C)
Clay soil, 4% H_2O	1666	4.5	0.57		
Concrete, 1:4 dry			0.762		
Corkboard	160.2	30	0.0433		
Cotton	80.1		0.055 (0°C)	0.061 (37.8°C)	0.068 (93.3°C)
Felt, wool	330	30	0.052		
Fiber insulation board	237	21	0.048		
Glass, window			0.52–1.06		
Glass wool	64.1	30	0.0310 (−6.7°C)	0.0414 (37.8°C)	0.0549 (93.3°C)
Ice	921	0	2.25		
Magnesia, 85%	271		0.068 (37.8°C)	0.071 (93.3°C)	0.080 (204.4°C)
	208		0.059 (37.8°C)	0.062 (93.3°C)	0.066 (148.9°C)
Oak, across grain	825	15	0.208		
Pine, across grain	545	15	0.151		
Paper			0.130		
Rock wool	192		0.0317 (−6.7°C)	0.0391 (37.8°C)	0.0486 (93.3°C)
	128		0.0296 (−6.7°C)	0.0395 (37.8°C)	0.0518 (93.3°C)
Rubber, hard	1198	0	0.151		
Sand soil					
4% H_2O	1826	4.5	1.51		
10% H_2O	1922	4.5	2.16		
Sandstone	2243	40	1.83		
Snow	559	0	0.47		
Wool	110.5	30	0.036		

* Room temperature when none is noted.

Source: L. S. Marks, *Mechanical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1951; W. H. McAdams, *Heat Transmission*, 3rd ed. New York: McGraw-Hill Book Company, 1954; F. H. Norton, *Refractories*. New York: McGraw-Hill Book Company, 1949; National Research Council, *International Critical Tables*. New York: McGraw-Hill Book Company, 1929; M. S. Kersten, *Univ. Minn. Eng. Ex. Sta., Bull. 28*, June 1949; R. H. Heilman, *Ind. Eng. Chem.*, 28, 782 (1936).

A.3-16 Thermal Conductivities, Densities, and Heat Capacities of Metals

Material	t (°C)	ρ $\left(\frac{kg}{m^3}\right)$	c_p $\left(\frac{kJ}{kg \cdot K}\right)$		$k(W/m \cdot K)$	
Aluminum	20	2707	0.896	202 (0°C) 230 (300°C)	206 (100°C)	215 (200°C)
Brass (70–30)	20	8522	0.385	97 (0°C)	104 (100°C)	109 (200°C)
Cast iron	20	7593	0.465	55 (0°C)	52 (100°C)	48 (200°C)
Copper	20	8954	0.383	388 (0°C)	377 (100°C)	372 (200°C)
Lead	20	11 370	0.130	35 (0°C)	33 (100°C)	31 (200°C)
Steel 1%C	20	7801	0.473	45.3 (18°C) 43 (300°C)	45 (100°C)	45 (200°C)
308 stainless	20	7849	0.461	15.2 (100°C)	21.6 (500°C)	
304 stainless	0	7817	0.461	13.8 (0°C)	16.3 (100°C)	18.9 (300°C)
Tin	20	7304	0.227	62 (0°C)	59 (100°C)	57 (200°C)

Source: L. S. Marks, *Mechanical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1951; E. R. G. Eckert and R. M. Drake, *Heat and Mass Transfer*, 2nd ed. New York: McGraw-Hill Book Company, 1959; R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; National Research Council, *International Critical Tables*. New York: McGraw-Hill Book Company, 1929.

A.3-17 Normal Total Emmissivities of Surfaces

Surface	*K*	*ε*	*Surface*	*K*	*ε*
Aluminum			Lead, unoxidized	400	0.057
highly oxidized	366	0.20	Nickel, polished	373	0.072
highly polished	500	0.039	Nickel oxide	922	0.59
	850	0.057	Oak, planed	294	0.90
Aluminum oxide	550	0.63	Paint		
Asbestos board	296	0.96	aluminum	373	0.52
Brass, highly	520	0.028	oil (16 different,		
			all colors)	373	0.92–0.96
polished	630	0.031	Paper	292	0.924
Chromium,					
polished	373	0.075	Roofing paper	294	0.91
Copper			Rubber (hard, glossy)	296	0.94
oxidized	298	0.78	Steel		
polished	390	0.023	oxidized at 867 K	472	0.79
Glass, smooth	295	0.94	polished stainless	373	0.074
Iron			304 stainless	489	0.44
oxidized	373	0.74	Water	273	0.95
tin-plated	373	0.07		373	0.963
Iron oxide	772	0.85			

Source: R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; W. H. McAdams, *Heat Transmission*, 3rd ed. New York: McGraw-Hill Book Company, 1954; E. Schmidt, *Gesundh.-Ing. Beiheft*, **20**, Reihe 1, 1 (1927).

A.3-18 Henry's Law Constants for Gases in Water ($H \times 10^{-4}$)*

T											
K	°*C*	CO_2	CO	C_2H_6	C_2H_4	He	H_2	H_2S	CH_4	N_2	O_2
273.2	0	0.0728	3.52	1.26	0.552	12.9	5.79	0.0268	2.24	5.29	2.55
283.2	10	0.104	4.42	1.89	0.768	12.6	6.36	0.0367	2.97	6.68	3.27
293.2	20	0.142	5.36	2.63	1.02	12.5	6.83	0.0483	3.76	8.04	4.01
303.2	30	0.186	6.20	3.42	1.27	12.4	7.29	0.0609	4.49	9.24	4.75
313.2	40	0.233	6.96	4.23		12.1	7.51	0.0745	5.20	10.4	5.35

* $p_A = Hx_A$, p_A = partial pressure of A in gas in atm, x_A = mole fraction of A in liquid, H = Henry's law constant in atm/mole frac.
Source: National Research Council, *International Critical Tables*, Vol. III. New York: McGraw-Hill Book Company, 1929.

A.3-19 Equilibrium Data for SO_2–Water System

Mole Fraction SO_2 in Liquid, x_A	Partial Pressure of SO_2 in Vapor, p_A (mm Hg)		Mole Fraction SO_2 in Vapor, y_A; $P = 1$ Atm	
	20°C (293 K)	30°C (303 K)	20°C	30°C
0	0	0	0	0
0.0000562	0.5	0.6	0.000658	0.000790
0.0001403	1.2	1.7	0.00158	0.00223
0.000280	3.2	4.7	0.00421	0.00619
0.000422	5.8	8.1	0.00763	0.01065
0.000564	8.5	11.8	0.01120	0.0155
0.000842	14.1	19.7	0.01855	0.0259
0.001403	26.0	36	0.0342	0.0473
0.001965	39.0	52	0.0513	0.0685
0.00279	59	79	0.0775	0.1040
0.00420	92	125	0.121	0.1645
0.00698	161	216	0.212	0.284
0.01385	336	452	0.443	0.594
0.0206	517	688	0.682	0.905
0.0273	698		0.917	

Source: T. K. Sherwood, *Ind. Eng. Chem.*, 17, 745 (1925).

A.3-20 Equilibrium Data for Methanol–Water System

Mole Fraction Methanol in Liquid, x_A	Partial Pressure of Methanol in Vapor, p_A (mm Hg)	
	39.9°C (313.1 K)	59.4°C (332.6K)
0	0	0
0.05	25.0	50
0.10	46.0	102
0.15	66.5	151

Source: National Research Council, *International Critical Tables*, Vol. III. New York: McGraw-Hill Book Company, 1929.

A.3-21 Equilibrium Data for Acetone–Water System at 20°C (293 K)

Mole Fraction Acetone in Liquid, x_A	*Partial Pressure of Acetone in Vapor, p_A (mm Hg)*
0	0
0.0333	30.0
0.0720	62.8
0.117	85.4
0.171	103

Source: T. K. Sherwood, *Absorption and Extraction.* New York: McGraw-Hill Book Company, 1937. With permission.

A.3-22 Equilibrium Data for Ammonia–Water System

Mole Fraction NH_3 in Liquid, x_A	*Partial Pressure of NH_3 in Vapor, p_A (mm Hg)*		*Mole Fraction NH_3 in Vapor, y_A; P = 1 Atm*	
	20°C (293 K)	*30°C (303 K)*	*20°C*	*30°C*
0	0	0	0	0
0.0126		11.5		0.0151
0.0167		15.3		0.0201
0.0208	12	19.3	0.0158	0.0254
0.0258	15	24.4	0.0197	0.0321
0.0309	18.2	29.6	0.0239	0.0390
0.0405	24.9	40.1	0.0328	0.0527
0.0503	31.7	51.0	0.0416	0.0671
0.0737	50.0	79.7	0.0657	0.105
0.0960	69.6	110	0.0915	0.145
0.137	114	179	0.150	0.235
0.175	166	260	0.218	0.342
0.210	227	352	0.298	0.463
0.241	298	454	0.392	0.597
0.297	470	719	0.618	0.945

Source: J. H. Perry, *Chemical Engineers' Handbook*, 4th ed. New York: McGraw-Hill Book Company, 1963. With permission.

A.3-23 Equilibrium Data for Ethanol–Water System at 101.325 kPa (1 Atm)*

Temperature		Vapor–Liquid Equilibria, Mass Fraction Ethanol		Temperature		Vapor–Liquid Equilibria, Mass Fraction Ethanol		Temperature		Mass Fraction	Enthalpy (btu/lb$_m$ of mixture)		Enthalpy (kJ/kg of mixture)	
°C	°F	x_A	y_A	°C	°F	x_A	y_A	°C	°F		Liquid	Vapor	Liquid	Vapor
100.0	212	0	0	81.0	177.8	0.600	0.794	100.0	212	0	180.1	1150	418.9	2675
98.1	208.5	0.020	0.192	80.1	176.2	0.700	0.822	91.8	197.2	0.1	159.8	1082	371.7	2517
95.2	203.4	0.050	0.377	79.1	174.3	0.800	0.858	84.7	184.5	0.3	135.0	943	314.0	2193
91.8	197.2	0.100	0.527	78.3	173.0	0.900	0.912	82.0	179.6	0.5	122.9	804	285.9	1870
87.3	189.2	0.200	0.656	78.2	172.8	0.940	0.942	80.1	176.2	0.7	111.1	664	258.4	1544
84.7	184.5	0.300	0.713	78.1	172.7	0.960	0.959	78.3	173.0	0.9	96.6	526	224.7	1223
83.2	181.7	0.400	0.746	78.2	172.8	0.980	0.978	78.3	173.0	1.0	89.0	457.5	207.0	1064
82.0	179.6	0.500	0.771	78.3	173.0	1.00	1.00							

* Reference state for enthalpy is pure liquid at 273 K or 0°C.

Source: Data from L. W. Cornell and R. E. Montonna, *Ind. Eng. Chem.*, **25**, 1331 (1933); and W. A. Noyes and R. R. Warfel, *J. Am. Chem. Soc.*, **23**, 463 (1901), as given by G. G. Brown, *Unit Operations*. New York: John Wiley & Sons, Inc., 1950. With permission.

A.3-24 Acetic Acid–Water–Isopropyl Ether System, Liquid–Liquid Equilibria at 293 K or 20°C

Water Layer (wt %)			*Isopropyl Ether Layer (wt %)*		
Acetic Acid	*Water*	*Isopropyl Ether*	*Acetic Acid*	*Water*	*Isopropyl Ether*
0	98.8	1.2	0	0.6	99.4
0.69	98.1	1.2	0.18	0.5	99.3
1.41	97.1	1.5	0.37	0.7	98.9
2.89	95.5	1.6	0.79	0.8	98.4
6.42	91.7	1.9	1.93	1.0	97.1
13.30	84.4	2.3	4.82	1.9	93.3
25.50	71.1	3.4	11.40	3.9	84.7
36.70	58.9	4.4	21.60	6.9	71.5
44.30	45.1	10.6	31.10	10.8	58.1
46.40	37.1	16.5	36.20	15.1	48.7

Source: *Trans. A.I.Ch.E.*, 36, 601, 628 (1940). With permission.

A.3-25 Liquid–Liquid Equilibrium Data for Acetone–Water–Methyl Isobutyl Ketone (MIK) System at 298–299 K or 25–26°C

Composition Data (wt %)			*Acetone Distribution Data (wt %)*	
MIK	*Acetone*	*Water*	*Water Phase*	*MIK Phase*
98.0	0	2.00	2.5	4.5
93.2	4.6	2.33	5.5	10.0
77.3	18.95	3.86	7.5	13.5
71.0	24.4	4.66	10.0	17.5
65.5	28.9	5.53	12.5	21.3
54.7	37.6	7.82	15.5	25.5
46.2	43.2	10.7	17.5	28.2
12.4	42.7	45.0	20.0	31.2
5.01	30.9	64.2	22.5	34.0
3.23	20.9	75.8	25.0	36.5
2.12	3.73	94.2	26.0	37.5
2.20	0	97.8		

Source: Reprinted with permission from D. F. Othmer, R. E. White, and E. Trueger, *Ind. Eng. Chem.*, 33, 1240 (1941). Copyright by the American Chemical Society.

APPENDIX A.4

Physical Properties of Foods and Biological Materials

A.4-1 Heat Capacities of Foods (Average c_p 273–373 K or 0–100°C)

Material	H_2O (wt %)	c_p (kJ/kg · K)
Apples	75–85	3.73–4.02
Apple sauce		4.02*
Asparagus		
Fresh	93	3.94†
Frozen	93	2.01‡
Bacon, lean	51	3.43
Banana purée		3.66§
Beef, lean	72	3.43
Bread, white	44–45	2.72–2.85
Butter	15	2.30¶
Cantaloupe	92.7	3.94†
Cheese, Swiss	55	2.68†
Corn, sweet		
Fresh		3.32†
Frozen		1.77‡
Cream, 45–60% fat	57–73	3.06–3.27
Cucumber	97	4.10
Eggs		
Fresh		3.18†
Frozen		1.68‡
Fish, cod		
Fresh	70	3.18
Frozen	70	1.72‡
Flour	12–13.5	1.80–1.88
Ice	100	1.958‖

Material	H_2O (*wt* %)	c_p ($kJ/kg \cdot K$)
Ice cream		
Fresh	58–66	3.27†
Frozen	58–66	1.88‡
Lamb	70	3.18*
Macaroni	12.5–13.5	1.84–1.88
Milk, cows'		
Whole	87.5	3.85
Skim	91	3.98–4.02
Olive oil		2.01**
Oranges		
Fresh	87.2	3.77†
Frozen	87.2	1.93‡
Peas, air-dried	14	1.84
Peas, green		
Fresh	74.3	3.31†
Frozen	74.3	1.76‡
Pea soup		4.10
Plums	75–78	3.52
Pork		
Fresh	60	2.85†
Frozen	60	1.34‡
Potatoes	75	3.52
Poultry		
Fresh	74	3.31†
Frozen	74	1.55‡
Sausage, franks		
Fresh	60	3.60†
Frozen	60	2.35‡
String beans		
Fresh	88.9	3.81†
Frozen	88.9	1.97‡
Tomatoes	95	3.98†
Veal	63	3.22
Water	100	4.185**

* 32.8°C.
† Above freezing.
‡ Below freezing.
§ 24.4°C.
¶ 4.4°C.
‖ −20°C.
** 20°C.

Source: W. O. Ordinanz, *Food Ind.*, **18**, 101 (1946); G. A. Reidy, Department of Food Science, Michigan State University, 1968; S. E. Charm, *The Fundamentals of Food Engineering*, 2nd ed. Westport, Conn.: Avi Publishing Co., Inc., 1971; R. L. Earle, *Unit Operations in Food Processing.* Oxford: Pergamon Press, Inc., 1966; ASHRAE, *Handbook of Fundamentals.* New York: ASHRAE, 1972, 1967; H. C. Mannheim, M. P. Steinberg, and A. I. Nelson, *Food Technol.*, **9**, 556 (1955).

A.4-2 Thermal Conductivities, Densities, and Viscosities of Foods

Material	H_2O (wt %)	Temperature (K)	k ($W/m \cdot K$)	ρ (kg/m^3)	μ [$(Pa \cdot s)10^3$, or cp]
Apple sauce		295.7	0.692		
Butter	15	277.6	0.197	998	
Cantaloupe			0.571		
Fish					
Fresh		273.2	0.431		
Frozen		263.2	1.22		
Flour, wheat	8.8		0.450		
Honey	12.6	275.4	0.50		
Ice	100	273.2	2.25		
	100	253.2	2.42		
Lamb	71	278.8	0.415		
Milk					
Whole		293.2		1030	2.12
Skim		274.7	0.538		
		298.2		1041	1.4
Oil					
Cod liver		298.2		924	
Corn		288.2		921	
Olive		293.2	0.168	919	84
Peanut		277.1	0.168		
Soybean		303.2		919	40
Oranges	61.2	303.5	0.431		
Pears		281.9	0.595		
Pork, lean					
Fresh	74	275.4	0.460		
Frozen		258.2	1.109		
Potatoes					
Raw			0.554		
Frozen		260.4	1.09	977	
Salmon					
Fresh	67	277.1	0.50		
Frozen	67	248.2	1.30		
Sucrose solution	80	294.3		1073	1.92
Turkey					
Fresh	74	276.0	0.502		
Frozen		248.2	1.675		
Veal					
Fresh	75	335.4	0.485		
Frozen	75	263.6	1.30		
Water	100	293.2	0.602		
	100	273.2	0.569		

Source: R. C. Weast, *Handbook of Chemistry and Physics*, 48th ed. Cleveland: Chemical Rubber Co., Inc., 1967; C. P. Lentz, *Food Technol.*, **15**, 243 (1961); G. A. Reidy, Department of Food Science, Michigan State University, 1968; S. E. Charm, *The Fundamentals of Food Engineering*, 2nd ed. Westport, Conn.: Avi Publishing Co., Inc., 1971; R. Earle, *Unit Operations in Food Processing*, Oxford: Pergamon Press, 1966; R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, 5th ed. New York: McGraw-Hill Book Company, 1973; V. E. Sweat, *J. Food Sci.*, **39**, 1080 (1974).

APPENDIX A.5

Properties of Pipes, Tubes, and Screens

A.5-1 Dimensions of Standard Steel Pipe

Nominal Pipe Size (in.)	Outside Diameter		Schedule Number	Wall Thickness		Inside Diameter		Inside Cross-Sectional Area	
	in.	mm		in.	mm	in.	mm	ft^2	$m^2 \times 10^4$
$\frac{1}{8}$	0.405	10.29	40	0.068	1.73	0.269	6.83	0.00040	0.3664
			80	0.095	2.41	0.215	5.46	0.00025	0.2341
$\frac{1}{4}$	0.540	13.72	40	0.088	2.24	0.364	9.25	0.00072	0.6720
			80	0.119	3.02	0.302	7.67	0.00050	0.4620
$\frac{3}{8}$	0.675	17.15	40	0.091	2.31	0.493	12.52	0.00133	1.231
			80	0.126	3.20	0.423	10.74	0.00098	0.9059
$\frac{1}{2}$	0.840	21.34	40	0.109	2.77	0.622	15.80	0.00211	1.961
			80	0.147	3.73	0.546	13.87	0.00163	1.511
$\frac{3}{4}$	1.050	26.67	40	0.113	2.87	0.824	20.93	0.00371	3.441
			80	0.154	3.91	0.742	18.85	0.00300	2.791
1	1.315	33.40	40	0.133	3.38	1.049	26.64	0.00600	5.574
			80	0.179	4.45	0.957	24.31	0.00499	4.641
$1\frac{1}{4}$	1.660	42.16	40	0.140	3.56	1.380	35.05	0.01040	9.648
			80	0.191	4.85	1.278	32.46	0.00891	8.275
$1\frac{1}{2}$	1.900	48.26	40	0.145	3.68	1.610	40.89	0.01414	13.13
			80	0.200	5.08	1.500	38.10	0.01225	11.40
2	2.375	60.33	40	0.154	3.91	2.067	52.50	0.02330	21.65
			80	0.218	5.54	1.939	49.25	0.02050	19.05
$2\frac{1}{2}$	2.875	73.03	40	0.203	5.16	2.469	62.71	0.03322	30.89
			80	0.276	7.01	2.323	59.00	0.02942	27.30
3	3.500	88.90	40	0.216	5.49	3.068	77.92	0.05130	47.69
				0.300	7.62	2.900	73.66	0.04587	42.61
$3\frac{1}{2}$	4.000	101.6	40	0.226	5.74	3.548	90.12	0.06870	63.79
			80	0.318	8.08	3.364	85.45	0.06170	57.35
4	4.500	114.3	40	0.237	6.02	4.026	102.3	0.08840	82.19
			80	0.337	8.56	3.826	97.18	0.07986	74.17
5	5.563	141.3	40	0.258	6.55	5.047	128.2	0.1390	129.1
			80	0.375	9.53	4.813	122.3	0.1263	117.5
6	6.625	168.3	40	0.280	7.11	6.065	154.1	0.2006	186.5
			80	0.432	10.97	5.761	146.3	0.1810	168.1
8	8.625	219.1	40	0.322	8.18	7.981	202.7	0.3474	322.7
			80	0.500	12.70	7.625	193.7	0.3171	294.7

A.5-2 Dimensions of Heat-Exchanger Tubes

Outside Diameter		BWG Number	Wall Thickness		Inside Diameter		Inside Cross-Sectional Area	
in.	*mm*		*in.*	*mm*	*in.*	*mm*	ft^2	$m^2 \times 10^4$
$\frac{5}{8}$	15.88	12	0.109	2.77	0.407	10.33	0.000903	0.8381
		14	0.083	2.11	0.459	11.66	0.00115	1.068
		16	0.065	1.65	0.495	12.57	0.00134	1.241
		18	0.049	1.25	0.527	13.39	0.00151	1.408
$\frac{3}{4}$	19.05	12	0.109	2.77	0.532	13.51	0.00154	1.434
		14	0.083	2.11	0.584	14.83	0.00186	1.727
		16	0.065	1.65	0.620	15.75	0.00210	1.948
		18	0.049	1.25	0.652	16.56	0.00232	2.154
$\frac{7}{8}$	22.23	12	0.109	2.77	0.657	16.69	0.00235	2.188
		14	0.083	2.11	0.709	18.01	0.00274	2.548
		16	0.065	1.65	0.745	18.92	0.00303	2.811
		18	0.049	1.25	0.777	19.74	0.00329	3.060
1	25.40	10	0.134	3.40	0.732	18.59	0.00292	2.714
		12	0.109	2.77	0.782	19.86	0.00334	3.098
		14	0.083	2.11	0.834	21.18	0.00379	3.523
		16	0.065	1.65	0.870	22.10	0.00413	3.836
$1\frac{1}{4}$	31.75	10	0.134	3.40	0.982	24.94	0.00526	4.885
		12	0.109	2.77	1.032	26.21	0.00581	5.395
		14	0.083	2.11	1.084	27.53	0.00641	5.953
		16	0.065	1.65	1.120	28.45	0.00684	6.357
$1\frac{1}{2}$	38.10	10	0.134	3.40	1.232	31.29	0.00828	7.690
		12	0.109	2.77	1.282	32.56	0.00896	8.326
		14	0.083	2.11	1.334	33.88	0.00971	9.015
2	50.80	10	0.134	3.40	1.732	43.99	0.0164	15.20
		12	0.109	2.77	1.782	45.26	0.0173	16.09

A.5-3 Tyler Standard Screen Scale

Sieve Opening		Nominal Wire Diameter		
mm	in. (approx. equivalents)	mm	in. (approx. equivalents)	Tyler Equivalent Designation
26.9	1.06	3.90	0.1535	1.050 in.
25.4	1.00	3.80	0.1496	
22.6	0.875	3.50	0.1378	0.883 in.
19.0	0.750	3.30	0.1299	0.742 in.
16.0	0.625	3.00	0.1181	0.624 in.
13.5	0.530	2.75	0.1083	0.525 in.
12.7	0.500	2.67	0.1051	
11.2	0.438	2.45	0.0965	0.441 in.
9.51	0.375	2.27	0.0894	0.371 in.
8.00	0.312	2.07	0.0815	$2\frac{1}{2}$ mesh
6.73	0.265	1.87	0.0736	3 mesh
6.35	0.250	1.82	0.0717	
5.66	0.223	1.68	0.0661	$3\frac{1}{2}$ mesh
4.76	0.187	1.54	0.0606	4 mesh
4.00	0.157	1.37	0.0539	5 mesh
3.36	0.132	1.23	0.0484	6 mesh
2.83	0.111	1.10	0.0430	7 mesh
2.38	0.0937	1.00	0.0394	8 mesh
2.00	0.0787	0.900	0.0354	9 mesh
1.68	0.0661	0.810	0.0319	10 mesh
1.41	0.0555	0.725	0.0285	12 mesh
1.19	0.0469	0.650	0.0256	14 mesh
1.00	0.0394	0.580	0.0228	16 mesh
0.841	0.0331	0.510	0.0201	20 mesh
0.707	0.0278	0.450	0.0177	24 mesh
0.595	0.0234	0.390	0.0154	28 mesh
0.500	0.0197	0.340	0.0134	32 mesh
0.420	0.0165	0.290	0.0114	35 mesh
0.354	0.0139	0.247	0.0097	42 mesh
0.297	0.0117	0.215	0.0085	48 mesh
0.250	0.0098	0.180	0.0071	60 mesh
0.210	0.0083	0.152	0.0060	65 mesh
0.177	0.0070	0.131	0.0052	80 mesh
0.149	0.0059	0.110	0.0043	100 mesh
0.125	0.0049	0.091	0.0036	115 mesh
0.105	0.0041	0.076	0.0030	150 mesh
0.088	0.0035	0.064	0.0025	170 mesh
0.074	0.0029	0.053	0.0021	200 mesh
0.063	0.0025	0.044	0.0017	250 mesh
0.053	0.0021	0.037	0.0015	270 mesh
0.044	0.0017	0.030	0.0012	325 mesh
0.037	0.0015	0.025	0.0010	400 mesh

Notation

SI units are given first (followed by English and/or cgs units).

a	particle radius, m (ft)
a	area, m^2 (ft^2); also m^2 area/m^3 volume bed or packing (ft^2/ft^3)
a_e	acceleration from centrifugal force, m/s^2 (ft/s^2)
a_v	specific surface area of particle, m^{-1} (ft^{-1})
A	cross-sectional area, m^2 (ft^2, cm^2); also area, m^2 (ft^2)
A	absorption factor $= L/mV$, dimensionless; also filter area, m^2 (ft^2)
A_m	membrane area, cm^2, m^2 (ft^2)
A_w	solvent permeability constant, $kg/s \cdot m^2 \cdot atm$
A_s	solute permeability constant, m/s (ft/h)
b	length, m (ft, cm)
B	flow rate of dry solid, kg/h (lb_m/h); also filtration constant, s/m^3 (s/ft^3)
B	physical property of membrane, atm^{-1}
c	concentration, kg/m^3, kg mol/m^3 (lb_m/ft^3, g mol/cm^3)
c	concentration of absorbate in fluid, kg/m^3 (lb_m/ft^3)
c_A	concentration of A, kg mol/m^3 (lb mol/ft^3, g mol/cm^3)
c_b	break-point concentration, kg/m^3 (lb_m/ft^3)
c_g	concentration of solute in gel, kg solute/m^3 (lb_m/ft^3, g/cm^3)
c_s	concentration of solute at surface of membrane, kg solute/m^3 (lb_m/ft^3, g/cm^3)
c_S	concentration of A in solid, kg mol A/m^3 (lb_m/ft^3, g mol/cm^3)
c_S	concentration of solids in slurry, kg/m^3 (lb_m/ft^3)
c_S	humid heat, kJ/kg dry air $\cdot$ K (btu/lb_m dry air $\cdot$ °F)
c_x	concentration of solids in slurry, mass frac
c_p	heat capacity at constant pressure, $J/kg \cdot K$, $kJ/kg \cdot K$, kJ/kg mol $\cdot$ K (btu/$lb_m \cdot$ °F, cal/g $\cdot$ °C)
$\bar{c}_w$	mean solvent concentration in membrane, kg/m^3 (lb_m/ft^3)
c'_A	deviation of concentration from mean concentration $\bar{c}_A$, kg mol/m^3
c_P	concentration of P, kg P/m^3
c_v	heat capacity at constant volume, $J/kg \cdot K$
C	filtration constant, N/m^2 ($lb_f\, ft^2$); also, number of components
C	fluid heat capacity, W/K (btu/h $\cdot$ °F)
C	height of bottom of agitator above tank bottom, m (ft)
C_p	pitot tube coefficient, dimensionless

C_D	drag coefficient, dimensionless
C_v, C_0	Venturi coefficient, orifice coefficient, dimensionless
D	molecular diffusivity, m^2/s (ft^2/h, cm^2/s); also diameter, m (ft)
D	decimal reduction time, min; also distillate flow rate, kg/h, kg mol/h (lb_m/h)
D_{AB}	molecular diffusivity, m^2/s (ft^2/h, cm^2/s)
D_p	particle diameter, m (ft)
D_{KA}	Knudsen diffusivity m^2/s (ft^2/h, cm^2/s)
D_{NA}	transition-region diffusivity, m^2/s (ft^2/h, cm^2/s)
$D_{A\,eff}$	effective diffusivity, m^2/s (ft^2/h, cm^2/s)
$D_{p,m}$	effective mean diameter for mixture, m (ft)
D_a	diameter of agitator, m (ft)
D_t	diameter of tank, m (ft)
D_{pc}	critical diameter, m (ft)
D_{AP}	diffusivity of A in protein solution, m^2/s
E	activation energy, J/kg mol (cal/g mol)
E	energy for size reduction, $kW \cdot h/ton$; also tray efficiency, dimensionless
E	total energy, J/kg ($ft \cdot lb_f/lb_m$)
E	fraction unaccomplished change, dimensionless
E	emitted radiation energy, W/m^2 ($btu/h \cdot ft^2$)
E	axial dispersion coefficient, m^2/s (ft^2/h)
$E_{B\lambda}$	monochromatic emissive power, W/m^3 ($btu/h \cdot ft^3$)
f	fraction of feed vaporized; also cycle fraction, dimensionless
f	Fanning friction factor, dimensionless
f_t	mixing factor, dimensionless
F	number of degrees of freedom
F	frictional loss, J/kg ($ft \cdot lb_f/lb_m$)
F	flow rate, kg/h, kg mol/h (lb_m/h)
F	force, N (lb_f, dyn)
F_T	correction factor for temperature difference, dimensionless
F_0	process time at 121.1°C (250°F), min
$\mathscr{F}_{12}$	geometric view factor for gray surfaces, dimensionless
F_{12}	geometric view factor, dimensionless
g	standard acceleration of gravity (see Appendix A.1)
g_c	gravitional conversion factor (see Appendix A.1)
G	mass velocity $= v\rho$, $kg/s \cdot m^2$, $kg/h \cdot m^2$ ($lb_m/h \cdot ft^2$)
G	growth constant, mm/h
G'	mass velocity $= v'\rho$, $kg/s \cdot m^2$, $kg/h \cdot m^2$ ($lb_m/h \cdot ft^2$)
G	irradiation on a body, W/m^2 ($btu/h \cdot ft^2$)
h	constant spacing in x for Simpson's rule
h	head, J/kg ($ft \cdot lb_f/lb_m$); also height of fluid, m (ft)
h	heat-transfer coefficient, $W/m^2 \cdot K$ ($btu/h \cdot ft^2 \cdot °F$)
h	enthalpy of liquid, J/kg, kJ/kg, kJ/kg mol (btu/lb_m)
h_{fg}	latent heat of vaporization, J/kg, kJ/kg (btu/lb_m)
h_c	contact resistance coefficient, $W/m^2 \cdot K$ ($btu/h \cdot ft^2 \cdot °F$)
H	distance, m (ft)
H	Henry's law constant, atm/mol frac
H	head, J/kg ($ft \cdot lb_f/lb_m$); also height of fluid, m (ft)
H	enthalpy, J/kg, kJ/kg, kJ/kg mol (btu/lb_m); also enthalpy kJ/kg dry air (btu/lb_m dry air)

H	humidity, kg water vapor/kg dry air (lb water vapor/lb dry air)
H	enthalpy of vapor, J/kg, kJ/kg, kJ/kg mol (btu/lb_m)
H	equilibrium relation, kg mol/$m^3 \cdot$ atm
H	bed length, m (ft); also effective length of spindle, m (ft)
H'	enthalpy, kJ/kg dry solid (btu/lb_m); also enthalpy, kJ/kg dry air (btu/lb_m dry air)
H_B	length of bed used up to break point, m (ft)
H_G, H_L, H_{OG}, H_{OL}	height of transfer unit, m (ft)
H_P, H_R	percentage humidity, percentage relative humidity, respectively
H_T	total bed length, m (ft)
H_{UNB}	length of unused bed, m (ft)
$\mathbf{i}$	unit vector along x axis
I	intensity of turbulence, dimensionless; also current, amp
I_B	radiation intensity of black body, W/$m^2 \cdot$ sr (btu/h $\cdot$ $ft^2 \cdot$ sr)
I_λ	intensity of radiation, W/m^2 (btu/h $\cdot$ ft^2)
$\mathbf{j}$	unit vector along y axis
J	width of baffle, m (ft)
j_A	mass flux of A relative to mass average velocity, kg/s $\cdot$ m^2
j_A^*	mass flux of A relative to molar average velocity, kg/s $\cdot$ m^2
J_A	molar flux of A relative to mass average velocity, kg mol/s $\cdot$ m^2
$\mathbf{J}_A^*$	molar flux vector of A relative to molar average velocity, kg mol/s $\cdot$ m^2 (lb mol/h $\cdot$ ft^2, g mol/s $\cdot$ cm^2)
J_D, J_H	mass-transfer and heat-transfer factors, dimensionless
$\mathbf{k}$	unit vector along z axis
k, k'	reaction velocity constant, h^{-1}, min^{-1}, or s^{-1}
k	thermal conductivity, W/m $\cdot$ K (btu/h $\cdot$ ft $\cdot$ °F)
k	reaction velocity constant, h^{-1}, min^{-1}, or s^{-1}
k_1'	first-order heterogeneous reaction velocity constant, m/s (cm/s)
$k_c', k_c, k_G, k_x, \ldots$	mass-transfer coefficient, kg mol/s $\cdot$ $m^2 \cdot$ conc diff (lb mol/h $\cdot$ $ft^2 \cdot$ conc diff, g mol/s $\cdot$ $cm^2 \cdot$ conc diff); kg mol/s $\cdot$ $m^2 \cdot$ Pa, kg mol/s $\cdot$ $m^2 \cdot$ atm (lb mol/h $\cdot$ $ft^2 \cdot$ atm). (See Table 7.2-1.)
k_c	mass-transfer coefficient, m/s (ft/h, cm/s)
$k_G a, k_x a, k_y a, \ldots$	volumetric mass-transfer coefficient, kg mol/s $\cdot$ $m^3 \cdot$ conc diff (lb mol/h $\cdot$ $ft^3 \cdot$ conc diff, g mol/s $\cdot$ $cm^3 \cdot$ conc diff); kg mol/s $\cdot$ $m^3 \cdot$ Pa
k_s	surface reaction coefficient, kg mol/s $\cdot$ $m^2 \cdot$ mol frac
k_w, k_w'	wall constants, dimensionless
K_y', K_x'	overall mass-transfer coefficient, kg mol/s $\cdot$ $m^2 \cdot$ mol frac (lb mol/h $\cdot$ $ft^2 \cdot$ mol frac, g mol/s $\cdot$ $cm^2 \cdot$ mol frac)
K	consistency index, N $\cdot$ s^n/m^2 ($lb_f \cdot s^n/ft^2$)
K_1	constant in Eq. (3.1-39), m/s (ft/s)
K', K_s	equilibrium distribution coefficient, dimensionless
K'	consistency index, N $\cdot$ $s^{n'}/m^2$ ($lb_f \cdot s^{n'}/ft^2$)
K	equilibrium distribution coefficient, dimensionless
K_p	filtration constant, s/m^6 (s/ft^6)
K_V	filtration constant, N/m^5 (lb_f/ft^5)
K_c, K_{ex}, K_f	contraction, expansion, fitting loss coefficient, dimensionless
L	length, m (ft); also amount, kg, kg mol (lb_m); also kg/h $\cdot$ m^2
L	liquid flow rate, kg/h, kg mol/h (lb_m/h)

L	Prandtl mixing length, m (ft)
L	mean beam length, m (ft)
L_S	dry solid weight, kg dry solid (lb_m dry solid)
L'	flow rate, kg inert/h, kg mol inert/h (lb_m inert/h)
m, m', m''	slope of equilibrium line, dimensionless
m	flow rate, kg/s, kg/h (lb_m/s)
m	dimensionless ratio $= k/hx_1$; also, position m
m	parameter in Table 7.1-1, dimensionless; also position parameter
m	ratio, kg wet cake/kg dry cake (lb wet cake/lb dry cake)
M	molecular weight, kg/kg mol (lb_m/lb mol)
M	total mass, kg (lb_m); also parameter $= (\Delta x)^2/\alpha \Delta t$, dimensionless
M	modulus $= (\Delta x)^2/D_{AB}\,\Delta t$, dimensionless
M	flow rate, kg/h, kg mol/h (lb_m/h)
M	amount of adsorbent, kg(lb_m)
n	exponent, dimensionless; also flow behavior index, dimensionless
n'	slope of line for power-law fluid, dimensionless
n	position parameter; also dimensionless ratio $= x/x_1$
n	total amount, kg mol (lb mol, g mol)
n_A	flux of A relative to stationary coordinates, kg/s $\cdot$ m^2
N	rpm or rps; also number of radiation shields
N	parameter $= h\ \Delta x/k$, dimensionless; also number of viable organisms, dimensionless
N	total flux relative to stationary coordinates, kg mol/s $\cdot$ m^2 (lb mol/h $\cdot$ ft^2, g mol/s $\cdot$ cm^2)
N	modulus $= k_c\,\Delta x/D_{AB}$, dimensionless; also number of stages
N	concentration of solid B, kg solid B/kg solution (lb solid B/lb solution)
N	number of equal temperature subdivisions, dimensionless
N_s	solute flux, kg/s $\cdot$ m^2 (lb_m/h $\cdot$ ft^2)
N_w	solvent flux, kg solvent/s $\cdot$ m^2 (lb_m/h $\cdot$ ft^2)
$\bar{N}_{n,m}$	residual defined by Eq. (6.6-3), kg mol/m^3 (lb mol/ft^3)
$\mathbf{N}_A$	molar flux vector of A relative to stationary coordinates, kg mol/s $\cdot$ m^2 (lb mol/h $\cdot$ ft^2, g mol/s $\cdot$ cm^2)
$\bar{N}_A$	mass transfer of A relative to stationary coordinates, kg mol/s (lb mol/h, g mol/s)
N_G, N_L, N_{OG}, N_{OL}	number of transfer units, dimensionless
N_{Gr}	Grashof number defined in Eq. (4.7-4), dimensionless
N_{Bi}	Biot number $= hx_1/k$, dimensionless
N_{Gz}	Graetz number defined in Eq. (4.12-3), dimensionless
$N_{Gr,\delta}$	Grashof number defined in Eq. (4.7-5), dimensionless
N_{Ma}	Mach number defined by Eq. (2.11-15), dimensionless
N_{Pe}	Peclet number $= N_{Re}N_{Pr}$, dimensionless
$N_{Nu,\delta}$	Nusselt number $= h\delta/k$, dimensionless
N_{Fr}	Froude number $= v^2/gL$, dimensionless
N_{Kn}	Knudsen number $= \lambda/2\bar{r}$, dimensionless
N_{Nu}	Nusselt number $= hL/k$, dimensionless
$N_{Nu,x}$	Nusselt number $= h_x x/k$, dimensionless
N_{Pr}	Prandtl number $= c_p\mu/k$, dimensionless
N_{Re}	Reynolds number $= Dv\rho/\mu$, dimensionless
N'_{Re}	Reynolds number $= D_a^2 N\rho/\mu$, dimensionless
$N_{Re,gen}$	Reynolds number defined by Eq. (3.5-11), dimensionless

$N_{Re,L}$	Reynolds number $= Lv_\infty \rho/\mu$, dimensionless
$N_{Re,x}$	Reynolds number $= xv_\infty \rho/\mu$, dimensionless
$N'_{Re,n}$	Reynolds number defined by Eq. (3.5-20), dimensionless
$N_{Re,p}$	Reynolds number defined by Eq. (3.1-15), dimensionless
$N_{Re,mf}$	Reynolds number at minimum fluidization defined by Eq. (3.1-35), dimensionless
N_{Eu}	Euler number $= p/\rho v^2$, dimensionless
N_{Sc}	Schmidt number $= \mu/\rho D_{AB}$, dimensionless
N_{Sh}	Sherwood number $= k'_c D/D_{AB}$, dimensionless
N_P	power number defined by Eq. (3.4-2), dimensionless
N_Q	flow number, dimensionless
N_{St}	Stanton number $= k'_c/v$, dimensionless
NTU	number of transfer units, dimensionless
O	flow rate, kg/h, kg mol/h (lb_m/h)
p	pressure, N/m^2, Pa (lb_f/ft^2, atm, psia, mm Hg)
p_A	partial pressure of A, N/m^2, Pa (lb_f/ft^2, atm, psia, mm Hg)
p_{BM}	log mean inert partial pressure of B in Eq. (6.2-21), N/m^2, Pa (lb_f/ft^2, atm, psia, mm Hg)
p_h	total pressure in high-pressure side (feed), cm Hg, Pa (atm)
p_l	total pressure in low-pressure side (permeate) cm Hg, Pa (atm)
p_M	permeability in solid, m/s (ft/h)
P	parameter in Eq. (5.5-12), dimensionless
P	total pressure, N/m^2, Pa (lb_f/ft^2, atm, psia, mm H)
P	power, W (ft · lb_f/s, hp)
P	flow rate, kg/h, kg/min; also number of phases at equilibrium
$\mathbf{P}$	momentum vector, kg · m/s (lb_m · ft/s)
P_A	vapor pressure of pure A, N/m^2, Pa (lb_f/ft^2, atm, psia, mm Hg)
P'_A	permeability of A, cm^3 (STP) · cm/s · cm^2 · cm Hg
P_w	solvent membrane permeability, kg solvent/s · m · atm (lb_m/h · ft · atm)
P_m	permeability, kg mol/s · m · atm (lb mol/h · ft · atm)
P_M	permeability, m^3(STP)/(s · m^2 C.S. · atm/m)
P'_M	permeability, cm^3(STP)/(s · cm^2 C.S. · atm/cm)
P''_M	permeability, cm^3(STP)/(s · cm^2 C.S. · cm Hg/mm)
q	heat-transfer rate, W (btu/h); also net energy added to system, W (btu/h); also J (btu)
q	flow rate, m^3/s (ft^3/s)
$\mathbf{q}$	heat flux vector, W/m^2 (btu/h · ft^2)
$\dot{q}$	rate of heat generation, W/m^3 (btu/h · ft^3)
q	feed condition defined by Eq. (11.4-12)
q'	flow rate in Darcy's law, cm^3/s
q	kg adsorbate/kg adsorbent (lb_m/lb_m)
q_1	flow rate of residue, m^3/s (ft^3/h, cm^3/s)
q_2	flow rate of permeate, m^3/s (ft^3/h, cm^3/s)
q_A	flow rate of A in permeate, cm^3 (STP)/s, m^3/s (ft^3/h)
q_c	condenser duty, kJ/h, kW (btu/h)
q_f	feed flow rate, cm^3 (STP)/s, m^3/s (ft^3/h)
$\bar{q}_{n,m}$	residual defined by Eq. (4.5-11), K (°F)
q_o	reject flow rate, cm^3 (STP)/s, m^3/s (ft^3/h)
q_p	permeate flow rate, cm^3 (STP)/s, m^3/s (ft^3/h)
q_R	reboiler duty, kJ/h, kW (btu/h)

Q	circulation rate, m^3/s (ft^3/h)
Q	amount absorbed, kg mol/m^2; also heat loss, W (btu/h); also heat absorbed, J/kg (btu/lb_m, ft · lb_f/lb_m)
r	radius, m (ft)
r_A	rate of generation, kg A/s · m^3 (lb_m A/h · ft^3)
r_H	hydraulic radius, m (ft)
$(r_2)_{cr}$	critical value of radius, m (ft)
R	rate of drying, kg/h · m^2 (lb_m/h · ft^2)
R	solute rejection, dimensionless
R	scaleup ratio, dimensionless
R	radius, m (ft); also resistance, K/W (h · °F/btu)
R	parameter in Eq. (5.5-12), dimensionless; also resistance, ohms
R	gas constant (see Appendix A.1); also reflux ratio = L_n/D, dimensionless
R_A	rate of generation, kg mol A/s · m^3 (lb mol A/h · ft^3)
R_b	radius of spindle, m (ft)
R_c	radius of outer cylinder, m (ft)
R_c	contact resistance, K/W (h · °F/btu)
R_g	gel layer resistance, s · m^2 · atm/kg
R_m	resistance of filter medium, m^{-1} (ft^{-1})
R_i	rate of generation of i, kg/s (lb_m/h)
R_x	x component of force, N (lb_f, dyn)
s	compressibility constant, dimensionless
s	mean surface renewal factor, s^{-1}
S	conduction shape factor, m (ft)
S	solubility of a gas, m^3 solute(STP)/m^3 solid · atm [cc solute(STP)/cc solid · atm]
S	distance between centers, m (ft); also steam flow rate, kg/h, kg mol/h (lb_m/h)
S	volume of feed solution, m^3 (ft^3)
S	cross-sectional area of tower, m^2 (ft^2); also stripping factor, $1/A$
S_0	specific surface area, m^2/m^3 volume (ft^2/ft^3 volume)
S_p	surface area of particle, m^2 (ft^2)
t	fin thickness, m (ft)
t	time, s, min, or h
t	temperature, K, °C (°F)
t	membrane thickness, cm, m (ft)
t_b	break-point time, h
t_t	time equivalent to total capacity, h
t_T	mixing time, s
t_u	time equivalent to usable capacity up to break-point time, h
T	torque, kg · m^2/s^2
T	temperature, K, °C (°F, °R); also feed rate, ton/min
T'	deviation of temperature from mean temperature $\bar{T}$, K (°F)
$\bar{u}$	average velocity, m/s (ft/s)
U	overall heat-transfer coefficient, W/m^2 · K (btu/h · ft^2 · °F)
U	internal energy, J/kg (btu/lb_m)
v	velocity, m/s (ft/s)
$\mathbf{v}$	velocity vector, m/s (ft/s)

v_A	velocity of A relative to stationary coordinates, m/s (ft/s, cm/s)
v_{Ad}	diffusion velocity of A relative to molar average velocity, m/s (ft/s, cm/s)
v_M	molar average velocity of stream relative to stationary coordinates, m/s (ft/s, cm/s)
v_H	humid volume, m^3/kg dry air (ft^3/lb_m dry air)
v_t	terminal settling velocity, m/s (ft/s)
v^+	dimensionless velocity defined by Eq. (3.10-34)
v^*	velocity defined by Eq. (3.10-42), dimensionless
v'_x	deviation of velocity in x direction from mean velocity $\bar{v}_x$, m/s (ft/s)
v'	superficial velocity based on cross section of empty tube, m/s (ft/s, cm/s)
v'_{mf}	velocity at minimum fluidization, m/s (ft/s)
v'_t	terminal settling velocity, m/s (ft/s)
V_A	solute molar volume, m^3/kg mol
V	flow rate, kg/h, kg mol/h, m^3/s (lb_m/h, ft^3/s)
V	volume, m^3 (ft^3, cm^3); also specific volume, m^3/kg (ft^3/lb_m)
V	velocity, m/s (ft/s); also total amount, kg, kg mol (lb_m)
V'	inert flow rate, kg/h, kg/s, kg mol/h (lb_m/h)
w_A	mass fraction of A
$\dot{W}$	work done on surroundings, W (ft · lb_f/s)
W	free water, kg (lb_m)
$\dot{W}_s$	mechanical shaft work done on surroundings, W (ft · lb_f/s)
W	flow rate, kg/h, kg mol/h (lb_m/h)
W	work done on surroundings, J/kg (ft · lb_f/lb_m)
W	weight of wet solid, kg (lb_m)
W	height or width, m (ft); also power, W (hp); also mass dry cake, kg (lb_m)
W	width of paddle, m (ft)
W_S	mechanical shaft work done on surroundings, J/kg (ft · lb_f/lb_m)
W_p	shaft work delivered to pump, J/kg (ft · lb_f/lb_m)
x	distance in x direction, m (ft)
x	mass fraction or mole fraction; also fraction remaining of original free moisture
x_A	mole fraction of A, dimensionless
x'_B	inert mole ratio, mol B/mol inert
x_f	mole fraction of A in feed, dimensionless
x_o	mole fraction of A in reject, dimensionless
x_{oM}	mole fraction of minimum reject concentration, dimensionless
x_{BM}	log mean mole fraction of inert or stagnant B given in Eq. (6.3-4)
$(1 - x_A)_{\bullet M}$	log mean inert mole fraction defined by Eq. (10.4-27)
$(1 - x_A)_{iM}$	log mean inert mole fraction defined by Eq. (10.4-7)
X	particle size, m (ft); also parameter $= \alpha t/x_1^2$, dimensionless
X	parameter $= Dt/x^2$, dimensionless; also free moisture, kg water/kg dry solid (lb water/lb dry solid)
y	distance in y direction, m (ft); also mole fraction
y_A	mass fraction of A or mole fraction of A; also kg A/kg solution (lb A/lb solution)
y_{BM}	log mean mole fraction of inert or stagnant B given in Eq. (7.2-11)
y^+	dimensionless number defined by Eq. (3.10-35)

y_i	mole fraction of A in permeate at outlet of residue stream, dimensionless
y_p	mole fraction of A in permeate, dimensionless
$(y - y_i)_M$	log mean driving force defined by Eq. (10.6-24)
$(1 - y_A)_{iM}$	log mean inert mole fraction defined by Eq. (10.4-6)
Y	temperature ratio defined by Eq. (4.10-2), dimensionless
Y	fraction of unaccomplished change in Table 5.3-1 or Eq. (7.1-12)
Y	expansion correction factor defined in Eqs. (3.2-9) and (3.2-11)
z	distance in z direction, m (ft); also tower height, m (ft)
z	temperature range for 10:1 change in D_T, °C (°F)
Z	height, m (ft); also temperature ratio in Eq. (4.10-2)
Greek letters	
α	correction factor = 1.0, turbulent flow and $\frac{1}{2}$, laminar flow
α	absorptivity, dimensionless; also flux ratio = $1 + N_B/N_A$
α	thermal diffusivity = $k/\rho c_p$, m^2/s (ft^2/h, cm^2/s)
α, α_{AB}	relative volatility of A with respect to B, dimensionless
α	specific cake resistance, m/kg (ft/lb_m)
α	angle, rad
α	kinetic-energy velocity correction factor, dimensionless
α^*	ideal separation factor = P'_A/P'_B, dimensionless
α_G	gas absorptivity, dimensionless
α_T	eddy thermal diffusivity, m^2/s (ft^2/h)
β	concentration polarization, ratio of salt concentration at membrane surface to the salt concentration in bulk feed stream, dimensionless
β	momentum velocity correction factor, dimensionless
β	volumetric coefficient of expansion, 1/K (1/°R)
γ	viscosity coefficient, $N \cdot s^{n'}/m^2$ ($lb_m/ft \cdot s^{2-n'}$)
γ	ratio of heat capacities = c_p/c_v, dimensionless
Γ	flow rate, kg/s · m ($lb_m/h \cdot ft$)
Γ	concentration of property, amount of property/m^3
δ	molecular diffusivity, m^2/s
δ	boundary-layer thickness, m (ft); also distance, m (ft)
δ	constant in Eq. (4.12-2), dimensionless
Δ	difference; also difference operating-point flow rate, kg/h(lb_m/h)
ΔT_a	arithmetic temperature drop, K, °C (°F)
ΔT_{lm}	log mean temperature driving force, K, °C(°F)
ΔH	enthalpy change, J/kg, kJ/kg, kJ/kg mol (btu/lb_m, btu/lb mol)
∇	design criterion for sterilization, dimensionless
Δp	pressure drop, N/m^2, Pa (lb_f/ft^2)
ε	roughness parameter, m (ft); or void fraction, dimensionless
ε	emissivity, dimensionless; also volume fraction, dimensionless
ε_M	mass eddy diffusivity m^2/s (ft^2/h, cm^2/s)
ε	heat-exchanger effectiveness, dimensionless
ε_G	gas emissivity, dimensionless
ε_t	momentum eddy diffusivity, m^2/s (ft^2/s)
ε_{mf}	void fraction at minimum fluidization, dimensionless
η_f	fin efficiency, dimensionless
η_t	turbulent eddy viscosity, Pa · s, kg/m · s ($lb_m/ft \cdot s$)
η	efficiency, dimensionless
θ	angle, rad

θ	parameter in Eq. (11.7-19)
θ	cut or fraction of feed permeated, dimensionless
θ^*	fraction permeated up to a value of $x = 1 - q/q_f$, dimensionless
λ	wavelength, m (ft)
λ	latent heat, J/kg, kJ/kg (btu/lb$_m$); also mean free path, m (ft)
λ_{Ab}	latent heat of A at normal boiling point, J/kg, kJ/kg mol (btu/lb$_m$)
μ	viscosity, Pa · s, kg/m · s, N · s/m^2 (lb$_m$/ft · s, lb$_m$/ft · h, cp)
μ_a	apparent viscosity, Pa · s, kg/m · s (lb$_m$/ft · s)
ν	momentum diffusivity μ/ρ, m^2/s (ft^2/s, cm^2/s)
π_1	dimensionless group, dimensionless
π	osmotic pressure, Pa, N/m^2 (lb$_f$/ft^2, atm)
ρ	density, kg/m^3 (lb$_m$/ft^3); also reflectivity, dimensionless
σ	constant, 5.676×10^{-8} W/m$^2 \cdot$ K^4 (0.1714×10^{-8} btu/h · ft^2 · °R^4); also collision diameter, Å
Σ	sigma value for centrifuge, m^2 (ft^2)
τ_{zx}	flux of x-directed momentum in z direction, (kg · m/s)/s · m^2 or N/m^2 (lb$_f$/ft^2, dyn/cm^2)
τ	shear stress, N/m^2 (lb$_f$/ft^2, dyn/cm^2)
τ	tortuosity, dimensionless
ϕ	velocity potential, m^2/s (ft^2/h)
ϕ	angle, rad; also association parameter, dimensionless
ϕ	osmotic coefficient, dimensionless
ϕ_S	shape factor of particle, dimensionless
Ψ_z	flux of property, amount of property/s · m^2
ψ	correction factor, dimensionless
ψ	stream function, m^2/s (ft^2/h)
ψ_p	parameter defined by Eq. (14.3-13), dimensionless
ω	angular velocity, rad/s
ω	solid angle, sr
$\Omega_{D,AB}$	collision integral, dimensionless

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