Appendix B

Miscellaneous Tables

Mass Transfer Operations for the Practicing Engineer. By Louis Theodore and Francesco Ricci

Table B.1 Common Engineering Conversion Factors

Length

1 ft = 12 in = 0.3048 m, 1 yard = 3 ft

1 mi = 5280 ft = 1609.344 m

1 nautical mile (nmi) = 6076 ft

Mass

1 slug = 32.174 lb = 14.594 kg

1 lb = 0.4536 kg = 7000 grains

Acceleration and Area

1 $ft/s^2 = 0.3048\ m/s^2$

1 $ft^2 = 0.092903\ m^2$

Mass flow and Mass flux

1 slug/s = 14.594 kg/s,

1 lb/s = 0.4536 kg/s

1 $kg/m^2 \cdot s = 0.2046\ lb/ft^2 \cdot s =$ $0.00636\ slug/ft^2 \cdot s$

Pressure

1 $lb_f/ft^2 = 47.88$ Pa, 1 torr = 1 mm Hg

1 psi = 144 psf, 1 bar = 10^5 Pa

1 atm = 2116.2 psf = 14.696 psi = 101,325 Pa = 29.9 in Hg = 33.9 ft H_2O

Power

1 hp = 550 $(ft \cdot lb_f)/s = 745.7$ W

1 $(ft \cdot lb_f)/s = 1.3558$ W

1 Watt = 3.4123 Btu/h = 0.00134 hp

Specific weight

1 $lb_f/ft^3 = 157.09\ N/m^3$

Viscosity

1 $slug/(ft \cdot s) = 47.88\ kg/(m \cdot s) =$ 478.8 poise (P)

1 P = 1 $g/(cm \cdot s) = 0.1\ kg/(m \cdot s) =$ $0.002088\ slug/(ft \cdot s)$

Temperature scale readings

$°F = (9/5)°C + 32$

$°C = (5/9)(°F - 32)$

$°R = °F + 459.69$

$K = °C + 273.16$

$°R = (1.8)\,K$

Specific heat or Gas constant*

1 $(ft \cdot lb_f)/(slug \cdot °R) = 0.16723\ (N \cdot m)/(kg \cdot K)$

1 $Btu/(lb \cdot °R) = 4186.8\ J/(kg \cdot K)$

Volume

1 $ft^3 = 0.028317\ m^3 = 7.481$ gal, 1 bbl = 42 U.S. gal

1 U.S. gal = 231 $in^3 = 3.7853$ L = 4 qt = 0.833 Imp. gal

1 L = 0.001 $m^3 = 0.035315\ ft^3 = 0.2642$ U.S. gal

Density

1 $slug/ft^3 = 515.38\ kg/m^3$, 1 $g/cm^3 = 1000\ kg/m^3$

1 $lb/ft^3 = 16.0185\ kg/m^3$, 1 $lb/in^3 = 27.68\ g/cm^3$

Velocity

1 ft/s = 0.3048 m/s, 1 knot = 1 nmi/h = 1.6878 ft/s

1 mi/h = 1.4666666 ft/s = 0.44704 m/s

Volume flow

1 gal/min = 0.002228 $ft^3/s =$ 0.06309 L/s

1 million gal/day = 1.5472 $ft^3/s = 0.04381\ m^3/s$

Force and Surface tension

1 $lb_f = 4.448222$ N = 16 oz, 1 dyne = 1 $g \cdot cm/s^2 = 10^{-5}$ N

1 $kg_f = 2.2046\ lb_f = 9.80665$ N

1 U.S. (short) ton = 2000 lb_f, 1 N = 0.2248 lb_f

1 N/m = 0.0685 lb_f/ft

Energy and Specific energy

1 $ft \cdot lb_f = 1.35582$ J, 1 $hp \cdot h = 2544.5$ Btu

1 Btu = 252 cal = 1055.056 J = 778.17 $ft \cdot lb_f$

1 cal = 4.1855 J, 1 $ft \cdot lb_f/lb = 2.9890\ J/kg$

Heat flux

1 $W/m^2 = 0.3171\ Btu/(h \cdot ft^2)$

Kinematic viscosity

1 $ft^2/h = 2.506 \times 10^{-5}\ m^2/s$, 1 $ft^2/s = 0.092903\ m^2/s$

1 stoke (st) = 1 $cm^2/s = 0.0001\ m^2/s = 0.001076\ ft^2/s$

Thermal conductivity*

1 $cal/(s \cdot cm \cdot °C) = 242\ Btu/(h \cdot ft \cdot °R)$

1 $Btu/(h \cdot ft \cdot °R) = 1.7307\ W/(m \cdot K)$

*Note that the intervals in absolute (Kelvin) and °C are equal. Also, 1°R = 1°F.

Latent heat: 1 J/kg = 4.2995×10^{-4} Btu/lb = 10.76 $lb_f \cdot ft/slug = 0.3345\ lb_f \cdot ft/lb$, 1 Btu/lb = 2325.9 J/kg.

Heat transfer coefficient: 1 $Btu/(h \cdot ft^2 \cdot °F) = 5.6782\ W/(m^2 \cdot °C)$.

Heat generation rate: 1 $W/m^3 = 0.09665\ Btu/(h \cdot ft^3)$.

Heat transfer per unit length: 1 W/m = 1.0403 $Btu/(h \cdot ft)$.

Mass transfer coefficient: 1 m/s = 11.811 ft/h, 1 $lbmol/(h \cdot ft^2) = 0.0013562\ kgmol/(s \cdot m^2)$.

Table B.2 Properties of Selected Gases at 1 atm and 20°C (68°F)

Gas	Molecular weight	Density, ρ, kg/m^3	Viscosity		Ratio of specific heats, k	T_{crit}, K	P_{crit}, atm
			Dynamic, μ, $kg/m \cdot s$ ($\times 10^5$)	Kinematic, ν, m^2/s ($\times 10^6$)			
Acetylene	26	1.09	0.97	8.3	1.30	309.5	61.6
Air (dry)	28.96	1.20	1.80	15.0	1.40	133	37
Ammonia	17.03	0.74	1.01	13.6	1.31	405	111.3
Argon	39.944	1.66	2.24	13.5	1.67		
Butane	58.1	2.49			1.11	425.2	37.5
Carbon dioxide	44.01	1.83	1.48	8.09	1.30	304	72.9
Carbon monoxide	28.01	1.16	1.82	15.7	1.40	133	34.5
Chlorine	70.91	2.95	1.03	3.49	1.34	417	76.1
Ethane	30.07	1.25	0.85	6.8	1.19	305	48.2
Ethylene	28	1.17	0.97	8.3	1.22	283.1	50.5
Helium	4.003	0.166	1.97	118.7	1.66	5.26	2.26
Hydrogen	2.016	0.0838	0.905	108.0	1.41	33	12.8
Hydrogen chloride	36.5	1.53	1.34	8.76	1.41	324.6	81.5
Hydrogen sulfide	34.1	1.43	1.24	8.67	1.30	373.6	88.9
Methane	16.04	0.667	1.34	20.1	1.32	190	45.8
Methyl chloride	50.5	2.15			1.20	416.1	65.8
Natural gas	19.5	0.804			1.27		
Nitrogen	28.02	1.16	1.76	15.2	1.40	126	33.5
Nitrogen oxide (NO)	30.01	1.23	1.90	15.4	1.40	179	65.0
Nitrous oxide (N_2O)	44.02	1.83	1.45	7.92	1.31	309	71.7
Oxygen	32.00	1.36	2.00	14.7	1.40	154	49.7
Propane	44.1	1.88			1.15	369.9	42.0
Sulfur dioxide	64	2.66	1.38	5.2	1.29	430	77.8
Water vapor	18.02	0.749	1.02	13.6	1.33	647	218.3

Example: At 20°C, the properties of argon gas are: molecular weight = 39.944, density = 1.66 kg/m^3 (0.00322 $slug/ft^3$ = 0.104 lb/ft^3), dynamic viscosity = 0.0000224 $kg/m \cdot s$ (0.0224 cP = 4.68×10^{-7} $slug/ft \cdot s$ = 1.51×10^{-5} $lb/ft \cdot s$), kinematic viscosity = 13.5×10^{-6} m^2/s (13.5 cSt = 1.45×10^{-4} ft^2/s = 0.523 ft^2/h), specific heat ratio = 1.67.

Table B.3 Properties of Selected Liquids at 1 atm and 20°C (68°F)

Liquid	Density, kg/m^3	Absolute viscosity, μ, $kg/m \cdot s \times 10{,}000$	Kinematic viscosity, ν, $m^2/s \times 10^6$	Surface tension, $N/m \times 100$	Vapor pressure, kPa	Sound velocity, m/s	Heat capacity, $J/kg \cdot K$	Thermal conductivity, k, $W/m \cdot K$	Coefficient of thermal expansion, β, $1000 \times K^{-1}$
Acetic acid							2051.6		
Acetone	785	3.16	0.403	2.31	27.6	1174	2210		
Ammonia	608	2.20	0.362	2.13	910		4798	0.521	2.45
Benzene	881	6.51	0.739	2.88	10.1	1298	1700	0.159	
Carbon disulfide	1272				47.9				
Carbon tetrachloride	1590	9.67	0.608	2.70	1.20	924		0.18	
Castor oil	970	9000	927.8			1474		0.18	
Crude oil	856	72	8.4	3.0					
Engine oil (unused)	888	7994	900.2				1880	0.145	0.7
Ethanol (ethyl alcohol)	789	11	1.4	2.28	5.7	1144	2433	0.182	
Ethylene glycol	1117	214	19.16	3.27		1644	2382	0.250	0.65
Freon-12	1330	2.63	0.198	1.58					
Fuel oil, heavy	908	1324	145.9						
Fuel oil, medium	854	32.7	3.82						
Gasoline	680	2.92	0.429	2.16	55.1				

(*Continued*)

TABLE B.3 Properties of Selected Liquids at 1 atm and 20°C (68°F) (*Continued*)

Glycerin	1260	14,900	1183	6.33	0.14	1909	2386	0.286	0.5
Kerosene	804	1.92	0.239	2.8	3.11	1320		0.149	
Mercury	13,500	15.6	0.115	48.4	11×10^{-7}	1450	13.9		
Methanol	791	5.98	0.756	2.25	13.4	1103	2512	0.215	
Milk (skim)	1041	14	1.34						
Milk (whole)	1030	21.2	2.06						
Olive oil	919	840	91.4						
Pentane	624				58.9				
Soybean oil	919	400	43.5						
SAE 10 oil	917	1040	113.4	3.6					
SAE 30 oil	917	2900	316.2	3.5					
Seawater	1025	10.7	1.04	7.28	2.34	1535			
Turpentine	862	14.9	1.73						
Water	998	10.0	1.06	7.28	2.34	1498	4186		

Example: At 20°C, the properties of liquid methanol are: density = 791 kg/m^3 (or SG = 0.791), dynamic viscosity = 0.000598 $kg/m \cdot s$ (or 0.598 cP), kinematic viscosity = 0.756×10^{-6} m^2/s (0.756 cP = 8.14×10^{-6} ft^2/s), surface tension = 0.0225 N/m (0.00154 lb_f/ft), vapor (or saturation) pressure = 13,400 Pa (1.943 psi), sound velocity = 1104 m/s, heat capacity = 2512 $J/kg \cdot K$, thermal conductivity = 0.215 $W/m \cdot K$.

Table B.4 Properties of Water at 1 atm (Critical Point 374°C, 22.09 MPa)

Temperature		Density, ρ		Absolute (dynamic) viscosity, μ		Kinematic viscosity, ν		Surface tension,	Vapor	Prandtl
°C	°F	kg/m^3	$slug/ft^3$	$kg/m \cdot s\ (\times 10^3)$	$slug/ft \cdot s\ (\times 10^5)$	$m^2/s\ (\times 10^6)$	$ft^2/s\ (\times 10^5)$	γ, N/m	pressure, kPa	number, Pr
0	32	1000	1.940	1.788	0.373	1.788	1.925	0.0756	0.611	13.25
5	41	1000	1.940	1.518	0.317	1.519	1.635	0.0749	0.87	
10	50	1000	1.940	1.307	0.273	1.307	1.407	0.0742	1.227	9.40
15	59	999	1.938	1.139	0.238	1.139	1.226	0.0735	1.70	7.87
20	68	998	1.937	1.003	0.209	1.005	1.082	0.0728	2.337	6.79
25	77	997	1.934	0.890	0.186	0.893	0.961	0.0720	3.17	5.86
30	86	996	1.932	0.799	0.167	0.802	0.864	0.0712	4.242	5.15
40	104	992	1.925	0.657	0.137	0.662	0.713	0.0696	7.375	
50	122	988	1.917	0.548	0.114	0.555	0.597	0.0679	12.34	
60	140	983	1.908	0.467	0.975	0.475	0.511	0.0662	19.92	
70	158	978	1.897	0.405	0.846	0.414	0.446	0.0644	31.16	
80	176	972	1.886	0.355	0.741	0.365	0.393	0.0626	47.35	
90	194	965	1.873	0.316	0.660	0.327	0.352	0.0608	70.11	
100	212	958	1.859	0.283	0.591	0.295	0.318	0.0589	101.33	

Example: At 50°C (122°F) $\rho = 988\ kg/m^3$ $(1.917\ slug/ft^3)$, $\mu = 0.548 \times 10^{-3}\ kg/m \cdot s$ $(0.114 \times 10^{-5}\ slug/ft \cdot s)$, $\nu = 0.555 \times 10^{-6}\ m^2/s$ $(0.597 \times 10^{-5}\ ft^2/s)$, $\gamma = 0.0679\ N/m$ $(0.00465\ lb_f/ft)$, vapor pressure = 12,340 Pa (1.79 psi).

Table B.5 Properties of Air at 1 atm

Temperature, °C	Density, ρ, kg/m^3	Viscosity, μ, kg/m · s ($\times 10^5$)	Kinematic viscosity, ν, m^2/s ($\times 10^5$)	Heat capacity, c_p, J/kg · K	Thermal conductivity, k, W/m · K ($\times 10^2$)	Thermal expansion coefficient, β, K (10^3)	Prandtl number, Pr
−40	1.52	1.51	0.98		2.0		
−20	1.40	1.61	1.15	1004.8	2.21		
0	1.29	1.71	1.32	1004.8	2.42	3.65	0.715
10	1.248	1.76	1.41	1004.8	2.49	3.53	0.713
20	1.205	1.81	1.50	1004.8			
30	1.165	1.86	1.60	1004.8			
40	1.128	1.90	1.68	1004.8	2.7		
50	1.09	1.95	1.79	1007.0	2.8		
60	1.060	2.00	1.87	1009.0			
80	1.000	2.09	2.09	1009.0			
100	0.946	2.17	2.30	1009.0	3.12		
150	0.835	2.38	2.85	1017.0	3.53		
200	0.746	2.57	3.45	1025.8	3.88		0.686
250	0.675	2.75	4.07	1034.1	4.24		0.680
300	0.616	2.93	4.76				
400	0.525	3.25	6.19				
500	0.457	3.55	7.77		5.73		0.709

Example: At 50°C, the air properties are: density = 1.09 kg/m^3 (0.00211 slug/ft^3 = 0.679 lb/ft^3), dynamic viscosity = 0.0000195 kg/m · s (4.073×10^{-7} slug/ft · s = 1.31×10^{-5} lb/ft · s), thermal conductivity, $k = 0.028$ W/m · K, coefficient of thermal expansion, $\beta = 1/T = 1/(273 + 50) = 0.0031$ K^{-1}. The Prandtl number, $\text{Pr} = c_p\mu/k \simeq 0.7$.

Table B.6 Dimensions, Capacities, and Weights of Standard Steel Pipes

Nominal pipe size, in.	Outside diameter, in.	Schedule no.	Wall thickness, in	ID, in	Cross-sectional area of metal, in^2	Inside sectional area, ft^2	Pipe weight, lb/ft
$\frac{1}{8}$	0.405	40	0.068	0.269	0.072	0.00040	0.24
		80	0.095	0.215	0.093	0.00025	0.31
$\frac{1}{4}$	0.540	40	0.088	0.364	0.125	0.00072	0.42
		80	0.119	0.302	0.157	0.00050	0.54
$\frac{3}{8}$	0.675	40	0.091	0.493	0.167	0.00133	0.57
		80	0.126	0.423	0.217	0.00098	0.74
$\frac{1}{2}$	0.840	40	0.109	0.622	0.250	0.00211	0.85
		80	0.147	0.546	0.320	0.00163	1.09
$\frac{3}{4}$	1.050	40	0.113	0.824	0.333	0.00371	1.13
		80	0.154	0.742	0.433	0.00300	1.47
1	1.315	40	0.133	1.049	0.494	0.00600	1.68
		80	0.179	0.957	0.639	0.00499	2.17
$1\frac{1}{4}$	1.660	40	0.140	1.380	0.668	0.01040	2.27
		80	0.191	1.278	0.881	0.00891	3.00
$1\frac{1}{2}$	1.900	40	0.145	1.610	0.800	0.01414	2.72
		80	0.200	1.500	1.069	0.01225	3.63
2	2.375	40	0.154	2.067	1.075	0.02330	3.65
		80	0.218	1.939	1.477	0.02050	5.02

(*Continued*)

TABLE B.6 Dimensions, Capacities, and Weights of Standard Steel Pipes (*Continued*)

$2\frac{1}{2}$	2.875	40	0.203	2.469	1.704	0.03322	5.79
		80	0.276	2.323	2.254	0.02942	7.66
3	3.500	40	0.216	3.068	2.228	0.05130	7.58
		80	0.300	2.900	3.016	0.04587	10.25
$3\frac{1}{2}$	4.000	40	0.226	3.548	2.680	0.06870	9.11
		80	0.318	3.364	3.678	0.06170	12.51
4	4.500	40	0.237	4.026	3.17	0.08840	10.79
		80	0.337	3.826	4.41	0.07986	14.98
5	5.563	40	0.258	5.047	4.30	0.1390	14.62
		80	0.375	4.813	6.11	0.1263	20.78
6	6.625	40	0.280	6.065	5.58	0.2006	18.97
		80	0.432	5.761	8.40	0.1810	28.57
8	8.625	40	0.322	7.981	8.396	0.3474	28.55
		80	0.500	7.625	12.76	0.3171	43.39
10	10.75	40	0.365	10.020	11.91	0.5475	40.48
		80	0.594	9.562	18.95	0.4987	64.40
12	12.75	40	0.406	11.938	15.74	0.7773	53.36
		80	0.688	11.374	26.07	0.7056	88.57

Table B.7 Dimensions of Heat Exchanger Tubes

Tube OD, in	B.W.G. gauge	Thickness, in	Tube ID, in	Flow area, in^2	Surface area, per foot of length, ft	
					External	Internal
$\frac{1}{4}$	22	0.028	0.194	0.0295	0.0655	0.0508
$\frac{1}{4}$	24	0.022	0.206	0.0333	0.0655	0.0539
$\frac{1}{2}$	18	0.049	0.402	0.1269	0.1309	0.1052
$\frac{1}{2}$	20	0.035	0.430	0.1452	0.1309	0.1126
$\frac{1}{2}$	22	0.028	0.444	0.1548	0.1309	0.1162
$\frac{3}{4}$	10	0.134	0.482	0.1825	0.1963	0.1262
$\frac{3}{4}$	14	0.083	0.584	0.2679	0.1963	0.1529
$\frac{3}{4}$	16	0.065	0.620	0.3019	0.1963	0.1623
$\frac{3}{4}$	18	0.049	0.652	0.3339	0.1963	0.1707
1	8	0.165	0.670	0.3526	0.2618	0.1754
1	14	0.083	0.834	0.5463	0.2618	0.2183
1	16	0.065	0.870	0.5945	0.2618	0.2278
1	18	0.049	0.902	0.6390	0.2618	0.2361
$1\frac{1}{4}$	8	0.165	0.920	0.6648	0.3272	0.2409
$1\frac{1}{4}$	14	0.083	1.084	0.9229	0.3272	0.2838
$1\frac{1}{4}$	16	0.065	1.120	0.9852	0.3272	0.2932
$1\frac{1}{4}$	18	0.049	1.152	1.042	0.3272	0.3016
2	11	0.120	1.760	2.433	0.5236	0.4608
2	12	0.109	1.782	2.494	0.5236	0.4665
2	13	0.095	1.810	2.573	0.5236	0.4739
2	14	0.083	1.834	2.642	0.5236	0.4801

(1 in = 25.4 mm; 1 in^2 = 645.16 mm^2; 1 ft = 0.3048 m; 1 ft^2 = 0.0929 m^2).