APPENDIX

A. TABLES

B. FIGURES

Fluid Flow for the Practicing Chemical Engineer. By J. Patrick Abulencia and Louis Theodore

A. TABLES

Table A.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·s) = 47.88 kg/(m·s) = 478.8 poise (p)
1 p = 1 g/(cm·s) = 0.1 kg/(m·s)= 0.002088 slug/(ft·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·m)/(kg·K)
1 Btu/(lb·°R) = 4186.8 J/(kg·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 (fps) = 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·h = 2544.5 Btu
1 Btu = 252 cal = 1055.056 J = 778.17 $ft \cdot lb_f$
1 cal = 4.1855 J, 1 $ft \cdot lb_f/lb_m$ = 2.9890 J/kg

Heat Flux

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

Kinematic Viscosity

1 ft^2/h = 2.506×10^{-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·cm·°C) = 242 Btu/(h·ft·°R)
1 Btu/(h·ft·°R) = 1.7307 W/(m·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·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 A.2 Properties of selected liquids at 1 atm and 20°C (68°F)

Liquid	Density, kg/m^3	Dynamic Viscosity, μ, $kg/m \cdot s$ ($\times 10^4$)	Kinematic Viscosity, ν, m^2/s ($\times 10^6$)	Surface Tension, N/m ($\times 10^2$)	Vapor Pressure, kPa	Sound Velocity, m/s
Acetone	785	3.16	0.403	2.31	27.6	1174
Ammonia	608	2.20	0.362	2.13	910.0	
Benzene	881	6.51	0.739	2.88	10.1	1298
Carbon disulfide	1272					
Carbon tetrachloride	1590	9.67	0.608	2.70	1.20	924
Castor oil	970	9000	927.8			1474
Crude oil	856	72	8.4	3.0		
Engine oil (unused)	888	7994	900.2			
Ethanol (or ethyl alcohol)	789	11	1.4	2.28	5.7	1144
Ethylene glycol	1117	214	19.16	3.27		1644
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	
Glycerin	1260	14,900	1183	6.33	0.14	1909
Kerosene	804	1.92	0.239	2.8	3.11	1320
Mercury	13,550	15.6	0.115	48.4	1.1×10^{-6}	1450
Methanol	791	5.98	0.756	2.25	13.4	1103
Milk (skimmed)	1041	14	1.34			
Milk (whole)	1030	21.2	2.06			
Olive oil	919	840	91.4			
Pentane	624					
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

Example: At 20°C, the properties 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).

Table A.3 Properties of selected gases at 1 atm and 20°C (68°F)

Gas	Molecular Weight	Density, kg/m^3	Viscosity: Dynamic, μ, $kg/m \cdot s\ (\times 10^5)$	Viscosity: Kinematic, ν, $m^2/s\ (\times 10^6)$	Ratio of Specific Heats, k	T_{crit}, K	P_{crit}, atm
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	32.0	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 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 A.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 Pressure,
°C	°F	kg/m^3	$slug/ft^3$	$kg/m\cdot s\,(\times 10^3)$	$slug/ft\cdot s\,(\times 10^5)$	$m^2/s\,(\times 10^6)$	$ft^2/s\,(\times 10^5)$	σ, N/m	p', kPa
0	32	1000	1.940	1.788	0.373	1.788	1.925	0.0756	0.611
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
15	59	999	1.938	1.139	0.238	1.139	1.226	0.0735	1.70
20	68	998	1.937	1.003	0.209	1.005	1.082	0.0728	2.337
25	77	997	1.934	0.890	0.186	0.893	0.961	0.0720	3.17
30	86	996	1.932	0.799	0.167	0.802	0.864	0.0712	4.242
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·s (0.114×10^{-5} slug/ft·s), $\nu = 0.555 \times 10^{-6}\ m^2/s$ ($0.597 \times 10^{-5}\ ft^2/s$), $\sigma = 0.0679$ N/m (0.00465 lb_f/ft), vapor pressure = 12,340 Pa (1.79 psi).

Table A.5 Dimensions, capacities, and weights of standard steel pipes

Nominal Pipe Size, in	Outside Diameter, in	Schedule Number	Wall Thickness, in	Inside Diameter (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
$2\frac{1}{2}$	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 A.6 Dimensions of heat exchanger tubes

Tube OD, in	B.W.G. Gauge	Thickness, in	Tube Inside Diameter (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).

Table A.7 Properties of saturated liquids

Temperature T, °C	Density ρ, kg/m^3	Heat Capacity c_p, kJ/kg·°C	Kinematic Viscosity ν, m^2/s	Thermal Conductivity k, W/m·°C	Diffusivity α, m^2/s	Prandtl Number Pr	Thermal Expansion Coefficient β, K^{-1}
				Ammonia, NH_3			
−50	703.69	4.463	0.435×10^{-6}	0.547	1.742×10^{-7}	2.60	
−40	691.68	4.467	0.406	0.547	1.775	2.28	
−30	679.34	4.476	0.387	0.549	1.801	2.15	
−20	666.69	4.509	0.381	0.547	1.819	2.09	
−10	653.55	4.564	0.378	0.543	1.825	2.07	
0	640.10	4.635	0.373	0.540	1.819	2.05	
10	626.16	4.714	0.368	0.531	1.801	2.04	
20	611.75	4.798	0.359	0.521	1.775	2.02	2.45×10^{-3}
30	596.37	4.890	0.349	0.507	1.742	2.01	
40	580.99	4.999	0.340	0.493	1.701	2.00	
50	564.33	5.116	0.330	0.476	1.654	1.99	
				Carbon Dioxide, CO_2			
−50	1156.34	1.84	0.119×10^{-6}	0.0855	0.4021×10^{-7}	2.96	
−40	1117.77	1.88	0.118	0.1011	0.4810	2.46	
−30	1076.76	1.97	0.117	0.1116	0.5272	2.22	
−20	1032.39	2.05	0.115	0.1151	0.5445	2.12	
−10	983.38	2.18	0.113	0.1099	0.5133	2.20	
0	926.99	2.47	0.108	0.1045	0.4578	2.38	
10	860.03	3.14	0.101	0.0971	0.3608	2.80	
20	772.57	5.0	0.091	0.0872	0.2219	4.10	14.00×10^{-3}
30	597.81	36.4	0.080	0.0703	0.0279	28.7	

(Continued)

Table A.7 *Continued*

Temperature T, °C	Density ρ, kg/m^3	Heat Capacity c_p, kJ/kg·°C	Kinematic Viscosity ν, m^2/s	Thermal Conductivity k, W/m·°C	Diffusivity α, m^2/s	Prandtl Number Pr	Thermal Expansion Coefficient β, K^{-1}
				Sulfur Dioxide, SO_2			
−50	1560.84	1.3595	0.484×10^{-6}	0.242	1.141×10^{-7}	4.24	
−40	1536.81	1.3607	0.424	0.235	1.130	3.74	
−30	1520.64	1.3616	0.371	0.230	1.117	3.31	
−20	1488.60	1.3624	0.324	0.225	1.107	2.93	
−10	1463.61	1.3628	0.288	0.218	1.097	2.62	
0	1438.46	1.3636	0.257	0.211	1.081	2.38	
10	1412.51	1.3645	0.232	0.204	1.066	2.18	
20	1386.40	1.3653	0.210	0.199	1.050	2.00	1.95×10^{-3}
30	1359.33	1.3662	0.190	0.192	1.035	1.83	
40	1329.22	1.3674	0.173	0.185	1.019	1.70	
50	1299.10	1.3683	0.162	0.177	0.999	1.61	
				Dichlorodifluoromethane (Freon), CCl_2F_2			
−50	1546.75	0.8750	0.310×10^{-6}	0.067	0.501×10^{-7}	6.2	2.63×10^{-3}
−40	1518.71	0.8847	0.279	0.069	0.514	5.4	
−30	1489.56	0.8956	0.253	0.069	0.526	4.8	
−20	1460.57	0.9073	0.235	0.071	0.539	4.4	
−10	1429.49	0.9203	0.221	0.073	0.550	4.0	
0	1397.45	0.9345	0.214×10^{-6}	0.073	0.557×10^{-7}	3.8	
10	1364.30	0.9496	0.203	0.073	0.560	3.6	
20	1330.18	0.9659	0.198	0.073	0.560	3.5	
30	1295.10	0.9835	0.194	0.071	0.560	3.5	
40	1257.13	1.0019	0.191	0.069	0.555	3.5	
50	1215.96	1.0216	0.190	0.067	0.545	3.5	

				Glycerin, $C_3H_5(OH)_3$			
0	1276.03	2.261	0.00831	0.282	0.983×10^{-7}	84.7×10^{3}	
10	1270.11	2.319	0.00300	0.284	0.965	31.0	
20	1264.02	2.386	0.00118	0.286	0.947	12.5	0.50×10^{-3}
30	1258.09	2.445	0.00050	0.286	0.929	5.38	
40	1252.01	2.512	0.00022	0.286	0.914	2.45	
50	1244.96	2.583	0.00015	0.287	0.893	1.63	
				Ethylene Glycol, $C_2H_4(OH)_2$			
0	1130.75	2.294	57.53×10^{-6}	0.242	0.934×10^{-7}	615	
20	1116.65	2.382	19.18	0.249	0.939	204	0.65×10^{-3}
40	1101.43	2.474	8.69	0.256	0.939	93	
60	1087.66	2.562	4.75	0.260	0.932	51	
80	1077.56	2.650	2.98	0.261	0.921	32.4	
100	1058.50	2.742	2.03	0.263	0.908	22.4	
				Engine Oil (unused)			
0	899.12	1.796	0.00428	0.147	0.911×10^{-7}	47,100	
20	888.23	1.880	0.00090	0.145	0.872	10,400	0.70×10^{-3}
40	876.05	1.964	0.00024	0.144	0.834	2870	
60	864.04	2.047	0.839×10^{-4}	0.140	0.800	1050	
80	852.02	2.131	0.375	0.138	0.769	490	
100	840.01	2.219	0.203	0.137	0.738	276	
120	828.96	2.307	0.124	0.135	0.710	175	
140	816.94	2.395	0.080	0.133	0.686	116	
160	805.89	2.483	0.056	0.132	0.663	84	

(Continued)

Table A.7 *Continued*

Temperature T, °C	Density ρ, kg/m^3	Heat Capacity c_p, kJ/kg·°C	Kinematic Viscosity ν, m^2/s	Thermal Conductivity k, W/m·°C	Diffusivity α, m^2/s	Prandtl Number Pr	Thermal Expansion Coefficient β, K^{-1}
				Mercury, Hg			
0	13,628.22	0.1403	0.124×10^{-6}	8.20	42.99×10^{7}	0.0288	
20	13,759.04	0.1394	0.114	8.69	46.06	0.0249	1.82×10^{-4}
50	13,505.84	0.1386	0.104	9.40	50.22	0.0207	
100	13,384.58	0.1373	0.0928	10.51	57.16	0.0162	
150	13,264.68	0.1365	0.0853	11.49	63.54	0.0134	
200	13,144.94	0.1570	0.0802	12.34	69.08	0.0116	
250	13,025.60	0.1357	0.0765	13.07	74.06	0.0103	
315.5	12,857	0.134	0.0673	81.5	0.0083		

Table A.8 Properties of gases at atmospheric pressure[a]

Temperature T, K	Density ρ, kg/m^3	Heat Capacity c_p, $kJ/kg \cdot °C$	Dynamic Viscosity μ, $kg/m \cdot s$	Kinematic Viscosity ν, m^2/s	Thermal Conductivity k, $W/m \cdot °C$	Diffusivity α, m^2/s	Prandtl Number Pr
				Helium			
144	0.3379	5.200	125.5×10^{-7}	37.11×10^{-6}	0.0928	0.5275×10^{-4}	0.70
200	0.2435	5.200	156.6	64.38	0.1177	0.9288	0.694
255	0.1906	5.200	181.7	95.50	0.1357	0.1375	0.70
366	0.13280	5.200	230.5	173.6	0.1691	2.449	0.71
477	0.10204	5.200	275.0	269.3	0.197	3.716	0.72
589	0.08282	5.200	311.3	375.8	0.225	5.215	0.72
700	0.07032	5.200	347.5	494.2	0.251	6.661	0.72
800	0.06023	5.200	381.7	634.1	0.275	8.774	0.72
				Hydrogen			
150	0.16371	12.602	5.595×10^{-6}	34.18×10^{-6}	0.0981	0.475×10^{-4}	0.718
200	0.12270	13.540	6.813	55.53	0.1282	0.772	0.719
250	0.09819	14.059	7.919	80.64	0.1561	1.130	0.713
300	0.08185	14.314	8.963	109.5	0.182	1.554	0.706
350	0.07016	14.436	9.954	141.9	0.206	2.031	0.697
400	0.06135	14.491	10.864	177.1	0.228	2.568	0.690
450	0.05462	14.499	11.779	215.6	0.251	3.164	0.682
500	0.04918	14.507	12.636	257.0	0.272	3.817	0.675
550	0.04469	14.532	13.475	301.6	0.292	4.516	0.668
600	0.04085	14.537	14.285	349.7	0.315	5.306	0.664
700	0.03492	14.574	15.89	455.1	0.351	6.903	0.659
800	0.03060	14.675	17.40	569	0.384	8.563	0.664
900	0.02723	14.821	18.78	690	0.412	10.217	0.676

(Continued)

Table A.8 *Continued*

Temperature T, K	Density ρ, kg/m^3	Heat Capacity c_p, kJ/kg·°C	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m^2/s	Thermal Conductivity k, W/m·°C	Diffusivity α, m^2/s	Prandtl Number Pr
				Oxygen			
150	2.6190	0.9178	11.490×10^{-6}	4.387×10^{-6}	0.01367	0.05688×10^{-4}	0.773
200	1.9559	0.9131	14.850	7.593	0.01824	0.10214	0.745
250	1.5618	0.9157	17.87	11.45	0.02259	0.15794	0.725
300	1.3007	0.9203	20.63	15.86	0.02676	0.22353	0.709
350	1.1133	0.9291	23.16	20.80	0.03070	0.2968	0.702
400	0.9755	0.9420	25.54	26.18	0.03461	0.3768	0.695
450	0.8682	0.9567	27.7	31.99	0.03828	0.4609	0.694
500	0.7801	0.9722	29.91	38.34	0.4173	0.5502	0.697
550	0.7096	0.9881	31.97	45.05	0.04517	0.641	0.700
				Nitrogen			
200	1.7108	1.0429	12.947×10^{-6}	7.568×10^{-6}	0.01824	0.10224×10^{-4}	0.747
300	1.1421	1.0408	17.84	15.63	0.02620	0.22044	0.713
400	0.8538	1.0459	21.98	25.74	0.03335	0.3734	0.691
500	0.6824	1.0555	25.70	37.66	0.03984	0.5530	0.684
600	0.5687	1.0756	29.11	51.19	0.04580	0.7486	0.686
700	0.4934	1.0969	32.13	65.13	0.05123	0.9466	0.691
800	0.4277	1.1225	34.84	81.46	0.05609	1.1685	0.700
900	0.3796	1.1464	37.49	91.06	0.06070	1.3946	0.711
1000	0.3412	1.1677	40.00	117.2	0.06475	1.6250	0.724
1100	0.3108	1.1857	42.28	136.0	0.06850	1.8591	0.736
1200	0.2851	1.2037	44.50	156.1	0.07184	2.0932	0.748
				Carbon Dioxide			
220	2.4733	0.783	11.105×10^{-6}	4.490×10^{-6}	0.010805	0.05920×10^{-5}	0.818
250	2.1657	0.804	12.590	5.813	0.012884	0.07401	0.793

300	1.7973	0.871	14.958	8.321	0.016572	0.10588	0.770
350	1.5362	0.900	17.205	11.19	0.02047	0.14808	0.755
400	1.3424	0.942	19.32	14.39	0.02461	0.19463	0.738
500	1.0732	1.013	23.26	21.67	0.03352	0.3084	0.702
550	0.9739	1.047	25.08	25.74	0.03821	0.3750	0.685
600	0.8938	1.076	26.83	30.02	0.04311	0.4483	0.668
				Ammonia			
273	0.7929	2.177	9.353×10^{-6}	1.18×10^{-5}	0.0220	0.1308×10^{-4}	0.90
323	0.6487	2.177	11.035	1.70	0.0270	0.1920	0.88
373	0.5590	2.236	12.886	2.30	0.0327	0.2619	0.87
423	0.4934	2.315	14.672	2.87	0.0391	0.3432	0.87
473	0.4405	2.395	16.49	3.74	0.0467	0.4421	0.84
				Water Vapor			
380	0.5863	2.060	12.71×10^{-6}	2.16×10^{-5}	0.0246	0.2036×10^{-4}	1.060
400	0.5542	2.014	13.44	2.42	0.0261	0.2338	1.040
450	0.4902	1.980	15.25	3.11	0.0299	0.307	1.010
500	0.4405	1.985	17.04	3.86	0.0339	0.387	0.996
550	0.4005	1.997	18.84	4.70	0.0379	0.475	0.991
600	0.3652	2.026	20.67	5.66	0.0422	0.573	0.986
650	0.3380	2.056	22.47	6.64	0.0464	0.666	0.995
700	0.3140	2.085	24.26	7.72	0.0505	0.772	1.000
750	0.2931	2.119	26.04	8.88	0.0549	0.883	1.005
800	0.2739	2.152	27.86	10.20	0.0592	1.001	1.010
850	0.2579	2.186	29.69	11.52	0.0637	1.130	1.019

[a]Values of dynamic viscosity μ, thermal conductivity k, specific heat c_p, and Prandtl number Pr, are not strongly pressure-dependent for He, H_2, O_2, and N_2 and may be used over a fairly wide range of pressures.

Table A.9 Properties of air at 1 atm

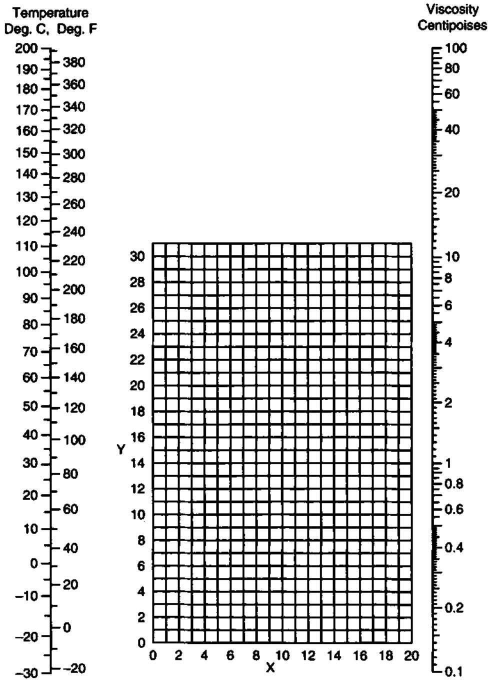
Temperature, °C	Density, ρ, kg/m^3	Dynamic Viscosity, μ, kg/m·s ($\times 10^5$)	Kinematic Viscosity, ν, m^2/s ($\times 10^5$)	Capacity Heat, c_p, J/kg·K	Thermal Conductivity, k, W/m·K ($\times 10^2$)	Thermal Expansion Coefficient, β, K (10^3)	Prandtl Number, Pr
−40	1.52	1.51	0.98		2.0		
−20	1.40	1.61	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, $\mathrm{Pr} = c_p\mu/k = 0.7$.

Table A.10 Properties of water (saturated liquid)

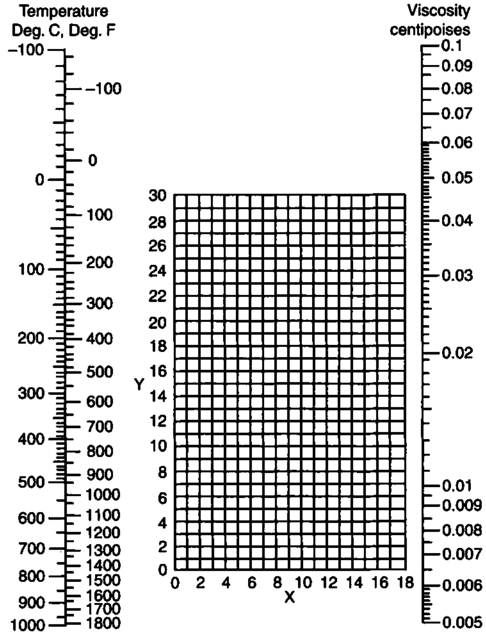
Temp. °F	Temp. °C	Heat Capacity c_p, kJ/kg·K	Density ρ, kg/m^3	Viscosity μ, kg/m·s	Thermal Conductivity k, W/m·°C	Prandtl Number Pr	$\frac{g\beta\rho^2 c_p}{\mu k}$ $1/m^3 \cdot °C$
32	0	4.225	999.8	1.79×10^{-3}	0.566	13.25	1.91×10^{9}
40	4.44	4.208	999.8	1.55×10^{-3}	0.575	11.35	1.91×10^{9}
50	10	4.195	999.2	1.31×10^{-3}	0.585	9.40	6.34×10^{9}
60	15.56	4.186	998.6	1.12×10^{-3}	0.595	7.88	1.08×10^{10}
70	21.11	4.179	997.4	9.8×10^{-4}	0.604	6.78	1.46×10^{10}
80	26.67	4.179	995.8	8.6×10^{-4}	0.614	5.85	1.91×10^{10}
90	32.22	4.174	994.9	7.65×10^{-4}	0.623	5.12	2.48×10^{10}
100	37.78	4.174	993.0	6.82×10^{-4}	0.630	4.53	3.3×10^{10}
110	43.33	4.174	990.6	6.16×10^{-4}	0.637	4.04	4.19×10^{10}
120	48.89	4.174	988.8	5.62×10^{-4}	0.644	3.64	4.89×10^{10}
130	54.44	4.179	985.7	5.13×10^{-4}	0.649	3.30	5.66×10^{10}
140	60	4.179	983.3	4.71×10^{-4}	0.654	3.01	6.48×10^{10}
150	65.55	4.183	980.3	4.3×10^{-4}	0.659	2.73	7.62×10^{10}
160	71.11	4.186	977.3	4.01×10^{-4}	0.665	2.53	8.84×10^{10}
170	76.67	4.191	973.7	3.72×10^{-4}	0.668	2.33	9.85×10^{10}
180	82.22	4.195	970.2	3.47×10^{-4}	0.673	2.16	1.09×10^{11}
190	87.78	4.199	966.7	3.27×10^{-4}	0.675	2.03	
200	93.33	4.204	963.2	3.06×10^{-4}	0.678	1.90	
220	104.4	4.216	955.1	2.67×10^{-4}	0.684	1.66	
240	115.6	4.229	946.7	2.44×10^{-4}	0.685	1.51	
260	126.7	4.250	937.2	2.19×10^{-4}	0.685	1.36	
280	137.8	4.271	928.1	1.98×10^{-4}	0.685	1.24	
300	148.9	4.296	918.0	1.86×10^{-4}	0.684	1.17	
350	176.7	4.371	890.4	1.57×10^{-4}	0.677	1.02	
400	204.4	4.467	859.4	1.36×10^{-4}	0.655	1.00	
450	232.2	4.585	825.7	1.20×10^{-4}	0.646	0.85	
500	260	4.731	785.2	1.07×10^{-4}	0.616	0.83	
550	287.7	5.024	735.5	9.51×10^{-5}			
600	315.6	5.703	678.7	8.68×10^{-5}			

Note: $Gr_x Pr$ = Rayleigh number, $Ra_x = \left(\frac{g\beta\rho^2 c_p}{\mu k}\right) L^3 \Delta T$.



No	Liquid	X	Y	No	Liquid	X	Y
1	Acetaldehyde	15.2	4.8	56	Freon-22	17.2	4.7
2	Acetic acid, 100%	12.1	14.2	57	Freon-113	12.5	11.4
3	Acetic acid, 70%	9.5	17.0	58	Glycerol, 100%	2.0	30.0
4	Acetic anhydride	12.7	12.8	59	Glycerol, 50%	6.9	19.6
5	Acetone, 100%	14.5	7.2	60	Heptane	14.1	8.4
6	Acetone, 35%	7.9	15.0	61	Hexane	14.7	7.0
7	Allyl alcohol	10.2	14.3	62	Hydrochloric acid, 31.5%	13.0	16.6
8	Ammonia, 100%	12.6	2.0	63	Isobutyl alcohol	7.1	18.0
9	Ammonia, 26%	10.1	13.9	64	Isobutyric acid	12.2	14.4
10	Amyl acetate	11.8	12.5	65	Isopropyl alcohol	8.2	16.0
11	Amyl alcohol	7.5	18.4	66	Kerosene	10.2	16.9
12	Aniline	8.1	18.7	67	Linseed oil, raw	7.5	27.2
13	Anisole	12.3	13.5	68	Mercury	18.4	16.4
14	Arsenic trichloride	13.9	14.5	69	Methanol, 100%	12.4	10.5
15	Benzene	12.5	10.9	70	Methanol, 90%	12.3	11.8
16	Bimethyl oxalate	12.3	15.8	71	Methanol, 40%	7.8	15.5
17	Biphenyl	12.0	18.3	72	Methyl acetate	14.2	8.2
18	Brine, $CaCl_2$, 25%	6.6	15.9	73	Methyl chloride	15.0	3.8
19	Brine, NaCl, 25%	10.2	16.6	74	Methyl ethyl ketone	13.9	8.6
20	Bromine	14.2	13.2	75	Naphtalene	7.9	18.1
21	Bromotoluene	20.0	15.9	76	Nitric acid, 95%	12.8	13.8
22	Butyl acetate	12.3	11.0	77	Nitric acid, 60%	10.8	17.0
23	Butyl alcohol	8.6	17.2	78	Nitrobenzene	10.6	16.2
24	Butyric acid	12.1	15.3	79	Nitrotoluene	11.0	17.0
25	Carbon dioxide	11.6	0.3	80	Octane	13.7	10.0
26	Carbon disulfide	16.1	7.5	81	Octyl alcohol	6.6	21.1
27	Carbon tetrachloride	12.7	13.1	82	Pentachloroethane	10.9	17.3
28	Chlorobenzene	12.3	12.4	83	Pentane	14.9	5.2
29	Chloroform	14.4	10.2	84	Phenol	6.9	20.8
30	Chlorosulfonic acid	11.2	18.1	85	Phosphorus tribromide	13.8	16.7
31	*o*-Chlorotoluene	13.0	13.3	86	Phosphorus trichloride	16.2	10.9
32	*m*-Chlorotoluene	13.3	12.5	87	Propionic acid	12.8	13.8
33	*p*-Chlorotoluene	13.3	12.5	88	Propyl alcohol	9.1	16.5
34	*m*-Cresol	2.5	20.8	89	Propyl bromide	14.5	9.6
35	Cyclohexanol	2.9	24.3	90	Propyl chloride	14.4	7.5
36	Dibromoethane	12.7	15.8	91	Propyl iodide	14.1	11.6
37	Dichloroethane	13.2	12.2	92	Sodium	16.4	13.9
38	Dichloromethane	14.6	8.9	93	Sodium hydroxide, 50%	3.2	25.8
39	Diethyl oxalate	11.0	16.4	94	Stannic chloride	13.5	12.8
40	Dipropyl oxalate	10.3	17.7	95	Sulfur dioxide	15.2	7.1
41	Ethyl acetate	13.7	9.1	96	Sulfuric acid, 110%	7.2	27.4
42	Ethyl alcohol, 100%	10.5	13.8	97	Sulfuric acid, 98%	7.0	24.8
43	Ethyl alcohol, 95%	9.8	14.3	98	Sulfuric acid, 60%	10.2	21.3
44	Ethyl alcohol, 40%	6.5	16.6	99	Sulfuryl chloride	15.2	12.4
45	Ethyl benzene	13.2	11.5	100	Tetrachloroethane	11.9	15.7
46	Ethyl bromide	14.5	8.1	101	Tetrachloroethylene	14.2	12.7
47	Ethyl chloride	14.8	6.0	102	Titanium tetrachloride	14.4	12.3
48	Ethyl ether	14.5	5.3	103	Toluene	13.7	10.4
49	Ethyl formate	14.2	8.4	104	Trichloroethylene	14.8	10.5
50	Ethyl iodide	14.7	10.3	105	Turpentine	11.5	14.9
51	Ethyl glycol	6.0	23.6	106	Vinyl acetate	14.0	8.8
52	Formic acid	10.7	15.8	107	Water	10.2	13.0
53	Freon-11	14.4	9.0	108	*o*-Xylene	13.5	12.1
54	Freon-1	16.8	5.6	109	*m*-Xylene	13.9	10.6
55	Freon-21	15.7	7.5	110	*p*-Xylene	13.9	10.9

Figure B.1 Absolute viscosity of liquids.



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	$3H_2 + N_2$	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	20.9
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 B.2 Absolute viscosity of gases and vapors at 1 atm.