

Appendix F

Gas Properties

Table F.1a Properties of Air (English Units)

T (°F)	ρ (lb/ft ³)	c_p (Btu/lb-°F)	μ (lb _m /hr-ft)	k (Btu/hr-ft-°F)	Pr
-9	0.08707	0.2403	0.0386	0.0129	0.720
81	0.07251	0.2405	0.0447	0.0152	0.707
171	0.06212	0.2410	0.0504	0.0173	0.700
261	0.05438	0.2422	0.0557	0.0195	0.690
351	0.04832	0.2439	0.0607	0.0216	0.686
441	0.04348	0.2460	0.0654	0.0235	0.684
531	0.03951	0.2484	0.0698	0.0254	0.683
621	0.03623	0.2510	0.0740	0.0271	0.685
711	0.03344	0.2539	0.0781	0.0287	0.690
801	0.03106	0.2567	0.0820	0.0303	0.695
891	0.02899	0.2596	0.0859	0.0317	0.702
981	0.02718	0.2625	0.0895	0.0331	0.709
1071	0.02558	0.2651	0.0931	0.0344	0.716
1161	0.02415	0.2677	0.0964	0.0358	0.720
1251	0.02289	0.2701	0.0996	0.0372	0.723
1341	0.02174	0.2725	0.1028	0.0385	0.726
1521	0.01977	0.2768	0.1087	0.0413	0.728
1701	0.01812	0.2806	0.1145	0.0441	0.728
1881	0.01673	0.2840	0.1201	0.0474	0.719
2061	0.01553	0.2883	0.1283	0.0526	0.703
2241	0.01450	0.2938	0.1349	0.0578	0.685

Source: Table A.8 on pp. A-32–A-33 of *The CRC Handbook of Mechanical Engineering*, ed. F Kreith. Boca Raton, FL: CRC Press, 1998.

Table F.1b Properties of Air (Metric Units)

T (K)	ρ (kg/m ³)	c_p [kJ/(kg · K)]	$\mu \times (10^7)$ [(N · s/m ²)]	$\lambda \times (10^3)$ [(W/(m · K)]	Pr
100	3.5562	1.032	71.1	9.34	0.786
150	2.3364	1.012	103.4	13.8	0.758
200	1.7458	1.007	132.5	18.1	0.737
250	1.3947	1.006	159.6	22.3	0.720
300	1.1614	1.007	184.6	26.3	0.707
350	0.9950	1.009	208.2	30.0	0.700
400	0.8711	1.014	230.1	33.8	0.690
450	0.7740	1.021	250.7	37.3	0.686
500	0.6964	1.030	270.1	40.7	0.684
550	0.6329	1.040	288.4	43.9	0.683
600	0.5804	1.051	305.8	46.9	0.685
650	0.5356	1.063	322.5	49.7	0.690
700	0.4975	1.075	338.8	52.4	0.695
750	0.4643	1.087	354.6	54.9	0.702
800	0.4354	1.099	369.8	57.3	0.709
850	0.4097	1.110	384.3	59.6	0.716
900	0.3868	1.121	398.1	62.0	0.720
950	0.3666	1.131	411.3	64.3	0.723
1000	0.3482	1.141	424.4	66.7	0.726
1100	0.3166	1.159	449.0	71.5	0.728
1200	0.2902	1.175	473.0	76.3	0.728
1300	0.2679	1.189	496.0	82	0.719
1400	0.2488	1.207	530	91	0.703
1500	0.2322	1.230	557	100	0.685

Source: From GF Hewitt, GL Shires, TR Bott, eds *Process Heat Transfer*. Boca Raton, FL: CRC Press, 1994.

Table F.2 Gas Properties

	Acetylene (Ethyne), C ₂ H ₂	Air (mixture)	Butadiene, C ₄ H ₆	n-Butane, C ₄ H ₁₀
CHEMICAL AND PHYSICAL PROPERTIES				
Molecular weight	26.04	28.966	54.09	58.12
Specific gravity, air = 1	0.90	1.00	1.87	2.07
Specific volume, ft ³ /lb	14.9	13.5	7.1	6.5
Specific volume, m ³ /kg	0.93	0.842	0.44	0.405
Density of liquid (at atm bp), lb/ft ³	43.0	54.6		37.5
Density of liquid (at atm bp), kg/m ³	693	879		604
Vapor pressure at 25 deg C, psia				35.4
Vapor pressure at 25 deg C, MN/m ²				0.0244
Viscosity (abs), lbm/ft sec	6.72 × 10 ⁻⁶	12.1 × 10 ⁻⁶		4.8 × 10 ⁻⁶
Viscosity (abs), centipoises ^a	0.01	0.018		0.007
Sound velocity in gas, m/sec	343	346	226	216
THERMAL AND THERMO-DYNAMIC PROPERTIES				
Specific heat, c _p , Btu/lb · deg F or cal/g · deg C	0.40	0.2403	0.341	0.39
Specific heat, c _p , J/kg · K	1,674	1,005.	1,427.	1,675
Specific heat ratio, c _p /c _v	1.25	1.40	1.12	1.096
Gas constant R, ft-lb/lb · deg F	59.3	53.3	28.55	26.56
Gas constant R, J/kg · deg C	319	286.8	154	143
Thermal conductivity, Btu/hr · ft · deg F	0.014	0.0151		0.01
Thermal conductivity, W/m · deg C	0.024	0.026		0.017
Boiling point (sat 14.7 psia), deg F	-103	-320	24.1	31.2
Boiling point (sat 760 mm), deg C	-75	-195	-4.5	-0.4
Latent heat of evap (at bp), Btu/lb	264	88.2		165.6
Latent heat of evap (at bp), J/kg	614,000	205,000		386,000
Freezing (melting) point, deg F (1 atm)	-116	-357.2	-164	-217
Freezing (melting) point, deg C (1 atm)	-82.2	-216.2	-109	-138
Latent heat of fusion, Btu/lb	23	10.0		19.2
Latent heat of fusion, J/kg	53,500	23,200		44,700
Critical temperature, deg F	97.1	-220.5		306
Critical temperature, deg C	36.2	-140.3	171	152
Critical pressure, psia	907	550	652	550
Critical pressure, MN/m ²	6.25	38		3.8
Critical volume, ft ³ /lb		0.050		0.070
Critical volume, m ³ /kg		0.003		0.0043
Flammable (yes or no)	Yes	No	Yes	Yes
Heat of combustion, Btu/ft ³	1,450	—	2,950	3,300
Heat of combustion, Btu/lb	21,600	—	20,900	21,400
Heat of combustion, kJ/kg	50,200	—	48,600	49,700

^aFor N · sec/m² divide by 1000.

Source: From F. Kreith ed. *The CRC Handbook of Mechanical Engineering*. Boca Ration, FL: CRC Press, 1998.

(Continued)

Table F.2 Continued

	Isobutane (2-Methyl- propane), C ₄ H ₁₀	1-Butene (Butylene), C ₄ H ₈	Carbon monoxide, CO	Ethane, C ₂ H ₆
CHEMICAL AND PHYSICAL PROPERTIES				
Molecular weight	58.12	56.108	28.011	30.070
Specific gravity, air = 1	2.07	1.94	0.967	1.04
Specific volume, ft ³ /lb	6.5	6.7	14.0	13.025
Specific volume, m ³ /kg	0.418	0.42	0.874	0.815
Density of liquid (at atm bp), lb/ft ³	37.2			28
Density of liquid (at atm bp), kg/m ³	599			449
Vapor pressure at 25 deg C, psia	50.4			
Vapor pressure at 25 deg C, MN/m ²	0.347			
Viscosity (abs), lbm/ft sec			12.1 × 10 ⁻⁶	64 × 10 ⁻⁶
Viscosity (abs), centipoises ^a			0.018	0.095
Sound velocity in gas, m/sec	216	222	352	316
THERMAL AND THERMO-DYNAMIC PROPERTIES				
Specific heat, c _p , Btu/lb · deg F or cal/g · deg C	0.39	0.36	0.25	0.41
Specific heat, c _p , J/kg · K	1,630	1,505	1,046	1,715
Specific heat ratio, c _p /c _v	1.10	1.112	1.40	1.20
Gas constant R, ft-lb/lb · deg F	26.56	27.52	55.2	51.4
Gas constant R, J/kg · deg C	143	148	297	276
Thermal conductivity, Btu/hr · ft · deg F	0.01		0.014	0.010
Thermal conductivity, W/m · deg C	0.0017		0.024	0.017
Boiling point (sat 14.7 psia), deg F	10.8	20.6	-312.7	-127
Boiling point (sat 760 mm), deg C	-11.8	-6.3	-191.5	-88.3
Latent heat of evap (at bp), Btu/lb	157.5	167.9	92.8	210
Latent heat of evap (at bp), J/kg	366,000	391,000	216,000	488,000
Freezing (melting) point, deg F (1 atm)	-229	-301.6	-337	-278
Freezing (melting) point, deg C (1 atm)	-145	-185.3	-205	-172.2
Latent heat of fusion, Btu/lb		16.4	12.8	41
Latent heat of fusion, J/kg		38,100		95,300
Critical temperature, deg F	273	291	-220	90.1
Critical temperature, deg C	134	144	-140	32.2
Critical pressure, psia	537	621	507	709
Critical pressure, MN/m ²	3.7	4.28	3.49	4.89
Critical volume, ft ³ /lb		0.068	0.053	0.076
Critical volume, m ³ /kg		0.0042	0.0033	0.0047
Flammable (yes or no)	Yes	Yes	Yes	Yes
Heat of combustion, Btu/ft ³	3,300	3,150	310	
Heat of combustion, Btu/lb	21,400	21,000	4,340	22,300
Heat of combustion, kJ/kg	49,700	48,800	10,100	51,800

(Continued)

Table F.2 Continued

	Ethylene (Ethene), C ₂ H ₄	Hydrogen, H ₂	Hydrogen sulfide, H ₂ S	Methane CH ₄
CHEMICAL AND PHYSICAL PROPERTIES				
Molecular weight	28.054	2.016	34.076	16.044
Specific gravity, air = 1	0.969	0.070	1.18	0.554
Specific volume, ft ³ /lb	13.9	194	11.5	24.2
Specific volume, m ³ /kg	0.87	12.1	0.0930	1.51
Density of liquid (at atm bp), lb/ft ³	35.5	4.43	62	26.3
Density of liquid (at atm bp), kg/m ³	569	71.0	993	421
Vapor pressure at 25 deg C, psia				
Vapor pressure at 25 deg C, MN/m ²				
Viscosity (abs), lbfm/ft sec	6.72×10^{-6}	6.05×10^{-6}	8.74×10^{-6}	7.39×10^{-6}
Viscosity (abs), centipoises ^a	0.010	0.009	0.013	0.011
Sound velocity in gas, m/sec	331	1,315	302	446
THERMAL AND THERMODYNAMIC PROPERTIES				
Specific heat, <i>c_p</i> , Btu/lb · deg F or cal/g · deg C	0.37	3.42	0.23	0.054
Specific heat, <i>c_p</i> , J/kg · K	1,548	14,310	962	2,260
Specific heat ratio, <i>c_p/c_v</i>	1.24	1.405	1.33	1.31
Gas constant <i>R</i> , ft-lb/lb · deg F	55.1	767	45.3	96
Gas constant <i>R</i> , J/kg · deg C	296	4,126	244	518
Thermal conductivity, Btu/hr · ft · deg F	0.010	0.105	0.008	0.02
Thermal conductivity, W/m · deg C	0.017	0.0182	0.014	0.035
Boiling point (sat 14.7 psia), deg F	-155	-423	-76	-259
Boiling point (sat 760 mm), deg C	-103.8	20.4 K	-60	-434.2
Latent heat of evap (at bp), Btu/lb	208	192	234	219.2
Latent heat of evap (at bp), J/kg	484,000	447,000	544,000	510,000
Freezing (melting) point, deg F (1 atm)	-272	-434.6	-119.2	-296.6
Freezing (melting) point, deg C (1 atm)	-169	-259.1	-84	-182.6
Latent heat of fusion, Btu/lb	51.5	25.0	30.2	14
Latent heat of fusion, J/kg	120,000	58,000	70,200	32,600
Critical temperature, deg F	49	-399.8	213	-116
Critical temperature, deg C	9.5	-240.0	100.4	-82.3
Critical pressure, psia	741	189	1,309	673
Critical pressure, MN/m ²	5.11	1.30	9.02	4.64
Critical volume, ft ³ /lb	0.073	0.53	0.046	0.099
Critical volume, m ³ /kg	0.0046	0.033	0.0029	0.0062
Flammable (yes or no)	Yes	Yes	Yes	Yes
Heat of combustion, Btu/ft ³	1,480	320	700	985
Heat of combustion, Btu/lb	20,600	62,050	8,000	22,900
Heat of combustion, kJ/kg	47,800	144,000	18,600	—

(Continued)

Table F.2 Continued

	Nitric oxide, NO	Nitrogen, N ₂	Nitrous oxide, N ₂ O	Oxygen O ₂
CHEMICAL AND PHYSICAL PROPERTIES				
Molecular weight	30.006	28.0134	44.012	31.9988
Specific gravity, air = 1	1.04	0.967	1.52	1.105
Specific volume, ft ³ /lb	13.05	13.98	8.90	12.24
Specific volume, m ³ /kg	0.814	0.872	0.555	0.764
Density of liquid (at atm bp), lb/ft ³		50.46	76.6	71.27
Density of liquid (at atm bp), kg/m ³		808.4	1,227	1,142
Vapor pressure at 25 deg C, psia				
Vapor pressure at 25 deg C, MN/m ²				
Viscosity (abs), lbm/ft sec	12.8 × 10 ⁻⁶	12.1 × 10 ⁻⁶	10.1 × 10 ⁻⁶	13.4 × 10 ⁻⁶
Viscosity (abs), centipoises ^a	0.019	0.018	0.015	0.020
Sound velocity in gas, m/sec	341	353	268	329
THERMAL AND THERMO-DYNAMIC PROPERTIES				
Specific heat, <i>c_p</i> , Btu/lb · deg F or cal/g · deg C	0.235	0.249	0.21	0.220
Specific heat, <i>c_p</i> , J/kg · K	983	1,040	879	920
Specific heat ratio, <i>c_p/c_v</i>	1.40	1.40	1.31	1.40
Gas constant <i>R</i> , ft-lb/lb · deg F	51.5	55.2	35.1	48.3
Gas constant <i>R</i> , J/kg · deg C	277	297	189	260
Thermal conductivity, Btu/hr · ft · deg F	0.015	0.015	0.010	0.015
Thermal conductivity, W/m · deg C	0.026	0.026	0.017	0.026
Boiling point (sat 14.7 psia), deg F	-240	-320.4	-127.3	-297.3
Boiling point (sat 760 mm), deg C	-151.5	-195.8	-88.5	-182.97
Latent heat of evap (at bp), Btu/lb		85.5	161.8	91.7
Latent heat of evap (at bp), J/kg		199,000	376,000	213,000
Freezing (melting) point, deg F (1 atm)	-258	-346	-131.5	-361.1
Freezing (melting) point, deg C (1 atm)	-161	-210	-90.8	-218.4
Latent heat of fusion, Btu/lb	32.9	11.1	63.9	5.9
Latent heat of fusion, J/kg	76,500	25,800	149,000	13,700
Critical temperature, deg F	-136	-232.6	97.7	-181.5
Critical temperature, deg C	-93.3	-147	36.5	-118.6
Critical pressure, psia	945	493	1,052	726
Critical pressure, MN/m ²	6.52	3.40	7.25	5.01
Critical volume, ft ³ /lb	0.0332	0.051	0.036	0.040
Critical volume, m ³ /kg	0.00207	0.00318	0.0022	0.0025
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft ³	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

(Continued)

Table F.2 Continued

	Ozone, O ₃	Propane, C ₃ H ₈	Propylene (Propene), C ₃ H ₆	Sulfur dioxide, SO ₂
CHEMICAL AND PHYSICAL PROPERTIES				
Molecular weight	47.998	44.097	42.08	64.06
Specific gravity, air = 1	1.66	1.52	1.45	2.21
Specific volume, ft ³ /lb	8.16	8.84	9.3	6.11
Specific volume, m ³ /kg	0.509	0.552	0.58	
Density of liquid (at atm bp), lb/ft ³		36.2	37.5	42.8
Density of liquid (at atm bp), kg/m ³		580	601.1	585
Vapor pressure at 25 deg C, psia		135.7	166.4	56.6
Vapor pressure at 25 deg C, MN/m ²		0.936	1.147	0.390
Viscosity (abs), lbfm/ft sec	8.74 × 10 ⁻⁶	53.8 × 10 ⁻⁶	57.1 × 10 ⁻⁶	8.74 × 10 ⁻⁶
Viscosity (abs), centipoises ^a	0.013	0.080	0.085	0.013
Sound velocity in gas, m/sec		253	261	220
THERMAL AND THERMO-DYNAMIC PROPERTIES				
Specific heat, c _p , Btu/lb · deg F or cal/g · deg C	0.196	0.39	0.36	0.11
Specific heat, c _p , J/kg · K	820	1,630	1,506	460
Specific heat ratio, c _p /c _v		1.2	1.16	1.29
Gas constant R, ft-lb/lb · deg F	32.2	35.0	36.7	24.1
Gas constant R, J/kg · deg C	173	188	197	130
Thermal conductivity, Btu/hr · ft · deg F	0.019	0.010	0.010	0.006
Thermal conductivity, W/m · deg C	0.033	0.017	0.017	0.010
Boiling point (sat 14.7 psia), deg F	-170	-44	-54	14.0
Boiling point (sat 760 mm), deg C	-112	-42.2	-48.3	-10
Latent heat of evap (at bp), Btu/lb		184	188.2	155.5
Latent heat of evap (at bp), J/kg		428,000	438,000	362,000
Freezing (melting) point, deg F (1 atm)	-315.5	-309.8	-301	-104
Freezing (melting) point, deg C (1 atm)	-193	-189.9	-185	-75.5
Latent heat of fusion, Btu/lb	97.2	19.1		58.0
Latent heat of fusion, J/kg	226,000	44,400		135,000
Critical temperature, deg F	16	205	197	315.5
Critical temperature, deg C	-9	96	91.7	157.6
Critical pressure, psia	800	618	668	1,141
Critical pressure, MN/m ²	5.52	4.26	4.61	7.87
Critical volume, ft ³ /lb	0.0298	0.073	0.069	0.03
Critical volume, m ³ /kg	0.00186	0.0045	0.0043	0.0019
Flammable (yes or no)	No	Yes	Yes	No
Heat of combustion, Btu/ft ³	—	2,450	2,310	—
Heat of combustion, Btu/lb	—	21,660	21,500	—
Heat of combustion, kJ/kg	—	50,340	50,000	—

(Continued)

Table F.2 Continued

	<i>cis</i> -2-Butene, C ₄ H ₈	<i>trans</i> -2-Butene C ₄ H ₈	Isobutene, C ₄ H ₈	Carbon dioxide, CO ₂
CHEMICAL AND PHYSICAL PROPERTIES				
Molecular weight	56.108	56.108	56.108	44.01
Specific gravity, air = 1	1.94	1.94	1.94	1.52
Specific volume, ft ³ /lb	6.7	6.7	6.7	8.8
Specific volume, m ³ /kg	0.42	0.42	0.42	0.55
Density of liquid (at atm bp), lb/ft ³				—
Density of liquid (at atm bp), kg/m ³				—
Vapor pressure at 25 deg C, psia				931
Vapor pressure at 25 deg C, MN/m ²				6.42
Viscosity (abs), lbm/ft sec				9.4 × 10 ⁻⁶
Viscosity (abs), centipoises ^a				0.014
Sound velocity in gas, m/sec	223	221	221	270
THERMAL AND THERMO- DYNAMIC PROPERTIES				
Specific heat, <i>c_p</i> , Btu/lb · deg F or cal/g · deg C	0.327	0.365	0.37	0.205
Specific heat, <i>c_p</i> , J/kg · K	1,368	1,527	1,548	876
Specific heat ratio, <i>c_p/c_v</i>	1.121	1.107	1.10	1.30
Gas constant <i>R</i> , ft-lb/lb · deg F				35.1
Gas constant <i>R</i> , J/kg · deg C				189
Thermal conductivity, Btu/hr · ft · deg F				0.01
Thermal conductivity, W/m · deg C				0.017
Boiling point (sat 14.7 psia), deg F	38.6	33.6	19.2	-109.4 ^b
Boiling point (sat 760 mm), deg C	3.7	0.9	-7.1	-78.5
Latent heat of evap (at bp), Btu/lb	178.9	174.4	169	246
Latent heat of evap (at bp), J/kg	416,000	406,000	393,000	572,000
Freezing (melting) point, deg F (1 atm)	-218	-158		
Freezing (melting) point, deg C (1 atm)	-138.9	-105.5		
Latent heat of fusion, Btu/lb	31.2	41.6	25.3	—
Latent heat of fusion, J/kg	72,600	96,800	58,800	—
Critical temperature, deg F				88
Critical temperature, deg C	160	155		31
Critical pressure, psia	595	610		1,072
Critical pressure, MN/m ²	4.10	4.20		7.4
Critical volume, ft ³ /lb				
Critical volume, m ³ /kg				
Flammable (yes or no)	Yes	Yes	Yes	No
Heat of combustion, Btu/ft ³	3,150	3,150	3,150	—
Heat of combustion, Btu/lb	21,000	21,000	21,000	—
Heat of combustion, kJ/kg	48,800	48,000	48,800	—

^bSublimes.

Table F.3a Requirements for fuel oils (per ASTM D 396)

Classification	No. 1 Distillate	No. 2 Distillate	No. 4 Distillate (Heavy)	No. 6 Residual
Density (kg/m ³) @ 60°F (15°C), max	850	876	—	—
Viscosity @ 104°F (40°C) mm/s ²				
min	1.3	1.9	> 5.5	—
max	2.1	3.4	24	—
Viscosity @ 212°F (100°C) mm/s ²				
min	—	—	—	—
max	—	—	—	—
Flash point °F (°C), min	100 (38)	100 (38)	131 (55)	140 (60)
Pour point °F (°C), max	-0.4 (-18)	21 (-6)	21 (-6)	—
Ash, % mass, max	—	—	0.01	—
Sulfur, % mass, max	0.5	0.5	—	—
Water sediment, % vol., max	0.05	0.05	0.5	2.0
Distillation temperature °F (°C)				
0% volume recovered, max	419 (215)	—	—	—
90% volume recovered, min	—	540 (282)	—	—
90% volume recovered, max	550 (228)	640 (338)	—	—

Source: CE Baukal, ed. *The John Zink Combustion Handbook*. Boca Raton, FL: CRC Press, 2001.

Table F.3b Typical analysis of different fuel oils

	No. 1 Fuel oil	No. 2 Fuel oil	No. 4 Fuel oil	No. 6 Fuel oil (sour)
Ash %	< 0.01	< 0.01	0.02	0.05
Hydrogen %	13.6	13.6	11.7	11.2
Nitrogen %	0.003	0.007	0.24	0.37
Sulfur %	0.09	0.1	1.35	2.1
Carbon %	86.4	86.6	86.5	85.7
Heat of combustion (HHV), Btu/lb	20,187	19,639	19,382	18,343
Specific gravity 60/60°F	0.825	0.84	0.898	0.97
Density (lb/U.S.gal)	6.877	6.96	7.488	8.08

Source: CE Baukal, ed. *The John Zink Combustion Handbook*. Boca Raton, FL: CRC Press, 2001.