Appendix 5: Thermo-physical Properties of Materials

This appendix includes various tables giving the thermo-physical properties of different materials.

Table A5.1 Physical Properties of Air at Atmospheric Pressure

T(K)	ρ (kg/m^3)	c_p (kJ/kg °C)	μ (kg/m s) × 10^{-5}	ν (m^2/s) × 10^{-6}	k (W/m °C)	α (m^2/s) × 10^{-4}	Pr
100	3.6010	1.0266	0.692	1.923	0.00925	0.0250	0.770
150	2.3675	1.0099	1.028	4.343	0.01374	0.0575	0.753
200	1.7684	1.0061	1.329	7.490	0.01809	0.1017	0.739
250	1.4128	1.0053	1.488	9.490	0.02227	0.1316	0.722
300	1.1774	1.0057	1.983	16.84	0.02624	0.2216	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	31.71	0.03707	0.4222	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.30	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06225	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702

Notes: T = *temperature,* ρ = *density,* c_p = *specific heat capacity,* μ = *viscosity,* $\nu = \mu/\rho$ = *kinetic viscosity,* k = *thermal conductivity,* $\alpha = c_p\rho/k$ = *heat (thermal) diffusivity, Pr = Prandtl number.*

Table A5.2 Physical Properties of Saturated Liquid Water

T (°C)	ρ (kg/m^3)	c_p (kJ/kg °C)	ν (m^2/s) $\times 10^{-6}$	k (W/m °C)	α (m^2/s) $\times 10^{-7}$	Pr	β (K^{-1}) $\times 10^{-3}$
0	1002.28	4.2178	1.788	0.552	1.308	13.6	
20	1000.52	4.1818	1.006	0.597	1.430	7.02	0.18
40	994.59	4.1784	0.658	0.628	1.512	4.34	
60	985.46	4.1843	0.478	0.651	1.554	3.02	
80	974.08	4.1964	0.364	0.668	1.636	2.22	
100	960.63	4.2161	0.294	0.680	1.680	1.74	
120	945.25	4.250	0.247	0.685	1.708	1.446	
140	928.27	4.283	0.214	0.684	1.724	1.241	
160	909.69	4.342	0.190	0.680	1.729	1.099	
180	889.03	4.417	0.173	0.675	1.724	1.004	
200	866.76	4.505	0.160	0.665	1.706	0.937	
220	842.41	4.610	0.150	0.652	1.680	0.891	
240	815.66	4.756	0.143	0.635	1.639	0.871	
260	785.87	4.949	0.137	0.611	1.577	0.874	
280	752.55	5.208	0.135	0.580	1.481	0.910	
300	714.26	5.728	0.135	0.540	1.324	1.019	

Notes: T = *temperature,* ρ = *density,* c_p = *specific heat capacity,* $\nu = \mu/\rho$ = *kinetic viscosity,* k = *thermal conductivity,* $\alpha = c_p\rho/k$ = *heat (thermal) diffusivity, Pr = Prandtl number,* β = *coefficient of volumetric expansion of fluid.*

Table A5.3 Properties of Materials

Material	Specific Heat (kJ/kg K)	Density (kg/m^3)	Thermal Conductivity (W/m K)	Volumetric Specific Heat (kJ/m^3 K)
Aluminum	0.896	2700	211	2420
Concrete	0.92	2240	1.73	2060
Copper	0.383	8795	385	3370
Fiberglass	0.71–0.96	5–30	0.0519	4–30
Glass	0.82	2515	1.05	2060
Polyurethane	1.6	24	0.0245	38
Rock pebbles	0.88	1600	1.8	1410
Steel	0.48	7850	47.6	3770
Water	4.19	1000	0.596	4190

Table A5.4 Thermal Properties of Building and Insulation Materials

Material	Density (kg/m^3)	Thermal Conductivity (W/m^2 K)
Granite	2500–2700	2.80
Crystalline rock	2800	3.50
Basaltic rock	2700–3000	3.50
Marble	2800	3.50
Limestone, soft	1800	1.10
Limestone, hard	2200	1.70
Limestone, very hard	2600	2.30
Plaster (cement + sand)	–	1.39
Gypsum board	700 900	0.21 0.25
Concrete, medium density	2000	1.35
Concrete, high density	2400	2.00
Hollow brick	1000	0.25
Solid brick	1600	0.70
Fiber wool	50	0.041
Expanded polystyrene	Min. 20	0.041
Extruded polystyrene	>20	0.030
Polyurethane	>30	0.025
Air	1.23	0.025
Argon	1.70	0.017
Krypton	3.56	0.0090
Xenon	5.58	0.0054

Table A5.5 Thermal Resistance of Stagnant Air and Surface Resistance (m^2 K/W)

	Heat-Flow Direction		
Thickness of Air (mm)	**Sideways**	**Up**	**Down**
5	0.11	0.11	0.11
7	0.13	0.13	0.13
10	0.15	0.15	0.15
15	0.17	0.16	0.17
25	0.18	0.16	0.19
50	0.18	0.16	0.21
100	0.18	0.16	0.22
300	0.18	0.16	0.23
Surface Resistance			
Internal surface	0.12	0.11	0.16
External surface	0.044 (applies to all directions)		

Table A5.6 Decimal Multiples

Multiple	**Prefix**	**Symbol**
10^{24}	yotta	Y
10^{21}	zeta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

Table A5.7 Curve Fits for Saturated Water and Steam

Range	Relation	Correlation
Saturated water and steam, temperature in °C as input		
$T = 1-100\,°C$	$h_f = 4.1861(T) + 0.0836$	$R^2 = 1.0$
	$h_g = -0.0012(T^2) + 1.8791(T) + 2500.5$	$R^2 = 1.0$
	$s_f = -2.052 \times 10^{-5}(T^2) + 1.507 \times 10^{-2}(T) + 2.199 \times 10^{-3}$	$R^2 = 1.0$
	$s_g = 7.402 \times 10^{-5}(T^2) - 2.515 \times 10^{-2}(T) + 9.144$	$R^2 = 0.9999$
Saturated water and steam, pressure in bar as input		
$P = 0.01-1$ bar	$h_f = -15772.4(P^6) + 52298.1(P^5) - 67823.6(P^4) + 43693.9(P^3) - 14854.1(P^2) + 2850.04(P) + 21.704$	$R^2 = 0.9981$
	$h_g = -6939.53(P^6) + 22965.64(P^5) - 29720.13(P^4) + 19105.32(P^3) - 6481.2(P^2) + 1232.74(P) + 2510.81$	$R^2 = 0.9978$
	$s_f = -55.76(P^6) + 184.508(P^5) - 238.5798(P^4) + 153.024(P^3) - 51.591(P^2) + 9.6043(P) + 0.0869$	$R^2 = 0.9973$
	$s_g = 92.086(P^6) - 304.24(P^5) + 392.33(P^4) - 250.3(P^3) + 83.356(P^2) - 14.841(P) + 8.9909$	$R^2 = 0.9955$
$P = 1.1-150$ bar	$h_f = -3.016 \times 10^{-10}(P^6) + 2.416 \times 10^{-7}(P^5) - 7.429 \times 10^{-5}(P^4) + 0.011(P^3) - 0.85596(P^2) + 37.0458(P) + 442.404$	$R^2 = 0.9984$
	$h_g = -3.48 \times 10^{-10}(P^6) + 2.261 \times 10^{-7}(P^5) - 5.6965 \times 10^{-5}(P^4) + 6.9969 \times 10^{-3}(P^3) - 0.441(P^2) + 12.458(P) + 2685.153$	$R^2 = 0.9961$
	$s_f = -9.656 \times 10^{-12}(P^6) + 4.743 \times 10^{-9}(P^5) - 9.073 \times 10^{-7}(P^4) + 8.565 \times 10^{-5}(P^3) - 4.213 \times 10^{-3}(P^2) + 0.1148(P) + 1.3207$	$R^2 = 0.9976$
	$s_g = 9.946 \times 10^{-12}(P^6) - 4.8593 \times 10^{-9}(P^5) + 9.225 \times 10^{-7}(P^4) - 8.602 \times 10^{-5}(P^3) + 4.13 \times 10^{-3}(P^2) - 0.1058(P) + 7.3187$	$R^2 = 0.9955$