

Annex A

Thermodynamics

Constants

$$N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$$

$$R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$$

$$k = \frac{R}{N_A} = 1.38 \times 10^{-23} \text{ J/K}$$

$$\sigma = 5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

$$c = 2.998 \times 10^8 \text{ m/s}$$

$$\rho_{\text{water}} = 1 \text{ g/ml}$$

Conversions:

$$1 \text{ L} = 10^3 \text{ cm}^3$$

$$1 \text{ atm} = 1.013 \times 10^5 \text{ N/m}^2$$

$$1 \text{ cal} = 4.186 \text{ J}$$

$$1 \text{ Btu} = 252 \text{ cal}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

$$1 \text{ hp} = 746 \text{ W}$$

Thermodynamics:

$$\Delta L = \alpha L_0 \Delta T$$

$$PV = NkT = nRT$$

$$P = F/A$$

$$\bar{F} = \frac{\Delta \vec{p}}{\Delta t}$$

$$T_F = \frac{9}{5} T_C + 32$$

$$T = T_C + 273.15$$

$$Q = mc\Delta T$$

$$Q = \pm mL$$

$$W = - \int_{V_i}^{V_f} PdV$$

$$\Delta E_{\text{int}} = Q + W$$

$$\frac{dE}{dt} = \kappa A \left| \frac{dT}{dx} \right|$$

$$\frac{dE}{dt} = \sigma A e T^4$$

$$\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m K}$$

$$\frac{1}{2} m \bar{v}^2 = \frac{3}{2} kT$$

$$P = \frac{2N}{3V} \left(\frac{1}{2} m \bar{v}^2 \right)$$

$$E_{\text{int}} = (\text{D.O.F.}) \frac{1}{2} NkT$$

(D.O.F. represents the number of degrees of freedom.)

$$\Delta E_{\text{int}} = nC_V \Delta T$$

$$C_V = \frac{(\text{D.O.F.})}{2} R$$

$$C_P - C_V = R$$

$$\gamma = \frac{C_P}{C_V}$$

$PV^\gamma = \text{constant}$
(for adiabatic processes)

$$n_V(E) = n_0 e^{-E/kT}$$

(Boltzmann distribution)

$$N_V = 4\pi N \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 e^{-mv^2/2kT}$$

(Maxwell-Boltzmann speed distribution)

$$v_{\text{rms}} = \sqrt{\bar{v}^2} = \sqrt{\frac{3kT}{m}}$$

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}}$$

$$v_{\text{mp}} = \sqrt{\frac{2kT}{m}}$$

$$W_{\text{eng}} = |Q_h| - |Q_c|$$

$$e = \frac{W_{\text{eng}}}{|Q_h|}$$

$$e_{\text{Carnot}} = 1 - \frac{T_c}{T_h}$$

$$dS = \frac{dQ_r}{T}$$

$$\Delta S = \int_i^f \frac{dQ_r}{T}$$

$$dS = \frac{dQ_r}{T} = nC_V \frac{dT}{T} + nR \frac{dV}{V}$$

(for an ideal gas)

See next page for tables of experimental values

Tables of experimental values

Average Expansion Coefficients for Some Materials Near Room Temperature				Molar mass of selected gases	
Material	Average Linear Expansion Coefficient (α)($^{\circ}\text{C}$) ⁻¹	Material	Average Volume Expansion Coefficient (β)($^{\circ}\text{C}$) ⁻¹	Gas	Molar mass (g/mol)
Aluminum	24×10^{-6}	Alcohol, ethyl	1.12×10^{-4}	H ₂	2.02
Brass and bronze	19×10^{-6}	Benzene	1.24×10^{-4}	He	4.00
Copper	17×10^{-6}	Acetone	1.5×10^{-4}	H ₂ O	18.0
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}	Ne	20.2
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}	N ₂ or CO	28.0
Lead	29×10^{-6}	Turpentine	9.0×10^{-4}	NO	30.0
Steel	11×10^{-6}	Gasoline	9.6×10^{-4}	O ₂	32.0
Invar (Ni-Fe alloy)	0.9×10^{-6}	Air ^a at 0 $^{\circ}\text{C}$	3.67×10^{-3}	CO ₂	44.0
Concrete	12×10^{-6}	Helium ^a	3.665×10^{-3}	SO ₂	64.1

Latent Heats of Fusion and Vaporization				
Substance	Melting Point ($^{\circ}\text{C}$)	Latent Heat of Fusion (J/kg)	Boiling Point ($^{\circ}\text{C}$)	Latent Heat of Vaporization (J/kg)
Helium	-269.65	5.23×10^3	-268.93	2.09×10^4
Nitrogen	-209.97	2.55×10^4	-195.81	2.01×10^5
Oxygen	-218.79	1.38×10^4	-182.97	2.13×10^5
Ethyl alcohol	-114	1.04×10^5	78	8.54×10^5
Water	0.00	3.33×10^5	100.00	2.26×10^6
Sulfur	119	3.81×10^4	444.60	3.26×10^5
Lead	327.3	2.45×10^4	1 750	8.70×10^5
Aluminum	660	3.97×10^5	2 450	1.14×10^7
Silver	960.80	8.82×10^4	2 193	2.33×10^6
Gold	1 063.00	6.44×10^4	2 660	1.58×10^6
Copper	1 083	1.34×10^5	1 187	5.06×10^6

Specific Heats of Some Substances at 25 $^{\circ}\text{C}$ and Atmospheric Pressure		
Substance	Specific heat c	
	J/kg $\cdot^{\circ}\text{C}$	cal/g $\cdot^{\circ}\text{C}$
<i>Elemental solids</i>		
Aluminum	900	0.215
Beryllium	1 830	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Germanium	322	0.077
Gold	129	0.030 8
Iron	448	0.107
Lead	128	0.030 5
Silicon	703	0.168
Silver	234	0.056
<i>Other solids</i>		
Brass	380	0.092
Glass	837	0.200
Ice (-5 $^{\circ}\text{C}$)	2 090	0.50
Marble	860	0.21
Wood	1 700	0.41
<i>Liquids</i>		
Alcohol (ethyl)	2 400	0.58
Mercury	140	0.033
Water (15 $^{\circ}\text{C}$)	4 186	1.00
<i>Gas</i>		
Steam (100 $^{\circ}\text{C}$)	2 010	0.48

Thermal Conductivities	
Substance	Thermal Conductivity (W/m $\cdot^{\circ}\text{C}$)
<i>Metals (at 25$^{\circ}\text{C}$)</i>	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427
<i>Nonmetals (approximate values)</i>	
Asbestos	0.08
Concrete	0.8
Diamond	2 300
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08
<i>Gases (at 20$^{\circ}\text{C}$)</i>	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8

Annex B

Relativity

Relativity:

$$\beta = v/c$$

$$\gamma = (1 - \beta^2)^{-1/2}$$

Lorentz-Einstein transformations

$$x' = \gamma(x - vt)$$

$$y' = y$$

$$t' = \gamma\left(t - \frac{vx}{c^2}\right)$$

$$x = \gamma(x' + vt')$$

$$y = y'$$

$$t = \gamma\left(t' + \frac{vx'}{c^2}\right)$$

Space-time invariant

$$S^2 = (ct)^2 - (x)^2 = (ct')^2 - (x')^2$$

Space-time interval

$$\begin{aligned} \Delta S^2 &= (c\Delta t)^2 - (\Delta x)^2 \\ &= (c\Delta t')^2 - (\Delta x')^2 \end{aligned}$$

Space contraction:

$$L = L_p/\gamma$$

Time dilation

$$\Delta t = \gamma\Delta t_p$$

Doppler effect

$$f' = \left(\frac{1 - \beta}{1 + \beta}\right)^{1/2} f$$

Velocity transformations

$$u_x = \frac{u'_x + v}{1 + vu'_x/c^2}$$

$$u_y = \frac{u'_y/\gamma}{1 + vu'_x/c^2}$$

$$u'_x = \frac{u_x - v}{1 - vu_x/c^2}$$

$$u'_y = \frac{u_y/\gamma}{1 - vu_x/c^2}$$

Momentum and energy

$$\vec{p} = \gamma m\vec{v}$$

$$K = (\gamma - 1)mc^2$$

$$E = K + mc^2$$

$$E^2 = (cp)^2 + (mc^2)^2$$

Physical constants

$$c = 2.997 \times 10^8 \text{ m/s}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$m_p = m_n = 1.67 \times 10^{-27} \text{ kg}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\text{eV} = 1.6 \times 10^{-19} \text{ J}$$

Annex C Astrophysics

Constants

$$L_{\odot} = 3.826 \times 10^{26} \text{ W}$$

$$R_{\odot} = 6.96 \times 10^8 \text{ m}$$

$$M_{\odot} = 1.989 \times 10^{30} \text{ kg}$$

$$T_{\odot} = 5770 \text{ K}$$

$$M_{\oplus} = 5.974 \times 10^{24} \text{ kg}$$

$$R_{\oplus} = 6.378 \times 10^6 \text{ m}$$

$$c = 2.997\,924\,58 \times 10^8 \text{ m/s}$$

$$\sigma = 5.670 \times 10^{-8} \text{ Wm}^{-2}\text{K}^4$$

$$h = 6.626 \times 10^{-34} \text{ J s}$$

$$k_B = 1.381 \times 10^{-23} \text{ J/K}$$

$$e = 1.602 \times 10^{-19} \text{ C}$$

$$E_u = 931.494 \text{ MeV/u}$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

$$1 \text{ AU} = 1.4960 \times 10^{11} \text{ m}$$

$$1 \text{ ly} = 9.4605 \times 10^{15} \text{ m}$$

$$1 \text{ pc} = 3.2616 \text{ ly}$$

Astrophysics

$$b = \frac{L}{4\pi d^2}$$

$$m_1 - m_2 = 2.5 \log \left(\frac{b_2}{b_1} \right)$$

$$m - M = 5 \log \left(\frac{d}{10} \right)$$

$$M = 4.77 - 2.5 \log(L/L_{\odot})$$

$$\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{ m K}$$

$$L = \sigma A T^4$$

binary system:

$$m_1(M_{\odot}) + m_2(M_{\odot}) = \frac{(A_{\text{AU}})^3}{(T_{\text{years}})^2}$$

$$\frac{m_1}{m_2} = \frac{a_2}{a_1} = \frac{v_2}{v_1}$$

