

Appendix A

Table A.1 Dimensions, SI Units, and conversion factors to c.g.s. for Common Quantities

| Quantity | Dimensions | SI | c.g.s. |
|--|-------------------------------|---|---|
| Length | L | 1 m | 10^2 cm |
| Area | L^2 | 1 m^2 | 10^4 cm 2 |
| Volume | L^3 | 1 m^3 | 10^6 cm 3 |
| Mass | M | 1 kg | 10^3 g |
| Density | $M L^{-3}$ | 1 kg m^{-3} | 10^{-3} g cm $^{-3}$ |
| Time | T | 1 s (or min, h, etc.) | 1 s |
| Velocity | $L T^{-1}$ | 1 m s^{-1} | 10^2 cm s $^{-1}$ |
| Acceleration | $L T^{-2}$ | 1 m s^{-2} | 10^2 cm s $^{-2}$ |
| Force | $M L T^{-2}$ | $1 \text{ kg m s}^{-2} = 1 \text{ N(Newton)}$ | 10^5 g cm s $^{-2} = 10^5$ dynes |
| Pressure | $M L^{-1} T^{-2}$ | $1 \text{ kg m}^{-1} \text{s}^{-2} = 1 \text{ N m}^{-2}$ (Pascal) | 10 g cm $^{-1}$ s $^{-2} = 10^{-2}$ mbar |
| Work, energy | $M L^2 T^{-2}$ | $1 \text{ kg m}^{-2} \text{s}^{-2} = 1 \text{ J(Joule)}$ | 10^7 g cm $^{-2}$ s $^{-2} = 10^7$ ergs |
| Power | $M L^2 T^{-3}$ | $1 \text{ kg m}^2 \text{s}^{-3} = 1 \text{ W(Watt)}$ | 10^7 g cm $^{-2}$ s $^{-3} = 10^7$ ergs s $^{-1}$ |
| Dynamic viscosity | $M L^{-1} T^{-1}$ | 1 N s m^{-2} | 10 dynes s cm $^{-2} = 10$ Poise |
| Kinematic viscosity | $L^{-2} T^{-1}$ | $1 \text{ m}^{-2} \text{s}^{-1}$ | 10^4 cm $^{-2}$ s $^{-1} = 10^4$ Stokes |
| Temperature | | 1 °C (or 1 K) | 1 °C (or 1 K) |
| Heat energy | H (or $M L^2 T^{-2}$) | 1 J | 0.2388 cal |
| Heat or radiation flux | $H T^{-1}$ | 1 W | 0.2388 cal s $^{-1}$ |
| Heat flux density | $H L^{-2} T^{-1}$ | 1 W m^{-2} | 2.388×10^{-5} cal cm $^{-2}$ s $^{-1}$ |
| Latent heat | $H M^{-1}$ | 1 J kg^{-1} | 2.388×10^{-4} cal g $^{-1}$ |
| Specific heat | $H M^{-1} \theta^{-1}$ | $1 \text{ J kg}^{-1} \text{K}^{-1}$ | 2.388×10^{-4} cal g $^{-1}$ K $^{-1}$ |
| Thermal conductivity | $H L^{-1} \theta^{-1} T^{-1}$ | $1 \text{ W m}^{-1} \text{K}^{-1}$ | 2.388×10^{-3} cal cm $^{-1}$ s $^{-1}$ K $^{-1}$ |
| Thermal diffusivity (and other diffusion coefficients) | $L^2 T^{-1}$ | $1 \text{ m}^2 \text{s}^{-1}$ | 10^4 cm 2 s $^{-1}$ |

Table A.2 Properties of Air, Water Vapor and CO₂ (treated as constant between –5 °C and 45 °C)

| | | Air | Water vapor | Carbon dioxide |
|----------------|--------------------------------------|------|-------------|----------------|
| Specific heat | (J g ⁻¹ K ⁻¹) | 1.01 | 1.88 | 0.85 |
| Prandtl number | $\text{Pr} = (\nu/\kappa)$ | 0.71 | – | – |
| | $\text{Pr}^{0.67}$ | 0.79 | – | – |
| | $\text{Pr}^{0.33}$ | 0.89 | – | – |
| | $\text{Pr}^{0.25}$ | 0.92 | – | – |
| Schmidt number | $\text{Sc} = (\nu/D)$ | – | 0.63 | 1.04 |
| | $\text{Sc}^{0.67}$ | – | 0.74 | 1.02 |
| | $\text{Sc}^{0.33}$ | – | 0.86 | 1.01 |
| | $\text{Sc}^{0.25}$ | – | 0.89 | 1.01 |
| Lewis number | $\text{Le} = (\kappa/D)$ | – | 0.89 | 1.48 |
| | $\text{Le}^{0.67}$ | – | 0.93 | 1.32 |
| | $\text{Le}^{0.33}$ | – | 0.96 | 1.14 |
| | $\text{Le}^{0.25}$ | – | 0.97 | 1.11 |

Table A.3 Properties of Air, Water Vapor, and CO₂ (changing by less than 1% per K)

| Temperature Densities of air | | | | Virtual temperature of air | Latent heat of vaporization of water | Psychrometer constant | Thermal conductivity of air | Molecular diffusion coefficients of air | | | |
|------------------------------|----|----------|--------------------|----------------------------|--------------------------------------|-----------------------|------------------------------------|---|---|-------|-------|
| Symbol | T | ρ_a | $\rho_{as}(T)$ | T_v | λ | γ | k | κ | ν | D_v | D_c |
| Unit | °C | K | kg m ⁻³ | °C | J g ⁻¹ | Pa K ⁻¹ | mW m ⁻¹ K ⁻¹ | | 10 ⁻⁶ m ² s ⁻¹ | | |
| | -5 | 268.2 | 1.316 | 1.314 | -4.57 | 2513 | 64.3 | 24.0 | 18.3 | 12.9 | 20.5 |
| | 0 | 273.2 | 1.292 | 1.286 | 0.64 | 2501 | 64.6 | 24.3 | 18.9 | 13.3 | 21.2 |
| | 5 | 278.2 | 1.269 | 1.265 | 5.92 | 2489 | 64.9 | 24.6 | 19.5 | 13.7 | 22.0 |
| | 10 | 283.2 | 1.246 | 1.240 | 11.32 | 2477 | 65.2 | 25.0 | 20.2 | 14.2 | 22.7 |
| | 15 | 288.2 | 1.225 | 1.217 | 16.87 | 2465 | 65.5 | 25.3 | 20.8 | 14.6 | 23.4 |
| | 20 | 293.2 | 1.204 | 1.194 | 22.62 | 2452 | 65.8 | 25.7 | 21.5 | 15.1 | 24.2 |
| | 25 | 298.2 | 1.183 | 1.169 | 28.62 | 2442 | 66.2 | 26.0 | 22.2 | 15.5 | 24.9 |
| | 30 | 303.2 | 1.164 | 1.145 | 34.97 | 2430 | 66.5 | 26.4 | 22.8 | 16.0 | 25.7 |
| | 35 | 308.2 | 1.146 | 1.121 | 41.73 | 2418 | 66.8 | 26.7 | 23.5 | 16.4 | 26.4 |
| | 40 | 313.2 | 1.128 | 1.096 | 49.03 | 2406 | 67.1 | 27.0 | 24.2 | 16.9 | 27.2 |
| | 45 | 318.2 | 1.110 | 1.068 | 57.02 | 2394 | 67.5 | 27.4 | 24.9 | 17.4 | 28.0 |
| | | | | | | | | | | | 17.0 |

 ρ_a density of dry air $\rho_{as}(T)$ density of air saturated with water vapor at temperature T°C T_v virtual temperature of saturated air λ latent heat of vaporization of water $\gamma \equiv \rho/\lambda e$ —“psychrometer constant” k thermal conductivity of dry air κ thermal diffusivity of dry air ν kinematic viscosity of dry air D_v diffusion coefficient of water vapor in air D_c diffusion coefficient of CO₂ in air

Table A.4 Quantities changing by more than 1% per K. $e_s(T)$ Saturation Vapor Pressure; Temperature T (°C); Δ Change of Saturation Vapor Pressure per K, i.e. $\partial e_s / \partial T$; Radiation at Temperature T (K); $4\sigma T^3$ Change of Full Radiation per K. Note that the Δ and $4\sigma T^3$ can be used as mean differences to interpolate between the tabulated values and σT^4 respectively

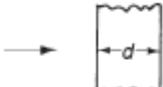
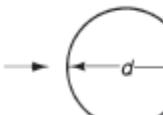
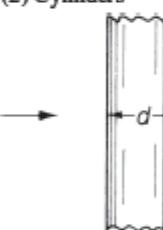
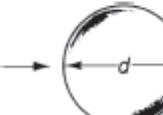
| T (°C) | T (K) | $e_s(T)$ kPa | $\Delta(T)$ Pa K ⁻¹ | σT^4 W m ⁻² | $4\sigma T^3$ W m |
|-----------|----------|-----------------|-----------------------------------|-----------------------------------|----------------------|
| -5 | 268.2 | 0.421 | 32 | 293.4 | 4.4 |
| -4 | 269.2 | 0.455 | 34 | 297.8 | 4.4 |
| -3 | 270.2 | 0.490 | 37 | 302.2 | 4.5 |
| -2 | 271.2 | 0.528 | 39 | 306.7 | 4.5 |
| -1 | 272.2 | 0.568 | 42 | 311.3 | 4.6 |
| 0 | 273.2 | 0.611 | 45 | 315.9 | 4.6 |
| 1 | 274.2 | 0.657 | 48 | 320.5 | 4.7 |
| 2 | 275.2 | 0.705 | 51 | 325.2 | 4.7 |
| 3 | 276.2 | 0.758 | 54 | 330.0 | 4.8 |
| 4 | 277.2 | 0.813 | 57 | 334.8 | 4.8 |
| 5 | 278.2 | 0.872 | 61 | 339.6 | 4.9 |
| 6 | 279.2 | 0.935 | 65 | 344.5 | 5.0 |
| 7 | 280.2 | 1.001 | 69 | 349.5 | 5.0 |
| 8 | 281.2 | 1.072 | 73 | 354.5 | 5.1 |
| 9 | 282.2 | 1.147 | 78 | 359.6 | 5.1 |
| 10 | 283.2 | 1.227 | 83 | 364.7 | 5.2 |
| 11 | 284.2 | 1.312 | 88 | 369.9 | 5.2 |
| 12 | 285.2 | 1.402 | 93 | 375.1 | 5.3 |
| 13 | 286.2 | 1.497 | 98 | 380.4 | 5.3 |
| 14 | 287.2 | 1.598 | 104 | 385.8 | 5.4 |
| 15 | 288.2 | 1.704 | 110 | 391.2 | 5.4 |
| 16 | 289.2 | 1.817 | 117 | 396.6 | 5.5 |
| 17 | 290.2 | 1.937 | 123 | 402.1 | 5.6 |
| 18 | 291.2 | 2.063 | 130 | 407.7 | 5.6 |
| 19 | 292.2 | 2.196 | 137 | 413.3 | 5.7 |
| 20 | 293.2 | 2.337 | 145 | 419.0 | 5.7 |
| 21 | 294.2 | 2.486 | 153 | 424.8 | 5.8 |
| 22 | 295.2 | 2.643 | 162 | 430.6 | 5.8 |
| 23 | 296.2 | 2.809 | 170 | 436.4 | 5.9 |
| 24 | 297.2 | 2.983 | 179 | 442.4 | 6.0 |
| 25 | 298.2 | 3.167 | 189 | 448.3 | 6.0 |
| 26 | 299.2 | 3.361 | 199 | 454.4 | 6.1 |
| 27 | 300.2 | 3.565 | 210 | 460.5 | 6.2 |
| 28 | 301.2 | 3.780 | 221 | 466.7 | 6.2 |
| 29 | 302.2 | 4.006 | 232 | 472.9 | 6.3 |
| 30 | 303.2 | 4.243 | 244 | 479.2 | 6.3 |
| 31 | 304.2 | 4.493 | 257 | 485.5 | 6.4 |
| 32 | 305.2 | 4.755 | 269 | 492.0 | 6.5 |
| 33 | 306.2 | 5.031 | 283 | 498.4 | 6.5 |
| 34 | 307.2 | 5.320 | 297 | 505.0 | 6.6 |

Table A.4 (Continued)

| T (°C) | T (K) | $e_s(T)$ kPa | $\Delta(T)$ Pa K ⁻¹ | σT^4 W m ⁻² | $4\sigma T^3$ W m ⁻² K ⁻¹ |
|-----------|----------|-----------------|-----------------------------------|-----------------------------------|--|
| 35 | 308.2 | 5.624 | 312 | 511.6 | 6.7 |
| 36 | 309.2 | 5.942 | 327 | 518.3 | 6.7 |
| 37 | 310.2 | 6.276 | 343 | 525.0 | 6.8 |
| 38 | 311.2 | 6.626 | 357 | 531.8 | 6.9 |
| 39 | 312.2 | 6.993 | 376 | 538.7 | 6.9 |
| 40 | 313.2 | 7.378 | 394 | 545.6 | 7.0 |
| 41 | 314.2 | 7.780 | 413 | 552.6 | 7.1 |
| 42 | 315.2 | 8.202 | 432 | 559.7 | 7.1 |
| 43 | 316.2 | 8.642 | 452 | 566.8 | 7.2 |
| 44 | 317.2 | 9.103 | 473 | 574.0 | 7.3 |
| 45 | 318.2 | 9.586 | 494 | 581.3 | 7.3 |

Table A.5 Nusselt Numbers for Air

(a) Forced Convection

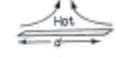
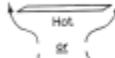
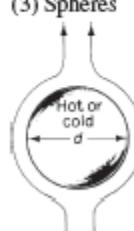
| Shape | Case | Range of Re | Nu |
|---|----------------------------------|---------------------------------|---------------------------------|
| (1) Flat plates | | | |
|  | Streamline flow | $< 2 \times 10^4$ | $0.60 \text{ Re}^{0.5}$ |
| | Turbulent flow | $> 2 \times 10^4$ | $0.032 \text{ Re}^{0.8}$ |
|  | | | |
|  | | | |
| (2) Cylinders | | | |
|  | Narrow range of Reynolds numbers | 1 – 4 | $0.89 \text{ Re}^{0.33}$ |
| | | 4 – 40 | $0.82 \text{ Re}^{0.39}$ |
| | | $40 - 4 \times 10^3$ | $0.62 \text{ Re}^{0.47}$ |
| | | $4 \times 10^3 - 4 \times 10^4$ | $0.17 \text{ Re}^{0.62}$ |
| | | $4 \times 10^4 - 4 \times 10^5$ | $0.024 \text{ Re}^{0.81}$ |
| | Wide range of Reynolds numbers | or | |
| | | $10^{-1} - 10^3$ | $0.32 + 0.51 \text{ Re}^{0.52}$ |
| | | $10^3 - 5 > 10^4$ | $0.24 \text{ Re}^{0.60}$ |
| (3) Spheres | | | |
|  | | $0 - 300$ | $2 + 0.54 \text{ Re}^{0.5}$ |
| | | $50 - 1.5 \times 10^5$ | $0.34 \text{ Re}^{0.6}$ |

Notes

- (i) Arrows show direction of airflow
- (ii) d is characteristic dimension; take width of a long crosswind strut as shown or mean side for a rectangle whose width and length are comparable
- (iii) To find corresponding Sherwood numbers multiply Nu by $\text{Le}^{0.33}$ (see values in Table A.1)
- (iv) Sources—Ede (1967), Fishenden and Saunders (1950), Bird, Stewart and Lightfoot (1960)

Table A.5 (Continued)

(b) Free Convection

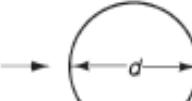
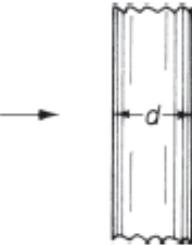
| Shape and relative temperature | Laminar flow | Range | Turbulent flow | Nu |
|---|---------------------------|--|----------------|------------------------------|
| (1) Horizontal flat plates or cylinders | | | | |
|  | $\text{Gr} < 10^5$ | | | $0.50 \text{ Gr}^{0.25}$ |
|  | | $\text{Gr} > 10^5$ | | $0.13 \text{ Gr}^{0.33}$ |
|  | | Arrangement not conductive to turbulence | | $0.23 \text{ Gr}^{0.25}$ |
|  | $10^4 < \text{Gr} < 10^9$ | | | $0.48 \text{ Gr}^{0.25}$ |
| | | $\text{Gr} > 10^9$ | | $0.09 \text{ Gr}^{0.33}$ |
| (2) Vertical flat plates or cylinders | | | | |
|  | $10^4 < \text{Gr} < 10^9$ | | | $0.58 \text{ Gr}^{0.25}$ |
| | | $10^9 < \text{Gr} < 10^{12}$ | | $0.11 \text{ Gr}^{0.33}$ |
|  | $\text{Gr}^{0.25} < 220$ | | | $2 + 0.54 \text{ Gr}^{0.25}$ |

Notes

- (i) Arrows indicate direction of air circulation
- (ii) d is characteristic dimensions for calculation of Gr: take height for vertical plate and average chord for horizontal plate
- (iii) To find corresponding Sherwood numbers, multiply Nu by $\text{Le}^{0.25}$ for laminar flow or turbulent flow (see values in Table A.1)
- (iv) Sources—Ede (1967), Fishenden and Saunders (1950), Bird, Stewart and Lightfoot (1960)

Table A.5 Nusselt Numbers for Air

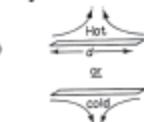
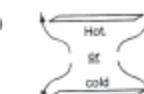
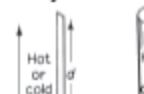
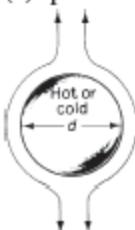
(a) Forced Convection

| Shape | Case | Range of Re | Nu |
|---|----------------------------------|---------------------------------|---------------------------------|
| (1) Flat plates | | | |
|  | Streamline flow | $< 2 \times 10^4$ | $0.60 \text{ Re}^{0.5}$ |
| | Turbulent flow | $> 2 \times 10^4$ | $0.032 \text{ Re}^{0.8}$ |
| (2) Cylinders | | | |
|  | Narrow range of Reynolds numbers | 1 – 4 | $0.89 \text{ Re}^{0.33}$ |
| | | 4 – 40 | $0.82 \text{ Re}^{0.39}$ |
| | | $40 - 4 \times 10^3$ | $0.62 \text{ Re}^{0.47}$ |
| | | $4 \times 10^3 - 4 \times 10^4$ | $0.17 \text{ Re}^{0.62}$ |
| | | $4 \times 10^4 - 4 \times 10^5$ | $0.024 \text{ Re}^{0.81}$ |
| | or | | |
|  | Wide range of Reynolds numbers | $10^{-1} - 10^3$ | $0.32 + 0.51 \text{ Re}^{0.52}$ |
| | | $10^3 - 5 > 10^4$ | $0.24 \text{ Re}^{0.60}$ |
| (3) Spheres | | | |
|  | | 0 – 300 | $2 + 0.54 \text{ Re}^{0.5}$ |
| | | $50 - 1.5 \times 10^5$ | $0.34 \text{ Re}^{0.6}$ |

Notes

- (i) Arrows show direction of airflow
- (ii) d is characteristic dimension; take width of a long crosswind strut as shown or mean side for a rectangle whose width and length are comparable
- (iii) To find corresponding Sherwood numbers multiply Nu by $\text{Le}^{0.33}$ (see values in Table A.1)
- (iv) Sources—Ede (1967), Fishenden and Saunders (1950), Bird, Stewart and Lightfoot (1960)

Table A.5 (Continued)

| (b) Free Convection | | | |
|---|--|--|------------------------------|
| Shape and relative temperature | Range | | |
| | Laminar flow | Turbulent flow | Nu |
| (1) Horizontal flat plates or cylinders | | | |
| (i) |  | $\text{Gr} < 10^5$ | $0.50 \text{ Gr}^{0.25}$ |
| | | $\text{Gr} > 10^5$ | $0.13 \text{ Gr}^{0.33}$ |
| (ii) |  | Arrangement not conductive to turbulence | $0.23 \text{ Gr}^{0.25}$ |
| (iii) |  | $10^4 < \text{Gr} < 10^9$ | $0.48 \text{ Gr}^{0.25}$ |
| | | $\text{Gr} > 10^9$ | $0.09 \text{ Gr}^{0.33}$ |
| (2) Vertical flat plates or cylinders | | | |
| |  | $10^4 < \text{Gr} < 10^9$ | $0.58 \text{ Gr}^{0.25}$ |
| |  | $10^9 < \text{Gr} < 10^{12}$ | $0.11 \text{ Gr}^{0.33}$ |
| (3) Spheres | | $\text{Gr}^{0.25} < 220$ | $2 + 0.54 \text{ Gr}^{0.25}$ |
| |  | | |

Notes

- (i) Arrows indicate direction of air circulation
- (ii) d is characteristic dimensions for calculation of Gr : take height for vertical plate and average chord for horizontal plate
- (iii) To find corresponding Sherwood numbers, multiply Nu by $\text{Le}^{0.25}$ for laminar flow or turbulent flow (see values in Table A.1)
- (iv) Sources—Ede (1967), Fishenden and Saunders (1950), Bird, Stewart and Lightfoot (1960)

Table A.6 Characteristic quantities for particle transfer in air*: D Diffusion coefficient ($\text{m}^2 \text{ s}^{-1}$); τ Relaxation time (μs); $\overline{\Delta x_B}$ Mean displacement in 1 s in a given direction $2(Dt/\pi)^{0.5}$ (μm); $\overline{\Delta x_s}$ Distance fallen in 1 s under gravity (μm)

| Radius r (μm) | D ($10^{-9} \text{ m}^2 \text{ s}^{-1}$) | τ (10^{-6} s) | $\overline{\Delta x_B}$ (μm) | $\overline{\Delta x_s}$ (μm) |
|------------------------------|--|--------------------------------|---|---|
| 1.0×10^{-3} | 1.28×10^3 | 1.33×10^{-3} | 1.28×10^3 | 1.31×10^{-2} |
| 5.0×10^{-3} | 5.24×10^1 | 6.76×10^{-3} | 2.58×10^2 | 6.63×10^{-2} |
| 1.0×10^{-2} | 1.35×10^1 | 1.40×10^{-2} | 1.31×10^2 | 1.37×10^{-1} |
| 5.0×10^{-2} | 6.82×10^{-1} | 8.81×10^{-2} | 2.95×10^1 | 8.64×10^{-1} |
| 0.1 | 2.21×10^{-1} | 0.23 | 1.68×10^1 | 2.24 |
| 0.5 | 2.7×10^{-2} | 3.54 | 5.90 | 3.47×10^1 |
| 1.0 | 1.3×10^{-2} | 1.31×10^1 | 4.02 | 1.28×10^2 |
| 5.0 | 2.4×10^{-3} | 3.08×10^2 | 1.74 | 3.0×10^3 |
| 10.0 | 1.4×10^{-3} | 1.23×10^3 | 1.23 | 1.2×10^4 |

*From Fuchs (1964), calculated at 23°C , standard atmospheric pressure; particle density 1 g cm^{-3} .