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Chapter 2

Introduction to Engineering Calculations

2.1 Unit conversion

(a)

From Table A.9 (Appendix A): 1 cP = 10^{-3} kg m^{-1} s^{-1}

1 m = 100 cm

Therefore:

$$1.5 \times 10^{-6}\ \text{cP} = 1.5 \times 10^{-6}\ \text{cP}\,.\left|\frac{10^{-3}\ \text{kg m}^{-1}\ \text{s}^{-1}}{1\ \text{cP}}\right|.\left|\frac{1\ \text{m}}{100\ \text{cm}}\right| = 1.5 \times 10^{-11}\ \text{kg s}^{-1}\ \text{cm}^{-1}$$

Answer: 1.5×10^{-11} kg s^{-1} cm^{-1}

(b)

From Table A.8 (Appendix A): 1 hp (British) = 42.41 Btu min^{-1}

Therefore:

$$0.122\ \text{hp} = 0.122\ \text{hp}\,.\left|\frac{42.41\ \text{Btu min}^{-1}}{1\ \text{hp}}\right| = 5.17\ \text{Btu min}^{-1}$$

Answer: 5.17 Btu min^{-1}

(c)

1 min = 60 s

rpm means revolutions per minute. As revolutions is a non-dimensional quantity (Section 2.1.2), the units of rpm are min^{-1}. Therefore:

$$10{,}000\ \text{min}^{-1} = 10{,}000\ \text{min}^{-1}\,.\left|\frac{1\ \text{min}}{60\ \text{s}}\right| = 167\ \text{s}^{-1}$$

Answer: 167 s^{-1}

(d)

From Table A.8 (Appendix A): 1 W = 1 J s^{-1}

From Table A.7 (Appendix A): 1 J = 9.869×10^{-3} l atm

From Table A.1 (Appendix A): 1 m = 3.281 ft

1 min = 60 s

As explained in Section 2.4.6, $°C^{-1}$ is the same as K^{-1}. Therefore:

$$4335\ \text{W m}^{-2}\ °\text{C}^{-1} = 4335\ \text{W m}^{-2}\ °\text{C}^{-1}.\left|\frac{1\ \text{J s}^{-1}}{1\ \text{W}}\right|.\left|\frac{9.869\times 10^{-3}\ \text{l atm}}{1\ \text{J}}\right|.\left|\frac{60\ \text{s}}{1\ \text{min}}\right|.\left|\frac{1\ \text{m}}{3.281\ \text{ft}}\right|^2$$

$$= 238.45\ \text{l atm min}^{-1}\text{ft}^{-2}\ \text{K}^{-1}$$

Answer: 238 l atm min^{-1} ft^{-2} K^{-1}

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2.2 Unit conversion

(a)

From Table A.7 (Appendix A): 1 Btu = 0.2520 kcal

From Table A.3 (Appendix A): 1 lb = 453.6 g

Therefore:

$$345\ \text{Btu lb}^{-1} = 345\ \text{Btu lb}^{-1} \cdot \left|\frac{0.2520\ \text{kcal}}{1\ \text{Btu}}\right| \cdot \left|\frac{1\ \text{lb}}{453.6\ \text{g}}\right| = 0.192\ \text{kcal g}^{-1}$$

Answer: 0.192 kcal g^{-1}

(b)

From Table A.5 (Appendix A): 1 mmHg = 1.316×10^{-3} atm

From Table A.1 (Appendix A): 1 ft = 0.3048 m

From Table A.7 (Appendix A): 1 l atm = 9.604×10^{-2} Btu

From Table A.8 (Appendix A): 1 Btu min^{-1} = 2.391×10^{-2} metric horsepower

1 m = 100 cm

1 l = 1000 cm^3

1 h = 60 min

Therefore:

$$670\ \text{mmHg ft}^3 = 670\ \text{mmHg ft}^3 \cdot \left|\frac{1.316\times10^{-3}\ \text{atm}}{1\ \text{mmHg}}\right| \cdot \left|\frac{9.604\times10^{-2}\ \text{Btu}}{1\ \text{l atm}}\right| \cdot \left|\frac{0.3048\ \text{m}}{1\ \text{ft}}\right|^3 \cdot \left|\frac{100\ \text{cm}}{1\ \text{m}}\right|^3 \cdot \left|\frac{1\ \text{l}}{1000\ \text{cm}^3}\right| \cdot \left|\frac{2.391\times10^{-2}\ \text{metric horsepower}}{1\ \text{Btu min}^{-1}}\right| \cdot \left|\frac{1\ \text{h}}{60\ \text{min}}\right|$$

$$= 9.56\times10^{-4}\ \text{metric horsepower h}$$

Answer: 9.56×10^{-4} metric horsepower h

(c)

From Table A.7 (Appendix A): 1 kcal = 4.187×10^3 J

1 kcal = 1000 cal

1 kg = 1000 g

As explained in Section 2.4.6, $°\text{C}^{-1}$ is the same as K^{-1}. Therefore:

$$0.554\ \text{cal g}^{-1}\ °\text{C}^{-1} = 0.554\ \text{cal g}^{-1}\ °\text{C}^{-1} \cdot \left|\frac{1\ \text{kcal}}{1000\ \text{cal}}\right| \cdot \left|\frac{4.187\times10^3\ \text{J}}{1\ \text{kcal}}\right| \cdot \left|\frac{1000\ \text{g}}{1\ \text{kg}}\right|$$

$$= 2319.6\ \text{J kg}^{-1}\ \text{K}^{-1}$$

Answer: 2320 J kg^{-1} K^{-1}

(d)

From Table A.2 (Appendix A): 1 m^3 = 10^3 l

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1 kg = 1000 g

Therefore:

$$10^3 \text{ g l}^{-1} = 10^3 \text{ g l}^{-1} \cdot \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| \cdot \left| \frac{10^3 \text{ l}}{1 \text{ m}^3} \right| = 10^3 \text{ kg m}^{-3}$$

Answer: 10^3 kg m^{-3}

2.3 Unit conversion

(a)

From Table A.2 (Appendix A): 1 m^3 = 10^3 l

1 g = 10^6 μg

1 l = 1000 ml

Therefore:

$$10^6 \text{ μg ml}^{-1} = 10^6 \text{ μg ml}^{-1} \cdot \left| \frac{1 \text{ g}}{10^6 \text{ μg}} \right| \cdot \left| \frac{1000 \text{ ml}}{1 \text{ l}} \right| \cdot \left| \frac{10^3 \text{ l}}{1 \text{ m}^3} \right| = 10^6 \text{ g m}^{-3}$$

Answer: 10^6 g m^{-3}

(b)

From Table A.9 (Appendix A): 1 cP = 10^{-3} Pa s

1 Pa s = 1000 mPa s

Therefore:

$$3.2 \text{ cP} = 3.2 \text{ cP} \cdot \left| \frac{10^{-3} \text{ Pa s}}{1 \text{ cP}} \right| \cdot \left| \frac{1000 \text{ mPa s}}{1 \text{ Pa s}} \right| = 3.2 \text{ mPa s}$$

Answer: 3.2 mPa s

(c)

From Table A.7 (Appendix A): 1 Btu = 1.055 × 10^3 J

From Table A.8 (Appendix A): 1 W = 1 J s^{-1}

From Table A.1 (Appendix A): 1 ft = 0.3048 m

1 h = 3600 s

From Section 2.4.6, a temperature difference of 1 K corresponds to a temperature difference of 1.8 °F. Therefore:

$$150 \text{ Btu h}^{-1} \text{ ft}^{-2} (\text{°F ft}^{-1})^{-1} = 150 \text{ Btu h}^{-1} \text{ ft}^{-1} \text{ °F}^{-1} \cdot \left| \frac{1.055 \times 10^3 \text{ J}}{1 \text{ Btu}} \right| \cdot \left| \frac{1 \text{ h}}{3600 \text{ s}} \right| \cdot \left| \frac{1 \text{ ft}}{0.3048 \text{ m}} \right| \cdot \left| \frac{1.8 \text{ °F}}{1 \text{ K}} \right| \cdot \left| \frac{1 \text{ W}}{1 \text{ J s}^{-1}} \right|$$

$$= 259.6 \text{ W m}^{-1} \text{ K}^{-1}$$

Answer: 260 W m^{-1} K^{-1}

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(d)

1 h = 3600 s

rph means revolutions per hour. As revolutions is a non-dimensional quantity (Section 2.1.2), the units of rph are h^{-1}. Therefore:

$$66\ \text{rph} = 66\ \text{h}^{-1} \cdot \left| \frac{1\ \text{h}}{3600\ \text{s}} \right| = 1.83 \times 10^{-2}\ \text{s}^{-1}$$

Answer: $1.83 \times 10^{-2}\ \text{s}^{-1}$

2.4 Unit conversion and calculation

Convert to units of kg, m, s.

From Table A.2 (Appendix A): 1 $\text{ft}^3 = 2.832 \times 10^{-2}\ \text{m}^3$

From Table A.2 (Appendix A): 1 $\text{m}^3 = 10^3$ l

From Table A.3 (Appendix A): 1 lb = 0.4536 kg

From Table A.8 (Appendix A): 1 metric horsepower = $7.355 \times 10^2\ \text{kg m}^2\ \text{s}^{-3}$

From Table A.1 (Appendix A): 1 m = 39.37 in.

Therefore:

$$t_\text{m} = 5.9\,(2.3\ \text{m})^{2/3} \left(\frac{65\ \text{lb}}{\text{ft}^3} \; \frac{10{,}000\,\text{l} \cdot \left| \dfrac{1\ \text{m}^3}{10^3\ \text{l}} \right|}{0.70\ \text{metric hp} \cdot \left| \dfrac{7.355 \times 10^2\ \text{kg m}^2\ \text{s}^{-3}}{1\ \text{metric hp}} \right|} \cdot \left| \frac{1\ \text{ft}^3}{2.832 \times 10^{-2}\ \text{m}^3} \right| \cdot \left| \frac{0.4536\ \text{kg}}{1\ \text{lb}} \right| \right)^{1/3} \left(\frac{2.3\ \text{m}}{45\ \text{in.}} \cdot \left| \frac{39.37\ \text{in.}}{1\ \text{m}} \right| \right)^{1/3}$$

$$= 5.9\,(2.3)^{2/3}\ \text{m}^{2/3}\,(2.724\ \text{m}^{-2/3}\ \text{s})\,1.262$$

$$= 35.3\ \text{s}$$

Answer: 35 s

2.5 Unit conversion and dimensionless numbers

Case 1

Convert to units of kg, m, s.

From Table A.3 (Appendix A): 1 lb = 0.4536 kg

From Table A.2 (Appendix A): 1 $\text{ft}^3 = 2.832 \times 10^{-2}\ \text{m}^3$

From Table A.9 (Appendix A): 1 cP = $10^{-3}\ \text{kg m}^{-1}\ \text{s}^{-1}$

1 m = 100 cm = 1000 mm

Using Eq. (2.1):

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$$Re = \frac{\left(2\ \text{mm} \cdot \left|\frac{1\ \text{m}}{1000\ \text{mm}}\right|\right)\left(3\ \text{cm s}^{-1} \cdot \left|\frac{1\ \text{m}}{100\ \text{cm}}\right|\right)\left(25\ \text{lb ft}^{-3} \cdot \left|\frac{0.4536\ \text{kg}}{1\ \text{lb}}\right| \cdot \left|\frac{1\ \text{ft}^3}{2.832\times10^{-2}\ \text{m}^3}\right|\right)}{10^{-6}\ \text{cP} \cdot \left|\frac{10^{-3}\ \text{kg m}^{-1}\ \text{s}^{-1}}{1\ \text{cP}}\right|}$$

$$= 2.4\times10^{7}$$

Answer: 2.4 × 10^7

Case 2

Convert to units of kg, m, s.

From Table A.1 (Appendix A): 1 in. = 2.54 × 10^{-2} m

From Table A.9 (Appendix A): 1 lb ft^{-1} h^{-1} = 4.134 × 10^{-4} kg m^{-1} s^{-1}

1 h = 3600 s

Using Eq. (2.1):

$$Re = \frac{\left(1\ \text{in.} \cdot \left|\frac{2.54\times10^{-2}\ \text{m}}{1\ \text{in.}}\right|\right)(1\ \text{m s}^{-1})\,(12.5\ \text{kg m}^{-3})}{0.14\times10^{-4}\ \text{lb}_m\ \text{s}^{-1}\ \text{ft}^{-1} \cdot \left|\frac{4.134\times10^{-4}\ \text{kg m}^{-1}\ \text{s}^{-1}}{1\ \text{lb ft}^{-1}\ \text{h}^{-1}}\right| \cdot \left|\frac{3600\ \text{s}}{\text{h}}\right|} = 1.5\times10^{4}$$

Answer: 1.5 × 10^4

2.6 Property data

Values were obtained from *Perry's Chemical Engineers' Handbook*, 8th edition, McGraw-Hill. Other sources may also be used.

(a)

The viscosity of ethanol can be evaluated as a function of temperature using the coefficients listed in Table 2-313 of *Perry's Chemical Engineers' Handbook*. Converting from °C to K using Eq. (2.27), T(K) = 40 + 273.15 = 313.15 K. Using the equation provided, the viscosity at 40°C is calculated as 8.18 × 10^{-4} Pa s. Alternatively, using the nomograph of Figure 2-32 in *Perry's Chemical Engineers' Handbook*, the viscosity of ethanol at 40°C is estimated at about 0.82 cP, which is consistent with the previous result.

Answer: 0.82 cP

(b)

From Table 2-325 in *Perry's Chemical Engineers' Handbook*, at 25°C and 1 atm pressure, the diffusivity of oxygen in water is 2.5 × 10^{-5} cm^2 s^{-1}.

Answer: 2.5 × 10^{-5} cm^2 s^{-1}

(c)

The thermal conductivity of borosilicate-type glass is listed in Table 2-326 of *Perry's Chemical Engineers' Handbook*. For temperatures between 30°C and 75°C, the thermal conductivity is 0.63 Btu h^{-1} ft^{-2} $(°\text{F/ft})^{-1}$.

Answer: 0.63 Btu h^{-1} ft^{-2} $(°\text{F/ft})^{-1}$

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(d)

The density of 100% acetic acid at 20°C is listed in Table 2-109 of *Perry's Chemical Engineers' Handbook* as 1.0498 g cm^{-3}.

Answer: 1.0498 g cm^{-3}

(e)

The specific heat capacity of liquid water at 80°C can be calculated using the values listed in Table 2-305 of *Perry's Chemical Engineers' Handbook*. Converting from °C to K using Eq. (2.27), T(K) = 80 + 273.15 = 353.15 K. From the table, C_p = 0.075567 kJ mol^{-1} K^{-1} at 350 K and C_p = 0.075708 kJ mol^{-1} K^{-1} at 360 K. Assuming that C_p changes linearly with temperature between 350 K and 360 K, the value at 353.15 K can be interpolated as:

$$C_p(353.15\text{ K}) = 0.075567\text{ kJ mol}^{-1}\text{ K}^{-1} + \frac{(353.15-350)\text{ K}}{(360-350)\text{ K}}(0.075708-0.075567)\text{ kJ mol}^{-1}\text{ K}^{-1}$$

$$= 0.075611\text{ kJ mol}^{-1}\text{ K}^{-1}$$

Answer: 0.07561 kJ mol^{-1} K^{-1}

2.7 Dimensionless groups and property data

From *Perry's Chemical Engineers' Handbook*, the diffusivity of oxygen in water at 25°C and 1 atm pressure is 2.5 × 10^{-5} cm^2 s^{-1}. Assuming this is the same at 28°C, $\mathscr{D}$ = 2.5 × 10^{-5} cm^2 s^{-1}. As fermentation medium is mostly water, it is reasonable to assume that the density of liquid in the fermenter is the same as that of water. Unless the culture produces a highly viscous extracellular product such as gum, it is also reasonable to assume that the viscosity of liquid in the fermenter is the same as that of water. From *Perry's Chemical Engineers' Handbook*, the density of water at 28°C ρ_L = 0.9962652 g cm^{-3} and the viscosity of water at 28°C μ_L = 0.87 cP. The density of oxygen at 28°C and 1 atm pressure can be calculated using the ideal gas law. As molar density is the same as n/V, from Eq. (2.35):

$$\rho_G = \frac{n}{V} = \frac{p}{RT}$$

Temperature in the ideal gas equation is absolute temperature; therefore, from Eq. (2.27):

$$T(\text{K}) = (28 + 273.15)\text{ K} = 301.15\text{ K}$$

From Appendix B, R = 82.057 cm^3 atm K^{-1} gmol^{-1}. Substituting parameter values into the above equation for gas density gives:

$$\rho_G = \frac{1\text{ atm}}{(82.057\text{ cm}^3\text{ atm K}^{-1}\text{ gmol}^{-1})\,(301.15\text{ K})} = 4.05\times10^{-5}\text{ gmol cm}^{-3}$$

Using the atomic weights in Table C.1 (Appendix C), the molecular weight of oxygen is 32.0. Converting the result for ρ_G to mass terms:

$$\rho_G = 4.05\times10^{-5}\text{ gmol cm}^{-3}\cdot\left|\frac{32.0\text{ g}}{1\text{ gmol}}\right| = 1.30\times10^{-3}\text{ g cm}^{-3}$$

From Table A.9 (Appendix A), 1 cP = 10^{-2} g cm^{-1} s^{-1}. From Eq. (2.17), g = 980.66 cm s^{-2}. 1 cm = 10 mm. The parameter values and conversion factors can now be used to calculate the dimensionless groups in the equation for the Sherwood number.

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$$Gr = \frac{(2\text{ mm})^3\,(1.30\times10^{-3}\text{ g cm}^{-3})\,(0.9962652-1.30\times10^{-3})\text{ g cm}^{-3}\,(980.66\text{ cm s}^{-2})\,.\left|\frac{1\text{ cm}}{10\text{ mm}}\right|^3}{(0.87\text{ cP})^2\,.\left|\frac{10^{-2}\text{ g cm}^{-1}\text{ s}^{-1}}{1\text{ cP}}\right|^2}$$

$$=134$$

Similarly for the Schmidt number:

$$Sc = \frac{0.87\text{ cP}\,.\left|\frac{10^{-2}\text{ g cm}^{-1}\text{ s}^{-1}}{1\text{ cP}}\right|}{(0.9962652\text{ g cm}^{-3})\,(2.5\times10^{-5}\text{ cm}^2\text{ s}^{-1})} = 349$$

Therefore:

$$Sh = 0.31\,(134)^{1/3}\,(349)^{1/3} = 11.2$$

From the equation for *Sh*:

$$k_{\text{L}} = \frac{Sh\,\mathscr{D}}{D_{\text{b}}} = \frac{(11.2)\,(2.5\times10^{-5}\text{ cm}^2\text{ s}^{-1})}{2\text{ mm}\,.\left|\frac{1\text{ cm}}{10\text{ mm}}\right|} = 1.40\times10^{-3}\text{ cm s}^{-1}$$

Answer: 1.40 × 10^{-3} cm s^{-1}

2.8 Dimensionless numbers and dimensional homogeneity

First, evaluate the units of the groups ($C_p\mu/k$) and (DG/μ):

$$\text{Units of}\left(\frac{C_p\mu}{k}\right) = \frac{(\text{Btu lb}^{-1}\,{}^\circ\text{F}^{-1})\text{ lb h}^{-1}\text{ ft}^{-1}}{\text{Btu h}^{-1}\text{ ft}^{-2}\,({}^\circ\text{F ft}^{-1})^{-1}} = 1$$

$$\text{Units of}\left(\frac{DG}{\mu}\right) = \frac{(\text{ft})\text{ lb h}^{-1}\text{ ft}^{-2}}{\text{lb h}^{-1}\text{ ft}^{-1}} = 1$$

Therefore, these groups are dimensionless. For the equation to be dimensionally homogeneous, (h/C_pG) must also be dimensionless; the units of h must therefore cancel the units of C_pG.

$$\text{Units of } h = \text{units of } C_pG = (\text{Btu lb}^{-1}\,{}^\circ\text{F}^{-1})\,(\text{lb h}^{-1}\text{ ft}^{-2}) = \text{Btu }{}^\circ\text{F}^{-1}\text{ h}^{-1}\text{ ft}^{-2}$$

The dimensions of h can be deduced from its units. From Table A.7 (Appendix A), Btu is a unit of energy with dimensions = L^2MT^{-2}. °F is a unit of temperature which, from Table 2.1, has the dimensional symbol Θ. h (hour) is a unit of time with dimension T; ft is a unit of length with dimension L. Therefore:

$$\text{Dimensions of } h = \text{L}^2\text{MT}^{-2}\Theta^{-1}\text{T}^{-1}\text{L}^{-2} = \text{MT}^{-3}\Theta^{-1}$$

Answer: Units = Btu $°F^{-1}$ h^{-1} ft^{-2}; dimensions = $MT^{-3}\Theta^{-1}$

2.9 Dimensional homogeneity

λ has dimensions L. ε has units W kg^{-1}; therefore, from Tables A.8 and A.3 in Appendix A, the dimensions of ε are $L^2MT^{-3}M^{-1}$ = L^2T^{-3}. Substituting this information into the equation for λ, for dimensional homogeneity:

$$\text{L} = \left(\frac{(\text{dimensions of }\nu)^3}{\text{L}^2\text{T}^{-3}}\right)^{1/4} = \frac{(\text{dimensions of }\nu)^{3/4}}{\text{L}^{1/2}\text{T}^{-3/4}}$$

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Solving for the dimensions of v:

$$(\text{dimensions of } v)^{3/4} = \mathrm{L}^{3/2}\mathrm{T}^{-3/4}$$

or

$$\text{dimensions of } v = \mathrm{L}^2\mathrm{T}^{-1}$$

Answer: $\mathrm{L}^2\mathrm{T}^{-1}$

2.10 Dimensional homogeneity and g_c

The dimensions of D_i (length) = L. From Table 2.2, the dimensions of $P = \mathrm{L}^2\mathrm{MT}^{-3}$ and the dimensions of $\rho = \mathrm{L}^{-3}\mathrm{M}$. From Section 2.3, the dimensions of $g = \mathrm{LT}^{-2}$. From Section 2.1.2, the dimensions of rotational speed $N_i = \mathrm{T}^{-1}$. Therefore:

$$\text{Dimensions of } \frac{P\,g}{\rho\,N_i^3\,D_i^5} = \frac{(\mathrm{L}^2\mathrm{MT}^{-3})\,(\mathrm{LT}^{-2})}{(\mathrm{L}^{-3}\mathrm{M})\,(\mathrm{T}^{-1})^3\,\mathrm{L}^5} = \mathrm{LT}^{-2}$$

As N_P is a dimensionless number, equation (i) is not dimensionally homogeneous and therefore cannot be correct. From Section 2.3, the dimensions of g_c = 1. Therefore:

$$\text{Dimensions of } \frac{P\,g_c}{\rho\,N_i^3\,D_i^5} = \frac{(\mathrm{L}^2\mathrm{MT}^{-3})\,(1)}{(\mathrm{L}^{-3}\mathrm{M})\,(\mathrm{T}^{-1})^3\,\mathrm{L}^5} = 1$$

Equation (ii) is dimensionally homogeneous and therefore likely to be correct.

Answer: (ii)

2.11 Mass and weight

From the definition of density in Section 2.4.1, mass is equal to density multiplied by volume. Therefore:

$$\text{Mass of water} = (10\ \mathrm{ft}^3)(62.4\ \mathrm{lb}_m\ \mathrm{ft}^{-3}) = 624\ \mathrm{lb}_m$$

From Section 2.3, weight is the force with which a body is attracted to the centre of the earth by gravity. According to Newton's law (Section 2.3), this force is the mass of the body multiplied by gravitational acceleration.

(a)

From Eq. (2.18), at sea level and 45° latitude, gravitational acceleration g = 32.174 ft s^{-2}. Therefore:

$$\text{Weight} = 624\ \mathrm{lb}_m\ (32.174\ \mathrm{ft\ s}^{-2}) = 2.008 \times 10^4\ \mathrm{lb}_m\ \mathrm{ft\ s}^{-2}$$

Converting these units to lb$_f$ using Eq. (2.19):

$$\text{Weight} = 2.008\times10^4\ \mathrm{lb}_m\ \mathrm{ft\ s}^{-2}\,.\left|\frac{1\ \mathrm{lb}_f}{32.174\ \mathrm{lb}_m\ \mathrm{ft\ s}^{-2}}\right| = 624\ \mathrm{lb}_f$$

Answer: 624 lb$_f$. *When g = 32.174 ft s^{-2}, lb mass is equal to lb force.*

(b)

From Table A.1 (Appendix A), 1 m = 3.281 ft. Using the same procedure as in **(a)**:

$$\text{Weight} = 624\ \mathrm{lb}_m\ (9.76\ \mathrm{m\ s}^{-2})\,.\left|\frac{3.281\ \mathrm{ft}}{1\ \mathrm{m}}\right| = 1.998\times10^4\ \mathrm{lb}_m\ \mathrm{ft\ s}^{-2}$$

Converting to lb$_f$ using Eq. (2.19):

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$$\text{Weight} = 1.998\times10^4\ \text{lb}_m\ \text{ft s}^{-2}\,.\left|\frac{1\ \text{lb}_f}{32.174\ \text{lb}_m\ \text{ft s}^{-2}}\right| = 621\ \text{lb}_f$$

Answer: 621 lb_f

2.12 Molar units

From the atomic weights in Table C.1 (Appendix C), the molecular weight of NaOH is 40.0.

(a)

From Eq. (2.22):

$$\text{lb-moles NaOH} = \frac{20.0\ \text{lb}}{40.0\ \text{lb lbmol}^{-1}} = 0.50\ \text{lbmol}$$

Answer: 0.50 lbmol

(b)

From Table A.3 (Appendix A), 1 lb = 453.6 g. Therefore:

$$20.0\ \text{lb} = 20.0\ \text{lb}\,.\left|\frac{453.6\ \text{g}}{1\ \text{lb}}\right| = 9072\ \text{g}$$

From Eq. (2.21):

$$\text{gram-moles NaOH} = \frac{9072\ \text{g}}{40.0\ \text{g gmol}^{-1}} = 227\ \text{gmol}$$

Answer: 227 gmol

(c)

From Section 2.4.4, 1 kgmol = 1000 gmol. Therefore, from **(b)**:

$$\text{kg-moles NaOH} = 227\ \text{gmol}\,.\left|\frac{1\ \text{kgmol}}{1000\ \text{gmol}}\right| = 0.227\ \text{kgmol}$$

Answer: 0.227 kgmol

2.13 Density and specific gravity

(a)

From Section 2.4.1, the density of water at 4°C is 1.0000 g cm^{-3}. Therefore, from Section 2.4.2, for a substance with specific gravity $1.5129^{20°\text{C}}_{4°\text{C}}$, the density at 20°C is 1.5129 g cm^{-3}.

(i)

1 kg = 1000 g

1 m = 100 cm

Therefore:

$$\text{Density} = 1.5129\ \text{g cm}^{-3}\,.\left|\frac{1\ \text{kg}}{1000\ \text{g}}\right|.\left|\frac{100\ \text{cm}}{1\ \text{m}}\right|^3 = 1512.9\ \text{kg m}^{-3}$$

Answer: 1512.9 kg m^{-3}

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(ii)

From the atomic weights in Table C.1 (Appendix C), the molecular weight of nitric acid (HNO_3) is 63.0. If the density of HNO_3 at 20°C is 1.5129 g cm^{-3}, in 1 cm^3 HNO_3, from Eq. (2.21):

$$\text{gram-moles} = \frac{1.5129\ \text{g}}{63.0\ \text{g gmol}^{-1}} = 0.024\ \text{gmol}$$

Therefore, the molar density is 0.024 gmol cm^{-3}. From the definition of specific volume in Section 2.4.3:

$$\text{Molar specific volume} = \frac{1}{\text{molar density}} = \frac{1}{0.024\ \text{gmol cm}^{-3}} = 41.67\ \text{cm}^3\ \text{gmol}^{-1}$$

Answer: 41.67 cm^3 gmol^{-1}

(b)

(i)

Density is defined as mass per unit volume (Section 2.4.1). Therefore, the mass flow rate is equal to the volumetric flow rate multiplied by the density:

$$\text{Mass flow rate} = (50\ \text{cm}^3\ \text{min}^{-1})(1.6\ \text{g cm}^{-3}) = 80\ \text{g min}^{-1}$$

Answer: 80 g min^{-1}

(ii)

From the atomic weights in Table C.1 (Appendix C), the molecular weight of carbon tetrachloride is 153.8. Using the mass flow rate from **(a)**:

$$\text{Molar flow rate} = 80\ \text{g min}^{-1} \cdot \left|\frac{1\ \text{gmol}}{153.8\ \text{g}}\right| = 0.52\ \text{gmol min}^{-1}$$

Answer: 0.52 gmol min^{-1}

2.14 Molecular weight

From Section 2.4.5, the composition of air is approximately 21% oxygen and 79% nitrogen. For gases at low pressures, this means 21 mol% O_2 and 79 mol% N_2. Therefore, in 1 gmol of air, there are 0.21 gmol O_2 and 0.79 gmol N_2 From the atomic weights in Table C.1 (Appendix C), the molecular weights of O_2 and N_2 are 32.0 and 28.0, respectively. The molecular weight of air is equal to the number of grams in 1 gmol of air:

$$1\ \text{gmol air} = 0.21\ \text{gmol O}_2 \cdot \left|\frac{32.0\ \text{g}}{1\ \text{gmol}}\right| + 0.79\ \text{gmol N}_2 \cdot \left|\frac{28.0\ \text{g}}{1\ \text{gmol}}\right| = 28.8\ \text{g}$$

Answer: 28.8

2.15 Mole fraction

The molecular weights are listed in Table C.7 (Appendix C): water 18.0; ethanol 46.1; methanol 32.0; glycerol 92.1; acetic acid 60.1; benzaldehyde 106.1. In 100 g solution, there are 30 g water, 25 g ethanol, 15 g methanol, 12 g glycerol, 10 g acetic acid, 8 g benzaldehyde, and no other components. Therefore:

$$\text{Moles water} = 30\ \text{g} \cdot \left|\frac{1\ \text{gmol}}{18.0\ \text{g}}\right| = 1.67\ \text{gmol}$$

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$$\text{Moles ethanol} = 25\text{ g}\,.\left|\frac{1\text{ gmol}}{46.1\text{ g}}\right| = 0.54\text{ gmol}$$

$$\text{Moles methanol} = 15\text{ g}\,.\left|\frac{1\text{ gmol}}{32.0\text{ g}}\right| = 0.47\text{ gmol}$$

$$\text{Moles glycerol} = 12\text{ g}\,.\left|\frac{1\text{ gmol}}{92.1\text{ g}}\right| = 0.13\text{ gmol}$$

$$\text{Moles acetic acid} = 10\text{ g}\,.\left|\frac{1\text{ gmol}}{60.1\text{ g}}\right| = 0.17\text{ gmol}$$

$$\text{Moles benzaldehyde} = 8\text{ g}\,.\left|\frac{1\text{ gmol}}{106.1\text{ g}}\right| = 0.075\text{ gmol}$$

The total number of moles is 1.67 + 0.54 + 0.47 + 0.13 + 0.17 + 0.075 = 3.055 gmol. From Eq. (2.23):

$$\text{Mole fraction water} = \frac{1.67}{3.055} = 0.55$$

$$\text{Mole fraction ethanol} = \frac{0.54}{3.055} = 0.18$$

$$\text{Mole fraction methanol} = \frac{0.47}{3.055} = 0.15$$

$$\text{Mole fraction glycerol} = \frac{0.13}{3.055} = 0.043$$

$$\text{Mole fraction acetic acid} = \frac{0.17}{3.055} = 0.056$$

$$\text{Mole fraction benzaldehyde} = \frac{0.075}{3.055} = 0.025$$

Answer: 0.55 water; 0.18 ethanol; 0.15 methanol; 0.043 glycerol; 0.056 acetic acid; 0.025 benzaldehyde

2.16 Solution preparation

A 6% w/v solution means 6 g of $MgSO_4 \cdot 7H_2O$ in 100 ml of solution (Section 2.4.5). To make up 100 ml of solution, weigh out 6 g of $MgSO_4 \cdot 7H_2O$ using the balance and place the solid in the measuring cylinder. Add water to dissolve the solid and make up to the 100 ml mark on the measuring cylinder.

2.17 Moles, molarity, and composition

(a)

From the atomic weights in Table C.1 (Appendix C), the molecular weight of $C_{12}H_{22}O_4$ is 230. 1 kg = 1000 g. Therefore:

$$21.2\text{ kg} = 21.2\text{ kg}\,.\left|\frac{1000\text{ g}}{1\text{ kg}}\right|.\left|\frac{1\text{ gmol}}{230\text{ g}}\right| = 92.2\text{ gmol}$$

Answer: 92.2 gmol

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(b)

From the atomic weights in Table C.1 (Appendix C), the molecular weight of $C_{12}H_{22}O_{11}$ is 342. 1 kg = 1000 g. Therefore:

$$4.5\text{ kg s}^{-1} = 4.5\text{ kg}\,.\left|\frac{1000\text{ g}}{1\text{ kg}}\right|.\left|\frac{1\text{ gmol}}{342\text{ g}}\right| = 13.2\text{ gmol s}^{-1}$$

1 min = 60 s. The amount of sucrose transferred in 30 min is:

$$13.2\text{ gmol s}^{-1}\,(30\text{ min})\,.\left|\frac{60\text{ s}}{1\text{ min}}\right| = 2.38\times10^{4}\text{ gmol}$$

Answer: 2.38×10^4 gmol

(c)

75 mM means 75×10^{-3} gmol per litre of solution (Section 2.4.5). 1 l = 1000 ml; therefore, in 10 ml or 1/100 of a litre, a 75 mM solution contains ($75 \times 10^{-3}/100$) gmol = 75×10^{-5} gmol. From the atomic weights in Table C.1 (Appendix C), the molecular weight of $C_4H_6O_6{\cdot}H_2O$ is 168. Therefore:

$$75\times10^{-5}\text{ gmol} = 75\times10^{-5}\text{ gmol}\,.\left|\frac{168\text{ g}}{1\text{ gmol}}\right| = 0.126\text{ g}$$

Answer: 0.126 g

(d)

60 μM salicylaldehyde means 60×10^{-6} gmol per litre of solution (Section 2.4.5). 1 l = 1000 ml; therefore, in 250 ml or 1/4 of a litre, a 60 μM solution contains ($60/4 \times 10^{-6}$) gmol = 15×10^{-6} gmol. From the atomic weights in Table C.1 (Appendix C), the molecular weight of $C_7H_6O_2$ is 122. Therefore:

$$15\times10^{-6}\text{ gmol} = 15\times10^{-6}\text{ gmol}\,.\left|\frac{122\text{ g}}{1\text{ gmol}}\right| = 1.83\times10^{-3}\text{ g}$$

330 ppm dichloroacetic acid means 330 g per 10^6 g of solution (Section 2.4.5). Because the solution being considered contains only very dilute concentrations of components in water, we can assume that the density of the solution is the same as the density of water or 1 g ml^{-1} (Section 2.4.1). Therefore, the concentration of dichloroacetic acid is 330 g per 10^6 ml of solution, and the mass of dichloroacetic acid in 250 ml of solution is 330 g × (250 ml/10^6 ml) = 0.083 g.

Answer: 1.83×10^{-3} g of salicylaldehyde and 0.083 g of dichloroacetic acid

2.18 Concentration

(a)

If the concentration of NaCl added is the same as that already in the tank, the concentration remains constant at 25 mM NaCl.

Answer: 25 mM

(b)

25 mM NaCl means 25×10^{-3} gmol NaCl per litre (Section 2.4.5). Therefore, in the original 1500 l, there are 25×10^{-3} gmol l^{-1} × 1500 l = 37.5 gmol NaCl. After addition of the water, there are 37.5 gmol NaCl in 4500 litres of solution. Therefore, the concentration is 37.5 gmol/4500 l = 8.33×10^{-3} gmol l^{-1} or 8.33 mM.

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Answer: 8.3 mM

(c)

From the calculation in **(b)**, the tank originally contains 37.5 gmol of NaCl. Adding 500 l of 25 mM NaCl increases the amount of NaCl present by 25×10^{-3} gmol $l^{-1} \times 500$ l = 12.5 gmol, making the total amount of NaCl equal to (37.5 gmol + 12.5 gmol) = 50 gmol. After addition of 3000 l of water, these 50 gmol of NaCl are present in (1500 l + 500 l + 3000 l) = 5000 l of solution.

(i)

There are 50 gmol of NaCl present in 5000 l of solution. Therefore, the concentration is 50 gmol/5000 l = 0.01 gmol l^{-1}. As 1 gmol l^{-1} is the same as 1 M (Section 2.4.5), the concentration is 0.01 M.

Answer: 0.01 M

(ii)

% w/v means g per 100 ml of solution (Section 2.4.5) From the atomic weights in Table C.1 (Appendix C), the molecular weight of NaCl is 58.44. Therefore, the mass corresponding to 50 gmol of NaCl is:

$$50 \text{ gmol} = 50 \text{ gmol} \cdot \left| \frac{58.44 \text{ g}}{1 \text{ gmol}} \right| = 2922 \text{ g}$$

This mass of NaCl is present in 5000 l of solution. Therefore, the concentration is 2922 g/5000 l = 0.584 g l^{-1}. 1 l = 1000 ml. In 100 ml or 1/10 of a litre of solution, the mass of NaCl is 0.584 g/10 = 0.0584 g. Therefore, the concentration is 0.0584 g per 100 ml, or 0.0584% w/v.

Answer: 0.0584% w/v

(iii)

From **(ii)**, the concentration of NaCl is 0.584 g l^{-1}. 1 l = 1000 cm^3. Therefore:

$$0.584 \text{ g l}^{-1} = 0.584 \text{ g l}^{-1} \cdot \left| \frac{1 \text{ l}}{1000 \text{ cm}^3} \right| = 5.84 \times 10^{-4} \text{ g cm}^{-3}$$

Answer: 5.84×10^{-4} g cm^{-3}

(iv)

ppm means g per 10^6 g of solution (Section 2.4.5) Because the solution of NaCl is very dilute, we can assume that the density of the solution is the same as the density of water = 1 g cm^{-3} (Section 2.4.1). Therefore, the concentration of NaCl calculated in **(iii)**, 5.84×10^{-4} g cm^{-3}, can be expressed as 5.84×10^{-4} g per g of solution. The mass of NaCl present in 10^6 g of solution is (5.84×10^{-4} g g^{-1}) $\times 10^6$ g = 584 g, so the concentration is 584 g per 10^6 g of solution, or 584 ppm.

Answer: 584 ppm, assuming that the density of the solution is equal to the density of water.

2.19 Gas composition

Gas compositions are expressed as volume % (Section 2.4.5). For relatively light gases such as oxygen, carbon dioxide, ammonia and nitrogen, we can assume that the ideal gas law is valid over the range of conditions applying to bioreactor operation (Section 2.5). This means that the relative partial volumes of the component gases will not change with temperature and pressure, so that the gas composition will be unaffected.

Answer: The composition is unaffected.

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2.20 Specific gravity and composition

A pharmaceutical concentration of 38.6% w/w means 38.6 g in 100 g of solution (Section 2.4.5). If the specific gravity of the solution is 1.036, the density referenced against water at 4°C is 1.036 g cm^{-3} (Section 2.4.2).

(a)

From the definition of density as mass per unit volume (Section 2.4.1), the volume of 100 g of solution = 100 g/(1.036 g cm^{-3}) = 96.53 cm^3. Therefore, the concentration of pharmaceutical is 38.6 g per 96.53 cm^3 of solution, or 38.6 g/(96.53 cm^3) = 0.40 g cm^{-3}. 1 l = 1000 cm^3 and 1 kg = 1000 g. Converting units gives:

$$0.40\text{ g cm}^{-3} = 0.40\text{ g cm}^{-3}\cdot\left|\frac{1000\text{ cm}^3}{1\text{ l}}\right|\cdot\left|\frac{1\text{ kg}}{1000\text{ g}}\right| = 0.40\text{ kg l}^{-1}$$

Answer: 0.40 kg l^{-1}

(b)

The flow rate of pharmaceutical is found by multiplying the solution flow rate by the pharmaceutical concentration:

$$\text{Pharmaceutical flow rate} = 8.6\text{ l min}^{-1}\times 0.40\text{ kg l}^{-1} = 3.44\text{ kg min}^{-1}$$

1 kg = 1000 g. Converting to molar units using the pharmaceutical molecular weight:

$$\text{Pharmaceutical flow rate} = 3.44\text{ kg min}^{-1}\cdot\left|\frac{1000\text{ g}}{1\text{ kg}}\right|\cdot\left|\frac{1\text{ gmol}}{1421\text{ g}}\right| = 2.42\text{ gmol min}^{-1}$$

Answer: 2.42 gmol min^{-1}

2.21 Temperature scales

From Eq. (2.30):

$$-40 = 1.8\,T(°\text{C}) + 32$$

$$T(°\text{C}) = -40$$

From Eq. (2.28):

$$T(°\text{R}) = -40 + 459.67$$

$$T(°\text{R}) = 420$$

From Eq. (2.27) and the result for T(°C):

$$T(\text{K}) = -40 + 273.15$$

$$T(\text{K}) = 233$$

Answer: 40°C, 420°R, 233 K

2.22 Pressure scales

(a)

Assume that the atmospheric (barometric) pressure is 14.7 psi (Section 2.4.7). From Eq. (2.31):

$$\text{Absolute pressure} = 15\text{ psi} + 14.7\text{ psi} = 29.7\text{ psi}$$

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From Table A.5 (Appendix A), 1 psi = 6.805×10^{-2} atm. Therefore:

$$\text{Absolute pressure} = 29.7\ \text{psi}\,.\left|\frac{6.805\times10^{-2}\ \text{atm}}{1\ \text{psi}}\right| = 2.02\ \text{atm}$$

Answer: 29.7 psi, 2.02 atm

(b)

Vacuum pressure is pressure below barometric (Section 2.4.7). If the barometric pressure is 14.7 psi (Section 2.4.7):

$$\text{Absolute pressure} = 14.7\ \text{psi} - 3\ \text{psi} = 11.7\ \text{psi}$$

Answer: 11.7 psi

2.23 Gas leak

The volume of the cylinder does not change as a result of the leak, so $V_1 = V_2 = 48$ l. $P_1 = 0.35$ MPa = 0.35×10^6 Pa. When the cylinder is left open to the atmosphere, $P_2 = 1$ atm. $T_1 = 22$°C; $T_2 = 33$°C. Let us assume that the ideal gas law applies to compressed air under the prevailing conditions (Section 2.5). Temperature in the ideal gas equation is absolute temperature; therefore, using Eq. (2.27), $T_1 = (22 + 273.15)$ K = 295.15 K and $T_2 = (33 + 273.15)$ K = 306.15 K. The ratio of the amounts of air in the tank before and after the leak can be determined using Eq. (2.35):

$$\frac{n_1}{n_2} = \frac{\dfrac{p_1V_1}{RT_1}}{\dfrac{p_2V_2}{RT_2}}$$

Because $V_1 = V_2$, these terms and R can be cancelled to give:

$$\frac{n_1}{n_2} = \frac{p_1T_2}{p_2T_1}$$

From Table A.5 (Appendix A), 1 atm = 1.013×10^5 Pa. Substituting values into the equation:

$$\frac{n_1}{n_2} = \frac{p_1T_2}{p_2T_1} = \frac{0.35\times10^6\ \text{Pa}\,.\left|\dfrac{1\ \text{atm}}{1.013\times10^5\ \text{Pa}}\right|.\,(306.15\ \text{K})}{1\ \text{atm}\ (295.15\ \text{K})} = 3.58$$

or

$$n_2 = 0.28\, n_1$$

The amount of air in the tank after the leak is 28% of that present before the leak. The amount lost is therefore 72%.

Answer: 72%, assuming that the ideal gas law applies

2.24 Gas supply

The flow rate of air required to operate the bioreactor is $0.8 \times 1.5 = 1.2$ l min^{-1}. The amount of air provided to the bioreactor between 4 pm Friday and 9 am Monday, i.e. over a period of 65 hours, can be determined using the ideal gas law with $T = 25$°C and $P = 1$ atm. Temperature in the ideal gas equation is absolute temperature; therefore, using Eq. (2.27), $T = (25 + 273.15)$ K = 298.15 K. From Appendix B, R = 0.082057 l atm gmol^{-1} K^{-1}. Using Eq. (2.35), the amount of air required to operate the bioreactor is:

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$$n = \frac{pV}{RT} = \frac{1\,\text{atm}\,(1.2\,\text{l}\,\text{min}^{-1})\,(65\,\text{h})\,.\left|\frac{60\,\text{min}}{1\,\text{h}}\right|}{0.082057\,\text{l}\,\text{atm}\,\text{gmol}^{-1}\,\text{K}^{-1}\,(298.15\,\text{K})} = 191\,\text{gmol}$$

This amount of air can be compared with the amount available in the gas cylinder. V = 48 l. T = 20°C; using Eq. (2.27), T = (20 + 273.15) K = 293.15 K. If the gauge pressure is 800 psi, the absolute pressure P in the cylinder is (800 + 14.7) psi = 814.7 psi (Section 2.4.7). From Table A.5 (Appendix A), 1 psi = 6.805 × 10^{-2} atm. Applying Eq. (2.35):

$$n = \frac{pV}{RT} = \frac{814.7\,\text{psi}\,.\left|\frac{6.805\times 10^{-2}\,\text{atm}}{1\,\text{psi}}\right|.\,(48\,\text{l})}{0.082057\,\text{l}\,\text{atm}\,\text{gmol}^{-1}\,\text{K}^{-1}(293.15\,\text{K})} = 111\,\text{gmol}$$

Even if the uncertainty factor of 5% is taken into account with respect to the values of n calculated, the amount of air in the cylinder is less than that required to operate the bioreactor over the weekend.

Answer: No

2.25 Stoichiometry and incomplete reaction

(a)

The molecular weights are calculated from Table C.1 (Appendix C): penicillin = 334.4; glucose = 180.2. The maximum theoretical yield from the stoichiometric equation is 1 gmol of penicillin for every 1.67 gmol of glucose. This is equivalent to 334.4 g of penicillin per 1.67 × 180.2 = 300.9 g of glucose, or 334.4 g/300.9 g = 1.1 g g^{-1}.

Answer: 1.1 g g^{-1}

(b)

The maximum theoretical yield in **(a)** is obtained when all the glucose consumed is directed into penicillin production according to the stoichiometric equation. If only 6% of the glucose is used in this way, the amount of penicillin produced for every 300.9 g of glucose consumed is much lower at 334.4 g × 0.06 = 20.06 g. Therefore, the actual yield of penicillin from glucose is 20.06 g/300.9 g = 0.067 g g^{-1}.

Answer: 0.067 g g^{-1}

(c)

From the atomic weights in Table C.1 (Appendix C), the molecular weight of phenylacetic acid is 136.2.

(i)

The only possible limiting substrates are glucose and phenylacetic acid. Using a basis of 1 l of medium, if (50 – 5.5) = 44.5 g of glucose are consumed but only 6% is available for penicillin synthesis, the mass of glucose used in the penicillin reaction is 44.5 × 0.06 = 2.67 g. Converting to gmol of glucose, this is equivalent to 2.67 g/(180.2 g gmol^{-1}) = 1.48 × 10^{-2} gmol of glucose available for penicillin synthesis. At the same time, 4 g or 4 g/(136.2 g gmol^{-1}) = 2.94 × 10^{-2} gmol of phenylacetic acid is available which, according to the stoichiometric equation, requires 1.67 × (2.94 × 10^{-2}) = 4.91 × 10^{-2} gmol of glucose for complete reaction. As the amount of glucose (4.91 × 10^{-2} gmol) required for complete reaction of the phenylacetic acid is greater than the amount of glucose (1.48 × 10^{-2} gmol) available after growth and maintenance activities, glucose is the limiting substrate.

Answer: Glucose

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(ii)

Of the 44.5 g l^{-1} glucose consumed, 24% or 10.7 g l^{-1} is used for growth. In a 100-litre tank, the total mass of glucose consumed for growth is therefore 10.7 g l^{-1} × 100 l = 1070 g, or 1.07 kg.

Answer: 1.07 kg

(iii)

From **(i)**, 1.48×10^{-2} gmol of glucose is used in the penicillin reaction per litre. According to the stoichiometry, this produces $(1.48 \times 10^{-2})/1.67 = 8.86 \times 10^{-3}$ gmol of penicillin per litre. Therefore, in a 100-litre tank, (8.86×10^{-3} gmol l^{-1}) × 100 l = 0.886 gmol of penicillin is formed. Converting to mass, 0.886 gmol × 334.4 g gmol^{-1} = 296 g penicillin are formed.

Answer: 296 g

(iv)

If, from **(i)**, 1.48×10^{-2} gmol glucose is used in the penicillin reaction per litre, from stoichiometry $(1.48 \times 10^{-2})/1.67 = 8.86 \times 10^{-3}$ gmol l^{-1} phenylacetic acid must also be used. Converting from moles to mass, this is equivalent to 8.86×10^{-3} gmol l^{-1} × 136.2 g gmol^{-1} = 1.21 g l^{-1} phenylacetic acid. As 4 g l^{-1} phenylacetic acid is provided, (4 – 1.21) g l^{-1} = 2.79 g l^{-1} phenylacetic acid must remain.

Answer: 2.79 g l^{-1}

2.26 Stoichiometry, yield, and the ideal gas law

(a)

Adding up the numbers of C, H, O and N atoms on both sides of the equation shows that the equation is balanced: C (16 = 16), H (38.3 = 38.3), O (32.6 = 32.6), N (1.42 = 1.42).

Answer: Yes

(b)

The molecular weights are calculated from Table C.1 (Appendix C): cells = 91.5; hexadecane = 226.4. From the stoichiometry, as 1 gmol of hexadecane is required to produce 1.65 gmol of cells, the maximum yield is 1.65 gmol × 91.5 g gmol^{-1} = 151 g cells per 226.4 g hexadecane, or 151 g/226.4 g = 0.67 g g^{-1}.

Answer: 0.67 g g^{-1}

(c)

From the atomic weights in Table C.1 (Appendix C), the molecular weight of oxygen is 32.0. From the stoichiometry, 16.28 gmol of oxygen is required to produce 1.65 gmol of cells which, from **(b)**, is equal to 151 g of cells. The maximum yield is therefore 151 g of cells per (16.28 gmol × 32.0 g gmol^{-1}) = 521 g oxygen, or 151 g/521 g = 0.29 g g^{-1}.

Answer: 0.29 g g^{-1}

(d)

2.5 kg = 2500 g. Converting to molar terms using the cell molecular weight from **(b)**, 2500 g = 2500 g/(91.5 g gmol^{-1}) = 27.3 gmol cells. The minimum amounts of substrates are required when 100% of the hexadecane is converted according to the stoichiometric equation.

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(i)

From the stoichiometry, production of 27.3 gmol of cells requires 27.3/1.65 = 16.5 gmol of hexadecane. Converting to mass terms using the molecular weight of hexadecane, 16.5 gmol = 16.5 gmol × 226.4 g gmol^{-1} = 3736 g = 3.74 kg of hexadecane.

Answer: 3.74 kg

(ii)

From the answer in **(d)(i)**, the concentration of hexadecane required is 3.74 kg in 3 m^3, or 1.25 kg m^{-3}.

Answer: 1.25 kg m^{-3}

(iii)

According to the stoichiometric equation, production of 27.3 gmol of cells requires 27.3 × 16.28/1.65 = 269.4 gmol of oxygen. As air contains approximately 21 mol% oxygen (Section 2.4.5), the moles of air required is 269.4/0.21 = 1282.9 gmol. The corresponding volume of air is calculated using the ideal gas law. From Eq. (2.35):

$$V = \frac{nRT}{p}$$

P = 1 atm; T = 20°C. As temperature in the ideal gas equation is absolute temperature, from Eq. (2.27):

$$T = (20 + 273.15)\ \text{K} = 293.15\ \text{K}$$

From Appendix B, R = 82.057 cm^3 atm K^{-1} gmol^{-1}. 1 m = 100 cm. Substituting these values into the equation for V:

$$V = \frac{(1282.9\ \text{gmol})(82.057\ \text{cm}^3\ \text{atm K}^{-1}\ \text{gmol}^{-1})(293.15\ \text{K})}{1\ \text{atm}} \cdot \left|\frac{1\ \text{m}}{100\ \text{cm}}\right|^3 = 31\ \text{m}^3$$

Answer: 31 m^3

2.27 Stoichiometry and the ideal gas law

(a)

Adding up the numbers of C, H, O and N atoms on both sides of the equation shows that the equation is balanced: C (6 = 6), H (12.6 ≈ 12.7), O (13.3 = 13.3), N (0.33 = 0.33)

Answer: Yes

(b)

From Table C.1 (Appendix C), the molecular weights are: glucose = 180.2; HNO_3 = 63.0; biomass 28.3. Converting to molar units, the concentration of glucose is 30 g l^{-1}/(180.2 g gmol^{-1}) = 0.166 gmol l^{-1}. From the stoichiometry, this requires 0.18 × 0.166 gmol l^{-1} = 0.030 gmol l^{-1} of HNO_3 for complete conversion.

Answer: 0.030 gmol l^{-1}

(c)

From the glucose concentration calculated in **(b)**, the gmol of glucose present in 50 l is 0.166 gmol l^{-1} × 50 l = 8.30 gmol. According to the stoichiometry, complete conversion of 8.30 gmol of glucose produces 2.5 × 8.30 gmol = 20.75 gmol of biomass. Converting to mass units using the molecular weight of the biomass, 20.75 gmol × 28.3 g gmol^{-1} = 587 g of biomass are produced.

Answer: 587 g

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(d)

According to the stoichiometric equation, complete conversion of 8.30 gmol of glucose requires 3.4 × 8.30 = 28.2 gmol of oxygen. The volume of oxygen required can be calculated using the ideal gas law with P = 1 atm. As temperature in the ideal gas equation is absolute temperature, 20°C is converted to K using Eq. (2.27):

$$T = (20 + 273.15)\text{ K} = 293.15\text{ K}$$

From Appendix B, R = 0.000082057 m^3 atm K^{-1} gmol^{-1}. Using Eq. (2.35), the volume of oxygen required is:

$$V = \frac{nRT}{p} = \frac{(28.2\text{ gmol})(0.000082057\text{ m}^3\text{ atm K}^{-1}\text{ gmol}^{-1})(293.15\text{ K})}{1\text{ atm}} = 0.678\text{ m}^3$$

Air contains approximately 21 volume % oxygen (Section 2.4.5). Therefore, the volume of air required is 0.678 m^3/0.21 = 3.2 m^3.

Answer: 3.2 m^3

2.28 Stoichiometry, yield, and limiting substrate

(a)

Adding up the numbers of C, H and O atoms and the charges on both sides of the equation shows that the equation is balanced: C (10 = 10), H (20 = 20), O (34 = 34), charge (–8 = –8).

Answer: Yes

(b)

From Table C.1 (Appendix C), the molecular weights are N_2 = 28.0 and acetate (≈ acetic acid) = 60.1. According to the stoichiometry, the yield is 4 gmol of N_2 for every 5 gmol of acetate consumed. Converting to mass units using the molecular weights, the yield is (4 × 28.0 g N_2)/(5 × 60.1 g acetate) = 0.37 g g^{-1}.

Answer: 0.37 g g^{-1}

(c)

Effectively, 0.75 × 6 mM = 4.5 mM of acetic acid and 0.85 × 7 mM = 5.95 mM of nitrate are available for the denitrification reaction. From the reaction stoichiometry, 8 mol of nitrate are required for every 5 mol of acetic acid consumed. Therefore, complete reaction of 4.5 mM acetic acid requires 4.5 mM × 8/5 = 7.2 mM nitrate. As only 5.95 mM nitrate is available, nitrate is the limiting substrate.

Answer: Nitrate

(d)

The conversion is based on the amount of limiting substrate available. From **(c)**, nitrate is the limiting substrate and 5.95 mM of nitrate is available for the denitrification reaction. Therefore, in 5000 l, the total amount of nitrate converted in the reaction is 5.95 × 10^{-3} gmol l^{-1} × 5000 l = 29.75 gmol. According to the stoichiometry, for each 8 gmol of nitrate reacted, 4 gmol of N_2 are formed. Therefore, conversion of 29.75 gmol of nitrate produces 29.75 × 4/8 = 14.88 gmol of N_2. Converting to mass units using the molecular weight of N_2, the mass of N_2 produced is 14.88 gmol × 28.0 g gmol^{-1} = 416.6 g.

Answer: 417 g

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2.29 Order-of-magnitude calculation

rpm means revolutions per minute. As revolutions is a non-dimensional quantity (Section 2.1.2), the units of rpm are min^{-1}. Therefore:

$$12{,}000\ \text{min}^{-1} = 12{,}000\ \text{min}^{-1}\cdot\left|\frac{1\ \text{min}}{60\ \text{s}}\right| = 200\ \text{s}^{-1}$$

$\pi = 3.14159$. From Eq. (2.16), $g = 9.8066\ \text{m s}^{-2}$. The equation for Σ using the actual data is:

$$\Sigma = \frac{3.14159\,(200\ \text{s}^{-1})^2\,(1.25\ \text{m})\,(0.37\ \text{m})^2}{2\,(9.8066\ \text{m s}^{-2})}$$

Using approximate values, this becomes:

$$\Sigma = \frac{3\,(200)^2\,(1)\,(0.4)^2\ \text{m}^3\ \text{s}^{-2}}{2\,(10)\ \text{m s}^{-2}} = 960\ \text{m}^2$$

This result is closer to 1000 m^2 than to 100 m^2.

Answer: 1000 m^2

2.30 Order-of-magnitude calculation

$\pi = 3.14159$. The equation for r^*_{As} using the actual data is:

$$r^*_{\text{As}} = \frac{4}{3}(3.14159)\,(3.2\times10^{-3})^3\ \text{m}^3\ \frac{(0.12\ \text{gmol s}^{-1}\ \text{m}^{-3})(41\ \text{gmol m}^{-3})}{(0.8+41)\ \text{gmol m}^{-3}}$$

Using approximate values, this becomes:

$$r^*_{\text{As}} = \frac{4}{3}(3)(30\times10^{-9})\frac{(4)}{(40)}\ \text{gmol s}^{-1} = 120\times10^{-10}\ \text{gmol s}^{-1} = 1.2\times10^{-8}\ \text{gmol s}^{-1}$$

This result indicates that the student reporting the value 1.6×10^{-8} gmol s^{-1} is more likely to be correct.

Answer: 1.6×10^{-8} gmol s^{-1}