Problem 1.1 [Difficulty 2]

1.1 Describe the conditions for which the following substances can be considered liquids.

Tar	Honey	Wax	Propane
Carbon dioxide	Sea water	Sand	Toothpaste

Given: Substances
Find: Conditions for which the substances can be considered liquids
Solution:
Tar and Wax behave as solids at room temperature or below at ordinary pressures. At high pressures or higher temperatures they become viscous fluids.
Honey behaves can behave as a liquid or a solid when it crystalizes
Propane behaves as a liquid at high pressure and a gas at low pressure.
Carbon dioxide behaves as a solid or a gas at room pressure and a liquid at high pressure)
Sea water behaves as a liquid above its freezing point (about 30 F)
Toothpaste behaves as a solid in the tube and becomes a liquid at hig pressure when the tube is squeezed
Sand acts solid when at rest a liquid when it moves.

Problem 1.2

[Difficulty: 2]

1.2 Give a word statement of each of the five basic conservation laws stated in Section 1.2 as they apply to a system.

Given: Five basic conservation laws stated in Section 1.2

Write: A word statement of each, as they apply to a system.

Solution: Assume that laws are to be written for a *system*.

a. Conservation of mass — The mass of a system is constant by definition.

b. Newton's second law of motion — The net force acting on a system is directly proportional to the product of the system mass times its acceleration.

c. First law of thermodynamics — The change in stored energy of a system equals the net energy added to the system as heat and work.

d. Second law of thermodynamics — The entropy of any isolated system cannot decrease during any process between equilibrium states.

e. Principle of angular momentum — The net torque acting on a system is equal to the rate of change of angular momentum of the system.

Problem 1.3

[Difficulty: 3]

1.3 The barrel of a bicycle tire pump becomes quite warm during use. Explain the mechanisms responsible for the temperature increase.

Open-Ended Problem Statement: The barrel of a bicycle tire pump becomes quite warm during use. Explain the mechanisms responsible for the temperature increase.

Discussion: Two phenomena are responsible for the temperature increase: (1) friction between the pump piston and barrel and (2) temperature rise of the air as it is compressed in the pump barrel.

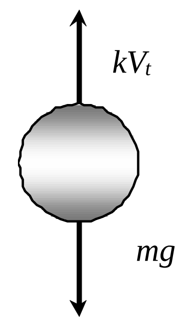
Friction between the pump piston and barrel converts mechanical energy (force on the piston moving through a distance) into thermal energy as a result of friction. Lubricating the piston helps to provide a good seal with the pump barrel and reduces friction (and therefore force) between the piston and barrel.

Temperature of the trapped air rises as it is compressed. The compression is not adiabatic because it occurs during a finite time interval. Heat is transferred from the warm compressed air in the pump barrel to the cooler surroundings. This raises the temperature of the barrel, making its outside surface warm (or even hot!) to the touch.

Problem 1.4

[Difficulty: 3]

1.4 In a pollution control experiment, minute solid particles (typical mass 1×10^{-13} slug) are dropped in air. The terminal speed of the particles is measured to be 0.2 ft/s. The drag of these particles is given by $F_D = kV$, where V is the instantaneous particle speed. Find the value of the constant k. Find the time required to reach 99 percent of terminal speed.



Given: Data on sphere and terminal speed.

Find: Drag constant k, and time to reach 99% of terminal speed.

Solution: Use given data; integrate equation of motion by separating variables.

The data provided are: $M = 1 \times 10^{-13} \cdot \text{slug} \quad V_t = 0.2 \cdot \frac{\text{ft}}{\text{s}}$

Newton's 2nd law for the general motion is (ignoring buoyancy effects) $M \cdot \frac{dV}{dt} = M \cdot g - k \cdot V \quad (1)$

Newton's 2nd law for the steady state motion becomes (ignoring buoyancy effects) $M \cdot g = k \cdot V_t$ so $k = \frac{M \cdot g}{V_t}$

$$k = 1 \times 10^{-13} \cdot \text{slug} \times 32.2 \cdot \frac{\text{ft}}{\text{s}^2} \times \frac{\text{s}}{0.2 \cdot \text{ft}} \times \frac{\text{lbf} \cdot \text{s}^2}{\text{slug} \cdot \text{ft}} \qquad k = 1.61 \times 10^{-11} \cdot \frac{\text{lbf} \cdot \text{s}}{\text{ft}}$$

To find the time to reach 99% of V_t, we need $V(t)$. From 1, separating variables $\frac{dV}{g - \frac{k}{M} \cdot V} = dt$

Integrating and using limits $t = -\frac{M}{k} \cdot \ln\left(1 - \frac{k}{M \cdot g} \cdot V\right)$

We must evaluate this when $V = 0.99 \cdot V_t \qquad V = 0.198 \cdot \frac{\text{ft}}{\text{s}}$

$$t = -1 \times 10^{-13} \cdot \text{slug} \times \frac{\text{ft}}{1.61 \times 10^{-11} \cdot \text{lbf} \cdot \text{s}} \times \frac{\text{lbf} \cdot \text{s}^2}{\text{slug} \cdot \text{ft}} \cdot \ln\left(1 - 1.61 \times 10^{-11} \cdot \frac{\text{lbf} \cdot \text{s}}{\text{ft}} \times \frac{1}{1 \times 10^{-13} \cdot \text{slug}} \times \frac{\text{s}^2}{32.2 \cdot \text{ft}} \times \frac{0.198 \cdot \text{ft}}{\text{s}} \times \frac{\text{slug} \cdot \text{ft}}{\text{lbf} \cdot \text{s}^2}\right)$$

$t = 0.0286\,\text{s}$

Problem 1.5 [Difficulty 2]

1.5 A rocket payload with a weight on earth of 2000 lbf is sent to the moon. The acceleration due to gravity in the moon is 1/6th that of the earth. Determine the mass of the payload on the earth and on the moon and the weight of the payload on the moon in SI, BG, EE units.

Given: Rocket payload weight on earth $W_e = 2000\ lbf$. The acceleration due to the moon's gravity $g_m \approx \frac{g_e}{6}$.

Find: The mass of payload on earth M_e and on moon M_m in SI, BG, EE units . The payload's moon weight W_m.

Solution:

Basic equation: Newton's law applied to mass and weight

$$M = \frac{W}{g}$$

Gravity on the moon relative to that on Earth:

$$g_m \approx \frac{g_e}{6}$$

The value of gravity is:

$$g_e = 32.2\ \frac{ft}{s^2}$$

The mass on earth is:

$$M_e = \frac{W_e}{g_e} = \frac{2000\ lbf}{32.2\ \frac{ft}{s^2}.} = 62.1\ slug$$

The mass on moon is the same as it on earth:

$$M_m = 62.1\ slug$$

The weight on the moon is then in BG units:

$$W_m = M_m g_m = M_m\left(\frac{g_e}{6}\right) = M_e\left(\frac{g_e}{6}\right) = \frac{W_e}{6} = 333\ lbf$$

The weight in EE units is the same as in BG units, or

$$W_m = 333\, lbf$$

In SI units, the conversion of the weight from lbf to Newtons yields the weight as

$$W_m = 333\, lbf \cdot \frac{4.444\, N}{lbf} = 1480\, N$$

Problem 1.6

[Difficulty: 3]

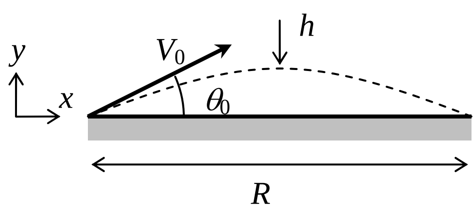
1.6 The English perfected the longbow as a weapon after the Medieval period. In the hands of a skilled archer, the longbow was reputed to be accurate at ranges to 100 m or more. If the maximum altitude of an arrow is less than $h = 10$ m while traveling to a target 100 m away from the archer, and neglecting air resistance, estimate the speed and angle at which the arrow must leave the bow. Plot the required release speed and angle as a function of height h.

Given: Long bow at range, R = 100 m. Maximum height of arrow is h = 10 m. Neglect air resistance.

Find: Estimate of (a) speed, and (b) angle, of arrow leaving the bow.

Plot: (a) release speed, and (b) angle, as a function of h

Solution: Let $\vec{V_0} = u_0\hat{i} + v_0\hat{j} = V_0(\cos\theta_0\hat{i} + \sin\theta_0\hat{j})$



$\Sigma F_y = m\frac{dv}{dt} = -mg$, so $v = v_0 - gt$, and $t_f = 2t_{v=0} = 2v_0/g$

Also, $$mv\frac{dv}{dy} = -mg,\ v\,dv = -g\,dy,\ 0 - \frac{v_0^2}{2} = -gh$$

Thus $$h = v_0^2/2g \qquad (1)$$

$$\Sigma F_x = m\frac{du}{dt} = 0,\ \text{so } u = u_0 = \text{const, and } R = u_0 t_f = \frac{2u_0 v_0}{g} \qquad (2)$$

From Eq. 1: $v_0^2 = 2gh$ (3)

From Eq. 2: $$u_0 = \frac{gR}{2v_0} = \frac{gR}{2\sqrt{2gh}} \qquad \therefore\ u_0^2 = \frac{gR^2}{8h}$$

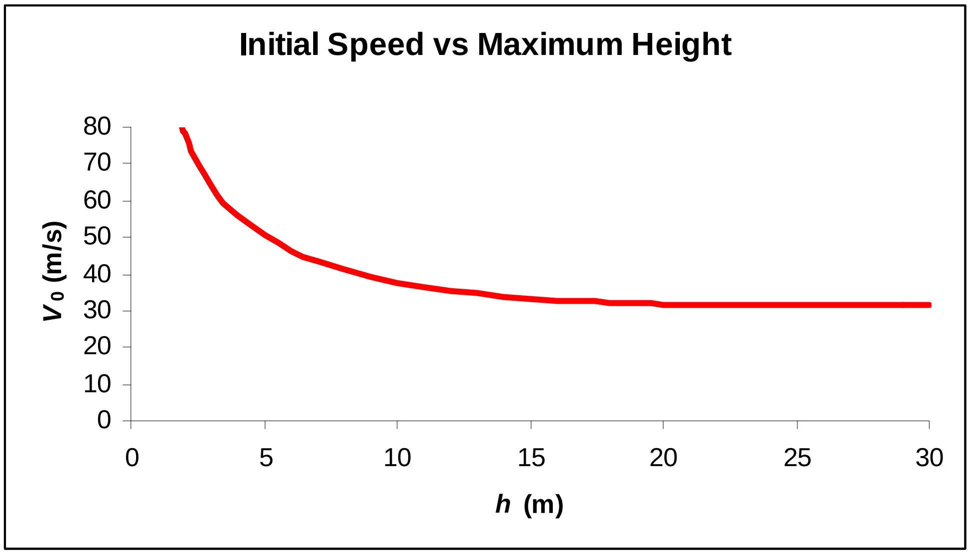
Then $$V_0^2 = u_0^2 + v_0^2 = \frac{gR^2}{8h} + 2gh \quad \text{and} \quad V_0 = \left(2gh + \frac{gR^2}{8h}\right)^{\frac{1}{2}} \qquad (4)$$

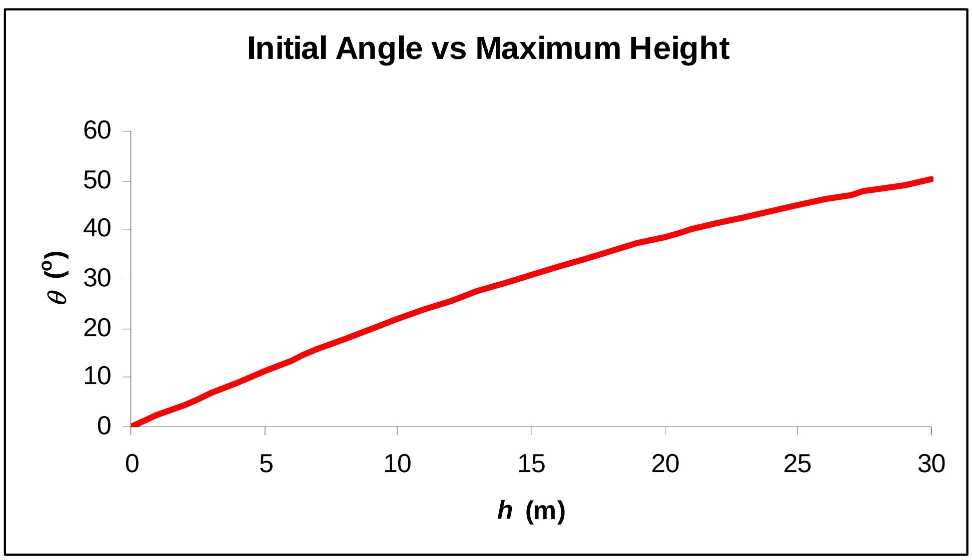
$$V_0 = \left(2 \times 9.81\frac{m}{s^2} \times 10\text{ m} + \frac{9.81}{8}\frac{m}{s^2} \times 100^2\text{ m}^2 \times \frac{1}{10\text{ m}}\right)^{\frac{1}{2}} = 37.7\frac{m}{s}$$

From Eq. 3: $$v_0 = \sqrt{2gh} = V_0 \sin\theta,\ \theta = \sin^{-1}\frac{\sqrt{2gh}}{V_0} \qquad (5)$$

$$\theta = \sin^{-1}\left[\left(2\times 9.81\frac{\text{m}}{\text{s}^2}\times 10\text{ m}\right)^{\frac{1}{2}}\times\frac{\text{s}}{37.7\text{ m}}\right] = 21.8°$$

Plots of $V_0 = V_0(h)$ (Eq. 4) and $\theta_0 = \theta_0(h)$ (Eq. 5) are presented below:





Problem 1.7 [Difficulty 2]

1.7 Air at standard atmospheric conditions enters the 6 in. diameter inlet of an air compressor at a velocity of 20 ft/s. The air is compressed and leaves the compressor through a 6 in. diameter outlet at 80 psia and 150 °F. Determine the mass flow rate of the air and the exit velocity.

Given Air at standard atmospheric conditions, V = 20 ft/s.

Find Mass flow rate of air and exit velocity

Solution: The mass flow rate is given by the continuity equation

$$\dot{m} = \rho A V$$

The density at standard conditions is taken from Table A.9 as $\rho = 0.00238 \frac{slug}{ft^3}$

The flow area is

$$A = \pi \frac{D^2}{4} = \pi \cdot \frac{(0.5\, ft)^2}{4} = 0.1963\, ft^2$$

The mass flow rate is then

$$\dot{m} = \rho A V = 0.00238 \frac{slug}{ft^3} \cdot 0.1963\, ft^2 \cdot 20 \frac{ft}{s} = 0.00935 \frac{slug}{s}$$

To determine the velocity at the exit, we need the density of air at 80 psia and 150 F. The ideal gas equation of state (Eq. 1.1) is used

$$\rho = \frac{p}{RT} = \frac{80 \frac{lbf}{in^2} \cdot \frac{144 in}{ft^2}}{53.33 \frac{ft \cdot lbf}{lbm \cdot R} \cdot (150 + 459.6) R} \cdot \frac{slug}{32.2\, lbm} = 0.01101 \frac{slug}{ft^3}$$

The exit velocity is then found using the continuity equation, where the outlet area equals the inlet area

$$V = \frac{\dot{m}}{\rho A} = \frac{0.00935 \frac{slug}{s}}{0.01101 \frac{slug}{ft^3} \cdot 0.1963 ft^2} = 4.32 \frac{ft}{s}$$

Problem 1.8 [Difficulty 2]

1.8 A water flow of 4.50 slug/s at 60 ºF enters the condenser of steam turbine and leaves at 140 ºF. Determine the heat transfer rate (Btu/hr) and the entropy change per slug of water.

Given: Condenser with water flow of 4500 slug/s entering at 60 ºF, leaving at 140 ºF.

Find: Heat transfer rate and entropy change of water

Solution: The heat transfer is determined using the energy equation

$$Q = \dot{m}\left(h_o - h_i\right)$$

For water, the enthalpy difference for a constant pressure process is

$$\left(h_o - h_i\right) = c\left(T_o - T_i\right)$$

The heat transfer is then

$$Q = \dot{m}\left(h_o - h_i\right) = \dot{m}c\left(T_o - T_i\right) = 4.50\frac{slug}{s}\cdot 1.00\frac{Btu}{lbm\cdot F}\left(140-60\right)F\cdot 32.2\frac{lbm}{slug}\cdot 3600\frac{s}{hr}$$

$$= 41.8x10^6\,\frac{Btu}{hr}$$

Problem 1.9

(Difficulty: 1)

1.9 Determine the weight (N) and specific volume of a cubic meter of air at 101 kPa and 15 °C. Determine the specific volume if the air is cooled to −10 °C at constant pressure.

Given: Specific weight $\gamma = 12.0\ \frac{N}{m^3}$ at $101\ kPa$ and 15 °C.

Find: The specific volume v at 101 kPa and 15 °C. Also the specific volume v at 101 kPa and -10 °C.

Assume: Air can be treated as an ideal gas

Solution:

Basic equation: ideal gas law:

$$pv = RT$$

The specific volume is equal to the reciprocal of the specific weight divided by gravity

$$v_1 = \frac{g}{\gamma}$$

Using the value of gravity in the SI units, the specific volume is

$$v_1 = \frac{g}{\gamma} = \frac{9.81\ \frac{m}{s^2}}{12.0\ N} = 0.818\ \frac{m^3}{kg}$$

The temperature conditions are

$$T_1 = 15\text{ °C} = 288\ K, \qquad T_2 = -10\text{ °C} = 263K$$

For v_2 at the same pressure of 101 kPa and cooled to -10 °C we have, because the gas constant is the same at both pressures:

$$\frac{v_1}{v_2} = \frac{\frac{RT_1}{p}}{\frac{RT_2}{p}} = \frac{T_1}{T_2}$$

So the specific volume is

$$v_2 = v_1 \frac{T_2}{T_1} = 0.818 \frac{m^3}{kg} \times \frac{263\ K}{288\ K} = 0.747\ \frac{m^3}{kg}$$

Problem 1.10

(Difficulty: 2)

1.10 Determine the specific weight, specific volume, and density of air at 40°F and 50 psia in BG units. Determine the specific weight, specific volume, and density when the air is then compressed isentropically to 100 psia.

Determine the specific weight, specific volume, and density of air at 40°F and 50 psia in BG units. Determine the specific weight, specific volume, and density when the air is then compressed isentropically to 100 psia.

Given: Air temperature: 40°F, Air pressure 50 psia.

Find: The specific weight, specific volume and density at 40°F and 50 psia and the values at 100 psia after isentropic compression.

Assume: Air can be treated as an ideal gas

Solution:

Basic equation: $pv = RT$

The absolute temperature is

$$T_1 = 40°\text{F} = 500°R$$

The gas constant is

$$R = 1715\ \frac{ft \cdot lbf}{slug \cdot °R}$$

The specific volume is:

$$v_1 = \frac{RT_1}{p} = \frac{1715\ \frac{ft \cdot lbf}{slug \cdot °R}}{50psia \times \frac{144in^2}{ft^2}} \times 500°R = 119.1\ \frac{ft^3}{slug}$$

The density is the reciprocal of the specific volume

$$\rho_1 = \frac{1}{v_1} = 0.0084\ \frac{slug}{ft^3}$$

Using Newton's second law, the specific weight is the density times gravity:

$$\gamma_1 = \rho g = 0.271\ \frac{lbf}{ft^3}$$

For the isentropic compression of air to 100 psia, we have the relation for entropy change of an ideal gas:

$$s_2 - s_1 = c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1}$$

The definition of an isentropic process is

$$s_2 = s_1$$

Solving for the temperature ratio

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{R/c_p}$$

The values of R and specific heat are

$$R = 1715\ \frac{ft \cdot lbf}{slug \cdot {}^\circ R} = 53.3\ \frac{ft \cdot lbf}{lb \cdot {}^\circ R} = 0.0686\ \frac{Btu}{lb \cdot {}^\circ R}$$

$$c_p = 0.24\frac{Btu}{lbm\ R}$$

The temperature after compression to 100 psia is

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{R/c_p} = 500\ R\left(\frac{100\ psia}{50\ psia}\right)^{0.0686/0.24} = 610\ {}^\circ R$$

$$p_2 = 100\ psia = 14400\frac{lbf}{ft^2}$$

The specific volume is computed using the ideal gas law:

$$v_2 = \frac{RT_2}{p_2} = \frac{1715\ \dfrac{ft \cdot lbf}{slug \cdot {}^\circ R}}{100psia \times \dfrac{144in^2}{ft^2}} \times 610.00{}^\circ R = 72.6\ \frac{ft^3}{slug}$$

The density is the reciprocal of the specific volume

$$\rho_2 = \frac{1}{v_2} = 0.0138\ \frac{slug}{ft^3}$$

The specific weight is:

$$\gamma_2 = \rho_2 g = 0.444\ \frac{lbf}{ft^3}$$

Problem 1.11

[Difficulty: 2]

1.11 For each quantity listed, indicate dimensions using mass as a primary dimension, and give typical SI and English units:

(a) Power
(b) Pressure
(c) Modulus of elasticity
(d) Angular velocity
(e) Energy
(f) Moment of a force
(g) Momentum
(h) Shear stress
(i) Strain
(j) Angular momentum

Given: Basic dimensions M, L, t and T.

Find: Dimensional representation of quantities below, and typical units in SI and English systems.

Solution:

(a) Power

$$\text{Power} = \frac{\text{Energy}}{\text{Time}} = \frac{\text{Force} \times \text{Distance}}{\text{Time}} = \frac{F \cdot L}{t}$$

From Newton's 2nd law $\quad \text{Force} = \text{Mass} \times \text{Acceleration} \quad$ so $\quad F = \frac{M \cdot L}{t^2}$

Hence $\quad \text{Power} = \frac{F \cdot L}{t} = \frac{M \cdot L \cdot L}{t^2 \cdot t} = \frac{M \cdot L^2}{t^3} \qquad \frac{kg \cdot m^2}{s^3} \qquad \frac{slug \cdot ft^2}{s^3}$

(b) Pressure $\quad \text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{F}{L^2} = \frac{M \cdot L}{t^2 \cdot L^2} = \frac{M}{L \cdot t^2} \qquad \frac{kg}{m \cdot s^2} \qquad \frac{slug}{ft \cdot s^2}$

(c) Modulus of elasticity $\quad \text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{F}{L^2} = \frac{M \cdot L}{t^2 \cdot L^2} = \frac{M}{L \cdot t^2} \qquad \frac{kg}{m \cdot s^2} \qquad \frac{slug}{ft \cdot s^2}$

(d) Angular velocity $\quad \text{AngularVelocity} = \frac{\text{Radians}}{\text{Time}} = \frac{1}{t} \qquad \frac{1}{s} \qquad \frac{1}{s}$

(e) Energy $\quad \text{Energy} = \text{Force} \times \text{Distance} = F \cdot L = \frac{M \cdot L \cdot L}{t^2} = \frac{M \cdot L^2}{t^2} \qquad \frac{kg \cdot m^2}{s^2} \qquad \frac{slug \cdot ft^2}{s^2}$

(f) Moment of a force $\quad \text{MomentOfForce} = \text{Force} \times \text{Length} = F \cdot L = \frac{M \cdot L \cdot L}{t^2} = \frac{M \cdot L^2}{t^2} \qquad \frac{kg \cdot m^2}{s^2} \qquad \frac{slug \cdot ft^2}{s^2}$

(g) Momentum $\quad \text{Momentum} = \text{Mass} \times \text{Velocity} = M \cdot \frac{L}{t} = \frac{M \cdot L}{t} \qquad \frac{kg \cdot m}{s} \qquad \frac{slug \cdot ft}{s}$

(h) Shear stress $\quad \text{ShearStress} = \frac{\text{Force}}{\text{Area}} = \frac{F}{L^2} = \frac{M \cdot L}{t^2 \cdot L^2} = \frac{M}{L \cdot t^2} \qquad \frac{kg}{m \cdot s^2} \qquad \frac{slug}{ft \cdot s^2}$

(i) Strain $\quad \text{Strain} = \frac{\text{LengthChange}}{\text{Length}} = \frac{L}{L} \qquad$ Dimensionless

(j) Angular momentum $\quad \text{AngularMomentum} = \text{Momentum} \times \text{Distance} = \frac{M \cdot L}{t} \cdot L = \frac{M \cdot L^2}{t} \qquad \frac{kg \cdot m^2}{s} \qquad \frac{slugs \cdot ft^2}{s}$

Problem 1.12

[Difficulty: 2]

1.12 For each quantity listed, indicate dimensions using force as a primary dimension, and give typical SI and English units:
(a) Power
(b) Pressure
(c) Modulus of elasticity
(d) Angular velocity
(e) Energy
(f) Momentum
(g) Shear stress
(h) Specific heat
(i) Thermal expansion coefficient
(j) Angular momentum

Given: Basic dimensions F, L, t and T.

Find: Dimensional representation of quantities below, and typical units in SI and English systems.

Solution:

(a) Power $\quad \text{Power} = \dfrac{\text{Energy}}{\text{Time}} = \dfrac{\text{Force} \times \text{Distance}}{\text{Time}} = \dfrac{F \cdot L}{t} \qquad \dfrac{N \cdot m}{s} \qquad \dfrac{lbf \cdot ft}{s}$

(b) Pressure $\quad \text{Pressure} = \dfrac{\text{Force}}{\text{Area}} = \dfrac{F}{L^2} \qquad \dfrac{N}{m^2} \qquad \dfrac{lbf}{ft^2}$

(c) Modulus of elasticity $\quad \text{Pressure} = \dfrac{\text{Force}}{\text{Area}} = \dfrac{F}{L^2} \qquad \dfrac{N}{m^2} \qquad \dfrac{lbf}{ft^2}$

(d) Angular velocity $\quad \text{AngularVelocity} = \dfrac{\text{Radians}}{\text{Time}} = \dfrac{1}{t} \qquad \dfrac{1}{s} \qquad \dfrac{1}{s}$

(e) Energy $\quad \text{Energy} = \text{Force} \times \text{Distance} = F \cdot L \qquad N \cdot m \qquad lbf \cdot ft$

(f) Momentum $\quad \text{Momentum} = \text{Mass} \times \text{Velocity} = M \cdot \dfrac{L}{t}$

From Newton's 2nd law $\quad \text{Force} = \text{Mass} \times \text{Acceleration} \quad$ so $\quad F = M \cdot \dfrac{L}{t^2} \quad$ or $\quad M = \dfrac{F \cdot t^2}{L}$

Hence $\quad \text{Momentum} = M \cdot \dfrac{L}{t} = \dfrac{F \cdot t^2 \cdot L}{L \cdot t} = F \cdot t \qquad N \cdot s \qquad lbf \cdot s$

(g) Shear stress $\quad \text{ShearStress} = \dfrac{\text{Force}}{\text{Area}} = \dfrac{F}{L^2} \qquad \dfrac{N}{m^2} \qquad \dfrac{lbf}{ft^2}$

(h) Specific heat $\quad \text{SpecificHeat} = \dfrac{\text{Energy}}{\text{Mass} \times \text{Temperature}} = \dfrac{F \cdot L}{M \cdot T} = \dfrac{F \cdot L}{\left(\dfrac{F \cdot t^2}{L}\right) \cdot T} = \dfrac{L^2}{t^2 \cdot T} \qquad \dfrac{m^2}{s^2 \cdot K} \qquad \dfrac{ft^2}{s^2 \cdot R}$

(i) Thermal expansion coefficient $\quad \text{ThermalExpansionCoefficient} = \dfrac{\dfrac{\text{LengthChange}}{\text{Length}}}{\text{Temperature}} = \dfrac{1}{T} \qquad \dfrac{1}{K} \qquad \dfrac{1}{R}$

(j) Angular momentum $\quad \text{AngularMomentum} = \text{Momentum} \times \text{Distance} = F \cdot t \cdot L \qquad N \cdot m \cdot s \qquad lbf \cdot ft \cdot s$

Problem 1.13 [Difficulty 2]

1.13 The maximum theoretical flow rate (slug/s) for air flow through a supersonic nozzle is given as $\dot{m} = 2.38 \dfrac{A_t p_0}{\sqrt{T_0}}$, where A_t is the nozzle throat area (ft^2), p_0 is the supply tank pressure (psia), and T_0 is the air temperature in the tank (°R). Determine the dimensions and units of the constant 2.38. Determine the equivalent equation in SI units.

Given: Equation for maximum flow rate.

Find: Whether it is dimensionally correct. If not, find units of 2.38 coefficient. Write a SI version of the equation

Solution: Rearrange equation to check units of 0.04 term. Then use conversions from Table or other sources (e.g., Google)

"Solving" the equation for the constant 2.38: $2.38 = \dfrac{m_{max}\sqrt{T_0}}{A_t \cdot p_0}$

Substituting the units of the terms on the right, the units of the constant are

$$\frac{slug}{s} \times R^{\frac{1}{2}} \times \frac{1}{ft^2} \times \frac{1}{psi} = \frac{slug}{s} \times R^{\frac{1}{2}} \times \frac{1}{ft^2} \times \frac{in^2}{lbf} \times \frac{lbf \cdot s^2}{slug \cdot ft} = \frac{R^{\frac{1}{2}} \cdot in^2 \cdot s}{ft^3}$$

Hence the constant is actually $c = 2.38 \cdot \dfrac{R^{\frac{1}{2}} \cdot in^2 \cdot s}{ft^3}$

For BG units we could start with the equation and convert each term (e.g., A_t), and combine the result into a new constant, or simply convert c directly:

$$c = 2.38 \cdot \frac{R^{\frac{1}{2}} \cdot in^2 \cdot s}{ft^3} = 2.38 \cdot \frac{R^{\frac{1}{2}} \cdot in^2 \cdot s}{ft^3} \times \left(\frac{K}{1.8 \cdot R}\right)^{\frac{1}{2}} \times \left(\frac{1 \cdot ft}{12 \cdot in}\right)^2 \times \frac{1 \cdot ft}{0.3048 m}$$

$$c = 0.04 \cdot \frac{K^{\frac{1}{2}} \cdot s}{m} \qquad \text{so} \qquad m_{max} = 0.04 \cdot \frac{A_t \cdot p_0}{\sqrt{T_0}}$$

with A_t in m^2, p_0 in Pa, and T_0 in K.

Problem 1.14 [Difficulty 1]

1.14 The mean free path λ of a molecule of gas is the average distance it travels before collision with another molecule. It is given by

$$\lambda = C\frac{m}{\rho d^2}$$

where m and d are the molecule's mass and diameter, respectively, and ρ is the gas density. Determine the dimensions of constant C for a dimensionally consistent equation.

Given: Equation for mean free path of a molecule.

Find: Dimensions of C for a diemsionally consistent equation.

Solution: Use the mean free path equation. Then "solve" for C and use dimensions.

The mean free path equation is
$$\lambda = C\cdot\frac{m}{\rho\cdot d^2}$$

"Solving" for C, and using dimensions
$$C = \frac{\lambda\cdot\rho\cdot d^2}{m}$$

$$C = \frac{L\times\frac{M}{L^3}\times L^2}{M} = 0$$

The constant C is dimensionless.

Problem 1.15

(Difficulty: 1)

1.15 The density of a sample of sea water is 1.99 slug/ft^3. Determine the value of density in SI and EE units, and the value of specific weight in SI, BG and EE units

Given: The density of sea water is $1.99\ slugs/ft^3$

Find: The density of sea water in SI and EE units the value of specific weight in SI, BG and EE units.

Solution:

For the density in SI units:

The relations between the units are $1\ m = 3.28\ ft$, $1\ kg = 0.0685\ slug$

$$\rho = 1.99\frac{slug}{ft^3} = \frac{1.99 \times \frac{1}{0.0685} kg}{\frac{1}{3.28^3} m^3} = 1026\ \frac{kg}{m^3}$$

For the density in EE units:

The relation between a lbm and a slug is $1\ lbm = 0.0311\ slug$

$$\rho = 1.99\frac{slug}{ft^3} = \frac{1.99 \times \frac{1}{0.0311} lbm}{ft^3} = 64.0\ \frac{lbm}{ft^3}$$

For the specific weight in SI units, we use the relation between mass and weigh from Newton's law

$$\gamma = \frac{W}{V} = \frac{mg}{V} = \rho g = 1026\frac{kg}{m^3} \cdot 9.81\frac{m}{s^2} = 10065\frac{N}{m^3}$$

For the specific weight in EE and BG units, we use the relation between mass and weigh from Newton's law

$$\gamma = \frac{W}{V} = \frac{mg}{Vg_c} = \rho\frac{g}{g_c} = 64.0\frac{lbm}{ft^3} \cdot \frac{32.2\,ft/s^2}{32.2\,ft \cdot lbm / lbf\ s^2} = 64.0\frac{lbf}{ft^3}$$

Problem 1.16

(Difficulty: 1)

1.16 A fluid occupying 3.2 m^3 has a mass of $4Mg$. Calculate its density and specific volume in SI, EE and BG units.

Given: The fluid volume $V = 3.2\ m^3$ and mass $m = 4Mg$.

Find: Density and specific volume in SI, EE and BG units.

Solution:

For SI units:

The density is the mass divided by the volume

$$\rho = \frac{m}{V} = \frac{4000\ kg}{3.2\ m^3} = 1250\ \frac{kg}{m^3}$$

The specific volume is the reciprocal of the density:

$$v = \frac{1}{\rho} = 8 \times 10^{-4} \frac{m^3}{kg}$$

For EE units:

$$1\ \frac{lbm}{ft^3} = 16.0\ \frac{kg}{m^3}$$

The density is:

$$\rho = \frac{1250}{16.0} \frac{lbm}{ft^3} = 78.0 \frac{lbm}{ft^3}$$

And the specific volume is:

$$v = \frac{1}{\rho} = \frac{1}{78.0} \frac{ft^3}{lbm} = 0.0128\ \frac{ft^3}{lbm}$$

For BG unit, the relation between slug and lbm is:

$$1\ \frac{slug}{ft^3} = 32.2\ \frac{lbm}{ft^3}$$

The density is:

$$\rho = \frac{78.0}{32.2} \frac{slug}{ft^3} = 2.43\ \frac{slug}{ft^3}$$

And the specific volume is

$$v = \frac{1}{\rho} = \frac{1}{2.43}\,\frac{ft^3}{slug} = 0.412\ \ \frac{ft^3}{slug}$$

Problem 1.17

[Difficulty: 1]

1.17 Derive the following conversion factors:
(a) Convert a pressure of 1 psi to kPa.
(b) Convert a volume of 1 liter to gallons.
(c) Convert a viscosity of 1 $\text{lbf}\cdot\text{s/ft}^2$ to $\text{N}\cdot\text{s/m}^2$.

Given: Pressure, volume and density data in certain units

Find: Convert to different units

Solution:

Using data from tables

(a) $$1\cdot\text{psi} = 1\cdot\text{psi}\times\frac{6895\cdot\text{Pa}}{1\cdot\text{psi}}\times\frac{1\cdot\text{kPa}}{1000\cdot\text{Pa}} = 6.89\cdot\text{kPa}$$

(b) $$1\cdot\text{liter} = 1\cdot\text{liter}\times\frac{1\cdot\text{quart}}{0.946\,\text{liter}}\times\frac{1\cdot\text{gal}}{4\cdot\text{quart}} = 0.264\,\text{gal}$$

(c) $$1\cdot\frac{\text{lbf}\cdot\text{s}}{\text{ft}^2} = 1\cdot\frac{\text{lbf}\cdot\text{s}}{\text{ft}^2}\times\frac{4.448\,\text{N}}{1\cdot\text{lbf}}\times\left(\frac{\frac{1}{12}\cdot\text{ft}}{0.0254\,\text{m}}\right)^2 = 47.9\cdot\frac{\text{N}\cdot\text{s}}{\text{m}^2}$$

Problem 1.18 [Difficulty: 1]

1.18 Express the following in SI units:
(a) 100 cfm (ft^3/min)
(b) 5 gal
(c) 65 mph
(d) 5.4 acres

Given: Quantities in English Engineering (or customary) units.

Find: Quantities in SI units.

Solution: Use Table and other sources (e.g., Google)

(a) $$100\cdot\frac{ft^3}{m} = 100\cdot\frac{ft^3}{min}\times\left(\frac{0.0254\cdot m}{1\cdot in}\times\frac{12\cdot in}{1\cdot ft}\right)^3\times\frac{1\cdot min}{60\cdot s} = 0.0472\cdot\frac{m^3}{s}$$

(b) $$5\cdot gal = 5\cdot gal\times\frac{231\cdot in^3}{1\cdot gal}\times\left(\frac{0.0254\cdot m}{1\cdot in}\right)^3 = 0.0189\cdot m^3$$

(c) $$65\cdot mph = 65\cdot\frac{mile}{hr}\times\frac{1852\cdot m}{1\cdot mile}\times\frac{1\cdot hr}{3600\cdot s} = 29.1\cdot\frac{m}{s}$$

(d) $$5.4\cdot acres = 5.4\cdot acre\times\frac{4047\cdot m^3}{1\cdot acre} = 2.19\times 10^4\cdot m^2$$

Problem 1.19

[Difficulty: 1]

1.19 Express the following in BG units:
(a) 50 m^2
(b) 250 cc
(c) 100 kW
(d) 5 kg/m^2

Given: Quantities in SI (or other) units.

Find: Quantities in BG units.

Solution: Use appropriate Table

(a) $$50 \cdot m^2 = 50 \cdot m^2 \times \left(\frac{1 \cdot in}{0.0254 \cdot m} \times \frac{1 \cdot ft}{12 \cdot in}\right)^2 = 538 \cdot ft^2$$

(b) $$250 \cdot cc = 250 \cdot cm^3 \times \left(\frac{1 \cdot m}{100 \cdot cm} \times \frac{1 \cdot in}{0.0254 \cdot m} \times \frac{1 \cdot ft}{12 \cdot in}\right)^3 = 8.83 \times 10^{-3} \cdot ft^3$$

(c) $$100 \cdot kW = 100 \cdot kW \times \frac{1000 \cdot W}{1 \cdot kW} \times \frac{1 \cdot hp}{746 \cdot W} = 134 \cdot hp$$

(d) $$5 \cdot \frac{kg}{m^2} = 5 \cdot \frac{kg}{m^2} \times \left(\frac{0.0254 \cdot m}{1 \cdot in} \times \frac{12 \cdot in}{1 \cdot ft}\right)^2 \times \frac{1 \cdot slug}{14.95 \cdot kg} = 0.0318 \frac{slug}{ft^2}$$

Problem 1.20 [Difficulty 1

1.20 Derive the conversion factors for the following quantities for volume flow rate
(a) Converting in^3/min to mm^3/s.
(b) Converting gallons per minute (gpm) to m^3/s.
(c) Converting gpm to liters/min.
(d) Converting cubic feet per minute (cfm) to m^3/s.

Given: Data in given units

Find: Convert to different units

Solution:

(a) $$1\cdot\frac{in^3}{min} = 1\cdot\frac{in^3}{min}\times\left(\frac{0.0254\,m}{1\cdot in}\times\frac{1000\,mm}{1\cdot m}\right)^3\times\frac{1\cdot min}{60\cdot s} = 273\cdot\frac{mm^3}{s}$$

(b) $$1\cdot\frac{m^3}{s} = 1\cdot\frac{m^3}{s}\times\frac{1\cdot gal}{4\times 0.000946m^3}\times\frac{60\cdot s}{1\cdot min} = 15850\,gpm$$

(c) $$1\cdot\frac{liter}{min} = 1\cdot\frac{liter}{min}\times\frac{1\cdot gal}{4\times 0.946\cdot liter}\times\frac{60\cdot s}{1\cdot min} = 0.264\cdot gpm$$

(d) $$1\cdot SCFM = 1\cdot\frac{ft^3}{min}\times\left(\frac{0.0254\cdot m}{\frac{1}{12}\cdot ft}\right)^3\times\frac{60\cdot min}{1\cdot hr} = 1.70\cdot\frac{m^3}{hr}$$

Problem 1.21

[Difficulty: 2]

1.21 Calculate the density of standard air in a laboratory from the ideal gas equation of state. Estimate the experimental uncertainty in the air density calculated for standard conditions (29.9 in. of mercury and 59°F) if the uncertainty in measuring the barometer height is ±0.1 in. of mercury and the uncertainty in measuring temperature is ±0.5°F. (Note that 29.9 in. of mercury corresponds to 14.7 psia.)

Given: Air at standard conditions – p = 29.9 in Hg, T = 59°F

Uncertainty in p is ± 0.1 in Hg, in T is ± 0.5°F

Note that 29.9 in Hg corresponds to 14.7 psia

Find: Air density using ideal gas equation of state; Estimate of uncertainty in calculated value.

Solution:

$$\rho = \frac{p}{RT} = 14.7\frac{\text{lbf}}{\text{in}^2} \times \frac{\text{lb}\cdot{}^{\circ}\text{R}}{53.3\,\text{ft}\cdot\text{lbf}} \times \frac{1}{519^{\circ}\text{R}} \times 144\frac{\text{in}^2}{\text{ft}^2}$$

The uncertainty in density is given by

$$u_\rho = \left[\left(\frac{p}{\rho}\frac{\partial\rho}{\partial p}u_p\right)^2 + \left(\frac{T}{\rho}\frac{\partial\rho}{\partial T}u_T\right)^2\right]^{\frac{1}{2}}$$

$$\frac{p}{\rho}\frac{\partial\rho}{\partial p} = RT\frac{1}{RT} = \frac{RT}{RT} = 1; \qquad u_p = \frac{\pm 0.1}{29.9} = \pm 0.334\%$$

$$\frac{T}{\rho}\frac{\partial\rho}{\partial T} = \frac{T}{\rho}\cdot -\frac{p}{RT^2} = -\frac{p}{\rho RT} = -1; \qquad u_T = \frac{\pm 0.5}{460+59} = \pm 0.0963\%$$

Then

$$u_\rho = \left[u_p^2 + \left(-u_T\right)^2\right]^{\frac{1}{2}} = \pm\left[0.334\%^2 + \left(-0.0963\%\right)^2\right]^{\frac{1}{2}}$$

$$u_\rho = \pm 0.348\% = \pm 2.66\times 10^{-4}\,\frac{\text{lbm}}{\text{ft}^3}$$

Problem 1.22

[Difficulty: 1]

1.22 A parameter that is often used in describing pump performance is the specific speed, $N_{S_{cu}}$, given by

$$N_{s_{cu}} = \frac{N(\text{rpm})[Q(\text{gpm})]^{1/2}}{[H(\text{ft})]^{3/4}}$$

Determine the units of specific speed. For a pump with a specific speed of 2000, determine the specific speed in SI units with angular velocity in rad/s.

Given: Specific speed in customary units

Find: Units; Specific speed in SI units

Solution:

The units are $\dfrac{\text{rpm}\cdot\text{gpm}^{\frac{1}{2}}}{\text{ft}^{\frac{3}{4}}}$ or $\dfrac{\text{ft}^{\frac{3}{4}}}{\text{s}^{\frac{3}{2}}}$

Using data from tables

$$N_{Scu} = 2000\cdot\frac{\text{rpm}\cdot\text{gpm}^{\frac{1}{2}}}{\text{ft}^{\frac{3}{4}}}$$

$$N_{Scu} = 2000 \times \frac{\text{rpm}\cdot\text{gpm}^{\frac{1}{2}}}{\text{ft}^{\frac{3}{4}}} \times \frac{2\cdot\pi\cdot\text{rad}}{1\cdot\text{rev}} \times \frac{1\cdot\text{min}}{60\cdot\text{s}} \times \left(\frac{4 \times 0.000946\cdot\text{m}^3}{1\cdot\text{gal}}\cdot\frac{1\cdot\text{min}}{60\cdot\text{s}}\right)^{\frac{1}{2}} \times \left(\frac{\frac{1}{12}\cdot\text{ft}}{0.0254\cdot\text{m}}\right)^{\frac{3}{4}}$$

$$N_{Scu} = 4.06\cdot\frac{\frac{\text{rad}}{\text{s}}\cdot\left(\frac{\text{m}^3}{\text{s}}\right)^{\frac{1}{2}}}{\text{m}^{\frac{3}{4}}}$$