Solutions Manual for

Fluid Mechanics: Fundamentals and Applications

Second Edition

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CHAPTER 1

INTRODUCTION AND BASIC CONCEPTS

Introduction, Classification, and System

1-1C

Solution We are to define a fluid and how it differs between a solid and a gas.

Analysis **A substance in the liquid or gas phase is referred to as a fluid**. A fluid differs from a solid in that a solid can resist an applied shear stress by deforming, whereas **a fluid deforms continuously under the influence of shear stress**, no matter how small. A liquid takes the shape of the container it is in, and **a liquid forms a free surface in a larger container in a gravitational field**. A gas, on the other hand, expands until it encounters the walls of the container and fills the entire available space.

Discussion The subject of fluid mechanics deals with ball fluids, both gases and liquids.

1-2C

Solution We are to define internal, external, and open-channel flows.

Analysis *External flow* is the **flow of an unbounded fluid over a surface** such as a plate, a wire, or a pipe. The flow in a pipe or duct is *internal flow* if the **fluid is completely bounded by solid surfaces**. The flow of liquids in a pipe is called *open-channel flow* if the pipe is **partially filled with the liquid and there is a free surface**, such as the flow of water in rivers and irrigation ditches.

Discussion As we shall see in later chapters, different approximations are used in the analysis of fluid flows based on their classification.

1-3C

Solution We are to define incompressible and compressible flow, and discuss fluid compressibility.

Analysis A fluid flow during which the **density of the fluid remains nearly constant** is called *incompressible flow*. A flow in which **density varies significantly** is called *compressible flow*. A fluid whose density is practically independent of pressure (such as a liquid) is commonly referred to as an "incompressible fluid," although it is more proper to refer to incompressible *flow*. The flow of compressible fluid (such as air) does not necessarily need to be treated as compressible since the density of a compressible fluid may still remain nearly constant during flow – especially flow at low speeds.

Discussion It turns out that the Mach number is the critical parameter to determine whether the flow of a gas can be approximated as an incompressible flow. If Ma is less than about 0.3, the incompressible approximation yields results that are in error by less than a couple percent.

1-4C

Solution We are to determine whether the flow of air over the wings of an aircraft and the flow of gases through a jet engine is internal or external.

Analysis The flow of air over the wings of an aircraft is **external** since this is an unbounded fluid flow over a surface. The flow of gases through a jet engine is **internal** flow since the fluid is completely bounded by the solid surfaces of the engine.

Discussion If we consider the entire airplane, the flow is both internal (through the jet engines) and external (over the body and wings).

1-5C

Solution We are to define the Mach number of a flow and the meaning for a Mach number of 2.

Analysis The Mach number of a flow is defined as **the ratio of the speed of flow to the speed of sound** in the flowing fluid. **A Mach number of 2 indicate a flow speed that is twice the speed of sound in that fluid**.

Discussion Mach number is an example of a dimensionless (or nondimensional) parameter.

1-6C

Solution We are to determine if the flow of air with a Mach number of 0.12 should be approximated as incompressible.

Analysis Gas flows can often be approximated as incompressible if the density changes are under about 5 percent, which is usually the case when Ma < 0.3. Therefore, air flow with a Mach number of 0.12 **may be approximated as being incompressible**.

Discussion Air is of course a compressible fluid, but at low Mach numbers, compressibility effects are insignificant.

1-7C

Solution We are to define the no-slip condition and its cause.

Analysis A **fluid in direct contact with a solid surface sticks to the surface and there is no slip**. This is known as the *no-slip condition*, and it is due to the *viscosity* of the fluid.

Discussion There is no such thing as an inviscid fluid, since all fluids have viscosity.

1-8C

Solution We are to define forced flow and discuss the difference between forced and natural flow. We are also to discuss whether wind-driven flows are forced or natural.

Analysis In *forced flow*, the fluid is forced to flow over a surface or in a tube **by *external* means** such as a pump or a fan. In *natural flow*, any fluid motion is caused by natural means such as the buoyancy effect that manifests itself as the rise of the warmer fluid and the fall of the cooler fluid. **The flow caused by winds is natural flow for the earth, but it is forced flow for bodies subjected to the winds** since for the body it makes no difference whether the air motion is caused by a fan or by the winds.

Discussion As seen here, the classification of forced vs. natural flow may depend on your frame of reference.

1-9C

Solution We are to define a boundary layer, and discuss its cause.

Analysis The **region of flow** (usually near a wall) **in which the velocity gradients are significant and frictional effects are important** is called the *boundary layer*. When a fluid stream encounters a solid surface that is at rest, the fluid velocity assumes a value of zero at that surface. The velocity then varies from zero at the surface to some larger value sufficiently far from the surface. **The development of a boundary layer is caused by the *no-slip condition***.

Discussion As we shall see later, flow within a boundary layer is *rotational* (individual fluid particles rotate), while that outside the boundary layer is typically *irrotational* (individual fluid particles move, but do not rotate).

1-10C

Solution We are to discuss the differences between classical and statistical approaches.

Analysis The *classical approach* is **a *macroscopic* approach**, based on experiments or analysis of the gross behavior of a fluid, without knowledge of individual molecules, whereas the *statistical approach* is a ***microscopic* approach** based on the average behavior of large groups of individual molecules.

Discussion The classical approach is easier and much more common in fluid flow analysis.

1-11C

Solution We are to define a steady-flow process.

Analysis A process is said to be *steady* if it involves **no changes with time** anywhere within the system or at the system boundaries.

Discussion The opposite of steady flow is *unsteady flow*, which involves changes with time.

1-12C

Solution We are to define stress, normal stress, shear stress, and pressure.

Analysis *Stress* is defined as **force per unit area**, and is determined by dividing the force by the area upon which it acts. The **normal component of a force acting on a surface per unit area** is called the *normal stress*, and the **tangential component of a force acting on a surface per unit area** is called *shear stress*. In a fluid at rest, the normal stress is called *pressure*.

Discussion Fluids in motion may have both shear stresses and additional normal stresses besides pressure, but when a fluid is at rest, the only normal stress is the pressure, and there are no shear stresses.

1-13C

Solution We are to define system, surroundings, and boundary.

Analysis A *system* is defined as a **quantity of matter or a region in space chosen for study**. The mass or **region outside the system** is called the *surroundings***.** The real or imaginary **surface that separates the system from its surroundings** is called the *boundary*.

Discussion Some authors like to define *closed systems* and *open systems*, while others use the notation "system" to mean a closed system and "control volume" to mean an open system. This has been a source of confusion for students for many years. [See the next question for further discussion about this.]

1-14C

Solution We are to discuss when a system is considered closed or open.

Analysis Systems may be considered to be *closed* or *open,* depending on whether a fixed mass or a volume in space is chosen for study. A *closed system* (also known as a *control mass* or simply a *system*) consists of a **fixed amount of mass, and no mass can cross its boundary**. An *open system***,** or a *control volume*, is a **selected region in space**. Mass may cross the boundary of a control volume or open system

Discussion In thermodynamics, it is more common to use the terms *open system* and *closed system*, but in fluid mechanics, it is more common to use the terms *system* and *control volume* to mean the same things, respectively.

1-15C

Solution We are to discuss how to select system for the operation of a reciprocating air compressor.

Analysis We would most likely take the system as **the air contained in the piston-cylinder device**. This system is a **closed or fixed mass system when it is compressing and no mass enters or leaves it**. However, it is an **open system during intake or exhaust**.

Discussion In this example, the system boundary is the same for either case – closed or open system.

1-16C

Solution We are to discuss how to select system when analyzing the acceleration of gases as they flow through a nozzle.

Analysis When analyzing the acceleration of gases as they flow through a nozzle, a wise choice for the system is **the volume within the nozzle**, bounded by the entire inner surface of the nozzle and the inlet and outlet cross-sections. This is a **control volume (or open system)** since mass crosses the boundary.

Discussion It would be much more difficult to follow a chunk of air as a closed system as it flows through the nozzle.

1-17 FlowLab

Solution We are to discuss what happens when a cylinder is heated or cooled in room air, and we are to run FlowLab to calculate maximum air velocity as a function of cylinder temperature.

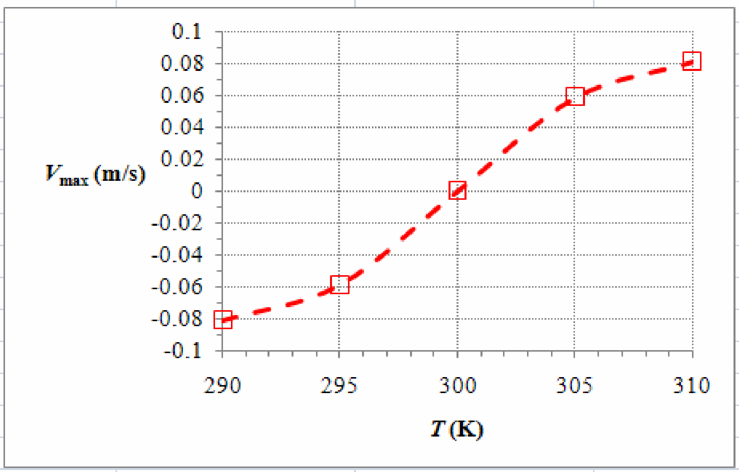
Assumptions **1** The flow is two-dimensional, and thus the end effects (front and back of the cylinder) are negligible. **2** The air volume is large so that there are no boundary effects, and the only flow set up is due to natural convection.

Analysis (*a*) When the cylinder is heated, **we expect the air around the cylinder to rise** because the air density decreases with temperature. **This is an example of natural convection**. This is also an **external flow**, since the walls are far away (the flow is not confined by walls).

(*b*) When the cylinder is cooled, **we expect the air around the cylinder to fall**. Again this is an example of natural convection (as opposed to forced convection, in which the air would be forced to flow over the cylinder).

(*c*) The FlowLab template was run with various values of T_c, with a fixed ambient air temperature of 300K. The results are tabulated and plotted below.

		FlowLab calculations	
$T_{cylinder}$		V_{max} (m/s)	
290		-0.0810181	
295		-0.0585983	
300		0	
305		0.0586003	
310		0.081018	



The **relationship between maximum velocity and cylinder temperature is *not* linear** – it looks more like a cubic function perhaps.

Discussion Newer versions of FlowLab may give slightly different results. As expected, a cool cylinder generates a downward flow (V_{max} is negative), while a hot cylinder generates an upward flow. Likewise as expected, the cooler (or hotter) the cylinder, the larger the magnitude of the velocity, although the relationship does not appear to be linear. There does, however, appear to be odd-function symmetry about $T_c = 0$.

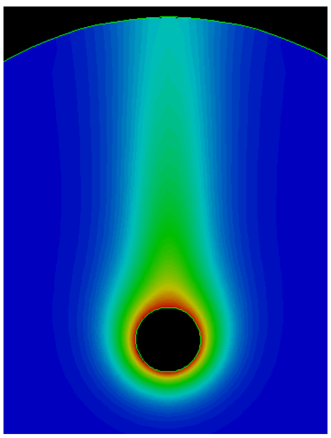
1-18 FlowLab

Solution We are to classify the flow when air flows over a heated cylinder, and we are to run FlowLab to observe the temperature contours as air velocity is varied.

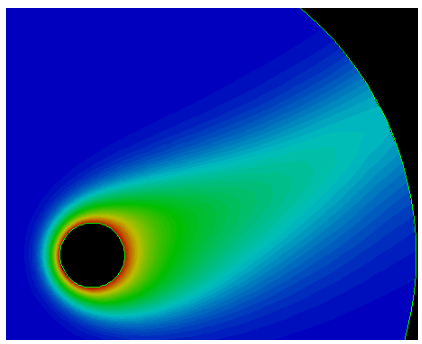
Assumptions **1** The flow is two-dimensional, and thus the end effects (front and back of the cylinder) are negligible. **2** The wind tunnel walls are far away so that there are no boundary effects.

Analysis (*a*) This is also an **external flow**, since the walls are far away (the flow is not confined by walls). When the air is stationary (no forced flow), **we expect the air around the cylinder to rise** because the air density decreases with temperature. **This is an example of natural convection**. As the air speed increases, we expect the thermal plume to bend more and more downstream. [**This is an example of mixed convection**.] Eventually, **if the air speed is high enough, forced convection effects will dominate over natural convection effects. This is an example of forced convection**.

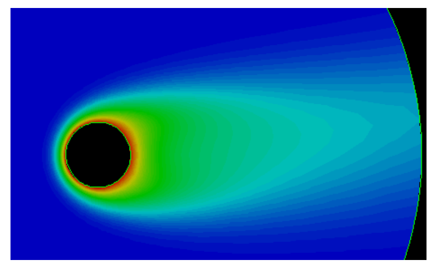
(*b*) The FlowLab template was run with various values of air speed V, with ambient air temperature = 300 K and cylinder wall temperature = 302.5 K. The temperature contour plots for three cases are shown below.



V = 0 m/s



V = 0.03 m/s



V = 0.05841 m/s

The CFD results agree with our intuition – namely, the flow changes from free (natural) convection to forced convection as air speed is increased. At the highest air speed, the thermal plume is nearly horizontal, indicating that convection eventually dominates buoyancy, as expected.

Discussion Newer versions of FlowLab may give slightly different results. The CFD program also reports Reynolds number and Grashof number. These are nondimensional parameters, as discussed in Chapter 7, the chapter on dimensional analysis.

1-19 FlowLab

Solution We are to compare 1-D, 2-D, and 3-D CFD simulations of steady, fully developed laminar pipe flow.

Assumptions **1** The flow is steady, incompressible, and fully developed. **2** The three CFD calculations are similar except for the geometry – 1-D, 2-D, or 3-D.

Analysis (*a*) We classify this flow as **internal** since it is confined within the pipe, and **one-dimensional** because velocity V is a function of radius r only. The flow is fully developed, which means that the velocity profile (across the pipe) remains the same regardless of downstream distance.

(*b*) CFD results: See the table below (all values are listed to three significant digits except CPU time, which is given to the nearest second). *Note that the required CPU time will vary greatly depending on the type of computer used.*

Parameter	**1-D case**	**2-D case**	**3-D case**
Number of cells	20	800	12000
dP/dx (Pa/m)	-48.3	-48.4	-48.8
V_{max} (m/s)	0.301	0.300	0.298
V_{avg} (m/s)	0.151	0.151	0.151
CPU time (s)	1 to 2	6 to 8	44 to 88

Comparison: The flow parameter results (pressure gradient, maximum velocity, and average velocity) are nearly identical. However, the number of cells grows by more than an order of magnitude from 1-D to 2-D and from 2-D to 3-D. Likewise, the required CPU time increases significantly. **For this flow, which is 1-D, there is no advantage to running a 2-D or 3-D simulation**.

Discussion Newer versions of FlowLab may give slightly different results. Other computers will give different CPU times, but the trend should be similar. The 1-D and 2-D cases take advantage of symmetry – only one slice of the pipe flow is modeled. To conserve computer resources, it is always wise to simplify the problem as much as possible. Here, running a 3-D simulation does not provide any more information or yield any better solution – all it does is take more computer time and memory – actually a *disadvantage*.

1-20 FlowLab

Solution We are to compare 2-D and 3-D CFD simulations of the entrance region of laminar pipe flow.

Assumptions **1** The flow is steady and incompressible; it is *not* fully developed. **2** The two CFD calculations are similar except for the geometry – 2-D (axisymmetric) or 3-D.

Analysis (*a*) We classify this flow as **internal** since it is confined within the pipe, and **two-dimensional** because velocity V is a function of radius r and downstream distance x only. The flow is not fully developed, which means that the velocity profile (across the pipe) changes with downstream distance.

(*b*) CFD results: See the table below (all values are listed to three significant digits except CPU time, which is given to the nearest second). *Note that the required CPU time will vary greatly depending on the type of computer used.*

Parameter	**2-D case**	**3-D case**
Number of cells	3200	46000
Pressure drop $\Delta P/L$ (Pa/m)	6.39	6.48
CPU time (s)	8 to 12	80 to 130

Comparison: The pressure drop is not identical, but very close – the error is only about 1.4%. However, the number of cells grows by more than an order of magnitude from 2-D to 3-D. Likewise, the required CPU time increases significantly – about an order of magnitude. **For this flow, which is 2-D, there is no advantage to running a 3-D simulation**.

Discussion Newer versions of FlowLab may give slightly different results. The 2-D case takes advantage of symmetry – only one axisymmetric slice of the pipe flow is modeled. To conserve computer resources, it is always wise to simplify the problem as much as possible. Here, running a 3-D simulation does not provide any more information or yield any better solution – all it does is take more computer time and memory – actually a *disadvantage*.

Mass, Force, and Units

1-21C

Solution We are to discuss the difference between pound-mass (lbm) and pound-force (lbf).

Analysis The "pound" mentioned here must be "**lbf**" since thrust is a force, and the lbf is the force unit in the English system.

Discussion You should get into the habit of *never* writing the unit "lb", but always use either "lbm" or "lbf" as appropriate since the two units have different dimensions.

1-22C

Solution We are to discuss the difference between pound-mass and pound-force.

Analysis *Pound-mass* lbm is the **mass unit in English system** whereas *pound-force* lbf is the **force unit in the English system**. One pound-force is the force required to accelerate a mass of 32.174 lbm by 1 ft/s^2. In other words, the weight of a 1-lbm mass at sea level on earth is 1 lbf.

Discussion It is *not* proper to say that one lbm is equal to one lbf since the two units have different dimensions.

1-23C

Solution We are to discuss the difference between kg-mass and kg-force.

Analysis The unit *kilogram* (kg) is the **mass unit in the SI system**, and it is sometimes called *kg-mass*, whereas *kg-force* (kgf) is a **force unit**. One kg-force is the force required to accelerate a 1-kg mass by 9.807 m/s^2. In other words, the weight of 1-kg mass at sea level on earth is 1 kg-force.

Discussion It is *not* proper to say that one kg-mass is equal to one kg-force since the two units have different dimensions.

1-24C

Solution We are to calculate the net force on a car cruising at constant velocity.

Analysis There is no acceleration (car moving at constant velocity), thus **the net force is zero in both cases**.

Discussion By Newton's second law, the force on an object is directly proportional to its acceleration. If there is zero acceleration, there must be zero net force.

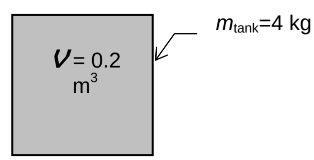
1-25

Solution A plastic tank is filled with water. The weight of the combined system is to be determined.

Assumptions The density of water is constant throughout.

Properties The density of water is given to be ρ = 1000 kg/m^3.

Analysis The mass of the water in the tank and the total mass are



$$m_w = \rho V = (1000\ \text{kg/m}^3)(0.2\ \text{m}^3) = 200\ \text{kg}$$
$$m_{\text{total}} = m_w + m_{tank} = 200 + 4 = 204\ \text{kg}$$

Thus,

$$W = mg = (204\ \text{kg})(9.81\ \text{m/s}^2)\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right) = 2001\ \text{N} \cong \mathbf{2000\ N}$$

where we give the final answer to three significant digits.

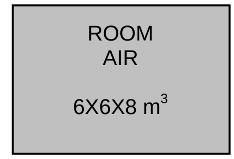
Discussion Note the unity conversion factor in the above equation.

1-26

Solution The interior dimensions of a room are given. The mass and weight of the air in the room are to be determined.

Assumptions The density of air is constant throughout the room.

Properties The density of air is given to be $\rho = 1.16$ kg/m^3.



Analysis The mass of the air in the room is

$$m = \rho V = (1.16 \text{ kg/m}^3)(6\times 6\times 8 \text{ m}^3) = 334.1 \text{ kg} \cong \mathbf{334\ kg}$$

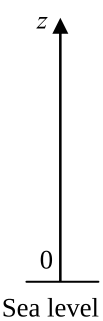
Thus,

$$W = mg = (334.1 \text{ kg})(9.81 \text{ m/s}^2)\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right) = 3277 \text{ N} \cong \mathbf{3280\ N}$$

Discussion Note that we round our final answers to three significant digits, but use extra digit(s) in intermediate calculations. Considering that the mass of an average man is about 70 to 90 kg, the mass of air in the room is probably larger than you might have expected.

1-27

Solution The variation of gravitational acceleration above sea level is given as a function of altitude. The height at which the weight of a body decreases by 1% is to be determined.



Analysis The weight of a body at the elevation z can be expressed as

$$W = mg = m(a - bz)$$

where $a = g_s = 9.807$ m/s^2 is the value of gravitational acceleration at sea level and $b = 3.32\times10^{-6}$ s^{-2}. In our case,

$$W = m(a - bz) = 0.99W_s = 0.99mg_s$$

We cancel out mass from both sides of the equation and solve for z, yielding

$$z = \frac{a - 0.99g_s}{b}$$

Substituting,

$$z = \frac{9.807 \text{ m/s}^2 - 0.99\left(9.807 \text{ m/s}^2\right)}{3.32\times10^{-6} \text{ 1/s}^2} = 29{,}539 \text{ m} \cong \mathbf{29{,}500\ m}$$

where we have rounded off the final answer to three significant digits.

Discussion This is more than three times higher than the altitude at which a typical commercial jet flies, which is about 30,000 ft (9140 m). So, flying in a jet is not a good way to lose weight – diet and exercise are always the best bet.

1-28E

Solution An astronaut takes his scales with him to the moon. It is to be determined how much he weighs on the spring and beam scales on the moon.

Analysis

(*a*) A spring scale measures weight, which is the local gravitational force applied on a body:

$$W = mg = (180\text{ lbm})(5.48\text{ ft/s}^2)\left(\frac{1\text{ lbf}}{32.2\text{ lbm}\cdot\text{ft/s}^2}\right) = \mathbf{30.6\ lbf}$$

(*b*) A beam scale compares masses and thus is not affected by the variations in gravitational acceleration. The beam scale reads what it reads on earth,

$$W = \mathbf{180\ lbf}$$

Discussion The beam scale may be marked in units of weight (lbf), but it really compares mass, not weight. Which scale would you consider to be more accurate?

1-29

Solution The acceleration of an aircraft is given in *g*'s. The net upward force acting on a man in the aircraft is to be determined.

Analysis From Newton's second law, the applied force is

$$F = ma = m(6\text{ g}) = (90\text{ kg})(6\times 9.81\text{ m/s}^2)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 5297\text{ N} \cong \mathbf{5300\ N}$$

where we have rounded off the final answer to three significant digits.

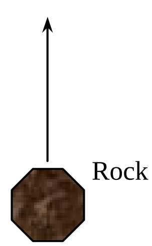
Discussion The man feels like he is six times heavier than normal. You get a similar feeling when riding an elevator to the top of a tall building, although to a much lesser extent.

1-30 **[*Also solved by EES on enclosed CD*]**

Solution A rock is thrown upward with a specified force. The acceleration of the rock is to be determined.

Analysis The weight of the rock is

$$W = mg = (5\text{ kg})(9.79\text{ m/s}^2)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 48.95\text{ N} \cong \mathbf{49.0\ N}$$



Then the net force that acts on the rock is

$$F_{net} = F_{up} - F_{down} = 150 - 48.95 = 101.05\text{ N}$$

From Newton's second law, the acceleration of the rock becomes

$$a = \frac{F}{m} = \frac{101.05\text{ N}}{5\text{ kg}}\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right) = \mathbf{20.2\ m/s^2}$$

Discussion This acceleration is more than twice the acceleration at which it would fall (due to gravity) if dropped.

1-31

Solution The previous problem is recalculated using EES. The entire EES solution is to be printed out, including the numerical results with proper units.

Analysis The EES *Equations* window is printed below, followed by the *Solution* window.

```
W=m*g "[N]"
m=5 [kg]
g=9.79 [m/s^2]
"The force balance on the rock yields the net force acting on the rock as"
F_net = F_up - F_down "[N]"
F_up=150 [N]
F_down=W "[N]"
"The acceleration of the rock is determined from Newton's second law."
F_net=a*m
"To Run the program, press F2 or click on the calculator icon from the Calculate menu"
```

SOLUTION
Variables in Main
a=20.21 [m/s^2]
F_down=48.95 [N]
F_net=101.1 [N]
F_up=150 [N]
g=9.79 [m/s^2]
m=5 [kg]
W=48.95 [N]

The final results are ***W*** **= 49.0 N** and ***a*** **= 20.2 m/s²**, to three significant digits, which agree with the results of the previous problem.

Discussion Items in quotation marks in the EES Equation window are comments. Units are in square brackets.

1-32

Solution Gravitational acceleration g and thus the weight of bodies decreases with increasing elevation. The percent reduction in the weight of an airplane cruising at 13,000 m is to be determined.

Properties The gravitational acceleration g is 9.807 m/s^2 at sea level and 9.767 m/s^2 at an altitude of 13,000 m.

Analysis Weight is proportional to the gravitational acceleration g, and thus the percent reduction in weight is equivalent to the percent reduction in the gravitational acceleration, which is determined from

$$\%\text{ Reduction in weight} = \%\text{ Reduction in } g = \frac{\Delta g}{g}\times 100 = \frac{9.807-9.767}{9.807}\times 100 = \mathbf{0.41\%}$$

Therefore, **the airplane and the people in it will weigh 0.41% less at 13,000 m altitude**.

Discussion Note that the weight loss at cruising altitudes is negligible. Sorry, but flying in an airplane is not a good way to lose weight. The best way to lose weight is to carefully control your diet, and to exercise.

1-33

SOLUTION During an analysis, a relation with inconsistent units is obtained. A correction is to be found, and the probable cause of the error is to be determined.

Analysis The two terms on the right-hand side of the equation

$$E = 25 \text{ kJ} + 7 \text{ kJ/kg}$$

do not have the same units, and therefore they cannot be added to obtain the total energy. **Multiplying the last term by mass will eliminate the kilograms in the denominator, and the whole equation will become dimensionally homogeneous**; that is, every term in the equation will have the same unit.

Discussion Obviously this error was caused by forgetting to multiply the last term by mass at an earlier stage.

1-34

Solution A resistance heater is used to heat water to desired temperature. The amount of electric energy used in kWh and kJ are to be determined.

Analysis The resistance heater consumes electric energy at a rate of 4 kW or 4 kJ/s. Then the total amount of electric energy used in 2 hours becomes

$$\begin{aligned}\text{Total energy} &= (\text{Energy per unit time})(\text{Time interval})\\ &= (4 \text{ kW})(2 \text{ h})\\ &= \mathbf{8\ kWh}\end{aligned}$$

Noting that 1 kWh = (1 kJ/s)(3600 s) = 3600 kJ,

$$\begin{aligned}\text{Total energy} &= (8 \text{ kWh})(3600 \text{ kJ/kWh})\\ &= \mathbf{28{,}800\ kJ}\end{aligned}$$

Discussion Note kW is a unit for power whereas kWh is a unit for energy.

1-35

Solution A gas tank is being filled with gasoline at a specified flow rate. Based on unit considerations alone, a relation is to be obtained for the filling time.

Assumptions Gasoline is an incompressible substance and the flow rate is constant.

Analysis The filling time depends on the volume of the tank and the discharge rate of gasoline. Also, we know that the unit of time is 'seconds'. Therefore, the independent quantities should be arranged such that we end up with the unit of seconds. Putting the given information into perspective, we have

$$t \text{ [s]} \quad \leftrightarrow \quad V \text{ [L]}, \text{ and } \dot{V} \text{ [L/s}\}$$

It is obvious that the only way to end up with the unit "s" for time is to divide the tank volume by the discharge rate. Therefore, the desired relation is

$$\boxed{t = \frac{V}{\dot{V}}}$$

Discussion Note that this approach may not work for cases that involve dimensionless (and thus unitless) quantities.

1-36

Solution A pool is to be filled with water using a hose. Based on unit considerations, a relation is to be obtained for the volume of the pool.

Assumptions Water is an incompressible substance and the average flow velocity is constant.

Analysis The pool volume depends on the filling time, the cross-sectional area which depends on hose diameter, and flow velocity. Also, we know that the unit of volume is m^3. Therefore, the independent quantities should be arranged such that we end up with the unit of seconds. Putting the given information into perspective, we have

$$\mathcal{V}\ [\mathrm{m^3}] \quad \text{is a function of} \quad t\ [\mathrm{s}],\ D\ [\mathrm{m}],\ \text{and}\ V\ [\mathrm{m/s}\}$$

It is obvious that the only way to end up with the unit "m^3" for volume is to multiply the quantities t and V with the square of D. Therefore, the desired relation is

$$\boldsymbol{\mathcal{V} = CD^2Vt}$$

where the constant of proportionality is obtained for a round hose, namely, $C = \pi/4$ so that $\boldsymbol{\mathcal{V} = (\pi D^2/4)Vt}$.

Discussion Note that the values of dimensionless constants of proportionality cannot be determined with this approach.

1-37

Solution It is to be shown that the power needed to accelerate a car is proportional to the mass and the square of the velocity of the car, and inversely proportional to the time interval.

Assumptions The car is initially at rest.

Analysis The power needed for acceleration depends on the mass, velocity change, and time interval. Also, the unit of power $\dot{W}$ is watt, W, which is equivalent to

$$\mathrm{W = J/s = N{\cdot}m/s = (kg{\cdot}m/s^2)m/s = kg{\cdot}m^2/s^3}$$

Therefore, the independent quantities should be arranged such that we end up with the unit $kg{\cdot}m^2/s^3$ for power. Putting the given information into perspective, we have

$$\dot{W}\ [\mathrm{kg{\cdot}m^2/s^3}] \quad \text{is a function of} \quad m\ [\mathrm{kg}],\ V\ [\mathrm{m/s}],\ \text{and}\ t\ [\mathrm{s}]$$

It is obvious that the only way to end up with the unit "$kg{\cdot}m^2/s^3$" for power is to multiply mass with the square of the velocity and divide by time. Therefore, the desired relation is

$$\dot{W} \quad \text{is proportional to} \quad mV^2/t$$

or,

$$\boxed{\dot{W} = CmV^2/t}$$

where C is the dimensionless constant of proportionality (whose value is ½ in this case).

Discussion Note that this approach cannot determine the numerical value of the dimensionless numbers involved.

1-38

Solution We are to estimate the work and power required to lift a crate.

Assumptions **1** The vertical speed of the crate is constant.

Properties The gravitational constant is taken as g = 9.807 m/s^2.

Analysis

(a) Work W is a form of energy, and is equal to force times distance. Here, the force is the weight of the crate, which is $F = mg$, and the vertical distance is Δz, where z is the elevation.

$$W = F\Delta z = mg\Delta z$$

$$= (90.5\text{ kg})(9.807\text{ m/s}^2)(1.80\text{ m})\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kJ}}{1000\text{ N}\cdot\text{m}}\right) = 1.5976\text{ kJ} \cong \mathbf{1.60\text{ kJ}}$$

where we give our final answer to 3 significant digits, but retain 5 digits to avoid round-off error in part (b).

(b) Power is work (energy) per unit time. Assuming a constant speed,

$$\dot{W} = \frac{W}{\Delta t} = \frac{1.5976\text{ kJ}}{12.3\text{ s}}\left(\frac{1000\text{ W}}{1\text{ kJ/s}}\right) = 129.88\text{ W} \cong \mathbf{130\text{ W}}$$

Again we give our final answer to 3 significant digits.

Discussion The actual required power will be greater than calculated here, due to frictional losses and other inefficiencies in the forklift system. Three unity conversion ratios are used in the above calculations.

1-39E

Solution We are to estimate the work required to lift a fireman, and estimate how long it takes.

Assumptions **1** The vertical speed of the fireman is constant.

Analysis

(a) Work W is a form of energy, and is equal to force times distance. Here, the force is the weight of the fireman (and equipment), and the vertical distance is Δz, where z is the elevation.

$$W = F\Delta z = (280\text{ lbf})(60.0\text{ ft})\left(\frac{1\text{ Btu}}{778.169\text{ ft}\cdot\text{lbf}}\right) = 21.589\text{ Btu} \cong \mathbf{21.6\text{ Btu}}$$

where we give our final answer to 3 significant digits, but retain 5 digits to avoid round-off error in part (b).

(b) Power is work (energy) per unit time. Assuming a constant speed,

$$\Delta t = \frac{W}{\dot{W}} = \frac{21.589\text{ Btu}}{3.50\text{ hp}}\left(\frac{1\text{ hp}}{0.7068\text{ Btu/s}}\right) = 8.7271\text{ s} \cong \mathbf{8.73\text{ s}}$$

Again we give our final answer to 3 significant digits.

Discussion The actual required power will be greater than calculated here, due to frictional losses and other inefficiencies in the boom's lifting system. One unity conversion ratio is used in each of the above calculations.

1-40E

Solution We are to estimate the rate of heat transfer into a room and the cost of running an air conditioner for one hour.

Assumptions **1** The rate of heat transfer is constant. **2** The indoor and outdoor temperatures do not change significantly during the hour of operation.

Analysis
(*a*) In one hour, the air conditioner supplies 5,000 Btu of cooling, but runs only 60% of the time. Since the indoor and outdoor temperatures remain constant during the hour of operation, the average rate of heat transfer into the room is the same as the average rate of cooling supplied by the air conditioner. Thus,

$$\dot{Q} = \frac{0.60(5000\ \text{Btu})}{1\ \text{h}} = \mathbf{3{,}000\ Btu/h}\left(\frac{1\ \text{kW}}{3412.14\ \text{Btu/h}}\right) = \mathbf{0.879\ kW}$$

(*b*) Energy efficiency ratio is defined as the amount of heat removed from the cooled space in Btu for 1 Wh (watt-hour) of electricity consumed. Thus, for every Wh of electricity, this particular air conditioner removes 9.0 Btu from the room. To remove 3,000 Btu in one hour, the air conditioner therefore consumes 3,000/9.0 = 333.33 Wh = 0.33333 kWh of electricity. At a cost of 7.5 cents per kWh, it costs only **2.50 cents** to run the air conditioner for one hour.

Discussion Notice the unity conversion ratio in the above calculation. We also needed to use some common sense and dimensional reasoning to come up with the appropriate calculations. While this may seem very cheap, if this air conditioner is run at these conditions continuously for one month, the electricity will cost ($0.025/h) (24 h/day) (30 day/mo) = $18/mo.

1-41

Solution We are to calculate the volume flow rate and mass flow rate of water.

Assumptions **1** The volume flow rate, temperature, and density of water are constant over the measured time.

Properties The density of water at 20°C is ρ = 998.0 kg/m^3.

Analysis The volume flow rate is equal to the volume per unit time, i.e.,

$$\dot{V} = \frac{V}{\Delta t} = \frac{2.0\ \text{L}}{2.85\ \text{s}}\left(\frac{60\ \text{s}}{1\ \text{min}}\right) = 42.105\ \text{L/min} \cong \mathbf{42.1\ Lpm}$$

where we give our final answer to 3 significant digits, but retain 5 digits to avoid round-off error in the second part of the problem. Since density is mass per unit volume, mass flow rate is equal to volume flow rate times density. Thus,

$$\dot{m} = \rho\dot{V} = \left(998.0\ \text{kg/m}^3\right)\left(42.105\ \text{L/min}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{m}^3}{1000\ \text{L}}\right) = \mathbf{0.700\ kg/s}$$

Discussion We used one unity conversion ratio in the first calculation, and two in the second. If we were interested only in the mass flow rate, we could have eliminated the intermediate calculation by solving for mass flow rate directly, i.e.,

$$\dot{m} = \rho\frac{V}{\Delta t} = \left(998.0\ \text{kg/m}^3\right)\frac{2.0\ \text{L}}{2.85\ \text{s}}\left(\frac{1\ \text{m}^3}{1000\ \text{L}}\right) = 0.700\ \text{kg/s}\,.$$

1-42

Solution We are to calculate the useful power delivered by an airplane propeller.

Assumptions **1** The airplane flies at constant altitude and constant speed. **2** Wind is not a factor in the calculations.

Analysis At steady horizontal flight, the airplane's drag is balanced by the propeller's thrust. Energy is force times distance, and power is energy per unit time. Thus, by dimensional reasoning, the power supplied by the propeller must equal thrust times velocity,

$$\dot{W} = F_{\text{thrust}}V = (1500\text{ N})(55.0\text{ m/s})\left(\frac{1\text{ kW}}{1000\text{ N}\cdot\text{m/s}}\right) = \mathbf{82.5\,kW}\left(\frac{1.341\text{ hp}}{1\text{ kW}}\right) = \mathbf{111\,hp}$$

where we give our final answers to 3 significant digits.

Discussion We used two unity conversion ratios in the above calculation. The actual shaft power supplied by the airplane's engine will of course be larger than that calculated above due to inefficiencies in the propeller.

1-43

Solution We are to calculate lift produced by an airplane's wings.

Assumptions **1** The airplane flies at constant altitude and constant speed. **2** Wind is not a factor in the calculations.

Analysis At steady horizontal flight, the airplane's weight is balanced by the lift produced by the wings. Thus, the net lift force must equal the weight, or F_L = **1450 lbf**. We use unity conversion ratios to convert to newtons:

$$F_L = (1450\text{ lbf})\left(\frac{1\text{ N}}{0.22481\text{ lbf}}\right) = \mathbf{6{,}450\ N}$$

where we give our final answers to 3 significant digits.

Discussion The answer is valid at any speed, since lift must balance weight in order to sustain straight, horizontal flight. As the fuel is consumed, the overall weight of the aircraft will decrease, and hence the lift requirement will also decrease. If the pilot does not adjust, the airplane will climb slowly in altitude.

Modeling and Solving Engineering Problems

1-44C

Solution We are to discuss the difference between accuracy and precision.

Analysis *Accuracy* refers to the **closeness of the measured or calculated value to the true value** whereas *precision* represents the **number of significant digits or the closeness of different measurements of the same quantity to each other**. **A measurement or calculation can be very precise without being very accurate, and vice-versa**. When measuring the boiling temperature of pure water at standard atmospheric conditions (100.00^{o}C), for example, a temperature measurement of 97.861°C is very precise, but not as accurate as the less precise measurement of 99.0°C.

Discussion Accuracy and precision are often confused; both are important for quality engineering measurements.

1-45C

Solution We are to discuss the difference between analytical and experimental approaches.

Analysis The *experimental approach* (**testing and taking measurements**) has the advantage of dealing with the actual physical system, and getting a physical value within the limits of experimental error. However, this approach is expensive, time consuming, and often impractical. The *analytical approach* (**analysis or calculations**) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions and idealizations made in the analysis.

Discussion Most engineering designs require both analytical and experimental components, and both are important. Nowadays, computational fluid dynamics (CFD) is often used in place of pencil-and-paper analysis and/or experiments.

1-46C

Solution We are to discuss the importance of modeling in engineering.

Analysis *Modeling* makes it possible to **predict the course of an event before it actually occurs, or to study various aspects of an event mathematically without actually running expensive and time-consuming experiments**. When preparing a mathematical model, all the variables that affect the phenomena are identified, reasonable assumptions and approximations are made, and the interdependence of these variables is studied. The relevant physical laws and principles are invoked, and the problem is formulated mathematically. Finally, the problem is solved using an appropriate approach, and the results are interpreted.

Discussion In most cases of actual engineering design, the results are verified by experiment – usually by building a prototype. CFD is also being used more and more in the design process.

1-47C

Solution We are to discuss choosing a model.

Analysis The right choice between a crude and complex model is usually **the *simplest* model that yields *adequate* results**. Preparing very accurate but complex models is not necessarily a better choice since such models are not much use to an analyst if they are very difficult and time consuming to solve. At a minimum, the model should reflect the essential features of the physical problem it represents. After obtaining preliminary results with the simpler model and optimizing the design, the complex, expensive model may be used for the final prediction.

Discussion Cost is always an issue in engineering design, and "adequate" is often determined by cost.

1-48C

Solution We are to discuss how differential equations arise in the study of a physical problem.

Analysis The description of most scientific problems involves equations that relate the *changes* in some key variables to each other, and the smaller the increment chosen in the changing variables, the more accurate the description. In **the limiting case of infinitesimal changes in variables**, we obtain *differential equations*, which provide precise mathematical formulations for the physical principles and laws by representing the rates of changes as *derivatives*.

Discussion As we shall see in later chapters, the differential equations of fluid mechanics are known, but very difficult to solve except for very simple geometries. Computers are extremely helpful in this area.

1-49C

Solution We are to discuss the value of engineering software packages.

Analysis *Software packages* **are of great value in engineering practice, and engineers today rely on software packages to solve large and complex problems quickly, and to perform optimization studies efficiently**. Despite the convenience and capability that engineering software packages offer, they are still just *tools*, and they cannot replace traditional engineering courses. They simply cause a shift in emphasis in the course material from mathematics to physics.

Discussion While software packages save us time by reducing the amount of number-crunching, we must be careful to understand how they work and what they are doing, or else incorrect results can occur.

1-50

Solution We are to determine a positive real root of the following equation using EES: $3.5x^3 - 10x^{0.5} - 3x = -4$.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

```
3.5*x^3-10*x^0.5-3*x = -4
```

Answer: $\boldsymbol{x = 1.554}$

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

1-51

Solution We are to solve a system of 2 equations and 2 unknowns using EES.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

```
x^3-y^2=10.5
3*x*y+y=4.6
```

Answers: $\boldsymbol{x = 2.215}$, $\boldsymbol{y = 0.6018}$

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

1-52

Solution We are to solve a system of 3 equations with 3 unknowns using EES.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

```
2*x-y+z=5
3*x^2+2*y=z+2
x*y+2*z=8
```

Answers: ***x* = 1.141, *y* = 0.8159, *z* = 3.535.**

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

1-53

Solution We are to solve a system of 3 equations with 3 unknowns using EES.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

```
x^2*y-z=1.5
x-3*y^0.5+x*z=-2
x+y-z=4.2
```

Answers: ***x* = 0.9149, *y* = 10.95, *z* = 7.665**

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

Review Problems

1-54

SOLUTION The flow of air through a wind turbine is considered. Based on unit considerations, a proportionality relation is to be obtained for the mass flow rate of air through the blades.

Assumptions Wind approaches the turbine blades with a uniform velocity.

Analysis The mass flow rate depends on the air density, average wind velocity, and the cross-sectional area which depends on hose diameter. Also, the unit of mass flow rate $\dot{m}$ is kg/s. Therefore, the independent quantities should be arranged such that we end up with the proper unit. Putting the given information into perspective, we have

$\dot{m}$ [kg/s] is a function of ρ [kg/m^3], D [m], and V [m/s}

It is obvious that the only way to end up with the unit "kg/s" for mass flow rate is to multiply the quantities ρ and V with the square of D. Therefore, the desired proportionality relation is

$\dot{m}$ is proportional to $\rho D^2 V$

or,

$$\dot{m} = C\rho D^2 V$$

Where the constant of proportionality is $C = \pi/4$ so that $\dot{m} = \rho(\pi D^2/4)V$

Discussion Note that the dimensionless constants of proportionality cannot be determined with this approach.

1-55

Solution The gravitational acceleration changes with altitude. Accounting for this variation, the weights of a body at different locations are to be determined.

Analysis The weight of an 80-kg man at various locations is obtained by substituting the altitude z (values in m) into the relation

$$W = mg = (80\ \text{kg})(9.807 - 3.32\times10^{-6} z)\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right) \quad \left(\text{where } z \text{ is in units of m/s}^2\right)$$

Sea level: (z = 0 m): W = 80×(9.807-3.32x10^{-6}×0) = 80×9.807 = **784.6 N**
Denver: (z = 1610 m): W = 80×(9.807-3.32x10^{-6}×1610) = 80×9.802 = **784.2 N**
Mt. Ev.: (z = 8848 m): W = 80×(9.807-3.32x10^{-6}×8848) = 80×9.778 = **782.2 N**

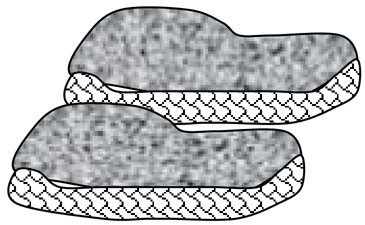
Discussion We report 4 significant digits since the values are so close to each other. The percentage difference in weight from sea level to Mt. Everest is only about -0.3%, which is negligible for most engineering calculations.

1-56

Solution A man is considering buying a 12-oz steak for \$3.15, or a 320-g steak for \$2.80. The steak that is a better buy is to be determined.

Assumptions The steaks are of identical quality.

Analysis To make a comparison possible, we need to express the cost of each steak on a common basis. We choose 1 kg as the basis for comparison. Using proper conversion factors, the unit cost of each steak is determined to be



12 ounce steak: $$\text{Unit Cost} = \left(\frac{\$3.15}{12\text{ oz}}\right)\left(\frac{16\text{ oz}}{1\text{ lbm}}\right)\left(\frac{1\text{ lbm}}{0.45359\text{ kg}}\right) = \mathbf{\$9.26/kg}$$

320 gram steak:

$$\text{Unit Cost} = \left(\frac{\$2.80}{320\text{ g}}\right)\left(\frac{1000\text{ g}}{1\text{ kg}}\right) = \mathbf{\$8.75/kg}$$

Therefore, **the steak at the international market is a better buy**.

Discussion Notice the unity conversion factors in the above equations.

1-57

Solution The thrust developed by the jet engine of a Boeing 777 is given to be 85,000 pounds. This thrust is to be expressed in N and kgf.

Analysis Noting that 1 lbf = 4.448 N and 1 kgf = 9.81 N, the thrust developed is expressed in two other units as

Thrust in N:

$$\text{Thrust} = (85{,}000\text{ lbf})\left(\frac{4.448\text{ N}}{1\text{ lbf}}\right) = \mathbf{3.78\times10^5\ N}$$

Thrust in kgf:

$$\text{Thrust} = (37.8\times10^5\text{ N})\left(\frac{1\text{ kgf}}{9.81\text{ N}}\right) = \mathbf{3.85\times10^4\ kgf}$$

Discussion Because the gravitational acceleration on earth is close to 10 m/s^2, it turns out that the two force units N and kgf differ by nearly a factor of 10. This can lead to confusion, and we recommend that you do not use the unit kgf.

1-58

SOLUTION A relation for the air drag exerted on a car is to be obtained in terms of on the drag coefficient, the air density, the car velocity, and the frontal area of the car.

Analysis The drag force depends on a dimensionless drag coefficient, the air density, the car velocity, and the frontal area. Also, the unit of force F is newton N, which is equivalent to kg·m/s^2. Therefore, the independent quantities should be arranged such that we end up with the unit kg·m/s^2 for the drag force. Putting the given information into perspective, we have

$$F_D\ [\text{kg·m/s}^2] \leftrightarrow C_{\text{Drag}}\ [\,],\ A_{\text{front}}\ [\text{m}^2],\ \rho\ [\text{kg/m}^3],\ \text{and}\ V\ [\text{m/s}]$$

It is obvious that the only way to end up with the unit "kg·m/s^2" for drag force is to multiply mass with the square of the velocity and the fontal area, with the drag coefficient serving as the constant of proportionality. Therefore, the desired relation is

$$F_D = C_{\text{Drag}}\rho A_{\text{front}}V^2$$

Discussion Note that this approach is not sensitive to dimensionless quantities, and thus a strong reasoning is required.

Design and Essay Problems

1-59 to 1-60

Solution Students' essays and designs should be unique and will differ from each other.