Solutions Manual for
Fluid Mechanics: Fundamentals and Applications
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CHAPTER 1
INTRODUCTION AND BASIC CONCEPTS

Introduction, Classification, and System

1-1C

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, there different approximations are used in the analysis of fluid flows based on their classification.

1-2C

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.

1-3C

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.

1-4C

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.

1-5C

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

Analysis 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 the freestream value sufficiently far from the surface. The **region of flow in which the velocity gradients are significant and frictional effects are important** is called the *boundary layer*. 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).

1-6C

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.

1-7C

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.

1-8C

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 additional normal stresses, but when a fluid is at rest, the only normal stress is the pressure.

1-9C

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.]

1-10C

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 **properly selected region in space**.

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.

Mass, Force, and Units

1-11C

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.

1-12C

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.

1-13C

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

Analysis There is no acceleration, 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.

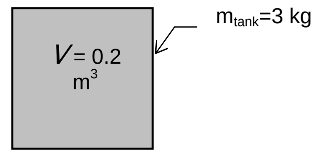
1-14

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 kg/m^3)(0.2 m^3) = 200 kg

$m_{total} = m_w + m_{tank}$ = 200 + 3 = 203 kg

Thus,

$$W = mg = (203\ \text{kg})(9.81\ \text{m/s}^2)\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right) = 1991\ \text{N} \cong \mathbf{1990\ N}$$

where we give the final answer to three significant digits.

Discussion Note the unity conversion factor in the above equation.

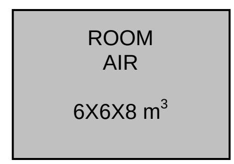
1-15

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 ρ = 1.16 kg/m^3.

Analysis The mass of the air in the room is



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

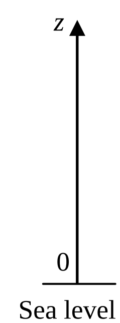
Thus,

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

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.

1-16

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

$$W = mg = m(9.807 - 3.32\times 10^{-6} z)$$

In our case,

$$W = 0.99W_s = 0.99mg_s = 0.99(m)(9.807)$$

Substituting,

$$0.99(9.807) = (9.807 - 3.32\times 10^{-6} z) \longrightarrow z = 29{,}540\ \text{m} \cong \mathbf{29{,}500\ m}$$

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.

1-17E

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:

$$W = mg = (150 \text{ lbm})(5.48 \text{ ft/s}^2)\left(\frac{1 \text{ lbf}}{32.2 \text{ lbm}\cdot\text{ft/s}^2}\right) = \mathbf{25.5\ lbf}$$

(*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,

$$W = \mathbf{150\ lbf}$$

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?

1-18

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.

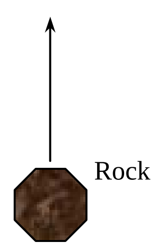
Discussion The man feels like he is six times heavier than normal. You get a similar feeling when riding an elevator to the top of a tall building, although to a much lesser extent.

1-19 **[*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.

1-20

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/s^2**, 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.

1-21

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.

Modeling and Solving Problems, and Precision

1-22C

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, 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.

1-23C

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.

1-24C

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 are 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.

1-25C

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.

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

1-26C

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.

1-27C

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.

1-28

Solution We are to determine a positive real root of the following equation using EES: $2x^3 - 10x^{0.5} - 3x = -3$.

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

```
2*x^3-10*x^0.5-3*x = -3
```

Answer: $\boldsymbol{x = 2.063}$ (using an initial guess of $x = 2$)

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

1-29

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=7.75
3*x*y+y=3.5
```

Answers: $\boldsymbol{x = 2.0}$, $\boldsymbol{y = 0.50}$.

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

1-30

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: $\boldsymbol{x = 1.141}$, $\boldsymbol{y = 0.8159}$, $\boldsymbol{z = 3.535}$.

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

1-31

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

Answers: $\boldsymbol{x = 1}$, $\boldsymbol{y = 1}$, $\boldsymbol{z = 0}$.

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

Review Problems

1-32

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

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

Sea level:	(z = 0 m): $W = 80\times(9.807-3.32\text{x}10^{-6}\times0) = 80\times9.807 =$ **784.6 N**
Denver:	(z = 1610 m): $W = 80\times(9.807-3.32\text{x}10^{-6}\times1610) = 80\times9.802 =$ **784.2 N**
Mt. Ev.:	(z = 8848 m): $W = 80\times(9.807-3.32\text{x}10^{-6}\times8848) = 80\times9.778 =$ **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.

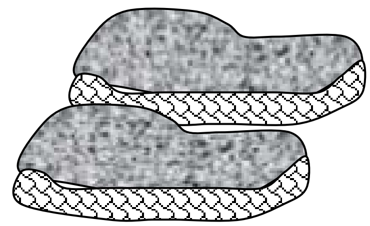
1-33

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.

1-34

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.

Design and Essay Problem

1-35

Solution We are to write an essay on mass- and volume-measurement devices.

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