1

Basic Considerations

Outline

Chapter Objectives

The objectives of this chapter are to:

- ▲ Introduce many of the quantities encountered in fluid mechanics including their dimensions and units.
- ▲ Identify the liquids to be considered in this text.
- ▲ Introduce the fluid properties of interest.
- ▲ Present the thermodynamic laws and associated quantities.

1.1 INTRODUCTION

A proper understanding of fluid mechanics is extremely important in many areas of engineering. In biomechanics the flow of blood and cerebral fluid are of particular interest; in meteorology and ocean engineering an understanding of the motions of air movements and ocean currents requires a knowledge of the mechanics of fluids, chemical engineers must understand fluid mechanics to design the many different kinds of chemical-processing equipment; aeronautical engineers use their knowledge of fluids to maximize lift and minimize drag on aircraft and to design fan-jet engines; mechanical engineers design pumps, turbines, internal combustion engines, air compressors, air-conditioning equipment, pollution-control equipment, and power plants using a proper understanding of fluid mechanics; and civil engineers must also utilize the results obtained from a study of the mechanics of fluids to understand the transport of river sediment and erosion, the pollution of the air and water, and to design piping systems, sewage treatment plants, irrigation channels, flood control systems, dams, and domed athletic stadiums.

KEY CONCEPT *We will present the fundamentals of fluids so that engineers are able to understand the role that fluid plays in particular applications.*

It is not possible to present fluid mechanics in such a way that all of the foregoing subjects can be treated specifically; it is possible, however, to present the fundamentals of the mechanics of fluids so that engineers are able to understand the role that the fluid plays in a particular application. This role may involve the proper sizing of a pump (the horsepower and flow rate) or the calculation of a force acting on a structure.

In this book we present the general equations, both integral and differential, that result from the conservation of mass principle, Newton's second law, and the first law of thermodynamics. From these a number of particular situations will be considered that are of special interest. After studying this book the engineer should be able to apply the basic principles of the mechanics of fluids to new and different situations.

In this chapter topics are presented that are directly or indirectly relevant to all subsequent chapters. We include a macroscopic description of fluids, fluid properties, physical laws dominating fluid mechanics, and a summary of units and dimensions of important physical quantities. Before we can discuss quantities of interest, we must present the units and dimensions that will be used in our study of fluid mechanics.

1.2 DIMENSIONS, UNITS, AND PHYSICAL QUANTITIES

Before we begin the more detailed studies of fluid mechanics, let us discuss the dimensions and units that will be used throughout the book. Physical quantities require quantitative descriptions when solving an engineering problem. Density is one such physical quantity. It is a measure of the mass contained in a unit volume. Density does not, however, represent a fundamental dimension. There are nine quantities that are considered to be fundamental dimensions: length, mass, time, temperature, amount of a substance, electric current, luminous intensity, plane angle, and solid angle. The dimensions of all other quantities can be expressed in terms of the fundamental dimensions. For example, the quantity "force" can be related to the fundamental dimensions of mass, length, and time. To do this, we use Newton's second law, named after Sir Isaac Newton (1642–1727), expressed in simplified form in one direction as

$$F = ma \tag{1.2.1}$$

Using brackets to denote "the dimension of," this is written dimensionally as

$$\begin{aligned} [F] &= [m][a] \\ F &= M\frac{L}{T^2} \end{aligned} \tag{1.2.2}$$

where F, M, L, and T are the dimensions of force, mass, length, and time, respectively. If force had been selected as a fundamental dimension rather than mass, a common alternative, mass would have dimensions of

$$\begin{aligned} [m] &= \frac{[F]}{[a]} \\ M &= \frac{FT^2}{L} \end{aligned} \tag{1.2.3}$$

where F is the dimension[1] of force.

There are also systems of dimensions in which both mass and force are selected as fundamental dimensions. In such systems conversion factors, such as a gravitational constant, are required; we do not consider these types of systems in this book, so they will not be discussed.

To give the dimensions of a quantity a numerical value, a set of units must be selected. In the United States, two primary systems of units are presently being used, the British Gravitational System, which we will refer to as English units, and the International System, which is referred to as SI (Système International) units. SI units are preferred and are used internationally; the United States is the only major country not requiring the use of SI units, but there is now a program of conversion in most industries to the predominant use of SI units. Following this trend, we have used primarily SI units. However, as English units are still in use, some examples and problems are presented in these units as well.

KEY CONCEPT *SI units are preferred and are used internationally.*

The fundamental dimensions and their units are presented in Table 1.1; some derived units appropriate to fluid mechanics are given in Table 1.2. Other units that are acceptable are the hectare (ha), which is 10 000 m^2, used for large areas; the metric ton (t), which is 1000 kg, used for large masses; and the liter (L), which is 0.001 m^3. Also, density is occasionally expressed as grams per liter (g/L).

In chemical calculations the mole is often a more convenient unit than the kilogram. In some cases it is also useful in fluid mechanics. For gases the

[1]Unfortunately, the quantity force F and the dimension of force $[F]$ use the same symbol.

Table 1.1 Fundamental Dimensions and Their Units

Quantity	*Dimensions*	*SI units*		*English units*	
Length ℓ	L	meter	m	foot	ft
Mass m	M	kilogram	kg	slug	slug
Time t	T	second	s	second	sec
Electric current i		ampere	A	ampere	A
Temperature T	Θ	kelvin	K	Rankine	°R
Amount of substance	M	kg-mole	kmol	lb-mole	lbmol
Luminous intensity		candela	cd	candela	cd
Plane angle		radian	rad	radian	rad
Solid angle		steradian	sr	steradian	sr

kilogram-mole (kmol) is the quantity that fills the same volume as 32 kilograms of oxygen at the same temperature and pressure. The mass (in kilograms) of a gas filling that volume is equal to the molecular weight of the gas; for example, the mass of 1 kmol of nitrogen is 28 kilograms.

When expressing a quantity with a numerical value and a unit, prefixes have been defined so that the numerical value may be between 0.1 and 1000. These

Table 1.2 Derived Units

Quantity	*Dimensions*	*SI units*	*English units*
Area A	L^2	m^2	ft^2
Volume $\forall$	L^3	m^3	ft^3
		L (liter)	
Velocity V	L/T	m/s	ft/sec
Acceleration a	L/T^2	m/s^2	ft/sec^2
Angular velocity ω	T^{-1}	rad/s	rad/sec
Force F	ML/T^2	kg·m/s^2	slug-ft/sec^2
		N (newton)	lb (pound)
Density ρ	M/L^3	kg/m^3	slug/ft^3
Specific weight γ	M/L^2T^2	N/m^3	lb/ft^3
Frequency f	T^{-1}	s^{-1}	sec^{-1}
Pressure p	M/LT^2	N/m^2	lb/ft^2
		Pa (pascal)	(psf)
Stress τ	M/LT^2	N/m^2	lb/ft^2
		Pa (pascal)	(psf)
Surface tension σ	M/T^2	N/m	lb/ft
Work W	ML^2/T^2	N·m	ft-lb
		J (joule)	
Energy E	ML^2/T^2	N·m	ft-lb
		J (joule)	
Heat rate $\dot{Q}$	ML^2/T^3	J/s	Btu/sec
Torque T	ML^2/T^2	N·m	ft-lb
Power P	ML^2/T^3	J/s	ft-lb/sec
$\dot{W}$		W (watt)	
Viscosity μ	M/LT	N·s/m^2	lb-sec/ft^2
Mass flux $\dot{m}$	M/T	kg/s	slug/sec
Flow rate Q	L^3/T	m^3/s	ft^3/sec
Specific heat c	$L^2/T^2\Theta$	J/kg·K	Btu/slug-°R
Conductivity K	$ML/T^3\Theta$	W/m·K	lb/sec-°R

Table 1.3 SI Prefixes

Multiplication factor	*Prefix*	*Symbol*
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi[a]	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

[a]Permissible if used alone as cm, cm^2, or cm^3.

prefixes are presented in Table 1.3. Using scientific notation, however, we use powers of 10 rather than prefixes (e.g., 2×10^6 N rather than 2 MN). If larger numbers are written the comma is not used; twenty thousand would be written as 20 000 with a space and no comma.[2]

KEY CONCEPT *When using SI units, if larger numbers are written (5 digits or more), the comma is not used. The comma is replaced by a space (i.e.,* 20 000*).*

Newton's second law relates a net force acting on a rigid body to its mass and acceleration. This is expressed as

$$\Sigma \mathbf{F} = m\mathbf{a} \tag{1.2.4}$$

Consequently, the force needed to accelerate a mass of 1 kilogram at 1 meter per second squared in the direction of the net force is 1 newton; using English units, the force needed to accelerate a mass of 1 slug at 1 foot per second squared in the direction of the net force is 1 pound. This allows us to relate the units by

$$\text{N} = \text{kg}\cdot\text{m/s}^2 \qquad \text{lb} = \text{slug-ft/sec}^2 \tag{1.2.5}$$

KEY CONCEPT *The relationship* $\text{N} = \text{kg}\cdot\text{m/s}^2$ *is often used in the conversion of units.*

which are included in Table 1.2. These relationships between units are often used in the conversion of units. In the SI system, weight is always expressed in newtons, never in kilograms. In the English system, mass is usually expressed in slugs, although pounds are used in some thermodynamic relations. To relate weight to mass, we use

$$W = mg \tag{1.2.6}$$

where g is the local gravity. The standard value for gravity is 9.80665 m/s^2 (32.174 ft/sec^2) and it varies from a minimum of 9.77 m/s^2 at the top of Mt. Everest to a maximum of 9.83 m/s^2 in the deepest ocean trench. A nominal value of 9.81 m/s^2 (32.2 ft/sec^2) will be used unless otherwise stated.

Finally, a note on significant figures. In engineering calculations we often do not have confidence in a calculation beyond three significant digits since the information

[2]In many countries commas represent decimal points, so they are not used where confusion may occur.

given in the problem statement is often not known to more than three significant digits; in fact, viscosity and other fluid properties may not be known to even three significant digits. The diameter of a pipe may be stated as 2 cm; this would, in general, not be as precise as 2.000 cm would imply. If information used in the solution of a problem is known to only two significant digits, it is incorrect to express a result to more than two significant digits. In the examples and problems we will assume that all information given is known to three significant digits, and the results will be expressed accordingly. If the numeral 1 begins a number, it is not counted in the number of significant digits, i.e., the number 1.210 has three significant digits.

KEY CONCEPT *We will assume that all information given is known to three significant digits.*

Example 1.1

A mass of 100 kg is acted on by a 400-N force acting vertically upward and a 600-N force acting upward at a 45° angle. Calculate the vertical component of the acceleration. The local acceleration of gravity is 9.81 m/s^2.

Solution

The first step in solving a problem involving forces is to draw a free-body diagram with all forces acting on it, as shown in Fig. E1.1.

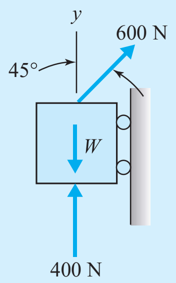

Fig. E1.1

Next, apply Newton's second law (Eq. 1.2.4). It relates the net force acting on a mass to the acceleration and is expressed as

$$\Sigma F_y = ma_y$$

Using the appropriate components in the y-direction, with $W = mg$, we have

$$400 + 600 \sin 45° - 100 \times 9.81 = 100a_y$$
$$a_y = -1.567 \text{ m/s}^2$$

The negative sign indicates that the acceleration is in the negative y-direction, i.e., down. *Note:* We have used only three significant digits in the answer since the information given in the problem is assumed known to three significant digits. (The number 1.567 has three significant digits. A leading "1" is not counted as a significant digit.)

1.3 CONTINUUM VIEW OF GASES AND LIQUIDS

Substances referred to as fluids may be **liquids** or **gases**. In our study of the fluid mechanics we restrict the liquids that are studied. Before we state the restriction, we must define a shearing stress. A force ΔF that acts on an area ΔA can be decomposed into a normal component ΔF_n and a tangential component ΔF_t, as shown in Fig. 1.1. The force divided by the area upon which it acts is called a *stress*. The force vector divided by the area is a **stress vector**[3], the normal component of force divided by the area is a **normal stress**, and the tangential force divided by the area is a **shear stress**. In this discussion we are interested in the shear stress τ. Mathematically, it is defined as

$$\tau = \lim_{\Delta A \to 0} \frac{\Delta F_t}{\Delta A} \tag{1.3.1}$$

Our restricted family of fluids may now be identified; the fluids considered in this book are *those liquids and gases that move under the action of a shear stress, no matter how small that shear stress may be.* This means that even a very small shear stress results in motion in the fluid. Gases obviously fall within this category of fluids, as do water and tar. Some substances, such as plastics and catsup, may resist small shear stresses without moving; a study of these substances is included in the subject of *rheology* and is not included in this book.

It is worthwhile to consider the microscopic behavior of fluids in more detail. Consider the molecules of a gas in a container. These molecules are not stationary but move about in space with very high velocities. They collide with each other and strike the walls of the container in which they are confined, giving rise to the pressure exerted by the gas. If the volume of the container is increased while the temperature is maintained constant, the number of molecules impacting on a given area is decreased, and as a result, the pressure decreases. If the temperature of a gas in a given volume increases (i.e., the velocities of the molecules increase), the pressure increases due to increased molecular activity.

Molecular forces in liquids are relatively high, as can be inferred from the following example. The pressure necessary to compress 20 grams of water vapor at 20 °C into 20 cm^3, assuming that no molecular forces exist, can be shown by the ideal gas law to be approximately 1340 times the atmospheric pressure. Of course, this pressure is not required, because 20 g of water occupies 20 cm^3. It follows that the cohesive forces in the liquid phase must be very large.

Despite the high molecular attractive forces in a liquid, some of the molecules at the surface escape into the space above. If the liquid is contained, an equilibrium is established between outgoing and incoming molecules. The presence of molecules above the liquid surface leads to a so-called *vapor pressure*.

Stress vector: *The force vector divided by the area.*

Normal stress: *The normal component of force divided by the area.*

Shear stress: *The tangential force divided by the area.*

Liquid: *A state of matter in which the molecules are relatively free to change their positions with respect to each other but restricted by cohesive forces so as to maintain a relatively fixed volume.*[4]

Gas: *A state of matter in which the molecules are practically unrestricted by cohesive forces. A gas has neither definite shape nor volume.*

KEY CONCEPT *Fluids considered in this text are those that move under the action of a shear stress, no matter how small that stress may be.*

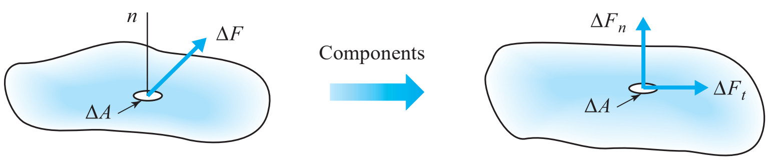

Fig. 1.1 Normal and tangential components of a force.

[3] *A quantity that is defined in the margin is in bold face whereas a quantity not defined in the margin is italic.*

[4] *Handbook of Chemistry and Physics*, 40th ed. CRC Press, Boca Raton, Fla.

This pressure increases with temperature. For water at 20°C this pressure is approximately 0.02 times the atmospheric pressure.

Continuum: *Continuous distribution of a liquid or gas throughout a region of interest.*

In our study of fluid mechanics it is convenient to assume that both gases and liquids are continuously distributed throughout a region of interest, that is, the fluid is treated as a **continuum**. The primary property used to determine if the continuum assumption is appropriate is the *density* ρ, defined by

$$\rho = \lim_{\Delta v \to 0} \frac{\Delta m}{\Delta V} \tag{1.3.2}$$

Standard atmospheric conditions: *A pressure of* 101.3 kPa *and temperature of* 15°C.

where Δm is the incremental mass contained in the incremental volume ΔV. The density for air at **standard atmospheric conditions**, that is, at a pressure of 101.3 kPa (14.7 psi) and a temperature of 15°C (59°F), is 1.23 kg/m^3 (0.00238 slug/ft^3). For water, the nominal value of density is 1000 kg/m^3 (1.94 slug/ft^3).

KEY CONCEPT *To determine if the continuum model is acceptable, compare a length l with the mean free path.*

Physically, we cannot let $\Delta V \to 0$ since, as ΔV gets extremely small, the mass contained in ΔV would vary discontinuously depending on the number of molecules in ΔV; this is shown graphically in Fig. 1.2. Actually, the zero in the definition of density should be replaced by some small volume ε, below which the continuum assumption fails. For most engineering applications, the small volume ε shown in Fig. 1.2 is extremely small. For example, there are 2.7×10^{16} molecules contained in a cubic millimeter of air at standard conditions; hence, ε is much smaller than a cubic millimeter. An appropriate way to determine if the continuum model is acceptable is to compare a characteristic length l (e.g., the diameter of a rocket) of the device or object of interest with the **mean free path** λ, the average distance a molecule travels before it collides with another molecule; if $l \gg \lambda$, the continuum model is acceptable. The mean free path is derived in molecular theory. It is

Mean free path: *The average distance a molecule travels before it collides with another molecule.*

$$\lambda = 0.225 \frac{m}{\rho d^2} \tag{1.3.3}$$

where m is the mass (kg) of a molecule, ρ the density (kg/m^3) and d the diameter (m) of a molecule. For air $m = 4.8 \times 10^{-26}$ kg and $d = 3.7 \times 10^{-10}$ m. At standard atmospheric conditions the mean free path is approximately 6.4×10^{-6} cm,

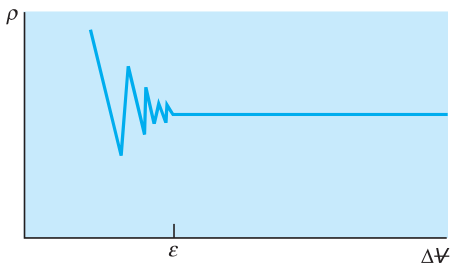

Fig. 1.2 Density at a point in a continuum.

at an elevation of 100 km it is 10 cm, and at 160 km it is 5000 cm. Obviously, at higher elevations the continuum assumption is not acceptable and the theory of rarefied gas dynamics (or free molecular flow) must be utilized. Satellites are able to orbit the earth if the primary dimension of the satellite is of the same order of magnitude as the mean free path.

With the continuum assumption, fluid properties can be assumed to apply uniformly at all points in a region at any particular instant in time. For example, the density ρ can be defined at all points in the fluid; it may vary from point to point and from instant to instant; that is, in Cartesian coordinates ρ is a continuous function of x, y, z, and t, written as $\rho(x, y, z, t)$.

1.4 PRESSURE AND TEMPERATURE SCALES

In fluid mechanics pressure results from a normal compressive force acting on an area. The *pressure p* is defined as (see Fig. 1.3)

$$p = \lim_{\Delta A \to 0} \frac{\Delta F_n}{\Delta A} \tag{1.4.1}$$

where ΔF_n is the incremental normal compressive force acting on the incremental area ΔA. The metric units to be used on pressure are newtons per square meter (N/m^2) or pascal (Pa). Since the pascal is a very small unit of pressure, it is more conventional to express pressure in units of kilopascal (kPa). For example, standard atmospheric pressure at sea level is 101.3 kPa. The English units for pressure are pounds per square inch (psi) or pounds per square foot (psf). Atmospheric pressure is often expressed as inches of mercury or feet of water, as shown in Fig. 1.4; such a column of fluid creates the pressure at the bottom of the column, providing the column is open to atmospheric pressure at the top.

KEY CONCEPT *In many relationships, absolute scales must be used for pressure and temperature.*

Both pressure and temperature are physical quantities that can be measured using different scales. There exist absolute scales for pressure and temperature, and there are scales that measure these quantities relative to selected reference points. In many thermodynamic relationships (see Section 1.7) absolute scales must be used for pressure and temperature. Figures 1.4 and 1.5 summarize the commonly used scales.

Absolute pressure: *The scale measuring pressure, where zero is reached when an ideal vacuum is achieved.*

The **absolute pressure** reaches zero when an ideal vacuum is achieved, that is, when no molecules are left in a space; consequently, a negative absolute pressure is an impossibility. A second scale is defined by measuring pressures relative

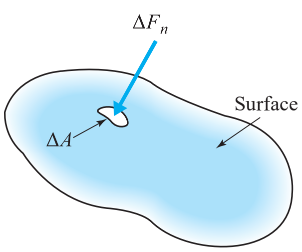

Fig. 1.3 Definition of pressure.

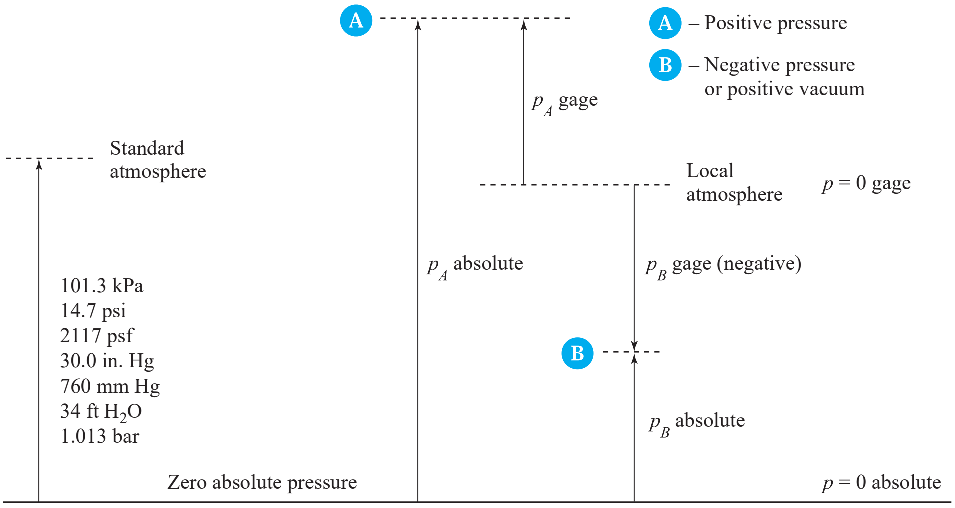

Fig. 1.4 Gage pressure and absolute pressure.

Gage pressure: *The scale measuring pressure relative to the local atmospheric pressure.*

to the local atmospheric pressure. This pressure is called **gage pressure**. A conversion from gage pressure to absolute pressure can be carried out using

$$p_{\text{absolute}} = p_{\text{atmospheric}} + p_{\text{gage}} \tag{1.4.2}$$

KEY CONCEPT
Whenever the absolute pressure is less than the atmospheric pressure, it may be called a vacuum.

Vacuum: *Whenever the absolute pressure is less than the atmospheric pressure.*

Note that the atmospheric pressure in Eq. 1.4.2 is the local atmospheric pressure, which may change with time, particularly when a weather "front" moves through. However, if the local atmospheric pressure is not given, we use the value given for a particular elevation, as given in Table B.3 of Appendix B, and assume zero elevation if the elevation is unknown. The gage pressure is negative whenever the absolute pressure is less than atmospheric pressure; it may then be called a **vacuum**. In this book the word "absolute" will generally follow the pressure value if the pressure is given as an absolute pressure (e.g., $p = 50$ kPa absolute). If it were stated as $p = 50$ kPa, the pressure would be taken as a gage pressure, except that atmospheric pressure is always an absolute pressure. Most often in fluid mechanics gage pressure is used.

	°C	K	°F	°R
Steam point	100°	373	212°	672°
Ice point	0°	273	32°	492°
Special point	–18°	255	0°	460°
Zero absolute temperature				

Fig. 1.5 Temperature scales.

Two temperature scales are commonly used, the Celsius (C) and Fahrenheit (F) scales. Both scales are based on the ice point and steam point of water at an atmospheric pressure of 101.3 kPa (14.7 psi). Figure 1.5 shows that the ice and steam point are 0 and 100°C on the Celsius scale and 32 and 212°F on the Fahrenheit scale. There are two corresponding absolute temperature scales. The absolute scale corresponding to the Celsius scale is the kelvin (K) scale. The relation between these scales is

$$K = °C + 273.15 \qquad (1.4.3)$$

The absolute scale corresponding to the Fahrenheit scale is the Rankine scale (°R). The relation between these scales is

$$°R = °F + 459.67 \qquad (1.4.4)$$

Note that in the SI system we do not write 100°K but simply 100 K, which is read "100 kelvins," similar to other units.

KEY CONCEPT *In the SI system, we write* 100 K, *which is read "*100 *kelvins."*

Reference will often be made to "standard atmospheric conditions" or "standard temperature and pressure." This refers to sea-level conditions at 40° latitude, which are taken to be 101.3 kPa (14.7 psi) for pressure and 15°C (59°F) for temperature. Actually, The standard pressure is usually taken as 100 kPa, sufficiently accurate for engineering calculations.

Example 1.2

A pressure gage attached to a rigid tank measures a vacuum of 42 kPa inside the tank shown in Fig. E1.2, which is situated at a site in Colorado where the elevation is 2000 m. Determine the absolute pressure inside the tank.

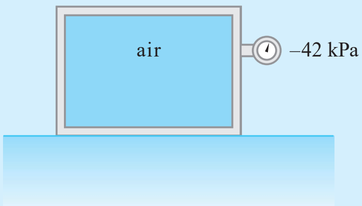

Fig. E1.2

Solution

To determine the absolute pressure, the atmospheric pressure must be known. If the elevation were not given, we would assume a standard atmospheric pressure of 100 kPa. However, with the elevation given, the atmospheric pressure is found from Table B.3 in Appendix B to be 79.5 kPa. Thus

$$p = -42 + 79.5 = 37.5 \text{ kPa absolute}$$

Note: A vacuum is always a negative gage pressure. Also, using standard atmospheric pressure of 100 kPa is acceptable, rather than 101.3 kPa, since it is within 1%, which is acceptable engineering accuracy.

1.5 FLUID PROPERTIES

In this section we present several of the more common fluid properties. If density variation or heat transfer is significant, several additional properties, not presented here, become important.

1.5.1 Density and Specific Weight

Specific weight: *Weight per unit volume ($\gamma = \rho g$).*

Fluid density was defined in Eq. 1.3.2 as mass per unit volume. A fluid property directly related to density is the **specific weight** γ or weight per unit volume. It is defined by

$$\gamma = \frac{W}{V\!\!\!\!-} = \frac{mg}{V\!\!\!\!-} = \rho g \tag{1.5.1}$$

Specific gravity: *The ratio of the density of a substance to the density of water.*

where g is the local gravity. The units of specific weight are N/m^3 (lb/ft^3). For water we use the nominal value of 9800 N/m^3 (62.4 lb/ft^3).

The **specific gravity** S is often used to determine the specific weight or density of a fluid (usually a liquid). It is defined as the ratio of the density of a substance to the density of water at a reference temperature of 4°C:

$$S = \frac{\rho}{\rho_{\text{water}}} = \frac{\gamma}{\gamma_{\text{water}}} \tag{1.5.2}$$

KEY CONCEPT *Specific gravity is often used to determine the density of a fluid.*

For example, the specific gravity of mercury is 13.6, a dimensionless number; that is, the mass of mercury is 13.6 times that of water for the same volume. The density, specific weight, and specific gravity of air and water at standard conditions are given in Table 1.4.

The density and specific weight of water do vary slightly with temperature; the approximate relationships are

$$\begin{aligned} \rho_{H_2O} &= 1000 - \frac{(T-4)^2}{180} \\ \gamma_{H_2O} &= 9800 - \frac{(T-4)^2}{18} \end{aligned} \tag{1.5.3}$$

TABLE 1.4 Density, Specific Weight, and Specific Gravity of Air and Water at Standard Conditions

	Density ρ		*Specific weight γ*		
	kg/m^3	slug/ft^3	N/m^3	lb/ft^3	*Specific gravity S*
Air	1.23	0.0024	12.1	0.077	0.00123
Water	1000	1.94	9810	62.4	1

For mercury the specific gravity relates to temperature by

$$S_{Hg} = 13.6 - 0.0024T \tag{1.5.4}$$

Temperature in the three equations above is measured in degrees Celsius. For temperatures under 50°C, using the nominal values stated earlier for water and mercury, the error is less than 1%, certainly within engineering limits for most design problems. Note that the density of water at 0°C (32°F) is less than that at 4°C; consequently, the lighter water at 0°C rises to the top of a lake so that ice forms on the surface. For most other liquids the density at freezing is greater than the density just above freezing.

1.5.2 Viscosity

Viscosity: *The internal stickiness of a fluid.*

Viscosity can be thought of as the internal stickiness of a fluid. It is one of the properties that influences the power needed to move an airfoil through the atmosphere. It accounts for the energy losses associated with the transport of fluids in ducts, channels, and pipes. Further, viscosity plays a primary role in the generation of turbulence. Needless to say, viscosity is an extremely important fluid property in our study of fluid flows.

KEY CONCEPT *Viscosity plays a primary role in the generation of turbulence.*

The rate of deformation of a fluid is directly linked to the viscosity of the fluid. For a given stress, a highly viscous fluid deforms at a slower rate than a fluid with a low viscosity. Consider the flow of Fig. 1.6 in which the fluid particles move in the x-direction at different speeds, so that particle velocities u vary with the y-coordinate. Two particle positions are shown at different times; observe how the particles move relative to one another. For such a simple flow field, in which $u = u(y)$, we can define the **viscosity** μ of the fluid by the relationship

$$\tau = \mu \frac{du}{dy} \tag{1.5.5}$$

where τ is the shear stress of Eq. 1.3.1 and u is the velocity in the x-direction. The units of τ are N/m^2 or Pa (lb/ft^2), and of μ are N·s/m^2 (lb-sec/ft^2). The quantity du/dy is a velocity gradient and can be interpreted as a **strain rate**. Stress velocity-gradient relationships for more complicated flow situations are presented in Chapter 5.

Strain rate: *The rate at which a fluid element deforms.*

The concept of viscosity and velocity gradients can also be illustrated by considering a fluid within the small gap between two concentric cylinders, as shown

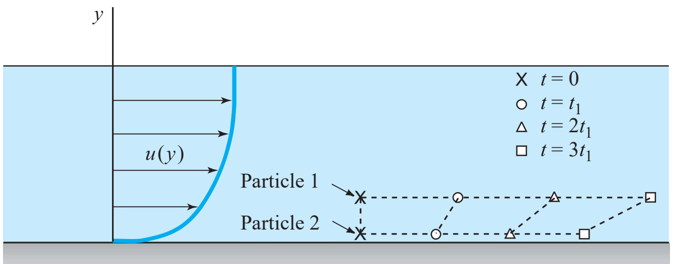

Fig. 1.6 Relative movement of two fluid particles in the presence of shear stresses.

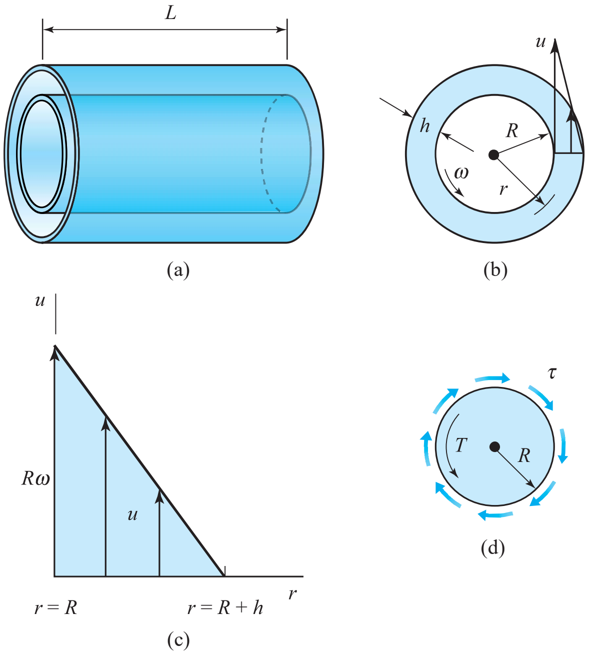

Fig. 1.7 Fluid being sheared between cylinders with a small gap: (a) the two cylinders; (b) rotating inner cylinder; (c) velocity distribution; (d) the inner cylinder. The outer cylinder is fixed and the inner cylinder is rotating.

in Fig. 1.7. A torque is necessary to rotate the inner cylinder at constant rotational speed ω while the outer cylinder remains stationary. This resistance to the rotation of the cylinder is due to viscosity. The only stress that exists to resist the applied torque for this simple flow is a shear stress, which is observed to depend directly on the velocity gradient; that is,

$$\tau = \mu \left|\frac{du}{dr}\right| \tag{1.5.6}$$

where du/dr is the velocity gradient and u is the tangential velocity component, which depends only on r. For a small gap ($h \ll R$), this gradient can be approximated by assuming a linear velocity distribution[5] in the gap. Thus

$$\left|\frac{du}{dr}\right| = \frac{\omega R}{h} \tag{1.5.7}$$

where h is the gap width. We can thus relate the applied torque T to the viscosity and other parameters by the equation

$$\begin{aligned} T &= \text{stress} \times \text{area} \times \text{moment arm} \\ &= \tau \times 2\pi RL \times R \\ &= \mu \frac{\omega R}{h} \times 2\pi RL \times R = \frac{2\pi R^3 \omega L \mu}{h} \end{aligned} \tag{1.5.8}$$

[5]If the gap is not small relative to R, the velocity distribution will not be linear (see Section 7.5). The distribution will also not be linear for relatively small values of ω.

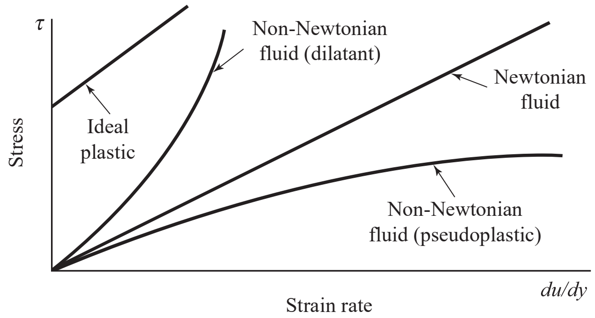

Fig. 1.8 Newtonian and non-Newtonian fluids.

where the shearing stress acting on the ends of the cylinder is negligible; L represents the length of the rotating cylinder. Note that the torque depends directly on the viscosity; thus the cylinders could be used as a *viscometer*, a device that measures the viscosity of a fluid.

Viscosity[6], 454

If the shear stress of a fluid is directly proportional to the velocity gradient, as was assumed in Eqs. 1.5.5 and 1.5.6, the fluid is said to be a **Newtonian fluid**. Fortunately, many common fluids, such as air, water, and oil, are Newtonian. *Non-Newtonian fluids*, with shear stress versus strain rate relationships as shown in Fig. 1.8, often have a complex molecular composition.

Newtonian fluid: *the shear stress of the fluid is directly proportional to the velocity gradient.*

Dilatants (quicksand, slurries) become more resistant to motion as the strain rate increases, and *pseudoplastics* (paint and catsup) become less resistant to motion with increased strain rate. *Ideal plastics* (or *Bingham fluids*) require a minimum shear stress to cause motion. Clay suspensions and toothpaste are examples that also require a minimum shear to cause motion, but they do not have a linear stress-strain rate relationship.

KEY CONCEPT *Viscosity causes fluid to adhere to a surface.*

An extremely important effect of viscosity is to cause the fluid to adhere to the surface; this is known as the **no-slip condition**. This was assumed in the example of Fig. 1.7. The velocity of the fluid at the rotating cylinder was taken to be ωR, and the velocity of the fluid at the stationary cylinder was set equal to zero, as shown in Fig. 1.7b. When a space vehicle reenters the atmosphere, the high speed creates very large velocity gradients at the surface of the vehicle, resulting in large stresses that heat up the surface; the high temperatures can cause the vehicle to disintegrate if not properly protected.

No-slip condition: *Condition where viscosity causes fluid to adhere to the surface.*

The viscosity is very dependent on temperature in liquids in which cohesive forces play a dominant role; note that the viscosity of a liquid decreases with increased temperature, as shown in Fig. B.1 in Appendix B. The curves are often approximated by the equation

$$\mu = Ae^{Bt} \tag{1.5.9}$$

known as *Andrade's equation*; the constants A and B would be determined from measured data. For a gas it is molecular collisions that provide the internal stresses, so that as the temperature increases, resulting in increased molecular

[6]To view a file on a specified page, simply open any of the eight major headings, then enter a page number in the box at the top and click on "go to page." The numbers after the descriptors refer to the pages on the DVD.

activity, the viscosity increases. This can be observed in the bottom curve for a gas of Fig. B.1 in Appendix B. Note, however, that the percentage change of viscosity in a liquid is much greater than in a gas for the same temperature difference. Also, one can show that cohesive forces and molecular activity are quite insensitive to pressure, so that $\mu = \mu(T)$ only for both liquids and gases.

Since the viscosity is often divided by the density in the derivation of equations, it has become useful and customary to define *kinematic viscosity* to be

$$v = \frac{\mu}{\rho} \tag{1.5.10}$$

where the units of v are m^2/s (ft^2/sec). Note that for a gas, the kinematic viscosity will also depend on the pressure since density is pressure sensitive. The kinematic viscosity is shown, at atmospheric pressure, in Fig. B.2 in Appendix B.

Example 1.3

A viscometer is constructed with two 30-cm-long concentric cylinders, one 20.0 cm in diameter and the other 20.2 cm in diameter. A torque of 0.13 N·m is required to rotate the inner cylinder at 400 rpm (revolutions per minute). Calculate the viscosity.

Solution

The applied torque is just balanced by a resisting torque due to the shear stresses (see Fig. 1.7c). This is expressed by the small gap equation, Eq. 1.5.8.

The radius is $R = d/2 = 10$ cm; the gap $h = (d_2 - d_1)/2 = 0.1$ cm; the rotational speed, expressed as rad/s, is $\omega = 400 \times 2\pi/60 = 41.89$ rad/s.

Equation 1.5.8 provides:

$$\begin{aligned}\mu &= \frac{Th}{2\pi R^3 \omega L} \\ &= \frac{0.13(0.001)}{2\pi(0.1)^3(41.89)(0.3)} = 0.001646 \text{ N}\cdot\text{s/m}^2\end{aligned}$$

Note: All lengths are in meters so that the desired units on μ are obtained. The units can be checked by substitution:

$$[\mu] = \frac{\text{N}\cdot\text{m}\cdot\text{m}}{\text{m}^3(\text{rad/s})\text{m}} = \frac{\text{N}\cdot\text{s}}{\text{m}^2}$$

1.5.3 Compressibility

Bulk modulus of elasticity: *The ratio of change in pressure to relative change in density.*

In the preceding section we discussed the deformation of fluids that results from shear stresses. In this section we discuss the deformation that results from pressure changes. All fluids compress if the pressure increases, resulting in a decrease in volume or an increase in density. A common way to describe the compressibility of a fluid is by the following definition of the **bulk modulus of elasticity** B:

$$B = \lim_{\Delta V \to 0}\left[-\frac{\Delta p}{\Delta V/V}\right]_T = \lim_{\Delta \rho \to 0}\frac{\Delta p}{\Delta \rho/\rho}\bigg|_T$$
$$= -V\frac{\partial p}{\partial V}\bigg|_T = \rho\frac{\partial p}{\partial \rho}\bigg|_T \qquad (1.5.11)$$

In words, the bulk modulus, also called the *coefficient of compressibility*, is defined as the ratio of the change in pressure (Δp) to relative change in density ($\Delta\rho/\rho$) while the temperature remains constant. The bulk modulus has the same units as pressure.

The bulk modulus for water at standard conditions is approximately 2100 MPa (310,000 psi), or 21 000 times the atmospheric pressure. For air at standard conditions, B is equal to 1 atm. In general, B for a gas is equal to the pressure of the gas. To cause a 1% change in the density of water a pressure of 21 MPa (210 atm) is required. This is an extremely large pressure needed to cause such a small change; thus liquids are often assumed to be incompressible. For gases, if significant changes in density occur, say 4%, they should be considered as compressible; for small density changes under 3% they may also be treated as incompressible. This occurs for atmospheric airspeeds under about 100 m/s (220 mph), which includes many airflows of engineering interest: air flow around automobiles, landing and take-off of aircraft, and air flow in and around buildings.

KEY CONCEPT *Gases with small density changes under 3% may be treated as incompressible.*

Small density changes in liquids can be very significant when large pressure changes are present. For example, they account for "water hammer," which can be heard shortly after the sudden closing of a valve in a pipeline; when the valve is closed an internal pressure wave propagates down the pipe, producing a hammering sound due to pipe motion when the wave reflects from the closed valve or pipe elbows. Water hammer is considered in detail in Section 11.5.

The bulk modulus can also be used to calculate the speed of sound in a liquid; in Section 9.2 it will be shown to be given by

$$c = \sqrt{\frac{\Delta p}{\Delta \rho}\bigg|_T} = \sqrt{\frac{B}{\rho}} \qquad (1.5.12)$$

This yields approximately 1450 m/s (4800 ft/sec) for the speed of sound in water at standard conditions. The speed of sound in a gas will be presented in Section 1.7.3.

1.5.4 Surface Tension

Surface tension is a property that results from the attractive forces between molecules. As such, it manifests itself only in liquids at an interface, usually a liquid-gas interface. The forces between molecules in the bulk of a liquid are equal in all directions, and as a result, no net force is exerted on the molecules. However, at an interface the molecules exert a force that has a resultant in the interface layer. This force holds a drop of water suspended on a rod and limits the size of the drop that may be held. It also causes the small drops from a

Surface tension: *A property resulting from the attractive forces between molecules.*

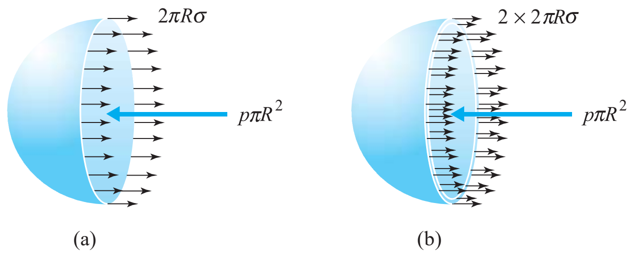

Fig. 1.9 Internal forces in (a) a droplet and (b) a bubble.

KEY CONCEPT *Force due to surface tension results from a length multiplied by the surface tension.*

Drop Formation, 453

sprayer or atomizer to assume spherical shapes. It may also play a significant role when two immiscible liquids (e.g., oil and water) are in contact with each other.

Surface tension has units of force per unit length, N/m (lb/ft). The force due to surface tension results from a length multiplied by the surface tension; the length to use is the length of fluid in contact with a solid, or the circumference in the case of a bubble. A surface tension effect can be illustrated by considering the free-body diagrams of half a droplet and half a bubble, as shown in Fig. 1.9. The droplet has one surface, and the bubble is composed of a thin film of liquid with an inside surface and an outside surface. An expression for the pressure inside the droplet and bubble can now be derived.

The pressure force $p\pi R^2$ in the droplet balances the surface tension force around the circumference. Hence

$$p\pi R^2 = 2\pi R\sigma$$

$$\therefore p = \frac{2\sigma}{R} \tag{1.5.13}$$

Similarly, the pressure force in the bubble is balanced by the surface tension forces on the two circumferences assuming the bubble thickness is small. Therefore,

$$p\pi R^2 = 2(2\pi R\sigma)$$

$$\therefore p = \frac{4\sigma}{R} \tag{1.5.14}$$

From Eqs. 1.5.13 and 1.5.14 we can conclude that the internal pressure in a bubble is twice as large as that in a droplet of the same size.

Figure 1.10 shows the rise of a liquid in a clean glass capillary tube due to surface tension. The liquid makes a contact angle β with the glass tube. Experiments have shown that this angle for water and most liquids in a clean glass tube is zero. There are also cases for which this angle is greater than 90° (e.g., mercury); such liquids have a capillary drop. If h is the capillary rise, D the diameter, ρ the density, and σ the surface tension, h can be determined from

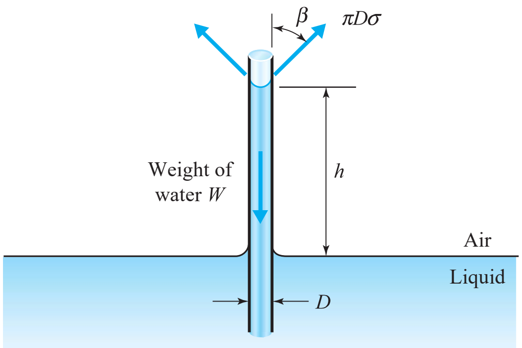

Fig. 1.10 Rise in a capillary tube.

equating the vertical component of the surface tension force to the weight of the liquid column:

$$\sigma\pi D\cos\beta = \gamma\frac{\pi D^2}{4}h \tag{1.5.15}$$

or, rearranged,

$$h = \frac{4\sigma\cos\beta}{\gamma D} \tag{1.5.16}$$

Surface tension may influence engineering problems when, for example, laboratory modeling of waves is conducted at a scale that surface tension forces are of the same order of magnitude as gravitational forces.

Example 1.4

A 2-mm-diameter clean glass tube is inserted in water at 15°C (Fig. E1.4). Determine the height that the water will climb up the tube. The water makes a contact angle of 0° with the clean glass.

Capillary, 346

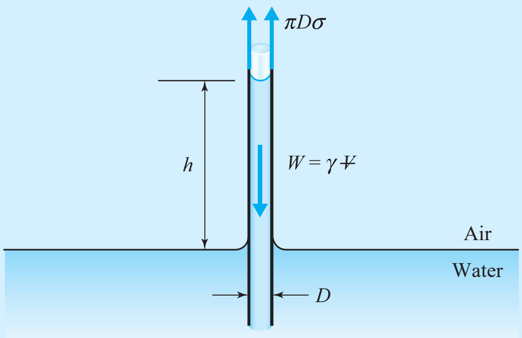

Fig. E1.4

Solution

A free-body diagram of the water shows that the upward surface-tension force is equal and opposite to the weight. Writing the surface-tension force as surface tension times distance, we have

$$\sigma \pi D = \gamma \frac{\pi D^2}{4} h$$

or

$$h = \frac{4\sigma}{\gamma D} = \frac{4 \times 0.0741 \text{ N/m}}{9800 \text{ N/m}^3 \times 0.002 \text{ m}} = 0.01512 \text{ m} \quad \text{or} \quad 15.12 \text{ mm}$$

The numerical values for σ and ρ were obtained from Table B.1 in Appendix B. Note that the nominal value used for the specific weight of water is $\gamma = \rho g = 9800 \text{ N/m}^3$.

Example 1.4a on the DVD, Similarity and Scaling, Capillary Rise 512

1.5.5 Vapor Pressure

Fig. 1.11 Cooking food in boiling water takes a longer amount of time at a high altitude. It would take longer to boil these eggs in Denver than in New York City. (Thomas Firak Photography/FoodPix/Getty Images)

Vapor pressure: *The pressure resulting from molecules in a gaseous state.*

KEY CONCEPT *Cavitation can be very damaging.*

Boiling: *The point where vapor pressure is equal to the atmospheric pressure.*

Cavitation: *Bubbles form in a liquid when the local pressure falls below the vapor pressure of the liquid.*

When a small quantity of liquid is placed in a closed container, a certain fraction of the liquid will vaporize. Vaporization will terminate when equilibrium is reached between the liquid and gaseous states of the substance in the container—in other words, when the number of molecules escaping from the water surface is equal to the number of incoming molecules. The pressure resulting from molecules in the gaseous state is the **vapor pressure**.

The vapor pressure is different from one liquid to another. For example, the vapor pressure of water at 15°C is 1.70 kPa absolute, and for ammonia it is 33.8 kPa absolute.

The vapor pressure is highly dependent on temperature; it increases significantly when the temperature increases. For example, the vapor pressure of water increases to 101.3 kPa (14.7 psi) if the temperature reaches 100°C (212°F). Water vapor pressures for other temperatures are given in Appendix B.

It is, of course, no coincidence that the water vapor pressure at 100°C is equal to the standard atmospheric pressure. At that temperature the water is **boiling**; that is, the liquid state of the water can no longer be sustained because the attractive forces are not sufficient to contain the molecules in a liquid phase. In general, a transition from the liquid state to the gaseous state occurs if the local absolute pressure is less than the vapor pressure of the liquid. At high elevations where the atmospheric pressure is relatively low, boiling occurs at temperatures less than 100°C; see Fig. 1.11. At an elevation of 3000 m, boiling would occur at approximately 90°C; see Tables B.3 and B.1.

In liquid flows, conditions can be created that lead to a pressure below the vapor pressure of the liquid. When this happens, bubbles are formed locally. This phenomenon, called **cavitation**, can be very damaging when these bubbles are transported by the flow to higher-pressure regions. What happens is that the bubbles collapse upon entering the higher-pressure region, and this collapse produces local pressure spikes which have the potential of damaging a pipe wall or a ship's propeller. Cavitation on a propeller is shown in Fig. 1.12. Additional information on cavitation is included in Section 8.3.4.

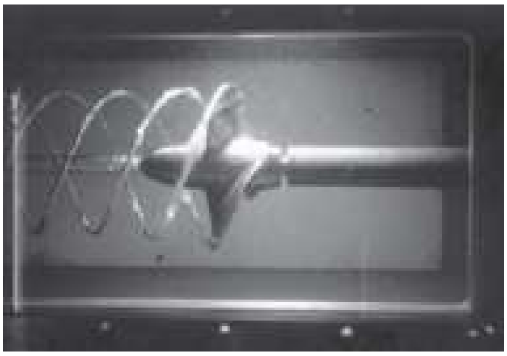

Fig. 1.12 A photograph of a cavitating propeller inside MIT's water tunnel. (Courtesy of Prof. S. A. Kinnas, Ocean Engineering Group, University of Texas - Austin.)

Example 1.5

Calculate the vacuum necessary to cause cavitation in a water flow at a temperature of 80°C in Colorado where the elevation is 2500 m.

Solution

The vapor pressure of water at 80°C is given in Table B.1. It is 47.3 kPa absolute. The atmospheric pressure is found by interpolation using Table B.3 to be 79.48 − (79.48 − 61.64)500\2000 ≅ 75.0. The required pressure is then

$$p = 47.3 - 75.0 = -27.7 \text{ kPa} \quad \text{or} \quad 27.7 \text{ kPa vacuum}$$

1.6 CONSERVATION LAWS

From experience it has been found that fundamental laws exist that appear exact; that is, if experiments are conducted with the utmost precision and care, deviations from these laws are very small and in fact, the deviations would be even smaller if improved experimental techniques were employed. Three such laws form the basis for our study of fluid mechanics. The first is the **conservation of mass**, which states that matter is indestructible. Even though Einstein's theory of relativity postulates that under certain conditions, matter is convertible into energy and leads to the statement that the extraordinary quantities of radiation from the sun are associated with a conversion of 3.3×10^{14} kg of matter per day into energy, the destructibility of matter under typical engineering conditions is not measurable and does not violate the conservation of mass principle.

Conservation of mass: *Matter is indestructible.*

For the second and third laws it is necessary to introduce the concept of a system. A **system** is defined as a fixed quantity of matter upon which attention is focused. Everything external to the system is separated by the system boundaries.

System: *A fixed quantity of matter.*

Newton's second law: *The sum of all external forces acting on a system is equal to the time rate of change of linear momentum of the system.*

Conservation of energy: *The total energy of an isolated system remains constant. Also known as the* first law of thermodynamics.

These boundaries may be fixed or movable, real, or imagined. With this definition we can now present our second fundamental law, the *conservation of momentum*: The momentum of a system remains constant if no external forces are acting on the system. A more specific law based on this principle is **Newton's second law**: The sum of all external forces acting on a system is equal to the time rate of change of linear momentum of the system. A parallel law exists for the moment of momentum: The rate of change of angular momentum is equal to the sum of all torques acting on the system.

The third fundamental law is the **conservation of energy**, which is also known as the *first law of thermodynamics*: The total energy of an isolated system remains constant. If a system is in contact with the surroundings, its energy increases only if the energy of the surroundings experiences a corresponding decrease. It is noted that the total energy consists of potential, kinetic, and internal energy, the latter being the energy content due to the temperature of the system. Other forms of energy[7] are not considered in fluid mechanics. The first law of thermodynamics and other thermodynamic relationships are presented in the following section.

1.7 THERMODYNAMIC PROPERTIES AND RELATIONSHIPS

For incompressible fluids, the three laws mentioned in the preceding section suffice. This is usually true for liquids but also for gases if relatively small pressure, density, and temperature changes occur. However, for a compressible fluid, it may be necessary to introduce other relationships, so that density, temperature, and pressure changes are properly taken into account. An example is the prediction of changes in density, pressure, and temperature when compressed gas is released from a rocket through a nozzle.

Extensive property: *A property that depends on the system's mass.*

Intensive property: *A property that is independent of the system's mass.*

Thermodynamic properties, quantities that define the state of a system, either depend on the system's mass or are independent of the mass. The former is called an **extensive property**, and the latter is called an **intensive property**. An intensive property can be obtained by dividing the extensive property by the mass of the system. Temperature and pressure are intensive properties; momentum and energy are extensive properties.

1.7.1 Properties of an Ideal Gas

The behavior of gases in most engineering applications can be described by the ideal-gas law, also called the perfect-gas law. When the temperature is relatively low and/or the pressure relatively high, caution should be exercised and real-gas laws should be applied. For air with temperatures higher than $-50°C$ ($-58°F$) the ideal-gas law approximates the behavior of air to an acceptable degree provided that the pressure is not extremely high.

[7] Other forms of energy include electric and magnetic field energy, the energy associated with atoms, and energy released during combustion.

The *ideal-gas law* is given by

$$p = \rho RT \tag{1.7.1}$$

where p is the absolute pressure, ρ the density, T the absolute temperature, and R the gas constant. The gas constant is related to the universal gas constant R_u by the relationship

$$R = \frac{R_u}{M} \tag{1.7.2}$$

where M is the molar mass. Values of M and R are tabulated in Table B.4 in Appendix B. The value of R_u is

$$\begin{aligned} R_u &= 8.314 \text{ kJ/kmol·K} \\ &= 49{,}710 \text{ ft-lb/slugmol-°R} \end{aligned} \tag{1.7.3}$$

For air $M = 28.97$ kg/kmol (28.97 slug/slugmol), so that for air $R = 0.287$ kJ/kg·K (1716 ft-lb/slug-°R), a value used extensively in calculations involving air.

Other forms that the ideal-gas law takes are

$$p\V = mRT \tag{1.7.4}$$

and

$$p\V = nR_uT \tag{1.7.5}$$

where n is the number of moles.

Example 1.6

A tank with a volume of 0.2 m^3 contains 0.5 kg of nitrogen. The temperature is 20°C. What is the pressure?

Solution

Assume this is an ideal gas. Apply Eq. 1.7.1 (R can be found in Table B.4). Solving the equation, $p = \rho RT$, we obtain, using $\rho = m/\V$,

$$p = \frac{0.5 \text{ kg}}{0.2 \text{ m}^3} \times 0.2968 \frac{\text{kJ}}{\text{kg·K}} (20 + 273) \text{ K} = 218 \text{ kPa absolute}$$

Note: The resulting units are kJ/m^3 = kN·m/m^3 = kN/m^2 = kPa. The ideal-gas law requires that pressure and temperature be in absolute units.

1.7.2 First Law of Thermodynamics

KEY CONCEPT *Energy exchange with surroundings is heat transfer or work.*

In the study of incompressible fluids, the first law of thermodynamics is particularly important. The first law of thermodynamics states that when a system, which is a fixed quantity of fluid, changes from state 1 to state 2, its energy content changes from E_1 to E_2 by energy exchange with its surroundings. The energy exchange is in the form of heat transfer or work. If we define heat transfer to the system as positive and work done by the system as positive,[8] the first law of thermodynamics can be expressed as

$$Q_{1\text{-}2} - W_{1\text{-}2} = E_2 - E_1 \tag{1.7.6}$$

where $Q_{1\text{-}2}$ is the amount of heat transfer to the system and $W_{1\text{-}2}$ is the amount of work done by the system. The energy E represents the total energy, which consists of kinetic energy ($mV^2/2$), potential energy (mgz), and internal energy ($m\tilde{u}$), where $\tilde{u}$ is the internal energy per unit mass; hence

$$E = m\left(\frac{V^2}{2} + gz + \tilde{u}\right) \tag{1.7.7}$$

Note that $V^2/2$, gz, and $\tilde{u}$ are all intensive properties and E is an extensive property.

For an isolated system, one that is thermodynamically disconnected from the surroundings (i.e., $Q_{1\text{-}2} = W_{1\text{-}2} = 0$), Eq. 1.7.6 becomes

$$E_1 = E_2 \tag{1.7.8}$$

This equation represents the conservation of energy.

KEY CONCEPT *Work results from a force moving through a distance.*

The work term in Eq. 1.7.6 results from a force F moving through a distance as it acts on the system's boundary; if the force is due to pressure, it is given by

$$\begin{aligned} W_{1\text{-}2} &= \int_{l_1}^{l_2} F\,dl \\ &= \int_{l_1}^{l_2} pA\,dl = \int_{V\!\!\!/_1}^{V\!\!\!/_2} p\,dV\!\!\!/ \end{aligned} \tag{1.7.9}$$

where $A\,dl = dV\!\!\!/$. An example that demonstrates an application of the first law of thermodynamics follows.

---

[8]In some presentations the work done on the system is positive, so that Eq. 1.7.6 would appear as $Q + W = \Delta E$. Either choice is acceptable.

Example 1.7

A cart with a mass of 2 slug is pushed up a ramp with an initial force of 100 lb (Fig. E1.7). The force decreases according to

$$F = 5(20 - l) \text{ lb}$$

If the cart starts from rest at $l = 0$, determine its velocity after it has traveled 20 ft up the ramp. Neglect friction.

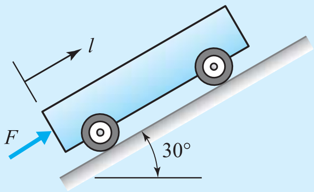

Fig. E1.7

Solution

The energy equation (Eq. 1.7.6) allows us to relate the quantities of interest. Since there is no heat transfer, we have

$$-W_{1\text{-}2} = E_2 - E_1$$

Recognizing that the force is doing work on the system, the work is negative. Hence the energy equation becomes

$$-\left[-\int_0^{20} 5(20 - l)\, dl\right] = m\left(\frac{V_2^2}{2} + gz_2\right) - m\left(\cancelto{0}{\frac{V_1^2}{2}} + \cancelto{0}{gz_1}\right)$$

Taking the datum as $z_1 = 0$, we have $z_2 = 20 \sin 30° = 10$ ft. Thus

$$100 \times 20 - 5 \times \frac{20^2}{2} = 2\left(\frac{V_2^2}{2} + 32.2 \times 10\right)$$

$$\therefore V_2 = 18.9 \text{ ft/sec}$$

Note: We have assumed no internal energy change and no heat transfer.

1.7.3 Other Thermodynamic Quantities

In compressible fluids it is sometimes useful to define thermodynamic quantities that are combinations of other thermodynamic quantities. One such combination is the sum $(m\tilde{u} + p\forall)$, which can be considered a system property; it is encountered in numerous thermodynamic processes. This property is defined as **enthalpy** H:

Enthalpy: *A property created to aid in thermodynamic calculations.*

$$H = m\tilde{u} + p\forall \qquad (1.7.10)$$

The corresponding intensive property (H/m) is

$$h = \tilde{u} + \frac{p}{\rho} \tag{1.7.11}$$

KEY CONCEPT *Constant-volume specific heat and constant-pressure specific heat are used to calculate the enthalpy and internal energy changes.*

Other useful thermodynamic quantities are the *constant-pressure specific heat* c_p and the *constant-volume specific heat* c_v; they are used to calculate the enthalpy and the internal energy changes in an ideal gas as follows:

$$\Delta h = \int c_p \, dT \tag{1.7.12}$$

and

$$\Delta \tilde{u} = \int c_v \, dT \tag{1.7.13}$$

For many situations we can assume constant specific heats in the foregoing relationships. Specific heats for common gases are listed in Table B.4. For an ideal gas c_p is related to c_v by using Eq. 1.7.11 in differential form:

$$dh = d\tilde{u} + RdT \qquad c_p = c_v + R \tag{1.7.14}$$

Ratio of specific heats: *The ratio of c_p to c_v.*

where we used $p/\rho = RT$. The **ratio of specific heats** k is often of use for an ideal gas; it is expressed as

$$k = \frac{c_p}{c_v} \tag{1.7.15}$$

For liquids and solids we use $\Delta u = c\,\Delta T$ where c is the specific heat of the substance. For water $c \cong 4.18$ kJ/kg·°C (1 Btu/lb-°F).

Quasi-equilibrium process: *A process in which properties are essentially constant at any instant throughout a system.*

A process in which pressure, temperature, and other properties are essentially constant at any instant throughout the system is called a **quasi-equilibrium** or *quasi-static* process. An example of such a process is the compression and expansion in the cylinder of an internal combustion engine.[9] If, in addition, no heat is transferred ($Q_{1\text{-}2} = 0$), the process is called an *adiabatic*, quasi-equilibrium process or an *isentropic* process. For such an isentropic[10] process the following relationships may be used:

$$\frac{p_1}{p_2} = \left(\frac{\rho_1}{\rho_2}\right)^k \qquad \frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{(k-1)/k} \qquad \frac{T_1}{T_2} = \left(\frac{\rho_1}{\rho_2}\right)^{k-1} \tag{1.7.16}$$

[9]Even though these processes may seem fast, they are thermodynamically slow. Molecules move very fast.
[10]An isentropic process occurs when the entropy is constant. We will not define or calculate entropy here; it is discussed in Section 9.1.

For a small pressure wave traveling in a gas at relatively low frequency, the wave speed is given by an isentropic process so that

$$c = \sqrt{\left.\frac{dp}{d\rho}\right|_s} = \sqrt{kRT} \tag{1.7.17}$$

If the frequency is relatively high, entropy is not constant and we use

$$c = \sqrt{\left.\frac{dp}{d\rho}\right|_T} = \sqrt{RT} \tag{1.7.18}$$

These are the primary thermodynamic relationships that will be used when considering compressible fluids.

Example 1.8

A cylinder fitted with a piston has an initial volume of 0.5 m^3. It contains 2.0 kg of air at 400 kPa absolute. Heat is transferred to the air while the pressure remains constant until the temperature is 300°C. Calculate the heat transfer and the work done. Assume constant specific heats.

Solution

Using the first law, Eq. 1.7.9, and the definition of enthalpy, we see that

$$\begin{aligned} Q_{1\text{-}2} &= p_2 V_2 - p_1 V_1 + m\tilde{u}_2 - m\tilde{u}_1 \\ &= m\tilde{u}_2 + p_2 V_2 - (m\tilde{u}_1 + p_1 V_1) \\ &= H_2 - H_1 = m(h_2 - h_1) = mc_p(T_2 - T_1) \end{aligned}$$

where Eq. 1.7.12 is used assuming c_p to be constant. The initial temperature is

$$T_1 = \frac{p_1 V_1}{mR} = \frac{400 \text{ kN/m}^2 \times 0.5 \text{ m}^3}{2.0 \text{ kg} \times 0.287 \text{ kJ/kg}\cdot\text{K}} = 348.4 \text{ K}$$

(Use kJ = kN·m to check the units.) Thus the heat transfer is (c_p is found in Table B.4)

$$Q_{1\text{-}2} = 2.0 \times 1.0[(300 + 273) - 348.4] = 449 \text{ kJ}$$

The final volume is found using the ideal-gas law:

$$V_2 = \frac{mRT_2}{p_2} = \frac{2 \text{ kg} \times (0.287 \text{ kJ/kg}\cdot\text{K}) \times 573 \text{ K}}{400 \text{ kN/m}^2} = 0.822 \text{ m}^3$$

The work done for the constant-pressure process is, using Eq. 1.7.9 with p = const,

$$\begin{aligned} W_{1\text{-}2} &= p(V_2 - V_1) \\ &= 400 \text{ kN/m}^2(0.822 - 0.5) \text{ m}^3 = 129 \text{ kN}\cdot\text{m or } 129 \text{ kJ} \end{aligned}$$

Example 1.9

The temperature on a cold winter day in the mountains of Wyoming is −22°F at an elevation of 10,000 ft. Calculate the density of the air assuming the same pressure as in the local atmosphere; also find the speed of sound.

Solution

From Table B.3 we find the atmospheric pressure at an elevation of 10,000 ft to be 10.1 psi. The absolute temperature is found to be

$$T = -22 + 460 = 438°\text{R}$$

Using the ideal-gas law, the density is calculated as

$$\begin{aligned}\rho &= \frac{p}{RT}\\ &= \frac{10.1\ \text{lb/in}^2 \times 144\ \text{in}^2/\text{ft}^2}{(1716\ \text{ft-lb/slug-°R}) \times 438°\text{R}} = 0.00194\ \text{slug/ft}^3\end{aligned}$$

The speed of sound, using Eq. 1.7.17, is determined to be

$$\begin{aligned}c &= \sqrt{kRT}\\ &= \sqrt{1.4 \times (1716\ \text{ft-lb/slug-°R}) \times 438°\text{R}} = 1026\ \text{ft/sec}\end{aligned}$$

Note: The gas constant in the foregoing equations has units of ft-lb/slug-°R so that the appropriate units result. Express slug = lb-sec^2/ft (from $m = F/a$) to observe that this is true.

1.8 SUMMARY

To relate units we often use Newton's second law, which allows us to write

$$\text{N} = \text{kg}\cdot\text{m/s}^2 \qquad \text{1b} = \text{slug-ft/sec}^2 \tag{1.8.1}$$

When making engineering calculations, an answer should have the same number of significant digits as the least accurate number used in the calculations. Most fluid properties are known to at most four significant digits. Hence, answers should be expressed to at most four significant digits, and often to only three significant digits.

In fluid mechanics pressure is expressed as gage pressure unless stated otherwise. This is unlike thermodynamics, in which pressure is assumed to be absolute. If absolute pressure is needed, add 101 kPa if the atmospheric pressure is not given in the problem statement.

The density, or specific weight, of a fluid is known if the specific gravity is known:

$$\rho_x = S_x \rho_{\text{water}} \qquad \gamma_x = S_x \gamma_{\text{water}} \tag{1.8.2}$$

The shear stress due to viscous effects in a simple flow where $u = u(y)$ is given by

$$\tau = \mu \frac{du}{dy} \tag{1.8.3}$$

This stress can be used to calculate the torque needed to rotate a shaft in a bearing.

Many air flows, and other gases too, are assumed to be incompressible at low speeds, speeds under about 100 m/s (220 mph) for atmospheric air.

The three fundamental laws used in our study of fluid mechanics are the conservation of mass, Newton's second law, and the first law of thermodynamics. These will take on various forms depending on the problem being studied. Much of our study of fluid mechanics will be expressing these laws in mathematical forms so that quantities of interest can be calculated.

FUNDAMENTALS OF ENGINEERING EXAM REVIEW PROBLEMS

1.1 If force, length, and time are selected as the three fundamental dimensions, the units of mass in the SI system could be written as:
(A) FT^2/L **(B)** FL/T^2
(C) $\text{N}\cdot\text{s}^2/\text{m}$ **(D)** $\text{N}\cdot\text{m/s}^2$

1.2 Select the dimensions of viscosity using the F-L-T system:
(A) FT^2/L
(B) FT/L^2
(C) $\text{N}\cdot\text{s/m}^2$
(D) $\text{N}\cdot\text{s}^2/\text{m}$

1.3 The quantity 2.36×10^{-8} Pa can be written as:
(A) 23.6 nPa **(B)** 236 μPa
(C) 236×10^{-3} mPa **(D)** 236 nPa

1.4 A body that weighs 250 N on earth would weigh how much on the moon where $g \cong 1.6\ \text{m/s}^2$?
(A) 5030 N **(B)** 250 N
(C) 40.77 N **(D)** 6.2 N

1.5 A 4200-N force acts on a 250-cm area at an angle of 30° to the normal. The shear stress acting on the area is:
(A) 84 Pa **(B)** 84 mPa
(C) 84 kPa **(D)** 84 MPa

1.6 The temperature at 11 000 m in the standard atmosphere, using a parabolic interpolation of the entries in Table B.3, is nearest:
(A) −62.4°C **(B)** −53.6°C
(C) −32.8°C **(D)** −17.3°C

1.7 Using an equation, estimate the density of water at 80°C:
(A) 980 kg/m^3 **(B)** 972 kg/m^3
(C) 976 kg/m^3 **(D)** 968 kg/m^3

1.8 The velocity distribution in a 4-cm-diameter pipe transporting 20°C water is given by $u(r) = 10(1 - 2500r^2)$ m/s. The shearing stress at the wall is nearest:
(A) 1.0 Pa **(B)** 0.1 Pa
(C) 0.01 Pa **(D)** 0.001 Pa

1.9 The distance 20°C water would climb in a long 10-μm-diameter, clean glass tube is nearest:
(A) 50 cm
(B) 100 cm
(C) 200 cm
(D) 300 cm

1.10 Which of the following is an intensive property?
(A) Kinetic energy **(B)** Enthalpy
(C) Density **(D)** Momentum

1.11 The mass of propane contained in a 4-m^3 tank maintained at 800 kPa and 10°C is nearest:

(A) 100 kg **(B)** 80 kg
(C) 60 kg **(D)** 20 kg

1.12 Five 40-cm^3 ice cubes completely melt in 2 liters of warm water (it takes 320 kJ to melt a kilogram of ice). The temperature drop in the water is nearest:

(A) 10°C **(B)** 8°C
(C) 6°C **(D)** 4°C

1.13 The speed of sound of a dog whistle in the atmosphere at a location where the temperature is 50°C is nearest:

(A) 396 m/s **(B)** 360 m/s
(C) 332 m/s **(D)** 304 m/s

PROBLEMS

Dimensions, Units, and Physical Quantities

1.14 State the three basic laws that are used in the study of the mechanics of fluids. State at least one global (integral) quantity that occurs in each. State at least one quantity that may be defined at a point that occurs in each.

1.15 Verify the dimensions given in Table 1.2 for the following quantities:

(a) Density **(b)** Pressure
(c) Power **(d)** Energy
(e) Mass **(f)** Flow rate

1.16 Express the dimensions of the following quantities using the *F-L-T* system:

(a) Density **(b)** Pressure
(c) Power **(d)** Energy
(e) Mass flux **(f)** Flow rate

1.17 Recognizing that all terms in an equation must have the same dimensions, determine the dimensions on the constants in the following equations:

(a) $d = 4.9\,t^2$ where d is distance and t is time.
(b) $F = 9.8\,m$ where F is a force and m is mass.
(c) $Q = 80AR^{2/3}\,S_0^{1/2}$ where A is area, R is a radius, S_0 is a slope and Q is a flow rate with dimensions of L^3/T.

1.18 Determine the units on each of the constants in the following equations, recognizing that all terms in an equation have the same dimensions:

(a) $d = 4.9\,t^2$ where d is in meters and t is in seconds.
(b) $F = 9.8\,m$ where F is in newtons and m is in kilograms.
(c) $Q = 80AR^{2/3}S_0^{1/2}$ where A is in meters squared, R is in meters, S_0 is the slope, and Q has units of meters cubed per second.

1.19 State the SI units of Table 1.1 on each of the following:

(a) Pressure **(b)** Energy
(c) Power **(d)** Viscosity
(e) Heat flux **(f)** Specific heat

1.20 Determine the units on c, k and $f(t)$ in
$$m\frac{d^2y}{dt^2} + c\frac{dy}{dt} + ky = f(t)$$ if m is in kilograms, y is in meters, and t is in seconds.

1.21 Write the following with the use of prefixes:

(a) 2.5×10^5 N **(b)** 5.72×10^{11} Pa
(c) 4.2×10^{-8} Pa **(d)** 1.76×10^{-5} m^3
(e) 1.2×10^{-4} m^2 **(f)** 7.6×10^{-8} m^3

1.22 Write the following with the use of powers; do not use a prefix:

(a) 125 MN **(b)** 32.1 μs
(c) 0.67 GPa **(d)** 0.0056 mm^3
(e) 520 cm^2 **(f)** 7.8 km^3

1.23 Rewrite Eq. 1.3.3 using the English units of Table 1.1.

1.24 Using the table of conversions on the inside front cover, express each of the following in the SI units of Table 1.2:

(a) 20 cm/hr **(b)** 2000 rpm
(c) 500 hp **(d)** 100 ft^3/min
(e) 2000 kN/cm^2 **(f)** 4 slug/min
(g) 500 g/L **(h)** 500 kWh

1.25 What net force is needed to accelerate a 10-kg mass at the rate of 40 m/s^2 (neglect all friction):

(a) Horizontally?
(b) Vertically upward?
(c) On an upward slope of 30°?

1.26 A particular body weighs 60 lb on earth. Calculate its weight on the moon, where $g \simeq 5.4$ ft/sec^2.

1.27 Calculate the mean free path in the atmosphere using Eq. 1.3.3 and Table B.3 in the Appendix at an elevation of:

(a) 30 000 m
(b) 50 000 m
(c) 80 000 m

Pressure and Temperature

1.28 A gage pressure of 52.3 kPa is read on a gage. Find the absolute pressure if the elevation is:
(a) At sea level **(b)** 1000 m
(c) 5000 m **(d)** 10 000 m
(e) 30 000 m

1.29 A vacuum of 31 kPa is measured in an airflow at sea level. Find the absolute pressure in:
(a) kPa
(b) mm Hg
(c) psi
(d) ft H_2O
(e) in. Hg

1.30 For a constant-temperature atmosphere, the pressure as a function of elevation is given by $p(z) = p_0 e^{-gz/RT}$, where g is gravity, $R = 287$ J/kg·K, and T is the absolute temperature. Use this equation and estimate the pressure at 4000 m assuming that $p_0 = 101$ kPa and $T = 15°C$. What is the error?

1.31 Estimate the pressure and temperature at an elevation of 22,560 ft using Table B.3–English. Employ:
(a) A linear interpolation: $f \simeq f_0 + n(f_1 - f_0)$.
(b) A parabolic interpolation: $f \simeq f_0 + n(f_1 - f_0) + (n/2)(n-1)(f_2 - 2f_1 + f_0)$.

1.32 Estimate the temperature in °C and °F at 33,000 ft, an elevation at which many commercial airplanes fly. Use Table B.3–English.

1.33 An applied force of 26.5 MN is distributed uniformly over a 152-cm^2 area; however, it acts at an angle of 42° with respect to a normal vector (see Fig. P1.33). If it produces a compressive stress, calculate the resulting pressure.

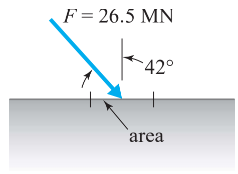

Fig. P1.33

1.34 The force on an area of 0.2 cm^2 is due to a pressure of 120 kPa and a shear stress of 20 Pa, as shown in Fig. P1.34. Calculate the magnitude of the force acting on the area and the angle of the force with respect to a normal coordinate.

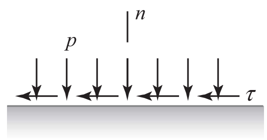

Fig. P1.34

Density and Specific Weight

1.35 Calculate the density and specific weight of water if 0.2 slug occupies 180 in^3.

1.36 Use Eq. 1.5.3 to determine the density and specific gravity of water at 70°C. What is the error in the calculation for density? Use Table B.1.

1.37 The specific gravity of mercury is usually taken as 13.6. What is the percent error in using a value of 13.6 at 50°C?

1.38 The specific weight of an unknown liquid is 12 400 N/m^3. What mass of the liquid is contained in a volume of 500 cm^3? Use:
(a) The standard value of gravity.
(b) The minimum value of gravity on the earth.
(c) The maximum value of gravity on the earth.

1.39 A liquid with a specific gravity of 1.2 fills a volume. If the mass in the volume is 10 slug, what is the magnitude of the volume?

Viscosity

1.40 In combustion systems that burn hydrocarbon fuels, the carbon dioxide gas that is produced eventually escapes to the atmosphere thereby contributing to global warming. Calculate the density, specific weight, viscosity, and kinematic viscosity of carbon dioxide at a pressure of 200 kPa absolute and 90°C.

1.41 In a single cylinder engine a piston without rings is designed to slide freely inside the vertical cylinder. Lubrication between the piston and cylinder is maintained by a thin oil film. Determine the velocity with which the 120-mm-diameter piston will fall inside the 120.5-mm-diameter cylinder. The 350-g piston is 10 cm long. The lubricant is SAE 10W-30 oil at 60°C.

1.42 Consider a fluid flow between two parallel fixed plates 5 cm apart, as shown in Fig. P1.42. The velocity distribution for the flow is given by $u(y) = 120(0.05y - y^2)$ m/s where y is in meters. The fluid is water at 10°C. Calculate the magnitude of the shear stress acting on each of the plates.

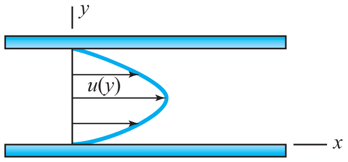

Fig. P1.42

1.43 A velocity distribution in a 2-in.-diameter pipe is measured to be $u(r) = 30(1 - r^2/r_0^2)$ ft/sec, where r_0 is the radius of the pipe. Calculate the shear stress at the wall if water at 75°F is flowing.

1.44 The velocity distribution in a 1.0-cm-diameter pipe is given by $u(r) = 16(1 - r^2/r_0^2)$ m/s, where r_0 is the pipe radius. Calculate the shearing stress at the centerline, at $r = 0.25$ cm, and at the wall if water at 20°C is flowing.

1.45 For two 0.2-m-long rotating concentric cylinders, the velocity distribution is given by $u(r) = 0.4/r - 1000r$ m/s. If the diameters of the cylinders are 2 cm and 4 cm, respectively, calculate the fluid viscosity if the torque on the inner cylinder is measured to be 0.0026 N·m.

1.46 A 4-ft-long, 1-in.-diameter shaft rotates inside an equally long cylinder that is 1.02 in. in diameter. Calculate the torque required to rotate the inner shaft at 2000 rpm if SAE-30 oil at 70°F fills the gap. Also, calculate the horsepower required. Assume concentric cylinders.

1.47 A 60-cm-wide belt moves at 10 m/s, as shown in Fig. P1.47. Calculate the horsepower requirement assuming a linear velocity profile in the 10°C water.

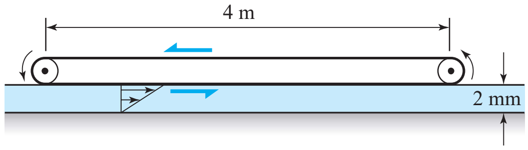

Fig. P1.47

1.48 A 6-in.-diameter horizontal disk rotates a distance of 0.08 in. above a solid surface. Water at 60°F fills the gap. Estimate the torque required to rotate the disk at 400 rpm.

1.49 Calculate the torque needed to rotate the cone shown in Fig. P1.49 at 2000 rpm if SAE-30 oil at 40°C fills the gap. Assume a linear velocity profile between the cone and the fixed wall.

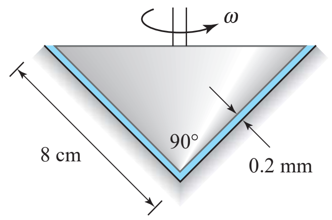

Fig. P1.49

1.50 A free-body diagram of the liquid between a moving belt and a fixed wall shows that the shear stress in the liquid is constant. If the temperature varies according to $T(y) = K/y$, where y is measured from the wall (the temperature at the wall is very large), what would be the shape of the velocity profile if the viscosity varies according to Andrade's equation $\mu = Ae^{B/T}$?

1.51 The viscosity of water at 20°C is 0.001 N·s/m^2 and at 80°C it is 3.57×10^{-4} N·s/m^2. Using Andrade's equation $\mu = Ae^{B/T}$ estimate the viscosity of water at 40°C. Determine the percent error.

Compressibility

1.52 Show that $d\rho/\rho = -dV\!\!\!/ /V\!\!\!/$, as was assumed in Eq. 1.5.11.

1.53 What is the volume change of 2 m^3 of water at 20°C due to an applied pressure of 10 MPa?

1.54 Two engineers wish to estimate the distance across a lake. One pounds two rocks together under water on one side of the lake and the other submerges his head and hears a small sound 0.62 s later, as indicated by a very accurate stopwatch. What is the distance between the two engineers?

1.55 A pressure is applied to 20 L of water. The volume is observed to decrease to 18.7 L. Calculate the applied pressure.

1.56 Calculate the speed of propagation of a small-amplitude wave through water at:
(a) 40°F
(b) 100°F
(c) 200°F

1.57 The change in volume of a liquid with temperature is given by $\Delta \mathcal{V} = \alpha_T \mathcal{V}\, \Delta T$, where α_T is the *coefficient of thermal expansion*. For water at 40°C, $\alpha_T = 3.8 \times 10^{-4}\ \text{K}^{-1}$. What is the volume change of 1 m^3 of 40°C water if $\Delta T = -20$°C? What pressure change would be needed to cause that same volume change?

Surface Tension

1.58 Calculate the pressure in the small 10-μm-diameter droplets that are formed by spray machines. Assume the properties to be the same as water at 15°C. Calculate the pressure for bubbles of the same size.

1.59 A small 1/16-in.-diameter bubble is formed by a stream of 60°F water. Estimate the pressure inside the bubble.

1.60 In diesel engines diesel fuel is injected directly into the engine cylinder during the compression stroke where the average air pressure could reach 8000 kPa. Assuming that liquid fuel droplets are formed as the fuel flows from the injector, determine the interior pressure in a 5-μm diameter spherical droplet. The surface tension for diesel fuel in air is 0.025 N/m.

1.61 Determine the height that 20°C water would climb in a vertical 0.02-cm-diameter tube if it attaches to the wall with an angle β of 30° to the vertical.

1.62 Mercury makes an angle of 130° (β in Fig. 1.10) when in contact with clean glass. What distance will mercury depress in a vertical 0.8-in.-diameter glass tube? Use $\sigma = 0.032$ lb/ft.

1.63 Find an expression for the rise of liquid between two parallel plates a distance t apart. Use a contact angle β and surface tension σ.

1.64 Write an expression for the maximum diameter d of a needle of length L that can float in a liquid with surface tension σ. The density of the needle is ρ.

1.65 Would a 7-cm-long 4-mm-diameter steel needle be able to float in 15°C water? Use $\rho_{\text{steel}} = 7850\ \text{kg/m}^3$.

1.66 Find an expression for the maximum vertical force F needed to lift a thin wire ring of diameter D slowly from a liquid with surface tension σ.

1.67 Two flat plates are positioned as shown in Fig. P1.67 with a small angle α in an open container with a small amount of liquid. The plates are vertical, and the liquid rises between the plates. Find an expression for the location $h(x)$ of the surface of the liquid assuming that $\beta = 0$.

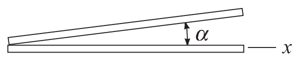

Fig. P1.67

Vapor Pressure

1.68 Water is transported through the pipe of Fig. P1.68 such that a vacuum of 80 kPa exists at a particular location. What is the maximum possible temperature of the water? Use $p_{\text{atm}} = 92$ kPa.

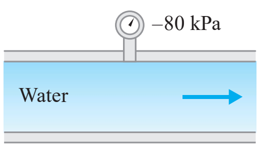

Fig. P1.68

1.69 A group of explorers desired their elevation. An engineer boiled water and measured the temperature to be 82°C. They found a fluid mechanics book in a backpack and the engineer told the group their elevation! What elevation should the engineer have quoted?

1.70 A tank half-filled with 40°C water is to be evacuated. What is the minimum pressure that can be expected in the space above the water?

1.71 Water is forced through a contraction causing low pressure. The water is observed to "boil" at a pressure of −11.5 psi. If atmospheric pressure is 14.5 psi, what is the temperature of the water?

1.72 Oil is transported through a pipeline by a series of pumps that can produce a pressure of 10 MPa in the oil leaving each pump. The losses in the pipeline cause a pressure drop of 600 kPa each kilometer. What is the maximum possible spacing of the pumps?

Ideal Gas

1.73 Determine the density and the specific gravity of air at standard conditions (i.e., 15°C and 101.3 kPa absolute).

1.74 Calculate the density of air inside a house and outside a house using 20°C inside and −25°C outside. Use an atmospheric pressure of 85 kPa. Do you think there would be a movement of air from the inside to the outside (infiltration), even without a wind? Explain.

1.75 A 15-ft^3 air tank is pressurized to 750 psia. When the temperature reaches 10°F, calculate the density and the air mass.

1.76 Estimate the weight of air contained in a classroom that measures 10 m × 20 m × 4 m. Assume reasonable values for the variables.

1.77 A car tire is pressurized to 35 psi in Michigan when the temperature is −10°F. The car is driven to Arizona, where the temperature on the highway, and in the tire, reaches 150°F. Estimate the maximum pressure in the tire.

1.78 The mass of all the air in the atmosphere contained above a 1-m^2 area is to be contained in a spherical volume. Estimate the diameter of the sphere if the air is at standard conditions.

First Law

1.79 A body falls from rest. Determine its velocity after 10 ft and 20 ft, using the energy equation.

1.80 Determine the final velocity of the 15-kg mass of Fig. P1.80 moving horizontally if it starts at 10 m/s and moves a distance of 10 m while the following net force acts in the direction of motion (where s is the distance in the direction of motion):

(a) 200 N **(b)** $20s$ N
(c) $200\cos(s\pi/20)$ N

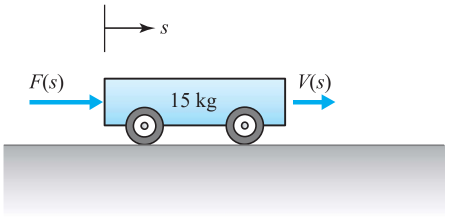

Fig. P1.80

1.81 The 10-kg mass shown in Fig. P1.81 is traveling at 40 m/s and strikes a plunger that is attached to a piston. The piston compresses 0.2 kg of air contained in a cylinder. If the mass is brought to rest, calculate the maximum rise of temperature in the air. What effects could lead to a lower temperature rise?

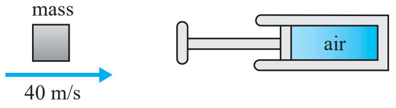

Fig. P1.81

1.82 A 1500-kg automobile traveling at 100 km/h is suddenly grabbed by a hook and all of its kinetic energy is dissipated in a hydraulic absorber containing 2000 cm^3 of water. Calculate the maximum temperature rise in the water.

1.83 A fuel mass of 0.2 kg contains 40 MJ/kg of energy. Calculate the temperature rise of 100 kg of water if complete combustion occurs and the water, which surrounds the fuel, is completely insulated from the surroundings.

1.84 Four pounds of air is compressed in a cylinder–piston arrangement while the temperature remains constant at 70°F. If the initial pressure is 30 psi absolute, calculate the work needed to compress the air such that the absolute pressure doubles. Also calculate the heat transfer.

1.85 Determine the heat transfer needed to double the absolute pressure in a fixed 2-m^3 volume containing air at 200 kPa absolute if the initial temperature is:

(a) 20°C
(b) 100°C
(c) 200°C

1.86 Heat is transferred to 2 kg of air in a cylinder so that the temperature doubles while the pressure remains constant. What work is required if the initial temperature is:

(a) 60°C?
(b) 150°C?
(c) 200°C?

Isentropic Flow

1.87 Air flows from a tank maintained at 5 MPa absolute and 20°C. It exits a hole and reaches a pressure of 500 kPa absolute. Assuming an adiabatic, quasi-equilibrium process, calculate the exiting temperature.

1.88 An airstream flows with no heat transfer such that the temperature changes from 20°C to 150°C. If the initial pressure is measured to be 150 kPa, estimate the maximum final pressure.

1.89 Air is compressed in an insulated cylinder from 20°C to 200°C. If the initial pressure is 100 kPa absolute, what is the maximum final pressure? What work is required?

Speed of Sound

1.90 Calculate the speed of sound at 20°C in:
- **(a)** Air
- **(b)** Carbon dioxide
- **(c)** Nitrogen
- **(d)** Hydrogen
- **(e)** Steam

1.91 Compare the speed of sound in the atmosphere at an elevation of 10 000 m with that at sea level by calculating a percentage decrease.

1.92 A lumberman, off in the distance, is chopping with an axe. An observer, using her digital stopwatch, measures a time of 8.32 s from the instant the axe strikes the tree until the sound is heard. How far is the observer from the lumberman if:
- **(a)** $T = -20°C$?
- **(b)** $T = 20°C$?
- **(c)** $T = 45°C$?