

Introduction and Preliminaries

1

The field of thermodynamics is concerned with the science of energy, focusing on energy storage and energy conversion processes. We will study the effects of energy on different substances, as we may expose a mass to heating/cooling or to volumetric compression/expansion. During such processes, we are transferring energy into or out of the mass, so it changes its conditions expressed by properties such as temperature, pressure, and volume. We use several processes similar to this in our daily lives; we heat water to make coffee or tea or cool it in a refrigerator to make cold water or ice cubes in a freezer. In nature, water evaporates from oceans and lakes and mixes with air where the wind can transport it, and later, the water may drop out of the air as either rain (liquid water) or snow (solid water). As we study these processes in detail, we will focus on situations that are physically simple and yet typical of real-life situations in industry or nature.

By a combination of processes, we are able to illustrate more complex devices or complete systems—for instance, a simple steam power plant that is the basic system that generates the majority of our electric power. Figure 1.1 shows a power plant that produces electric power and hot water for district heating by burning coal. The coal is supplied by ship, and the district heating pipes are located in underground tunnels and thus are not visible. For a better understanding and a technical description, see the simple schematic of the power plant shown in Fig. 1.2. This includes various outputs from the plant as electric power to the net, warm water for district heating, slag from burning coal, and other materials such as ash and gypsum; the last output is a flow of exhaust gases out of the chimney.

Another set of processes forms a good description of a refrigerator that we use to cool food or apply it at very low temperatures to produce a flow of cold fluid for cryogenic surgery by freezing tissue for minimal bleeding. A simple schematic for such a system is shown in Fig. 1.3. The same system can also function as an air conditioner with the dual purpose of cooling a building in summer and heating it in winter; in this last mode of use, it is also called a *heat pump*. For mobile applications, we can make simple models for gasoline and diesel engines typically used for ground transportation and gas turbines in jet engines used in aircraft, where low weight and volume are of prime concern. These are just a few examples of familiar systems that the theory of thermodynamics allows us to analyze. Once we learn and understand the theory, we will be able to extend the analysis to other cases we may not be familiar with.

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FIGURE 1.1
The Avedøre
Power Station,
Denmark
(Courtesy of Dong
Energy,
Denmark.)

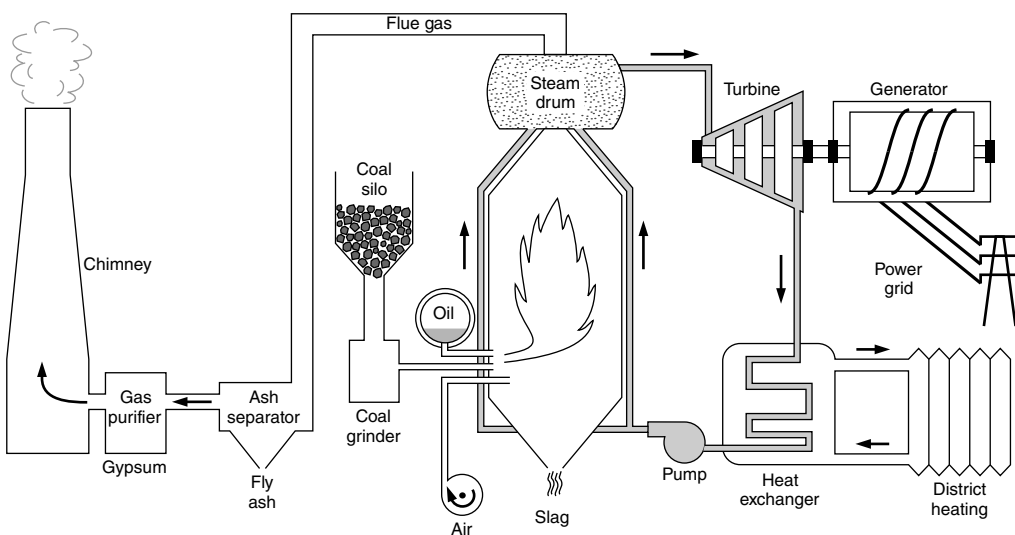
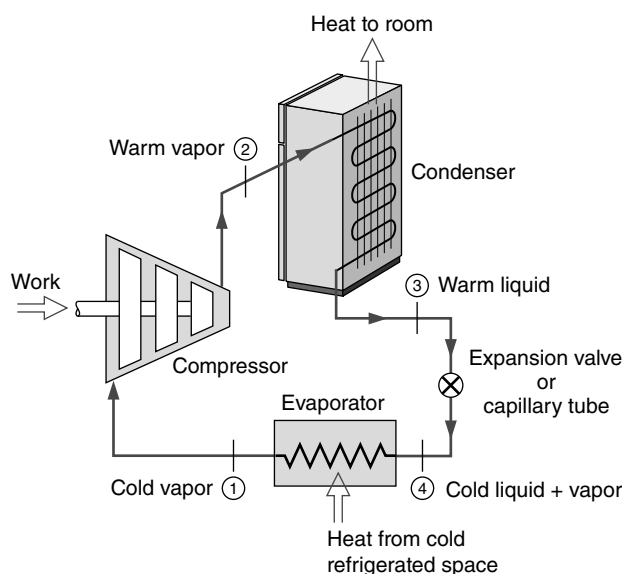


FIGURE 1.2 Schematic diagram of a steam power plant.

**FIGURE 1.3**

Schematic diagram of a refrigerator.

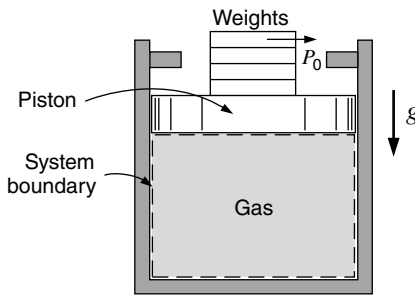
Beyond the description of basic processes and systems, thermodynamics is extended to cover special situations like moist atmospheric air, which is a mixture of gases, and the combustion of fuels for use in the burning of coal, oil, or natural gas, which is a chemical and energy conversion process used in nearly all power-generating devices. Many other extensions are known; these can be studied in specialty texts. Since all the processes engineers deal with have an impact on the environment, we must be acutely aware of the ways in which we can optimize the use of our natural resources and produce a minimal amount of negative consequences for our environment. For this reason, the treatment of efficiencies for processes and devices is important in modern analysis and is required knowledge for a complete engineering study of system performance and operation.

Before considering the application of the theory, we will cover a few basic concepts and definitions for our analysis and review some material from physics and chemistry that we will need.

1.1

A THERMODYNAMIC SYSTEM AND THE CONTROL VOLUME

A thermodynamic system is a device or combination of devices containing a quantity of matter under study. To define this more precisely, a control volume is chosen so that it contains the matter and devices inside a control surface. Everything external to the control volume is the surroundings, with the separation provided by the control surface. The surface may be open or closed to mass flows, and it may have flows of energy in terms of heat transfer and work across it. The boundaries may be movable or stationary. In the case of a control surface closed to mass flow so that no mass can escape or enter the control volume; it is called a control mass containing the same amount of matter at all times.

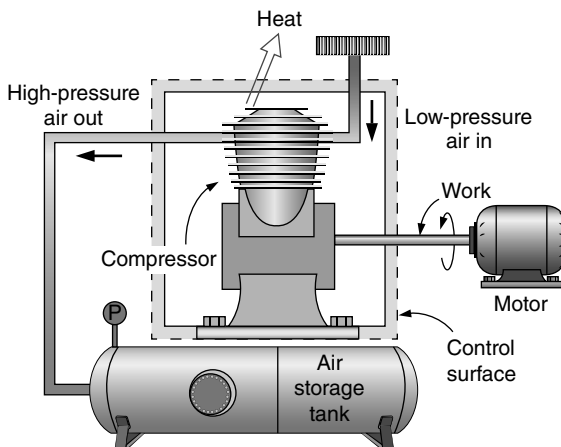
**FIGURE 1.4**

Example of a control mass.

Selecting the gas in the cylinder of Fig. 1.4 as a control volume by placing a control surface around it, we recognize this as a control mass. If a Bunsen burner is placed under the cylinder, the temperature of the gas will increase, and the piston will move out. As the piston moves, the boundary of the control mass also changes. As we will see later, heat and work cross the boundary of the control mass during this process, but the matter that composes the control mass can always be identified and remains the same.

An isolated system is one that is not influenced in any way by the surroundings so that no mass, heat, or work is transferred across the boundary of the system. In a more typical case, a thermodynamic analysis should be conducted for a device such as an air compressor in which mass flows in and out, as shown schematically in Fig. 1.5. The real system includes possibly a storage tank, as shown in Fig. 1.20. In such an analysis, we specify a control volume that surrounds the compressor with a surface called the control surface, across which there may be a transfer of mass and momentum as well as heat and work.

Thus, the more general control surface defines a control volume, where mass may flow in or out, while a control mass is the special case of no mass flowing in or out. Hence, the control mass contains a fixed mass at all times, which explains its name. The general formulation of the analysis is considered in detail in Chapter 4. The terms closed system (fixed mass) and open system (involving a flow of mass) are sometimes used to make this distinction. Here, we use the term system as a more general and loose description for a mass, device, or combination

**FIGURE 1.5**

Example of a control volume.

of devices that is then more precisely defined when a control volume is selected. The procedure that will be followed in presenting the first and second laws of thermodynamics is first to present these laws for a control mass and then to extend the analysis to the more general control volume.

1.2 MACROSCOPIC VERSUS MICROSCOPIC POINTS OF VIEW

The behavior of a system may be investigated from either a microscopic or macroscopic point of view. Let us briefly describe a system from a microscopic point of view. Consider a system consisting of a cube 25 mm on each side and containing a monatomic gas at atmospheric pressure and temperature. This volume contains approximately 10^{20} atoms. To describe the position of each atom, we need to specify three coordinates; to describe the velocity of each atom, we specify three velocity components.

Thus, to describe completely the behavior of this system from a microscopic point of view, we must deal with at least 6×10^{20} equations. Even with a modern computer, this is a hopeless computational task. However, there are two approaches to this problem that reduce the number of equations and variables to a few that can be computed relatively easily. One is the statistical approach, in which, on the basis of statistical considerations and probability theory, we deal with average values for all particles under consideration. This is usually done in connection with a model of the atom under consideration. This is the approach used in the disciplines of kinetic theory and statistical mechanics.

The other approach to reducing the number of variables to a few that can be handled relatively easily involves the macroscopic point of view of classical thermodynamics. As the word *macroscopic* implies, we are concerned with the gross or average effects of many molecules. These effects can be perceived by our senses and measured by instruments. However, what we really perceive and measure is the time-averaged influence of many molecules. For example, consider the pressure a gas exerts on the walls of its container. This pressure results from the change in momentum of the molecules as they collide with the wall. From a macroscopic point of view, however, we are concerned not with the action of the individual molecules but with the time-averaged force on a given area, which can be measured by a pressure gauge. In fact, these macroscopic observations are completely independent of our assumptions regarding the nature of matter.

Although the theory and development in this book are presented from a macroscopic point of view, a few supplementary remarks regarding the significance of the microscopic perspective are included as an aid to understanding the physical processes involved. For those who wish to study this in a little more detail an introduction to statistical thermodynamics is included as Chapter 16 in a form that is flexible with respect to the material covered.

A few remarks should be made regarding the continuum approach. We are normally concerned with volumes that are very large compared to molecular dimensions and with time scales that are very large compared to intermolecular

collision frequencies. For this reason, we deal with very large numbers of molecules that interact extremely often during our observation period, so we view the system as a simple, uniformly distributed mass in the volume called a continuum. This concept, of course, is only a convenient assumption that loses validity when the mean free path of the molecules approaches the order of magnitude of the dimensions of the vessel, as, for example, in high-vacuum technology. In much engineering work, the assumption of a continuum is valid and convenient, consistent with the macroscopic point of view.

1.3 PROPERTIES AND STATE OF A SUBSTANCE

If we consider a given mass of water, we recognize that this water can exist in various forms. If it is a liquid initially, it may become a vapor when it is heated or a solid when it is cooled. Thus, we speak of the different phases of a substance. A phase is describing a condition of matter that is homogeneous throughout, commonly referred to as solid, liquid, or gas phases. When more than one phase is present, the phases are separated from each other by the phase boundaries. In each phase, the substance may exist at various pressures and temperatures or, to use the thermodynamic term, in various states. The state may be identified or described by certain observable, macroscopic properties; some familiar ones are temperature, pressure, and density. In later chapters, other properties will be introduced. Each of the properties of a substance in a given state has only one definite value, and these properties always have the same value for a given state, regardless of how the substance arrived at the state. In fact, a property can be defined as any quantity that depends on the state of the system and is independent of the path (i.e., the prior history) by which the system arrived at the given state. Conversely, the state is specified or described by the properties. Later, we will consider the number of independent properties a substance can have, that is, the minimum number of properties that must be specified to fix the state of the substance.

Thermodynamic properties can be divided into two general classes: intensive and extensive. An intensive property is independent of the mass; the value of an extensive property varies directly with the mass. Thus, if a quantity of matter in a given state is divided into two equal parts, each part will have the same value of intensive properties as the original and half the value of the extensive properties. Pressure, temperature, and density are examples of intensive properties. Mass and total volume are examples of extensive properties. Extensive properties per unit mass, such as specific volume, see Section 1.6, are intensive properties.

Frequently, we will refer not only to the properties of a substance but also to the properties of a system. When we do so, we necessarily imply that the value of the property has significance for the entire system, and this implies equilibrium. For example, if the gas that composes the system (control mass) in Fig. 1.4 is in thermal equilibrium, the temperature will be the same throughout the entire system, and we may speak of the temperature as a property of the system. We may also consider mechanical equilibrium, which is related to pressure. If a system is in mechanical equilibrium, there is no tendency for the pressure at any point to

change with time as long as the system is isolated from the surroundings. There will be variation in pressure with elevation because of the influence of gravitational forces, although under equilibrium conditions, there will be no tendency for the pressure at any location to change. However, in many thermodynamic problems, this variation in pressure with elevation is so small that it can be neglected. Chemical equilibrium is also important and will be considered in Chapter 14. When a system is in equilibrium regarding all possible changes of state, we say that the system is in thermodynamic equilibrium.

1.4 PROCESSES AND CYCLES

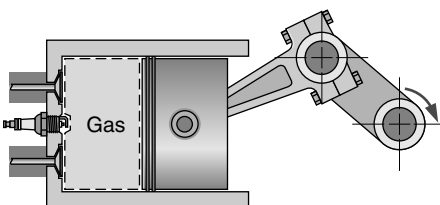
Whenever one or more of the properties of a system change, we say that a change in state has occurred. For example, when the crank moves, as shown in Fig. 1.6, the piston moves to give a larger cylinder volume, so a change in state occurs toward a lower pressure and higher specific volume. The path of the succession of states through which the system passes is called the process.

Let us consider the equilibrium of a system as it undergoes a change in state. The moment the piston in Fig. 1.6 is moved, mechanical equilibrium does not exist; as a result, the volume and pressure change until mechanical equilibrium is restored. The question is this: Since the properties describe the state of a system only when it is in equilibrium, how can we describe the states of a system during a process if the actual process occurs only when equilibrium does not exist? One step in finding the answer to this question concerns the definition of an ideal process, which we call a *quasi-equilibrium* process. A quasi-equilibrium process is one in which the deviation from thermodynamic equilibrium is infinitesimal, and all the states the system passes through during a quasi-equilibrium process may be considered equilibrium states. Many actual processes closely approach a quasi-equilibrium process and may be so treated with essentially no error. If the piston moves slowly, the process could be considered quasi-equilibrium. However, if the piston moves fast, there will be a nonuniform pressure distribution in the gas. This would be a nonequilibrium process, and the system would not be in equilibrium at any time during this change of state.

For nonequilibrium processes, we are limited to a description of the system before the process occurs and after the process is completed and equilibrium is restored. We are unable to specify each state through which the system passes or the rate at which the process occurs. However, as we will see later, we are able to describe certain overall effects that occur during the process.

FIGURE 1.6

An example of a system that may undergo a quasi-equilibrium process.



Several processes are described by the fact that one property remains constant. The prefix *iso-* is used to describe such a process. An isothermal process is a constant-temperature process, an isobaric process is a constant-pressure process, and an isochoric process is a constant-volume process.

When a system in a given initial state goes through a number of different changes of state or processes and finally returns to its initial state, the system has undergone a cycle. Therefore, at the conclusion of a cycle, all the properties have the same value they had at the beginning. Steam (water) that circulates through a steam power plant undergoes a cycle.

A distinction should be made between a thermodynamic cycle, which has just been described, and a mechanical cycle. A four-stroke-cycle internal-combustion engine goes through a mechanical cycle once every two revolutions. However, the working fluid does not go through a thermodynamic cycle in the engine since air and fuel are burned and changed to products of combustion that are exhausted to the atmosphere. In this book, the term *cycle* will refer to a thermodynamic cycle unless otherwise designated.

1.5 UNITS FOR MASS, LENGTH, TIME, AND FORCE

Since we are considering thermodynamic properties from a macroscopic perspective, we are dealing with quantities that can, either directly or indirectly, be measured or counted. Therefore, the matter of units becomes an important consideration, and they are all shown in appendix Table A.1. In the remaining sections of this chapter, we will define certain thermodynamic properties and the basic units. Because the relation between force and mass is often difficult for students to understand, it is considered in this section in some detail.

Force, mass, length, and time are related by Newton's second law of motion, which states that the force acting on a body is proportional to the product of the mass and the acceleration in the direction of the force:

$$F \propto ma$$

The concept of time is well established. The basic unit of time is the second (s), which in the past was defined in terms of the solar day, the time interval for one complete revolution of the earth relative to the sun. Since this period varies with the season of the year, an average value over a 1-year period is called the *mean solar day*, and the mean solar second is 1/86 400 of the mean solar day. In 1967, the General Conference of Weights and Measures (CGPM) adopted a definition of the second as the time required for a beam of cesium-133 atoms to resonate 9 192 631 770 cycles in a cesium resonator.

For periods of time less than 1 s, the prefixes *milli*, *micro*, *nano*, *pico*, or *femto*, as listed in Table A.0, are commonly used. For longer periods of time, the units minute (min), hour (h), or day (day) are frequently used. It should be pointed out that the prefixes are used with many other units as well.

The concept of length is also well established. The basic unit of length is the meter (m), which used to be marked on a platinum–iridium bar. Currently, the

CGPM has adopted a more precise definition of the meter in terms of the speed of light (which is now a fixed constant). The meter is the length of the path traveled by light in a vacuum during a time interval of $1/299\,792\,458$ of a second.

The fundamental unit of mass is the kilogram (kg). As adopted by the first CGPM in 1889 and restated in 1901, it is the mass of a certain platinum–iridium cylinder maintained under prescribed conditions at the International Bureau of Weights and Measures. A related unit that is used frequently in thermodynamics is the mole (mol), defined as an amount of substance containing as many elementary entities as there are atoms in 0.012 kg of carbon-12. These elementary entities must be specified; they may be atoms, molecules, electrons, ions, or other particles or specific groups. For example, 1 mol of diatomic oxygen, having a molecular mass of 32 (compared to 12 for carbon), has a mass of 0.032 kg. The mole is often termed a *gram mole* since it is an amount of substance in grams numerically equal to the molecular mass. In this book, when using the metric SI system, we will use the kilomole (kmol), the amount of substance in kilograms numerically equal to the molecular mass, rather than the mole.

The system of units in use presently throughout most of the world is the metric International System, commonly referred to as *SI units* (from Le Système International d’Unités). In this system, the second, meter, and kilogram are the basic units for time, length, and mass, respectively, as just defined, and the unit of force is defined directly from Newton’s second law. The unit conversions are shown in Table A.1 and cover most of the commonly used ones in SI and English unit systems.

Therefore, a proportionality constant is unnecessary, and we may write that law as an equality:

$$F = ma \quad (1.1)$$

The unit of force is the newton (N), which by definition is the force required to accelerate a mass of 1 kg at the rate of 1 m/s^2 :

$$1 \text{ N} = 1 \text{ kg m/s}^2$$

It is worth noting that SI units derived from proper nouns use capital letters for symbols; others use lowercase letters. The liter, with the symbol L, is an exception.

The traditional system of units used in the United States is the English Engineering System. In this system, the unit of time is the second, which was discussed earlier. The basic unit of length is the foot (ft), which at present is defined in terms of the meter as

$$1 \text{ ft} = 0.3048 \text{ m} = 12 \text{ in.},$$

and therefore also relates to the inch (in.). The unit of mass in this system is the pound mass (lbm). It was originally defined as the mass of a certain platinum cylinder kept in the Tower of London, but now it is defined in terms of the kilogram as

$$1 \text{ lbm} = 0.453\,592\,37 \text{ kg}$$

A related unit is the pound mole (lb mol), which is an amount of substance in pounds mass numerically equal to the molecular mass of that substance. It is important to distinguish between a pound mole and a mole (gram mole).

In the English Engineering System of Units, the unit of force is the pound force (lbf), defined as the force with which the standard pound mass is attracted to the earth under conditions of standard acceleration of gravity, which is that at 45° latitude and sea level elevation, 9.806 65 m/s² or 32.1740 ft/s². Thus, it follows from Newton's second law that

$$1 \text{ lbf} = 32.174 \text{ lbf} \cdot \text{ft/s}^2,$$

which is a necessary factor for the purpose of unit conversion and consistency. Note that we must be careful to distinguish between an lbf and an lbf, and we do not use the term *pound* alone.

The term *weight* is often used with respect to a body and is sometimes confused with mass. Weight is really correctly used only as a force. When we say that a body weighs so much, we mean that this is the force with which it is attracted to the earth (or some other body), that is, the product of its mass and the local gravitational acceleration. The mass of a substance remains constant with elevation, but its weight varies with elevation.

Example 1.1

What is the weight of a 1-kg mass at an altitude where the local acceleration of gravity is 9.75 m/s²?

Solution

Weight is the force acting on the mass, which, from Newton's second law, is

$$F = mg = 1 \text{ kg} \times 9.75 \text{ m/s}^2 \times [1 \text{ N s}^2/\text{kg m}] = 9.75 \text{ N}$$

Example 1.1E

What is the weight of a 1-lbm mass at an altitude where the local acceleration of gravity is 32.0 ft/s²?

Solution

Weight is the force acting on the mass, which from Newton's second law is

$$F = mg = 1 \text{ lbm} \times 32.0 \text{ ft/s}^2 \times [\text{lbf s}^2/32.174 \text{ lbm ft}] = 0.9946 \text{ lbf}$$

In-Text Concept Questions

- Make a control volume around the turbine in the steam power plant in Fig. 1.2 and list the flows of mass and energy located there.
- Take a control volume around a house air conditioning system indicate where the components shown in Fig. 1.3 are located, and show all energy transfers.

1.6 SPECIFIC VOLUME AND DENSITY

The specific volume of a substance is defined as the volume per unit mass and is given the symbol v . The density of a substance is defined as the mass per unit volume, and it is, therefore, the reciprocal of the specific volume. Density is designated by the symbol ρ . Specific volume and density are intensive properties.

The specific volume of a system in a gravitational field may vary from point to point. For example, if the atmosphere is considered a system, the specific volume increases as the elevation increases. Therefore, the definition of specific volume involves the specific volume of a substance at a point in a system.

Consider a small volume δV of a system and let the mass be designated δm . The specific volume is defined by the relation

$$v \equiv \lim_{\delta V \rightarrow \delta V'} \frac{\delta V}{\delta m}, \quad (1.2)$$

where $\delta V'$ is the smallest volume for which the mass can be considered a continuum. Volumes smaller than this will lead to the recognition that mass is not evenly distributed in space but is concentrated in particles such as molecules, atoms, electrons, and so on. This is tentatively indicated in Fig. 1.7, where in the limit of a zero volume, the specific volume may be infinite (the volume does not contain any mass) or very small (the volume is part of a nucleus).

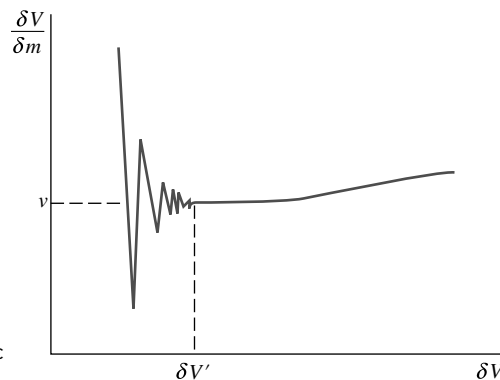


FIGURE 1.7
The continuum
limit for the specific
volume.

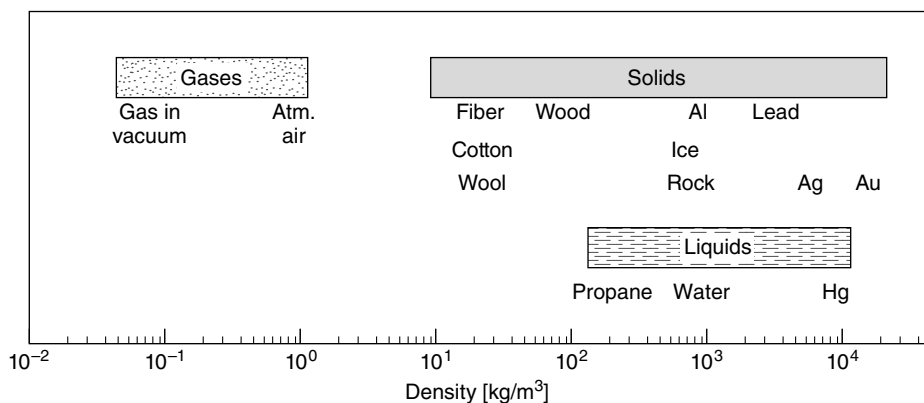


FIGURE 1.8 Density of common substances.

Thus, in a given system, when we speak of the specific volume or density at a point in the system, we recognize that this may vary with elevation. However, most of the systems that we consider are relatively small, and the change in specific volume with elevation is not significant. Therefore, we can assign one value of specific volume or density to the entire system.

In this book, the specific volume and density will be given either on a mass or a mole basis. A bar over the symbol (lowercase) will be used to designate the property on a mole basis. Thus, $\bar{v}$ will designate molal-specific volume and $\bar{\rho}$ will designate molal density. In SI units, those for specific volume are m^3/kg and m^3/mol (or m^3/kmol); for density, the corresponding units are kg/m^3 and mol/m^3 (or kmol/m^3). In English units, those for specific volume are ft^3/lbm and $\text{ft}^3/\text{lb mol}$; the corresponding units for density are lbm/ft^3 and $\text{lb mol}/\text{ft}^3$.

Although the SI unit for volume is the cubic meter, a commonly used volume unit is the liter (L), which is a special name given to a volume of 0.001 m^3 , that is, $1 \text{ L} = 10^{-3} \text{ m}^3$. The general ranges of density for some common solids, liquids, and gases are shown in Fig. 1.8. Specific values for various solids, liquids, and gases in SI units are listed in Tables A.3, A.4, and A.5, respectively, and in English units in Tables F.2, F.3, and F.4.

Example 1.2

A 1 m^3 container, shown in Fig. 1.9, is filled with 0.12 m^3 of granite, 0.15 m^3 of sand, and 0.2 m^3 of liquid 25°C water; the rest of the volume, 0.53 m^3 , is air with a density of $1.15 \text{ kg}/\text{m}^3$. Find the overall (average) specific volume and density.

Solution

From the definition of specific volume and density, we have

$$v = V/m \text{ and } \rho = m/V = 1/v$$



FIGURE 1.9 Sketch for Example 1.2.

We need to find the total mass, taking density from Tables A.3 and A.4:

$$m_{\text{granite}} = \rho V_{\text{granite}} = 2750 \text{ kg/m}^3 \times 0.12 \text{ m}^3 = 330 \text{ kg}$$

$$m_{\text{sand}} = \rho_{\text{sand}} V_{\text{sand}} = 1500 \text{ kg/m}^3 \times 0.15 \text{ m}^3 = 225 \text{ kg}$$

$$m_{\text{water}} = \rho_{\text{water}} V_{\text{water}} = 997 \text{ kg/m}^3 \times 0.2 \text{ m}^3 = 199.4 \text{ kg}$$

$$m_{\text{air}} = \rho_{\text{air}} V_{\text{air}} = 1.15 \text{ kg/m}^3 \times 0.53 \text{ m}^3 = 0.61 \text{ kg}$$

Now, the total mass becomes

$$m_{\text{tot}} = m_{\text{granite}} + m_{\text{sand}} + m_{\text{water}} + m_{\text{air}} = 755 \text{ kg}$$

and the specific volume and density can be calculated:

$$v = V_{\text{tot}}/m_{\text{tot}} = 1 \text{ m}^3/755 \text{ kg} = 0.001325 \text{ m}^3/\text{kg}$$

$$\rho = m_{\text{tot}}/V_{\text{tot}} = 755 \text{ kg}/1 \text{ m}^3 = 755 \text{ kg/m}^3$$

Remark: It is misleading to include air in the numbers for ρ and V , as the air is separate from the rest of the mass.

In-Text Concept Questions

- c. Why do people float high in the water when swimming in the Dead Sea as compared with swimming in a freshwater lake?
- d. The density liquid water is $\rho = 1008 - T/2$ (kg/m³) with T in °C. If the temperature increases, what happens to the density and specific volume?

1.7 PRESSURE

When dealing with liquids and gases, we ordinarily speak of pressure; for solids, we speak of stresses. The pressure in a fluid at rest at a given point is the same in all directions, and we define pressure as the normal component of force per unit

area. More specifically, if δA is a small area, $\delta A'$ is the smallest area over which we can consider the fluid a continuum, and δF_n is the component of force normal to δA , we define pressure, P , as

$$P = \lim_{\delta A \rightarrow \delta A'} \frac{\delta F_n}{\delta A}, \quad (1.3)$$

where the lower limit corresponds to sizes as mentioned for the specific volume, shown in Fig. 1.7. The pressure P at a point in a fluid in equilibrium is the same in all directions. In a viscous fluid in motion, the variation in the state of stress with orientation becomes an important consideration. These considerations are beyond the scope of this book, and we will consider pressure only in terms of fluid in equilibrium.

The unit for pressure in the International System is the force of one newton acting on a square meter area, which is called the *Pascal* (Pa). That is,

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

Two other units, not part of the International System, continue to be widely used. These are the bar, where

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa}$$

and the standard atmosphere, where

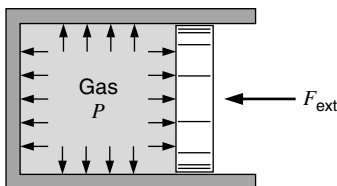
$$1 \text{ atm} = 101\,325 \text{ Pa} = 14.696 \text{ lbf/in.}^2,$$

which is slightly larger than the bar. In this book, we will normally use the SI unit, the Pascal, and especially the multiples of kilopascal and mega Pascal. The bar will be utilized often in the examples and problems, but the atmosphere will not be used except in specifying certain reference points.

Consider a gas contained in a cylinder fitted with a movable piston, as shown in Fig. 1.10. The pressure exerted by the gas on all of its boundaries is the same, assuming that the gas is in an equilibrium state. This pressure is fixed by the external force acting on the piston since there must be a balance of forces for the piston to remain stationary. Thus, the product of the pressure and the movable piston area must be equal to the external force. If the external force is now changed in either direction, the gas pressure inside must accordingly adjust, with appropriate movement of the piston, to establish a force balance at a new equilibrium state. As another example, if the gas in the cylinder is heated by an outside body, which tends to increase the gas pressure, the piston will move instead, such that the pressure remains equal to whatever value is required by the external force.

FIGURE 1.10

The balance of forces on a movable boundary relates to inside gas pressure.



Example 1.3

The hydraulic piston/cylinder system shown in Fig. 1.11 has a cylinder diameter of $D = 0.1$ with a piston and rod mass of 25 kg. The rod has a diameter of 0.01 with an outside atmospheric pressure of 101 kPa. The inside hydraulic fluid pressure is 250 kPa. How large a force can the rod push in the upward direction?

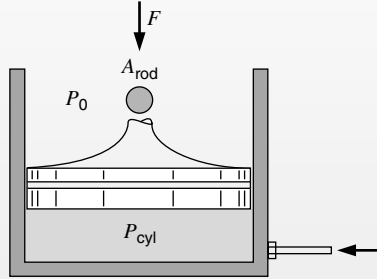


FIGURE 1.11 Sketch for Example 1.3.

Solution

We will assume a static balance of forces on the piston (positive upward), so

$$\begin{aligned} F_{\text{net}} &= ma = 0 \\ &= P_{\text{cyl}}A_{\text{cyl}} - P_0(A_{\text{cyl}} - A_{\text{rod}}) - F - m_p g \end{aligned}$$

Solve for F :

$$F = P_{\text{cyl}}A_{\text{cyl}} - P_0(A_{\text{cyl}} - A_{\text{rod}}) - m_p g$$

The areas are

$$A_{\text{cyl}} = \pi r^2 = \pi D^2/4 = \frac{\pi}{4} 0.1^2 \text{ m}^2 = 0.007854 \text{ m}^2$$

$$A_{\text{rod}} = \pi r^2 = \pi D^2/4 = \frac{\pi}{4} 0.01^2 \text{ m}^2 = 0.00007854 \text{ m}^2$$

The force becomes

$$\begin{aligned} F &= [250 \text{ kPa} \times 0.007854 \text{ m}^2 - 101 \text{ kPa} (0.007854 - 0.00007854) \text{ m}^2] 1000 \text{ Pa/kPa} \\ &\quad - 25 \text{ kg} \times 9.81 \text{ m/s}^2 = [1963.5 - 785.32 - 245.25] \text{ N} = 932.9 \text{ N} \end{aligned}$$

Note that we must convert kPa to Pa to get units of N.

In most thermodynamic investigations, we are concerned with absolute pressure. Most pressure and vacuum gauges, however, read the difference between the absolute pressure and the atmospheric pressure existing at the gauge. This is referred to as *gauge pressure*.

$$P_{\text{gauge}} = \Delta P = P - P_0 \quad (1.4)$$

It is shown graphically in Fig. 1.12, and the following examples illustrate the principles. Pressures below atmospheric and slightly above atmospheric, and

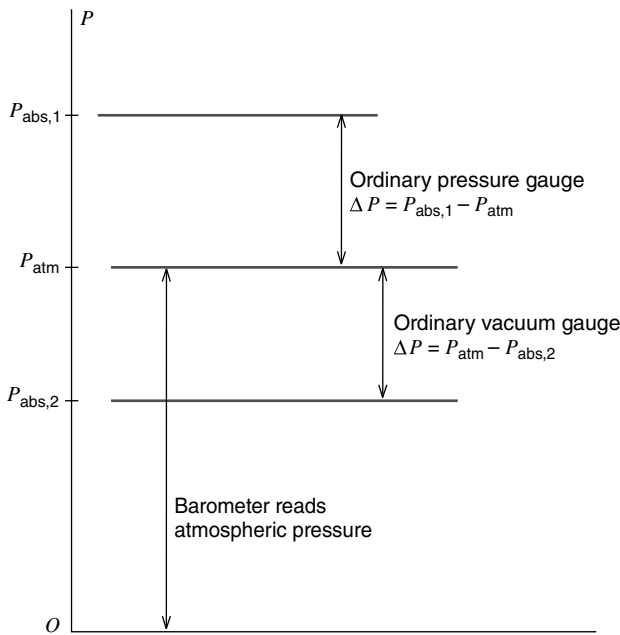
**FIGURE 1.12**

Illustration of terms used in pressure measurement.

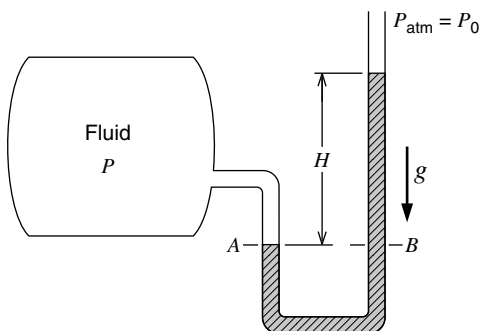
pressure differences (for example, across an orifice in a pipe), are frequently measured with a manometer, which contains water, mercury, alcohol, oil, or other fluids.

Consider the column of fluid of height H standing above point B in the manometer shown in Fig. 1.13. The force acting downward at the bottom of the column is

$$P_0 A + mg = P_0 A + \rho A g H,$$

where m is the mass of the fluid column, A is its cross-sectional area, and ρ is its density. This force must be balanced by the upward force at the bottom of the column, which is $P_B A$. Therefore,

$$P_B - P_0 = \rho g H$$

**FIGURE 1.13**

Example of pressure measurement using a column of fluid.

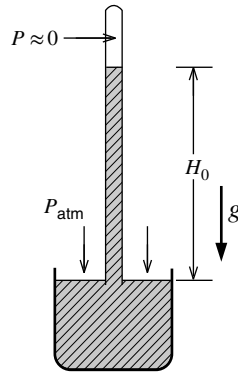


FIGURE 1.14
Barometer.

Since points A and B are at the same elevation in columns of the same fluid, their pressures must be equal (the fluid being measured in the vessel has a much lower density, such that its pressure P is equal to P_A). Overall,

$$\Delta P = P - P_0 = \rho g H. \quad (1.5)$$

For distinguishing between absolute and gauge pressure in this book, the term *Pascal* will always refer to absolute pressure. Any gauge pressure will be indicated as such.

Consider the barometer used to measure atmospheric pressure, as shown in Fig. 1.14. Since there is a near vacuum in the closed tube above the vertical column of fluid, usually mercury, the height of the fluid column gives the atmospheric pressure directly from Eq. 1.5:

$$P_{\text{atm}} = \rho g H_0 \quad (1.6)$$

If the density is variable, we should consider Eq. 1.5 in differential form as

$$dP = -\rho g dh,$$

including the sign, so pressure drops with increasing height. Now, the finite difference becomes

$$P = P_0 - \int_0^H \rho g dh \quad (1.7)$$

with the pressure P_0 at zero height. Consider a volume of liquid at some depth from the surface. The net force on that volume equals the normal force, $F = mg$, to have a static equilibrium. That force is the net force up from the pressure distribution around the volume regardless of its shape, which is a buoyancy effect. We normally do not notice this except when we place an object instead of

the liquid volume that has a different mass in that volume ($\rho_{\text{object}} \neq \rho_{\text{liq}}$). Now, there will be a net force up as

$$F_{\text{net}} = F_{\text{buoyancy}} - m_{\text{object}} g = (\rho_{\text{liq}} - \rho_{\text{object}}) V g = (m_{\text{liq}} - m_{\text{object}}) g \quad (1.8)$$

If the object is heavier, the force is down, and if it is lighter, the force is up, which is what we experience when we swim in water or float in a boat.

Example 1.4

A mercury barometer located in a room at 25°C has a height of 750 mm. What is the atmospheric pressure in kPa?

Solution

The density of mercury at 25°C is found in Table A.4 to be 13 534 kg/m³. Using Eq. 1.6,

$$\begin{aligned} P_{\text{atm}} &= \rho g H_0 = 13\,534 \text{ kg/m}^3 \times 9.807 \text{ m/s}^2 \times 0.750 \text{ m} \\ &= 99\,540 \text{ Pa} = 99.54 \text{ kPa} \end{aligned}$$

Example 1.5

A mercury (Hg) manometer is used to measure the pressure in a vessel as shown in Fig. 1.13. The mercury has a density of 13 590 kg/m³, and the height difference between the two columns is measured to be 24 cm. We want to determine the pressure inside the vessel.

Solution

The manometer measures the gauge pressure as a pressure difference. From Eq. 1.5,

$$\begin{aligned} \Delta P &= P_{\text{gauge}} = \rho g H = 13\,590 \text{ kg/m}^3 \times 9.807 \text{ m/s}^2 \times 0.24 \text{ m} \\ &= 31\,985 \text{ Pa} = 31.985 \text{ kPa} = 0.316 \text{ atm} \end{aligned}$$

To get the absolute pressure inside the vessel, we have

$$P_A = P_{\text{vessel}} = P_B = \Delta P + P_{\text{atm}}$$

We need to know the atmospheric pressure measured by a barometer (absolute pressure). Assume that this pressure is known to be 750 mm Hg. The absolute pressure in the vessel becomes

$$\begin{aligned} P_{\text{vessel}} &= \Delta P + P_{\text{atm}} = 31\,985 \text{ Pa} + 13\,590 \text{ kg/m}^3 \times 0.750 \text{ m} \times 9.807 \text{ m/s}^2 \\ &= 31\,985 + 99\,954 = 131\,940 \text{ Pa} = 1.302 \text{ atm} \end{aligned}$$

Example 1.5E

A mercury (Hg) manometer is used to measure the pressure in a vessel as shown in Fig. 1.13. The mercury has a density of 848 lbf/ft^3 , and the height difference between the two columns is measured to be 9.5 in. We want to determine the pressure inside the vessel.

Solution

The manometer measures the gauge pressure as a pressure difference. From Eq. 1.5,

$$\begin{aligned}\Delta P &= P_{\text{gauge}} = \rho g H \\ &= 848 \frac{\text{lbf}}{\text{ft}^3} \times 32.174 \frac{\text{ft}}{\text{s}^2} \times 9.5 \text{ in.} \times \frac{1}{1728} \frac{\text{ft}^3}{\text{in.}^3} \times \left[\frac{1 \text{ lbf s}^2}{32.174 \text{ lbf ft}} \right] = 4.66 \text{ lbf/in.}^2\end{aligned}$$

To get the absolute pressure inside the vessel, we have

$$P_A = P_{\text{vessel}} = P_0 = \Delta P + P_{\text{atm}}$$

We need to know the atmospheric pressure measured by a barometer (absolute pressure). Assume that this pressure is known to be 29.5 in. Hg. The absolute pressure in the vessel becomes

$$\begin{aligned}P_{\text{vessel}} &= \Delta P + P_{\text{atm}} \\ &= \left[848 \times 32.174 \times 29.5 \times \frac{1}{1728} \times \frac{1}{32.174} \right] \text{ lbf/in.}^2 + 4.66 \text{ lbf/in.}^2 \\ &= 19.14 \text{ lbf/in.}^2\end{aligned}$$

Example 1.6

A research submarine for ocean exploration has a volume of 22 m^3 , a mass of 16 000 kg plus 2000 kg instrumentation and crew. It has some ballast tanks initially empty. How big a water volume is displaced when the submarine is floating on the water's surface? How much ocean water ($\rho_{\text{liq}} = 1025 \text{ kg/m}^3$) should be pumped into the ballast tanks for the submarine to be able to submerge?

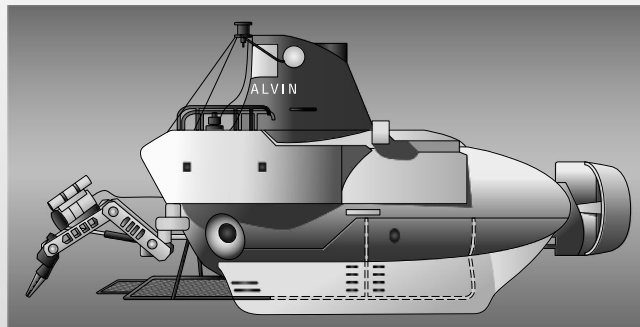


FIGURE 1.15 Alvin is a submersible owned by the United States Navy and operated by the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts.

Solution

The submarine will float when the net force is zero; the force up must equal the normal force, $F = N = mg$, so it must displace exactly that much mass of water.

$$F = mg = m_{\text{liq}}g = \rho_{\text{liq}}V_{\text{liq}}g \Rightarrow V_{\text{liq}} = m/\rho_{\text{liq}};$$

$$V_{\text{liq}} = (16\,000 + 2000) \text{ kg} / (1025 \text{ kg/m}^3) = 17.56 \text{ m}^3$$

For the submarine to submerge, it must be neutrally buoyant, that means from Eq. 1.8 that the mass of the submarine plus ballast must equal the mass of the displaced water.

$$m_{\text{liq}} = \rho_{\text{liq}}V_{\text{submarine}} = m_{\text{submarine}} + m_{\text{ballast}} \Rightarrow$$

$$m_{\text{ballast}} = \rho_{\text{liq}}V_{\text{submarine}} - m_{\text{submarine}}$$

$$= 1025 \text{ kg/m}^3 \times 22 \text{ m}^3 - (16\,000 + 2000) \text{ kg} = 4550 \text{ kg}$$

This takes up 4.4 m^3 a significant volume compared to total volume.

Example 1.7

A piston/cylinder with a cross-sectional area of 0.01 m^2 is connected with a hydraulic line to another piston/cylinder with a cross-sectional area of 0.05 m^2 . Assume that both chambers and the line are filled with hydraulic fluid of density 900 kg/m^3 and the larger second piston/cylinder is 6 m higher up in elevation. The telescope arm and the buckets have hydraulic pistons/cylinders moving them, as seen in Fig. 1.16. With an outside atmospheric pressure of 100 kPa and a net force of 25 kN on the smallest piston, what is the balancing force on the second larger piston?

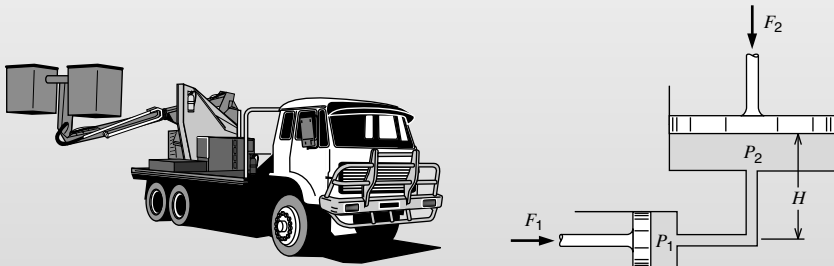


FIGURE 1.16 Sketch for Example 1.7.

Solution

When the fluid is stagnant, and at the same elevation, we have the same pressure throughout the fluid. The force balance on the smaller piston is then related to the pressure (we neglect the rod area) as

$$F_1 + P_0 A_1 = P_1 A_1$$

From which the fluid pressure is

$$P_1 = P_0 + F_1/A_1 = 100 \text{ kPa} + 25 \text{ kN}/0.01 \text{ m}^2 = 2600 \text{ kPa}$$

The pressure at the higher elevation in piston/cylinder 2 is from Eq. 1.5,

$$\begin{aligned} P_2 &= P_1 - \rho g H = 2600 \text{ kPa} - 900 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 \times 6 \text{ m}/(1000 \text{ Pa/kPa}) \\ &= 2547 \text{ kPa}, \end{aligned}$$

where the second term is divided by 1000 to convert from Pa to kPa. Then, the force balance on the second piston gives:

$$\begin{aligned} F_2 + P_0 A_0 &= P_2 A_2 \\ F_2 &= (P_2 - P_0) A_2 = (2547 - 100) \text{ kPa} \times 0.05 \text{ m}^2 = 122.4 \text{ kN} \end{aligned}$$

In-Text Concept Questions

- e. A car tire gauge shows 210 kPa; to raise absolute pressure 10% what is the new air pressure inside?
- f. Can I always neglect ΔP in the fluid above location A in Fig. 1.13? What circumstances does that depend on?
- g. A U tube manometer has the left branch connected to a box with a pressure of 90 kPa and the right branch open. Which side has a higher column of fluid?
- h. If the right-side pipe section in Fig. 1.13 is V-shaped like a funnel, does that change the pressure at location B?
- i. If the cylinder pressure in Example 1.3 does not give $F_{\text{net}} = 0$ what happens?

1.8 ENERGY

A macroscopic amount of mass can possess energy in the form of internal energy inherent in its internal structure, kinetic energy in its motion, and potential energy associated with external forces acting on the mass. We write the total energy as

$$E = \text{Internal} + \text{Kinetic} + \text{Potential} = U + \text{KE} + \text{PE}$$

and the specific total energy becomes

$$e = E/m = u + ke + pe = u + \frac{1}{2}\mathbf{V}^2 + gz, \quad (1.9)$$

where the kinetic energy is taken as the translational energy, and the potential energy is written for the external force, which is the gravitational force assumed constant. If the mass is rotating, we should add a rotational kinetic energy ($\frac{1}{2}I\omega^2$) to the translational term. What is called internal energy on the *macro-scale* has a similar set of energies associated with the *microscale* motion of the individual molecules. This enables us to write

$$u = u_{\text{ext molecule}} + u_{\text{translation}} + u_{\text{int molecule}} \quad (1.10)$$

as a sum of the potential energy from intermolecular forces between molecules, the molecule translational kinetic energy, and the energy associated with the molecular internal and atomic structure.

Without going into detail, we realize that there is a difference between the intermolecular forces. Thus, the first term of the energy for a configuration where the molecules are close together, as in a solid or liquid (high density), contrasts with the situation for a gas such as air, where the distance between the molecules is large (low density). In the limit of a very thin gas, the molecules are so far apart that they do not sense each other unless they collide, and the first term becomes near zero. This is the limit we have when we consider a substance to be an ideal gas, as will be covered in Chapter 2.

The translational energy depends only on the mass and center of mass velocity of the molecules, whereas the last energy term depends on the detailed structure. In general, we can write the energy as:

$$u_{\text{int molecule}} = u_{\text{potential}} + u_{\text{rotation}} + u_{\text{vibration}} + u_{\text{atoms}}. \quad (1.11)$$

To illustrate the potential energy associated with the intermolecular forces, consider an oxygen molecule of two atoms, as shown in Fig. 1.17. If we want to separate the two atoms, we pull them apart with a force and thereby we do some work on the system, as explained in Chapter 3. That amount of work equals the binding (potential) energy associated with the two atoms as they are held together in the oxygen molecule.

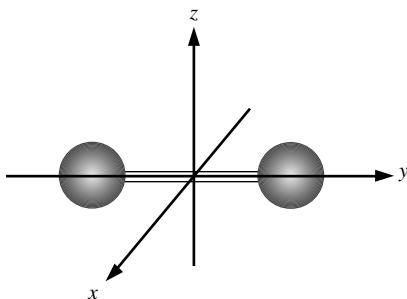


FIGURE 1.17

The coordinate system for a diatomic molecule.

Consider a simple monatomic gas such as helium. Each molecule consists of a helium atom. Such an atom possesses electronic energy as a result of both the orbital angular momentum of the electrons about the nucleus and the angular momentum of the electrons spinning on their axes. The electronic energy is commonly very small compared with the translational energy. (Atoms also possess nuclear energy, which, except in the case of nuclear reactions, is constant. We are not concerned with nuclear energy at this time.) When we consider more complex molecules, such as those composed of two or three atoms, additional factors must be considered. In addition to having electronic energy, a molecule can rotate about its center of gravity and thus have rotational energy. Furthermore, the atoms may vibrate with respect to each other and have vibrational energy. In some situations, there may be an interaction between the rotational and vibrational modes of energy.

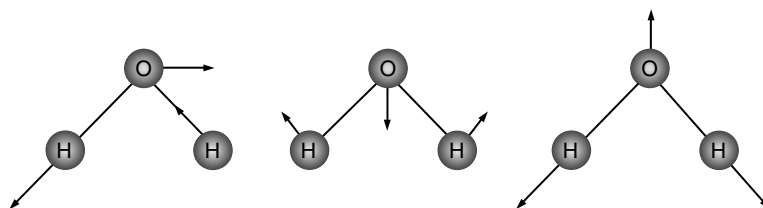
In evaluating the energy of a molecule, we often refer to the degree of freedom, f , of these energy modes. For a monatomic molecule such as helium, $f = 3$, which represents the three directions x , y , and z in which the molecule can move. For a diatomic molecule, such as oxygen, $f = 6$. Three of these are the translation of the molecule as a whole in the x , y , and z directions, and two are for rotation. The reason there are only two modes of rotational energy is evident from Fig. 1.17, where we take the origin of the coordinate system at the center of gravity of the molecule and the y -axis along the molecule's internuclear axis. The molecule will then have an appreciable moment of inertia about the x -axis and the z -axis but not about the y -axis. The sixth degree of freedom of the molecule is vibration, which relates to the stretching of the bond joining the atoms.

For a more complex molecule, such as H_2O , there are additional vibrational degrees of freedom. Figure 1.18 shows a model of the H_2O molecule. From this diagram, we infer there are three vibrational degrees of freedom. It is also possible to have rotational energy about all three axes. Thus, for the H_2O molecule, there are nine degrees of freedom ($f = 9$): three translational, three rotational, and three vibrational.

Most complex molecules, such as typical polyatomic molecules, are usually three-dimensional in structure and have multiple vibrational modes, each of which contributes to the energy storage of the molecule. The more complicated the molecule is, the larger the number of degrees of freedom that exist for energy storage. The modes of energy storage and their evaluation are discussed in some detail in Appendix C and in much more detail analyzed in Chapter 16 for those interested in further development of the quantitative effects from a molecular viewpoint.

FIGURE 1.18

The three principal vibrational modes for the H_2O molecule.



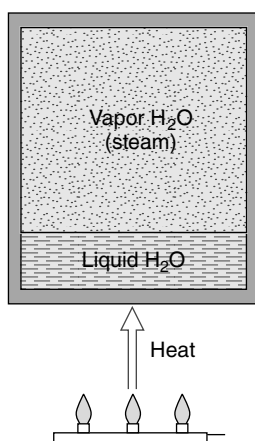


FIGURE 1.19
Heat transfer
to H₂O.

This general discussion can be summarized by referring to Fig. 1.19. Let heat be transferred to H₂O. During this process, the temperature of the liquid and vapor (steam) will increase, and eventually, all the liquid will become vapor. From the macroscopic point of view, we are concerned only with the energy that is transferred as heat, the change in properties such as temperature and pressure, and the total amount of energy (relative to some base) that the H₂O contains at any instant. Thus, questions about how energy is stored in the H₂O do not concern us. From a microscopic viewpoint, we are concerned about the way in which energy is stored in the molecules. We might be interested in developing a model of the molecule so that we can predict the amount of energy required to change the temperature a given amount. Although the focus in this book is on the macroscopic or classical viewpoint, it is helpful to keep in mind the microscopic or statistical perspective, as well as the relationship between the two, which helps us understand basic concepts such as energy.

1.9 EQUALITY OF TEMPERATURE

Although temperature is a familiar property, defining it exactly is difficult. We are aware of temperature first of all as a sense of hotness or coldness when we touch an object. We also learn early that when a hot body and a cold body are brought into contact, the hot body becomes cooler and the cold body becomes warmer. If these bodies remain in contact for some time, they usually appear to have the same hotness or coldness. However, we also realize that our sense of hotness or coldness is very unreliable. Sometimes, very cold bodies may seem hot, and bodies of different materials that are at the same temperature appear to be at different temperatures.

Because of these difficulties in defining temperature, we define equality of temperature. Consider two blocks of copper, one hot and the other cold, each of which is in contact with a mercury-in-glass thermometer. If these two blocks

of copper are brought into thermal communication, we observe that the electrical resistance of the hot block decreases with time, and that of the cold block increases with time. After a period of time has elapsed, however, no further changes in resistance are observed. Similarly, when the blocks are first brought in thermal communication, the length of a side of the hot block decreases with time, but the length of a side of the cold block increases with time. After a period of time, no further change in the length of either block is perceived. In addition, the mercury column of the thermometer in the hot block drops at first, and that in the cold block rises, but after a period of time, no further changes in height are observed. We may say, therefore, that two bodies have equality of temperature if, when they are in thermal communication, no change in any observable property occurs.

1.10 THE ZEROth LAW OF THERMODYNAMICS

Now, consider the same two blocks of copper and another thermometer. Let one block of copper be brought into contact with the thermometer until equality of temperature is established, and then remove it. Then, let the second block of copper be brought into contact with the thermometer. Suppose that no change in the mercury level of the thermometer occurs during this operation with the second block. We then can say that both blocks are in thermal equilibrium with the given thermometer.

The zeroth law of thermodynamics states that when two bodies have equality of temperature with a third body, they in turn have equality of temperature with each other. This seems obvious to us because we are so familiar with this experiment. Because the principle is not derivable from other laws, and because it precedes the first and second laws of thermodynamics in the logical presentation of thermodynamics, it is called the zeroth law of thermodynamics. This law is really the basis of temperature measurement. Every time a body has equality of temperature with the thermometer, we can say that the body has the temperature we read on the thermometer. The problem remains of how to relate temperatures that we might read on different mercury thermometers or obtain from different temperature-measuring devices, such as thermocouples and resistance thermometers. This observation suggests the need for a standard scale for temperature measurements.

1.11 TEMPERATURE SCALES

Two scales are commonly used for measuring temperature, namely, the Fahrenheit (after Gabriel Fahrenheit, 1686–1736) and the Celsius. The Celsius scale was formerly called the centigrade scale but is now designated the Celsius scale after Anders Celsius (1701–1744), the Swedish astronomer who devised this scale.

The Fahrenheit temperature scale is used with the English Engineering System of Units, and the Celsius scale with the SI unit system. Until 1954, both

of these scales were based on two fixed, easily duplicated points: the ice point and the steam point. The temperature of the ice point is defined as the temperature of a mixture of ice and water that is in equilibrium with saturated air at a pressure of 1 atm. The temperature of the steam point is the temperature of water and steam, which are in equilibrium at a pressure of 1 atm. On the Fahrenheit scale, these two points are assigned the numbers 32 and 212, respectively, and on the Celsius scale, the points are 0 and 100, respectively. Why Fahrenheit chose these numbers is an interesting story. In searching for an easily reproducible point, Fahrenheit selected the temperature of the human body and assigned it the number 96. He assigned the number 0 to the temperature of a certain mixture of salt, ice, and salt solution. On this scale, the ice point was approximately 32. When this scale was slightly revised and fixed in terms of the ice point and steam point, the normal temperature of the human body was found to be 98.6 F.

In this book, the symbols F and °C will denote the Fahrenheit and Celsius scales, respectively (the Celsius scale symbol includes the degree symbol since the letter C alone denotes Coulomb, the unit of electrical charge in the SI system of units). The symbol T refers to temperature on all temperature scales.

At the tenth CGPM meeting in 1954, the Celsius scale was redefined in terms of a single fixed point and the ideal gas temperature scale. The single fixed point is the triple point of water (the state in which the solid, liquid, and vapor phases of water exist together in equilibrium). The magnitude of the degree is defined in terms of the ideal gas temperature scale, which is discussed in Chapter 5. The essential features of this new scale are a single fixed point and a definition of the magnitude of the degree. The triple point of water is assigned the value of 0.01°C. On this scale, the steam point is experimentally found to be 100.00°C. Thus, there is essential agreement between the old and new temperature scales.

We have not yet considered an absolute scale of temperature. The possibility of such a scale comes from the second law of thermodynamics and is discussed in Chapter 5. On the basis of the second law of thermodynamics, a temperature scale that is independent of any thermometric substance can be defined. This absolute scale is usually referred to as the *thermodynamic scale of temperature*. However, it is difficult to use this scale directly; therefore, a more practical scale, the International Temperature Scale, which closely represents the thermodynamic scale, has been adopted.

The absolute scale related to the Celsius scale is the Kelvin scale (after William Thomson, 1824–1907, who is also known as Lord Kelvin) and is designated K (without the degree symbol). The relation between these scales is

$$T[\text{K}] = T[^\circ\text{C}] + 273.15 \quad (1.12)$$

In 1967, the CGPM defined the kelvin as 1/273.16 of the temperature at the triple point of water. The Celsius scale is now defined by this equation instead of by its earlier definition.

The absolute scale related to the Fahrenheit scale is the Rankine scale and is designated R. The relation between these scales is

$$T[\text{R}] = T[\text{F}] + 459.67 \quad (1.13)$$

A number of empirically based temperature scales, to standardize temperature measurement and calibration, have been used. The most recent of these is the International Temperature Scale of 1990, or ITS-90. It is based on a number of fixed and easily reproducible points that are assigned definite numerical values of temperature and further details can be found in the literature.

1.12 ENGINEERING APPLICATIONS

When we deal with materials to move or trade them, we need to specify the amount; that is often done as either the total mass or volume. For substances with reasonably well-defined density, we can use either measure. For instance, water, gasoline, oil, natural gas, and many food items are common examples of materials for which we use volume to express the amount. Other examples are amounts of gold, coal, and food items, where we use mass as the amount. To store or transport materials, we often need to know both measures to be able to size the equipment appropriately.

Pressure is used in applications for process control or limit control for safety reasons. In most cases, this is the gauge pressure. For instance, a storage tank has a pressure indicator to show how close it is to being full, but it may also have a pressure-sensitive safety valve that will open and let material escape if the pressure exceeds a preset value. An air tank with a compressor on top is shown in Fig. 1.20. As a portable unit, it is used to drive air tools, such as nailers. A pressure gauge will activate a switch to start the compressor when the pressure drops below a preset value, and it will disengage the compressor when a preset high value is reached.

Tire pressure gauges, shown in Fig. 1.21, are connected to the valve stem on the tire. Some gauges have a digital readout. The tire pressure is important for the safety and durability of automobile tires. Too low a pressure causes large deflections, and the tire may overheat; too high a pressure leads to excessive wear in the center.

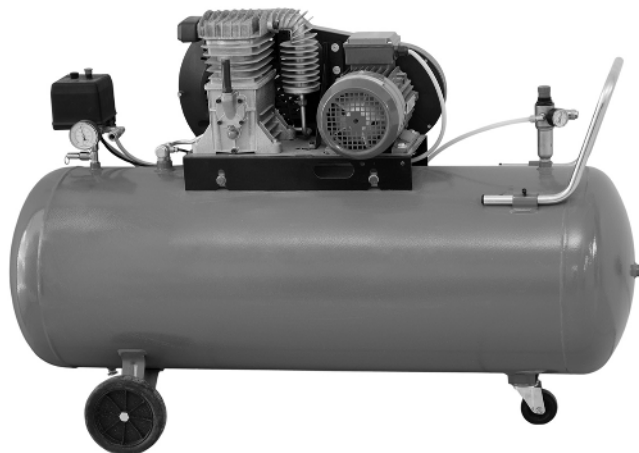


FIGURE 1.20

Air compressor with tank. (Max Tactic/Adobe Stock Photos)

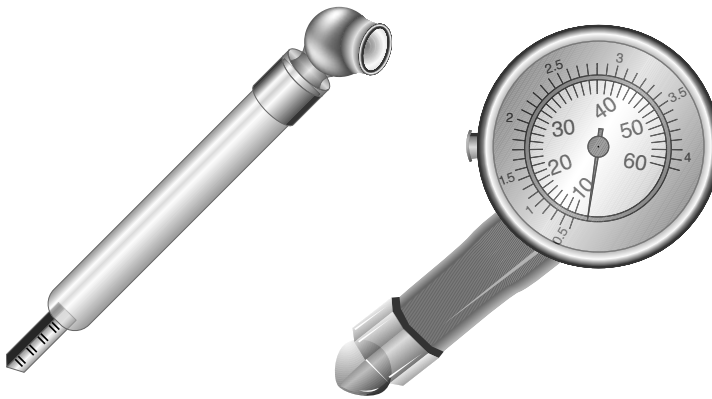


FIGURE 1.21
Automotive tire
pressure gauges.

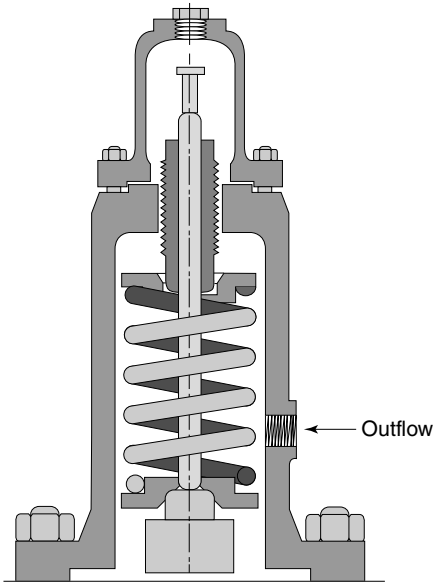


FIGURE 1.22
Schematic of a
pressure
relief valve.

A spring-loaded pressure relief valve is shown in Fig. 1.22. With the cap, the spring can be compressed to make the valve open at a higher pressure, or the opposite. This valve is used for pneumatic systems.

When a throttle plate in an intake system for an automotive engine restricts the flow (Fig. 1.23), it creates a vacuum behind it that is measured by a pressure gauge sending a signal to the computer control. The smallest absolute pressure (highest vacuum) occurs when the engine idles, and the highest pressure (smallest vacuum) occurs when the engine is at full throttle. In Fig. 1.23, the throttle is shown completely closed.

A pressure difference, ΔP , can be used to measure flow velocity indirectly, as shown schematically in Fig. 1.24 (this effect is felt when you hold your hand out of a car window, with a higher pressure on the side facing forward and a lower pressure on the other side, giving a net force on your hand). The engineering analysis of such processes is developed and presented in Chapter 7. In a speedboat, a

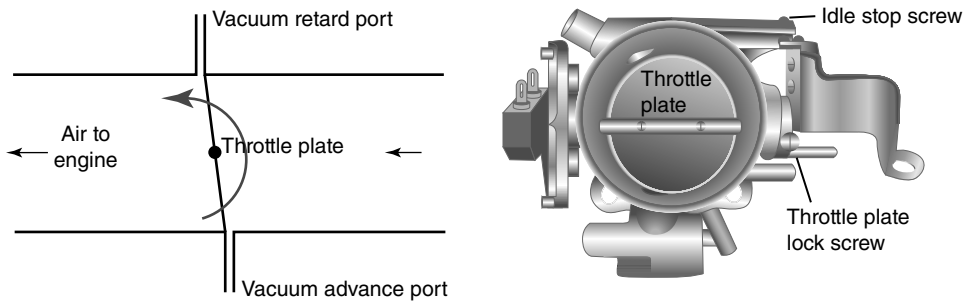


FIGURE 1.23 Automotive engine intake throttle.

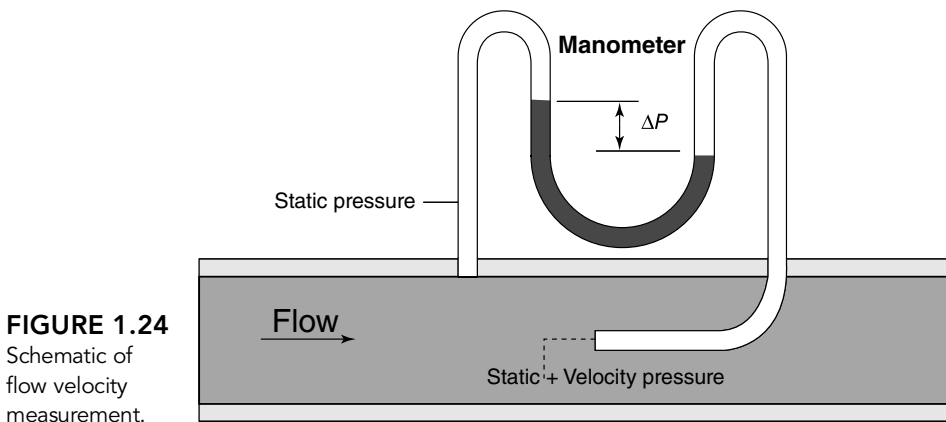


FIGURE 1.24 Schematic of flow velocity measurement.

small pipe has its end pointing forward, feeling the higher pressure due to the relative velocity between the boat and the water. The other end goes to a speedometer transmitting the pressure signal to an indicator.

An aneroid barometer, shown in Fig. 1.25, measures the absolute pressure used for weather predictions. It consists of a thin metal capsule or bellows that



FIGURE 1.25 Aneroid barometer.

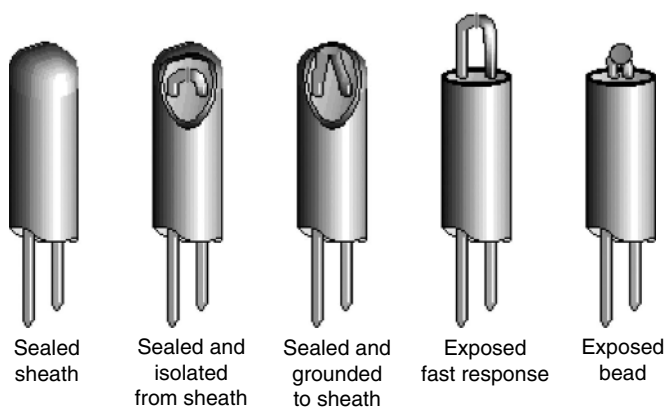


FIGURE 1.26
Thermocouples.

expands or contracts with atmospheric pressure. Measurement is by a mechanical pointer or by a change in electrical capacitance with distance between two plates.

Numerous types of devices are used to measure temperature. Perhaps the most familiar of these is the liquid-in-glass thermometer, in which the liquid is commonly mercury. Since the volume of the liquid expands with temperature, the height of the liquid column rises accordingly. Other liquids are also used in such thermometers, depending on the range of temperature to be measured.

Two types of devices commonly used in temperature measurement are thermocouples and thermistors. Examples of thermocouples are shown in Fig. 1.26. A thermocouple consists of a pair of junctions of two dissimilar metals that create an electrical potential (voltage) that increases with the temperature difference between the junctions. One junction is maintained at a known reference temperature (for example, in an ice bath), such that the voltage measured indicates the temperature of the other junction. Different material combinations are used for different temperature ranges, and the size of the junction is kept small to have a short response time. Thermistors change their electrical resistance with temperature, so if a known current is passed through the thermistor, the voltage across it becomes proportional to the resistance. The output signal is improved if this is arranged in an electrical bridge that provides input to an instrument. The small signal from these sensors is amplified and scaled so that a meter can show the temperature, or the signal can be sent to a computer or a control system. High-precision temperature measurements are made in a similar manner using a platinum resistance thermometer. A large portion of the ITS-90 (13.8033–1234.93 K) is measured in such a manner. Higher temperatures are determined from visible-spectrum radiation intensity observations.

KEY CONCEPTS AND FORMULAS

Concepts from Physics

Newton's law of motion $F = ma$ (1.1)

Acceleration $a = \frac{d^2x}{dt^2} = \frac{d\mathbf{V}}{dt}$

Velocity $\mathbf{V} = \frac{dx}{dt}$

Control volume everything inside a control surface

Specific volume $v = V/m$ (1.2)

Density $\rho = m/V = 1/v$ Tables A.3, A.4, A.5, F.2, F.3, F.4

Pressure definition $P = F/A$ mathematical limit for small A (1.3)

Gauge pressure $P_{\text{gauge}} = \Delta P = P - P_0$ (1.4)
 $P_0 = P_{\text{atm}}$

Static pressure variation $\Delta P = \rho g H$ depth H in fluid of density ρ (1.5)

Buoyancy force $F_{\text{buoyancy}} = \rho_{\text{liq}} V_{\text{object}} g = m_{\text{liq}} g$

Net force $F_{\text{net}} = F_{\text{buoyancy}} - m_{\text{object}} g$ (1.8)

Specific total energy $e \equiv u + \frac{1}{2} \mathbf{V}^2 + gz$ (internal + kinetic + potential) (1.9)

Internal energy $u = u_{\text{ext molecule}} + u_{\text{translation}} + u_{\text{int molecule}}$ (1.10)

$u_{\text{int molecule}} = u_{\text{potential}} + u_{\text{rotation}} + u_{\text{vibration}} + u_{\text{atoms}}$ (1.11)

Absolute temperature $T[\text{K}] = T[^\circ\text{C}] + 273.15$ (1.12)

$T[\text{R}] = T[\text{F}] + 459.67$ (1.13)

Unit conversions Table A.1

Fundamental constants Table A.0

CHAPTER 1 PROBLEMS

CONCEPT-STUDY GUIDE PROBLEMS

- 1.1 Separate the list P , F , V , v , ρ , T , a , m , L , t , and $\mathbf{V}$ into intensive properties, extensive properties, and nonproperties.
- 1.2 A tray of liquid water is placed in a freezer where it cools from 20 to -5°C . Show the energy flow(s) and storage and explain what changes.
- 1.3 The overall density of fibers, rock wool insulation, foams, and cotton is fairly low. Why?
- 1.4 Is density a unique measure of mass distribution in a volume? Does it vary? If so, on what kind of scale (distance)?
- 1.5 Water in nature exists in three different phases: solid, liquid, and vapor (gas). Indicate the relative magnitude of density and the specific volume for the three phases.
- 1.6 What is the approximate mass of 1 L of gasoline? Of helium in a balloon at T_0 , P_0 ?
- 1.7 You must mail 100 cm^3 of copper (Cu), how heavy a package is that?
- 1.8 A heavy refrigerator has four height-adjustable feet. What feature of the feet will ensure that they do not make dents in the floor?
- 1.9 A swimming pool has an evenly distributed pressure at the bottom. Consider a stiff steel plate lying on the ground. Is the pressure below it just as evenly distributed?
- 1.10 If something floats in water, what does it say about its density?
- 1.11 Two divers swim at a depth of 20 m. One of them swims directly under a supertanker; the other avoids the tanker. Who feels a greater pressure?
- 1.12 An operating room has a positive gage pressure, whereas an engine test cell has a vacuum; why is that?
- 1.13 Mention some reasons to have hydraulic cylinders and some reasons to have pneumatic cylinders for motion activation.
- 1.14 A water skier does not sink too far down in the water if the speed is high enough. What makes that situation different from our static pressure calculations?
- 1.15 What is the lowest temperature in degrees Celsius? In degrees Kelvin?
- 1.16 How cold can it be on Earth and in empty space?
- 1.17 A thermometer that indicates the temperature with a liquid column has a bulb with a larger volume of liquid. Why?
- 1.18 How can you illustrate the binding energy between the three atoms in water as they sit in a triatomic water molecule. *Hint*: imagine what must happen to create three separate atoms.

HOMEWORK PROBLEMS

Properties, Units, and Force

- 1.19 One kilopond (1 kp) is the weight of 1 kg in the standard gravitational field. What is the weight of 1 kg in newtons (N)?
- 1.20 A fuel container has $1/3$ kmol of ethanol and $1/4$ kmol of methanol. What is the total mass of fuel?
- 1.21 A steel cylinder of mass 4 kg contains 4 L of dry sand at 25°C at 100 kPa. Find the total mass and volume of the system. List two extensive and three intensive properties of the sand.
- 1.22 As a clothes washer is nearly done it spins 5 kg of wet clothes with 20 m/s at a radius

of 0.3 m. What is the force on the rotating drum? *Hint:* acceleration in rotation is V^2/r .

- 1.23** A short freight train moves at 60 km/h with a total mass of 55 tonne and starts to decelerate at a constant rate of 0.5 m/s^2 to a full stop. What are the force and total time required?
- 1.24** At a building site the work elevator has a mass of 550 kg, and it has supplies with a total mass of 400 kg. How much force should the cable pull up with to have an acceleration of 1.5 m/s^2 in the upward direction?
- 1.25** If a worker, 85 kg, gets on the work elevator in the previous problem how much weight does this person feel when the elevator starts moving?

Specific Volume

- 1.26** A power plant that separates carbon dioxide from the exhaust gases compresses it to a density of 110 kg/m^3 and stores it in an unminable coal seam with a porous volume of $100\,000 \text{ m}^3$. Find the mass that can be stored.
- 1.27** A cement mixer should deliver 2 m^3 mix of granite stone, dry sand and water in a mass ratio of 2 to 1 to 1 (cement is included in the sand). Using properties from Tables A.3 and A.4, find the mass of each component
- 1.28** A container is filled with 1100 kg of granite (density of 2400 kg/m^3) together with 5 kg air, with density 1.15 kg/m^3 . Find the total volume and the overall (average) specific volume.

Pressure

- 1.29** A 5000-kg elephant has a cross-sectional area of 0.02 m^2 on each foot. Assuming an even distribution, what is the pressure under its feet?

- 1.30** A valve in the cylinder shown in Fig. P1.30 has a cross-sectional area of 11 cm^2 with a pressure of 735 kPa inside the cylinder and 99 kPa outside. How large a force is needed to open the valve?

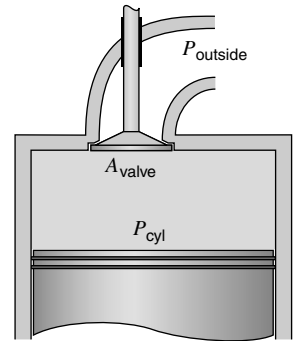


FIGURE P1.30

- 1.31** The piston cylinder in Fig. P1.30 has a diameter of 10 cm, inside pressure 1235 kPa. What is the force holding the massless piston up as the piston lower side has P_0 besides the force?
- 1.32** A hydraulic lift has a piston diameter of 10 cm. What should the hydraulic pressure be in order to lift a mass of 1250 kg?
- 1.33** A hydraulic cylinder has a 125-mm diameter piston with an ambient pressure of 1 bar. Assuming standard gravity, find the total mass this piston can lift if the inside hydraulic fluid pressure is 2000 kPa.
- 1.34** A 75-kg human total footprint is 0.05 m^2 when the human is wearing boots. Suppose that you want to walk on snow that can at most support an extra 3 kPa; what should the total snowshoe area be?
- 1.35** A piston/cylinder with a diameter of 0.11 m has a piston mass of 60 kg plus a force of 700 N resting on the stops, as shown in Fig. P1.35. With an outside atmospheric pressure of 101 kPa, what should the water pressure be to lift the piston?

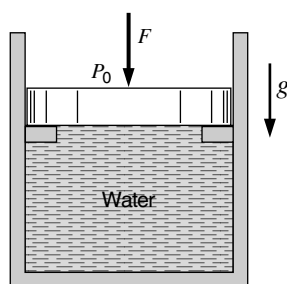


FIGURE P1.35

- 1.36** A 2.5-m-tall steel cylinder has a cross-sectional area of 1.5 m^2 . At the bottom, with a height of 0.5 m, is liquid glycol, on top of which is a 1.5-m-high layer of engine oil. This is shown in Fig. P1.36. The oil surface is exposed to atmospheric air at 101 kPa. What is the pressure at the bottom and at the interphase between glycol and oil?

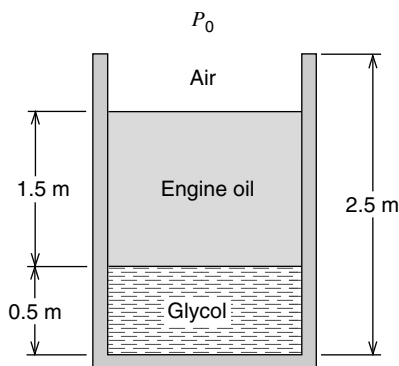


FIGURE P1.36

- 1.37** An underwater buoy is anchored at the seabed with a cable, and it contains a total mass of 250 kg in a 0.4 m^3 volume. What is the cable force?
- 1.38** If an oil rig mass is 20 000 tonnes and the net pull of the cables should be 5000 kN from the seabed, how much water displacement is needed?
- 1.39** You go parasailing getting up 55 m in the air and later dive 10 m down in the ocean. Assume the atmospheric pressure is 1025

mbar at the beach, a density of water is 1000 kg/m^3 , and density of air is 1.18 kg/m^3 . What pressure do you feel at each place?

- 1.40** A steel tank of cross-sectional area 2 m^2 and height 13 m mass is 10000 kg and is open at the top, as shown in Fig. P1.40. We want to float it in the ocean so that it is positioned 10 m straight down by pouring concrete into its bottom. How much concrete should we use?

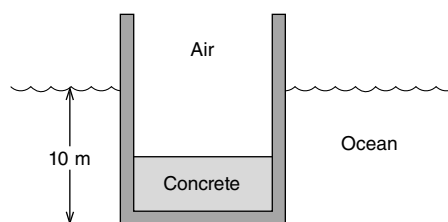


FIGURE P1.40

- 1.41** A piston, $m_p = 5 \text{ kg}$, is fitted in a cylinder, $A = 15 \text{ cm}^2$, that contains a gas. The setup is in a centrifuge that creates an acceleration of 25 m/s^2 in the direction of piston motion toward the gas. Assuming standard atmospheric pressure outside the cylinder, find the gas pressure.
- 1.42** A container ship is 240 m long and 32 m wide. Assume that the shape is like a rectangular box. How much mass does the ship carry as load if it is 10 m down in the water and the mass of the ship itself is 30 000 tonnes?

Manometers and Barometers

- 1.43** A probe is lowered 16 m into a lake. Find the absolute pressure there.
- 1.44** A hang glider is about 22 m^2 for the sail with and 45 kg mass plus the person say 75 kg. How large a gauge pressure under the sail is needed for level flight? Suppose you accelerate down with 2 m/s^2 how large must the gauge pressure then be?

- 1.45** A vacuum pump keeps a gage pressure of 3.1 cm water column underneath a basement floor to suck out radon gas. What force does that put under a floor of area 20 m^2 ?
- 1.46** A barometer to measure absolute pressure shows a mercury column height of 745 mm. The temperature is such that the density of the mercury is $13\,550 \text{ kg/m}^3$. Find the ambient pressure.
- 1.47** A differential pressure gauge mounted on a vessel shows 1.25 MPa, and a local barometer gives atmospheric pressure as 0.96 bar. Find the absolute pressure inside the vessel.
- 1.48** A barometer measures 760 mm Hg at street level and 745 mm Hg on top of a building. How tall is the building if we assume air density of 1.15 kg/m^3 ?
- 1.49** An exploration submarine should be able to descend 2000 m down in the ocean. If the ocean density is 1025 kg/m^3 , what is the maximum pressure on the submarine hull?
- 1.50** The absolute pressure in a tank is 245 kPa and the local ambient absolute pressure is 101 kPa. If a U-tube with mercury (density = $13\,550 \text{ kg/m}^3$) is attached to the tank to measure the gauge pressure, what column height difference will it show?
- 1.51** An absolute pressure gauge attached to a steel cylinder shows 135 kPa. We want to attach a manometer using liquid water on a day that $P_{\text{atm}} = 101 \text{ kPa}$. How high a fluid level difference must we plan for?
- 1.52** A pipe flowing light oil has a manometer attached, as shown in Fig. P1.52. What is the absolute pressure in the pipe flow?

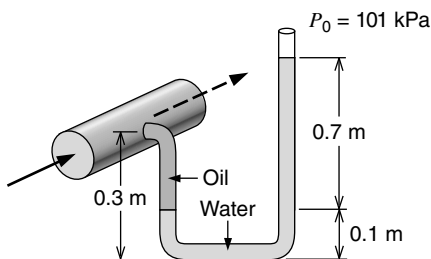


FIGURE P1.52

- 1.53** A piece of experimental apparatus, Fig. P1.53, is located where $g = 9.5 \text{ m/s}^2$ and the temperature is 5°C . Air flow inside the apparatus is determined by measuring the pressure drop across an orifice with a mercury manometer (density = $13\,580 \text{ kg/m}^3$) showing a height difference of 200 mm. What is the pressure drop in kPa?

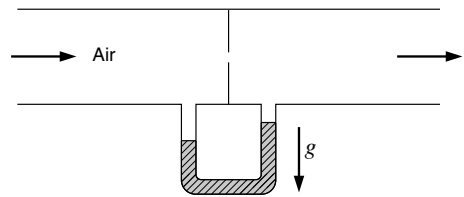


FIGURE P1.53

Energy and Temperature

- 1.54** A 0.25 m^3 piece of softwood is lifted up to the top shelf in a storage bin that is 4 m above the ground floor. How much increase in potential energy does the wood get?
- 1.55** A racecar of mass 1275 kg travels with a velocity of 20 km/h. Find the kinetic energy. How high should the car be lifted in the standard gravitational field to have a potential energy that equals the kinetic energy?
- 1.56** What is a temperature of -15°C in degrees Kelvin?
- 1.57** A mercury thermometer measures temperature by measuring the volume expansion of a fixed mass of liquid mercury due to a change in density as $\rho_{\text{Hg}} = 13\,595 - 2.5 T \text{ kg/m}^3$ (T in Celsius). Find the relative change (%) in volume for a change in temperature from 10 to 25°C .
- 1.58** The density of liquid water is $\rho = 1008 - T/2 \text{ (kg/m}^3\text{)}$ with T in $^\circ\text{C}$. If the temperature increases 10°C , how much deeper does a 1-m layer of water become?

Review Problems

- 1.59** Repeat Problem 1.53 if the flow inside the apparatus is liquid water ($\rho = 1000 \text{ kg/m}^3$) instead of air. Find the pressure difference between the two holes flush with the bottom of the channel. You cannot neglect the two unequal water columns.
- 1.60** A dam retains a lake 6 m deep, as shown in Fig. P1.60. To construct a gate in the dam, we need to know the net horizontal force on a 5-m-wide, 6-m-tall port section that then replaces a 5-m section of the dam. Find the net horizontal force from the water on one side and air on the other side of the port.

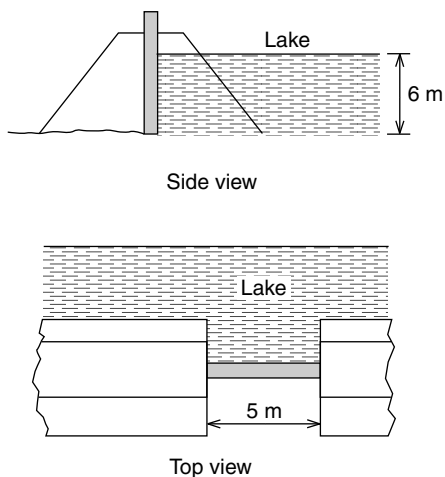


FIGURE P1.60

- 1.61** In the city water tower, water is pumped up to a level of 25 m above ground in a pressurized tank with air at 150 kPa over the water surface. This is illustrated in

Fig. P1.61. Assuming water density of 1000 kg/m^3 and standard gravity, find the pressure required to pump more water in at ground level.

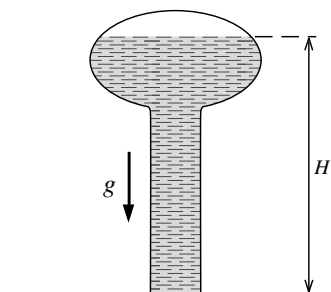


FIGURE P1.61

- 1.62** The main waterline into a tall building has a pressure of 600 kPa at 5-m elevation below ground level. The building is shown in Fig. P1.62. How much extra pressure does a pump need to add to ensure a water-line pressure of 200 kPa at the top floor 150 m above ground?

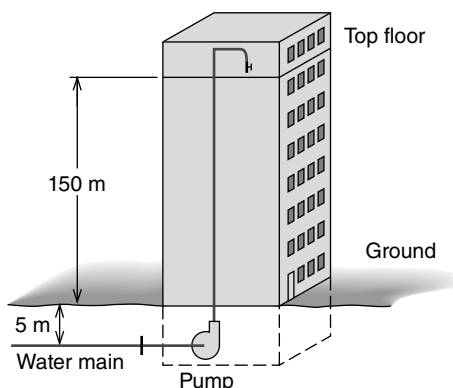


FIGURE P1.62

ENGLISH UNIT PROBLEMS

Unit Concept Problems

- 1.63E** A mass of 2 lbm has an acceleration of 15 ft/s^2 . What is the needed force in lbf?

- 1.64E** How much mass is in 1 gal of gasoline? In helium in a balloon at atmospheric P and T ?

- 1.65E** Can you easily carry a 1-gal bar of solid gold?
- 1.66E** What is the temperature of -15°F in degrees Rankine?
- 1.67E** What is the lowest possible temperature in degrees Fahrenheit? In degrees Rankine?
- 1.68E** What is the relative magnitude of degree Rankine to degree Kelvin?

English Unit Problems

- 1.69E** The Rover Explorer has a mass of 410 lbm, how much does this “weigh” on the Moon ($g = g_{\text{std}}/6$) and on Mars where $g = 12.3 \text{ ft/s}^2$.
- 1.70E** A short freight train moves at 45 mi/h with a total mass of 55 tons and starts to decelerate at a constant rate of 2 ft/s^2 to a full stop. What are the force and total time required?
- 1.71E** A building site elevator brings material with mass of 900 lbm and an 800-lbm cage up with an acceleration of 3 ft/s^2 . What is the needed force in the cable?
- 1.72E** A car of mass 4000 lbm travels with a velocity of 60 mi/h. Find the kinetic energy. How high should the car be lifted in the standard gravitational field to have a potential energy that equals the kinetic energy?
- 1.73E** A power plant that separates carbon dioxide from the exhaust gases compresses it to a density of 8 lbm/ft^3 and stores it in an unminable coal seam with a porous volume of $3\,500\,000 \text{ ft}^3$. Find the mass that can be stored.
- 1.74E** The piston cylinder in Fig. P1.30 has a diameter of 4 in., inside pressure 100 psia. What force must hold the massless piston up as the piston lower side has P_0 besides the force?
- 1.75E** A laboratory room keeps a vacuum of 1 in. of water due to the exhaust fan. What is the net force on a door of size 6 ft by 3 ft?
- 1.76E** A person, 175 lbm, wants to fly (hoover) on a 4 lbm skateboard of size 2 ft by 0.8 ft. How large a gauge pressure under the board is needed?
- 1.77E** If an oil rig mass is 20 000 ton and the net pull of the cables should be $1.1 \times 10^6 \text{ lbf}$ from the seabed, how much water displacement is needed?
- 1.78E** A container ship is 790 ft long and 100 ft wide. Assume the shape is like a rectangular box. How much mass does the ship carry as load if it is 30 ft down in the water and the mass of the ship itself is 30 000 tons.
- 1.79E** A manometer shows a pressure difference of 3.5 in. of liquid mercury. Find ΔP in psi.
- 1.80E** What pressure difference does a 300-ft column of atmospheric air show?
- 1.81E** A piston/cylinder with a cross-sectional area of 0.1 ft^2 has a piston mass of 100 lbm and a force of 180 lbf resting on the stops, as shown in Fig. P1.35. With an outside atmospheric pressure of 1 atm, what should the water pressure be to lift the piston?
- 1.82E** The main waterline into a tall building has a pressure of 90 psia at 16 ft elevation below ground level. How much extra pressure does a pump need to add to ensure a waterline pressure of 30 psia at the top floor 450 ft above ground?
- 1.83E** As a clothes washer is nearly done it spins 10 lbm of wet clothes with 7 ft/s at a radius of 1 ft. What is the force on the rotating drum? *Hint:* acceleration in rotation is V^2/r .
- 1.84E** The human comfort zone is between 18°C and 24°C . What is the range in Fahrenheit?

