1-1 The Nature of Thermodynamics

Thermodynamics is a science that includes the study of energy transformations and of the relationships among the physical properties of substances which are affected by these transformations. Engineering thermodynamics traditionally has involved the study of such diverse areas as stationary and mobile power-producing devices, refrigeration and air-conditioning processes, fluid expanders and compressors, jet engines and rockets, chemical processing as in oil refineries, and the combustion of hydrocarbon fuels (coal, oil, and natural gas). More recently, other areas of interest have evolved. For example, the use of passive and active solar energy units, including solar ponds, is undergoing tremendous growth. Commercial power production from fluids heated by geothermal sources beneath the ground is available on a growing scale. In addition, wind power systems continue to be developed and to be added to the electric power grid. Tidal power is under active investigation, as well as the use of the temperature difference between the surface and deeper layers of the oceans as a potential source of power production. This latter energy system is called ocean thermal energy conversion (OTEC). Study continues on a magnetohydrodynamic (MHD) power cycle which generates electricity by passing a high-temperature gas through a magnetic field. Other processes of interest include thermionic and photovoltaic devices, as well as biomedical applications.

Thermodynamic properties and energy relationships can be studied by two methods. ***Classical thermodynamics*** involve studies which are undertaken without recourse to the nature of the individual particles which make up a substance and to their interactions. This is a *macroscopic viewpoint* toward matter, and it requires no hypothesis about the detailed structure of matter on the atomic scale. Consequently, the general laws of classical thermodynamics are based on macroscopic measurements and are not subject to change as knowledge concerning the nature of matter is discovered.

A second method called ***statistical thermodynamics*** is based on the statistical behavior of large groups of individual particles. This is a *microscopic viewpoint* of matter. It postulates that the values of macroscopic properties (such as pressure, temperature, and density, among others), which we measure directly or calculate from other measurements, merely reflect some sort of statistical average of the behavior of a tremendous number of particles. This theory has been helpful in the modern development of new, direct energy-conversion methods, such as thermionics and thermoelectrics.

What is the major difference in the viewpoints of classical and statistical thermodynamics?

Five laws, or postulates, govern the study of energy transformations and the relationships among properties. Two of these—the first and second laws—deal with energy, directly or indirectly. Consequently, they are of fundamental importance in engineering studies of energy transformations and use. The remaining three statements—the zeroth law, the third law, and the state postulate—relate to thermodynamic properties. The first law of thermodynamics leads to the concept of energy and a conservation of energy principle. When energy is transferred from one region to another or changes form within a region of space, the total quantity of energy is constant. (In this text we do not consider nuclear transformations of mass to energy.)

The second law of thermodynamics has many ramifications with respect to engineering processes. One of these is that the first law deals with the *quantity* of energy, while the second law deals with the *quality* of energy. The idea of quality arises when one needs to optimize the conversion and transmission of energy. We find that the second law places restrictions on the transformation of some forms of energy to more "useful" types. The second law enables the engineer to measure the "degradation," or change in quality, of energy in quantitative terms. The second law also introduces an important thermodynamic property—entropy.

What is the difference between the quantity and the quality of energy?

The use of energy by industrialized countries is an important factor in their continued growth. In addition, the desire of underdeveloped nations to improve their standards of living will lead to continuing studies of improving energy use throughout the world. A move must be made to cut wasteful use of energy in industry, in transportation, and in residential and commercial applications. With the increasing cost and decreasing supply of conventional fossil fuels in the future, it is imperative that engineers look seriously at increasing the efficiency of energy use. As an example several methods are under development for increasing the overall energy conversion efficiency for large electric power generation units. Thus thermodynamics will continue to make a valuable contribution to the study of new energy systems as well as to the revitalization of older energy systems.

1-2 DIMENSIONS AND UNITS

Dimensions are names that characterize physical quantities. Common examples of dimensions include length L, time t, force F, mass m, electric charge Q_c, and temperature T. In engineering analysis any equation which relates physical quantities must be *dimensionally homogeneous;* that is, the dimensions on one side of an equation equal those of the other side. Such homogeneity also is retained during any subsequent mathematical operation and thus is a powerful tool for checking the internal consistency of an equation.

To make numerical computations involving physical quantities, there is the additional requirement that units, as well as the dimensions, be homogeneous. ***Units*** are those arbitrary magnitudes and names assigned to dimensions which are adopted as standards for measurements. For example, the primary dimension of length may be measured in units of feet, miles, centimeters, etc. These are all arbitrary lengths which may relate to each other by *unit conversion factors,* or unitary constants. Unit conversion factors include 12 in = 1 ft and 60 s = 1 min. A comparable way of writing unit conversion factors is

$$\frac{12 \text{ in}}{1 \text{ ft}} = 1 \qquad \frac{60 \text{ s}}{1 \text{ min}} = 1$$

What is the difference between the dimensions and units of a physical quantity?

Terms in equations can always be multiplied by unit conversion factors, since it is always permissible to multiply by unity. A given physical quantity may often be measured in several sets of units. Therefore, a tabulation of common unit conversion factors for thermodynamic analyses is presented in Tables A-1 and A-1E, in the Appendix, as well as inside the front cover.

A number of systems of units have been developed over the years. However, in this text we consider only two: the International System of Units (SI) and the United States Customary System (USCS). The latter system is also known as the English engineering system.

1-2-1 The Système Internationale (International System)

The fundamental system of units chosen for scientific work is the ***Système Internationale,*** which is usually abbreviated as SI. The SI employs seven *primary dimensions:* mass, length, time, temperature, electric current, luminous intensity, and amount of substance. Table 1-1 lists the SI *primary units* which are standards for these dimensions. All these units are defined operationally. For example, the SI unit of length is the meter (m), and it is defined as 1,650,763.73 wavelengths of the orange-red line of emission from krypton-86 atoms in vacuum. The unit of time is the second (s), and it is defined as the duration of 9,192,631,770 ± 20 cycles of a specified transition within the cesium atom. There are also precise operational definitions of mass (kg), temperature (K), electric current (A), and luminous intensity (cd).

When very large or small values of a quantity are involved, a set of standard prefixes is used to simplify writing a value in SI units. These prefixes designate certain decimal multiples of the unit. Table 1-2 lists the values of

Table 1-1 SI primary dimensions and units

Physical Quantity	Unit and Symbol
Mass	kilogram (kg)
Length	meter (m)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Luminous intensity	candela (cd)
Amount of substance	mole (mol)

Table 1-2 Standard SI prefixes

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

the multiplier factor, the name of the prefix, and the symbol for the prefix. For example, kW denotes a kilowatt, that is, 10^3 watts, while mg denotes a milligram, that is, 10^{-3} grams. Although multiples of 10^3 are used in SI, other multiples are sometimes employed in specific fields.

The seventh SI primary unit, the *mole* (mol), is the amount of substance containing the same number of elementary particles (atoms, molecules, ions, electrons) as there are atoms in 0.012 kg of the pure carbon nuclide ^{12}C. The number of particles per mole, 6.02205×10^{23}, is known as an *Avogadro's number* N_A. For engineering calculations it is useful to express mass in kilomoles (kmol). A kilomole is 1000 times as large as a mole. For example, a kilomole of diatomic oxygen O_2 contains 32 kg of oxygen, and has $1000N_A$ molecules of O_2. The number of moles N of a substance is defined as

$$N = \frac{m}{M} \qquad [1\text{-}1]$$

What are the two different sets of SI units commonly used for the molar mass?

where M is the molar mass. The ***molar mass*** is the mass of a substance that is numerically equal to its molecular weight, expressed as mass per mole. For example, the molar mass of helium is 4.003 g/mol or 4.003 kg/kmol.

All other SI units are *secondary units* and are derivable in terms of the seven primary units shown in Table 1-1. The secondary SI unit of force is the newton (N), and it is derived from Newton's second law, $F = kma$. The proportionality constant k is chosen to be unity, so that $F = ma$. On the basis of this equation, a derived force of one newton is required to accelerate one kilogram of mass at one meter per second per second. Since 1 N = 1 kg × 1 m/s^2,

$$\frac{1\ \text{N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}} = 1 \qquad [1\text{-}2]$$

Equation [1-2] is a unit conversion factor which relates the derived force unit to the primary mass, length, and time units in SI. It is useful in converting other secondary units, which are partially defined in terms of force, to a set of primary units containing only the kilogram, the meter, and the second. For example, the secondary SI unit for pressure is the *pascal* (Pa), which is defined in force and length units as 1 N/m^2. Employing Eq. [1-2], we find that

$$1\ \text{Pa} = \frac{1\ \text{N}}{\text{m}^2} \times \frac{\text{kg}\cdot\text{m}}{1\ \text{N}\cdot\text{s}^2} = 1\ \text{kg}/(\text{m}\cdot\text{s}^2)$$

As a result, the secondary unit of pressure, the pascal, can be expressed in terms of its *primary equivalent,* 1 $kg/m \cdot s^2$.

Note that weight W always refers to a force. When it is stated that a body weighs a given amount, this means that this is the force with which the body is attracted toward another body, such as the earth or moon. The acceleration of gravity varies with distance between two bodies (such as the height of a body above the earth's surface). Thus the weight of a body varies with elevation, while the mass of a body is constant with elevation. The value for the ***standard gravitational acceleration*** on the earth at sea level and 45 degrees latitude is 9.80665 m/s^2. This is shortened to 9.807 m/s^2 in this text.

Example 1-1

The weight of a piece of metal is 100.0 N at a location where the local acceleration of gravity g is 9.60 m/s^2. Find (*a*) the mass of the metal in kilograms, and (*b*) the weight of the metal on the surface of the moon, where $g = 1.67\ m/s^2$.

Solution:

Given: A piece of metal under two gravity conditions is shown in Fig. 1-1.

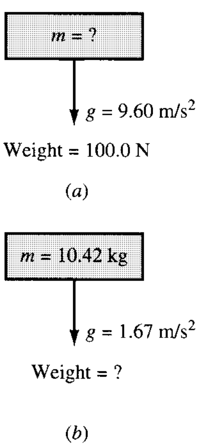

Figure 1-1
Mass-weight relationship in SI.

Find: (*a*) mass on the earth, in kg, and (*b*) weight on the moon, in N.

Analysis: (*a*) The SI unit system is based on Newton's second law. Since weight W is a force, and $a = g$ in this case, we write the second law as $W = mg$. Hence,

$$m = \frac{W}{g} = \frac{100.0\ \text{N}}{9.60\ \text{m/s}^2} = 10.42 \frac{\text{N}\cdot\text{s}^2}{\text{m}} \times \frac{1\ \text{kg}\cdot\text{m}}{\text{N}\cdot\text{s}^2} = 10.42\ \text{kg}$$

where 1 $N \cdot s^2/m \cdot kg = 1$ by definition.

(*b*) The mass of the piece of metal will remain the same regardless of its location. The weight will change, however, with a change in gravitational acceleration. Equating weight to force on the surface of the moon gives

$$\text{Weight} = F_{\text{moon}} = mg = 10.42\ \text{kg} \times 1.67 \frac{\text{m}}{\text{s}^2} \times \frac{1\ \text{N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}} = 17.4\ \text{N}$$

Comment: Although the mass is the same at the two locations, the weight is quite different.
