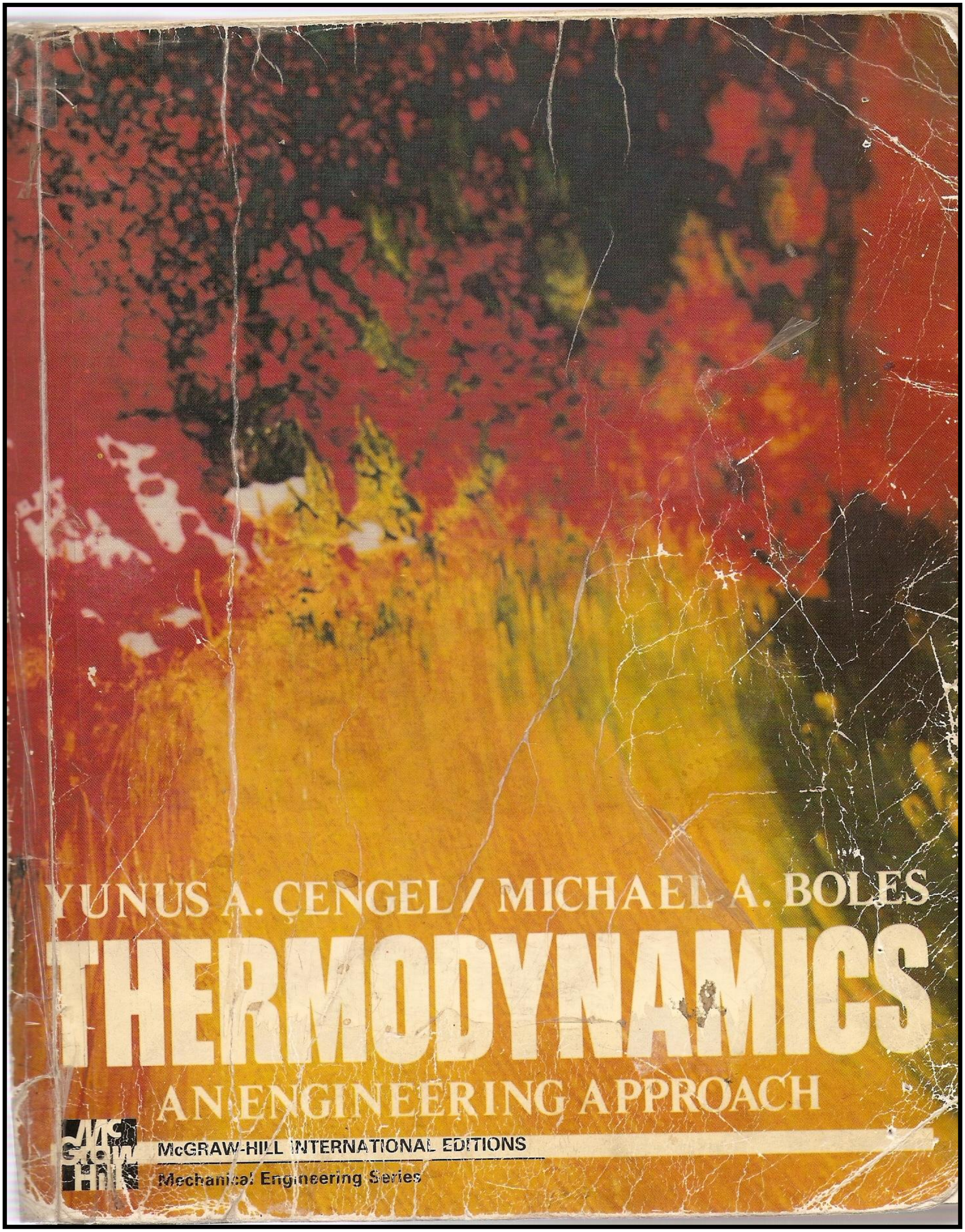
YUNUS A. ÇENGEL / MICHAEL A. BOLES
THERMODYNAMICS
AN ENGINEERING APPROACH
McGRAW-HILL INTERNATIONAL EDITIONS
Mechanical Engineering Series

Conversion Factors

DIMENSION	SI	SI/ENGLISH
Acceleration	$1\ m/s^2 = 100\ cm/s^2$	$1\ m/s^2 = 3.2808\ ft/s^2$
Area	$1\ m^2 = 10^4\ cm^2 = 10^6\ mm^2$ $= 10^{-6}\ km^2$	$1\ m^2 = 1550\ in^2 = 10.764\ ft^2$ $1\ ft^2 = 144\ in^2 = 0.092903\ m^2$
Density	$1\ g/cm^3 = 1\ kg/L = 1000\ kg/m^3$	$1\ g/cm^3 = 62.428\ lbm/ft^3 = 0.036127\ lbm/in$ $1\ lbm/in^3 = 1728\ lbm/ft^3$
Energy, heat, work	$1\ kJ = 1000\ J = 1000\ Nm = 1\ kPa{\cdot}m^3$ $1\ kJ/kg = 1000\ m^2/s^2$ 1 kWh = 3600 kJ	1 kJ = 0.94783 Btu 1 Btu = 1.05504 kJ $= 5.4039\ psia{\cdot}ft^3$ = 778.16 lbf·ft $1\ Btu/lbm = 25{,}037\ ft^2/s^2 = 2.326\ kJ/kg$ 1 kJ/kg = 0.430 Btu/lbm 1 kWh = 3412.2 Btu
Force	$1\ N = 1\ kg{\cdot}m/s^2$	$1\ lbf = 32.174\ lbm{\cdot}ft/s^2$ 1 N = 0.22481 lbf
Length	1 m = 100 cm = 1000 mm 1 km = 1000 m	1 m = 39.370 in = 3.2808 ft = 1.0936 yd 1 ft = 12 in = 0.304800 m 1 mile = 5280 ft = 1.6093 km
Mass	1 kg = 1000 g 1 metric ton = 1000 kg	1 kg = 2.2046226 lbm 1 lbm = 0.45359237 1 slug = 32.174 lbm = 14.5939 kg 1 short ton = 2000 lbm

DIMENSION	SI	SI/ENGLISH
Power	1 W = 1 J/s 1 kW = 1000 W = 1.341 hp	1 kW = 3412.2 Btu/h = 0.73756 lbf·ft/s 1 hp = 550 lbf·ft/s = 0.7068 Btu/s = 42.41 Btu/min = 2544.5 Btu/h = 0.74570 kW
Pressure	1 Pa = 1 N/m^2 1 kPa = 10^3 Pa = 10^{-3} MPa 1 atm = 101.325 kPa = 1.01325 bars = 760 mmHg at 0°C	1 Pa = 1.4504×10^{-4} psia = 0.020886 lbf/ft^2 1 psia = 144 lbf/ft^2 1 atm = 14.696 psia = 29.92 inHg at 32°F
Specific Heat	1 kJ/(kg·°C) = 1 kJ/(kg·K) = 1 J/(g·°C)	1 Btu/(lbm·°F) = 4.1868 kJ/(kg·°C) 1 kJ/(kg·°C) = 0.23885 Btu/(lbm·°F) = 0.23885 Btu/(lbm·R)
Specific Volume	1 m^3/kg = 1000 L/kg = 1000 cm^3/g	1 m^3/kg = 16.02 ft^3/lbm
Temperature	T (K) = T (°C) + 273.15 ΔT (K) = ΔT (°C)	T (R) = T (°F) + 459.67 T (°F) = 1.8 T (°C) + 32 ΔT (°F) = ΔT (R) = 1.8 ΔT (K)
Velocity	1 m/s = 3.60 km/h	1 m/s = 3.2808 ft/s = 2.237 mi/h 1 mi/h = 1.609 km/h
Volume	1 m^3 = 1000 L = 10^6 cm^3 (cc)	1 m^3 = 6.1022×10^4 in^3 = 35.313 ft^3 = 264.17 gal (U.S.) 1 U.S. gallon = 231 in^3 = 3.7853 L

Chapter 1

Basic concepts of thermodynamics

In this chapter the unit systems that will be used are reviewed, and the basic concepts of thermodynamics such as system, energy, property, state, process, cycle, pressure, and temperature are explained.

1-1.Thermodynamics and energy

Thermodynamics can be defined as the science of energy. Energy can be viewed as the capacity to work or as the ability to cause changes.

One of the most fundamental laws of nature is the conservation of energy principle. It simply states that during an interaction, energy can change from one form to another but that the total amount of energy remains constant. That is, energy cannot be created or destroyed. A rock falling off a cliff, for example, picks up speed as a result of its potential energy being converted to kinetic energy (Fig. 1-1).

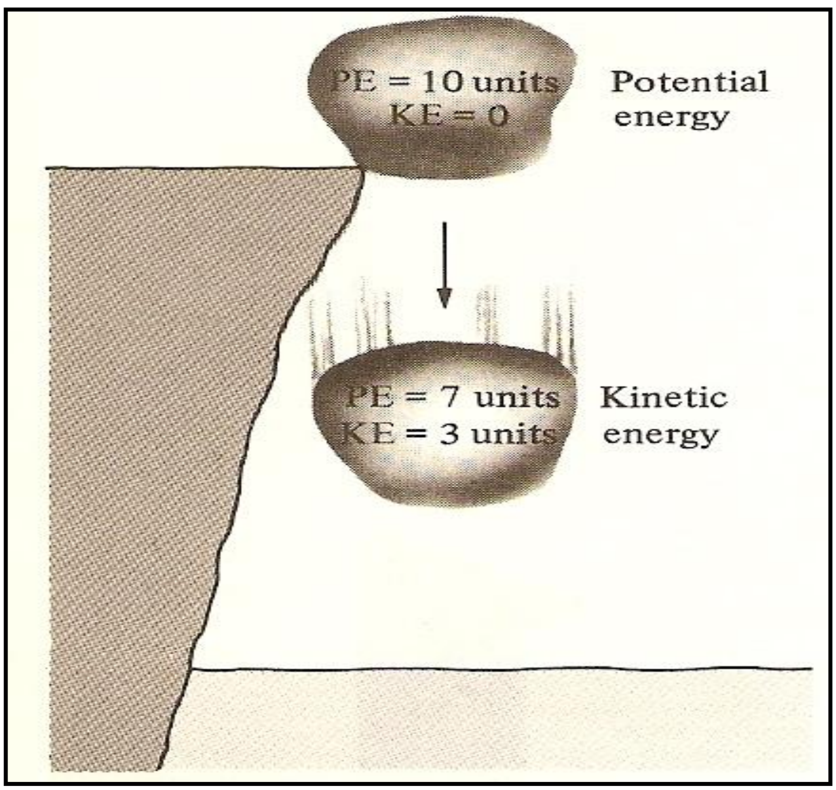

Figure 1-1, Energy cannot be created or destroyed; it can only change forms (the first law).

Thermodynamics deals with the conversion of energy from one form to another. It also deals with various properties of substances and the changes in these properties as a result of energy transformations. The first law of thermodynamics, for example, is simply an expression of the conservation of energy principle. The second law of thermodynamics asserts that processes occur in a certain direction but not in the reverse direction. A cup of hot coffee left on a table in an office, for example, eventually cools, but a cup of cool coffee on the same table never gets hot by itself (Fig.1-3).

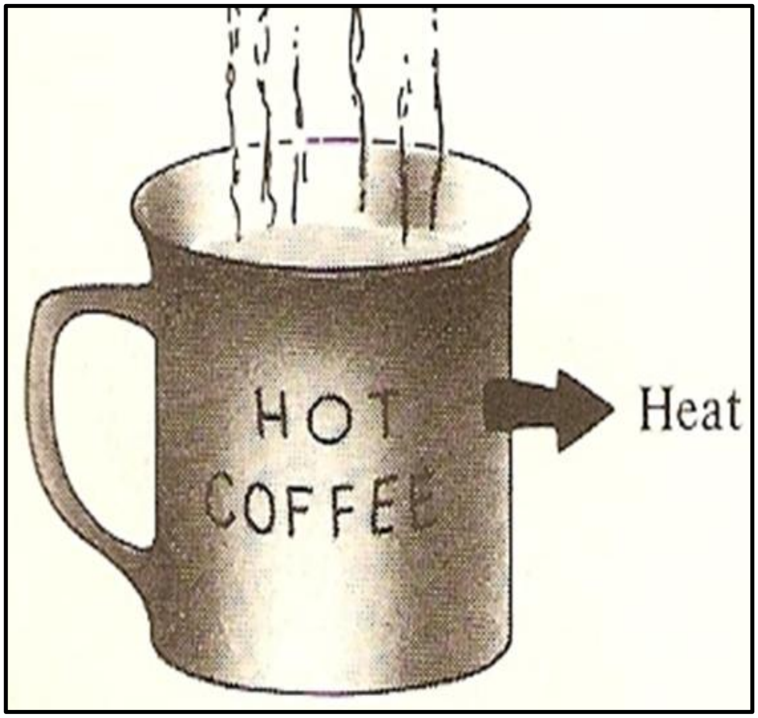

Figure 1-3. Heat can flow only from hot to cold bodies (the second law).

Application Areas of Thermodynamics

Every engineering activity involves an interaction between energy and matter, thus it is hard to imagine an area which does not relate to thermodynamics in some respect. An ordinary house is, in some respects, an exhibition hall filled with thermodynamics wonders. Some examples include the electric or gas range, the heating and air-conditioning systems,

the refrigerator, the humidifier, the pressure cooker, the water heater, the shower, the iron, and even the computer, the TV, and VCR set.

On large scale, thermodynamics plays a major part in the design and analysis of automotive engines, rockets, jet engines, and conventional or nuclear power plants (Fig.1-4). We should also mention the human body as an interesting application area of thermodynamics.

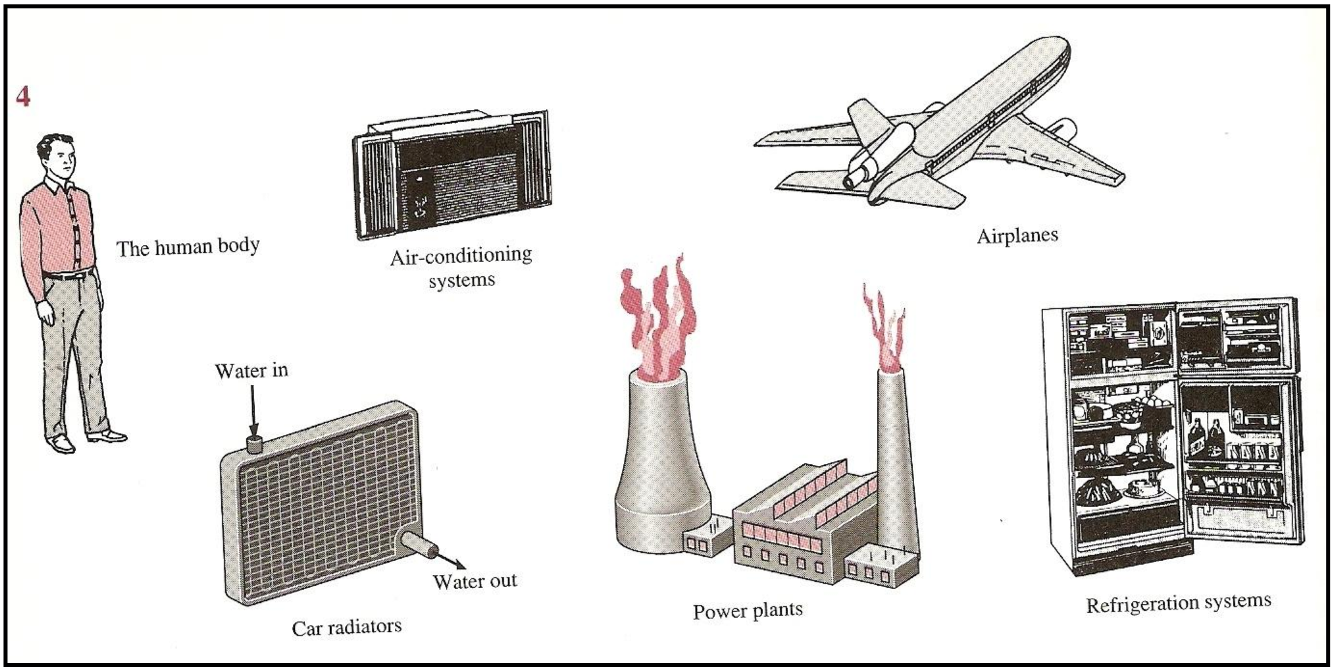

Figure 1-4. Some applications areas of thermodynamics.

1-2. A note on dimensions and units

Any physical quantity can be characterized by dimensions. The arbitrary magnitudes assigned to the dimensions are called units. Some basic dimensions such as mass *m*, length *L*, time *t*, and temperature *T* are selected as primary or fundamental dimensions, while others such as velocity V, energy *E*, and volume *V* are expressed in terms of the primary dimensions and are called secondary dimensions, or derived dimensions. In 1960, the *General Conference of and Measurements* (CGPM) produced the SI, which was based on six fundamental quantities and their units adopted in 1954 at the Tenth CGPM: *meter* (m) for length, *kilogram* (kg) for mass, *second* (s) for time, *ampere* (A) for electrical current, degree *Kelvin* (K) for temperature, and *candela* (cd) for luminous intensity (amount of

light). In 1971, the CGPM added a seventh fundamental quantity and unit: ***mole*** (mol) for the amount of matter (Table 1-1).

Table 1-1. The seven fundamental dimensions and their units in SI.

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (c)
Amount of matter	mole (mol)

A number of unit systems have been developed over the years. Two sets of units are still in common use today: the English system which is also known as the *United States Customary System* (USCS) and the metric SI which also known as the *International System*. The SI is a simple and logical system based on a decimal relationship between the various units, and it is being used for scientific and engineering work in most of the industrialized nations, including England. The English system, however, has no numerical base, and various units in this system are related to each other rather arbitrarily (12 in in 1 ft, 16 oz in 1 lb, 4 qt in 1 gal, etc.) which makes it confusing and difficult to learn.

As pointed out earlier, the SI is based on decimal relationship between units. The prefixes used to express the multiples of the various units are listed in (Table 1-2).

Table 1-2. Standard prefixes in SI units.

Multiple	Prefix
10^{12}	tetra, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

Some SI and English Unites

In SI, the unites of mass, length, and time are the kilogram (kg), meter (m), and second (s), respectively. The respective unites in the English system are the pound-mass (lbm), foot (ft), and second (s or sec). The mass and length unites in the two systems are related to each other by:

1 lbm = 0.45359 kg

1 ft = 0.3048 m

In the English system, force is usually considered to be one of the primary dimensions and is assigned a nonderived unit. This is a source of confusion and error that necessitates the use of a conversion factor (g_c) in many formulas. To avoid this nuisance, we consider force to be a secondary dimension whose unit is derived from Newton's second law, i.e.,

Force = (mass) (acceleration)

$$F = ma \qquad (1\text{-}1)$$

or

In SI, the force unit is the newton (N), and is defined as *the force required to accelerate a mass of 1 kg at a rate of 1 m/s²*. In the English system, the force unit is the pound-force (lbf) and is defined as *the force required to accelerate a mass of 32.174 lbm (1 slug) at a rate of 1 ft/s²*.

That is,

$$1\ N = 1\ kg.m/s^2$$

$$1\ lbf = 32.174\ lbm.ft/s^2$$

The term weight is often incorrectly to express mass, particularly by the "weight watchers". Unlike mass, weight W is a *force*. It is the gravitational force applied to a body, and its magnitude is determined from Newton's second law,

$$W = mg \quad (N) \qquad (1\text{-}2)$$

Where m is the mass of the body and g is the local gravitational acceleration (g is 9.807 m/s^2 or 32.174 ft/s^2 at sea level and 45° latitude). The weight of a unit volume of a substance is called the specific weight w and is determined from $w = \rho g$, where ρ is density.

1-3. Closed and open systems

Thermodynamic system, or simply a system, is defined as *a quantity of matter or a region in space chosen for study.* The region outside the system is called the surroundings. The real or imaginary surface that separates the system from its surroundings is called the boundary. These terms are illustrated in (Fig. 1-14). The boundary of a system can be *fixed or movable.*

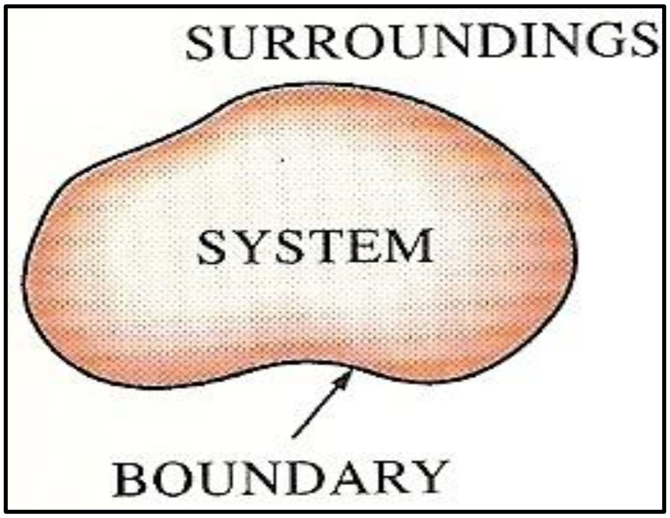

Figure 1-14. System, surrounding, and boundary.

Systems may be considered to be *closed* or *open*. A closed system also known as a (control mass) consists of a fixed amount of mass (Fig. 1-15).

A open system, or a (control volume), as it is often called, is a properly selected region in space. It usually encloses a device which involves mass flow such as a compressor, turbine, or nozzle. Flow through these devices is not best studied by selecting the region within device as the control volume. Both mass and energy can cross the boundary of a control volume, which is called a control surface. This is illustrated in (Fig. 1-17).

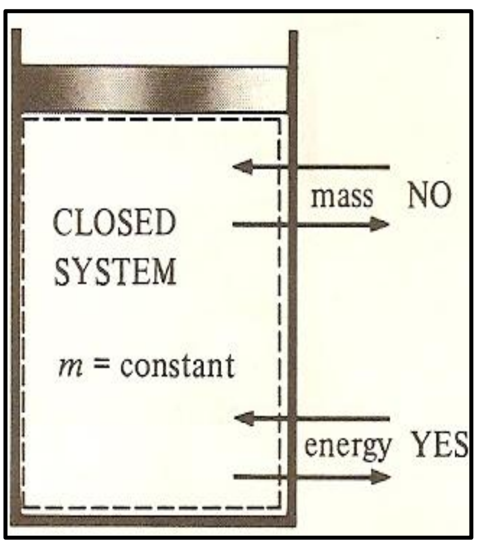

Figure 1-15. Mass cannot cross the boundary of a closed close system, but energy can.

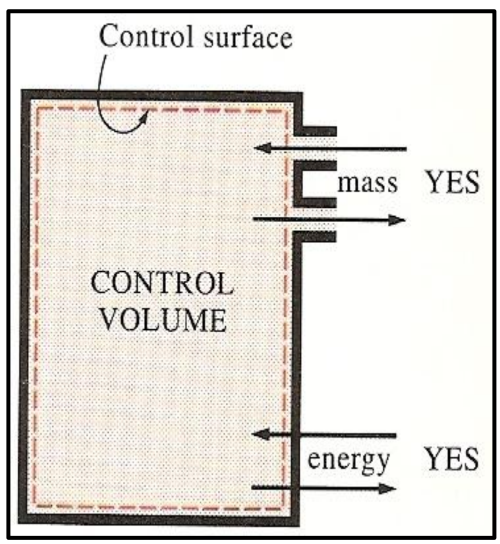

Figure 1-17. Both mass and energy can cross the boundaries of a control volume.

1-4. Forms of energy

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear, and their sum constitutes the total energy *E* of the system. The total energy of a system on a unit mass basis is denoted by *e* and is defined as:

$$e = \frac{E}{m} \qquad \text{(kJ/kg)} \qquad (1\text{-}3)$$

In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups: ***macroscopic*** and ***microscopic***. The macroscopic forms of energy, on one hand, are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies (Fig. 1-19).

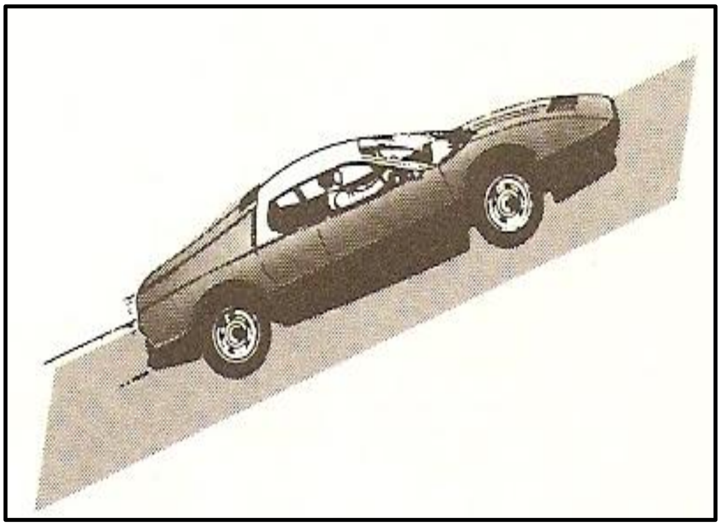

Figure 1-19. The macroscopic energy of an object changes with velocity and elevation.

The microscopic forms of energy, on the other hand, are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the internal energy of a system and is denoted by *U*.

The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity,

and surface tension. The energy that a system possesses as a result of its motion relative to some reference frame is called kinetic energy KE.

$$\text{KE} = \frac{mV^2}{2} \qquad \text{(kJ)} \qquad \text{(1-4)}$$

or, on a unit mass basis,

$$\text{ke} = \frac{V^2}{2} \qquad \text{(kJ/kg)} \qquad \text{(1-5)}$$

where, *m* = mass, and V = velocity

The energy that a system possesses as a result of its elevation to some fixed reference frame is called potential energy PE:

$$\text{PE} = mgz \qquad \text{(kJ)} \qquad \text{(1-6)}$$

Or, on a unit mass basis,

$$\text{pe} = gz \qquad \text{(kJ/kg)} \qquad \text{(1-7)}$$

where, g = gravitational acceleration, and z = elevation relative to selected reference place.

The total energy of a system consists of internal, kinetic, and potential energies:

$$E = U + \text{KE} + \text{PE} = U + \frac{mV^2}{2} + mgz \qquad \text{(kJ)} \qquad \text{(1-8)}$$

or, on a unit mass basis,

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \qquad \text{(kJ/kg)} \qquad \text{(1-9)}$$

Most closed systems remain stationary during a process and thus experience no change in their kinetic and potential energies.

The internal energy of the system is the sum of all forms of the microscopic energies (Fig. 1-21).

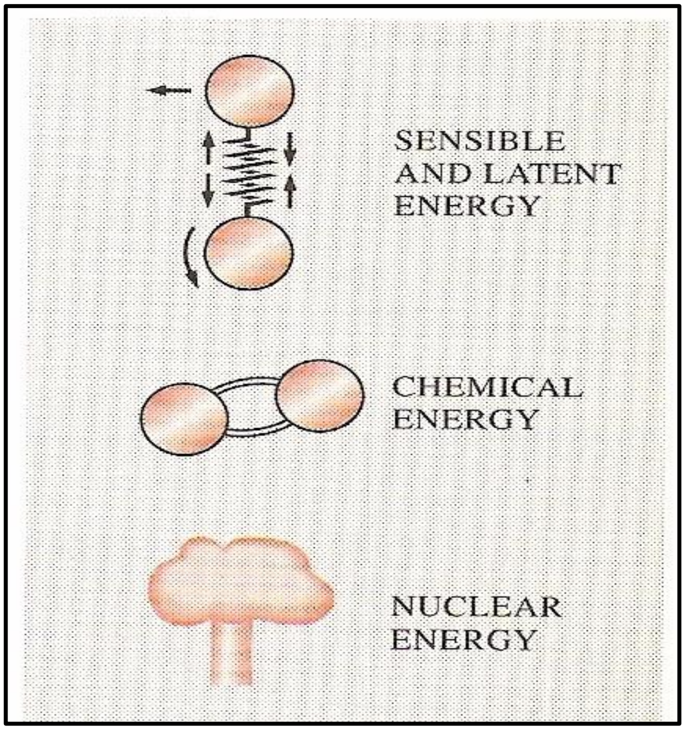

Figure 1-21. The internal energy of a system is the sum of all forms of the microscopic energies.

1-5. Properties of a system

Any characteristic of a system is called a property. Some familiar examples are pressure *P*, temperature *T*, volume *V*, and mass *m*. Properties are considered to be either *intensive* or *extensive*. Intensive properties are those which are independent of the size of a system such as temperature, pressure, and density. Extensive properties vary directly with the size-or extent-of the system. Mass *m*, volume *V*, and total energy *E* are some examples of extensive properties. An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with a partition, as shown in (Fig.1-25).

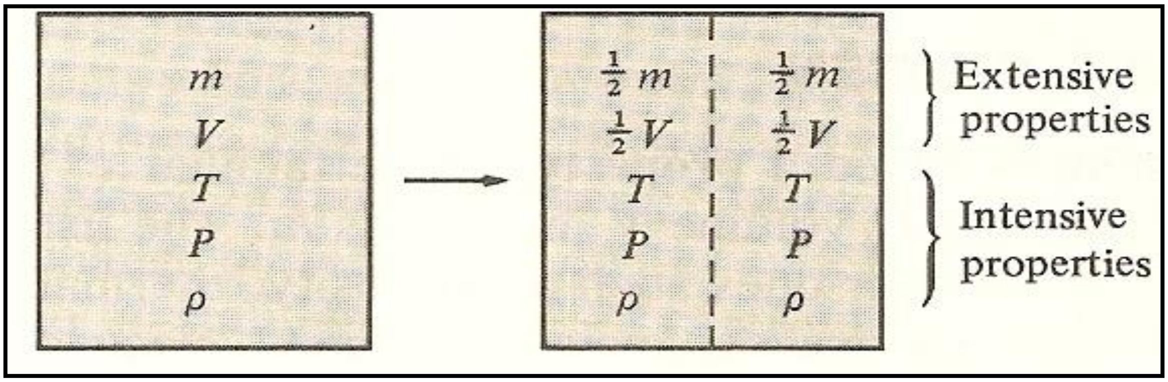

Figure 1-25. Criteria to different intensive and extensive properties.

1-6. State and equilibrium

Consider a system which is not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system. At a given state, all the properties of a system have fixed values, If the value of even one property changes, the state will change to a different one. In (Fig. 1-26) a system is shown in two different states.

Thermodynamics deals with equilibrium states. The word *equilibrium* implies a state of balance.

There are many types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium. For example, a system is in thermal equilibrium if the temperature is the same throughout the entire system (Fig. 1-28).

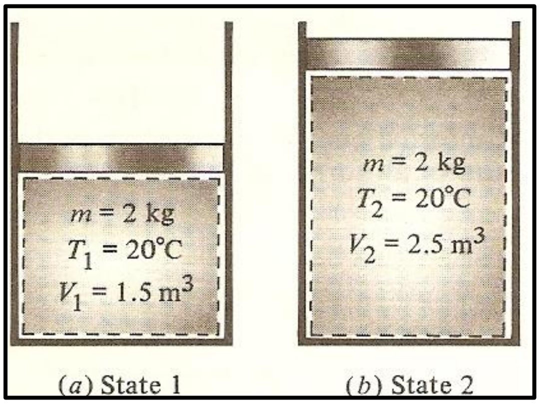

Figure 1-26. A system at two different states.

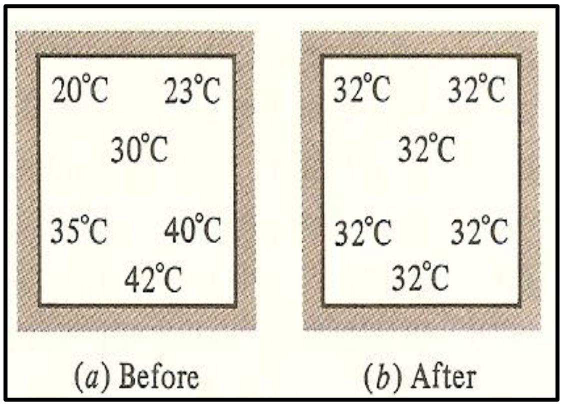

Figure 1-28. A closed system reaching thermal equilibrium..

1-7. Processes and cycles

Any change that a system undergoes from one equilibrium state to another is called a process, and the series of states through which a system passes during a process is called the path (Fig. 1-30).

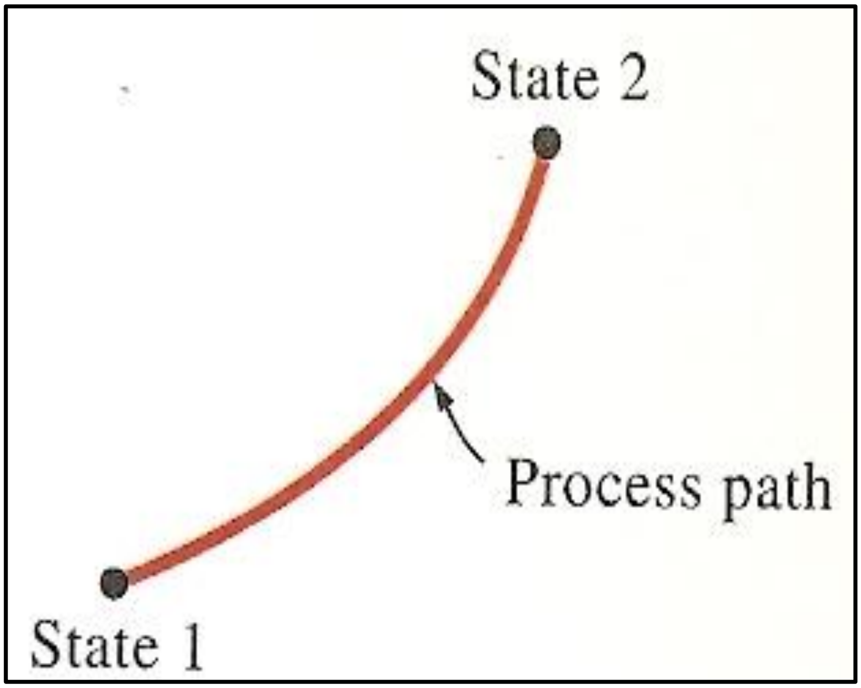

Figure 1-30. A process between state 1 and 2 and the process path.

When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a quasi-static, or quasi-equilibrium, process. A quasi-equilibrium process can be viewed as a sufficiently slow which allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts (Fig.1-31).

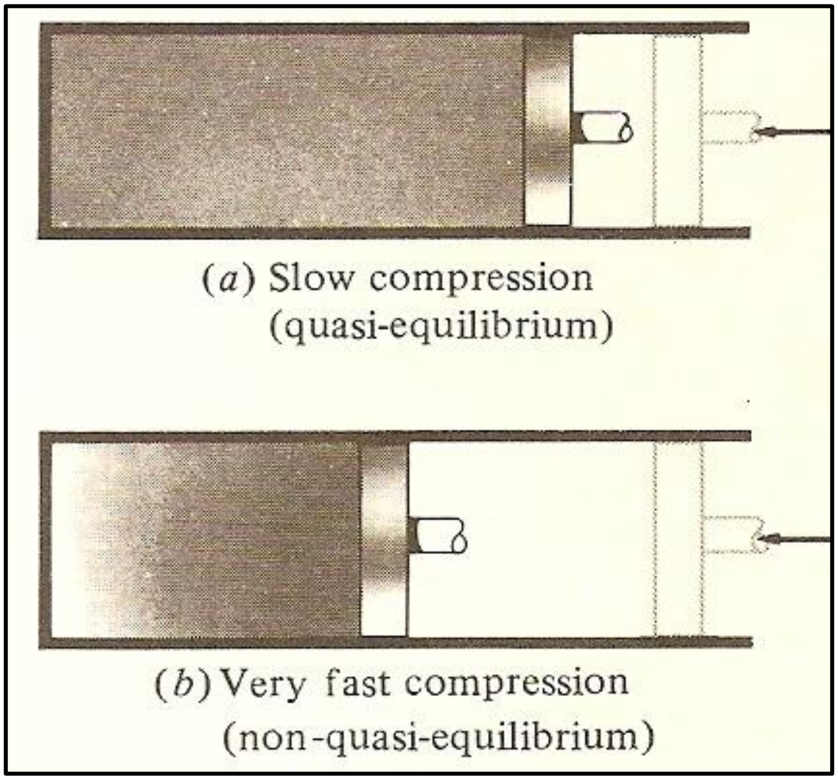

Figure 1-31. Quasi-equilibrium and non-quasi-equilibrium processes.

A system is said to have undergone a cycle if it returns to its initial state at the end of the process. The cycle in (Fig. 1-35a) consists of two processes, and the one in (Fig. 1-35b) consists of four processes.

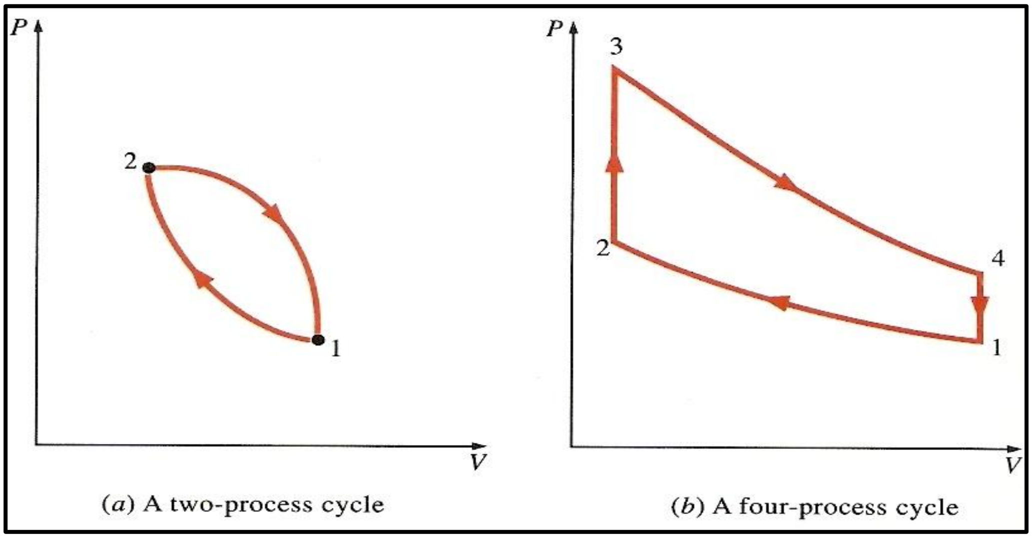

Figure 1-35. Two thermodynamic cycles.

1-9. Pressure

Pressure is *the force exerted by a fluid per unit area*. We speak of pressure only when we deal with a gas or a liquid. The counterpart of pressure in solids is *stress*. For a fluid at rest, the pressure at a given point is the same in all directions. The pressure in a fluid increases with the depth as a result of the weight of the fluid, as shown in (Fig. 1-37).

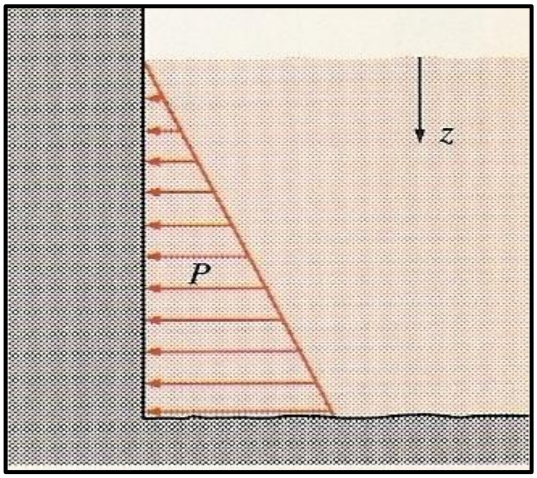

Figure 1-37. The pressure of a fluid at rest increases with depth (as a result of added weight).

Since pressure is defined as force per unit area, it has the unit of newtons per square meter (N/m^2), which is called a *pascal* (Pa). That is,

$$1\ Pa = 1\ N/m^2$$

$$1\ kPa = 10^3\ Pa$$

$$1\ MPa = 10^6\ Pa$$

$$1\ bar = 10^5\ Pa = 0.1\ MPa = 100\ kPa$$

$$1\ atm = 101325\ Pa = 101.325\ kPa = 1.01325\ bars$$

In the English system, the pressure is *pound-force per square inch* (lbf/in^2, or psi), and 1 atm = 14.696 psi.

The actual pressure at relative to a given position is called the absolute pressure, and it is a measured relative to absolute vacuum, i.e., absolute pressure. Most pressure-measuring devices, however, are calibrated to

read zero in the atmosphere (Fig. 1-39), and so they indicate the difference between the absolute pressure and the local atmospheric pressure. This difference is called the gage pressure. Pressures below atmospheric pressure are called vacuum pressure. Absolute, gage, and vacuum pressures are all positive quantities and are related to each other by:

$$P_{gage} = P_{abs} - P_{atm} \qquad \text{(for pressures above } P_{atm}\text{)} \qquad (1\text{-}13)$$

$$P_{vac} = P_{atm} - P_{abs} \qquad \text{(for pressures below } P_{atm}\text{)} \qquad (1\text{-}14)$$

This is illustrated in (Fig. 1-40).

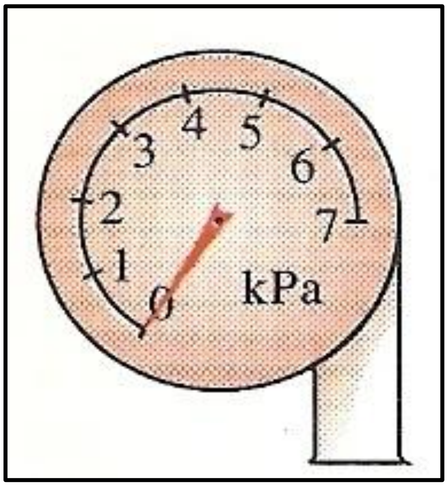

Figure 1-39. A pressure gage which is open to the atmospheric reads zero.

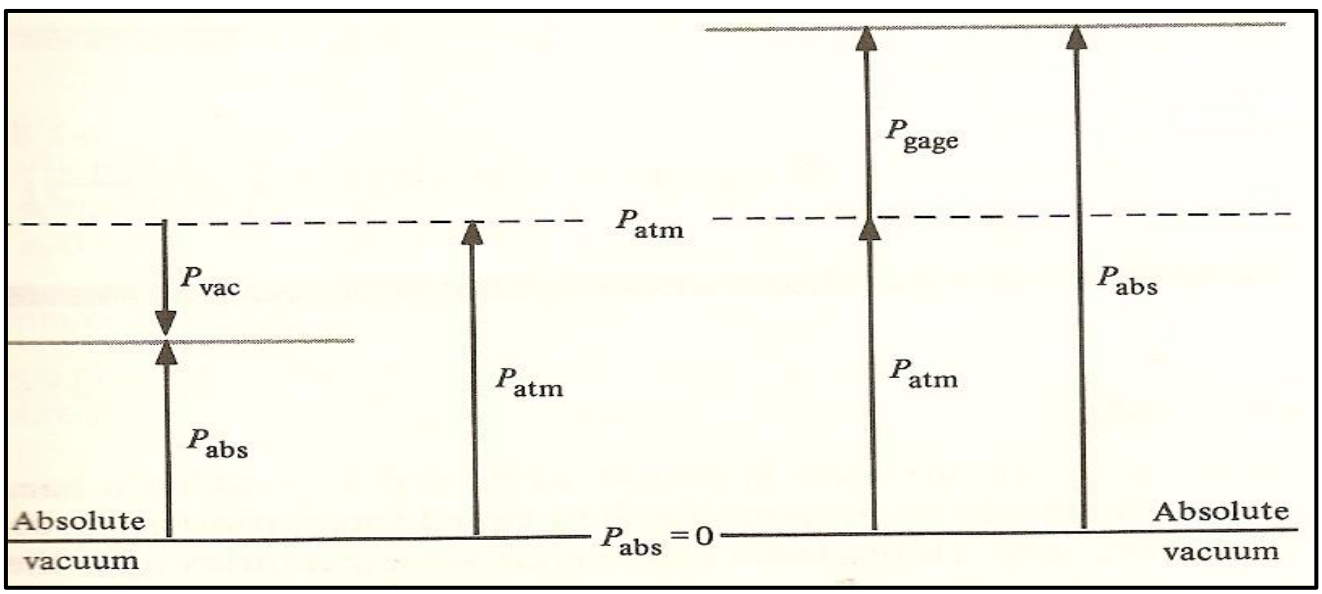

Figure 1-40. Absolute, gage, and vacuum pressures.

Example 1-3.

A vacuum gage connected to a chamber reads 5.8 psi at a location where the atmospheric pressure is 14.5 psi. Determine the absolute pressure in the chamber.

Solution

The absolute pressure is easily determined from (Eq. 1-14).

$$P_{abs} = P_{atm} - P_{vac} = (14.5 - 5.8) \text{ psi} = 8.7 \text{ psi}$$

Manometer

Small and moderate pressure difference are often measured by using a device known as a manometer, which mainly consists of a glass or plastic U-tube containing a fluid such as mercury, water, alcohol, or oil.

Consider the manometer shown in (Fig. 1-41) which is used to measure the pressure in the tank.

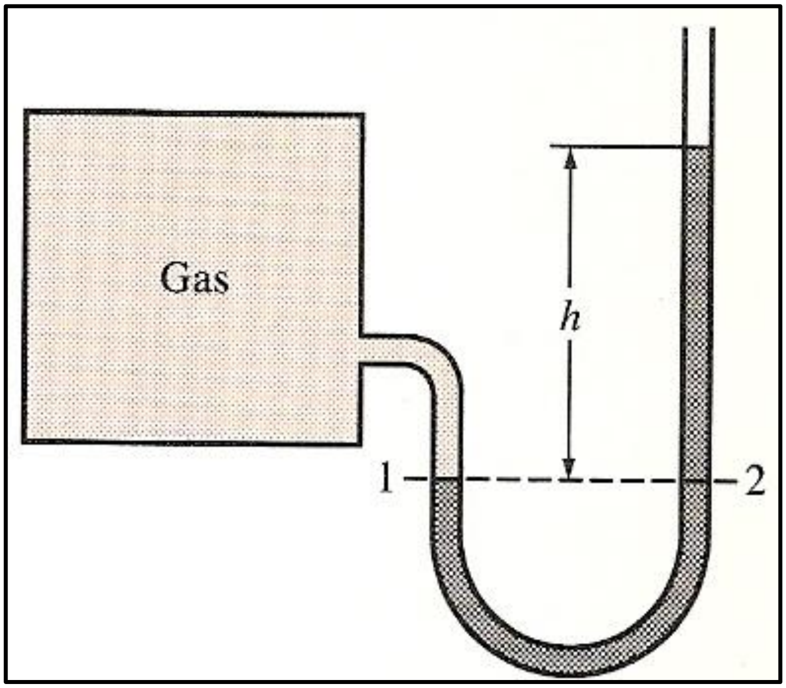

Figure 1-41. The basic manometer.

Since the pressure does not vary in the horizontal direction within a fluid, the pressure at 2 is the same as the pressure at 1, or $P_1 = P_2$

A force balance (Fig.1-42) in the vertical direction:

$$AP_1 = AP_{atm} + W$$

Where $$W = mg = \rho Vg = \rho Ahg$$

Thus $$P_1 = P_{atm} + \rho gh \qquad (\text{kPa}) \qquad (1\text{-}15)$$

$$\Delta P = P_1 - P_{atm} = \rho gh \qquad (\text{kPa}) \qquad (1\text{-}16)$$

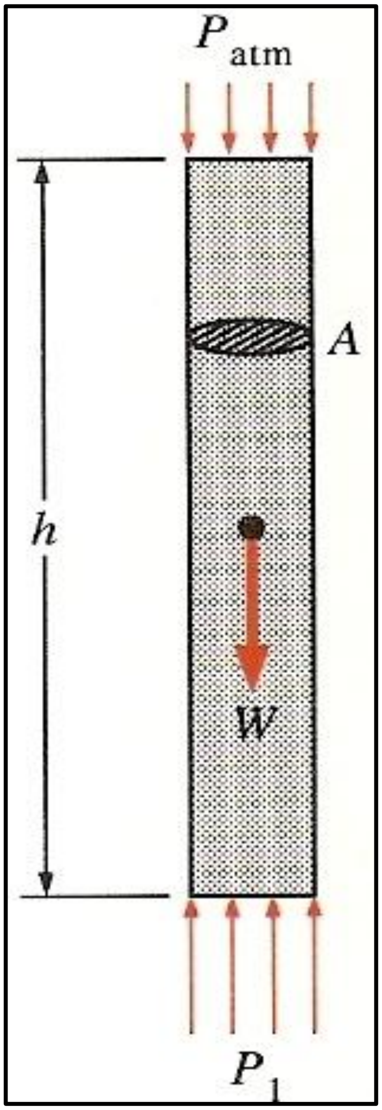

Figure 1-42. The free-body diagram of a fluid column of height *h*.

Example 1-4.

A manometer is used to measure the pressure in a tank. The fluid used has a specific gravity of 0.85, and the manometer column height is 55 cm, as shown in (Fig. 1-43). If the local atmospheric pressure is 96 kPa, determine the absolute pressure within the tank.

Solution

ρ_{H2O} = 1000 kg/m^3
g = 9.807 m/s^2

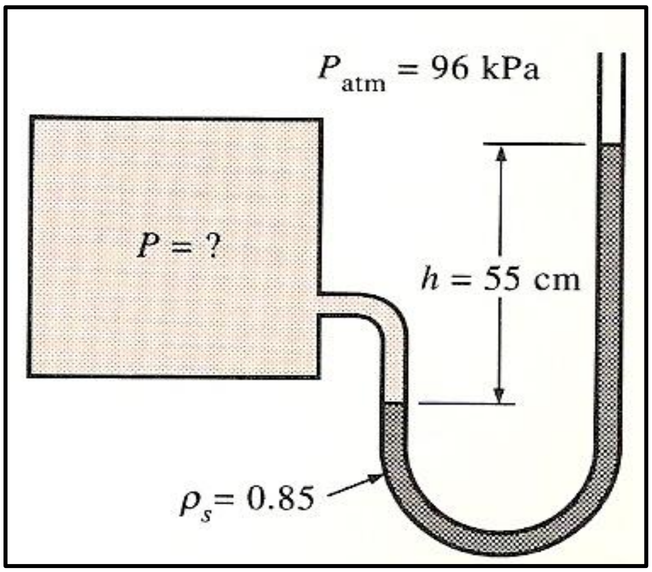

Figure 1-43. Sketch for Example 1-4.

$\rho = (\rho_s)(\rho_{H2O}) = (0.85)(1000\ kg/m^3) = 850\ kg/m^3$

$P = P_{atm} + \rho gh$

$P = 96\ kPa + (850\ kg/m^3)(9.807\ m/s^2)(0.55\ m)\left(\frac{1\ kPa}{1000\ N/m^2}\right)\left(\frac{1\ N}{kg.m/s^2}\right)$

$P = 100.6$ kPa

Barometer

The atmospheric pressure is measured by a device called a barometer, thus the atmospheric pressure is often called the *barometric pressure*.

The pressure at point *B* is equal to the atmospheric pressure, and the pressure at *C* can be taken to be zero since there is only mercury vapor above point *C* and the pressure it exerts is negligible.

$$P_{atm} = \rho g h \qquad (1\text{-}17)$$

P_{atm} = 760 mmHg in height at 0 ℃ (ρ_{Hg} = 13595 kg/m^3) under standard gravitational acceleration (g = 9.807 m/s^2).

The standard atmospheric pressure, for example, is 760 mmHg = 29.92 inHg at 0 ℃.

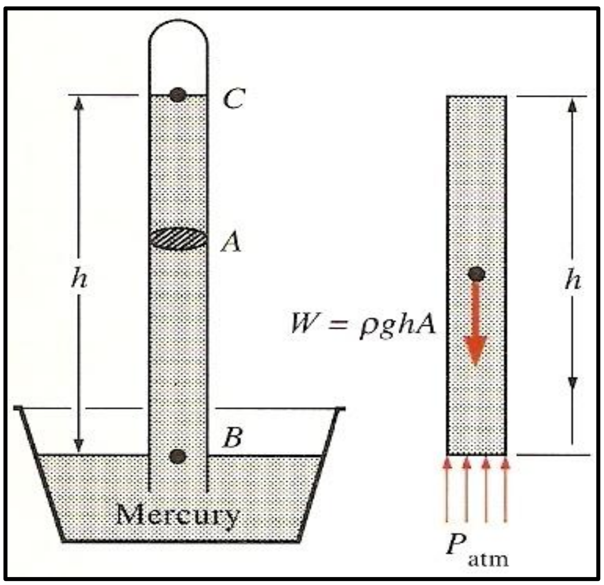

Figure 1-44. The basic barometer.

Example 1-5.

Determine the atmospheric pressure at a location where the barometric reading is 740 mmHg and the gravitational acceleration is g = 9.7 m/s^2. Assume T = 10 ℃, ρ_{Hg} = 13570 kg/m^3.

Solution

$$P_{atm} = \rho g h = (13570\ \text{kg/m}^3)\,(9.7\ \text{m/s}^2)\,(0.74\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg.m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right)$$

$$= 97.41\ \text{kPa}$$

Example 1-6.

The piston off a piston-cylinder containing gas has a mass of 60 kg and a cross-sectional area of 0.04 m^2, as shown in (Fig.1-46). The local atmospheric pressure is 0.97 bar, and the gravitational acceleration is 9.8 m/s^2?

(*a*)Determine the pressure inside the cylinder?

(*b*)If some heat is transferred to the gas, and its volume doubles, do you expect the pressure inside the cylinder to change?

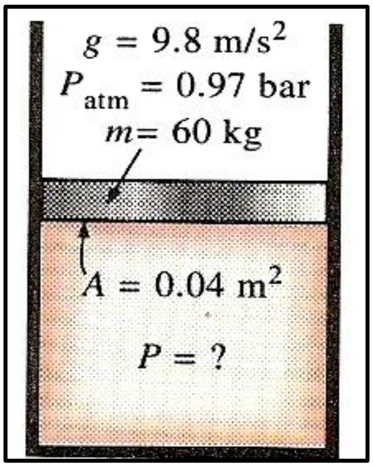

Figure 1-46. Sketch for example 1-6.

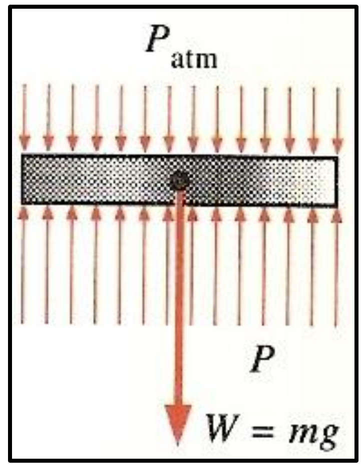

Figure 1-47. Free-body diagram of the piston.

Solution

(*a*) Drawing the free-body diagram of the piston (Fig. 1-47) and the balancing the vertical forces yield:

$$PA = P_{atm} A + W$$

$$P = P_{atm} + \frac{mg}{A} = 0.97 \text{ bar} + \frac{(60 \text{ kg})(9.8 \text{ m/s}^2)}{0.04 \text{ m}^2} \left(\frac{1 \text{ N}}{1 \text{ kg.m/s}^2}\right) * *\left(\frac{1 \text{ bar}}{10^5 \text{ N/m}^2}\right)$$

P = 1.117 bar

(*b*)The volume change will have no effect on the free-body diagram in part (*a*), and therefore the pressure inside the cylinder will remain the same.

1-10. Temperature and the zeroth law of thermodynamics

The zeroth law of thermodynamics that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other (Fig.1-49).

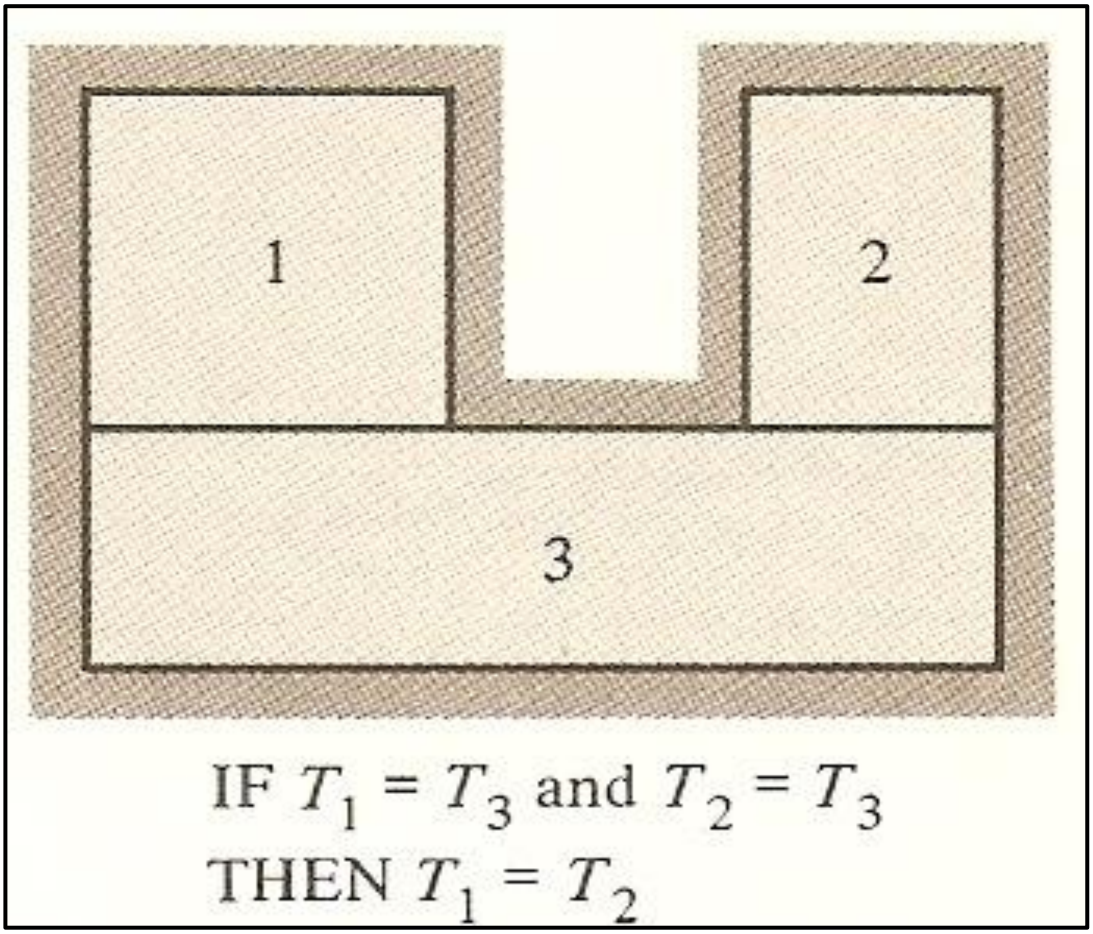

Figure 1-49. The zeroth law of thermodynamics.

Temperature scales

A comparison of various temperature scales is given in (Fig. 1-51):

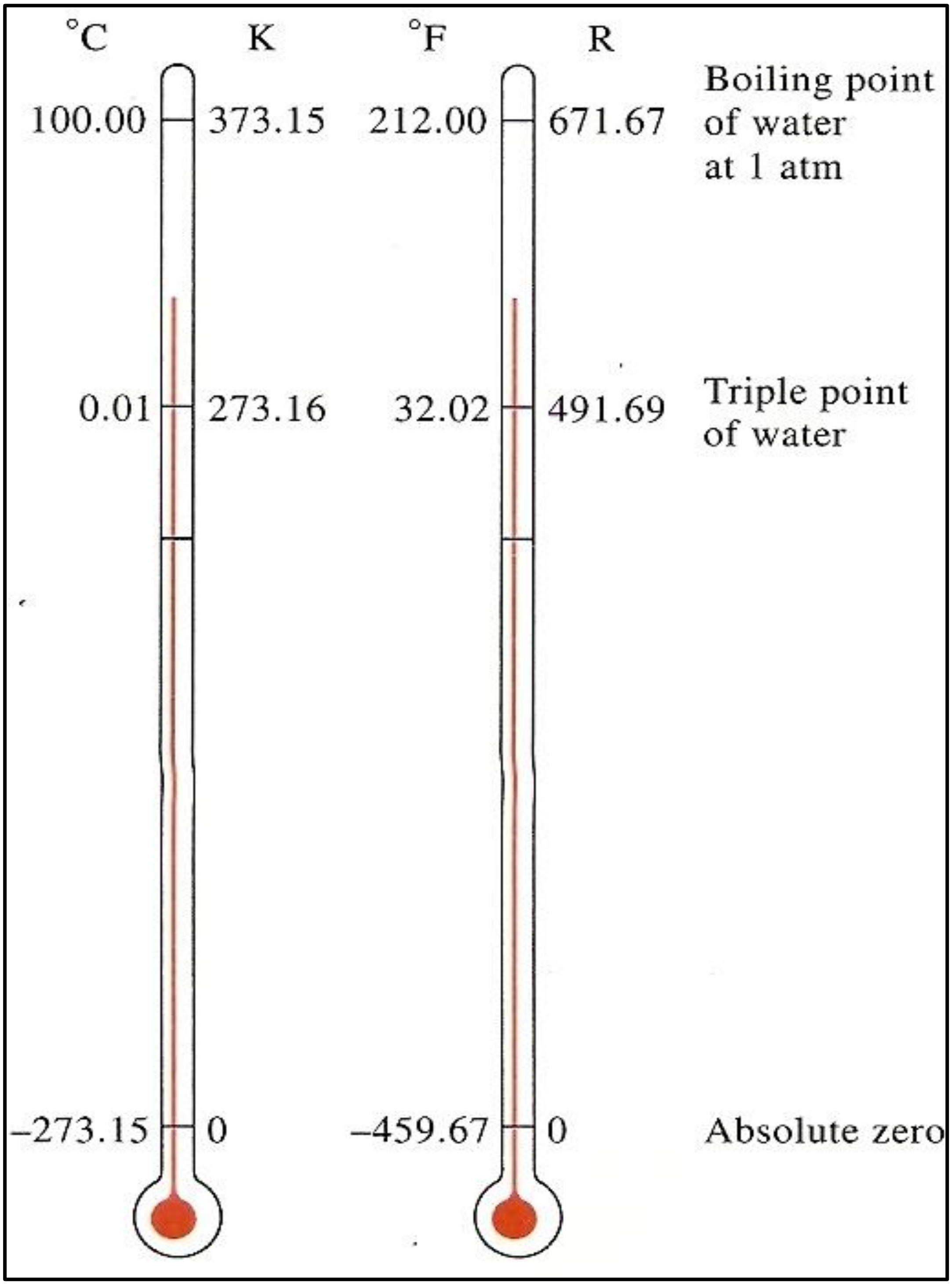

Figure 1-51. Comparison of temperature scales.

$$T(K) = T(°C) + 273.15 \quad (1\text{-}18)$$

$$T(R) = T(°F) + 459.67 \quad (1\text{-}19)$$

$$T(R) = 1.8\,T(K) \quad (1\text{-}20)$$

$$T(°F) = 1.8\,T(°C) + 32 \quad (1\text{-}21)$$

$$\Delta T(K) = \Delta T(°C) \quad (1\text{-}22)$$

$$\Delta T(R) = \Delta T(°F) \quad (1\text{-}23)$$

Where,

$T(K)$: Kelvin scale
$T(°C)$: Celsius scale
$T(°F)$: Fahrenheit scale
$T(R)$: Rankine scale
Δ : difference (delta)