Thermodynamics

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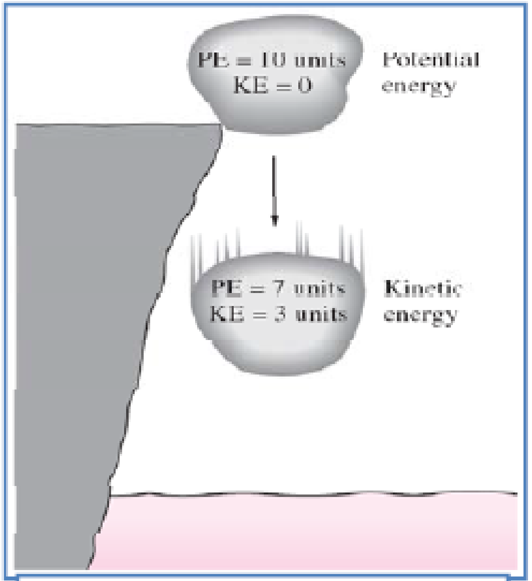
Chapter One

INTRODUCTION AND BASIC CONCEPTS

1.1 THERMODYNAMICS AND ENERGY

- **Thermodynamics**: The science of *energy*.
- **Energy**: The ability to cause changes. The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.



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

- **Substance** *consists of a large number of particles called* ***molecules****. The properties of the substance naturally depend on the behavior of these particles. For example, the pressure of a gas in a container is the result of momentum transfer between the molecules and the walls of the container.*

Application Areas of Thermodynamics

- Other applications of thermodynamics are right where one lives. An ordinary house is, in some respects, an exhibition hall filled with wonders of thermodynamics

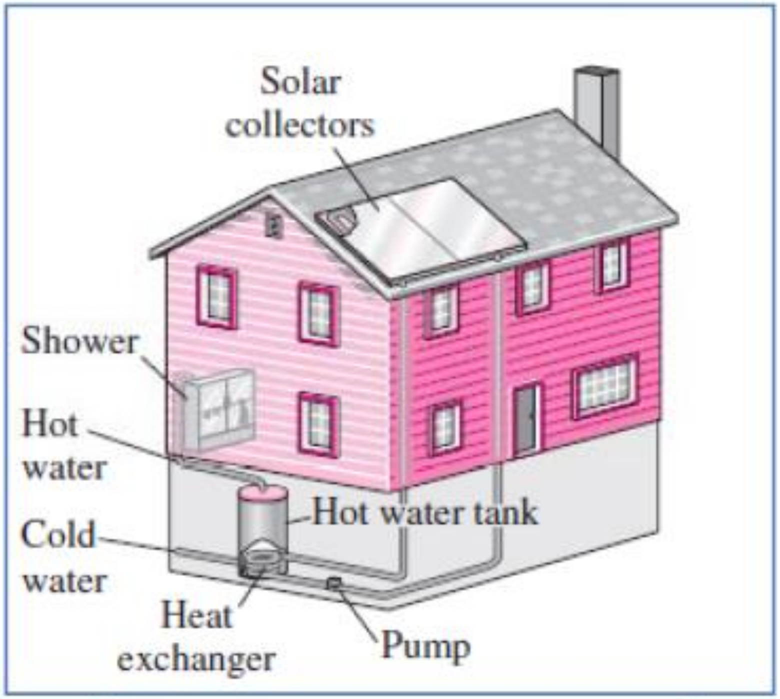
1- Air conditioning systems

2- Airplanes

3- Refrigeration systems

4- Power plants

5- Car radiators



The design of many engineering systems, such as this solar hot water system, involves thermodynamics.

- The energy-efficient home that you may be living in, for example, is designed on the basis of minimizing heat loss in winter and heat gain in summer. The size, location, and the power input of the fan of your computer is also selected after an analysis that involves thermodynamics.

1.2 IMPORTANCE OF DIMENSIONS AND UNITS

- Any physical quantity can be characterized by **dimensions**.
- The 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**.
- **Metric SI system:** A simple and logical system based on a decimal relationship between the various units.
- **English system:** It has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

TABLE 1–1

The seven fundamental (or primary) 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 (cd)
Amount of matter	mole (mol)

TABLE 1–2

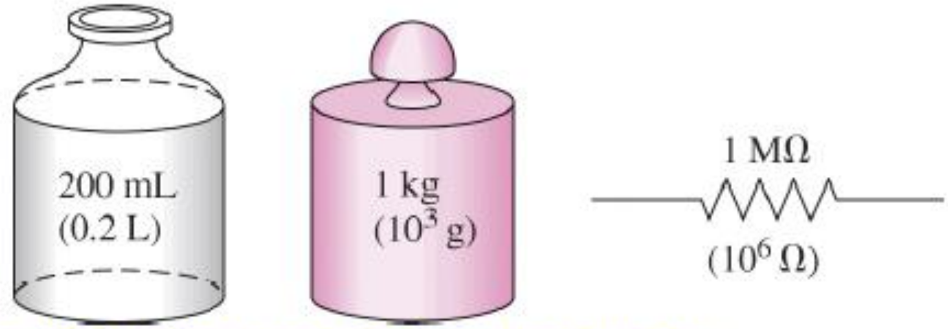
Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, 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 Units

$$1 \text{ lbm} = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$



The SI unit prefixes are used in all branches of engineering.

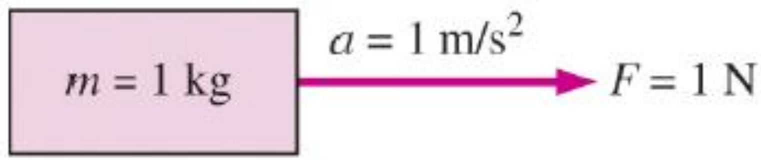
Work = Force × Distance
1 J = 1 N·m
1 cal = 4.1868 J
1 Btu = 1.0551 kJ

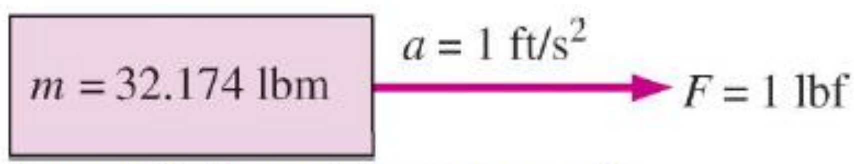
$$\text{Force} = (\text{Mass})(\text{Acceleration})$$

$$F = ma$$

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

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





The definition of the force units.

- **Weight** *W* is a *force*. It is the gravitational force applied to a body, and its magnitude is determined from Newton's second law,

$$W = mg \quad (\text{N})$$

- A more common unit for energy in SI is the kilojoule (1 kJ = 10^3 J).
- **English system,** the energy unit is the **Btu** (British thermal unit), which is defined as the energy required to raise the temperature of 1 lbm of water at 68°F by 1°F.
- **In the metric system,** the amount of energy needed to raise the temperature of 1 g of water at 14.5°C by 1°C is defined as 1 **calorie** (cal), and 1 cal =4.1868 J.
- The magnitudes of the kilojoule and Btu are almost identical (1 Btu = 1.0551 kJ).

Unity Conversion Ratios

- All nonprimary units (secondary units) can be formed by combinations of primary units. Force units, for example, can be expressed as

$$\mathrm{N} = \mathrm{kg}\,\frac{\mathrm{m}}{\mathrm{s}^2} \quad \text{and} \quad \mathrm{lbf} = 32.174\ \mathrm{lbm}\,\frac{\mathrm{ft}}{\mathrm{s}^2}$$

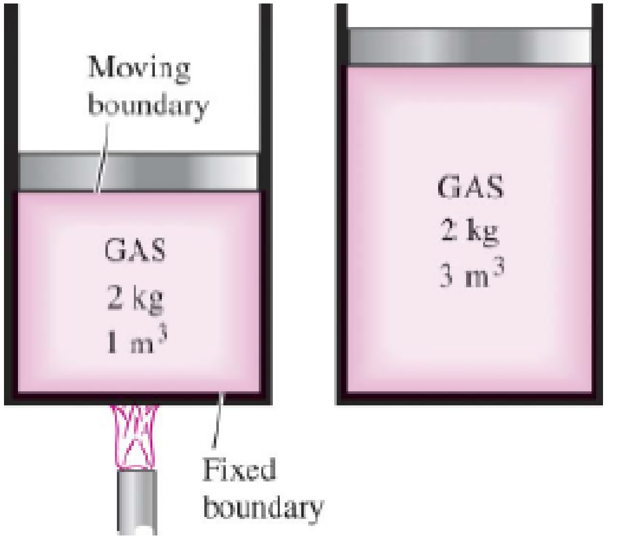
They can also be expressed more conveniently as unity conversion ratios as

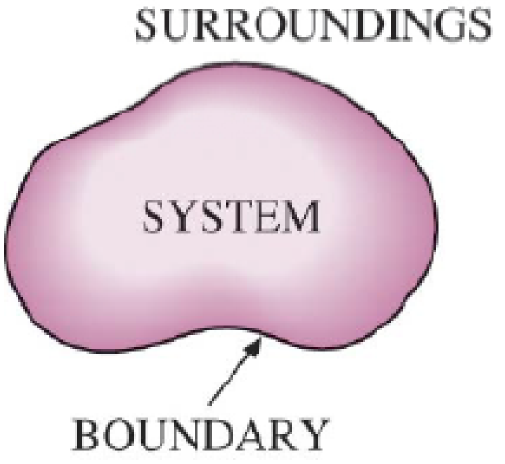
$$\frac{\mathrm{N}}{\mathrm{kg}\cdot\mathrm{m/s}^2} = 1 \quad \text{and} \quad \frac{\mathrm{lbf}}{32.174\ \mathrm{lbm}\cdot\mathrm{ft/s}^2} = 1$$

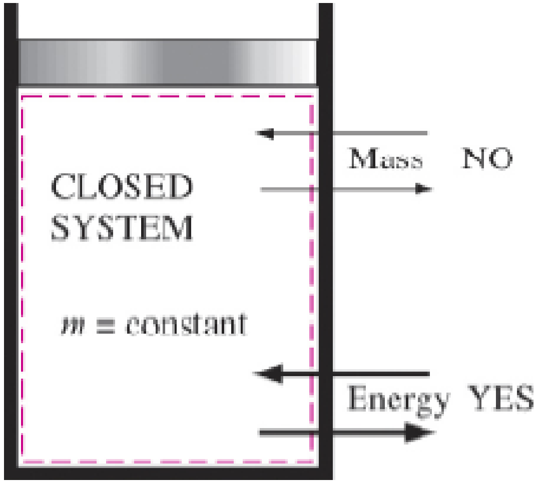
- Unity conversion ratios are identically equal to 1 and are unit less, and thus such ratios (or their inverses) can be inserted conveniently into any calculation to properly convert units.

1.3 SYSTEMS AND CONTROL VOLUMES

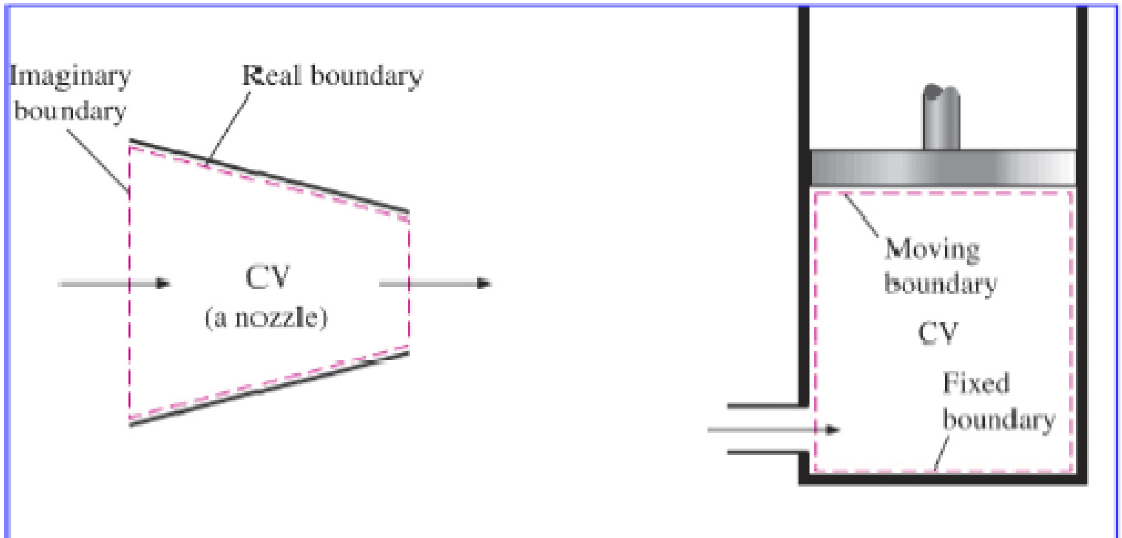
- **System:** A quantity of matter or a region in space chosen for study.
- **Surroundings:** The mass or region outside the system
- **Boundary:** The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.
- **Closed system (Control mass):** A fixed amount of mass, and no mass can cross its boundary.





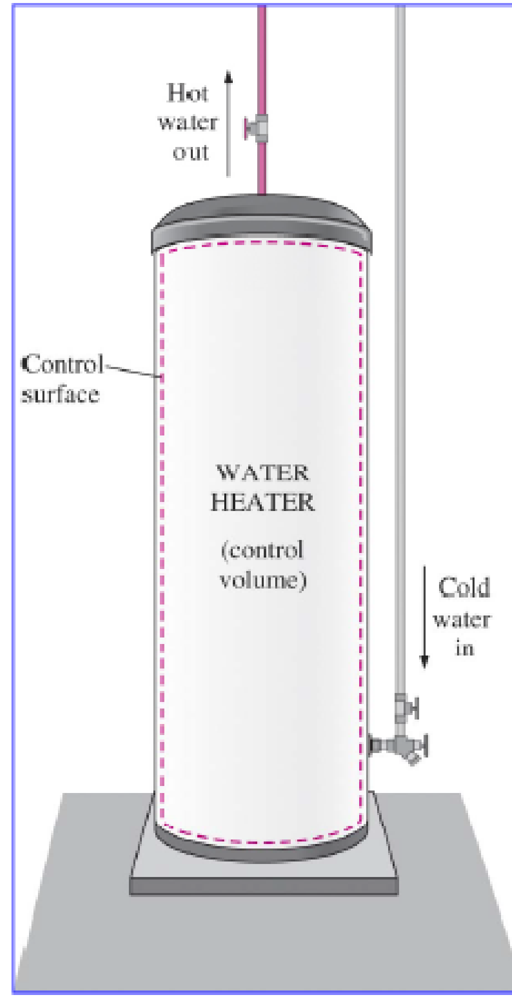


- **Open system (control volume):** A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface:** The boundaries of a control volume. It can be real or imaginary.



(a) A control volume with real and imaginary boundaries

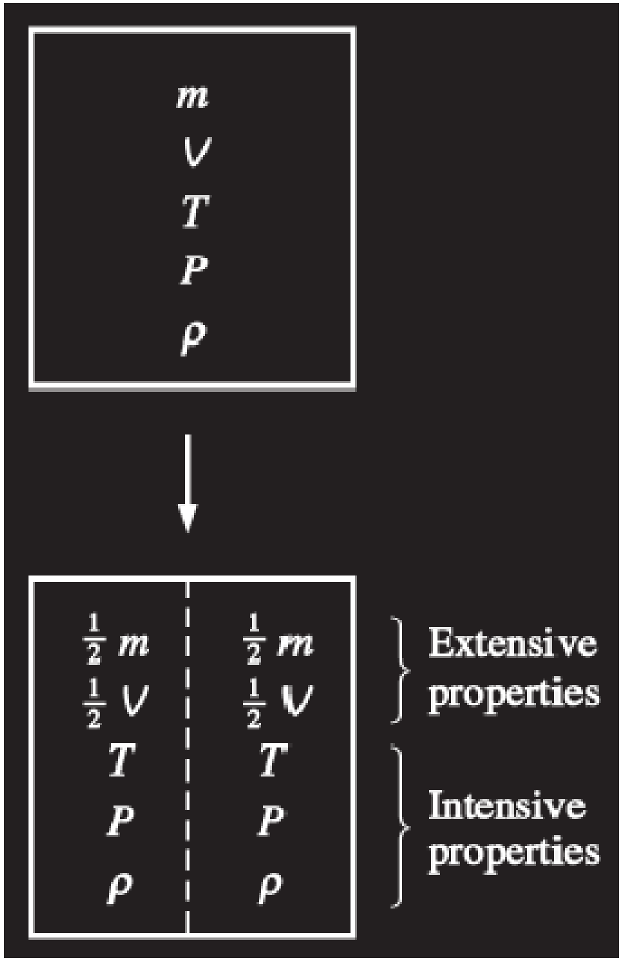
(b) A control volume with fixed and moving boundaries



An open system (a control volume) with one inlet and one exit.

1.4 PROPERTIES OF A SYSTEM

- **Property:** Any characteristic of a system.
- Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*.
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties:** Those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size—or extent—of the system.
- **Specific properties:** Extensive properties per unit mass.



Criterion to differentiate intensive and extensive properties.

1.5 DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\mathrm{kg/m^3})$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

$V = 12\ \mathrm{m^3}$
$m = 3\ \mathrm{kg}$
↓
$\rho = 0.25\ \mathrm{kg/m^3}$
$v = \frac{1}{\rho} = 4\ \mathrm{m^3/kg}$

Density is mass per unit volume; specific volume is volume per unit mass.

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$SG = \frac{\rho}{\rho_{H_2O}}$$

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\mathrm{N/m^3})$$

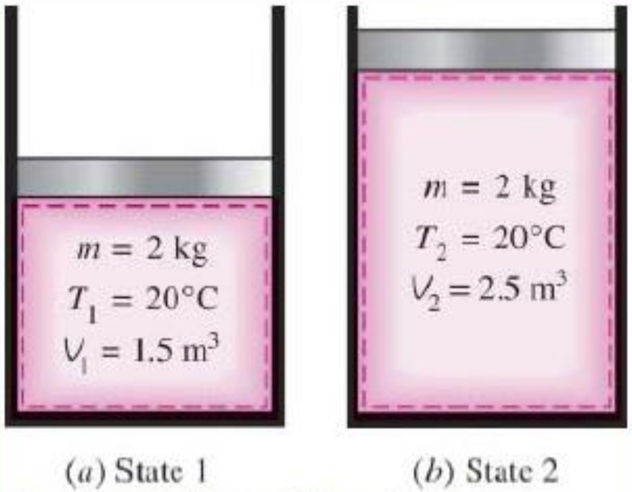
TABLE 1–3

Specific gravities of some substances at 0°C

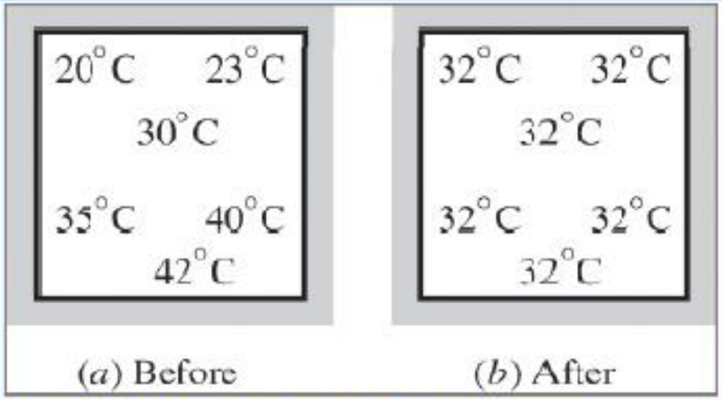
Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

1.6 STATE AND EQUILIBRIUM

- Thermodynamics deals with *equilibrium* states.
- **Equilibrium:** A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



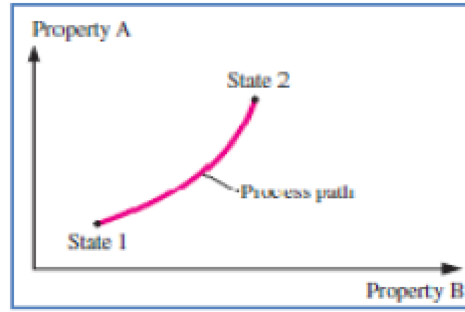
A system at two different states.

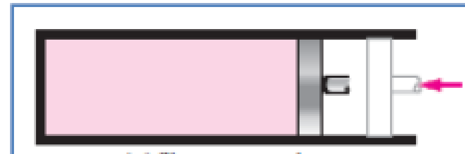


A closed system reaching thermal equilibrium.

1.7 PROCESSES AND CYCLES

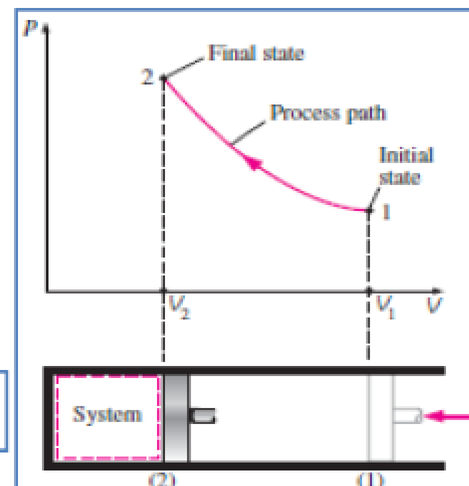
- **Process:** Any change that a system undergoes from one equilibrium state to another.
- **Path:** The series of states through which a system passes during a process. To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.
- **Quasistatic or quasi-equilibrium process:** When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.
- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes. Some common properties that are used as coordinates are temperature T, pressure P, and volume V (or specific volume v).
- The prefix iso- is often used to designate a process for which a particular property remains constant.
- **Isothermal process:** A process during which the temperature T remains constant.
- **Isobaric process:** A process during which the pressure *P* remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume *v* remains constant.
- **Cycle:** A process during which the initial and final states are identical.





(*a*) Slow compression (quasi-equilibrium)

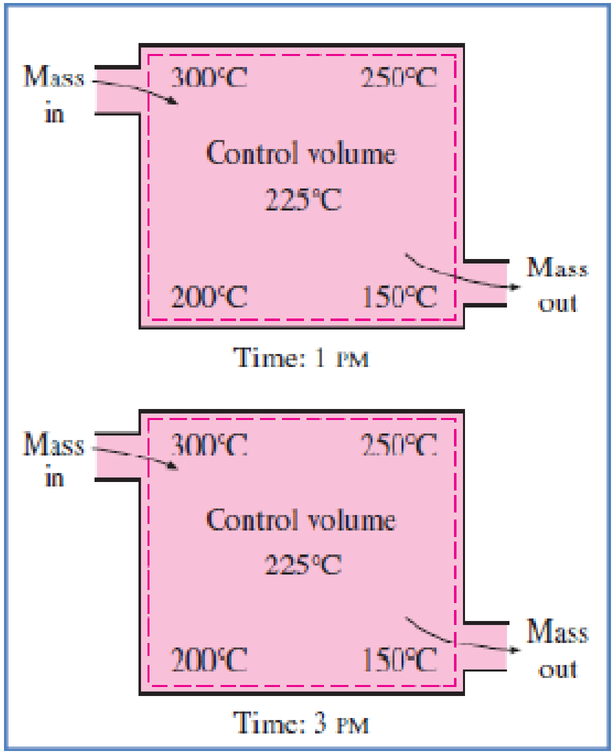
(*b*) Very fast compression (nonquasi-equilibrium)

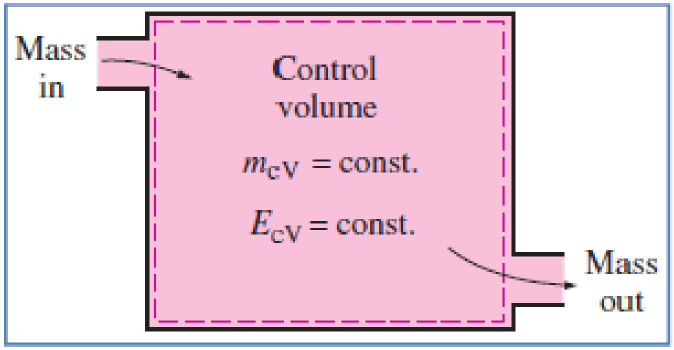


The *P-V* diagram of a compression process.

The Steady-Flow Process

- The term ***steady*** implies ***no change with time.*** The opposite of steady is ***unsteady***, or ***transient.***
- *A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as* ***steady-flow devices.***
- **Steady-flow process**: *process during which a fluid flows through a control volume steadily.*
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

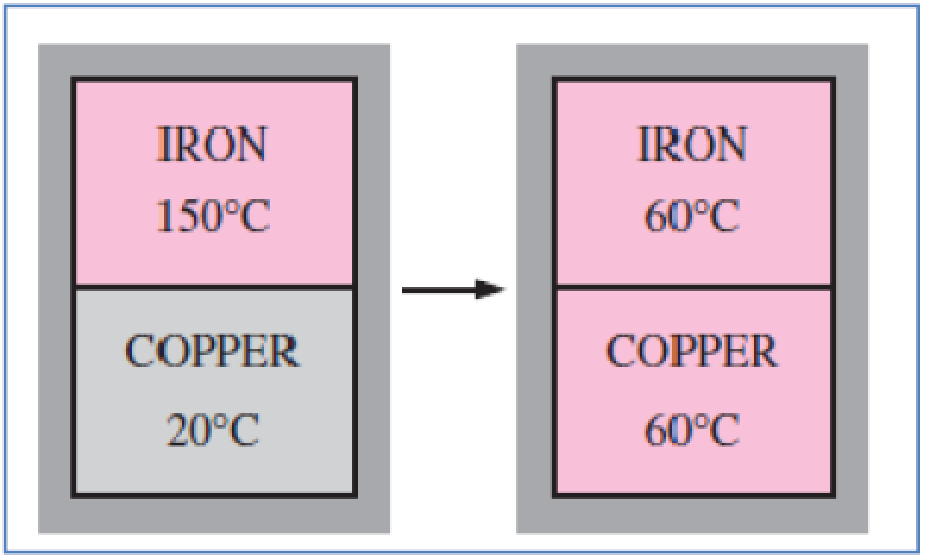




Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

1.8 TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

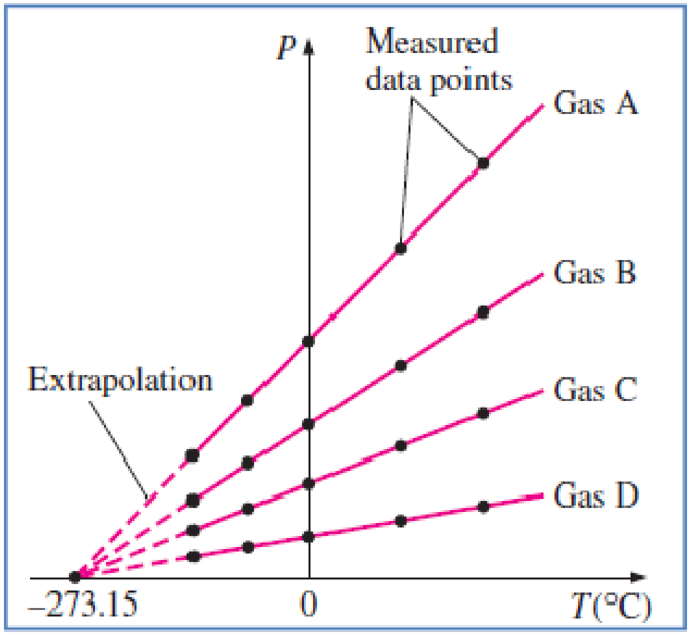
- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as ***two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.***



Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water, which are also called the ice point and the steam point,
- **Ice point:** A mixture of ice and water that is equilibrium with air that in saturated with vapor at 1 atm pressure (0°C or 32°F).
- **Steam point:** A mixture of liquid water and water vapor (with no air) in (equilibrium at 1 atm pressure (100°C or 212°F).
- **Celsius scale:** in SI unit system
- **Fahrenheit** in English unit system
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale (SI) Rankin scale (E)**
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale** The Temperatures on this scale are measured using a constant-volume gas thermometer.



P versus T plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.

$$T(\text{K}) = T(^\circ\text{C}) + 273.15$$

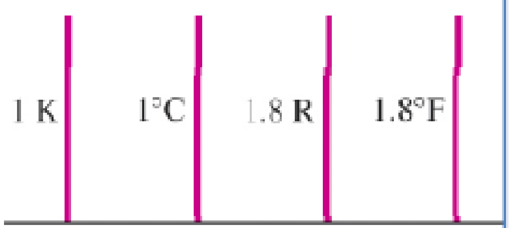
$$T(\text{R}) = T(^\circ\text{F}) + 459.67$$

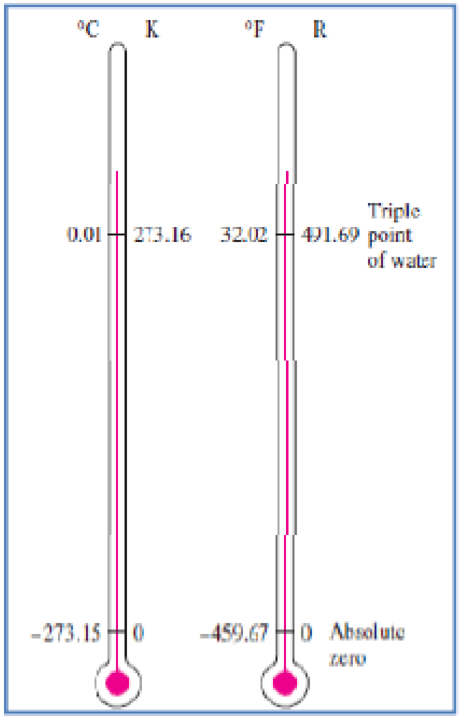
$$T(\text{R}) = 1.8T(\text{K})$$

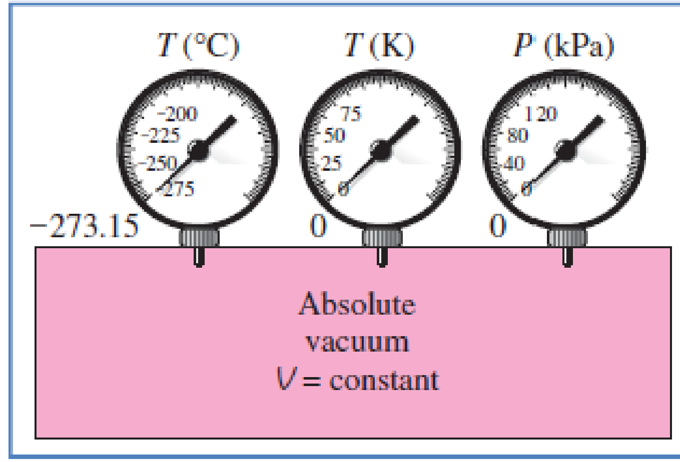
$$T(^\circ\text{F}) = 1.8T(^\circ\text{C}) + 32$$

$$\Delta T(\text{K}) = \Delta T(^\circ\text{C})$$

$$\Delta T(\text{R}) = \Delta T(^\circ\text{F})$$







A constant-volume gas thermometer would read −273.15°C at absolute zero pressure.

Comparison of temperature scales

- The reference temperature in the original Kelvin scale was the ***ice point***,273.15 K, which is the temperature at which water freezes (or ice melts).
- The reference point was changed to a much more precisely reproducible point, the ***triple point*** of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.

1.9 PRESSURE

Pressure: normal force exerted by a fluid per unit area

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

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

$$1\ \text{atm} = 101{,}325\ \text{Pa} = 101.325\ \text{kPa} = 1.01325\ \text{bars}$$

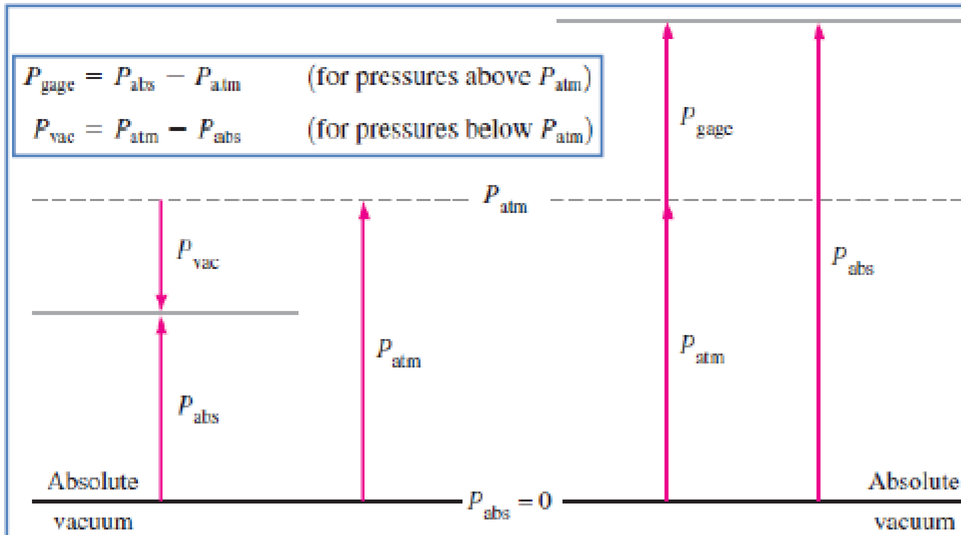
$$1\ \text{kgf/cm}^2 = 9.807\ \text{N/cm}^2 = 9.807 \times 10^4\ \text{N/m}^2 = 9.807 \times 10^4\ \text{Pa}$$

$$= 0.9807\ \text{bar}$$

$$= 0.9679\ \text{atm}$$

Some basic pressure gages.

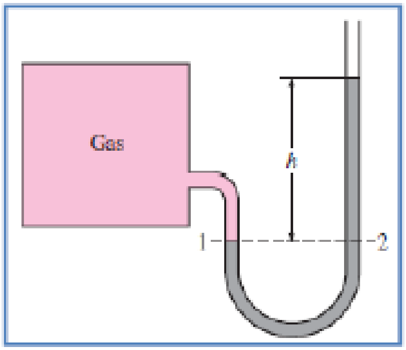
- **Absolute pressure:** The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gage pressure**: The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gage pressure.
- **Vacuum pressures**: Pressures below atmospheric pressure.



Absolute, gage, and vacuum pressures.

1.10 The Manometer

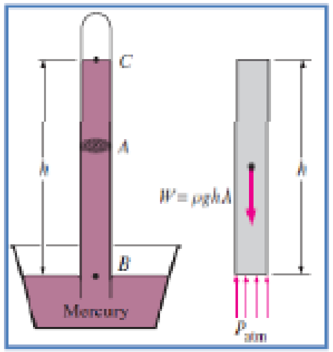
It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.



$$P_2 = P_{atm} + \rho g h$$

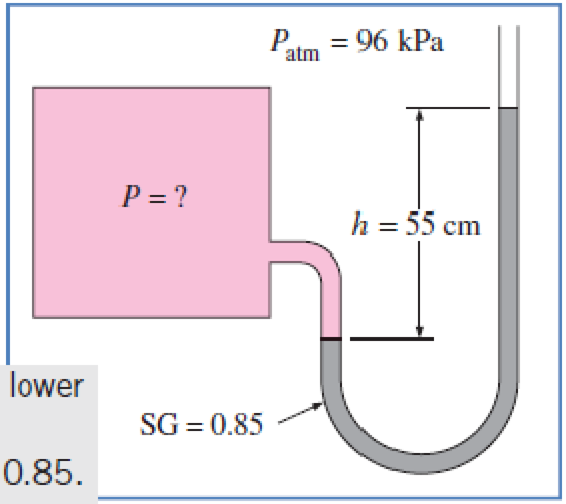
1.11 THE BAROMETER AND ATMOSPHERIC PRESSURE

Atmospheric pressure is measured by a device called a **barometer**; thus, the atmospheric pressure is often referred to as the ***barometric pressure***.



$$P_{atm} = \rho g h$$

<u>Example 1.1:-</u> 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 Figure. If the local atmospheric pressure is 96 kPa, determine the absolute pressure within the tank.



Assumptions The fluid in the tank is a gas whose density is much lower than the density of manometer fluid.

Properties The specific gravity of the manometer fluid is given to be 0.85. We take the standard density of water to be 1000 kg/m^3.

Analysis The density of the fluid is obtained by multiplying its specific gravity by the density of water, which is taken to be 1000 kg/m^3:

$$\rho = \text{SG}\,(\rho_{H_2O}) = (0.85)(1000\ \text{kg/m}^3) = 850\ \text{kg/m}^3$$

Then from Eq. 1–23,

$$P = P_{\text{atm}} + \rho g h$$

$$= 96\ \text{kPa} + (850\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.55\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right)$$

$$= \mathbf{100.6\ kPa}$$

Solved Problems

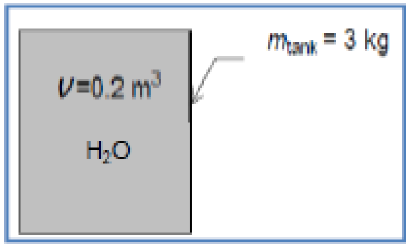
Problem 1.1:- A 3-kg plastic tank that has a volume of 0.2 m^3 is filled with liquid water. Assuming the density of water is 1000 kg/m^3, determine the weight of the combined system.

Solution:-

$$m_w = \rho V = (1000\ \text{kg/m}^3)(0.2\ \text{m}^3) = 200\ \text{kg}$$

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

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



Problem 1.2:- The temperature of a system drops by 45°F during a cooling process. Express this drop in temperature in K, R, and °C.

Solution: - This problem deals with temperature changes, which are identical in Rankine and

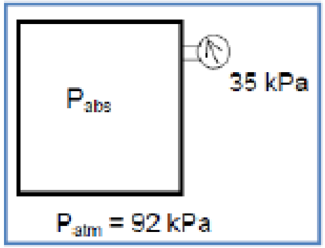
$$\Delta T(\text{R}) = \Delta T(°\text{F}) = \mathbf{45\ R}$$

The temperature changes in Celsius and Kelvin scales are also identical, and are related to the changes in Fahrenheit and Rankine scales by

$$\Delta T(\text{K}) = \Delta T(\text{R})/1.8 = 45/1.8 = \mathbf{25\ K}$$

and $$\Delta T(°\text{C}) = \Delta T(\text{K}) = \mathbf{25°C}$$

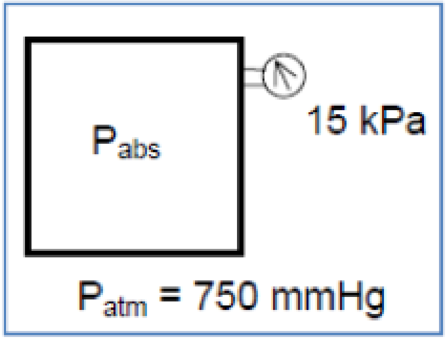
Problem 1.3:- A vacuum gage connected to a chamber reads 35 kPa at a location where the atmospheric pressure is 92 kPa. Determine the absolute pressure in the chamber.



Solution: -

$$P_{abs} = P_{atm} - P_{vac} = 92 - 35 = \mathbf{57\ kPa}$$

Problem 1.4:- A vacuum gage connected to a tank reads 15 kPa at a location where the barometric reading is 750 mm Hg. Determine the absolute pressure in the tank. Take ρHg =13,590 kg/m^3.



Solution: -

$$P_{atm} = \rho g h$$

$$= (13{,}590\ \text{kg/m}^3)(9.807\ \text{m/s}^2)(0.750\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right)$$

$$= 100.0\ \text{kPa}$$

Then the absolute pressure in the tank becomes

$$P_{abs} = P_{atm} - P_{vac} = 100.0 - 15 = \mathbf{85.0\ kPa}$$

Home works

Problem 1.1:-

A pressure gage connected to a tank reads 500 kPa at a location where the atmospheric pressure is 94 kPa. Determine the absolute pressure in the tank. **Answer: 594 kPa**

Problem 1.2:-

Determine the atmospheric pressure at a location where the barometric reading is 750 mm Hg. Take the density of mercury to be 13,600 kg/m^3. **Answer: 100.1 kPa**

Problem 1.3:-

Determine the mass and the weight of the air contained in a room whose dimensions are 6 m x 6 m x 8 m. Assume the density of the air is 1.16 kg/m^3.

Answers: 334.1 kg, 3277 N