

Engineering Thermodynamics

MEE1003

Basic Concepts in Thermodynamics

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- Engineers use principles drawn from thermodynamics and other engineering sciences, including fluid mechanics and heat and mass transfer, to analyze and design devices intended to meet human needs.
- Engineering applications of thermodynamics helped pave the way for significant improvements in our quality of life with advances in major areas such as surface transportation, air travel, space flight, electricity generation and transmission, building heating and cooling, and improved medical practices.

We are going to look at several aspects of thermodynamics.

Course Contents:

- | | |
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| 1. Fundamentals | 7. Available Energy and irreversibility |
| 2. Temperature | 8. Second law efficiency-Quality of Energy |
| 3. Work and heat transfer | 9. Properties of Pure Substance |
| 4. First law of thermodynamics | 10. Properties of Gases and Gas Mixtures |
| 5. Second law of thermodynamics | 11. Thermodynamic relations, equilibrium and third law |
| 6. Entropy | 12. Gas power cycles |
| | 13. Vapour and Refrigeration Cycles |

We start this chapter with an overview of thermodynamics and the unit systems, and continue with a discussion of some basic concepts such as system, state, state postulate, equilibrium, and process.

The objectives of the Chapter are to:

- ✓ Identify the unique vocabulary associated with thermodynamics through the precise definition of basic concepts to form a sound foundation for the development of the principles of thermodynamics.
- ✓ Review the metric SI and the English unit systems that will be used throughout the text.
- ✓ Explain the basic concepts of thermodynamics such as system, state, state postulate, equilibrium, process, and cycle.
- ✓ Review concepts of temperature, temperature scales, pressure, and absolute and gage pressure.
- ✓ Introduce an intuitive systematic problem-solving technique.

THERMODYNAMICS AND ENERGY

- Thermodynamics can be defined as the science of energy.
- The name thermodynamics stems from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power.
- Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power generation, refrigeration, and relationships among the properties of matter.
- 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 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).
- The conservation of energy principle also forms the backbone of the diet industry: A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight (Fig. 1–2).

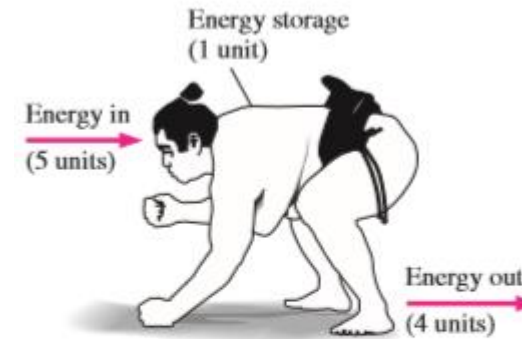


FIGURE 1–2
Conservation of energy principle for the human body.

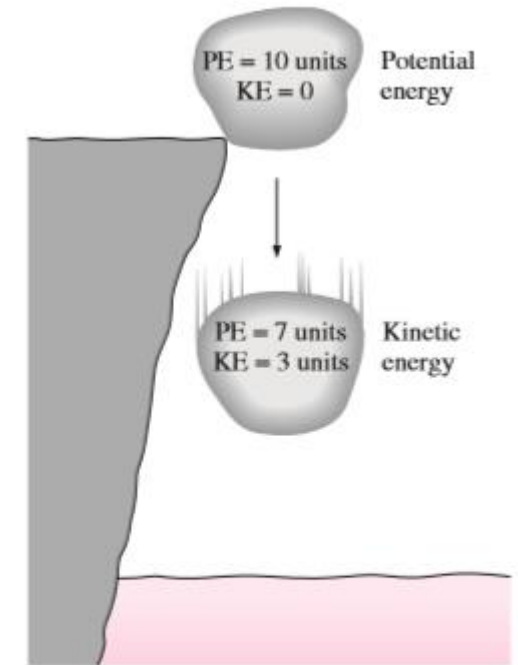


FIGURE 1–1
Energy cannot be created or destroyed; it can only change forms (the first law).

- The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as $E_{\text{in}} - E_{\text{out}} = \Delta E$.
- The first law of thermodynamics is simply an expression of the conservation of energy principle, and it asserts that energy is a thermodynamic property.
- The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy.
- For example, a cup of hot coffee left on a table eventually cools, but a cup of cool coffee in the same room never gets hot by itself (Fig. 1–3). The high-temperature energy of the coffee is degraded (transformed into a less useful form at a lower temperature) once it is transferred to the surrounding air.
- Although the principles of thermodynamics have been in existence since the creation of the universe, thermodynamics did not emerge as a science until the construction of the first successful atmospheric steam engines in England by Thomas Savery in 1697 and Thomas Newcomen in 1712.
- The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolph Clausius, and Lord Kelvin (formerly William Thomson).

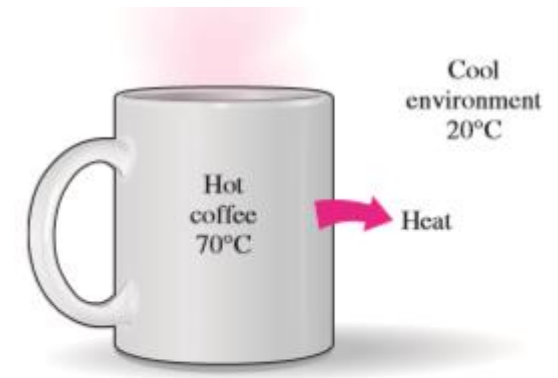


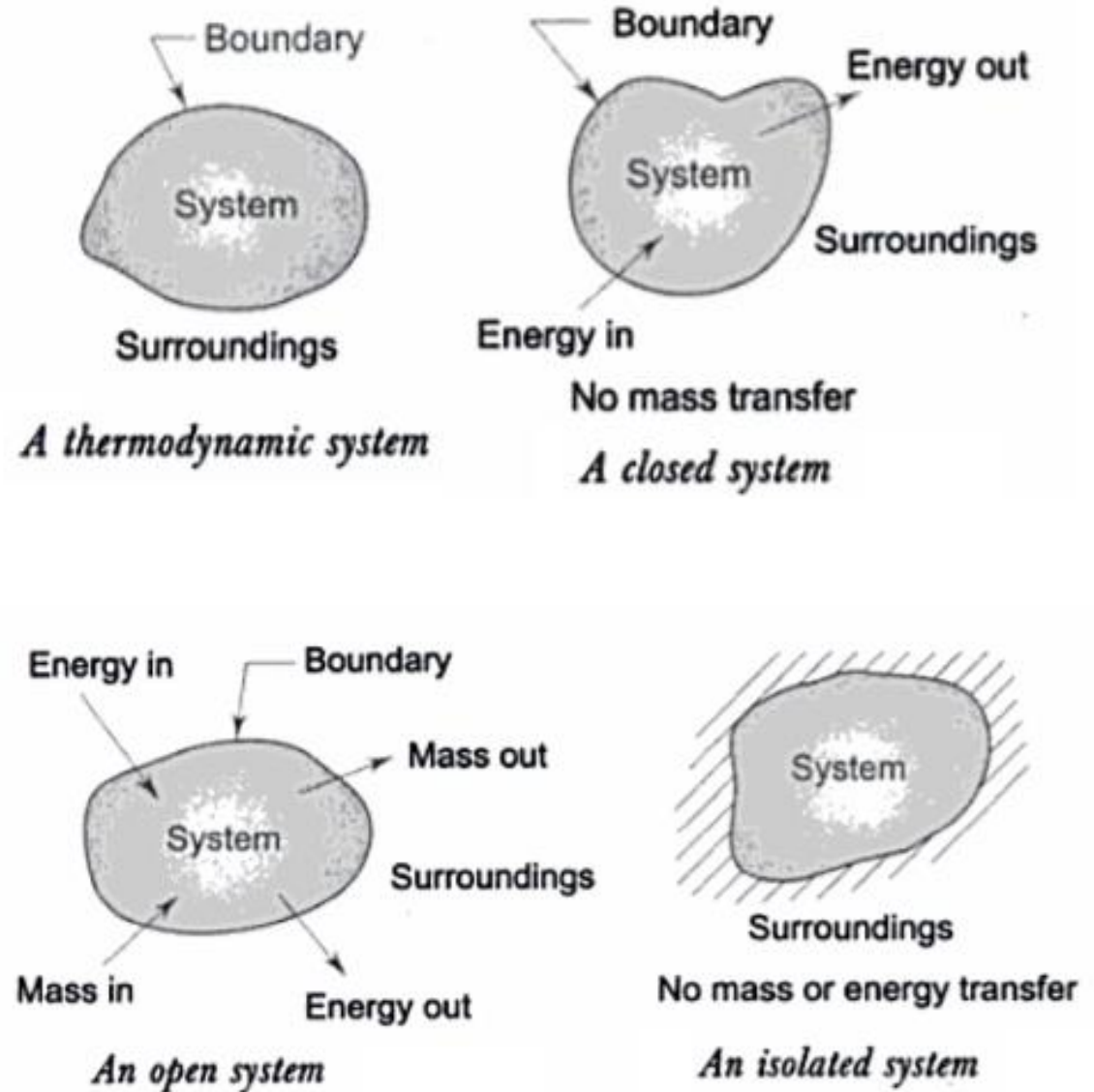
FIGURE 1–3

Heat flows in the direction of decreasing temperature.

- It is well-known that a substance consists of a large number of particles called molecules. The properties of the substance naturally depend on the behaviour 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.
- This macroscopic approach to the study of thermodynamics that does not require a knowledge of the behaviour of individual particles is called *classical thermodynamics*.
- It provides a direct and easy way to the solution of engineering problems.
- A more elaborate approach, based on the average behaviour of large groups of individual particles, is called *statistical thermodynamics*. This microscopic approach is rather involved and is used in this text only in the supporting role.
- In thermodynamics the term system is used to identify the subject of the analysis. Once the system is defined and the relevant interactions with other systems are identified, one or more physical laws or relations are applied.

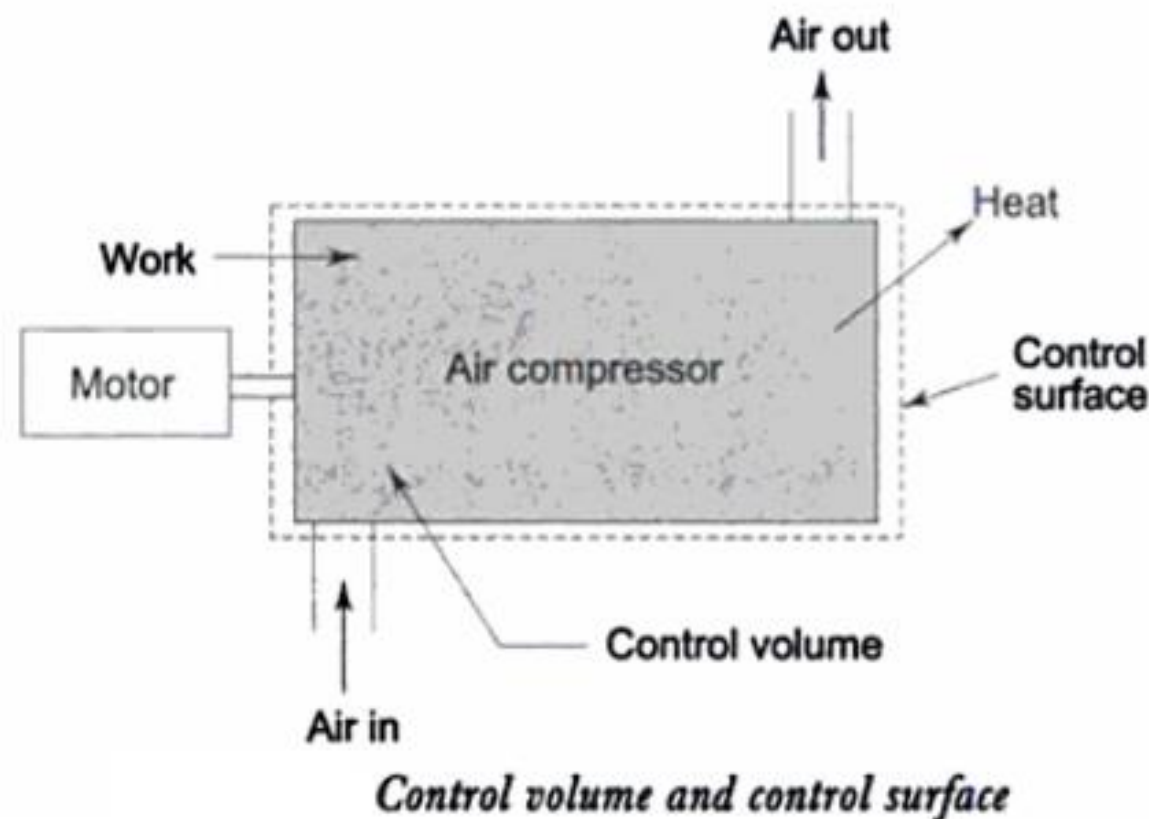
Defining Systems:

- The *system* is whatever we want to study. It may be as simple as a free body or as complex as an entire chemical refinery.
- Everything external to the system is considered to be part of the system's surroundings.
- The system is distinguished from its surroundings by a specified *boundary*, which may be at rest or in motion.
- You will see that the interactions between a system and its surroundings, which take place across the boundary, play an important part in engineering thermodynamics.
- Generally, two basic kinds of systems are distinguished i.e. **closed systems** and **control volumes**.



- A closed system refers to a fixed quantity of matter. There can be no transfer of mass across its boundary, whereas a control volume is a region of space through which mass may flow.
- The open system is one in which matter crosses the boundary of the system. There may be energy transfer also.
- The term control mass is sometimes used in place of closed system, and the term open system is used interchangeably with control volume.
- When the terms control mass and control volume are used, the system boundary is often referred to as a control surface.
- Most of the engineering devices are generally open systems, e.g., an air compressor in which air enters at low pressure and leaves at high pressure and there are energy transfers across the system boundary.
- A special type of closed system that does not interact in any way with its surroundings is called an isolated system.
- It is of fixed mass and energy, and there is no mass or energy transfer across the system boundary.

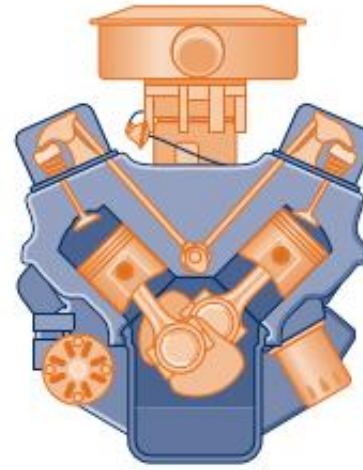
For thermodynamic analysis of an open system, such as an air compressor, attention is focussed on a certain volume in space surrounding the compressor, known as the *control volume*, bounded by a surface called the *control surface*. Matter as well as energy crosses the control surface.



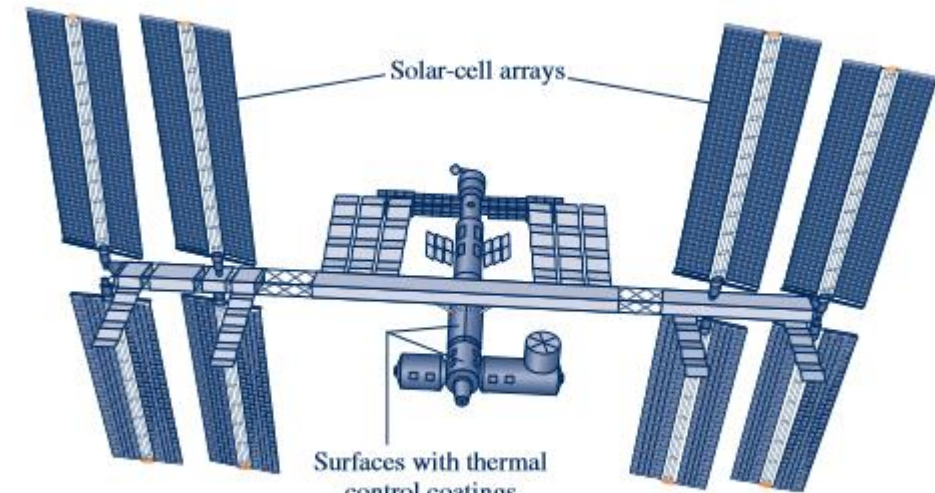
A closed system is a system closed to matter flow, though its volume can change against a flexible boundary. When there is matter flow, then the system is considered to be a volume of fixed identity, the control volume. There is thus no difference between an open system and a control volume.

Application Areas of Thermodynamics

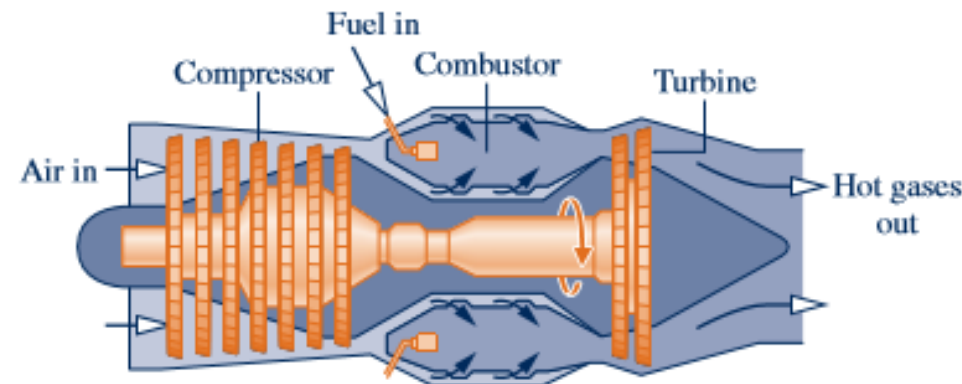
- ✓ Aircraft and rocket propulsion
- ✓ Alternative energy systems
- ✓ Fuel cells
- ✓ Geothermal systems
- ✓ Magnetohydrodynamic (MHD) converters
- ✓ Ocean thermal, wave, and tidal power generation
- ✓ Thermoelectric and thermionic devices
- ✓ Cryogenic systems, gas separation, and liquefaction
- ✓ Fossil and nuclear-fueled power stations
- ✓ Heating, ventilating, and air-conditioning systems
- ✓ Absorption refrigeration and heat pumps
- ✓ Vapor-compression refrigeration and heat pumps
- ✓ Solar-activated heating, cooling, and power generation
- ✓ Wind turbines
- ✓ Automobile engines
- ✓ Bioengineering applications
- ✓ Biomedical applications
- ✓ Combustion systems
- ✓ Compressors, pumps
- ✓ Cooling of electronic equipment
- ✓ Steam and gas turbines
- ✓ Power production
- ✓ Propulsion



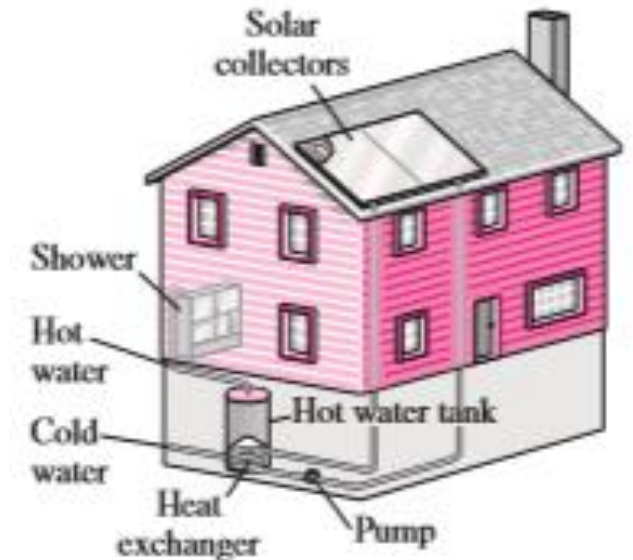
Vehicle engine



Surfaces with thermal control coatings
International Space Station



Turbojet engine





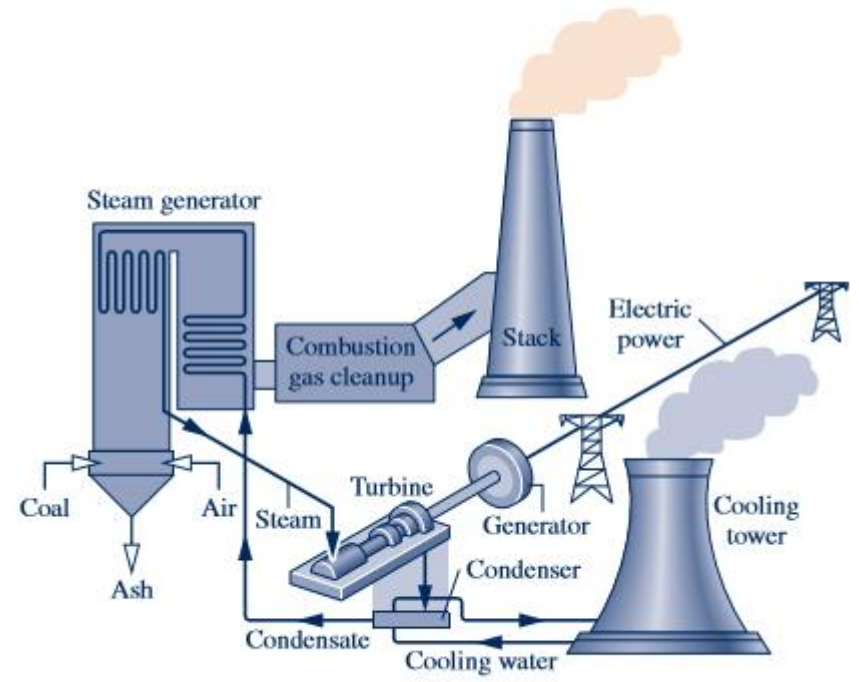
The human body



Air conditioning systems



Airplanes



Electrical power plant



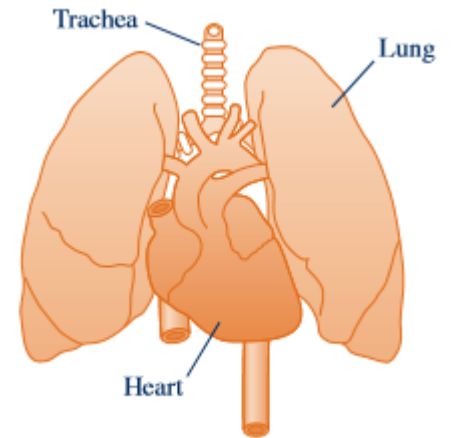
Car radiators



Power plants



Refrigeration systems

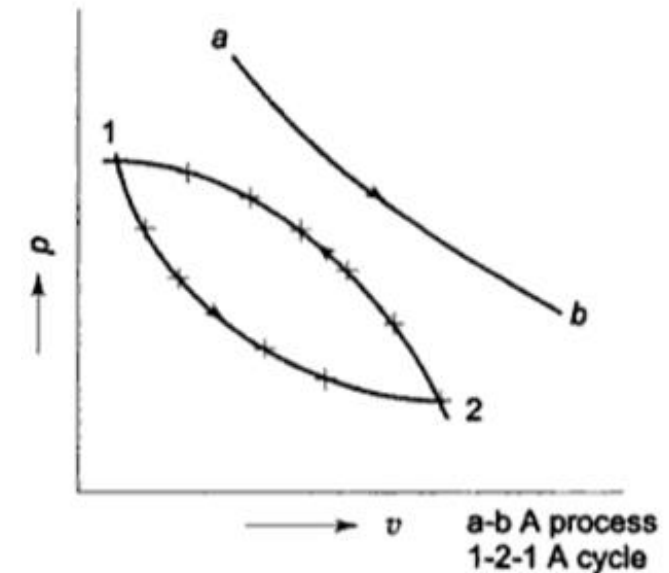


Biomedical applications

Thermodynamic Properties, Processes and Cycle

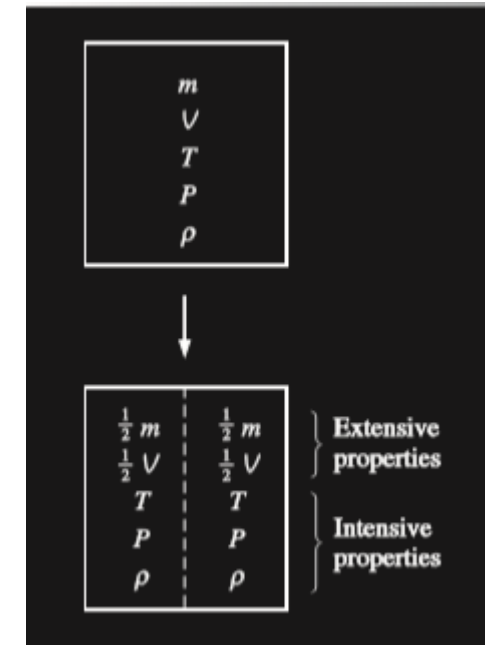
Properties of a System

- Any characteristic of a system is called a property. Some familiar properties are pressure (P), temperature (T), volume (V), and mass (m). These are all macroscopic in nature.
- The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.
- When all the properties of a system have definite values, the system is said to exist at a definite state. Properties are the coordinates to describe the state of a system.
- Any operation in which one or more of the properties of a system changes is called a change of state.
- The succession of states passed through during a change of state is called the path of the change of state.
- When the path is completely specified, the change of state is called process, e.g. , a constant pressure process.
- A thermodynamic cycle is defined as a series of state changes such that the final state is identical with the initial state.
- Properties are considered to be either intensive or extensive.



A process and a cycle

- Intensive properties are those that are independent of the mass of a system, such as temperature, pressure, and density.
- Extensive properties are those whose values depend on the size—or extent—of the system. Total mass, total volume, and total momentum are some examples of extensive properties.
- We can also say that Extension properties are related to mass, e.g., volume, energy, etc. If mass is increased, the values of the extensive properties also increase.
- An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition, as shown in Fig. 1–6.
- Each part will have the same value of intensive properties as the original system, but half the value of the extensive properties.
- Generally, uppercase letters are used to denote extensive properties (with mass m being a major exception), and lowercase letters are used for intensive properties (with pressure P and temperature T being the obvious exceptions).
- Extensive properties per unit mass are called specific properties and also intensive properties. Some examples of specific properties are specific volume ($v = V/m$) and specific total energy ($e = E/m$) and density (ρ)



DENSITY AND SPECIFIC GRAVITY

- Density is defined as mass per unit volume.

Density: $\rho = \frac{m}{V} \text{ (kg/m}^3\text{)}$

- The reciprocal of density is the specific volume (ϑ), which is defined as volume per unit mass. That is, $\vartheta = \frac{V}{m} = \frac{1}{\rho}$
- For a differential volume element of mass dm and volume dV , density can be expressed as $\rho = dm/dV$.
- The density of a substance, in general, depends on temperature and pressure. The density of most gases is proportional to pressure and inversely proportional to temperature.
- Liquids and solids, on the other hand, are essentially incompressible substances, and the variation of their density with pressure is usually negligible.
- At 20°C, for example, the density of water changes from 998 kg/m³ at 1 atm to 1003 kg/m³ at 100 atm, a change of just 0.5 percent. The density of liquids and solids depends more strongly on temperature than it does on pressure.
- At 1 atm, for example, the density of water changes from 998 kg/m³ at 20°C to 975 kg/m³ at 75°C, a change of 2.3 percent, which can still be neglected in many engineering analyses.

- Sometimes the density of a substance is given relative to the density of a well-known substance. Then it is called specific gravity, or relative density, and is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C, for which $\rho_{H_2O} = 1000 \text{ kg/m}^3$). That is,

Specific gravity: $SG = \frac{\rho}{\rho_{H_2O}}$

- Note that the specific gravity of a substance is a dimensionless quantity.
- The weight of a unit volume of a substance is called specific weight and is expressed as

Specific weight: $\gamma = \rho g$

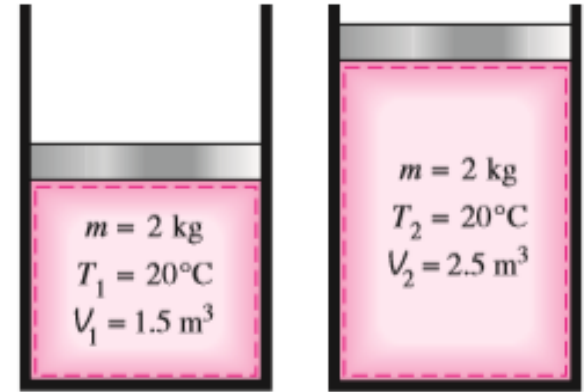
where g is the gravitational acceleration. The densities of liquids are essentially constant, and thus they can often be approximated as being incompressible substances during most processes without sacrificing much in accuracy.

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

STATE AND EQUILIBRIUM

- Consider a system is not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or the state, of the 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. A system at two different states is explained in the figure below.
- Thermodynamics deals with equilibrium states. The word equilibrium implies a state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- A system in equilibrium experiences no changes when it is isolated from its surroundings.
- There are many types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the relevant types of equilibrium are satisfied.

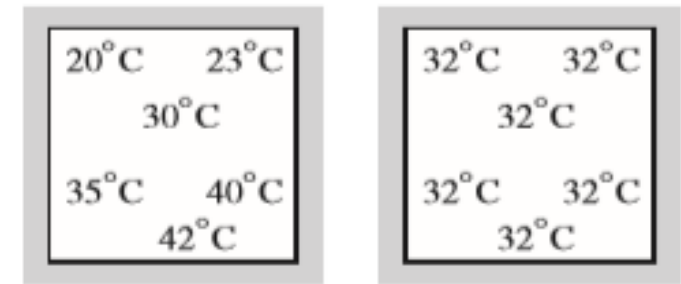


(a) State 1

(b) State 2

A system at two different states

For example, a system is in thermal equilibrium if the temperature is the same throughout the entire system, as shown in Figure. That is, the system involves no temperature differential, which is the driving force for heat flow.



(a) Before

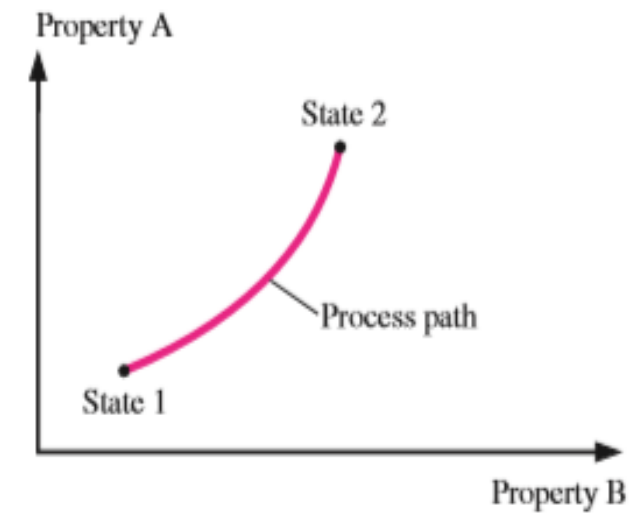
(b) After

A closed system reaching thermal equilibrium.

- Mechanical equilibrium is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time.
- However, the pressure may vary within the system with elevation as a result of gravitational effects.
- For example, the higher pressure at a bottom layer is balanced by the extra weight it must carry, and, therefore, there is no imbalance of forces.
- The variation of pressure as a result of gravity in most thermodynamic systems is relatively small and usually disregarded.
- If a system involves two phases, it is in phase equilibrium when the mass of each phase reaches an equilibrium level and stays there.
- Finally, a system is in chemical equilibrium if its chemical composition does not change with time, that is, no chemical reactions occur.
- A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

PROCESSES AND CYCLES

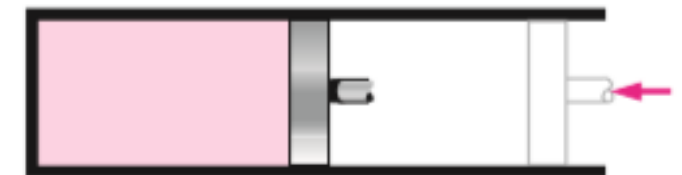
- Any change that a system undergoes from one equilibrium state to another is called a process, and the series of states through which a system passes during a process is called the path of the process.
- To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.
- 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 process that 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.
- Because of this pressure difference, the system can no longer be said to be in equilibrium, and this makes the entire process non quasi-equilibrium.
- It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process.



A process between states 1 and 2 and the process path.



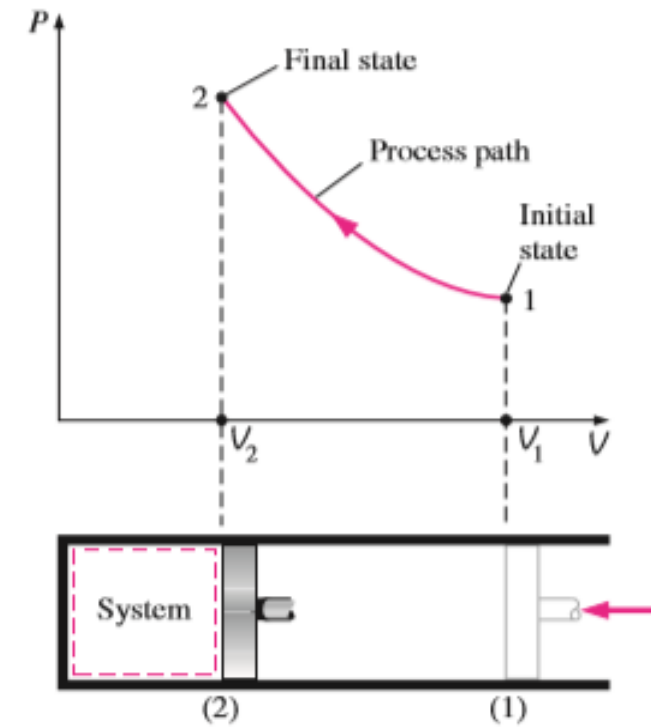
(a) Slow compression
(quasi-equilibrium)



(b) Very fast compression
(nonquasi-equilibrium)

Quasi-equilibrium and nonquasi-equilibrium compression processes.

- Engineers are interested in quasi equilibrium processes for two reasons. First, they are easy to analyze; second work-producing devices deliver the most work when they operate on quasi equilibrium processes.
- Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.
- 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).
- Above Figure shows the P - V diagram of a compression process of a gas. Note that the process path indicates a series of equilibrium states through which the system passes during a process and has significance for quasi-equilibrium processes only.
- For nonquasi-equilibrium processes, we are not able to characterize the entire system by a single state, and thus we cannot speak of a process path for a system as a whole.
- A nonquasi-equilibrium process is denoted by a dashed line between the initial and final states instead of a solid line.

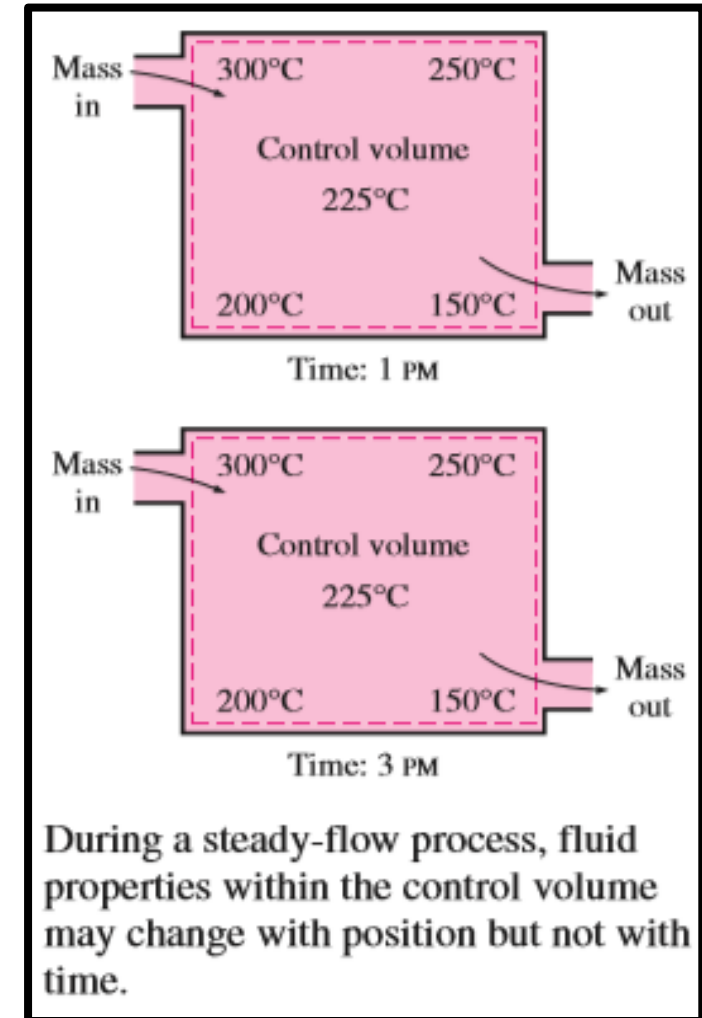


The P - V diagram of a compression process.

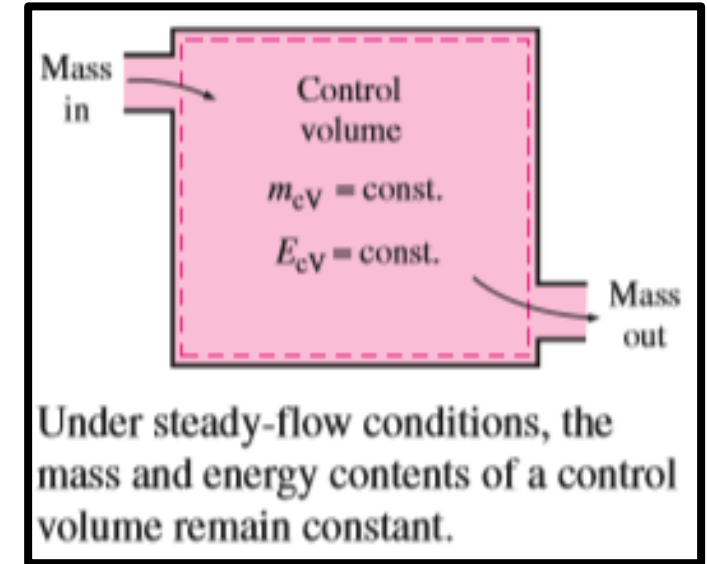
- An isothermal process, for example, is a process during which the temperature T remains constant; an isobaric process is a process during which the pressure P remains constant; and an isochoric (or isometric) process is a process during which the specific volume v remains constant.
- A system is said to have undergone a cycle if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.

The Steady-Flow Process

- The terms steady and uniform are used frequently in engineering, and thus it is important to have a clear understanding of their meanings.
- The term steady implies no change with time. The opposite of steady is unsteady, or transient.
- The term uniform, however, implies no change with location over a specified region.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as steady-flow devices.
- Processes involving such devices can be represented reasonably well by a somewhat idealized process, called the steady-flow process, which can be defined as a process during which a fluid flows through a control volume steadily.



- That is, the fluid properties can change from point to point within the control volume, but at any fixed point they remain the same during the entire process.
- Therefore, the volume V , the mass m , and the total energy content E of the control volume remain constant during a steady flow process.
- 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.
- Some cyclic devices, such as reciprocating engines or compressors, do not satisfy any of the conditions stated above since the flow at the inlets and the exits will be pulsating and not steady.
- However, the fluid properties vary with time in a periodic manner, and the flow through these devices can still be analyzed as a steady-flow process by using time-averaged values for the properties.



Closed System:

- If the boundary of the system is impervious to the flow of matter, it is called a closed system.
- An example of this system is mass of gas or vapour contained in an engine cylinder, the boundary of which is drawn by the cylinder walls, the cylinder head and piston crown. Here the boundary is continuous and no matter may enter or leave.

Open System:

An open system is one in which matter flows into or out of the system.

Most of the engineering systems are open.

Isolated System:

An isolated system is that system which exchanges neither energy nor matter with any other system or with environment.

Adiabatic System:

- An adiabatic system is one which is thermally insulated from its surroundings.
- It can, however, exchange work with its surroundings. If it does not, it becomes an isolated system.

Phase:

A phase is a quantity of matter which is homogeneous throughout in chemical composition and physical structure.

Homogeneous System:

A system which consists of a single phase is termed as homogeneous system.

Examples : Mixture of air and water vapour, water plus nitric acid and octane plus heptane.

Heterogeneous System:

A system which consists of two or more phases is called a heterogeneous system.

Examples : Water plus steam, ice plus water and water plus oil.

Macroscopic and Microscopic Points of View

Thermodynamic studies are undertaken by the following two different approaches.

1. Macroscopic approach—(Macro mean big or total)
2. Microscopic approach—(Micro means small)

Sl. No.	Macroscopic approach	Microscopic approach
1.	<ul style="list-style-type: none">• In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level.• In other words this approach to thermodynamics is concerned with gross or overall behaviour.• This is known as classical thermodynamics.	<ul style="list-style-type: none">• The approach considers that the system is made up of a very large number of discrete particles known as molecules.• These molecules have different velocities and energies.• The values of these energies are constantly changing with time.• This approach to thermodynamics which is concerned directly with the structure of the matter is known as statistical thermodynamics.
2.	In order to describe a system only a few properties are needed.	Large number of variables are needed to describe a system. So the approach is complicated.

Sl. No.	Macroscopic approach	Microscopic approach
3.	The analysis of macroscopic system requires simple mathematical formulae.	<ul style="list-style-type: none"> The behaviour of the system is found by using statistical methods as the number of molecules is very large. So advanced statistical and mathematical methods are needed to explain the changes in the system.
4.	<ul style="list-style-type: none"> The values of the properties of the system are their average values. For example, consider a sample of a gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules. Similarly the temperature of this gas is the average value of translational kinetic energies of millions of individual molecules. These properties like pressure and temperature can be measured very easily. The changes in properties can be felt by our senses. 	<ul style="list-style-type: none"> The properties like velocity, momentum, impulse, kinetic energy, force of impact etc. which describe the molecule cannot be easily measured by instruments. Our senses cannot feel them.

Note. *Although the macroscopic approach seems to be different from microscopic one, there exists a relation between them. Hence when both the methods are applied to a particular system, they give the same result.*

PURE SUBSTANCE

- A pure substance is one that has a homogeneous and invariable chemical composition even though there is a change of phase.
- In other words, it is a system which is (a) homogeneous in composition, (b) homogeneous in chemical aggregation.
- Examples : Liquid, water, mixture of liquid water and steam, mixture of ice and water. The mixture of liquid air and gaseous air is not a pure substance.

THERMODYNAMIC EQUILIBRIUM

- A system is in thermodynamic equilibrium if the temperature and pressure at all points are same ; there should be no velocity gradient ; the chemical equilibrium is also necessary.
 - Systems under temperature and pressure equilibrium but not under chemical equilibrium are sometimes said to be in metastable equilibrium conditions.
 - It is only under thermodynamic equilibrium conditions that the properties of a system can be fixed.
 - Thus for attaining a state of thermodynamic equilibrium the following three types of equilibrium states must be achieved :
1. **Thermal equilibrium:** The temperature of the system does not change with time and has same value at all points of the system.
 2. **Mechanical equilibrium:** There are no unbalanced forces within the system or between the surroundings. The pressure in the system is same at all points and does not change with respect to time.
 3. **Chemical equilibrium:** No chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.

PROPERTIES OF SYSTEMS

A property of a system is a characteristic of the system which depends upon its state, but not upon how the state is reached.

There are two sorts of property :

1. **Intensive properties:** These properties do not depend on the mass of the system. Examples : Temperature and pressure.
2. **Extensive properties:** These properties depend on the mass of the system. Example : Volume.

Extensive properties are often divided by mass associated with them to obtain the intensive properties.

Eg: If the volume of a system of mass m is V , then the specific volume of matter within the system is $\frac{V}{M} = v$ which is an intensive property.

STATE:

- **State** is the condition of the system at an instant of time as described or measured by its properties. Or each unique condition of a system is called a **state**.
- It follows from the definition of state that each property has a single value at each state.
- Stated differently, all properties are state or point functions.
- Therefore, all properties are identical for identical states.
- On the basis of the above discussion, we can determine if a given variable is property or not by applying the following tests :
 - A variable is a property, if and only if, it has a single value at each equilibrium state.
 - A variable is a property, if and only if, the change in its value between any two prescribed equilibrium states is single-valued.
- Therefore, any variable whose change is fixed by the end states is a property.

PROCESS

- A process occurs when the system undergoes a change in a state or an energy transfer at a steady state.
- A process may be non-flow in which a fixed mass within the defined boundary is undergoing a change of state.

Example: A substance which is being heated in a closed cylinder undergoes a non-flow process. Closed systems undergo non-flow processes.

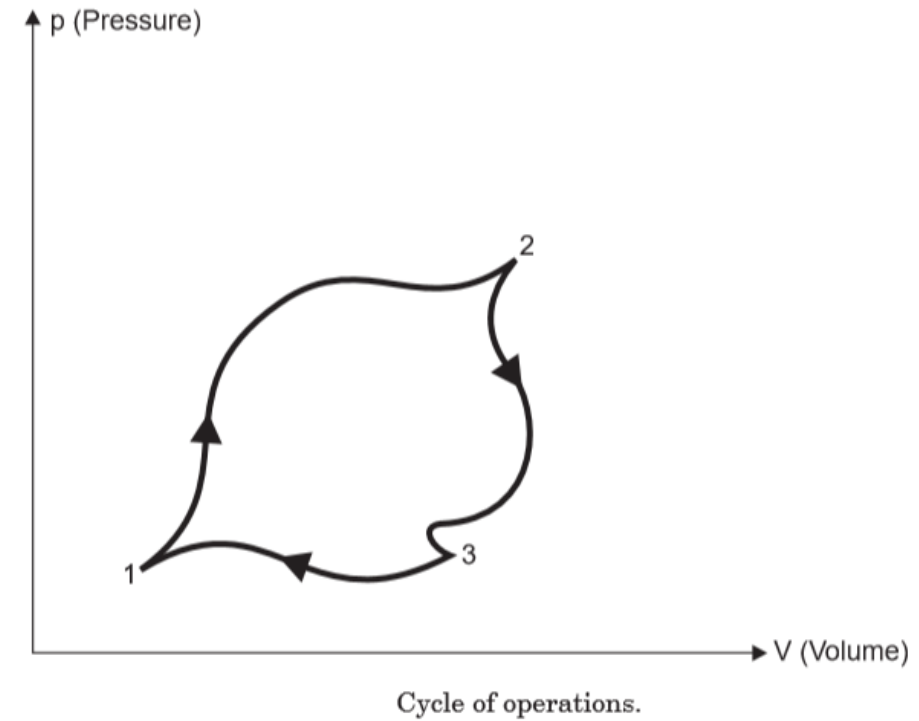
- A process may be a flow process in which mass is entering and leaving through the boundary of an open system.
- In a steady flow process, mass is crossing the boundary from surroundings at entry, and an equal mass is crossing the boundary at the exit so that the total mass of the system remains constant.
- In an open system it is necessary to take account of the work delivered from the surroundings to the system at entry to cause the mass to enter, and also of the work delivered from the system at surroundings to cause the mass to leave, as well as any heat or work crossing the boundary of the system.

Quasi-static process:

Quasi means 'almost'. A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and infinite slowness is its characteristic feature.

CYCLE

- Any process or series of processes whose end states are identical is termed a cycle.
- The processes through which the system has passed can be shown on a state diagram, but a complete section of the path requires in addition a statement of the heat and work crossing the boundary of the system.
- Figure shows such a cycle in which a system commencing at condition '1' changes in pressure and volume through a path 123 and returns to its initial condition '1'.



POINT FUNCTION

When two properties locate a point on the graph (co-ordinate axes) then those properties are called as point function. Examples. Pressure, temperature, volume etc.

$$\int_1^2 dV = V_2 - V_1 \text{ (an exact differential).}$$

PATH FUNCTION

There are certain quantities which cannot be located on a graph by a point but are given by the area or so, on that graph.

In that case, the area on the graph, pertaining to the particular process, is a function of the path of the process. Such quantities are called path functions.

Examples. Heat, work etc.

Heat and work are inexact differentials. Their change cannot be written as difference between their end states.

$$\int_1^2 \delta Q \neq Q_2 - Q_1 \text{ and is shown as } Q_{1-2}$$

Note: The operator δ is used to denote inexact differentials and operator d is used to denote exact differentials.

TEMPERATURE AND THE ZEROth LAW OF THERMODYNAMICS

- The temperature is a thermal state of a body which distinguishes a hot body from a cold body.
- The temperature of a body is proportional to the stored molecular energy i.e., the average molecular kinetic energy of the molecules in a system.

(A particular molecule does not have a temperature, it has energy. The gas as a system has temperature).

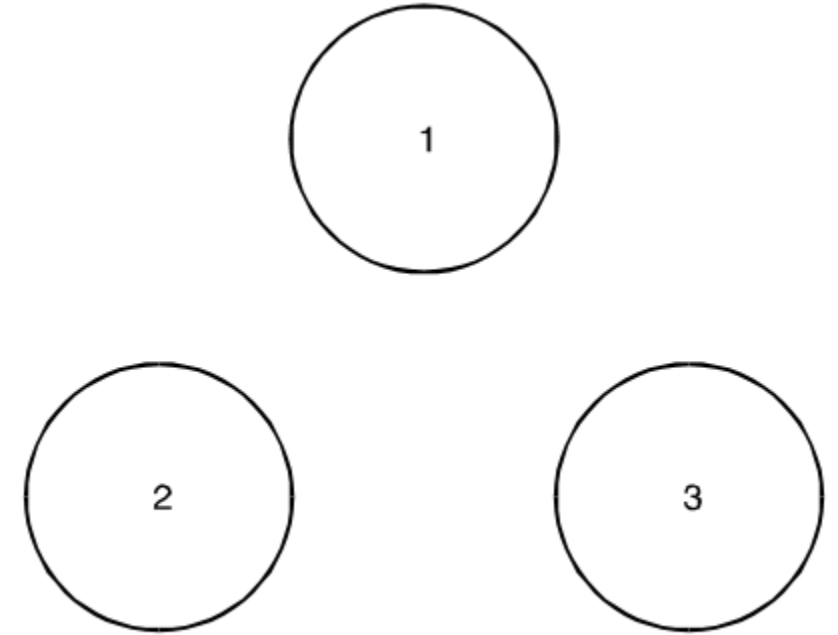
- Instruments for measuring ordinary temperatures are known as thermometers and those for measuring high temperatures are known as pyrometers.
- It has been found that a gas will not occupy any volume at a certain temperature.
- This temperature is known as absolute zero temperature.
- The temperatures measured with absolute zero as basis are called absolute temperatures.
- Absolute temperature is stated in degrees centigrade.
- The point of absolute temperature is found to occur at 273.15°C below the freezing point of water.

ZEROth LAW OF THERMODYNAMICS

‘Zeroth law of thermodynamics’ states that if two systems are each equal in temperature to a third, they are equal in temperature to each other.

Example.

- System ‘1’ may consist of a mass of gas enclosed in a rigid vessel fitted with a pressure gauge.
- If there is no change of pressure when this system is brought into contact with system ‘2’ a block of iron, then the two systems are equal in temperature (assuming that the systems 1 and 2 do not react each other chemically or electrically).
- Experiment reveals that if system ‘1’ is brought into contact with a third system ‘3’ again with no change of properties then systems ‘2’ and ‘3’ will show no change in their properties when brought into contact provided they do not react with each other chemically or electrically. Therefore, ‘2’ and ‘3’ must be in equilibrium.



Zeroth law of thermodynamics.

This law was enunciated by R.H. Fowler in the year 1931. However, since the first and second laws already existed at that time, it was designated as zeroth law so that it precedes the first and second laws to form a logical sequence.

Temperature Scales

- Temperature scales enable us to use a common basis for temperature measurements.
- All temperature scales are based on some easily reproducible states such as the **freezing (ice point)** and **boiling points (steam point)** of water.
- A mixture of ice and water that is in equilibrium with air saturated with vapour at 1 atm pressure is said to be at the **ice point**.
- A mixture of liquid water and water vapour (with no air) in equilibrium at 1 atm pressure is said to be at the **steam point**.
- The temperature scales used in the SI and in the English system today are the **Celsius scale** (formerly called the **centigrade scale**; in 1948 it was renamed after the Swedish astronomer A. Celsius, 1702–1744, who devised it) and the **Fahrenheit scale** (named after the German instrument maker G. Fahrenheit, 1686–1736), respectively.
- On the **Celsius scale**, the **ice and steam points** were originally assigned the values of **0 and 100°C**, respectively.
- On the **Fahrenheit scale**, the **ice and steam points** were originally assigned the values of 32 and 212°F, respectively.

- In **thermodynamics**, it is very desirable to have a temperature scale that is *independent of the properties of any substance or substances*.
- Such a temperature scale is called a thermodynamic temperature scale, which is developed in conjunction with the second law of thermodynamics.
- The **thermodynamic temperature scale** in the SI is the **Kelvin scale (K)**, named after Lord Kelvin (1824–1907).
- The lowest temperature on the Kelvin scale is absolute zero, or 0 K.
- The **thermodynamic temperature scale** in the English system is the **Rankine scale (R)**, named after William Rankine (1820–1872).
- A temperature scale that turns out to be 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**, which is basically a *rigid vessel filled with a gas* (usually hydrogen or helium), at low pressure.
- This thermometer is based on the principle that “**at low pressures, the temperature of a gas is proportional to its pressure at constant volume**”.

- That is, the temperature of a gas of fixed volume varies linearly with pressure at sufficiently low pressures.
- Then the relationship between the temperature and the pressure of the gas in the vessel can be expressed as

$$T = a + bp$$

where the values of the constants a and b for a gas thermometer are determined experimentally.

Once a and b are known, the temperature of a medium can be calculated from this relation by immersing the rigid vessel of the gas thermometer into the medium and measuring the gas pressure when thermal equilibrium is established between the medium and the gas in the vessel whose volume is held constant.

- An ideal-gas temperature scale can be developed by measuring the pressures of the gas in the vessel at two reproducible points (such as the ice and the steam points) and assigning suitable values to temperatures at those two points.
- The values of the constants will be different for each thermometer, depending on the type and the amount of the gas in the vessel, and the temperature values assigned at the two reference points.
- If the ice and steam points are assigned the values 0°C and 100°C , respectively, then the gas temperature scale will be identical to the Celsius scale.
- It should be noted that the absolute gas temperature scale is not a thermodynamic temperature scale, since it cannot be used at very low temperatures (due to condensation) and at very high temperatures (due to dissociation and ionization).

THE THERMOMETER AND THERMOMETRIC PROPERTY

- ✓ The **zeroth law of thermodynamics** provides the basis for the **measurement of temperature**.
- It enables us to compare temperatures of two bodies ‘1’ and ‘2’ with the help of a third body ‘3’ and say that the temperature of ‘1’ is the same as the temperature of ‘2’ without actually bringing ‘1’ and ‘2’ in thermal contact.
- In practice, body ‘3’ in the zeroth law is called the thermometer.
- It is brought into thermal equilibrium with a set of standard temperature of a body ‘2’, and is thus calibrated.
- Later, when any other body ‘1’ is brought in thermal communication with the thermometer, we say that the body ‘1’ has attained equality of temperature with the thermometer, and hence with body ‘2’.
- This way, the body ‘1’ has the temperature of body ‘2’ given for example by, say the height of mercury column in the thermometer ‘3’.

✓ The **height** of mercury column in a thermometer, therefore, becomes a **thermometric property**.

✓ There are other methods of temperature measurement which utilize various other properties of materials, that are functions of temperature, as thermometric properties such as:

Sl No.	Thermometer	Thermometric property
1	Constant volumes gas	Pressure (p)
2	Constant pressure gas	Volume (V)
3	Alcohol or mercury-in-glass	Length (L)
4	Electric resistance	Resistance (R)
5	Thermocouple	Electromotive force
6	Radiation (pyrometer)	Intensity of radiation (I or J)

Measurement of Temperature

Temperature can be depicted as a thermal state which depends upon the internal or molecular energy of the body.

Temperature Measuring Instruments

These instruments may be classified in two broad categories:

1. Non-electrical methods:

- (i) By using change in volume of a liquid when its temperature is changed.
- (ii) By using change in pressure of a gas when its temperature is changed.
- (iii) By using changes in the vapour pressure when the temperature is changed.

2. Electrical method:

- (i) By thermocouples.
- (ii) By change in resistance of material with change in temperature.
- (iii) By comparing the colours of filament and the object whose temperature is to be found out.
- (iv) By ascertaining the energy received by radiation.

The thermometers may also be classified as follows:

1. Expansion thermometers

- (i) Liquid-in-glass thermometers
- (ii) Bimetallic thermometers.

2. Pressure thermometers

- (i) Vapour pressure thermometers
- (ii) Liquid-filled thermometers
- (iii) Gas-filled thermometers.

3. Thermocouple thermometers

4. Resistance thermometers

5. Radiation pyrometers

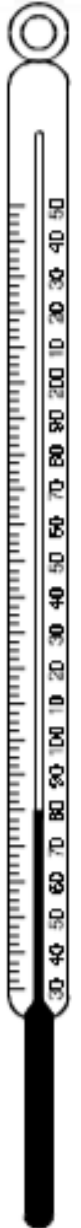
6. Optical pyrometers.

1. Expansion Thermometers:

- ✓ The expansion thermometers make use of the differential expansion of two different substances.
- ✓ Thus in liquid-in-glass thermometers, it is the difference in expansion of liquid and the containing glass.
- ✓ And in bimetallic thermometers, the indication is due to the difference in expansion of the two solids.

Liquid-in-glass thermometer

- ✓ This is a very familiar type of thermometer.
- ✓ The mercury or other liquid fills the glass bulb and extends into the bore of the glass stem.
- ✓ Mercury is the most suitable liquid and is used from -38.9°C (melting point) to about 600°C .
- ✓ The thermometers employed in the laboratory have the scale engraved directly on the glass stem.
- ✓ An expansion bulb is usually provided at the top of the stem to allow room for expansion of mercury, in case the thermometer is subjected to temperature above its range.
- ✓ The upper limit for mercury-in-glass thermometers is about 600°C .
- ✓ As the upper limit is far above the boiling point of mercury, some inert gas i.e., nitrogen is introduced above the mercury to prevent boiling.



Mercury-in-glass
thermometer

- Pentane, ethyl alcohol and toluene are the other liquids which can be used for liquid-in-glass thermometers.
- Since these liquids are normally colourless a dye is added to facilitate reading.
- These liquids have a low freezing point as shown below and are suitable for low temperature thermometers.

Liquid	Boiling point	Freezing point
Pentane	36°C	– 130°C
Ethyl alcohol	78°C	– 100°C
Toluene	110°C	– 92°C

Bimetallic thermometers

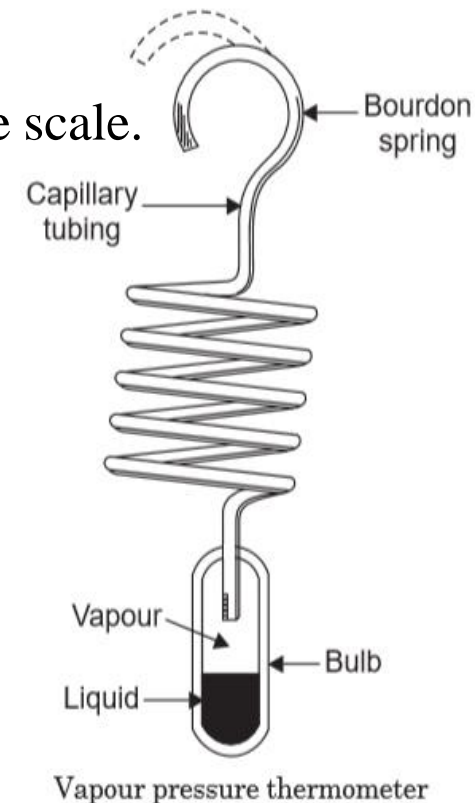
- In a bimetallic thermometer differential expansion of bimetallic strips is used to indicate the temperature.
- It has the advantage over the liquid-in-glass thermometer, that it is *less fragile* and is *easier to read*.
- In this type of thermometer two flat strips of different metals are placed side by side and are welded together.
- Many different metals can be used for this purpose. Generally one is a *low expanding metal* and the other is *high expanding metal*.
- The bimetal strip is coiled in the form of a spiral or helix.
- *Due to rise in temperature, the curvature of the strip changes.*
- *The differential expansion of a strip causes the pointer to move on the dial of the thermometer.*

2. Pressure Thermometers:

- In pressure thermometers liquids, gases and vapours can all be used.
- The fluid is confined in a closed system.
- In this case the *pressure is a function of the temperature*, so that when the fluid is heated, the pressure will rise and the temperature can be indicated by Bourdon type pressure gauge.
- In general, the thermometer consists of a bulb which contains bulk of the fluid.
- The bulb is placed in the region whose temperature is required.
- A capillary tube connects the bulb to a Bourdon tube, which is graduated with a temperature scale.

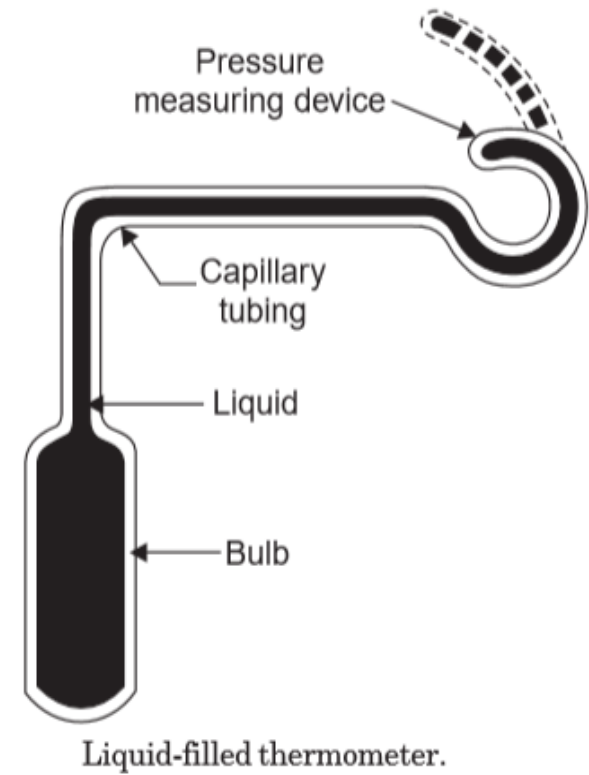
(i) Vapour pressure thermometer

- ✓ When the bulb containing the fluid is installed in the region whose temperature is required, some of the fluid vapourizes, and increases the vapour pressure.
- ✓ This change of pressure is indicated on the Bourdon tube.
- ✓ The relation between temperature and vapour pressure of a volatile liquid is of the *exponential form*.
- ✓ Therefore, the scale of a vapour pressure thermometer will not be linear.



(ii) Liquid-filled thermometer

- In this case, the *expansion of the liquid causes the pointer to move in the dial.*
- Therefore liquids having high co-efficient of expansion should be used.
- In practice many liquids e.g., mercury, alcohol, toluene and glycerine have been successfully used.
- The operating pressure varies from about 3 to 100 bar.
- These type of thermometers could be used for a temperature upto 650°C in which mercury could be used as the liquid.
- In actual design, the internal diameter of the capillary tube and Bourdon tube is, made much smaller than that of the bulb.
- This is because the capillary tube is subjected to a temperature which is quite different from that of the bulb.
- Therefore, to minimise the effect of variation in temperature to which the capillary tube is subjected, the *volume of the bulb is made as large as possible as compared with the volume of the capillary.*
- However, large volume of bulb tends to increase time lag, therefore, a *compensating device is usually built into the recording or indicating mechanism, which compensates the variations in temperature of the capillary and Bourdon tubes.*

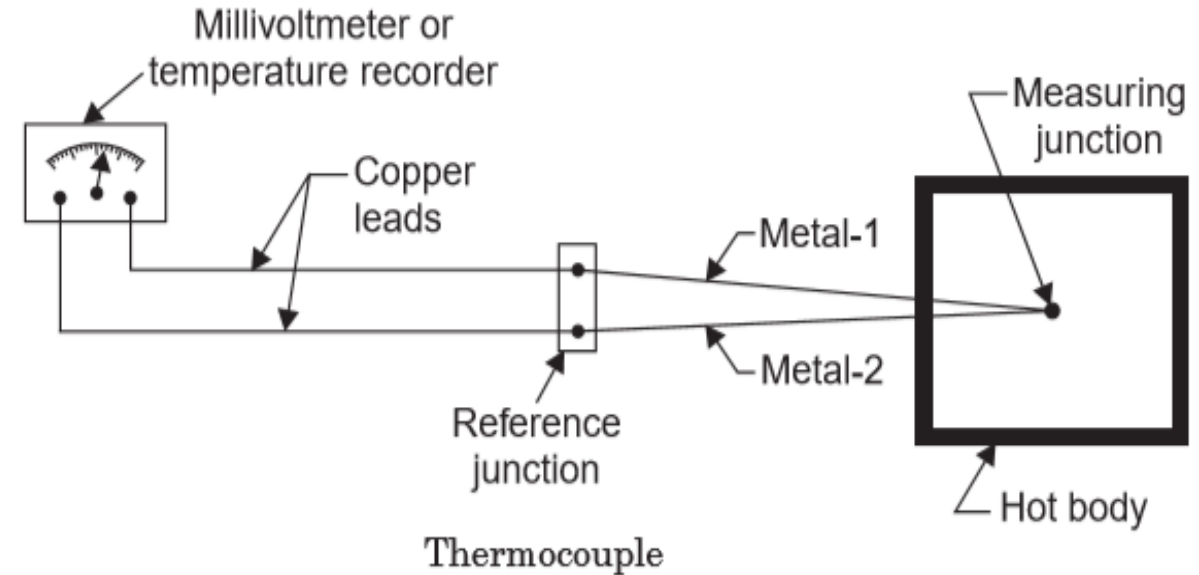


(iii) Gas-filled thermometers

- The temperature range for gas thermometer is practically the same as that of liquid filled thermometer.
- The gases used in the gas thermometers are nitrogen and helium.
- Both these gases are chemically inert, have good values for their co-efficient of expansion and have low specific heats.
- The construction of this type of thermometer is more or less the same as mercury-thermometer in which Bourdon spring is used.
- The errors are also compensated likewise. The only difference in this case is that bulb is made much larger than used in liquid-filled thermometers.
- For good performance the volume of the bulb should be made at least 8 times than that of the rest of the system. These thermometers are generally used for pressures below 35 bar.

3. Thermocouple Thermometers:

- For higher range of temperature i.e., above 650°C , filled thermometers are unsuitable. For higher range of temperature, thermocouples and pyrometers are used.
- In its simplest form a thermocouple consists of two dissimilar metals or alloys which develop e.m.f. when the reference and measuring junctions are at different temperatures.
- The reference junction or cold junction is usually maintained at some constant temperature, such as 0°C .
- In many industrial installations the instruments are equipped with automatic compensating devices for temperature changes of the reference junction, thus eliminating the necessity of maintaining this junction at constant temperature.



4. Resistance thermometers:

- The fact that the electrical resistance of the metals increases with temperature is made use of in resistance thermometers which are purely electrical in nature.
- A resistance thermometer is used for precision measurements below 150°C.
- A simple resistance thermometer consists of a resistance element or bulb, electrical leads and a resistance measuring or recording instrument.
- The resistance element (temperature sensitive element) is usually supplied by the manufacturers with its protecting tube and is ready for electrical connections.
- The resistance of the metal used as resistance element should be reproducible at any given temperature.
- The resistance is reproducible if the composition or physical properties of the metal do not change with temperature.
- For this purpose platinum is preferred.
- A platinum resistance thermometer can measure temperatures to within $\pm 0.01^\circ\text{C}$. However, because of high cost of platinum, nickel and copper are used as resistance elements for industrial purposes for low temperatures.
- The fine resistance wire is wound in a spiral form on a mica frame.
- The delicate coil is then enclosed in a porcelain or quartz tube.
- The change of resistance of this unit can be measured by instruments such as Wheatstone bridge, potentiometer or galvanometer.

Advantages:

The resistance thermometers possess the following advantages over other devices:

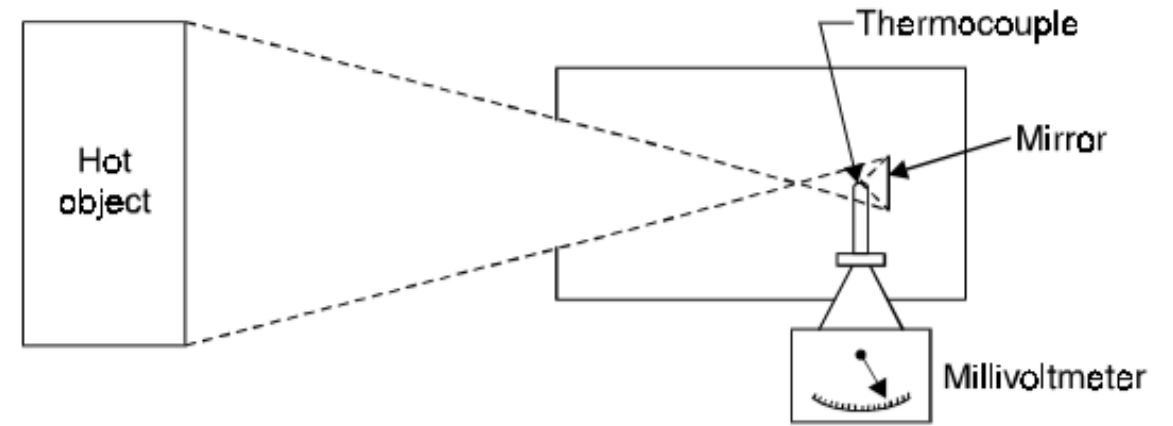
1. A resistance thermometer is very accurate for low ranges below 150°C .
2. It requires no reference junction like thermocouples and as such is more effective at room temperature.
3. The distance between the resistance element and the recording element can be made much larger than is possible with pressure thermometers.
4. It resists corrosion and is physically stable.

Disadvantages:

1. The resistance thermometers cost more.
2. They suffer from time lag.

5. Radiation pyrometers:

- A device which measures the total intensity of radiation emitted from a body is called radiation pyrometer.
- It collects the radiation from an object (hot body) whose temperature is required.
- A mirror is used to focus this radiation on a thermocouple.



A schematic diagram of radiation pyrometer

- This energy which is concentrated on the thermocouple raises its temperature, and in turn generates an e.m.f. This e.m.f. is then measured either by the galvanometer or potentiometer method.
- Thus rise of temperature is a function of the amount of radiation emitted from the object.

Advantages of the pyrometers

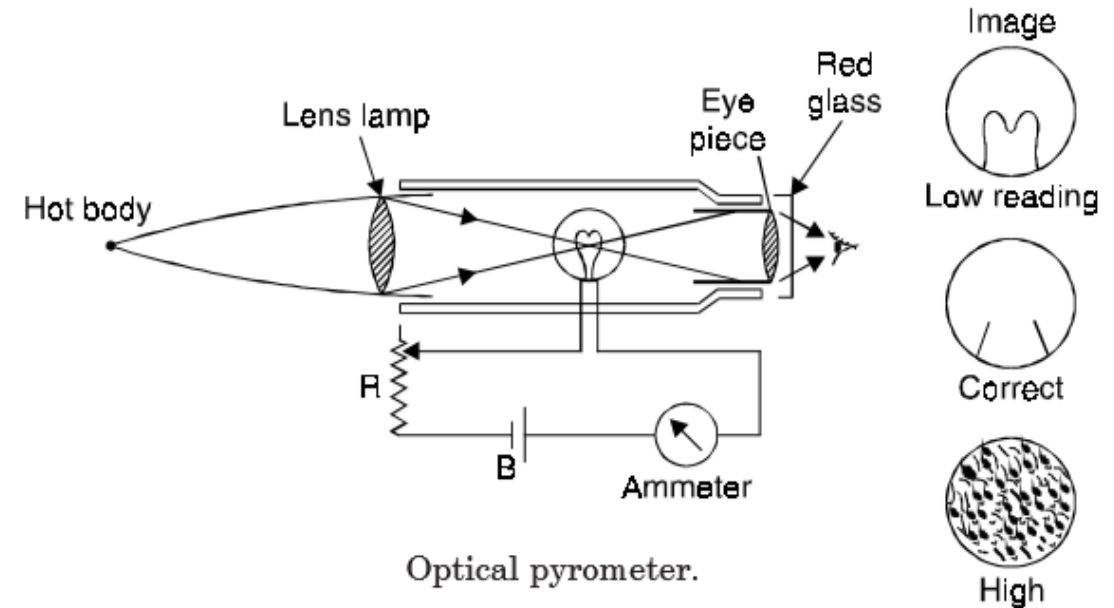
1. The temperatures of moving objects can be measured.
2. A higher temperature measurement is possible than that possible by thermocouples etc.
3. The average temperatures of the extended surface can be measured.
4. The temperature of the objects which are not easily accessible can be measured.

6. Optical pyrometer:

- ✓ An optical pyrometer works on the principle *that matters glow above 480°C and the colour of visible radiation is proportional to the temperature of the glowing matter.*
- ✓ The amount of light radiated from the glowing matter (solid or liquid) is measured and employed to determine the temperature.

Operation :

- The optical pyrometer is sighted at the hot body and focused.
- In the beginning filament will appear dark as compared to the background which is bright (being hot).
- By varying the resistance (R) in the filament circuit more and more current is fed into it, till filament becomes equally bright as the background and hence disappears.
- The current flowing in the filament at this stage is measured with the help of an ammeter which is calibrated directly in terms of temperature.
- If the filament current is further increased, the filament appears brighter as compared to the background which then looks dark.
- An optical pyrometer can measure temperatures ranging from 700 to 4000°C .



Method in use before 1954:

- Celsius and Fahrenheit scales are the two commonly used scales for the measurement of temperature. Symbols C and F are respectively used to denote the readings on these two scales.
- Until 1954 the temperature scales were based on two fixed points : (i) the steam point (boiling point of water at standard atmospheric pressure), and (ii) the ice point (freezing point of water).
- The fixed points for these temperature scales are :

Temperature	Celsius scale	Fahrenheit scale
Steam point	100	212
Ice point	0	32
Interval	100	180

- The relation between a particular value C on celsius scale and F on Fahrenheit scale is found to be as mentioned below :

$$\frac{C}{100} = \frac{F - 32}{180} \text{ or } \frac{C}{5} = \frac{F - 32}{9}$$

Method in use after 1954:

- It was suggested by Kelvin that a single fixed point only was necessary to establish a temperature.
- He pointed out that triple point of water (the state at which ice, liquid water and water vapour coexist in equilibrium) could be used as the single point.
- In 1954, adopted this fixed point, and value was set at 0.01°C or 273.16 K in the Kelvin scale thus established.
- Correspondingly, the ice point of 0°C on the Celsius scale becomes equal to 273.15 K on the Kelvin scale.
- Celsius and Kelvin scales are distinguished by using distinct symbols t and T, the relation between these two is then given by :

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

- A gas thermometer would read zero kelvin at absolute zero pressure, which corresponds to -273.15°C on the Celsius scale.
- The Kelvin scale is related to the Celsius scale by

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

- The Rankine scale is related to the Fahrenheit scale by

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

- The temperature scales in the two unit systems are related by

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

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

- The reference temperature chosen in the original Kelvin scale was 273.15 K (or 0°C), which is the temperature at which water freezes (or ice melts) and water exists as a solid–liquid mixture in equilibrium under standard atmospheric pressure (the ice point).
- The boiling temperature of water (the steam point) was experimentally determined to be again 100.00°C .

Q. Expressing Temperature Rise in Different Units During a heating process, the temperature of a system rises by 10°C . Express this rise in temperature in K, $^{\circ}\text{F}$, and R.

Solution This problem deals with temperature changes, which are identical in Kelvin and Celsius scales. Then,

$$\Delta T(\text{K}) = \Delta T(^{\circ}\text{C}) = \mathbf{10\text{ K}}$$

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

$$\Delta T(\text{R}) = 1.8 \Delta T(\text{K}) = (1.8)(10) = \mathbf{18\text{ R}}$$

and

$$\Delta T(^{\circ}\text{F}) = \Delta T(\text{R}) = \mathbf{18^{\circ}\text{F}}$$

Ideal Gas

From experimental observations it has been established that an ideal gas (to a good approximation) behaves according to the simple equation

$$pV = mRT$$

where p , V and T are the pressure, volume and temperature of gas having mass m and R is a constant for the gas known as its **gas constant**.

$$pv = RT$$

(where $v = V/m$)

In reality there is no gas which can be qualified as an ideal or perfect gas. However *all gases tend to ideal or perfect gas behaviour at all temperatures as their pressure approaches **zero pressure***.

For two states of the gas,

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \times \frac{V_2}{V_1}$$

With the help of this eqn., the temperatures can be measured or compared.

PRESSURE

- Pressure is defined as a normal force exerted by a fluid per unit area.
- The counterpart of pressure in solids is normal stress.
- 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,
- Another units, its multiples kilopascal ($1 \text{ kPa} = 10^3 \text{ Pa}$) and megapascal ($1 \text{ MPa} = 10^6 \text{ Pa}$).
- Three other pressure units commonly used in practice i.e. bar, standard atmosphere, and kilogram-force per square centimeter

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

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

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

$$= 0.9807 \text{ bar}$$

$$= 0.9679 \text{ atm}$$

- In the English system, the pressure unit is pound-force per square inch (lbf/in², or psi).

$$1 \text{ atm} = 14.696 \text{ psi}$$

- The pressure units kgf/cm² and lbf/in² are also denoted by kg/cm² and lb/in², respectively, and they are commonly used in tire gages.

$$1 \text{ kgf/cm}^2 = 14.223 \text{ psi}$$

- Pressure is also used for solids as *synonymous* to *normal stress*, which is force acting perpendicular to the surface per unit area.

For example, a 150 pound person with a total foot imprint area of 50 in² exerts a pressure of $150 \text{ lbf}/50 \text{ in}^2 = 3.0 \text{ psi}$ on the floor.

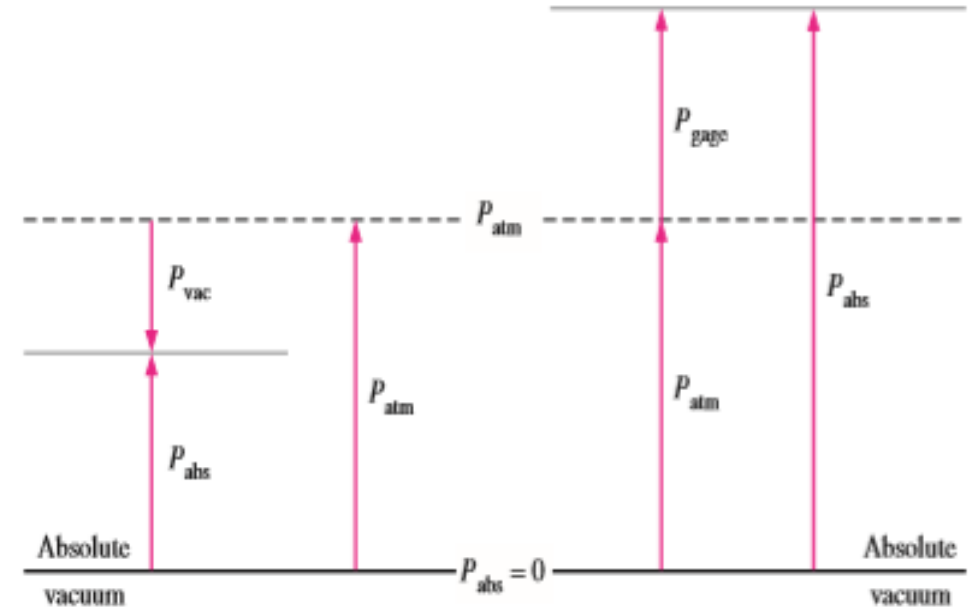
- ✓ The actual pressure at a given position is called the absolute pressure, and it is measured relative to absolute vacuum (i.e., absolute zero pressure).
- ✓ Most pressure-measuring devices, however, are calibrated to read zero in the atmosphere, and so they indicate the difference between the absolute pressure and the local atmospheric pressure. This difference is called the gage pressure.

- ✓ Pressures below atmospheric pressure are called vacuum pressures and are measured by vacuum gages that indicate the difference between the atmospheric pressure and the absolute pressure.
- ✓ Absolute, gage, and vacuum pressures are all positive quantities and are related to each other by

$$P_{\text{gauge}} = P_{\text{abs}} - P_{\text{atm}}$$

$$P_{\text{vacuum}} = P_{\text{atm}} - P_{\text{abs}}$$

- ✓ Pressure is the compressive force per unit area, and it gives the impression of being a vector. However, pressure at any point in a fluid is the same in all directions.
- ✓ That is, it has magnitude but not a specific direction, and thus it is a scalar quantity.
- ✓ Vacuum is defined as the absence of pressure. A perfect vacuum is obtained when absolute pressure is zero, at this instant molecular momentum is zero.



Absolute, gage, and vacuum pressures.

Q. 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 gage pressure of a vacuum chamber is given. The absolute pressure in the chamber is to be determined.

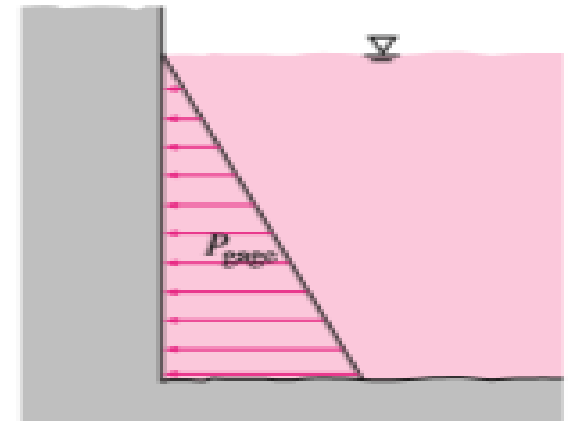
Analysis The absolute pressure is easily determined from Eq. to be

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

Discussion Note that the local value of the atmospheric pressure is used when determining the absolute pressure.

Variation of Pressure with Depth

- Pressure in a fluid at rest does not change in the horizontal direction.
- This can be shown easily by considering a thin horizontal layer of fluid and doing a force balance in any horizontal direction.
- However, this is not the case in the vertical direction in a gravity field.
- Pressure in a fluid increases with depth because more fluid rests on deeper layers, and the effect of this “extra weight” on a deeper layer is balanced by an increase in pressure.



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

To obtain a relation for the variation of pressure with depth, consider a rectangular fluid element of height Δz , length Δx , and unit depth in equilibrium, as shown in given Figure.

Assuming the density of the fluid ρ to be constant, a force balance in the vertical z -direction gives

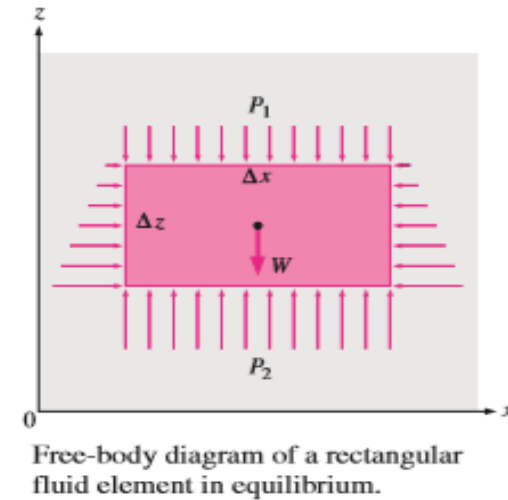
$$\sum F_z = ma_z = 0: \quad P_2 \Delta x - P_1 \Delta x - \rho g \Delta x \Delta z = 0$$

where $W = mg = \rho g \Delta x \Delta z$ is the weight of the fluid element. Dividing by Δx and rearranging gives

$$\Delta P = P_2 - P_1 = \rho g \Delta z = \gamma_s \Delta z$$

where $\gamma_s = \rho g$ is the *specific weight* of the fluid.

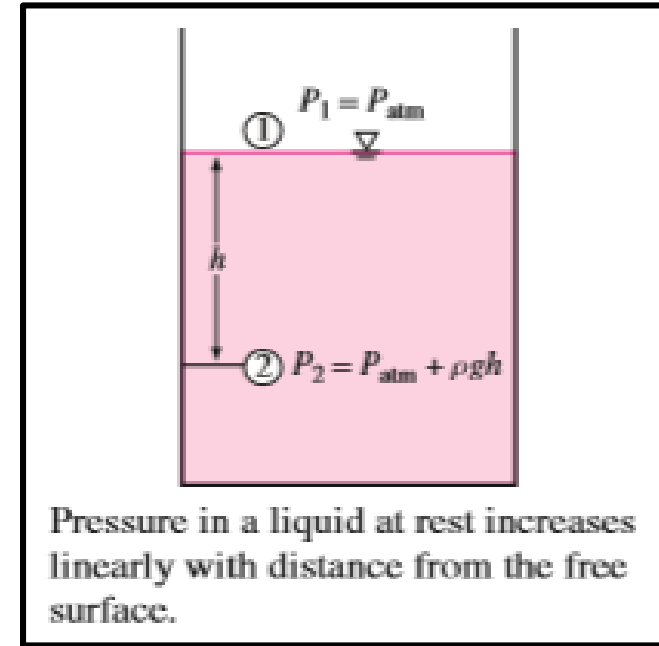
- ✓ Thus, we conclude that the pressure difference between two points in a constant density fluid is proportional to the vertical distance Δz between the points and the density ρ of the fluid.
- ✓ In other words, pressure in a fluid increases linearly with depth.
- ✓ This is what a diver experiences when diving deeper in a lake.
- ✓ For a given fluid, the vertical distance Δz is sometimes used as a measure of pressure, and it is called the pressure head.



We also conclude that for small to moderate distances, the variation of pressure with height is negligible for gases because of their low density.

If we take point 1 to be at the free surface of a liquid open to the atmosphere, where the pressure is the atmospheric pressure P_{atm} , then the pressure at a depth h from the free surface becomes

$$P = P_{\text{atm}} + \rho gh \quad \text{or} \quad P_{\text{gage}} = \rho gh$$



- Liquids are essentially incompressible substances, and thus the variation of density with depth is negligible. This is also the case for gases when the elevation change is not very large.
- The variation of density of liquids or gases with temperature can be significant, however, and may need to be considered when high accuracy is desired.

When the variation of density with elevation is known, the pressure difference between points 1 and 2 can be determined by integration to be

$$\Delta P = P_2 - P_1 = - \int_1^2 \rho g \, dz$$

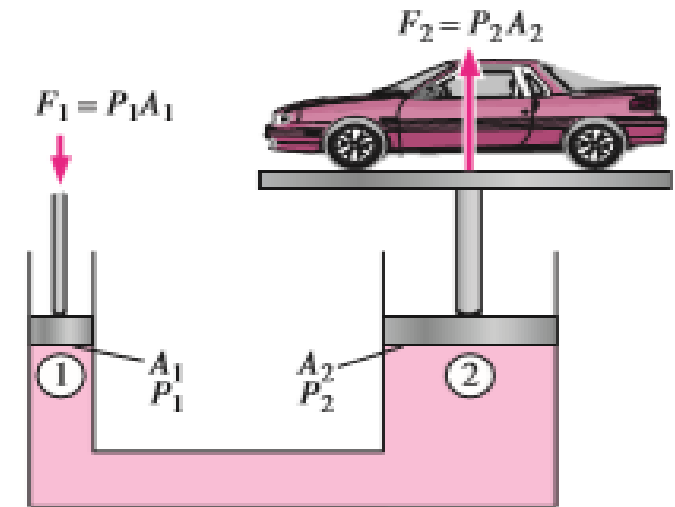
Pascal's Law

- Pressure in a fluid at rest is independent of the shape or cross section of the container.
- It changes with the vertical distance, but remains constant in other directions.
- Therefore, the pressure is the same at all points on a horizontal plane in a given fluid.
- Pascal also knew that the force applied by a fluid is proportional to the surface area.
- He realized that two hydraulic cylinders of different areas could be connected, and the larger could be used to exert a proportionally greater force than that applied to the smaller.
- “Pascal’s machine” has been the source of many inventions that are a part of our daily lives such as hydraulic brakes and lifts.

This is what enables us to lift a car easily by one arm, as shown in Fig. Nothing that $P_1 = P_2$ since both pistons are at the same level (the effect of small height differences is negligible, especially at high pressures), the ratio of output force to input force is determined to be

$$P_1 = P_2 \rightarrow \frac{F_1}{A_1} = \frac{F_2}{A_2} \rightarrow \frac{F_2}{F_1} = \frac{A_2}{A_1}$$

The area ratio A_2/A_1 is called the ideal mechanical advantage of the hydraulic lift.



Lifting of a large weight by a small force by the application of Pascal's law.

Types of Pressure Measurement Devices

- ✓ The pressure may be measured by means of indicating gauges or recorders.
- ✓ These instruments may be mechanical, electro-mechanical, electrical or electronic in operation.

1. Mechanical instruments.

These instruments may be classified into following two groups :

- The first group includes those instruments in which the pressure measurement is made by balancing an unknown force with a known force.
- The second group includes those employing quantitative deformation of an elastic member for pressure measurement.

2. Electro-mechanical instruments.

These instruments usually employ a mechanical means for detecting the pressure and electrical means for indicating or recording the detected pressure.

3. Electronic instruments.

Electronic pressure measuring instruments normally depend on some physical change that can be detected and indicated or recorded electronically.

Mechanical-type Instruments

The mechanical-type instruments are classified as follows :

1. Manometer gauges

- (i) U-tube manometer
- (ii) Cistern manometer
- (iii) Micro-manometer etc.

2. Pressure gauges

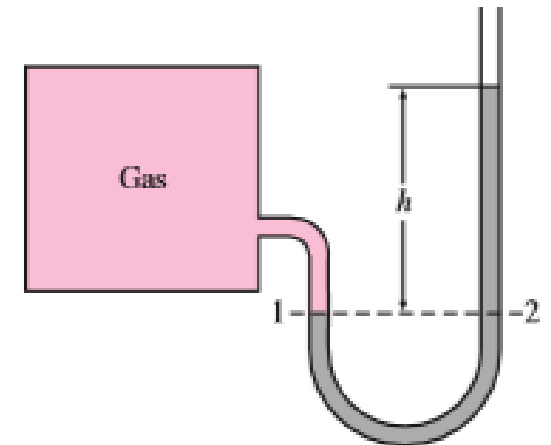
- (i) Bourdon tube pressure gauge
- (ii) Diaphragm gauge
- (iii) Vacuum gauge.

Liquid manometers

- Low pressures are generally determined by *manometers* which employ liquid columns.
- It is difficult and costly to construct manometers to measure high pressures, as otherwise the liquid column will become unwieldy and temperature corrections will also be difficult.
- Their use is, therefore, restricted to low pressures only, and for such purposes they are quite accurate.
- The liquids commonly employed for manometers are mercury and water.
- Mercury is used for high and water for low pressures.
- For this purpose a liquid is suitable if it has a low viscosity, so that it can adjust itself quickly, and also a low co-efficient of thermal expansion, so that density changes with temperature are minimum.

The U-tube manometer

- An elevation change of Δz in a fluid at rest corresponds to $\Delta P/\rho g$, which suggests that a fluid column can be used to measure pressure differences.
- A device based on this principle is called a manometer, and it is commonly used to measure small and moderate pressure differences.
- A manometer mainly consists of a glass or plastic U-tube containing one or more fluids such as mercury, water, alcohol, or oil.
- To keep the size of the manometer to a manageable level, heavy fluids such as mercury are used if large pressure differences are anticipated.
- Consider the manometer shown in Fig. that is used to measure the pressure in the tank.
- Since the gravitational effects of gases are negligible, the pressure anywhere in the tank and at position 1 has the same value.
- Furthermore, since pressure in a fluid does not vary in the horizontal direction within a fluid, the pressure at point 2 is the same as the pressure at point 1, $P_2 = P_1$.



The basic manometer.

- The differential fluid column of height h is in static equilibrium, and it is open to the atmosphere.
- Then the pressure at point 2 is determined directly from the Eq. given by: $P_2 = P_{\text{atm}} + \rho gh$
where ρ is the density of the fluid in the tube.

Eg. 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. If the local atmospheric pressure is 96 kPa, determine the absolute pressure within the tank.

Solution The reading of a manometer attached to a tank and the atmospheric pressure are given. The absolute pressure in the tank is to be determined.

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 :

$$\rho = \text{SG} (\rho_{\text{H}_2\text{O}}) = (0.85)(1000 \text{ kg/m}^3) = 850 \text{ kg/m}^3$$

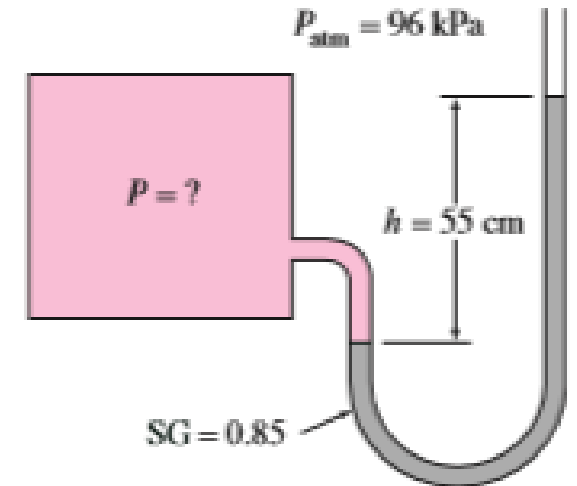
Then from Eq. 1–23,

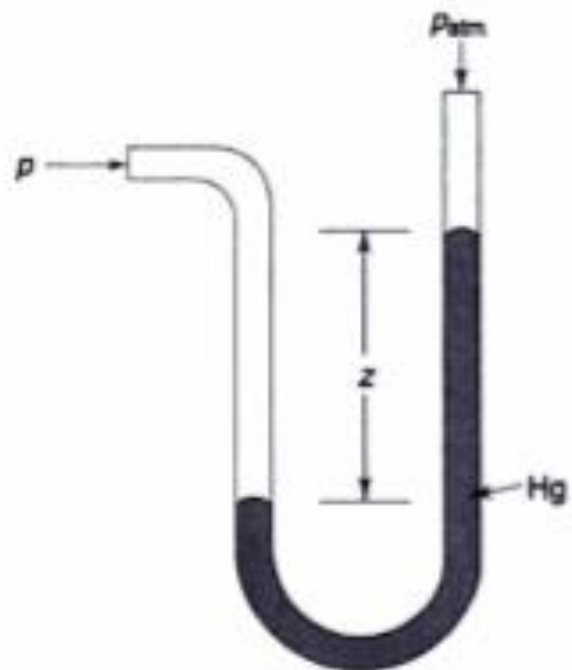
$$P = P_{\text{atm}} + \rho gh$$

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

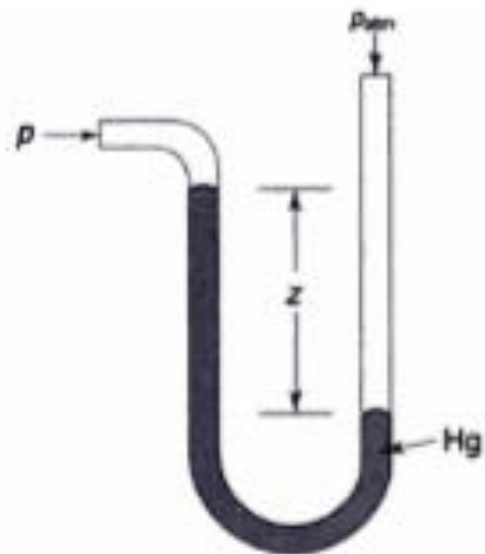
$$= \mathbf{100.6 \text{ kPa}}$$

Discussion Note that the gage pressure in the tank is 4.6 kPa.

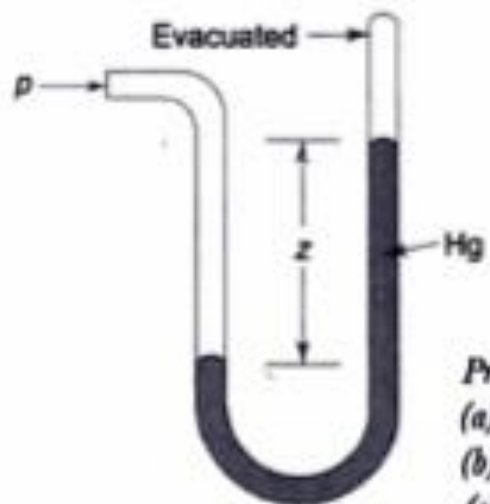




(a)



(b)



(c)

Pressure gauges

(a) Open U-tube indicating gauge pressure

(b) Open U-tube indicating vacuum

(c) Closed U-tube indicating absolute pressure

Many engineering problems and some manometers involve multiple immiscible fluids of different densities stacked on top of each other.

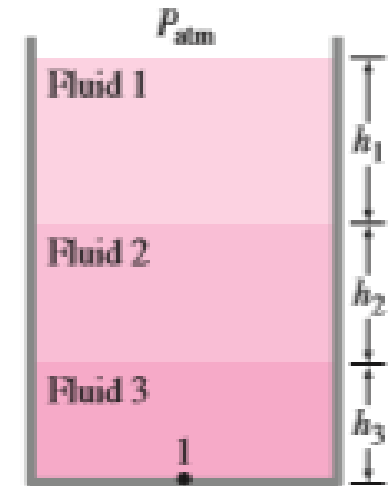
Such systems can be analyzed easily by remembering that

- (1) the pressure change across a fluid column of height h is $\Delta P = \rho gh$,
- (2) pressure increases downward in a given fluid and decreases upward (i.e., $P_{\text{bottom}} > P_{\text{top}}$), and
- (3) two points at the same elevation in a continuous fluid at rest are at the same pressure.

Then the pressure at any point can be determined by starting with a point of known pressure and adding or subtracting ρgh terms as we advance toward the point of interest.

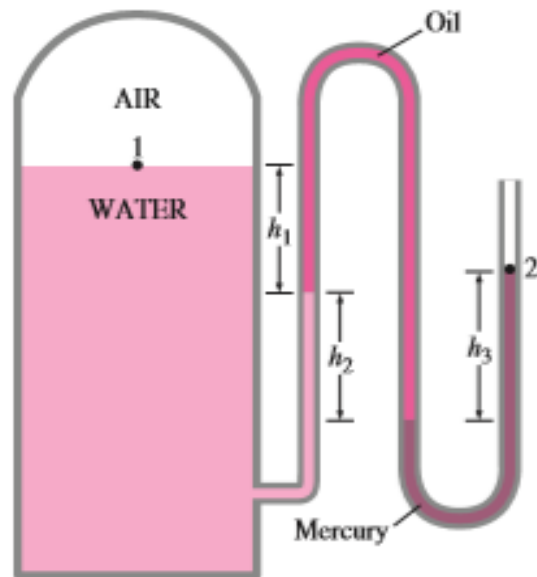
For example, the pressure at the bottom of the tank in Fig. can be determined by starting at the free surface where the pressure is P_{atm} , moving downward until we reach point 1 at the bottom, and setting the result equal to P_1 .

It gives: $P_{\text{atm}} + \rho_1 gh_1 + \rho_2 gh_2 + \rho_3 gh_3 = P_1$



In stacked-up fluid layers, the pressure change across a fluid layer of density ρ and height h is ρgh .

Ex. The water in a tank is pressurized by air, and the pressure is measured by a multifluid manometer as shown in Figure. The tank is located on a mountain at an altitude of 1400 m where the atmospheric pressure is 85.6 kPa. Determine the air pressure in the tank if $h_1 = 0.1$ m, $h_2 = 0.2$ m, and $h_3 = 0.35$ m. Take the densities of water, oil, and mercury to be 1000 kg/m^3 , 850 kg/m^3 , and $13,600 \text{ kg/m}^3$, respectively.



Solution The pressure in a pressurized water tank is measured by a multi-fluid manometer. The air pressure in the tank is to be determined.

Assumption The air pressure in the tank is uniform (i.e., its variation with elevation is negligible due to its low density), and thus we can determine the pressure at the air–water interface.

Properties The densities of water, oil, and mercury are given to be 1000 kg/m^3 , 850 kg/m^3 , and $13,600 \text{ kg/m}^3$, respectively.

Analysis Starting with the pressure at point 1 at the air–water interface, moving along the tube by adding or subtracting the ρgh terms until we reach point 2, and setting the result equal to P_{atm} since the tube is open to the atmosphere gives

$$P_1 + \rho_{\text{water}}gh_1 + \rho_{\text{oil}}gh_2 - \rho_{\text{mercury}}gh_3 = P_{\text{atm}}$$

Solving for P_1 and substituting,

$$\begin{aligned} P_1 &= P_{\text{atm}} - \rho_{\text{water}}gh_1 - \rho_{\text{oil}}gh_2 + \rho_{\text{mercury}}gh_3 \\ &= P_{\text{atm}} + g(\rho_{\text{mercury}}h_3 - \rho_{\text{water}}h_1 - \rho_{\text{oil}}h_2) \\ &= 85.6 \text{ kPa} + (9.81 \text{ m/s}^2)[(13,600 \text{ kg/m}^3)(0.35 \text{ m}) - 1000 \text{ kg/m}^3(0.1 \text{ m}) \\ &\quad - (850 \text{ kg/m}^3)(0.2 \text{ m})]\left(\frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1000 \text{ N/m}^2}\right) \\ &= \mathbf{130 \text{ kPa}} \end{aligned}$$

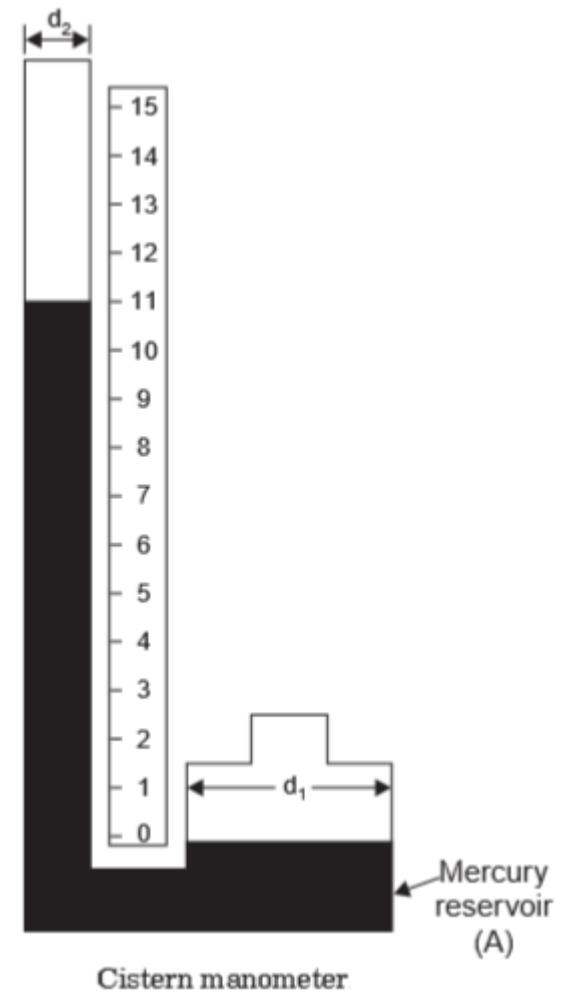
However, readings have to be taken at two different places. Moreover, the deflection of the two columns may not be the same. To avoid this difficulty *cistern or well type* manometer is used.

2. Cistern manometer :

- The mercury reservoir A is made large enough so that change of level in the reservoir is negligible.
- This form of manometer is generally used for measuring pressures above atmospheric.
- In this case, only one reading of the level in the column is required. However, a zero setting is necessary.

3. Micro-manometer :

- The U-tube manometer is not very suitable for measuring very low pressures. Therefore, for such purposes, precision types are required.
- They are called multiplying or micro-manometers, because they multiply the movement of the level of the liquid.
- By far the most widely used type of multiplying manometer is the inclined manometer.
- If the tube is inclined, the sensitiveness of the U-tube manometer is increased.
- The inclined tube causes a larger displacement of the liquid along the tube for a given pressure difference.



The principle of the inclined manometer

- ✓ If pressure $p_1 = p_2$, then the level of liquid is shown by LM.
- ✓ However, when p_1 is slightly greater than p_2 , the level in the reservoir sinks by h_2 , whilst level in the tube rises by a greater distance h_1 as shown in the diagram.
- ✓ If h is the vertical distance between the two surfaces due to difference of pressure, then

$$h = h_1 + h_2$$

also

$$h_1 = d \sin \theta$$

and

$$h_2 \times A = d \times a$$

or

$$h_2 = d \times \frac{a}{A}$$

where A = Area of cross-section of the reservoir, and

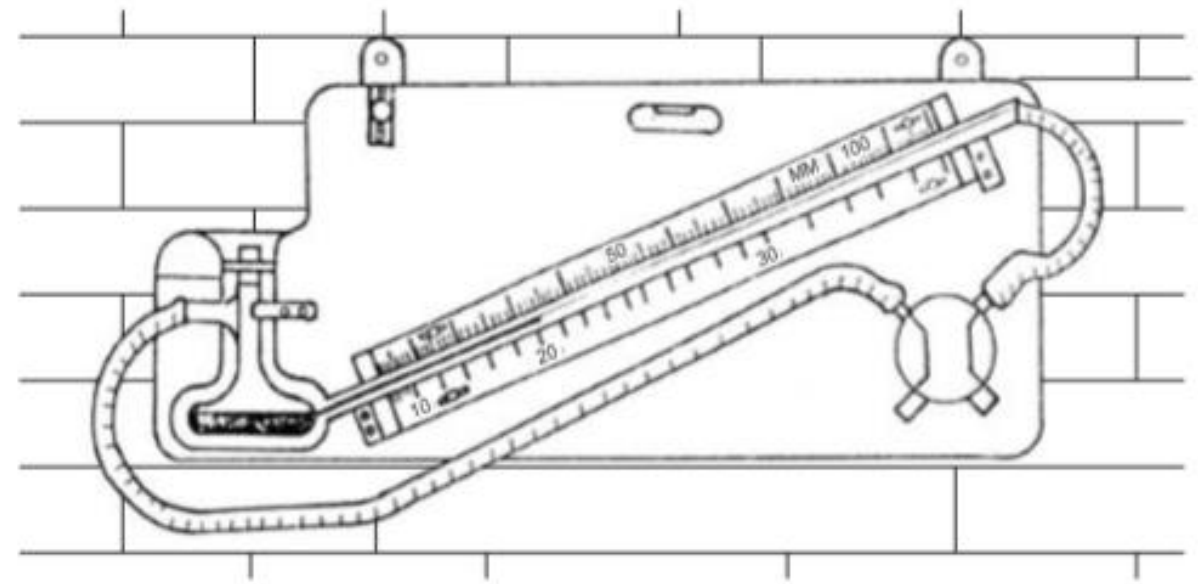
a = Area of cross-section of the inclined tube.

Also the pressure difference Δp i.e., $(p_1 - p_2)$

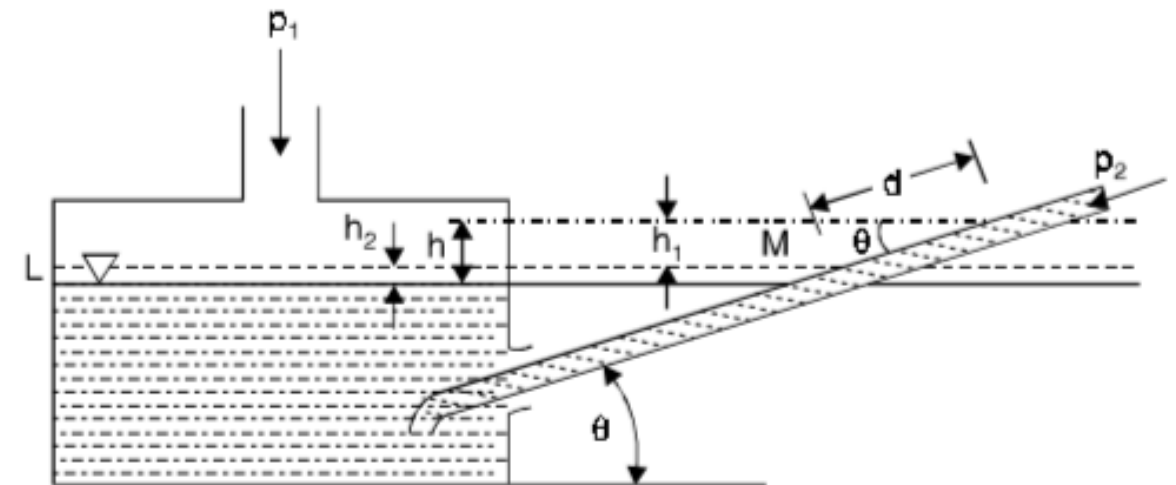
$$= hw = \left(d \times \sin \theta + d \times \frac{a}{A} \right) w$$

$$= dw \left(\sin \theta + \frac{a}{A} \right)$$

where w is the specific weight of the liquid.



Inclined manometer



Principle of inclined manometer

The sensitiveness of the instrument can be varied by changing the slope of the inclined tube.

The position of the inclined tube is so arranged that $\left(\sin\theta + \frac{a}{A}\right)$ is round figure.

The multiplication factor of the gauge is:
$$\frac{d}{h} = \frac{1}{\sin\theta + \frac{a}{A}}$$

Thus the multiplication factor depends on θ and $\frac{a}{A}$. The smaller the values of θ and $\frac{a}{A}$, the greater the multiplication factor.

Advantages of manometers:

1. Relatively inexpensive.
2. Easy to fabricate.
3. Requires very little maintenance.
4. Good accuracy and sensitivity.
5. Their sensitivity can be changed by changing manometric fluids.
6. Particularly suitable to low pressures and low differential pressures.

Disadvantages of manometers:

1. Unsuitable for recording.
2. Generally large, bulky and fragile.
3. Their calibration is affected by changes in gravitational force and density of fluids and their calibration changes with altitude and temperature.
4. Surface tension of manometric fluid creates a capillary effect and possible hysteresis.
5. A particular manometer can be used only for measurement of a particular fluid/fluids.
6. Meniscus height has to be determined by accurate means to ensure improved accuracy.

Elastic pressure elements

Elastic pressure elements or mechanical type of transducers are used for measurement of very high pressures upto about 700 MN/m^2 .

There are three main types of pressure elements.

- (a) Bourdon tube
- (b) Diaphragms
- (c) Bellows.

- The action of these mechanical transducers depends upon the displacement caused by the pressure.
- The displacement produced may actuate a pointer whose deflection may be direct measure of the pressure applied or the displacement is measured with the help of a secondary transducer which is electrical in nature.
- The output of the secondary transducer which is electrical in format is a measure of the pressure applied.

Bourdon tube:

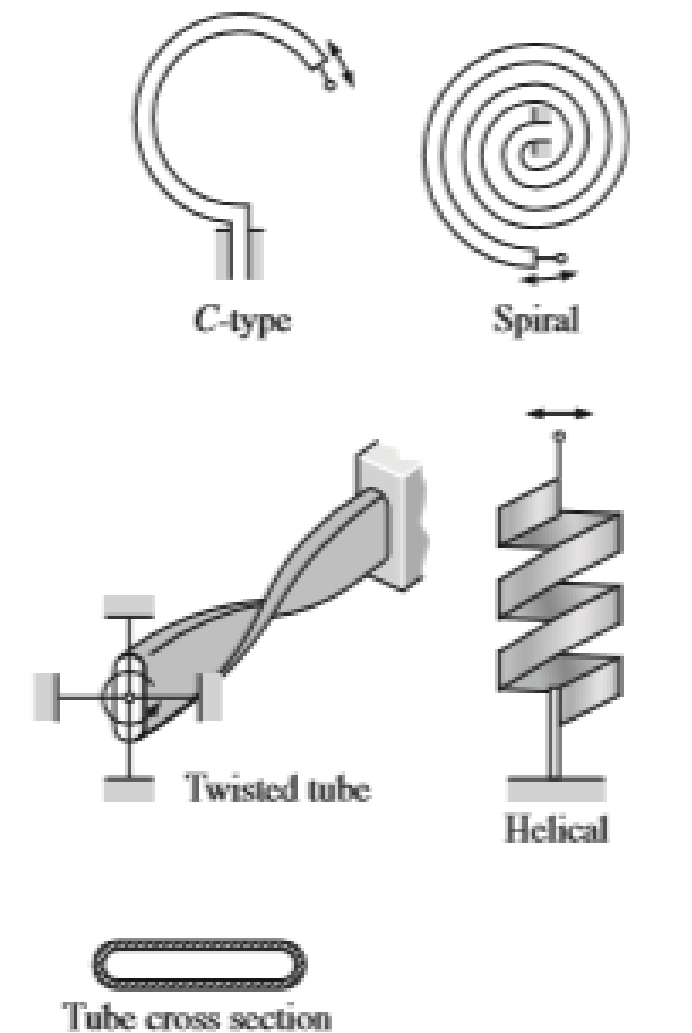
- The Bourdon tube, named after the French engineer and inventor Eugene Bourdon (1808–1884), which consists of a hollow metal tube bent like a hook whose end is closed and connected to a dial indicator needle.

Advantages:

1. Simple in construction and cheap.
2. Available in several different ranges.
3. Capability to measure gauge, absolute and differential pressures.
4. The sensitivities of Bourdon tube may be changed by changes in their dimensions.
5. Excellent sensitivity.
6. Simple and straight forward calibration with dead weight tester.
7. Easily adapted to strain, capacitance, magnetic and other electrical transducers.

Disadvantages:

1. Susceptibility to shock and vibration.
2. Inherent hysteresis and slow response to pressure changes.
3. Unsuitable for low pressure applications.

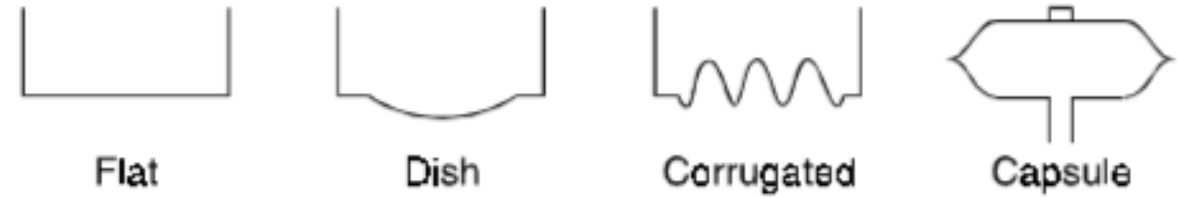


Various types of Bourdon tubes used to measure pressure.

Diaphragm elements :

Advantages :

1. Small in size and moderately priced.
2. Wide linear range.
3. Can withstand high over pressures and under pressures.
4. Small hysteresis.
5. Can be used for measurement of absolute and differential pressures as also vacuum.



Basic diaphragm types.

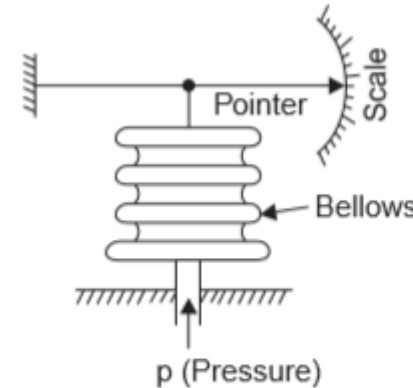
Disadvantages :

1. Need protection against shocks and vibrations.
2. Cannot be used to measure high pressures.
3. Difficult to repair.

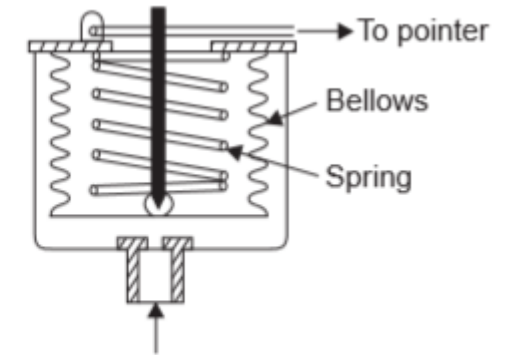
Bellow gauges/elements :

Advantages :

1. Simple and rugged construction.
2. Useful for measurement of low and medium pressures.
3. Moderate cost.
4. Can be used for measurement of absolute, gauge and differential pressures.



(a) Bellows pressure gauge



(b) Spring loaded bellows gauge

Bellow gauges.

Disadvantages :

1. Need spring for accurate characterisation.
2. Greater hysteresis and zero drift problems.
3. Unsuitable for transient measurements due to longer relative motion and mass.
4. Requires compensation for ambient temperature changes.

Important types of pressure gauges

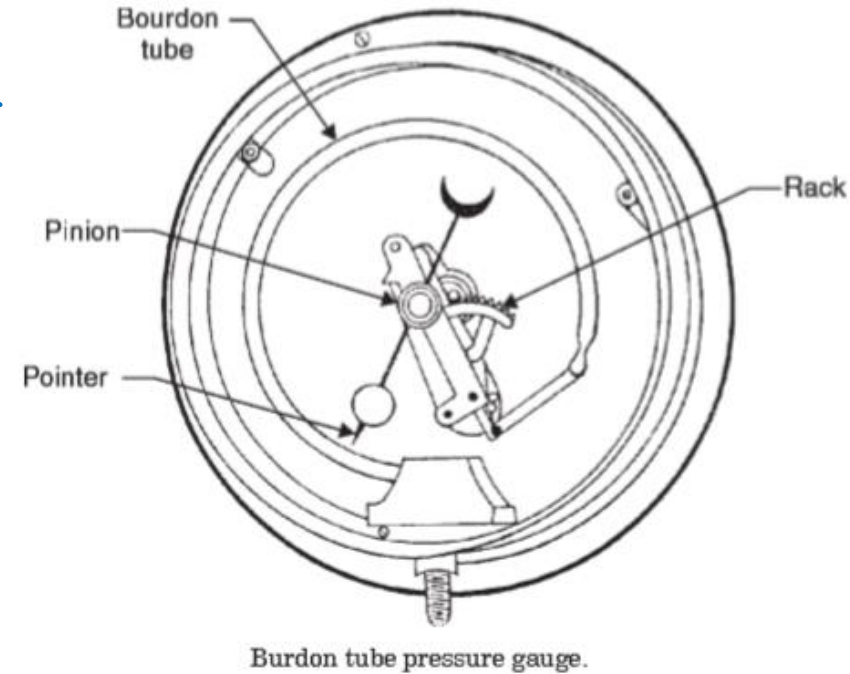
- ✓ The manometers and U-tubes are suitable for comparatively low pressures.
- ✓ For high pressures they become unnecessarily larger even when they are filled with heavy liquids.
- ✓ Therefore for measuring medium and high pressures, we make use of elastic pressure gauges.
- ✓ They employ different forms of elastic systems such as tubes, diaphragms or bellows etc. to measure the pressure.
- ✓ The elastic deformation of these elements is used to show the effect of pressure.
- ✓ Since these elements are deformed within the elastic limit only, therefore these gauges are sometimes called elastic gauges.
- ✓ Sometimes they are also called secondary instruments, which implies that they must be calibrated by comparison with primary instruments such as manometer etc.

Some of the important types of these gauges are enumerated and discussed below :

1. Bourdon tube pressure gauge
2. Diaphragm gauge
3. Vacuum gauge.

1. Bourdon tube type pressure gauge :

- ✓ A Bourdon type tube pressure gauge is used for measuring high as well as low pressures.
- ✓ In this case the pressure element consists of a metal tube of approximately elliptical cross-section.
- ✓ This tube is bent in the form of a segment of a circle and responds to pressure changes.
- ✓ When one end of the tube which is attached to the gauge case, is connected to the source of pressure, the internal pressure causes the tube to expand, whereby circumferential stress i.e., hoop tension is set up.
- ✓ The free end of the tube moves and is in turn connected by suitable levers to a rack, which engages with a small pinion mounted on the same spindle as the pointer.
- ✓ Thus the pressure applied to the tube causes the rack and pinion to move.
- ✓ The pressure is indicated by the pointer over a dial which can be graduated in a suitable scale.
- ✓ The Bourdon tubes are generally made of bronze or nickel steel. The former is generally used for low pressures and the latter for high pressures.
- ✓ Depending upon the purpose for which they are required Bourdon tube gauges are made in different forms, some of them are :
 - (i) Compound Bourdon tube: used for measuring pressures both above and below atmospheric.
 - (ii) Double Bourdon tube: used where vibrations are encountered.



Example. Convert the following readings of pressure to kPa assuming that barometer reads 760 mm of Hg.

(i) 80 cm of Hg (ii) 30 cm Hg vacuum (iii) 1.35 m H₂O gauge (iv) 4.2 bar.

Solution. Assuming density of Hg, $\rho_{\text{Hg}} = 13.596 \times 1000 \text{ kg/m}^3$

Pressure of 760 mm of Hg will be

$$\begin{aligned} &= \rho \times g \times h = 13.596 \times 1000 \times 9.806 \times \frac{760}{1000} \\ &= 101325 \text{ Pa} = 101.325 \text{ kPa} \end{aligned}$$

Note.

Pressure of 1 atmosphere =
760 mm of Hg or
= 101325 N/m².

(i) Pressure of 80 cm of Hg

$$= \frac{800}{760} \times 101.325 = \mathbf{106.65 \text{ kPa. (Ans.)}}$$

(ii) 30 cm Hg vacuum

$$= 76 - 30 = 46 \text{ cm of Hg absolute.}$$

Pressure due to 46 cm of Hg

$$= \frac{460}{760} \times 101.325 = \mathbf{61.328 \text{ kPa. (Ans.)}}$$

(iii) Pressure due to 1.35 m H₂O gauge

$$= 1000 \times 9.806 \times 1.35 = 13238 \text{ Pa} = \mathbf{13.238 \text{ kPa. (Ans.)}}$$

(iv) 4.2 bar

$$= 4.2 \times 10^2 \text{ kPa} = \mathbf{420 \text{ kPa. (Ans.)}}$$