1

Introduction—Outline of Some Descriptive Systems

1.1. STEAM POWER PLANT

1.1.1. Layout

Refer to Fig. 1.1. The layout of a modern steam power plant comprises of the following four circuits :

1. Coal and ash circuit.
2. Air and gas circuit.
3. Feed water and steam flow circuit.
4. Cooling water circuit.

Coal and Ash Circuit. Coal arrives at the storage yard and after necessary handling, passes on to the furnaces through the *fuel feeding device*. Ash resulting from combustion of coal collects at the back of the boiler and is removed to the ash storage yard through *ash handling equipment*.

Air and Gas Circuit. Air is taken in from atmosphere through the action of a forced or induced draught fan and passes on to the furnace through the *air preheater*, where it has been heated by the heat of flue gases which pass to the chimney *via* the preheater. The flue gases after passing around boiler tubes and superheater tubes in the furnace pass through a *dust* catching device or precipitator, then through the economiser, and finally through the air preheater before being exhausted to the atmosphere.

Feed Water and Steam Flow Circuit. In the water and steam circuit condensate leaving the condenser is first heated in a closed feed water heater through extracted steam from the lowest pressure extraction point of the turbine. It then passes through the *deaerator* and a few more water heaters before going into the boiler through *economiser.*

In the boiler drum and tubes, water circulates due to the difference between the density of water in the lower temperature and the higher temperature sections of the boiler. Wet steam from the drum is further heated up in the superheater for being supplied to the primemover. After expanding in high pressure turbine steam is taken to the reheat boiler and brought to its original dryness or superheat before being passed on to the low pressure turbine. From there it is exhausted through the condenser into the hot well. The condensate is heated in the feed heaters using the steam trapped (blow steam) from different points of turbine.

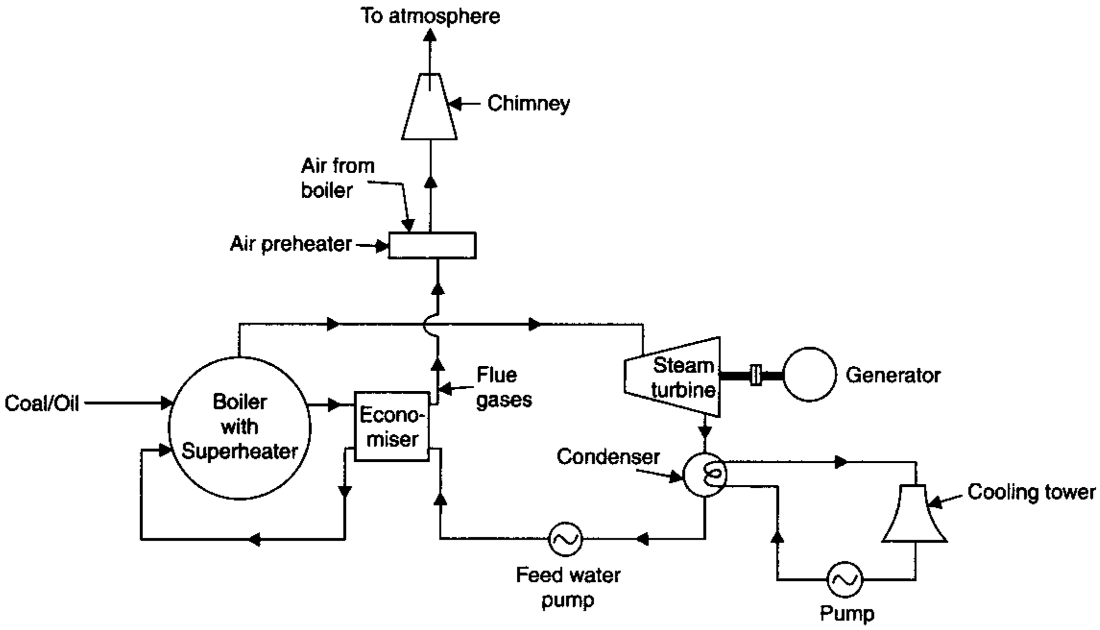


Fig. 1.1. Layout of a steam power plant.

A part of steam and water is lost while passing through different components and this is compensated by supplying additional feed water. This feed water should be purified before hand, to avoid the scaling of the tubes of the boiler.

Cooling Water Circuit. The cooling water supply to the condenser helps in maintaining a low pressure in it. The water may be taken from a natural source such as river, lake or sea or the same water may be cooled and circulated over again. In the latter case the cooling arrangement is made through spray pond or cooling tower.

1.1.2. Components of a Modern Steam Power Plant

A modern steam power plant comprises of the following *components* :

1. Boiler
    - (*i*) Superheater
    - (*ii*) Reheater
    - (*iii*) Economiser
    - (*iv*) Air-heater.
2. Steam turbine
3. Generator
4. Condenser
5. Cooling towers
6. Circulating water pump
7. Boiler feed pump
8. Wagon tippler
9. Crusher house
10. Coal mill
11. Induced draught fans
12. Ash precipitators
13. Boiler chimney
14. Forced draught fans
15. Water treatment plant
16. Control room
17. Switch yard.

Functions of some important parts of a steam power plant :

1. ***Boiler.*** Water is converted into wet steam.
2. ***Superheater.*** It converts wet steam into superheated steam.
3. ***Turbine.*** Steam at high pressure expands in the turbine and drives the generator.

4. ***Condenser.*** It condenses steam used by the steam turbine. The condensed steam (known as *condensate*) is used as a feed water.

5. ***Cooling tower.*** It cools the condenser circulating water. Condenser cooling water absorbs heat from steam. This heat is discharged to atmosphere in cooling water.

6. ***Condenser circulating water pump.*** It circulates water through the condenser and the cooling tower.

7. ***Feed water pump.*** It pumps water in the water tubes of boiler against boiler steam pressure.

8. ***Economiser.*** In economiser heat in flue gases is partially used to heat incoming feed water.

9. ***Air preheater.*** In air preheater heat in flue gases (the products of combustion) is partially used to heat incoming air.

1.2. NUCLEAR POWER PLANT

Fig. 1.2 shows schematically a *nuclear power plant.*

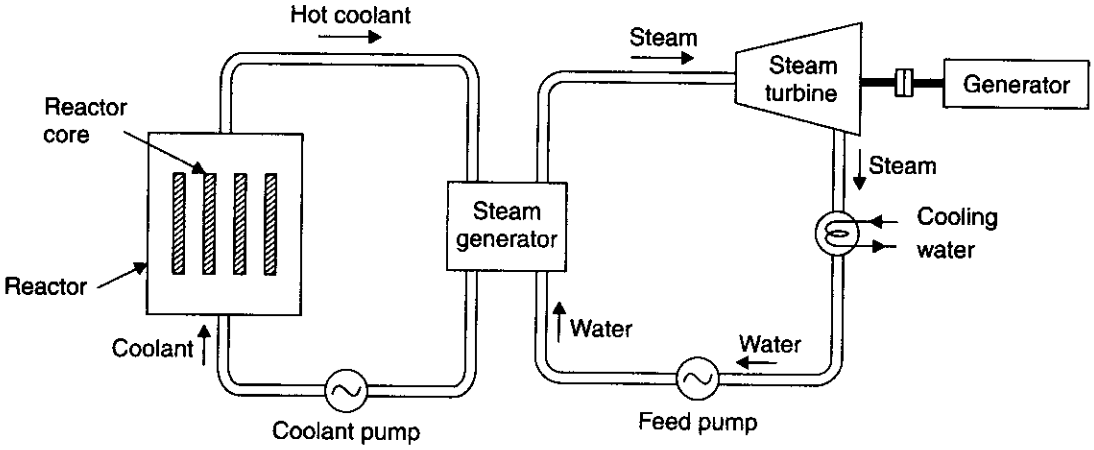


Fig. 1.2. Nuclear power plant.

The main components of a nuclear power plant are :

1. Nuclear reactor
2. Heat exchanger (steam generator)
3. Steam turbine
4. Condenser
5. Electric generator.

In a nuclear power plant the reactor performs the same function as that of the furnace of steam power plant (*i.e.*, produces heat). The heat liberated in the reactor as a result of the nuclear fission of the fuel is taken up by the coolants circulating through the reactor core. Hot coolant leaves the reactor at the top and then flows through the tubes of steam generator and passes on its heat to the feed water. The steam so produced expands in the steam turbine, producing work, and thereafter is condensed in the condenser. The steam turbine in turn runs an electric generator thereby producing electrical energy. In order to maintain the flow of coolant, condensate and feed water pumps are provided as shown in Fig. 1.2.

1.3. INTERNAL COMBUSTION ENGINES

1.3.1. Heat Engines

Any type of engine or machine which derives heat energy from the combustion of fuel or any other source and converts this energy into mechanical work is termed as a **heat engine.**

Heat engines may be *classified* into two main classes as follows :

1. External Combustion Engine.
2. Internal Combustion Engine.

1. **External Combustion Engines** (*E.C. Engines*)

In this case, combustion of fuel takes place outside the cylinder as in case of steam engines where the heat of combustion is employed to generate steam which is used to move a piston in a cylinder. Other examples of external combustion engines are *hot air engines, steam turbine* and *closed cycle gas turbine*. These engines are generally needed for driving locomotives, ships, generation of electric power etc.

2. **Internal Combustion Engines** (*I.C. Engines*)

In this case combustion of the fuel with oxygen of the air occurs within the cylinder of the engine. The internal combustion engines group includes engines employing mixtures of combustible gases and air, known as gas engines, those using lighter liquid fuel or spirit known as *petrol engines* and those using heavier liquid fuels, known as oil *compression ignition or diesel engines.*

1.3.2. Development of I.C. Engines

Many experimental engines were constructed around 1878. The first really successful engine did not appear, however until 1879, when a German engineer Dr. Otto built his famous Otto gas engine. The operating cycle of this engine was based upon principles first laid down in 1860 by a French engineer named Bea de Rochas. The majority of modern I.C. engines operate according to these principles.

The development of the well known Diesel engine began about 1883 by Rudoff Diesel. Although this differs in many important respects from the otto engine, the operating cycle of modern high speed Diesel engines is thermodynamically very similar to the Otto cycle.

1.3.3. Different parts of I.C. Engines

A cross-section of an air-cooled I.C. engines with principal parts is shown in Fig. 1.3.

A. Parts common to both petrol and diesel engines

1. Cylinder
2. Cylinder head
3. Piston
4. Piston rings
5. Gudgeon pin
6. Connecting rod
7. Crankshaft
8. Crank
9. Engine bearing
10. Crank case
11. Flywheel
12. Governor
13. Valves and valve operating mechanism.

B. Parts for petrol engines only

1. Spark plugs
2. Carburettor
3. Fuel pump.

C. Parts for Diesel engine only

1. Fuel pump.
2. Injector.

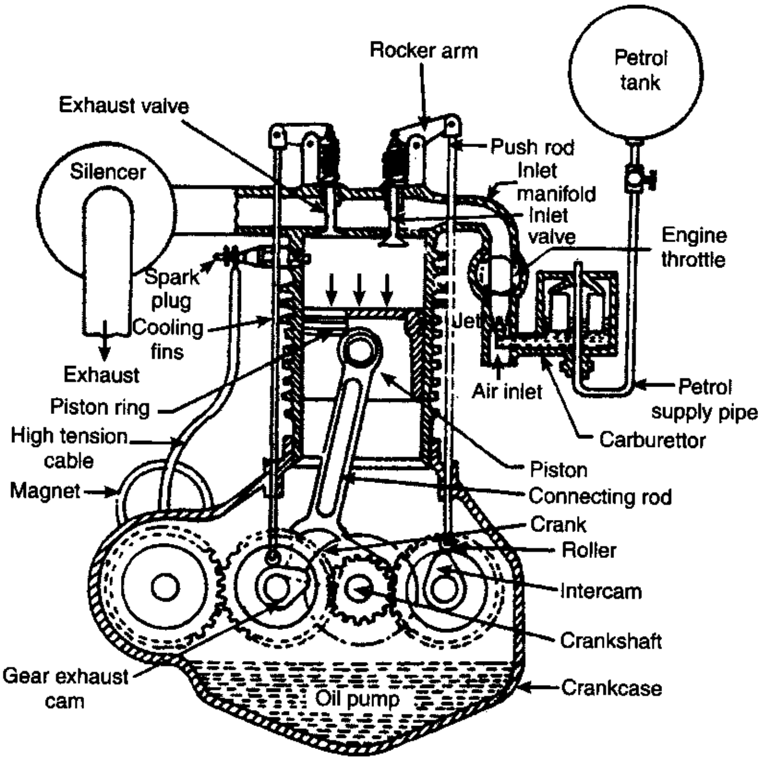


Fig. 1.3. An air-cooled four-stroke petrol engine.

1.3.4. Spark Ignition (S.I.) Engines

These engines may work on either *four stroke cycle* or *two stroke cycle*, majority of them, of course, operate on four stroke cycle.

Four stroke petrol engine :

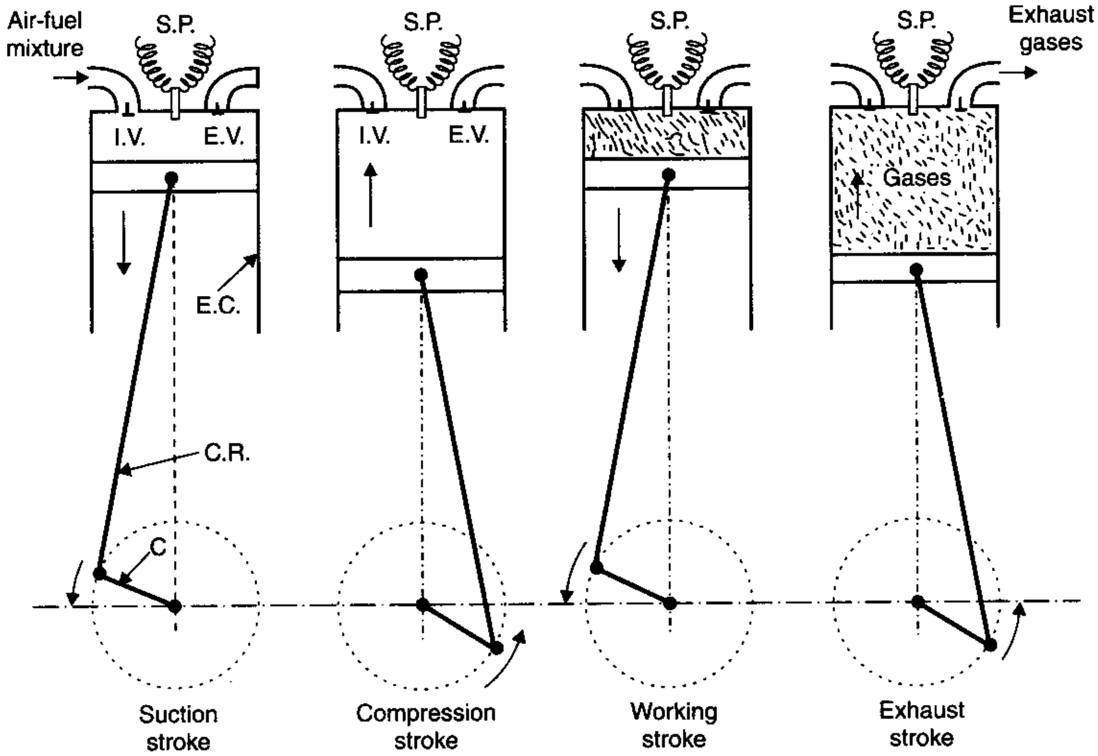
Fig. 1.4 illustrates the various strokes/series of operations which take place in a four stroke petrol (Otto cycle) engine.

Suction stroke. During *suction stroke* a mixture of air and fuel (petrol) is sucked through the inlet valve (I.V.). The exhaust valve remains closed during this operation.

Compression stroke. During *compression stroke*, both the valves remain closed, and the pressure and temperature of the mixture increase. Near the end of compression stroke, the fuel is ignited by means of an electric spark in the spark plug, causing combustion of fuel at the instant of ignition.

Working stroke. Next is the *working* (also called *power* or *expansion*) stroke. During this stroke, both the valves remain closed. Near the end of the expansion stroke, only the exhaust valve opens and the pressure in the cylinder at this stage forces most of the gases to leave the cylinder.

Exhaust stroke. Next follows the exhaust stroke, when all the remaining gases are driven away from the cylinder, while the inlet valve remains closed and the piston returns to the *top dead centre*. The cycle is then repeated.



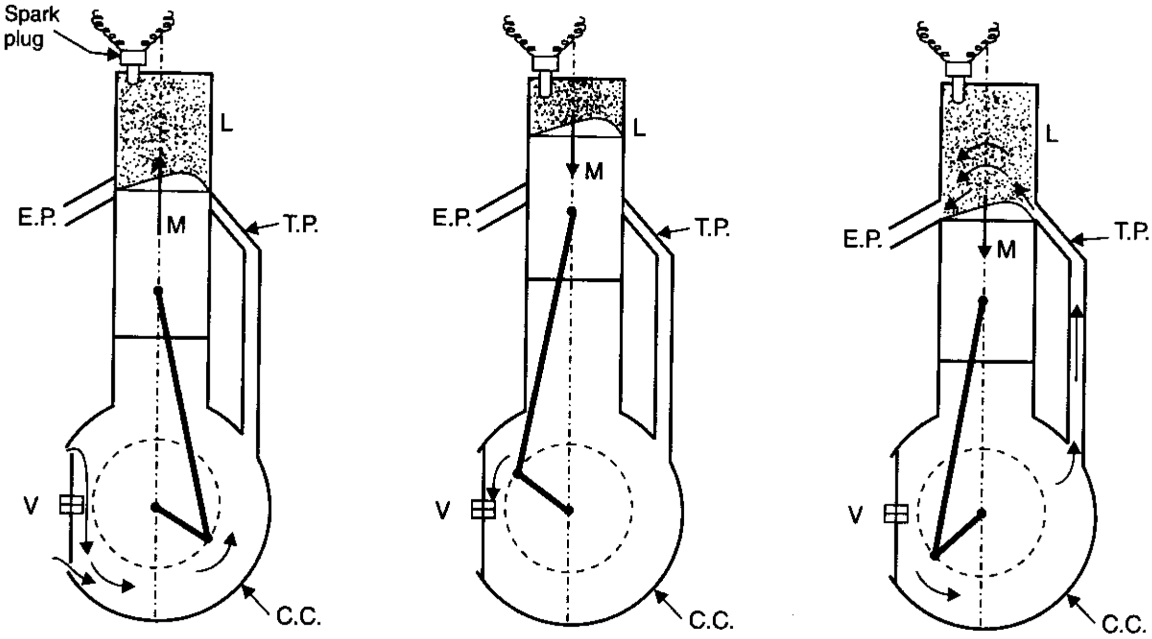
I.V = Intel valve, E.V. = Exhaust valve, E.C. = Engine cylinder,
C.R. = Connecting rod, C = Crank, S.P. = Spark plug.

Fig. 1.4. Four stroke otto cycle engine.

Two stroke petrol engine :

In 1878, Dugald-clerk, a British engineer introduced a cycle which could be completed in two strokes of piston rather than four strokes as is the case with the four stroke cycle engines. The engines using this cycle were called two stroke cycle engines. In this engine suction and exhaust strokes are eliminated. Here *instead of valves, ports are used. The exhaust gases are driven out from engine cylinder by the fresh change of fuel entering the cylinder nearly at the end of the working stroke.*

Fig. 1.5 shows a two stroke petrol engine (used in scooters, motor cycles etc.). The *cylinder* L is connected to a closed *crank chamber* C.C. During the upward stroke of the piston M, the gases in L are compressed and at the same time fresh air and fuel (petrol) mixture enters the crank chamber through the valve V. When the piston moves downwards, V closes and the mixture in the crank chamber is compressed. Refer Fig. 1.5 (*i*) the piston is moving upwards and is compressing an explosive change which has previously been supplied to L. Ignition takes place at the end of the stroke. The piston then travels downwards due to expansion of the gases [Fig. 1.5 (*ii*)] and near the end of this stroke the piston uncovers the *exhaust port* (E.P.) and the burnt exhaust gases escape through this port [Fig. 1.5 (*iii*)]. The *transfer port* (T.P.) then is uncovered immediately, and the compressed charge from the crank chamber flows into the cylinder and is deflected upwards by the hump provided on the head of the piston. It may be noted that the incoming air petrol mixture helps the removal of gases from the engine-cylinder ; if, in case these exhaust gases do not leave the cylinder, the fresh charge gets diluted and efficiency of the engine will decrease. The piston then again starts moving from bottom dead centre (B.D.C.) to top dead centre (T.D.C.) and the charge gets compressed when E.P. (exhaust port) and T.P. are covered by the piston ; thus the cycle is repeated.



(*i*) (*ii*) (*iii*)

L = Cylinder ; E.P. = Exhaust port ; T.P. = Transfer port ; V = Valve ; C.C. = Crank chamber

(*i*) (*ii*) (*iii*)

Fig. 1.5. Two-stroke petrol engine.

The power obtained from a two-stroke cycle engine is *theoretically twice* the power obtainable from a four-stroke cycle engine.

1.3.5. Compression Ignition (C.I.) Engines

The operation of C.I. engines (or diesel engines) is practically the same as those of S.I. engines. The cycle in both the types, consists of *suction, compression, ignition, expansion* and *exhaust*. However, the combustion process in a C.I. engine is different from that of a S.I. engine as given below :

In C.I. engine, *only air* is sucked during the stroke and the fuel is injected in the cylinder near the end of the compression stroke. Since the compression ratio is very high (between 14 : 1 to 22 : 1), the temperature of the air after compression is quite high. So when fuel is injected in the form of a spray at this stage, it ignites and burns almost as soon as it is introduced. The burnt gases are expanded and exhausted in the same way as is done in a S.I. engine.

1.4. GAS TURBINES

1.4.1. General Aspects

Probably a wind-mill was the first turbine to produce useful work, wherein there is no precompression and no combustion. The characteristic features of a gas turbine as we think of the name today include a *compression process* and an *heat addition* (or combustion) *process*. The gas turbine represents perhaps the most satisfactory way of producing very large quantities of power in a self-contained and compact unit. The gas turbine may have a future use in conjunction with the oil engine. For smaller gas turbine units, the inefficiencies in compression and expansion processes become greater and *to* improve the thermal efficiency it is necessary to use a heat exchanger. In order that a small gas turbine may compete for economy with the small oil engine or petrol engine it is necessary that a compact effective heat exchanger be used in the gas turbine cycle. The thermal efficiency of the gas turbine alone is still quite modest 20 to 30% compared with that of a modern steam turbine plant 38 to 40%. It is possible to construct combined plants whose efficiencies are of order of 45% or more. Higher efficiencies might be attained in future.

The following *are* the major fields of application of gas turbines :

1. Aviation
2. Power generation
3. Oil and gas industry
4. Marine propulsion.

The efficiency of a gas turbine is not the criteria for the choice of this plant. A gas turbine is used in aviation and marine fields because it is *self-contained, light weight, not requiring cooling water and generally fits into the overall shape of the structure.* It is selected for power generation because of its *simplicity, lack of cooling water, needs quick installation and quick starting*. It is used in oil and gas industry because of *cheaper supply of fuel and low installation cost.*

The gas turbines have the following limitations : (*i*) *They are not self-starting* ; (*ii*) *Low efficiencies at part loads* ; (*iii*) *Non-reversibility* ; (*iv*) *Higher rotor speeds ; and* (*v*) *Overall efficiency of the plant is low.*

1.4.2. Classification of Gas Turbines

The gas turbines are mainly *divided* into two groups :

1. **Constant pressure combustion gas turbine :**

(*a*) Open cycle constant pressure gas turbine

(*b*) Closed cycle constant pressure gas turbine.

2. **Constant volume combustion gas turbine.**

In almost *all the fields open cycle gas turbine plants are used. Closed cycle plants were introduced at one stage because of their ability to burn cheap fuel.* In between their progress remained slow because of availability of cheap oil and natural gas. Because of rising oil prices, now again, the attention is being paid to closed cycle plants.

1.4.3. Merits and Demerits of Gas Turbines

Merits over I.C. engines :

1. The mechanical efficiency of a gas turbine (95%) is quite high as compared with I.C. engine (85%) since the I.C. engine has a large many sliding parts.
2. A gas turbine does not require a flywheel as the torque on the shaft is continuous and uniform. Whereas a flywheel is a must in case of an I.C. engine.
3. The weight of gas turbine per H.P. developed is less than that of an I.C. engine.
4. The gas turbine can be driven at a very high speeds (40,000 r.p.m.) whereas this is not possible with I.C. engines.
5. The work developed by a gas turbine per kg of air is more as compared to an I.C. engine. This is due to the fact that gases can be expanded upto atmospheric pressure in case of a gas turbine whereas in an I.C. engine expansion upto atmospheric pressure is not possible.

6. The components of the gas turbine can be made lighter since the pressures used in it are very low, say 5 bar compared with I.C. engine, say 60 bar.
7. In the gas turbine the ignition and lubrication systems are much simpler as compared with I.C. engines.
8. Cheaper fuels such as paraffine type, residue oils or powdered coal can be used whereas special grade fuels are employed in petrol engine to check knocking or pinking.
9. The exhaust from gas turbine is less polluting comparatively since excess air is used for combustion.
10. Because of low specific weight the gas turbines are particularly suitable for use in aircrafts.

Demerits of gas turbines

1. The thermal efficiency of a simple turbine cycle is low (15 to 20%) as compared with I.C. engines (25 to 30%).
2. With wide operating speeds the fuel control is comparatively difficult.
3. Due to higher operating speeds of the turbine, it is imperative to have a speed reduction device.
4. It is difficult to start a gas turbine as compared to an I.C. engine.
5. The gas turbine blades need a special cooling system.

1.4.4. A Simple Gas Turbine Plant

A gas turbine plant may be defined as one *"in which the principal prime-mover is of the turbine type and the working medium is a permanent gas"*.

Refer to Fig. 1.6. A simple gas turbine plant consists of the following :

1. *Turbine.*
2. *A compressor* mounted on the same shaft or coupled to the turbine.
3. *The combustor.*
4. *Auxiliaries* such as starting device, auxiliary lubrication pump, fuel system, oil system and the duct system etc.

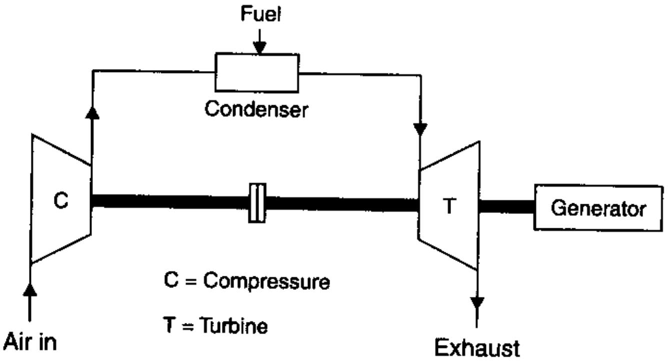


Fig. 1.6. Simple gas turbine plant.

A modified plant may have in addition to above an *intercooler, regenerator*, a *reheater* etc.

The working fluid is compressed in a compressor which is generally rotary, multistage type. Heat energy is added to the compressed fluid in the combustion chamber. This high energy fluid, at high temperature and pressure, then expands in the turbine unit thereby generating power. Part of the power generated is consumed in driving the generating compressor and accessories and the rest is utilised in electrical energy. The gas turbines work on open cycle, semiclosed cycle or closed cycle. In order to improve efficiency, compression and expansion of working fluid is carried out in multistages.

1.4.5. Energy Cycle for a Simple-Cycle Gas Turbine

Fig. 1.7 shows an energy-flow diagram for a simple-cycle gas turbine, the description of which is given below :

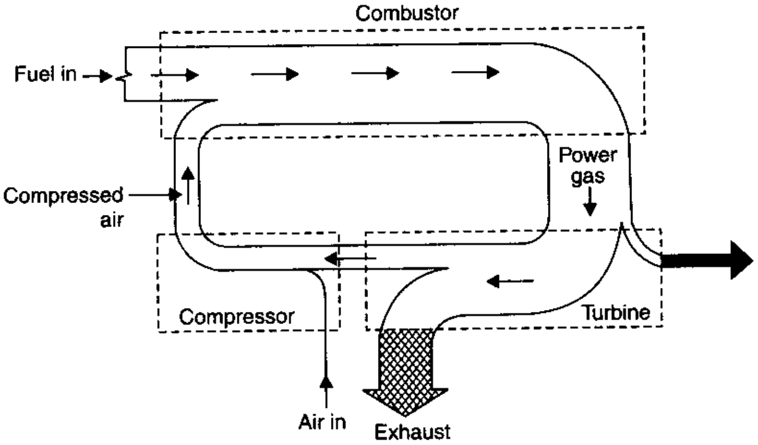


Fig. 1.7. Energy flow diagram for gas-turbine unit.

- The air brings in minute amount of energy (measured above 0°C).
- Compressor adds considerable amount of energy.
- Fuel carries major input to cycle.
- Sum of fuel and compressed-air energy leaves combustor to enter turbine.
- In turbine smallest part of entering energy goes to useful output, largest part leaves in exhaust.

Shaft energy to drive compressor is about twice as much as the useful shaft output.

Actually the shaft energy keeps circulating in the cycle as long as the turbine runs. The important comparison is *the size of the output with the fuel input*. For the simple-cycle gas turbine the output may run about 20% of the fuel input for certain pressure and temperature conditions at turbine inlet. This means 80% of the fuel energy is wasted. While the 20% thermal efficiency is not too bad, it can be improved by including *additional heat recovery apparatus*.

1.5. REFRIGERATION SYSTEMS

Refrigeration means the *cooling of or removal of heat from a system*. Refrigerators work mainly on two processes :

1. Vapour compression, and
2. Vapour absorption.

Simple Vapour Compression System :

In a simple vapour compression system the following fundamental processes are completed in one cycle :

1. Expansion 2. Vapourisation 3. Compression 4. Condensation.

The flow diagram of such a cycle is shown in Fig. 1.8.

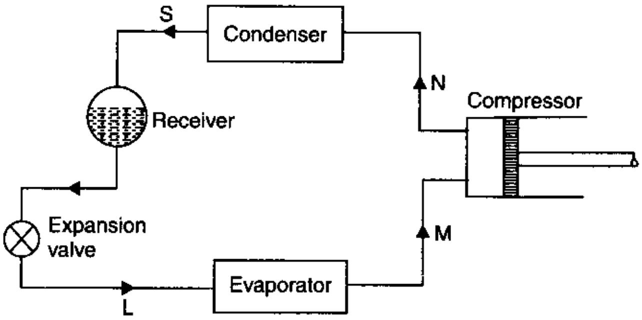


Fig. 1.8. Simple vapour compression cycle.

The *vapour at low temperature and pressure* (state '*M*') enters the *compressor* where it is compressed isoentroprically and subsequently its temperature and pressure increase considerably (state '*N*'). This vapour after leaving the compressor enters the *condenser* where it is condensed into *high pressure liquid* (state '*S*') and is collected in a *receiver*. From receiver it passes through the *expansion valve*, here it is *throttled down to a lower pressure* and has *a low temperature* (state '*L*'). After finding its way through *expansion valve* it finally passes on to *evaporator* where it *extracts heat from the surroundings and vapourises to low pressure vapour* (state '*M*').

Domestic Refrigerator :

Refrigerators, these days, are becoming the common item for *house hold use, vendor's shop, hotels, motels, offices, laboratories, hospitals, chemists* and *druggists shops, studios etc.* They are manufactured in different size to meet the needs of various groups of people. They are usually rated with *internal gross volume* and the *freezer volume*. The freezer space is meant to preserve perishable products at a temperature much below 0°C such as fish, meat, chicken etc. and to produce ice and icecream as well. The refrigerators in India are available in different sizes of various makes, *i.e.*, 90, 100, 140, 160, 200, 250, 380 litres of gross volume. The freezers are usually provided at top portion of the refrigerator space occupying around one-tenth to one-third of the refrigerator volume. In some refrigerators, freezers are provided at the bottom.

A domestic refrigerator consists of the following two main parts :

1. The refrigeration system.
2. The insulated cabinet.

Fig. 1.9 shows a flow diagram of a typical refrigeration system used in a domestic refrigerator. A simple domestic refrigerator consists of a *hermetic compressor placed in the cabinet base. The condenser is installed at the back and the evaporator is placed inside the cabinet at the top.*

The working of the refrigerator is as follows :

— The low pressure and low temperature refrigerant vapour (*usually* R12) is drawn through the suction line to the compressor. The *accumulator* provided between the *suction line* and the evaporator collects liquid refrigerant coming out of the evaporator due to incomplete evaporation, if any, prevents it from entering the compressor. The *compressor* then compresses the refrigerant vapour to a high pressure and high temperature. The compressed vapour flows through the *discharge line* into condenser (vertical natural draft, wire-tube type).

— In the *condenser* the vapour refrigerant at high pressure and at high temperature is condensed to the liquid refrigerant at high pressure and low temperature.

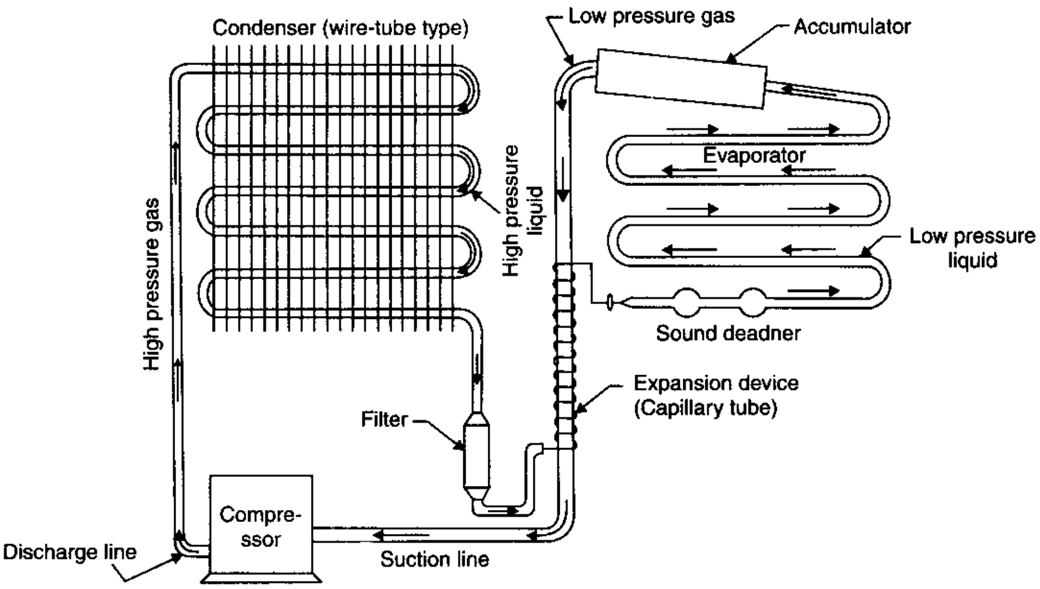


Fig. 1.9. Domestic refrigerator.

— The high pressure liquid refrigerant then flows through the *filter* and then enters the *capillary tube* (expansion device). The capillary tube is attached to the suction line as shown in Fig. 1.9. The warm refrigerant passing through the capillary tube gives some of its heat to cold suction line vapour. This increases the heat absorbing quality of the liquid refrigerant slightly and increases the superheat of vapour entering the compressor.

The capillary tube expands the liquid refrigerant at high pressure to the liquid refrigerant at low pressure so that a measured quantity of liquid refrigerant is passed into the *evaporator*.

— In the *evaporator* the liquid refrigerant gets evaporated by absorbing heat from the container/articles placed in the evaporative chamber and is sucked back into the compressor and the cycle is repeated.

HIGHLIGHTS

1. The layout of a modern steam power plant comprises of the following four circuits :
   (*i*) Coal and ash circuit
   (*ii*) Air and gas circuit
   (*iii*) Feed water and steam flow circuit
   (*iv*) Cooling water circuit.
2. Any type of engine or machine which derives heat energy from the combustion of fuel or any other source and converts this energy into mechanical work is termed as a heat engine.
3. The major fields of application of gas turbines are :
   (*i*) Aviation
   (*ii*) Power generation
   (*iii*) Oil and gas industry and
   (*iv*) Marine propulsion.
4. A simple gas turbine plant consists of the following :
   — Turbine
   — Compressor

- — Combustor
- — Auxiliaries such as starting device, auxiliary lubrication pump, fuel system, oil system and the duct system etc.

5. Refrigeration means the cooling or removal of heat from a system. Refrigerators work mainly on two processes
   (*i*) Vapour compression and
   (*ii*) Vapour absorption.

THEORETICAL QUESTIONS

1. Give the layout of a modern steam power plant and explain its various circuits.
2. List the components of a nuclear power plant.
3. Draw the cross-section of an air cooled I.C. engine and label its various parts.
4. Explain with neat sketches the working of a four stroke petrol engine.
5. How are gas turbines classified ?
6. What are the major fields of application of gas turbines ?
7. With the help of a neat diagram explain the working of a simple gas turbine plant.
8. Draw the energy cycle for a simple-cycle gas turbine.
9. Explain with a neat sketch the working of a simple vapour compression system.
10. Draw the neat diagram of a domestic refrigerator, showing its various parts. Explain its working also.

2

Basic Concepts of Thermodynamics

2.1. INTRODUCTION TO KINETIC THEORY OF GASES

The kinetic theory of gases deals with the behaviour of molecules constituting the gas. According to this theory, the molecules of all gases are in continuous motion. As a result of this they possess kinetic energy which is transferred from molecule to molecule during their collision. The energy so transferred produces a change in the velocity of individual molecules.

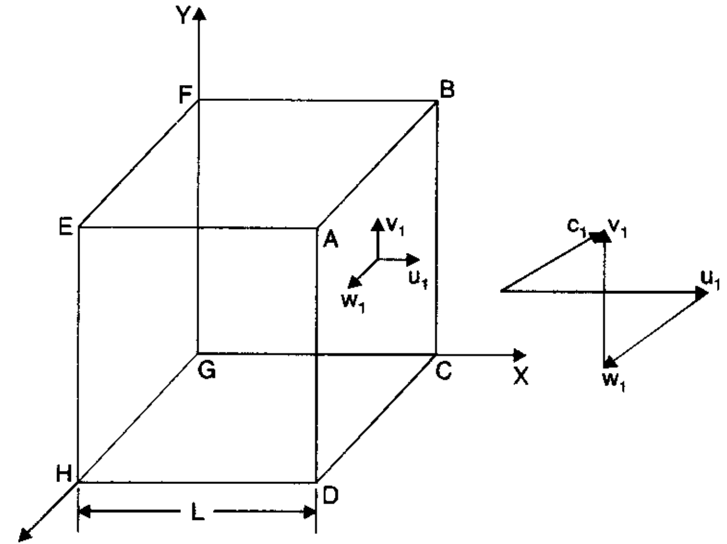
The complete phenomenon of molecular behaviour is quite complex. The *assumptions* are therefore made to simplify the application of theory of an ideal gas.

Assumptions :

1. The molecules of gases are assumed to be rigid, perfectly elastic solid spheres, identical in all respects such as mass, form etc.
2. The mean distance between molecules is very large compared to their own dimensions.
3. The molecules are in state of random motion moving in all directions with all possible velocities and gas is said to be in state of molecular chaos.
4. The collisions between the molecules are perfectly elastic and there are no intermolecular forces of attraction or repulsion. This means that energy of gas is all kinetic.
5. The number of molecules in a small volume is very large.
6. The time spent in collision is negligible, compared to the time during which the molecules are moving independently.
7. Between collisions, the molecules move in a straight line with uniform velocity because of frictionless motion between molecules. The distance between two collisions is called *'free path'* of the molecule, the average distance travelled by a molecule between successive collision is known as *'mean free path'*.
8. The volume of molecule is so small that it is negligible compared to total volume of the gas.

Pressure exerted by an Ideal Gas :

Let us consider a quantity of gas to be contained in a cubical vessel of side l with perfectly elastic wall and N represent the very large number of molecules in the vessel. Now let us consider a molecule which may be assumed to have a velocity C_1 in a certain direction. The velocity can be resolved into three components u_1, v_1, w_1 parallel to three co-ordinate axes X, Y and Z which are again assumed parallel to the sides of the cube as shown in Fig. 2.1.



(a) (b)

Fig. 2.1

Thus, $$C_1^2 = u_1^2 + v_1^2 + w_1^2 .$$

Let this molecule having mass m strike wall surface $ABCD$ of the cube with velocity u_1. Since the collision is perfectly elastic, the molecule will rebound from this surface with the same velocity u_1. Therefore,

The momentum of the molecule before it strikes the face $ABCD = mu_1$

The momentum of the molecule after impact $= - mu_1$.

Hence change of momentum at each impact in direction normal to the surface

$$ABCD = mu_1 - (- mu_1) = 2mu_1$$

After striking the surface $ABCD$, the molecule rebounds and travels back to the face $EFGH$, collides with it and travels back again to the face $ABCD$ covering $2l$ distance. This means molecule covers $2l$ distance to hit the same face again. Hence the time taken by the same molecule to strike the same face $ABCD$ again is $\frac{2l}{u_1}$.

Therefore, the rate of change of momentum for one molecule of the gas

$$= \frac{2mu_1}{\frac{2l}{u_1}} = \frac{mu_1^2}{l}$$

According to Newton's second law of motion the rate of change of 'momentum is the force'. If F_1 is the force due to one molecule, then

$$F_1 = \frac{mu_1^2}{l}$$

Similarly, then force F_2 due to the impact of another molecule having velocity C_2 whose components are u_2, v_2, w_2 is given by

$$F_2 = \frac{mu_2^2}{l}$$

Hence total force F_x on the face *ABCD* due to impact of *N* molecules is given by

$$F_x = \frac{m}{l}(u_1^2 + u_2^2 + \ldots\ldots u_N^2)$$

Since the pressure (p) is the force per unit area, hence pressure exerted on the wall *ABCD* is given by

$$p_x = \frac{F_x}{l^2} = \frac{m}{l^3}(u_1^2 + u_2^2 + \ldots\ldots u_N^2)$$

Similarly, if p_y and p_z represent the pressures on other faces which are perpendicular to the *Y* and *Z* axis respectively, we have

$$p_y = \frac{m}{l^3}(v_1^2 + v_2^2 + \ldots\ldots v_N^2)$$

and $$p_z = \frac{m}{l^3}(w_1^2 + w_2^2 + \ldots\ldots w_N^2)$$

Since pressure exerted by the gas is the same in all directions, *i.e.*, $p_x = p_y = p_z$ the average pressure p of the gas is given by

$$p = \frac{p_x + p_y + p_z}{3}$$

or $$p = \frac{m}{l^3}[(u_1^2 + v_1^2 + w_1^2) + (u_2^2 + v_2^2 + w_2^2) + \ldots\ldots(u_N^2 + v_N^2 + w_N^2)]$$

But $$C_1^2 = (u_1^2 + v_1^2 + w_1^2)$$

$$C_2^2 = (u_2^2 + v_2^2 + w_2^2) \text{ and so on}$$

$$l^3 = V = \text{volume of gas } (m^3)$$

$\therefore$ $$p = \frac{1}{3}\frac{m}{v}(C_1^2 + C_2^2 + C_3^2 + \ldots\ldots C_N^2)$$

or $$p = \frac{1}{3}\frac{m}{v}N\bar{C}^2 \qquad \ldots(2.1)$$

where $\bar{C}^2 = \left(\frac{C_1^2 + C_2^2 + C_3^2 + \ldots\ldots C_N^2}{N}\right)$ known as mean square velocity

or $$\bar{C} = \sqrt{\frac{C_1^2 + C_2^2 + C_3^2 + \ldots\ldots C_N^2}{N}}$$

where $\bar{C}$ is called the root *mean square velocity* of the molecules and equal to the square root of the mean of square of velocities of individual molecules which is evidently not the same as mean of velocities of different molecules

$$\left[i.e., C_{mean} = \frac{C_1 + C_2 + C_3 + \ldots\ldots C_N}{N}\right]$$

or
$$pV = \frac{1}{3} m N\bar{C}^2 \qquad ...(2.2)$$

This *equation is the fundamental equation of kinetic theory of gases* and is often referred to as **kinetic equation of gases.**

Equation (2.2) may be written as

$$pV = 2/3 \times 1/2\ m\ N\bar{C}^2$$

where $\frac{1}{2} mN\bar{C}^2$ is the *average transmission or linear kinetic energy of the system of particles.*

Equation (2.1) can be written as

$$p = 1/3\ \rho\ \bar{C}^2 \qquad ...(2.3)$$

where ρ is the density. $\left[\because \quad \rho = \frac{mN}{V}, \text{ i.e., } \frac{\text{Total mass}}{\text{Total volume}}\right]$

This equation expresses the pressure which any volume of gas exerts in terms of its density under the prevailing conditions and its mean square molecular speed.

From equations (2.2) and (2.3),

$$\bar{C} = \sqrt{\frac{3p}{\rho}} = \sqrt{\frac{3pV}{mN}}$$

Kinetic interpretation of Temperature :

If V_{mol} is the volume occupied by a gram molecule of a gas and N_0 is the number of moles in one gram molecule of gas,

$$M = \text{molecular weight} = mN_0. \qquad ...(i)$$

Since $p\ V_{mol} = R_0T$ ......Molar gas equation ...(*ii*)

From equations (2.2) and (*ii*),

$$1/3\ m\ N_0\,\bar{C} = R_0T$$

or
$$2/3 \times \tfrac{1}{2}m\ N_0\,\bar{C}^2 = R_0T$$

or
$$\tfrac{1}{2}\ m\bar{C}^2 = 3/2\ KT \qquad ...(2.4)$$

(*i.e.*, K.E. per molecule = 3/2 *KT*)

or
$$\bar{C} = \sqrt{\frac{3KT}{m}}$$

or
$$\bar{C} = \sqrt{\frac{3R_0T}{M}}$$

or
$$\bar{C} = \sqrt{3RT} \qquad ...(2.5)$$

R_0 = Universal gas constant

N_0 = Avogadro's number

$\frac{R_0}{N_0}$ = K (Boltzman's constant)

$$\because \frac{K}{m} = \frac{R_0}{N_0\,m} = \frac{R_0}{M}$$

$$\because R = \frac{R_0}{M}$$

where R is characteristic gas constant.

From equation (2.4) it is seen that *temperature is a measure* of the *average kinetic energy of translation possessed by molecule.* It is known as the **kinetic interpretation of temperature.** Hence, the absolute temperature of a gas is proportional to the mean translational kinetic energy of the molecules it consists. If the temperature is fixed, then the average K.E. of the molecules remains constant despite encounters.

2.2. DEFINITION OF THERMODYNAMICS

Thermodynamics may be *defined* as follows :

- *Thermodynamics is an axiomatic science which deals with the relations among heat, work and properties of system which are in equilibrium. It describes state and changes in state of physical systems.*

  Or

  Thermodynamics is *the science of the regularities governing processes of energy conversion.*

  Or

  Thermodynamics is *the science that deals with the interaction between energy and material systems.*

Thermodynamics, basically entails *four laws* or axioms known as Zeroth, First, Second and Third law of thermodynamics.

- The ***First law*** throws light on *concept of internal energy.*
- The ***Zeroth law*** deals with *thermal equilibrium* and establishes a *concept of temperature.*
- The ***Second law*** indicates the limit of *converting heat into work* and introduces the *principle of increase of entropy.*
- The ***Third law*** defines the *absolute zero of entropy.*

These laws are based on experimental observations and have no *mathematical proof.* Like all physical laws, these laws are based on *logical reasoning.*

2.3. THERMODYNAMIC SYSTEMS

2.3.1. System, Boundary and Surroundings

System. A system is *a finite quantity of matter or a prescribed region of space* (Refer Fig. 2.2)

Boundary. The *actual or hypothetical envelope enclosing the system* is the boundary of the system. The boundary may be fixed or it may move, as and when a system containing a gas is compressed or expanded. The boundary may be *real* or *imaginary.* It is not difficult to envisage a real boundary but an example of imaginary boundary would be one drawn around a system consisting of the fresh mixture about to enter the cylinder of an I.C. engine together with the remanants of the last cylinder charge after the exhaust process (Refer Fig. 2.3).

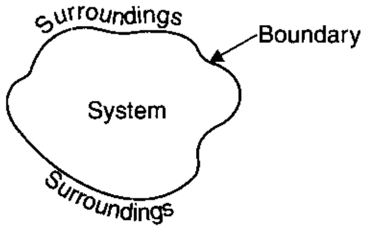


Fig. 2.2. The system.

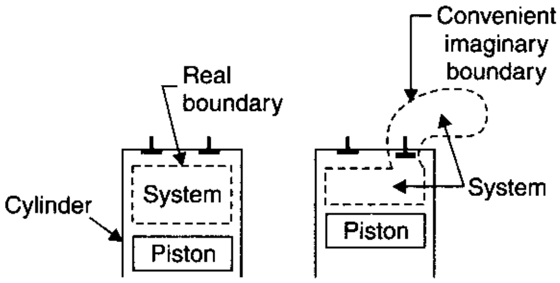


Fig. 2.3. The real and imaginary boundaries.

2.3.2. Closed System

Refer to Fig. 2.4. *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.*

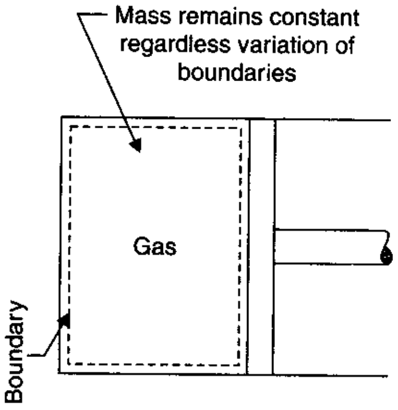


Fig. 2.4. Closed system.

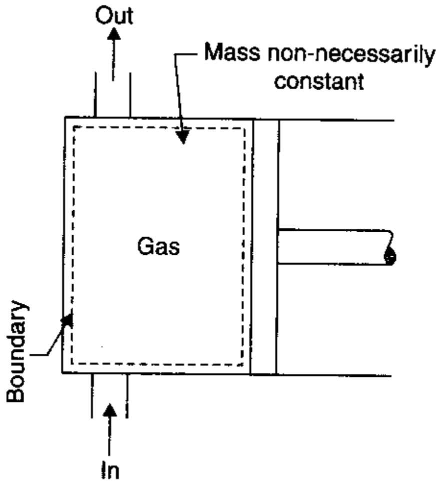


Fig. 2.5. Open system.

2.3.3. Open System

Refer to Fig. 2.5. An open system is one in which *matter flows into or out of the system.* Most of the engineering systems are open.

2.3.4. Isolated System

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

2.3.5. 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.

2.3.6. 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.

2.3.7. 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.

2.4. 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*)

These approaches are discussed (in a comparative way) below :

S. No.	*Macroscopic approach*	*Microscopic approach*
1.	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*.	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.	The analysis of macroscopic system requires simple mathematical formulae.	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.
3.	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.*	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.*
4.	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.

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.

2.5. 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.

2.6. 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.

2.7. 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. For example, 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.

2.8. 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.*

2.9. 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*** (Fig. 2.4). *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 (Fig. 2.5) 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.*

2.10. 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. Fig. 2.6 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'.

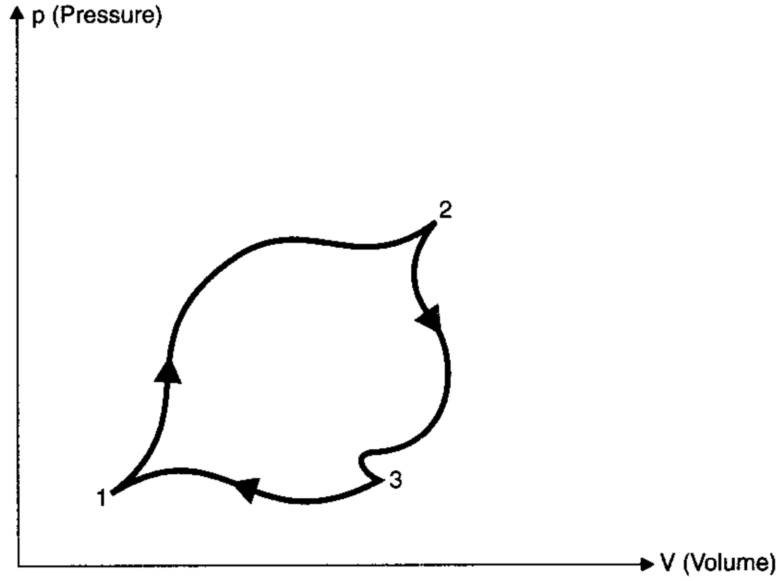


Fig. 2.6. Cycle of operations.

2.11. 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.

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

2.12. 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.

Thus $\int_1^2 \delta Q \neq Q_2 - Q_1$ and is shown as ${}_1Q_2$ or Q_{1-2}

Similarly $\int_1^2 \delta W \neq W_2 - W_1$, and is shown as ${}_1W_2$ or W_{1-2}

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

2.13. TEMPERATURE

- *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 hhave 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.

Then : Absolute temperature = Thermometer reading in °C + 273.15.

Absolute temperature is degree centigrade is known as degrees kelvin, denoted by K (SI unit).

2.14. 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.*

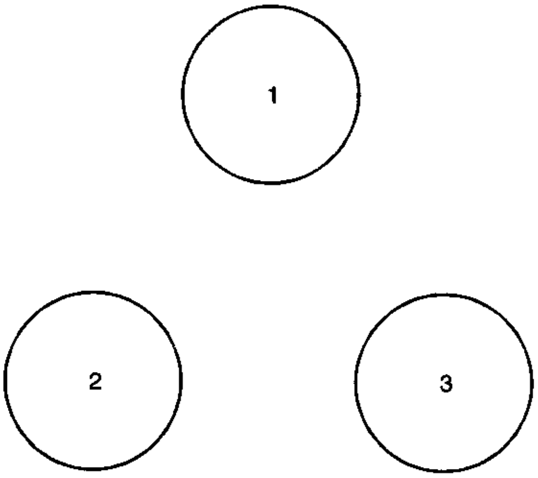


Fig. 2.7. Zeroth law of thermodynamics.

Example. Refer Fig. 2.7. 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.

- 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.*

2.15. THE THERMOMETER AND THERMOMETRIC PROPERTY

2.15.1. Introduction

- 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.

Six different kinds of thermometers, and the names of the corresponding thermometric properties employed are given below :

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 (E)
6. Radiation (pyrometer)	Intensity of radiation (I or J)

2.15.2. Measurement of Temperature

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

2.15.2.1. 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. These thermometers are discussed below :

(*i*) **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. A usual type of mercury-in-glass thermometer is shown in Fig. 2.8. 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.

Fig. 2.8. 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

(*ii*) **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 principle on which they work is quite simple. 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.

Pressure thermometers are discussed below :

(*i*) **Vapour pressure thermometer.** A schematic diagram of a vapour pressure thermometer is shown in Fig. 2.9. 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.

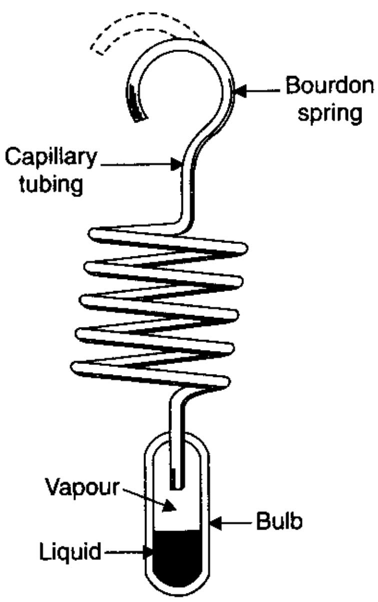


Fig. 2.9. Vapour pressure thermometer.

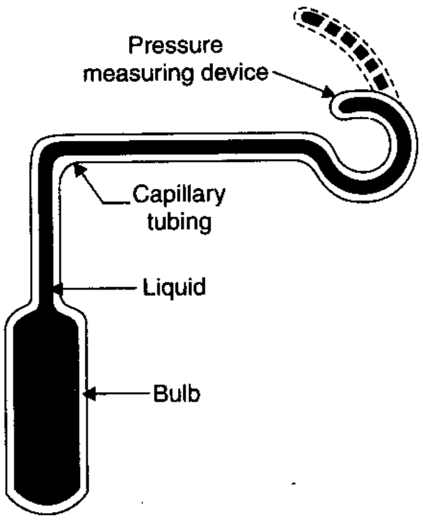


Fig. 2.10. Liquid-filled thermometer.

(*ii*) **Liquid-filled thermometer.** A liquid-filled thermometer is shown in Fig. 2.10. 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.

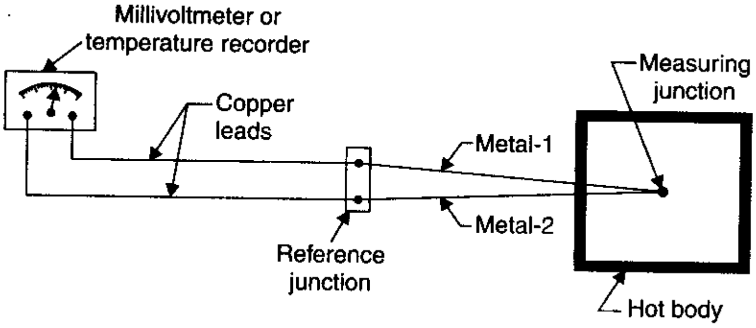


Fig. 2.11. Thermocouple.

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. Fig. 2.11, shows a simple circuit of a thermocouple and the temperature measuring device. 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.

Table 2.1 gives the composition, useful temperatures range and temperature versus e.m.f. relationship for some commercial thermocouples.

Table 2.1. Composition, useful temperature range and e.m.f. produced for some thermocouples

S.No.	*Thermocouple*	*Composition*	*Temperature (°C)*		*Thermoelectric power*		*Remarks*
			Useful range	*Max.*	*°C*	*Millivolt*	
1.	Platinum vs Platinum-rhodium	Pure platinum vs Pt + 10 or 13% Rh	400 to 1450	1700	0	0.0	Used for high temperature measurements
					500	4.219	
					1000	9.569	
					1500	15.498	
2.	Chromel vs alumel	90% Ni + 10% Cr vs 95% Ni + 5% (Al + Sn) Mn	– 200 to 1200	1450	– 200	– 5.75	High resistance to oxidation
					0	0.0	
					300	12.21	
					600	24.90	
					900	37.36	
					1200	48.85	

3.	Iron vs constantan	Pure iron vs 45-60% Cu + 55-40% Ni	– 200 to 750	1000	– 200	– 8.27	—
					0	0.0	
					300	16.59	
					600	33.27	
					900	52.29	
4.	Copper vs constantan	Pure copper vs Cu-Ni constantan	– 200 to 350	600	– 200	– 5.539	Not suitable in air due to excessive oxidation
					0	0.0	
					200	9.285	
					400	20.865	

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 loads* 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 ± 0.01°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.***

The elements of a total radiation pyrometer are illustrated in Fig. 2.12. It collects the radiation from an object (hot body) whose temperature is required. A mirror is used to focus this radiation on a thermocouple. 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.*

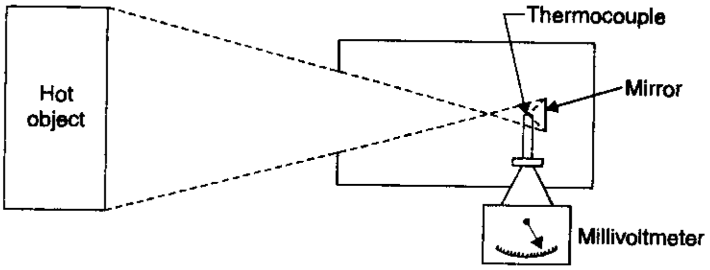


Fig. 2.12. A schematic diagram of radiation pyrometer.

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.

Fig. 2.13 shows a *disappearing filament pyrometer*.

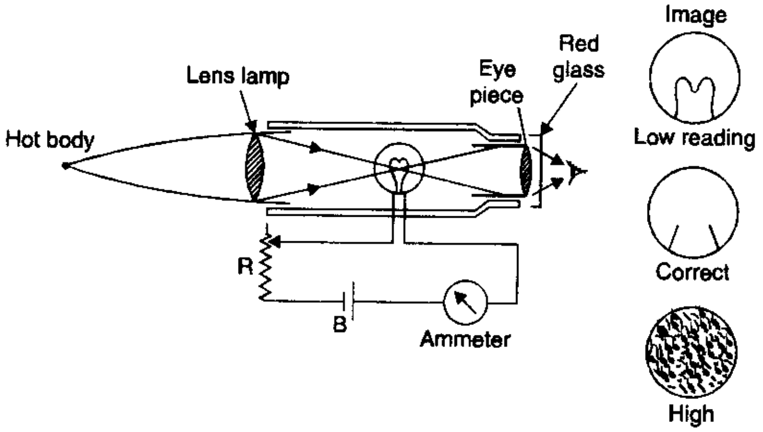


Fig. 2.13. Optical pyrometer.

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.

Table 2.2 gives the summary of temperature range of different instruments on next page.

Table 2.2. Summary of temperature range of different instruments

Types of instruments	*Liquid in glass thermometer*	*Bimetallic thermometer*	*Pressure thermometers*			*Thermocouples*				*Resistance thermometers*			*Radiation pyrometers*	*Optical pyrometers*
	Mercury		Vapour pressure	Liquid filled	Gas filled	Iron-Constantan	Copper-Constantan	Chromel-Alumel -	Platinum Platinum-Rhodium	Copper	Nickel	Platinum	–	–
Low temperature limit	– 39°C	– 75°C	– 250°C	– 87°C	– 269°C	– 196°C	– 250°C	–184°C	0°C	– 140°C	– 184°C	– 184°C	About room temp.	760°C
High temperature limit	600°C	540°C	316°C	650°C	540°C	760°C	350°C	1260°C	1540°C	120°C	316°C	760°C	As high as desired	As high as desired
Remark	Low price ; Fairly accurate ; Easily broken	Easier to read than Liquid-in-glass thermometers	Normally scale non-linear	To be compensated for variation in ambient temperatures	Requires large bulb ; Linear scale	Widely used in Industry.	Constantan is 60% Cu 40% Ni	Chromel is 20% ; Cr 80% ; Ni-Alumel is 2% Al, 98% Ni,	Expensive	Very sensitive. Suitable for narrow range instruments			—	—

2.15.3. The International Practical Temperature Scale

For the calibration of thermometric instruments the Seventh General Conference on Weight and Measures held in 1927 formulated a convenient scale known as the *International Practical Temperature Scale*. It was revised at Thirteenth General Conference in 1968. It consists of *reproducible reference temperatures or primary fixed points* defined by a number of pure substances with assigned values of temperatures determined with precision on ideal or perfect gas temperature scale as given in Table 2.3.

Table 2.3. Fixed Points of the International Practical Temperature Scale of 1968

Equilibrium state	*Assigned value of temperature*	
	T, K	*t°C*
1. Triple point of hydrogen	13.81	–259.34
2. Boiling point of hydrogen at 33.306 kPa	17.042	–266.108
3. Normal boiling point of hydrogen	20.28	–252.87
4. Normal boiling point of neon	27.102	–246.048
5. Triple point of oxygen	54.361	–218.789
6. Normal boiling point of oxygen	90.188	–182.962
7. Triple point of water	273.16	0.01
8. Normal boiling point of water	373.15	100.00
9. Normal freezing point of antimony (antimony point)	630.74	357.59
10. Normal freezing point of zinc (zinc point)	692.73	419.58
11. Normal freezing point of silver (silver point)	1235.08	961.93
12. Normal freezing point of gold (gold point)	1337.58	1064.43

It is stated here that :

— The *triple point* represents an equilibrium state between solid, liquid and vapour phases of a substance.

— *Normal boiling point* is the temperature at which the substance boils at standard atmospheric pressure of 760 mm Hg.

— *Normal freezing point* is the solidification or the melting point temperature of the substance at standard atmospheric pressure.

Based on the available method of measurement, the whole temperature scale may be divided into four ranges. The equations for interpolation for each range are as follows :

1. From – 259.34°C (triple point of hydrogen) to 0°C :

A *platinum resistance thermometer of a standard design* is used and a polynomial of the following form is fitted between the resistance of the wire R_t and temperature t

$$R_t = R_0 (1 + At + Bt^2 + Ct^3) \qquad \text{...(2.6)}$$

where R_0 = resistance at the ice point.

2. From 0°C to 630.74°C (Antimony point) :

- It is also based on *platinum resistance thermometer.*
- The diameter of the platinum wire must lie between 0.05 and 0.2 mm.

3. From 630.74°C to 1064.43°C (Gold point) :

- It is based on *standard platinum versus platinum-rhodium thermocouple.*
- Following equation between e.m.f. E and temperature t is employed :

$$E = a + bt + ct^2 \qquad \text{...(2.7)}$$

4. **Above 1064.43°C :**

- It is *based on the intensity of radiation J_T at temperature T emitted by a black body at a wavelength λ in the visible spectrum and by comparing this to the intensity of radiation J_{Au} at the same wavelength emitted by a black body at the gold point.*
- The temperature is calculated from Planck's equation for black body radiation

$$\frac{J_T}{J_{Au}} = \frac{\exp\left(\dfrac{C_2}{\lambda\, T_{Au}}\right) - 1}{\exp\left(\dfrac{C_2}{\lambda T}\right) - 1} \quad \text{...(2.8)}$$

where C_2 = 0.01438 in °C, and λ = wavelength in metres.

Following points are worth noting for gas thermometers :

- *The gas thermometers are never used for the measurement of temperatures.* However, *they are ideal when used for calibration for establishing the ideal gas temperature scale, and for establishing a standard because of precision, reproducible results, and their reading being independent of the thermometric substance used.*
- *The gas thermometers can be used only for temperatures upto which gases do not liquify.*

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 :

$$\frac{C}{100} = \frac{F-32}{180} \text{ or } \frac{C}{5} = \frac{F-32}{9} \quad \text{...(2.9)}$$

- Further the relation between a temperature difference Δt_F on Fahrenheit scale and Δt_C on celsius scale is

$$\Delta t_F = \frac{180}{100}\Delta t_C = \frac{9}{5}\Delta t_C = 1.8\ \Delta t_C \quad \text{...(2.10)}$$

- The use of two fixed points was found unsatisfactory and later *abandoned* because of the following *reasons* :

(*i*) It is difficult to achieve equilibrium between pure ice and air-saturated water (since when ice melts, it surrounds itself only with pure water and prevents intimate contact with air-saturated water).

(*ii*) There is extreme sensitiveness of the steam point to the change in pressure.

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. The tenth CGPM, 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 :

$$T(K) = t(°C) + 273.15 \qquad ...(2.11)$$

2.15.4. Ideal Gas

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

$$pV = mRT \qquad ...(2.12)$$

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.***

Eqn. (2.10) can be written as

$$pv = RT \qquad ...(2.13)$$

(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, eqn. (2.10) can be written as,

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

or

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \times \frac{V_2}{V_1} \qquad ...(2.14)$$

With the help of this eqn. (2.12), the temperatures can be measured or compared.

2.16. PRESSURE

2.16.1. Definition of Pressure

Pressure is defined as a *force per unit area.* Pressures are exerted by gases, vapours and liquids. The instruments that we generally use, however, record pressure as the difference between two pressures. Thus, it is the *difference between the pressure exerted by a fluid of interest and the ambient atmospheric pressure.* Such devices indicate the pressure either above or below that of the atmosphere. When it is *above the atmospheric pressure*, it is termed *gauge pressure* and is *positive*. When it is *below* atmospheric, it is *negative* and is known as *vacuum*. Vacuum readings are given in millimetres of mercury or millimetres of water below the atmosphere.

It is necessary to establish an absolute pressure scale which is independent of the changes in atmospheric pressure. A pressure of absolute zero can exist only in complete vacuum. *Any pressure measured above the absolute zero of pressure* is termed an '*absolute pressure*'.

A schematic diagram showing the *gauge pressure, vacuum pressure* and the *absolute pressure* is given in Fig. 2.14.

Mathematically :

(*i*) Absolute pressure = Atmospheric pressure + Gauge pressure

$$p_{\text{abs.}} = p_{\text{atm.}} + p_{\text{gauge}}.$$

(*ii*) Vacuum pressure = Atmospheric pressure − Absolute pressure.

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.*

Atmospheric pressure is measured with the help of barometer.

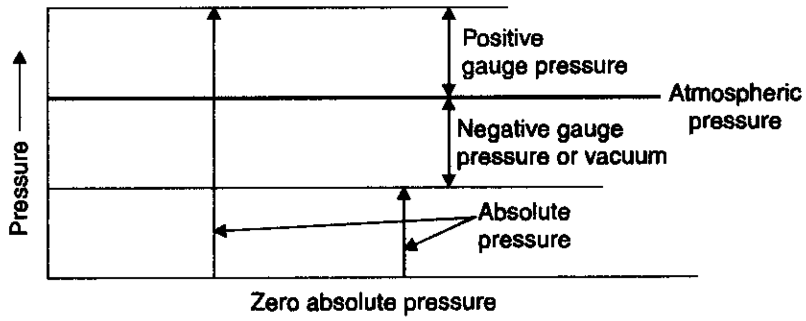


Fig. 2.14. Schematic diagram showing gauge, vacuum and absolute pressures.

2.16.2. Unit for Pressure

The fundamental SI unit of pressure is N/m^2 (sometimes called *pascal*, Pa) or bar. 1 bar = 10^5 N/m^2 = 10^5 Pa.

Standard atmospheric pressure = 1.01325 bar = 0.76 m (or 760 mm) Hg.

Low pressures are often expressed in terms of mm of water or mm of mercury. This is an abbreviated way of saying that the pressure is such that which will support a liquid column of stated height.

2.16.3. 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.

2.16.4. 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.

2.16.4.1. 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.

1. *U-tube manometer :*

A U-tube manometer is in the form of U-tube and is made of glass. When no pressure is applied, the height of the liquid in the two legs is the same. The pressure is then applied to one leg, whilst the other is open to the atmosphere. Under this pressure the liquid will *sink* in this leg and will *rise* in the other. As the other leg is open to the air, therefore, the pressure on this side is known, and is barometric. Now the pressure applied to the first leg can be calculated. This is explained with reference to Fig. 2.15. This consists of a water manometer.

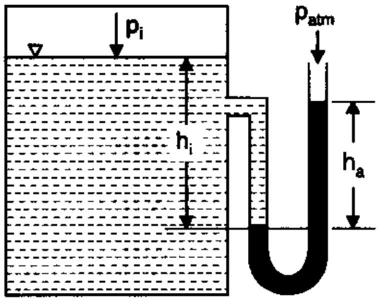


Fig. 2.15. Principle of U-tube manometer.

Considering equilibrium condition, we have

$$p_{\text{atm}} + w_a h_a = p_i + w_i h_i$$

$$\therefore \quad p_i = p_{\text{atm}} + w_a h_a - w_i h_i$$

where $p_{\text{atm.}}$ = Atmospheric pressure,

p_i = Pressure over water surface in the container,

h_a = Height of liquid in U-tube manometer,

h_i = Difference between water surface and lower surface of the liquid in manometer,

w_a = Specific weight of liquid,

w_i = Specific weight of water.

The U-tube manometer shown in Fig. 2.16 is of the simplest form. 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 :*

Fig. 2.17 shows a 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 (discussed above) 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 as shown in Fig. 2.18 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.*

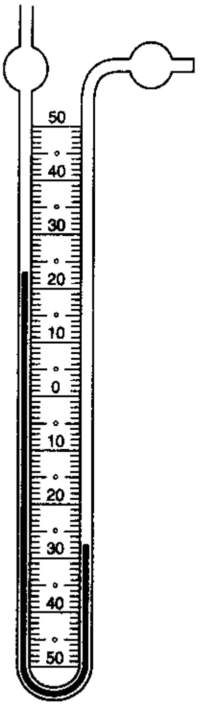


Fig. 2.16. U-tube manometer.

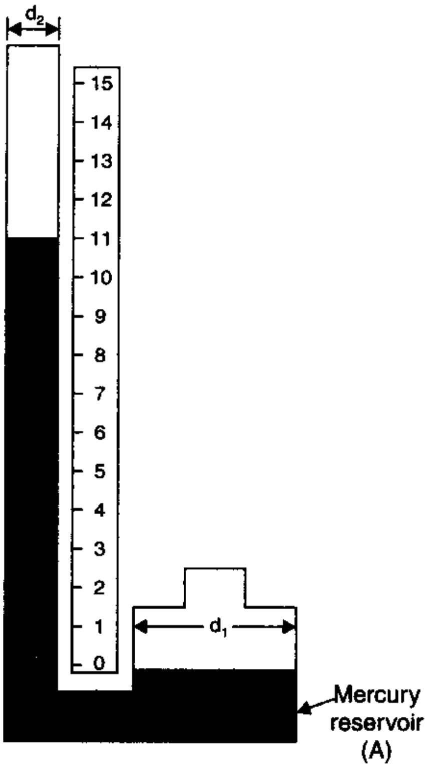


Fig. 2.17. Cistern manometer.

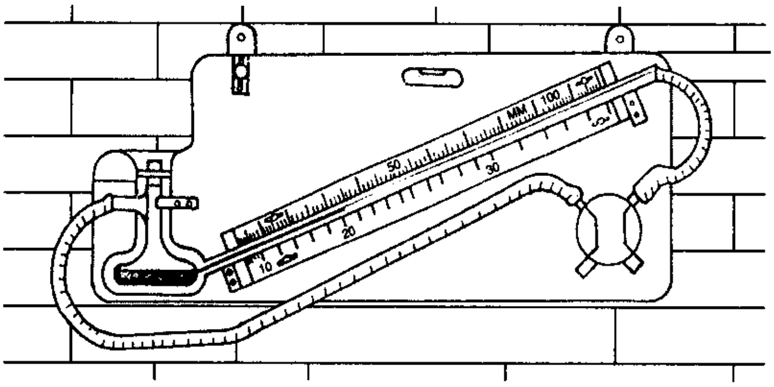


Fig. 2.18. Inclined manometer.

The principle of the inclined manometer is explained in Fig. 2.19. 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 is 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

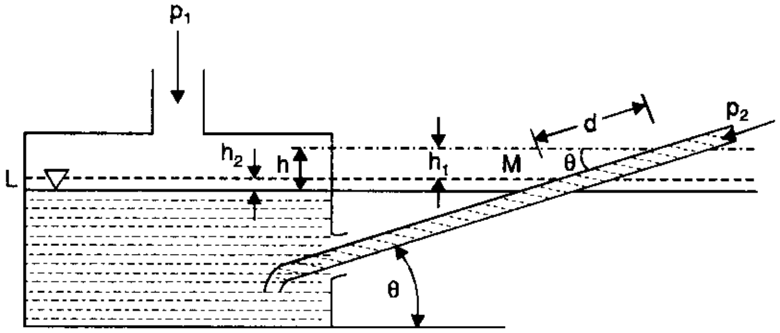


Fig. 2.19. Principle of inclined manometer.

$$h = h_1 + h_2$$

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.

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 and disadvantages of manometers :

Advantages. The manometer claims the following advantages :

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. The *disadvantages* of manometers are as follows :

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.

(*a*) Bourdon tubes/elements :

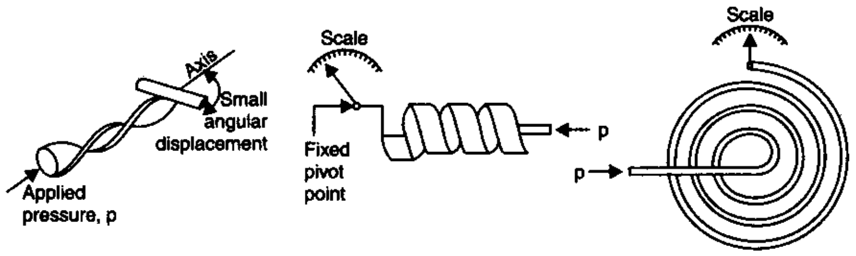
Fig. 2.20 shows Bourdon tube configurations.

Advantages. The Bourdon tube element has the following *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.



(*a*) (*b*) (*c*)

Fig. 2.20. (*a*) Twisted tube, (*b*) Helical, (*c*) Spiral.

(*b*) **Diaphragm elements :**

Fig. 2.21 shows basic diaphragm types.

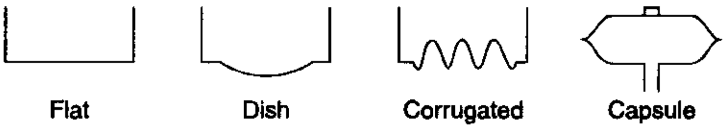


Fig. 2.21. Basic diaphragm types.

Advantages :

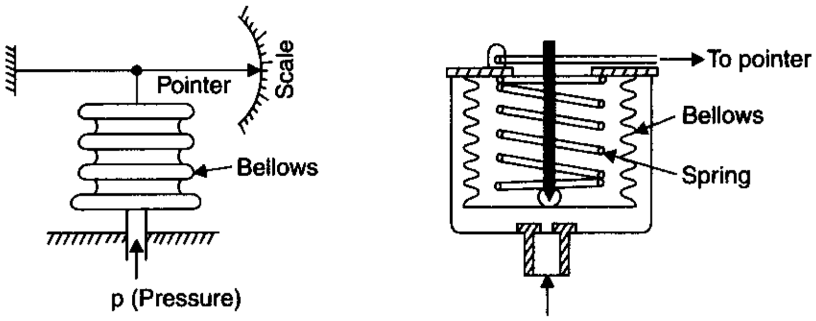
1. Small in size and moderately priced.
2. Wide linear range.
3. Can withstand high over pressures and under pressures.
4. Small hysteresis.
5. Can be used for measurement of absolute and differential pressures as also vacuum.

Disadvantages :

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

(*c*) **Bellow gauges/elements :**

Fig. 2.22 shows some bellow gauges.



(a) Bellows pressure gauge (b) Spring loaded bellows gauge

Fig. 2.22. Bellow gauges.

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.

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.

2.16.4.2. Important types of pressure gauges

The manometers and U-tubes (discussed earlier) 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. Diahragm 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.* A simple form of this gauge is shown in Fig. 2.23. 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 :

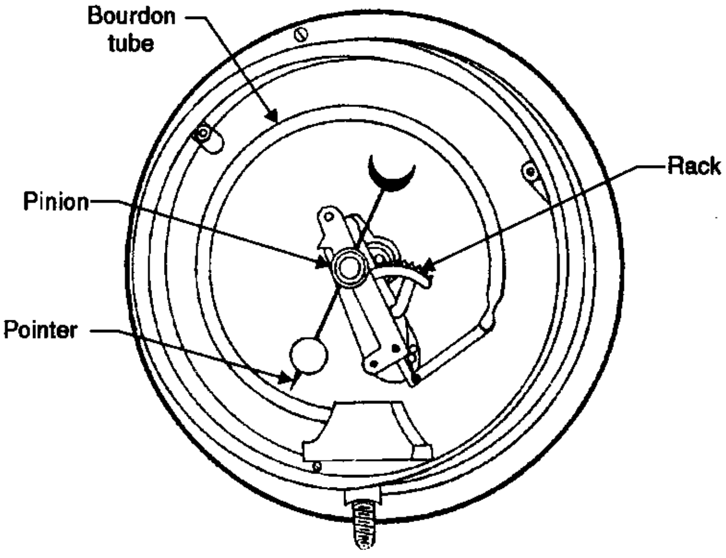


Fig. 2.23. Burdon tube pressure gauge.

(*i*) ***Compound Bourdon tube*** ...... used for measuring pressures both above and below atmospheric.

(*ii*) ***Double Bourdon tube*** ...... used where vibrations are encountered.

2. *Diaphragm gauge :*

This type of gauge employs a metallic disc or diaphragm instead of a bent tube. This disc or diaphragm is used for *actuating* the indicating device.

Refer Fig. 2.24. When pressure is applied on the lower side of the diaphragm, it is deflected upward. This movement of the diaphragm is transmitted to a rack and pinion. The latter is attached to the spindle of needle moving on a graduated dial. The dial can again be graduated in a suitable scale.

3. *Vacuum gauge :*

Bourdon gauges discussed earlier can be used to measure vacuum instead of pressure. Slight changes in the design are required for this purpose. Thus, in this case, the tube be *bent inward instead of outward* as in pressure gauge. *Vacuum gauges* are graduated in millimetres of mercury below atmospheric pressure. In such cases, therefore, absolute pressure in millimetres of mercury is the difference between barometer reading and vacuum gauge reading.

Vacuum gauges are used to measure the vacuum in the *condensers* etc. If there is leakage, the vacuum will drop.

The pressure gauge installation require the following *considerations* :

(*i*) Flexible copper tubing and compression fittings are recommended for most installations.

(*ii*) The installation of a gauge cock and tee in the line close to the gauge is recomm- ended because it permits the gauge to be removed for testing or replacement without having to shut down the system.

(*iii*) Pulsating pressures in the gauge line are not required.

(*iv*) The gauge and its connecting line is filled with an inert liquid and as such liquid seals are provided. Trapped air at any point of gauge lines may cause serious errors in pressure reading.

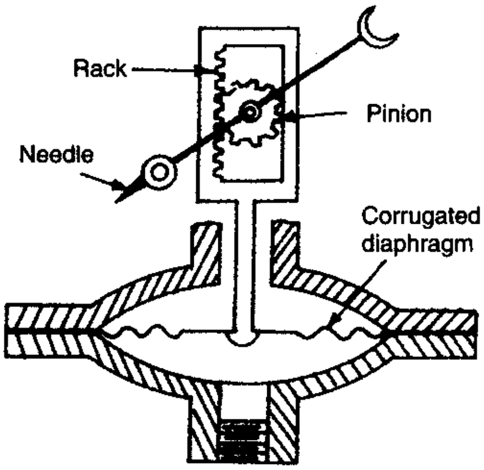


Fig. 2.24. Principle of diaphragm gauge.

2.17. SPECIFIC VOLUME

The *specific volume* of a system is the volume occupied by the unit mass of the system. The symbol used is v and units are ; for example, m^3/kg. The symbol V will be used for volume. (Note that specific volume is *reciprocal of density*).

Example 2.1. *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 H_2O gauge*

(*iv*) *4.2 bar.*

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

Pressure of 760 mm of Hg will be

$$= \rho \times g \times h = 13.596 \times 1000 \times 9.806 \times \frac{760}{1000}$$

$$= 101325 \text{ Pa} = 101.325 \text{ kPa.}$$

(*i*) **Pressure of 80 cm of Hg**

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

(*ii*) **30 cm Hg vacuum**

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

Pressure due to 46 cm of Hg

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

(*iii*) **Pressure due to 1.35 m H_2O gauge**

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

(*iv*) **4.2 bar**

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

Note. Pressure of 1 atmosphere

= 760 mm of Hg

or = 101325 N/m^2.

The above values are standard. To get this value we have to use $\rho_{Hg} = 13596$ kg/m^3 and $g = 9.806$ m/s^2. When we use $\rho_{Hg} = 13600$ kg/m^3 and $g = 9.81$ m/s^2, we get $p_{atm.} = 101396$ N/m^2 which is slightly different from 101325 N/m^2. It is recommended that for pressure of 1 atm. the value 101325 N/m^2 should be used.

Example 2.2. *On a piston of 10 cm diameter a force of 1000 N is uniformly applied. Find the pressure on the piston.*

Solution. Diameter of the piston $d = 10$ cm (= 0.1 m)

Force applied on the piston, $F = 1000$ N

$$\therefore \quad \text{Pressure on the piston, } p = \frac{\text{Force}}{\text{Area}} = \frac{F}{A} = \frac{1000}{\pi / 4 \times (0.1)^2}$$

$$= 127307 \text{ N/m}^2 = \mathbf{127.307\ kN/m^2.} \quad \textbf{(Ans.)}$$

Example 2.3. *A tube contains an oil of specific gravity 0.9 to a depth of 120 cm. Find the gauge pressure at this depth (in kN/m^2).*

Solution. Specific gravity of oil = 0.9

Depth of oil in the tube, $h = 120$ cm = (1.2 m)

We know that $p = wh$

$= \rho.g.h$, ρ being the mass density

$= (0.9\ \rho_w) \times g \times h$, ρ_w being mass density of water

$$\left[\text{Specific gravity} = \frac{\rho}{\rho_w}\right]$$

$$= 0.9 \times 1000 \times 9.81 \times 1.2 \text{ N/m}^2$$

$$= 10594.8 \text{ N/m}^2 = \mathbf{10.595\ kN/m^2.} \quad \textbf{(Ans.)}$$

Example 2.4. *A vacuum recorded in the condenser of a steam power plant is 740 mm of Hg. Find the absolute pressure in the condenser in Pa. The barometric reading is 760 mm of Hg.*

Solution. Vacuum recorded in the condenser = 740 mm of Hg

Barometric reading = 760 mm of Hg

We know that,

Absolute pressure in the condenser

= Barometric reading – vacuum in the condenser

= 760 – 740 = 20 mm of Hg

$= 20 \times 133.4 \text{ N/m}^2 \quad (\because \ 1 \text{ mm of Hg} = 133.4 \text{ N/m}^2)$

$= 2668 \text{ N/m}^2 =$ **2668 Pa.(Ans.)**

Example 2.5. *A vessel of cylindrical shape is 50 cm in diameter and 75 cm high. It contains 4 kg of a gas. The pressure measured with manometer indicates 620 mm of Hg above atmosphere when barometer reads 760 mm of Hg. Determine :*

(i) The absolute pressure of the gas in the vessel in bar.

(ii) Specific volume and density of the gas.

Solution. Diameter of the vessel, $d = 50$ cm (= 0.5 m)

Height of the vessel, $h = 75$ cm (= 0.75 m)

Mass of gas in the vessel, $m = 4$ kg

Manometer reading = 620 mm of Hg above atmosphere

Barometer reading = 760 mm of Hg

Now, volume of the vessel $= \frac{\pi}{4} d^2 \times h = \frac{\pi}{4} \times (0.5)^2 \times (0.75) = 0.147 \text{ m}^3.$

(*i*) **Total pressure in the vessel**

= 760 + 620 = 1380 mm of Hg

$= 1380 \times 133.4 \text{ N/m}^2 \quad [\because 1 \text{ mm of Hg} = 133.4 \text{ N/m}^2]$

$= 1.841 \times 10^5 \text{ N/m}^2 =$ **1.841 bar.(Ans.)** $[\because \ 1 \text{ bar} = 10^5 \text{ N/m}^2]$

(*ii*) **Specific volume** $= \frac{0.147}{4} =$ **0.03675 m³/kg.(Ans.)**

Density $= \frac{4}{0.147} =$ **27.21 kg/m³.(Ans.)**

Example 2.6. *In a pipe line the pressure of gas is measured with a mercury manometer having one limb open to the atmosphere (Fig. 2.25). If the difference in the height of mercury in the two limbs is 550 mm, calculate the gas pressure.*

Given : Barometric reading = 761 mm of Hg

Acceleration due to gravity = 9.79 m/s²

Density of mercury = 13640 kg/m³.

Solution. At the plane LM, we have

$$p = p_0 + \rho g h$$

Now $p_0 = \rho g h_0$

where h_0 = barometric height ; ρ = density of mercury ; p_0 = atmospheric pressure

Therefore, $p = \rho g h_0 + \rho g h = \rho g (h_0 + h)$

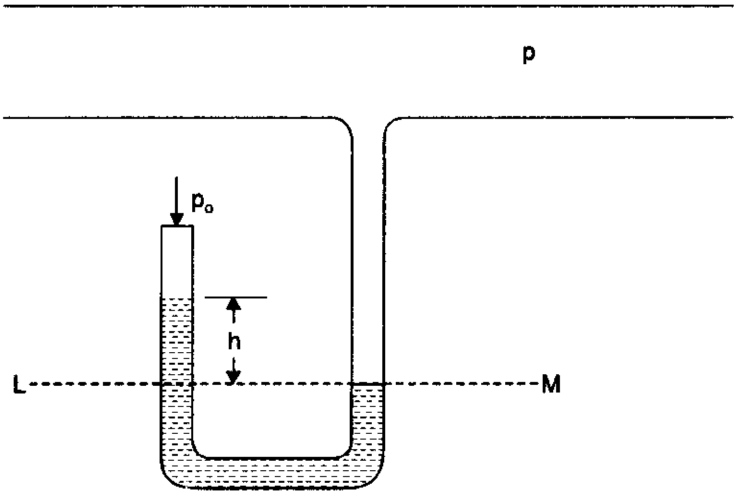


Fig. 2.25

$$= 13640 \times 9.79 \left(\frac{761}{1000} + \frac{550}{1000}\right) = 13640 \times 9.79\ (0.761 + 0.55)$$

$$= 175.065 \times 10^3\ \text{N/m}^2 = 175.065\ \text{kPa} = \mathbf{1.75\ bar.}\ \ \textbf{(Ans.)}$$

Example 2.7. *A U-tube mercury manometer with one arm open to atmosphere is used to measure pressure in a steam pipe. The level of mercury in open arm is 97.5 mm greater than that in the arm connected to the pipe. Some of steam in the pipe condenses in the manometer arm connected to the pipe. The height of this column is 34 mm. The atmospheric pressure is 760 mm of Hg. Find the absolute pressure of steam.* **(Poona University, Nov. 1997)**

Solution. Equating the pressure in mm of Hg on both arms above the line *XX* (Fig. 2.26), we get

$$p_{\text{abs.}} + p_{\text{water}} = p_{\text{Hg}} + p_{\text{atm.}}$$

Now, $p_{\text{water}} = \dfrac{34}{13.6} = 2.5$ mm of Hg.

$\therefore \quad p_{\text{abs}} + 2.5 = 97.5 + 760$

or $\quad p_{\text{abs}} = 97.5 + 760 - 2.5$

$= 855$ mm of Hg.

$= 855 \times \rho_{\text{Hg}} \times g \times 10^{-5}$ bar

$= \dfrac{855}{1000}\ (m) \times (13.6 \times 1000)\ (\text{kg/m}^3) \times 9.81 \times 10^{-5}$

= **1.1407 bar. (Ans.)**

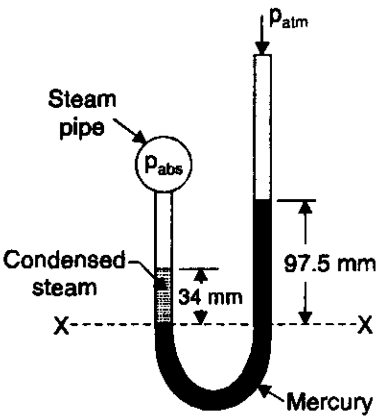


Fig. 2.26

Example 2.8. *A U-tube manometer is connected to a gas pipe. The level of the liquid in the manometer arm open to the atmosphere is 170 mm lower than the level of the liquid in the arm connected to the gas pipe. The liquid in the manometer has specific gravity of 0.8. Find the absolute pressure of the gas if the manometer reads 760 mm of Hg.*

(Poona University, Dec. 2000)

Solution. Equating pressure on both arms above the line *XX* (Fig. 2.27), we get

$$p_{gas} + p_{liquid} = p_{atm.} \quad ...(i)$$

Now, $p_{liquid} = \rho.g.h$

$$= (0.8 \times 1000) \times 9.81 \times \frac{170}{1000}$$

$$= 1334.16 \text{ N/m}^2$$

$$= 0.0133416 \text{ bar}$$

$$p_{atm.} = 760 \text{ mm of Hg} = 1.01325 \text{ bar}$$

Substituting these value is eqn. (*i*) above, we have

$$p_{gas} + 0.0133416 = 1.01325$$

$\therefore$ $\boldsymbol{p_{gas} = 0.9999}$ **bar. (Ans.)**

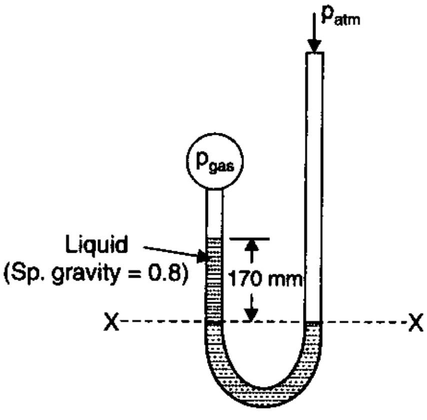


Fig. 2.27

Example 2.9. *Estimate the mass of a piston that can be supported by a gas entrapped under the piston in a 200 mm diameter vertical cylinder when a manometer indicates a difference of 117 mm of Hg column for the gas pressure.* **(Poona University, May 1996)**

Solution. Refer Fig. 2.28.

Let m = mass of the piston, kg.

p = pressure of the gas

= 117 mm of Hg column

Dia. of vertical cylinder, d = 200 mm

Now, downward force = $m.g$ ...(*i*)

and upward force = $p \times \pi/4 \; d^2$ ...(*ii*)

Equating eqns. (*i*) and (*ii*), we get

$$m.g = p \times \pi/4 \; d^2$$

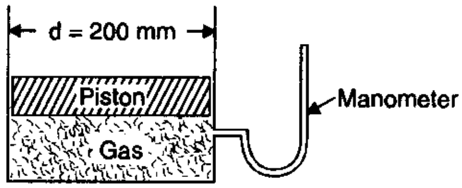


Fig. 2.28

$$m \times 9.81 = \left(13.6 \times 1000 \times 9.81 \times \frac{117}{1000}\right) \times \frac{\pi}{4} \times \left(\frac{200}{1000}\right)^2 \qquad (\because \; p = \rho gh)$$

$\therefore$ **m = 49.989 kg.(Ans.)**

2.18. REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible process. *A reversible process (also sometimes known as quasi-static process) is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.*

This process has the following *characteristics* :

1. It must pass through the same states on the reversed path as were initially visited on the forward path.

2. This process when undone will leave no history of events in the surroundings.

3. It must pass through a continuous series of equilibrium states.

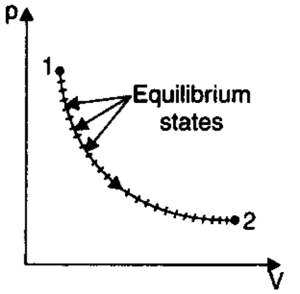


Fig. 2.29. Reversible process.

No real process is truely reversible but some processes may approach reversibility, to close approximation.

Examples. Some examples of nearly reversible processes are :

(*i*) Frictionless relative motion.
(*ii*) Expansion and compression of spring.
(*iii*) Frictionless adiabatic expansion or compression of fluid.
(*iv*) Polytropic expansion or compression of fluid.
(*v*) Isothermal expansion or compression.
(*vi*) Electrolysis.

Irreversible process. An *irreversible process* is one *in which heat is transferred through a finite temperature.*

Examples.

(*i*) Relative motion with friction
(*ii*) Combustion
(*iii*) Diffusion
(*iv*) Free expansion
(*v*) Throttling
(*vi*) Electricity flow through a resistance
(*vii*) Heat transfer
(*viii*) Plastic deformation.

An irreversible process is usually represented by a dotted (or discontinuous) line joining the end states to indicate that the intermediate states are indeterminate (Fig. 2.30).

Irreversibilities are of *two types* :

1. **External irreversibilities.** These are associated with *dissipating effects outside the working fluid.*

Example. *Mechanical friction occurring during a process due to some external source.*

2. **Internal irreversibilities.** These are associated with *dissipating effects within the working fluid.*

Example. *Unrestricted expansion of gas, viscosity and inertia of the gas.*

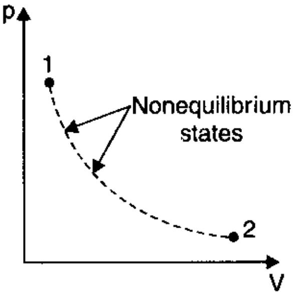


Fig. 2.30. Irreversible process.

2.19. ENERGY, WORK AND HEAT

2.19.1. Energy

Energy is a general term embracing *energy in transition* and *stored energy.* The stored energy of a substance may be in the forms of *mechanical energy* and *internal energy* (other forms of stored energy may be chemical energy and electrical energy). Part of the stored energy may take the form of either potential energy (which is the gravitational energy due to height above a chosen datum line) or kinetic energy due to velocity. The balance part of the energy is known as *internal energy*. In a ***non-flow process*** *usually there is no change of potential or kinetic energy and hence change of mechanical energy will not enter the calculations.* In a ***flow process***, however, *there may be changes in both potential and kinetic energy and these must be taken into account while considering the changes of stored energy.* ***Heat and work*** are *the forms of energy in transition.* These are the only forms in which energy can cross the boundaries of a system. *Neither heat nor work can exist as stored energy.*

2.19.2. Work and Heat

Work

Work is said to be done when a *force moves through a distance.* If a part of the boundary of a system undergoes a displacement under the action of a pressure, the work done *W* is the product of the force (pressure × area), and the distance it moves in the direction of the force. Fig. 2.31 (*a*) illustrates this with the conventional piston and cylinder arrangement, the heavy line defining the boundary of the system. Fig. 2.31 (*b*) illustrates another way in which work might be applied to a system. A force is exerted by the paddle as it changes the momentum of the fluid, and since this force moves during rotation of the paddle work is done.

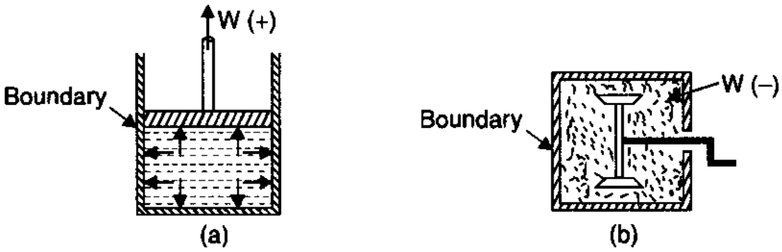


Fig. 2.31

Work is a transient quantity which only appears at the boundary while a change of state is taking place within a system. Work is 'something' which appears at the boundary when a system changes its state due to the movement of a part of the boundary under the action of a force.

Sign convention :

- If the work is done *by* the system *on* the surroundings, *e.g.*, when a fluid expands pushing a piston outwards, the work is said to be *positive.*

i.e., *Work output of the system* = + *W*

- If the work is done *on* the system *by* the surroundings, *e.g.*, when a force is applied to a rotating handle, or to a piston to compress a fluid, the work is said to be *negative.*

i.e., *Work input to system* = – *W*

Heat

Heat (denoted by the symbol Q), may be, defined in an analogous way to work as follows :

"Heat is 'something' which appears at the boundary when a system changes its state due to a difference in temperature between the system and its surroundings".

Heat, like work, is a transient quantity which only appears at the boundary while a change is taking place within the system.

It is apparent that neither δW or δQ are exact differentials and therefore any integration of the elemental quantities of work or heat which appear during a change from state 1 to state 2 must be written as

$$\int_1^2 \delta W = W_{1-2} \text{ or } {}_1W_2 \text{ (or } W\text{), and}$$

$$\int_1^2 \delta Q = Q_{1-2} \text{ or } {}_1Q_2 \text{ (or } Q\text{)}$$

Sign convention :

If the heat flows *into* a system *from* the surroundings, the quantity is said to be *positive* and, conversely, if heat flows *from* the system to the surroundings it is said to be *negative.*

In other words :

Heat received by the system = + *Q*

Heat rejected or given up by the system = – *Q*.

Comparison of Work and Heat

Similarities :

(*i*) Both are *path functions and inexact differentials.*

(*ii*) Both are boundary phenomenon *i.e.,* both are recognized at the boundaries of the system as they cross them.

(*iii*) Both are associated with a process, not a state. Unlike properties, work or heat has no meaning at a state.

(*iv*) Systems possess energy, but not work or heat.

Dissimilarities :

(*i*) In heat transfer temperature difference is required.

(*ii*) In a stable system there cannot be work transfer, however, there is no restriction for the transfer of heat.

(*iii*) The sole effect external to the system could be reduced to rise of a weight but in the case of a heat transfer other effects are also observed.

2.20. REVERSIBLE WORK

Let us consider an ideal frictionless fluid contained in a cylinder above a piston as shown in Fig. 2.32. *Assume that the pressure and temperature of the fluid are uniform and that there is no friction between the piston and the cylinder walls.*

Let A = Cross-sectional area of the piston,

p = Pressure of the fluid at any instant,

$(p - dp) A$ = Restraining *force exerted* by the surroundings on the piston, and

dl = The distance moved by the piston under the action of the *force exerted.*

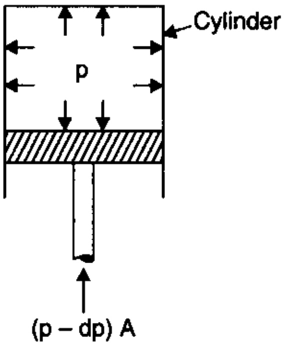


Fig. 2.32

Then work done by the fluid on the piston is given by force times the distance moved,

i.e., Work done by the fluid

$= (pA) \times dl = pdV$

(where dV = a small increase in volume)

Or considering unit mass

Work done $= pdv$ (where v = specific volume)

This is only *true* when (*a*) the *process is frictionless and (b) the difference in pressure between the fluid and its surroundings during the process is infinitely small.* Hence when a reversible process takes place between state 1 and state 2, we have

$$\text{Work done by the unit mass of fluid} = \int_1^2 pdv \qquad ...(2.15)$$

When a fluid undergoes a reversible process a series of state points can be joined up to form a line on a diagram of properties. The work done by the fluid during any reversible process is therefore given by the area under the line of process plotted on a p-v diagram (Fig. 2.32).

i.e., Work done = Shaded area on Fig. 2.33

$$= \int_1^2 pdv .$$

When p can be expressed in terms of v then the integral, $\int_1^2 pdv$, can be evaluated.

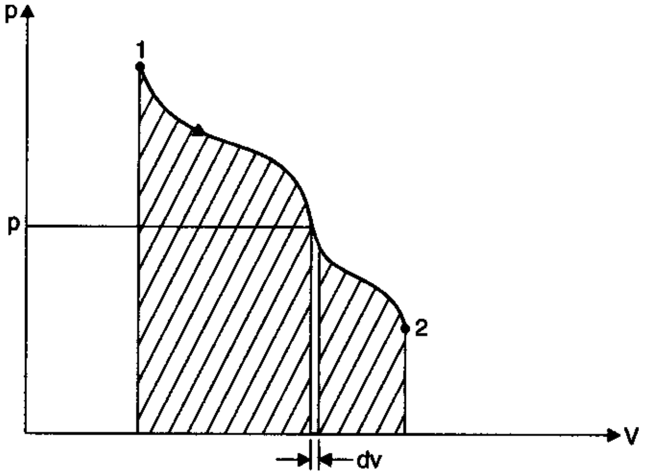


Fig. 2.33

Example 2.10. *An artificial satellite revolves round the earth with a relative velocity of 800 m/s. If acceleration due to gravity is 9 m/s² and gravitational force is 3600 N, calculate its kinetic energy.*

Solution. Relatively velocity of satellite, $v = 800$ m/s

Acceleration due to gravity, $g = 9$ m/s²

Gravitational force, $m.g = 3600$ N

$$\therefore \text{ Mass, } \quad m = \frac{3600}{g} = \frac{3600}{9} = 400 \text{ kg.}$$

Kinetic energy $= \frac{1}{2} mv^2 = \frac{1}{2} \times 400 \times (800)^2$ J $= 128 \times 10^6$ J or **128 MJ. (Ans.)**

Example 2.11. *The specific heat capacity of the system during a certain process is given by*

$$c_n = (0.4 + 0.004\ T) \text{ kJ/kg°C.}$$

If the mass of the gas is 6 kg and its temperature changes from 25°C to 125°C find :

(i) Heat transferred ; *(ii) Mean specific heat of the gas.*

Solution. Mass of the gas, $m = 6$ kg

Change in temperature of the gas = 25°C to 125°C

(*i*) **Heat transferred, Q :**

We know that heat transferred is given by,

$$Q = \int m\ c_n\ dT = 6 \int_{25}^{125} (0.4 + 0.004\ T)\ dT$$

$$= 6\left[0.4\ T + 0.04\left(\frac{T^2}{2}\right)\right]_{25}^{125}$$

$$= 6[0.4\ (125 - 25) + 0.002\ (125^2 - 25^2)]$$

$= 6(40 + 30) =$ **420 kJ.(Ans.)**

(*ii*) **Mean specific heat of the gas, c_n :**

$$Q = m.c_n.dT$$

i.e., $420 = 6 \times c_n \times (125 - 25)$

$\therefore$ $\mathbf{c_n} = \dfrac{420}{6 \times 100} = \mathbf{0.7\ kJ/kg°\text{-}C.}$ **(Ans.)**

Example 2.12. *A temperature scale of certain thermometer is given by the relation*

$$t = a \ln p + b$$

where a and b are constants and p is the thermometric property of the fluid in the thermometer. If at the ice point and steam point the thermometric properties are found to be 1.5 and 7.5 respectively what will be the temperature corresponding to the thermometric property of 3.5 on Celsius scale. **(Poona University, Nov. 2001)**

Solution. $t = a \ln p + b$ ...(*Given*)

On Celsius scale :

Ice point = 0°C, and

Steam point = 100°C

$\therefore$ From given conditions, we have

$$0 = a \ln 1.5 + b \quad ...(i)$$

and $100 = a \ln 7.5 + b$ ...(*ii*)

i.e., $0 = a \times 0.4054 + b$ ...(*iii*)

and $100 = a \times 2.015 + b$ ...(*iv*)

Subtracting (*iii*) from (*iv*), we get

$$100 = 1.61a$$

or $a = 62.112$

Substituting this value in eqn. (*iii*), we get

$$b = -\ 0.4054 \times 62.112 = -\ 25.18$$

$\therefore$ When $p = 3.5$ the value of temperature is given by

$\boldsymbol{t} = 62.112 \ln (3.5) - 25.18 =$ **52.63°C. (Ans.)**

Example 2.13. *A thermocouple with test junction at t°C on gas thermometer scale and reference junction at ice point gives the e.m.f. as*

$$e = 0.20\ t - 5 \times 10^{-4} t^2\ mV.$$

The millivoltmeter is calibrated at ice and steam points. What will be the reading on this thermometer where the gas thermometer reads 70°C ?

Solution. $e = 0.20\ t - 5 \times 10^{-4} t^2$ mV ...(Given)

At ice point : When $t = 0°C$, $e = 0$

At steam point : When $t = 100°C$,

$$e = 0.20 \times 100 - 5 \times 10^{-4} \times (100)^2 = 15 \text{ mV}$$

Now, when $t = 70°C$

$$e = 0.20 \times 70 - 5 \times 10^{-4} \times (70)^2 = 11.55 \text{ mV}$$

$\therefore$ When the gas thermometer reads 70°C the thermocouple will read

$\boldsymbol{t} = \dfrac{100 \times 11.55}{15} =$ **77°C. (Ans.)**

☞**Example 2.14.** *Comment whether the following quantities can be called as properties or not :*

(*i*) $\int pdV$, (*ii*) $\int Vdp$,*and* (*iii*) $\int pdV + \int Vdp$.

Solution. (*i*) $\int pdV$:

p is a function of *V* and integral can only be evaluated if relation between *p* and *V* is known. It is thus an *inexact differential* and hence **not a property.**

(*ii*) $\int Vdp$:

It is **not a property** for the *same reason* as mentioned in (*i*).

(*iii*) $\int pdV + \int Vdp$:

$$\int pdV + \int Vdp = \int pdV + Vdp = \int d(pV) = pV.$$

Thus the integral can be evaluated without knowing the relation between *p* and *V*. It is an *exact differential* and hence **it is a property.**

Example 2.15. *Gas from a cylinder of compressed helium is used to inflate an inelastic flexible balloon, originally folded completely flat, to a volume 0.6 m³. If the barometer reads 760 mm Hg, what is the amount of work done upon the atmosphere by the balloon ? Sketch the system before and after the process.*

Solution. Refer Fig. 2.34. The firm line B_1 shows the boundary of the system before the process, and dotted line B_2 shows the boundary after the process.

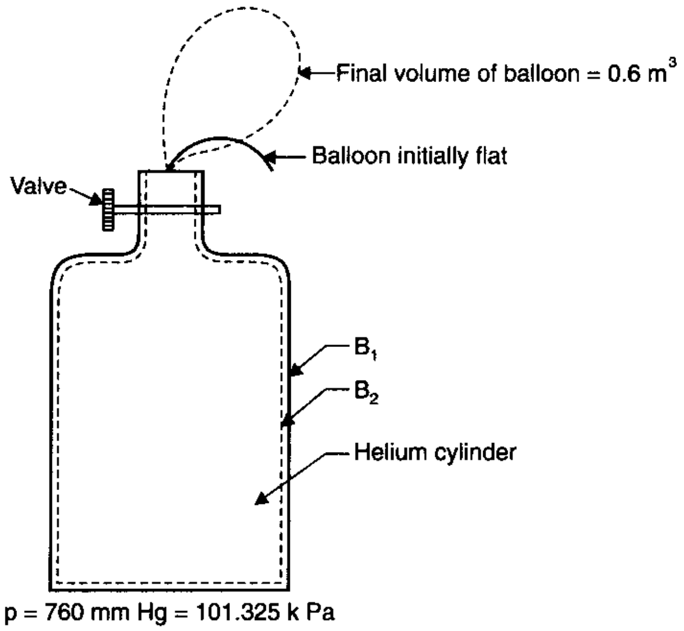


Fig. 2.34

The displacement work,

$$W_d = \int_{\text{cylinder}} pdV + \int_{\text{balloon}} pdV = 0 + \int_{\text{balloon}} pdV$$

$$= 101.325 \times 0.6 \qquad [\because \; dV = 0.6 \text{ m}^3]$$

$$= \mathbf{60.795 \text{ kJ}}. \quad \textbf{(Ans.)}$$

This is a positive work, because the *work is done by the system*. Work done by the atmosphere is – 60.795 kJ. Since the wall of the cylinder is rigid there is no pdV-work involved in it.

It is assumed that the pressure in the balloon is atmospheric at all times, since the balloon fabric is light, inelastic and unstressed. If the balloon were elastic and stressed during the filling process, the work done by the gas would be *greater* than 60.795 kJ by an amount equal to the work done in stretching the balloon, although the displacement work done by atmosphere is still – 60.795 kJ. However, if the system includes both the gas and the balloon, the displacement work should be 60.795 kJ, as estimated above.

Example 2.16. *Determine the work done by the air which enters into an evacuated vessel from atmosphere when the valve is opened. The atmospheric pressure is 1.013 bar and 1.5 m³ of air at atmospheric condition enters into the vessel.*

Solution. Fig. 2.35 shows the initial and final condition of the system.

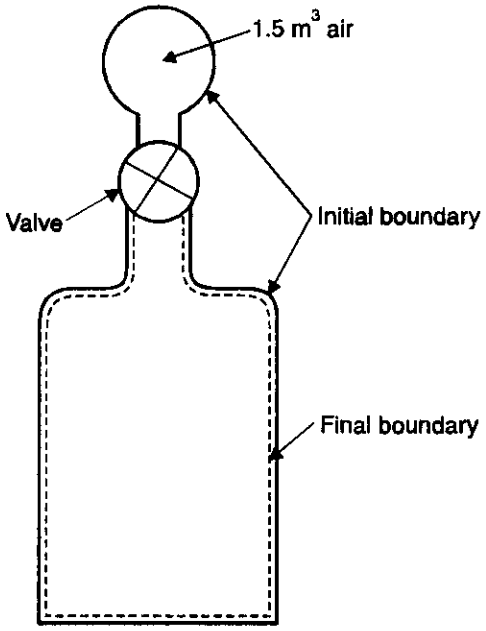


Fig. 2.35

No work is done by the boundary in contact with the vessel as the boundary does not move. Work is done by the external boundary at constant pressure.

$$\therefore \qquad W = \int_{V_1}^{V_2} p\,dV = \int_{1.5}^{0} p\,dV \qquad [\because \; V_1 = 1.5 \text{ m}^3 \text{ and } V_2 = 0]$$

$$= p(0 - 1.5) = 1.013 \times 10^5 \times (-1.5)$$

$$= -1.5195 \times 10^5 \text{ J} = -\mathbf{151.95 \text{ kJ}}. \quad \textbf{(Ans.)}$$

Since the free air boundary is contracting, the work done by the system is negative, and the surroundings do positive work upon the system.

☞ **Example 2.17.** *A piston and cylinder machine containing a fluid system has a stirring device as shown in Fig. 2.36. The piston is frictionless, and it is held down against the fluid due to atmospheric pressure of 101.3 kPa. The stirring device is turned 9500 revolutions with an average torque against the fluid of 1.25 Nm. Meanwhile the piston of 0.65 m diameter moves out 0.6 m. Find the net work transfer for the system.*

Solution. Refer Fig. 2.36.

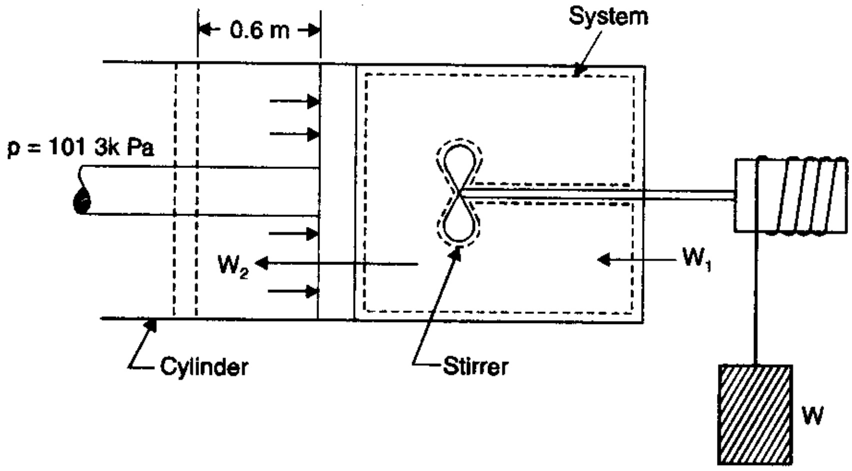


Fig. 2.36

Work done by *the stirring device* upon the system,

$$W_1 = 2\pi NT$$

where T = torque = 1.25 Nm

N = number of revolutions = 9500

$$W_1 = 2\pi \times 9500 \times 1.25 = 74622 \text{ Nm} = 74.622 \text{ kJ}$$

This is *negative work* for the system.

Work done *by the system* upon the surroundings

$$W_2 = (pA).\ L$$

where, p = Pressure = 101.3 kPa

A = Area of the piston = $\pi/4 \times (0.65)^2 = 0.3318 \text{ m}^2$, and

L = Distance moved by the piston = 0.6 m

$$W_2 = 101.3 \times 0.3318 \times 0.6 = 20.167 \text{ kJ}$$

This is a *positive work for the system.*

Hence, the net work transfer for the system

$$W_{net} = W_1 + W_2 = -74.622 + 20.167 = \mathbf{-54.455\ kJ.}\quad \textbf{(Ans.)}$$

Example 2.18. *A diesel engine piston which has an area of 45 cm^2 moves 5 cm during part of suction stroke. 300 cm^3 of fresh air is drawn in from the atmosphere. The pressure in the cylinder during suction stroke is 0.9 × 10^5 N/m^2 and the atmospheric pressure is 1.013 × 10^5 N/m^2. The difference between the suction and atmospheric pressure is accounted for flow resistance in the suction pipe and inlet valve. Find the net work done during the process.*

Solution. Area of diesel engine piston

$= 45 \text{ cm}^2 = 45 \times 10^{-4} \text{ m}^2$

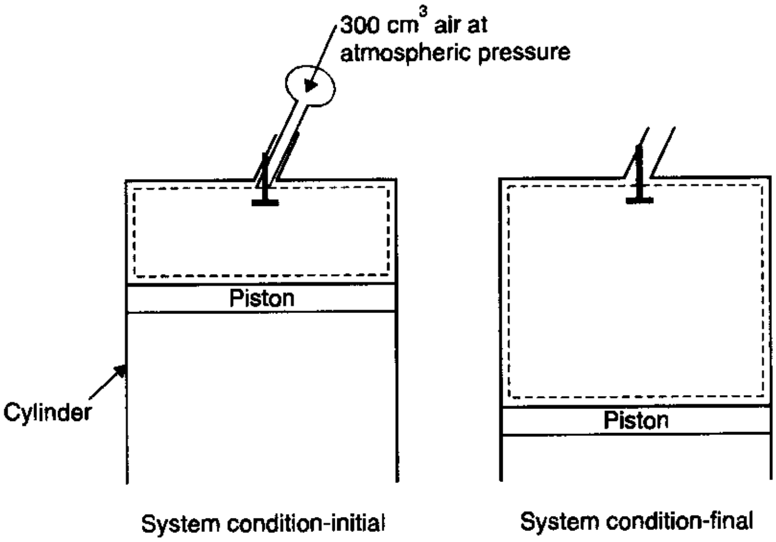


Fig. 2.37

Amount of fresh air drawn in from atmosphere

$= 300 \text{ cm}^3 = 300 \times 10^{-6} \text{ m}^3$

The pressure inside the cylinder during suction stroke

$= 0.9 \times 10^5 \text{ N/m}^2$

Atmospheric pressure $= 1.013 \times 10^5 \text{ N/m}^2$

Initial and final conditions of the system are shown in Fig. 2.37.

Net work done = Work done by free air boundary + work done on the piston

The work done by the free air = – ve because *boundary contracts*

The work done by the cylinder on the piston = + ve because the *boundary expands*

$$\therefore \quad \textbf{Net work done} = \int_{\text{Piston}} pdV + \int_{\text{Free air boundary}} pdV$$

$$= \left[0.9 \times 10^5 \times 45 \times 10^{-4} \times \frac{5}{100} - 1.013 \times 10^5 \times 300 \times 10^{-6}\right]$$

$$= [20.25 - 30.39] = -\ \mathbf{10.14\ Nm\ or\ J.(Ans.)}$$

Example 2.19. *The properties of a closed system change following the relation between pressure and volume as $pV = 3.0$ where p is in bar V is in m^3. Calculate the work done when the pressure increases from 1.5 bar to 7.5 bar.*

Solution. Initial pressure, $p_1 = 1.5$ bar

Final pressure, $p_2 = 7.5$ bar

Relation between p and V, $pV = 3.0$

Work done, W :

The work done during the process is given by

$$W = \int_{V_1}^{V_2} p\,dV$$

$$V_1 = \frac{3.0}{p_1} = \frac{3.0}{1.5} = 2 \text{ m}^3$$

$$V_2 = \frac{3.0}{p_2} = \frac{3.0}{7.5} = 0.4 \text{ m}^3$$

$$\therefore \quad W = 10^5 \int_2^{0.4} \frac{3.0}{V}\,dV \text{ Nm} \qquad [\because \ 1 \text{ bar} = 10^5 \text{ N/m}^2]$$

$$= 10^5 \times 3.0 \left[\log_e V\right]_2^{0.4} = 10^5 \times 3.0(\log_e 0.4 - \log_e 2)$$

$$= -3 \times 10^5 \log_e (2/0.4) = -3 \times 10^5 \times \log_e 5 = -3 \times 10^5 \times 1.61 \text{ Nm}$$

$$= -4.83. \times 10^5 \text{ Nm} = -4.83 \times 10^5 \text{ J} = \mathbf{-\ 483\ kJ.} \quad \textbf{(Ans.)}$$

Example 2.20. *To a closed system 150 kJ of work is supplied. If the initial volume is 0.6 m³ and pressure of the system changes as p = 8 – 4V, where p is in bar and V is in m³, determine the final volume and pressure of the system.*

Solution. Amount of work supplied to a closed system = 150 kJ

Initial volume = 0.6 m³

Pressure-volume relationship, $p = 8 - 4V$

The work done during the process is given by

$$W = \int_{V_1}^{V_2} p\,dV$$

$$= 10^5 \int_{0.6}^{V_2} (8 - 4V)\,dV = 10^5 \left[8V - 4 \times \frac{V^2}{2}\right]_{0.6}^{V}$$

$$= 10^5[8(V_2 - 0.6) - 2(V_2^2 - 0.6^2)]$$

$$= 10^5[8V_2 - 4.8 - 2V_2^2 + 0.72]$$

$$= 10^5[8V_2 - 2V_2^2 - 4.08] \text{ Nm or J}$$

But this work is equal to – 150 × 10³ J as this work is supplied to the system.

$$\therefore \quad -150 \times 10^3 = 10^5[8V_2 - 2V_2^2 - 4.08]$$

or $\quad 2V_2^2 - 8V_2 + 2.58 = 0$

$$V_2 = \frac{8 \pm \sqrt{64 - 4 \times 2 \times 2.58}}{4} = \frac{8 \pm 6.585}{4} = 0.354 \text{ m}^3$$

Positive sign is incompatible with the present problem, therefore it is not considered.

$\therefore$ **Final volume,** $\mathbf{V_2 = 0.354\ m^3}$. **(Ans.)**

and, **final pressure,** $p_2 = 8 - 4V = 8 - 4 \times 0.354$

$= 6.584$ bar = $\mathbf{6.584 \times 10^5\ N/m^2}$ **or Pa. (Ans.)**

REVERSIBLE WORK

Example 2.21. *A fluid at a pressure of 3 bar, and with specific volume of 0.18* m^3/kg*, contained in a cylinder behind a piston exapnds reversibly to a pressure of 0.6 bar according to a law,* $p = \frac{C}{v^2}$ *where C is a constant. Calculate the work done by the fluid on the piston.*

Solution. Refer Fig. 2.38.

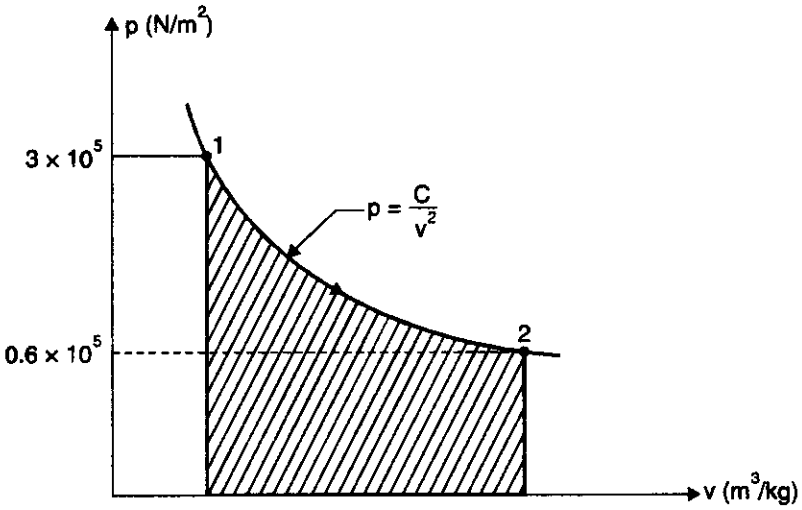


Fig. 2.38

$$p_1 = 3 \text{ bar} = 3 \times 10^5 \text{ N/m}^2$$
$$v_1 = 0.18 \text{ m}^3/\text{kg}$$

Work done = Shaded area = $\int_1^2 p\,dv$

i.e.,

$$\text{Work done, } W = \int_1^2 \frac{C}{v^2}\,.dv = C\int_1^2 \frac{dv}{v^2} = C\left|\frac{v^{-2+1}}{-2+1}\right|_{v_1}^{v_2}$$

$$= C\left[-v^{-1}\right]_{v_1}^{v_2} = C\left[-\frac{1}{v}\right]_{v_1}^{v_2} = C\left[\frac{1}{v_1} - \frac{1}{v_2}\right] \qquad ...(i)$$

Also $$C = pv^2 = p_1 v_1^2 = 3 \times 0.18^2 = 0.0972 \text{ bar } (\text{m}^3/\text{kg})^2$$

and $$v_2 = \sqrt{\frac{C}{p_2}} = \sqrt{\frac{0.0972}{0.6}} = 0.402 \text{ m}^3/\text{kg}$$

Substituting the values of C, v_1 and v_2 in eqn. (*i*), we get

Work done, $$W = 0.0972 \times 10^5 \left[\frac{1}{0.18} - \frac{1}{0.402}\right] \text{ Nm/kg}$$

$$= \mathbf{29840 \text{ Nm/kg.}} \quad \textbf{(Ans.)}$$

☞**Example 2.22.** *A cylinder contains 1 kg of a certain fluid at an initial pressure of 20 bar. The fluid is allowed to expand reversibly behind a piston according to a law* pV^2 = *constant until the volume is doubled. The fluid is then cooled reversibly at constant pressure until the piston regains its original position ; heat is then supplied reversibly with the piston firmly locked in position until the pressure rises to the original value of 20 bar. Calculate the net work done by the fluid, for an initial volume of 0.05* m^3.

Solution. Refer Fig. 2.39.

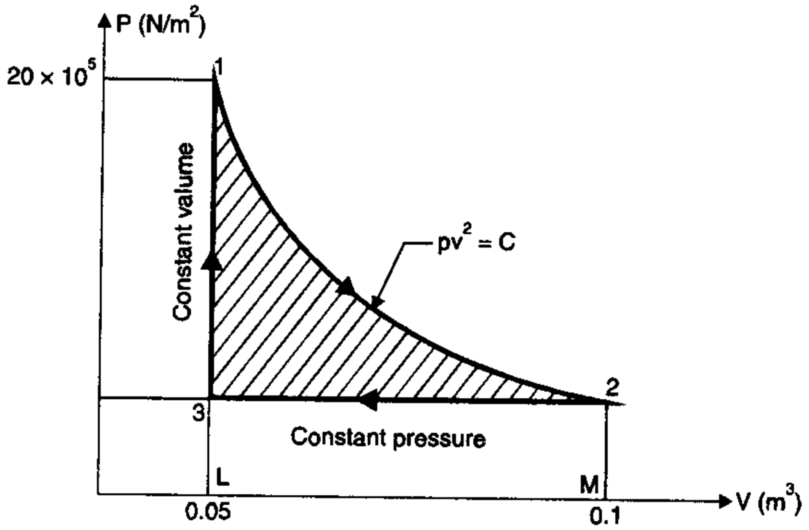


Fig. 2.39

Mass of fluid, $m = 1$ kg

$p_1 = 20 \text{ bar} = 20 \times 10^5 \text{ N/m}^2$

$V_1 = 0.05 \text{ m}^3$

Considering the process 1-2

$$p_1V_1^2 = p_2V_2^2$$

$$\therefore \quad p_2 = p_1\left(\frac{V_1}{V_2}\right)^2 = 20\left(\frac{V_1}{2V_1}\right)^2 \qquad [\because \; V_2 = 2V_1 \text{ (given)}]$$

$$= \frac{20}{4} = 5 \text{ bar}$$

Work done by the fluid from 1 to 2 = Area 12 ML1 = $\int_1^2 p\,dV$

i.e., $$W_{1-2} = \int_{v_1}^{v_2} \frac{C}{V^2}\,dV \text{, where } C = p_1V_1^2 = 20 \times 0.05^2 \text{ bar m}^6$$

$$\therefore \quad W_{1-2} = 10^5 \times 20 \times 0.0025\left[-\frac{1}{V}\right]_{0.05}^{0.1}$$

$$= 10^5 \times 20 \times 0.0025 \left(\frac{1}{0.05} - \frac{1}{0.1}\right) = 50000 \text{ Nm}$$

Work done on fluid from 2 to 3

$$= \text{Area } 32ML3 = p_2 (V_2 - V_3) = 10^5 \times 5 \times (0.1 - 0.05) = 25000 \text{ Nm}$$

Work done during the process 3-1

= 0, because piston is locked in position (*i.e., Volume remains constant*)

∴ **Net work done by the fluid**

= Enclosed area 1231 = 50000 – 25000

= **25000 Nm.** **(Ans.)**

HIGHLIGHTS

1. *Thermodynamics* is an axiomatic science which deals with the relations among heat, work and properties of systems which are in equilibrium. It basically entails four laws or axioms known as *Zeroth, First, Second* and *Third* law of thermodynamics.
2. A *system* is a finite quantity of matter or a prescribed region of space.

   A system may be a *closed, open* or *isolated* system.
3. A *phase* is a quantity of matter which is homogeneous throughout in chemical composition and physical structure.
4. A *homogeneous system* is one which consists of a *single phase.*
5. A *heterogeneous system* is one which consists of *two or more phases.*
6. A *pure substance* is one that has a homogeneous and invariable chemical composition even though there is a change of phase.
7. A system is in *thermodynamic equilibrium* if temperature and pressure at all points are same ; there should be no *velocity gradient.*
8. A *property of a system* is a characteristic of the system which depends upon its state, but not upon how the state is reached.

   Intensive properties do not depend on the mass of the system.

   Extensive properties depend on the mass of the system.
9. *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.
10. A *process* occurs when the system undergoes a change in state or an energy transfer takes place at a steady state.
11. Any process or series of processes whose end states are identical is termed a *cycle.*
12. The *pressure* of a system is the force exerted by the system on unit area of boundaries. Vacuum is defined as the absence of pressure.
13. A *reversible process* is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.

    An *irreversible process* is one in which heat is transferred through a finite temperature.
14. Zeroth law of termodynamics states that if two systems are each equal in temperature to a third, they are equal in temperature to each other.
15. Infinite slowness is the characteristic feature of a quasi-static process. A quasi-static process is a succession of equilibrium states. It is also called a reversible process.

OBJECTIVE TYPE QUESTIONS

Choose the Correct Answer :

1. A definite area or space where some thermodynamic process takes place is known as
   (*a*) thermodynamic system
   (*b*) thermodynamic cycle
   (*c*) thermodynamic process
   (*d*) thermodynamic law.
2. An open system is one in which .
   (*a*) heat and work cross the boundary of the system, but the mass of the working substance does not
   (*b*) mass of working substance crosses the boundary of the system but the heat and work do not
   (*c*) both the heat and work as well as mass of the working substances cross the boundary of the system
   (*d*) neither the heat and work nor the mass of the working substances cross the boundary of the system.
3. An isolated system
   (*a*) is a specified region where transfer of energy and/or mass take place
   (*b*) is a region of constant mass and only energy is allowed to cross the boundaries
   (*c*) cannot transfer either energy or mass to or from the surroundings
   (*d*) is one in which mass within the system is not necessarily constant
   (*e*) none of the above.
4. In an extensive property of a thermodynamic system
   (*a*) extensive heat is transferred
   (*b*) extensive work is done
   (*c*) extensive energy is utilised
   (*d*) all of the above
   (*e*) none of the above.
5. Which of the following is an intensive property of a thermodynamic system ?
   (*a*) Volume
   (*b*) Temperature
   (*c*) Mass
   (*d*) Energy.
6. Which of the following is the extensive property of a thermodynamic system ?
   (*a*) Pressure
   (*b*) Volume
   (*c*) Temperature
   (*d*) Density.
7. When two bodies are in thermal equilibrium with a third body they are also in thermal equilibrium with each other. This statement is called
   (*a*) Zeroth law of thermodyamics
   (*b*) First law of thermodynamics
   (*c*) Second law of thermodynamics
   (*d*) Kelvin Planck's law.
8. The temperature at which the volume of a gas becomes zero is called
   (*a*) absolute scale of temperature
   (*b*) absolute zero temperature
   (*c*) absolute temperature
   (*d*) none of the above.
9. The value of one bar (in SI units) is equal to
   (*a*) 100 N/m^2
   (*b*) 1000 N/m^2
   (*c*) 1×10^4 N/m^2
   (*d*) 1×10^5 N/m^2
   (*e*) 1×10^6 N/m^2.
10. The absolute zero pressure will be
    (*a*) when molecular momentum of the system becomes zero
    (*b*) at sea level
    (*c*) at the temperature of – 273 K
    (*d*) under vacuum conditions
    (*e*) at the centre of the earth.
11. Absolute zero temperature is taken as
    (*a*) – 273°C
    (*b*) 273°C
    (*c*) 237°C
    (*d*) – 373°C.
12. Which of the following is *correct* ?
    (*a*) Absolute pressure = gauge pressure + atmospheric pressure
    (*b*) Gauge pressure = absolute pressure + atmospheric pressure
    (*c*) Atmospheric pressure = absolute pressure + gauge pressure
    (*d*) Absolute pressure = gauge pressure – atmospheric pressure.

13. The unit of energy in SI units is
(*a*) Joule (J) (*b*) Joule metre (Jm)
(*c*) Watt (W) (*d*) Joule/metre (J/m).

14. One watt is equal to
(*a*) 1 Nm/s (*b*) 1 N/min
(*c*) 10 N/s (*d*) 100 Nm/s
(*e*) 100 Nm/m.

15. One joule (J) is equal to
(*a*) 1 Nm (*b*) kNm
(*d*) 10 Nm/s (*d*) 10 kNm/s.

16. The amount of heat required to raise the temperature of 1 kg of water through 1°C is called
(*a*) specific heat at constant volume (*b*) specific heat at constant pressure
(*c*) kilo calorie (*d*) none of the above.

17. The heating and expanding of a gas is called
(*a*) thermodynamic system (*b*) thermodynamic cycle
(*c*) thermodynamic process (*d*) thermodynamic law.

18. A series of operations, which take place in a certain order and restore the initial condition is known as
(*a*) reversible cycle (*b*) irreversible cycle
(*c*) thermodynamic cycle (*d*) none of the above.

19. The condition for the reversibility of a cycle is
(*a*) the pressure and temperature of the working substance must not differ, appreciably, from those of the surroundings at any stage in the process
(*b*) all the processes, taking place in the cycle of operation, must be extremely slow
(*c*) the working parts of the engine must be friction free
(*d*) there should be no loss of energy during the cycle of operation
(*e*) all of the above (*f*) none of the above.

20. In an irreversible process, there is a
(*a*) loss of heat (*b*) no loss of heat
(*c*) gain of heat (*d*) no gain of heat.

21. The main cause of the irreversibility is
(*a*) mechanical and fluid friction (*b*) unrestricted expansion
(*c*) heat transfer with a finite temperature difference
(*d*) all of the above (*e*) none of the above.

22. According to kinetic theory of heat
(*a*) temperature should rise during boiling (*b*) temperature should fall during freezing
(*c*) at low temperature all bodies are in solid state
(*d*) at absolute zero there is absolutely no vibration of molecules
(*e*) none of the above.

23. A system comprising a single phase is called a
(*a*) closed system (*b*) open system
(*c*) isolated system (*d*) homogeneous system
(*e*) heterogeneous system.

Answers

1. (*a*) **2.** (*c*) **3.** (*c*) **4.** (*e*) **5.** (*b*) **6.** (*b*) **7.** (*a*)
8. (*b*) **9.** (*d*) **10.** (*a*) **11.** (*a*) **12.** (*a*) **13.** (*a*) **14.** (*a*)
15. (*a*) **16.** (*c*) **17.** (*b*) **18.** (*c*) **19.** (*e*) **20.** (*a*) **21.** (*d*)
22. (*d*) **23.** (*d*).

THEORETICAL QUESTIONS

1. Define a thermodynamic system. Differentiate between open system, closed system and an isolated system.
2. How does a homogeneous system differ from a heterogeneous system ?
3. What do you mean by a pure substance ?
4. Explain the following terms :
   (*i*) State, (*ii*) Process, and (*iii*) Cycle.
5. Explain briefly zeroth law of thermodynamics.
6. What is a quasi-static process ?
7. What do you mean by 'reversible work' ?

UNSOLVED EXAMPLES

1. A cylindrical vessel of 60 cm diameter and 80 cm height contains 3.2 kg of a gas. The pressure measured with manometer indicates 60 cm of Hg above atmosphere when barometer reads 760 mm of Hg. Find : (*i*) The absolute pressure of the gas in the vessel in bar, and (*ii*) Specific volume and density of gas. [**Ans.**1.81 bar ; 0.09 m/kg ; 11.11 kg/m]
2. A force of 1600 N is applied uniformly on a piston of 8 cm diameter. Determine the pressure on the piston. [**Ans.**319 kN/m]
3. An oil of specific gravity 0.8 is contained in a tube to a depth of 80 cm. Determine the gauge pressure at this depth in kN/m. [**Ans.**6.275 kN/m]
4. A vacuum recorded in the condenser of a steam power plant is 745 mm of Hg. Find the absolute pressure in the condenser in Pa. The barometer reading is 760 mm of Hg. [**Ans.**2262 Pa]
5. The pressure of gas in a pipe line is measured with a mercury manometer having one limb open to the atmosphere. If the difference in the height of mercury in the two limbs is 562 mm, calculate the gas pressure. The barometer reads 761 mm Hg, the acceleration due to gravity is 9.79 m/s, and the density of mercury is 13640 kg/m. [**Ans.**1.77 bar]
6. A turbine is supplied with steam at a gauge pressure of 1.4 MPa. After expansion in the turbine the steam flows into a condenser which is maintained at a vacuum of 710 mm Hg. The barometric pressure is 772 mm Hg. Express the inlet and exhaust steam pressures in pascals (absolute). Take the density of mercury as 13600 kg/m. [**Ans.**1.503 MPa ; 8.27 kPa]
7. Gas from a bottle of compressed helium is used to inflate an inelastic flexible balloon, originally folded completely flat to a volume of 0.5 m. If the barometer reads 760 mm Hg, what is the amount of work done upon the atmosphere by the balloon ? [**Ans.**50.66 kJ]
8. A rubber balloon (flexible) is to be filled with hydrogen from a storage cylinder which contains hydrogen at 5 bar pressure until it has a volume of 1 m. The atmospheric pressure may be taken as 1.013 × 10 N/m. Determine the work done by the system comprising the hydrogen initially in the bottle. [**Ans.**101.3 kJ]
9. When the valve of the evacuated bottle is opened, atmospheric air rushes into it. If the atmospheric pressure is 101.325 kPa, and 1.2 m of air (measured at atmospheric conditions) enters into the bottle, calculate the work done by the air. [**Ans.**– 60.8 kJ]
10. A pump forces 1.2 m/min of water horizontally from an open well to a closed tank where the pressure is 0.9 MPa. Compute the work the pump must do upon the water in an hour just to force the water into the tank against the pressure. [**Ans.**15972 kJ]
11. 14.5 litres of gas at 172 MN/m is expanded at constant pressure until its volume becomes 130.5 litres. Determine the work done by the gas. [**Ans.**199.5 kJ]
12. 1 kg of a fluid is compressed reversibly according to a law $pv = 0.25$ where p is in bar and v is in m/kg. The final volume is 1/4 of the initial volume. Calculate the work done on the fluid and sketch the process on a p-v diagram. [**Ans.**34660 Nm]

13. A gas having a volume of 0.05 m and pressure of 6.9 bar expands reversibly in a cylinder behind a piston according to law pv = constant until the volume is 0.08 m. Calculate the work done by the gas. Also sketch the process on a p-v diagram. [**Ans.** 15300 Nm]

14. A certain fluid at 10 bar is contained in a cylinder behind a piston, the initial volume being 0.05 m. Calculate the work done by the fluid when it expands reversibly, (*a*) At constant pressure to final volume of 0.2 m^3 ; (*b*) According to linear law to final volume of 0.2 m and a final pressure of 2 bar ; (*c*) According to a law pV = constant to a final volume of 0.1 m ; (*d*) According to law pV = constant to a final volume of 0.06 m. Sketch all processes on p-V diagram. [**Ans.** 150000 ; 90000 ; 34700 ; 7640 Nm]

15. A fluid undergoes the following processes :

(*i*) Heated reversibly at a constant pressure of 1.05 bar until it has a specific volume of 0.1 m^3/kg.

(*ii*) It is then compressed reversibly according to a law pv = constant to a pressure of 4.2 bar.

(*iii*) It is then allowed to expand reversibly according to a law $pv^{1.3}$ = constant.

(*iv*) Finally it is heated at constant volume back to initial conditions.

The work done in the constant pressure process is 515 Nm and the mass of fluid present is 0.2 kg. Calculate the net work done on or by the fluid in the cycle and sketch the cycle on a p-v diagram. [**Ans.** – 422 Nm]

3

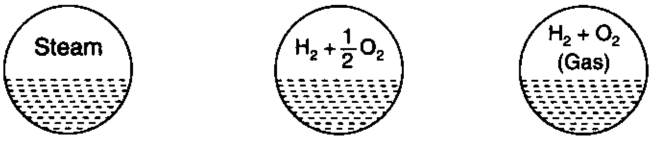
Properties of Pure Substances

3.1. DEFINITION OF THE PURE SUBSTANCE

A pure substance is a system which is (*i*) *homogeneous in composition*, (*ii*) *homogeneous in chemical aggregation*, and (*iii*) *invariable in chemical aggregation*.

— "*Homogeneous in composition*" means that the composition of each part of the system is the *same* as the composition of *every other part*. "*Composition* means the relative proportions of the chemical elements into which the sample can be analysed. It does not matter how these elements are combined.

For example in Fig. 3.1 system (*a*), comprising steam and water, is homogeneous in composition, since chemical analysis would reveal that hydrogen and oxygen atoms are presents in the ratio 2 : 1 whether the sample be taken from the steam or from the water. The same is true of system (*b*) containing uncombined hydrogen and oxygen gas in the atomic ratio 2 : 1 in the upper part, and water in the lower part. System (*c*) however, is not homogeneous in composition, for the hydrogen and oxygen are present in the ratio 1 : 1 in the upper part, but in the ratio 2 : 1 (as water) in the lower part.



(a) Satisfies condition (i) Satisfies condition (ii)

(b) Satisfies condition (i) Does not satisfy condition (ii)

(c) Does not satisfy condition (i)

Fig. 3.1. Illustrating the definition of a pure substance.

— "*Homogeneous in chemical aggregation*" means that the chemical elements must be combined chemically in the same way in all parts of the system. Consideration of Fig. 3.1 again shows that the system (*a*) satisfies this condition also ; for steam and water consist of identical molecules. System (*b*) on the other hand is not homogeneous in chemical aggregation since in the upper part of the system the hydrogen and oxygen are not combined chemically (individual atoms of *H* and *O* are not uniquely associated), whereas in the lower part of the system the hydrogen and oxygen are combined to form water.

Note however that a uniform mixture of steam, hydrogen gas, and oxygen gas would be regarded as homogeneous in both composition and chemical aggregation whatever the relative proportions of the components.

— "*Invariable in chemical aggregation*" means that the state of chemical combination of the system does not change with *time* (condition (*ii*) referred to variation with *position*). Thus a mixture of hydrogen and oxygen, which changed into steam during the time that the system was under consideration, would not be a pure substance.

3.2. PHASE CHANGE OF A PURE SUBSTANCE

Let us consider 1 kg of liquid water at a temperature of 20°C in a cylinder fitted with a piston, which exerts on the water a constant pressure of one atmosphere (1.0132 bar) as shown in Fig. 3.2 (*i*).

— As the water is heated slowly its temperature rises until the temperature of the liquid water becomes 100°C. During the process of heating, the *volume slightly increases* as indicated by the line 1-2 on the temperature-specific volume diagram (Fig. 3.3). The piston starts moving upwards.

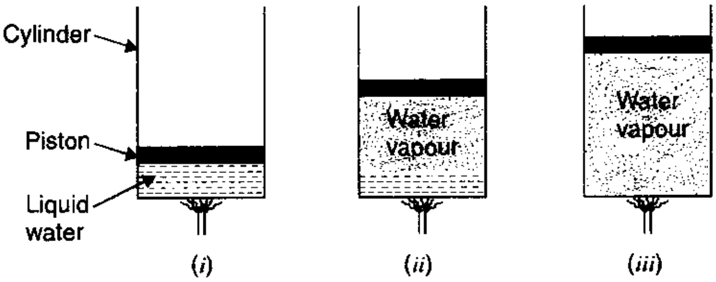


Fig. 3.2. Phase change of water at constant pressure from liquid to vapour phase.

— If the heating of the liquid, after it attains a temperature of 100°C, is continued it *undergoes a change in phase*. A portion of the liquid water changes into vapour as shown in Fig. 3.2 (*ii*). This state is described by the line 2-3 in Fig. 3.3. The amount of heat required to convert the liquid water completely into vapour under this condition is called the *heat of vapourisation*. The temperature at which vapourisation takes place at a given pressure is called the *saturation temperature* and the given pressure is called the *saturation pressure*.

During the process represented by the line 2-3 (Fig. 3.3) the volume increases rapidly and piston moves upwards Fig. 3.2 (*iii*).

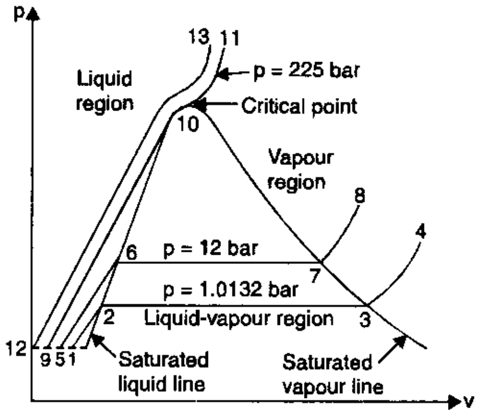


Fig. 3.3

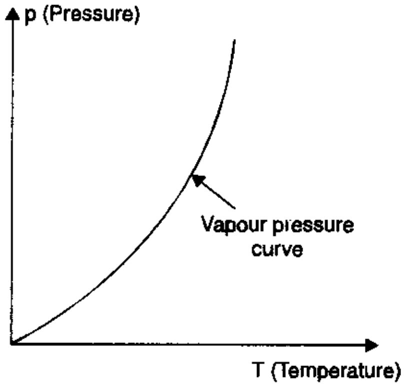


Fig. 3.4. Vapour pressure curve for water.

For a pure substance, definite relationship exists between the saturation pressure and saturation temperature as shown in Fig. 3.4, the curve so obtained is called *vapour pressure curve*.

— It may be noted that if the temperature of the liquid water on cooling becomes lower than the saturation temperature for the given pressure, the liquid water is called a *sub-cooled liquid*. The point '1' (in Fig. 3.3) illustrates this situation, when the liquid water is cooled under atmospheric pressure to a temperature of 20°C, which is below the saturation temperature (100°C).

— Further, at point '1' the temperature of liquid is 20°C and corresponding to this temperature, the saturation pressure is 0.0234 bar, which is lower than the pressure on the liquid water, which is 1 atmosphere. Thus the pressure on the liquid water is greater than the saturation pressure at a given temperature. In this condition, the liquid water is known as the *compressed liquid*.

The term *compressed liquid* or *sub-cooled liquid* is used to distinguish it from *saturated liquid. All points in the liquid region indicate the states of the compressed liquid.*

— When all the liquid has been evaporated completely and heat is further added, the *temperature of the vapour increases*. The curve 3-4 in Fig. 3.3 describes the process. When the temperature increases above the saturation temperature (in this case 100°C), the vapour is known as the *superheated vapour* and the temperature at this state is called the *superheated temperature*. There is *rapid increase in volume* and the piston moves upwards [Fig. 3.2 (*iii*)].

The difference between the superheated temperature and the saturation temperature at the given pressure is called the *degree of superheat*.

— If the above mentioned heating process is repeated at different pressures a number of curve similar to 1-2-3-4 are obtained. Thus, if the heating of the liquid water in the piston cylinder arrangement takes place under a constant pressure of 12 bar with an initial temperature of 20°C until the liquid water is converted into superheated steam, then curve 5-6-7-8 will represent the process.

— In the above heating process, it may be noted that, as the pressure increases the *length of constant temperature vapourisation gets reduced.*

From the heating process at a constant pressure of 225 bar represented by the curve 9-10-11 in Fig. 3.3, it can be seen that there is *no constant temperature vapourisation line*. The specific volume of the saturated liquid and of the saturated vapour is the same, *i.e.*, $v_f = v_g$. Such a state of the substance is called the *critical state*. The parameters like temperature, pressure, volume, etc. at such a state are called *critical parameters*.

— The curve 12-13 (Fig. 3.3) *represents a constant pressure heating process, when the pressure is greater than the critical pressure.* At this state, *the liquid water is directly converted into superheated steam.* As there is no definite point at which the liquid water changes into superheated steam, it is generally called *liquid water when the temperature is less than the critical temperature and superheated steam when the temperature is above the critical temperature.*

3.3. p-T (Pressure-Temperature) DIAGRAM FOR A PURE SUBSTANCE

If the vapour pressure of a solid is measured at various temperatures until the *triple point* is reached and then that of the liquid is measured until the critical point is reached, the result when plotted on a *p-T* diagram appears as in Fig. 3.5.

If the substance at the triple point is compressed until there is no vapour left and the pressure on the resulting mixture of liquid and solid is increased, the temperature will have to be changed for equilibrium to exist between the solid and the liquid.

Measurements of these pressures and temperatures give rise to a third curve on the *p-T* diagram, starting at the triple point and continuing indefinitely.

The points representing the coexistence of (*i*) *solid* and *vapour* lie on the '*sublimation curve*', (*ii*) *liquid* and *vapour* lie on the '*vapourisation curve*', (*iii*) *liquid* and *solid* lie on the '*fusion curve*'. In the particular case of *water*, the sublimation curve is called the *frost line*, the vapourisation curve is called the *steam line*, and the fusion curve is called the *ice line*.

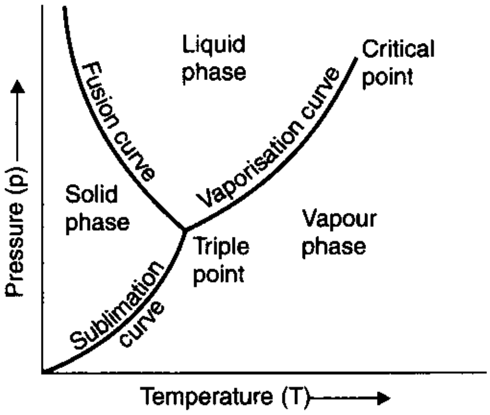


Fig. 3.5. *p*-T diagram for a substance such as water.

The slopes of sublimation and the vapourisation curves for all substances are *positive*. The slope of the fusion curve, however may be positive or negative. The fusion curve of *most substances* have a *positive slope*. Water is one of the important exceptions.

Triple point

The ***triple point*** *is merely the point of intersection of sublimation and vapourisation curves.* It must be understood that only on *p-T* diagram is the triple point represented by a *point*. On *p-V* diagram it is a *line*, and on a *U-V* diagram it is a *triangle*.

— The pressure and temperature at which all three phases of a pure substance coexist may be measured with the apparatus that is used to measure vapour pressure.

— Triple-point data for some interesting substances are given in Table 3.1.

Table 3.1. Triple-point Data

S. No.	*Substance*	*Temp., K*	*Pressure, mm Hg*
1.	Hydrogen (normal)	13.96	54.1
2.	Deuterium (normal)	18.63	128
3.	Neon	24.57	324
4.	Nitrogen	63.18	94
5.	Oxygen	54.36	1.14
6.	Ammonia	195.40	45.57
7.	Carbon dioxide	216.55	3.880
8.	Sulphur dioxide	197.68	1.256
9.	Water	273.16	4.58

3.4. p-V-T (Pressure-Volume-Temperature) SURFACE

A detailed study of the heating process reveals that the temperature of the solid rises and then during the change of phase from solid to liquid (or solid to vapour) the temperature remains constant. This phenomenon is common to all phase changes. Since the temperature is constant, pressure and temperature are not independent properties and connot be used to specify state during a change of phase.

The combined picture of change of pressure, specific volume and temperature may be shown on a three dimensional state model. Fig. 3.6 illustrates the equilibrium states for a pure substance which expands on fusion. Water is an example of a substance that exhibits this phenomenon.

All the equilibrium states lie on the surface of the model. States represented by the space above or below the surface are not possible. It may be seen that the *triple point appears as a line in this representation.* The point *C.P.* is called the *critical point* and no liquid phase exists at temperatures above the isotherms through this point. The term evaporation is meaningless in this situation.

At the critical point the temperature and pressure are called the critical temperature and the critical pressure respectively and when the temperature of a substance is above the critical value, it is called a gas. It is not possible to cause a phase change in a gas unless the temperature is lowered to a value less than the critical temperature. Oxygen and nitrogen are examples of gases that have critical temperatures below normal atmospheric temperature.

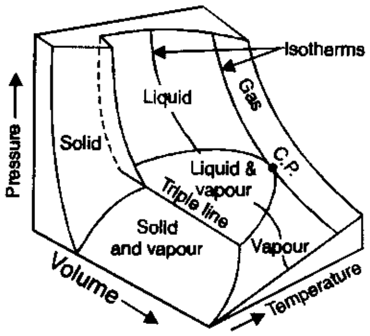


Fig. 3.6. A pressure-volume-temperature (*p-V-T*) surface.

3.5. PHASE CHANGE TERMINOLOGY AND DEFINITIONS

Suffices :	Solid	*i*
	Liquid	*f*
	Vapour	*g*

Phase change	**Name**	**Process**	**Process suffix**
1. Solid-liquid	Fusion	Freezing, melting	*if*
2. Solid-vapour	Sublimation	Frosting, defrosting	*ig*
3. Liquid-vapour	Evaporation	Evaporating, Condensing	*fg*

Triple point—The only state at which the solid, liquid and vapour phases *coexist in equilibrium.*

Critical point (C.P.). The *limit of distinction between a liquid and vapour.*

Critical pressure. The pressure at the critical point.

Critical temperature. The temperature at the critical point.

Gas—A vapour whose *temperature is greater than the critical temperature.*

Liquid-vapour terms : Refer Fig. 3.7.

Saturation temperature. The phase change temperature corresponding to the saturation pressure. Sometimes called the *boiling temperature.*

Saturation pressure. The phase change pressure.

Compressed liquid. Liquid whose temperature is *lower than the saturation temperature.* Sometimes called a *sub-cooled liquid.*

Saturated liquid. Liquid at the saturation temperature corresponding to the saturation pressure. That is liquid about to commence evaporating, represented by the point *f* on a diagram.

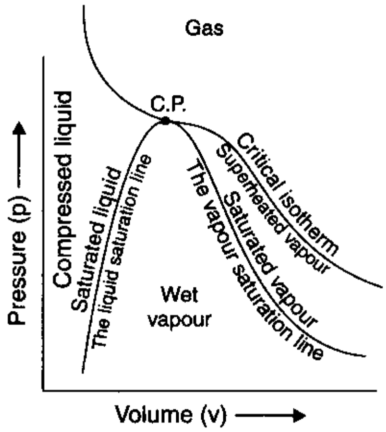


Fig. 3.7. Phase change terminology.

Saturated vapour. A term including wet and dry vapour.

Dry (saturated) vapour. Vapour which has just completed evaporation. The pressure and temperature of the vapour are the saturation values. Dry vapour is represented by a point *g* on a diagram.

Wet vapour. The mixture of saturated liquid and dry vapour during the phase change.

Superheated vapour. Vapour whose temperature is greater than the saturation temperature corresponding to the pressure of the vapour.

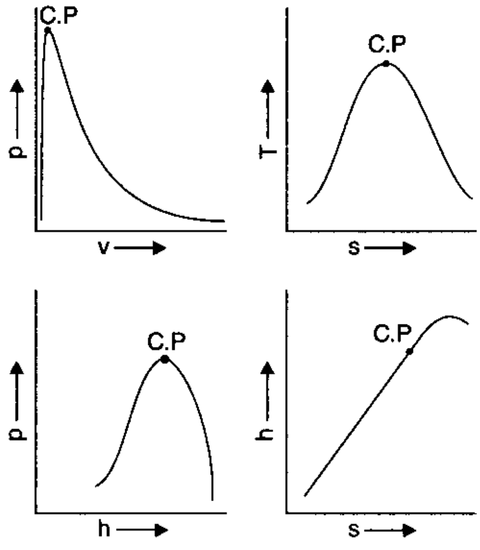
Degree of superheat. The term used for the numerical amount by which the temperature of a superheated vapour exceeds the saturation temperature.

3.6. PROPERTY DIAGRAMS IN COMMON USE

Besides *p-V* diagram which is useful because *pressure and volume are easily visualised* and the T-*s* chart which is used in *general thermodynamic work,* there are other charts which are of *practical use for particular applications.* The *specific enthalpy-specific entropy chart is used for steam plant work and the pressure-specific enthalpy chart is used in refrigeration work.* Sketches of these charts are shown in Fig. 3.8. These charts are drawn for H_2O (water and steam) and represent the correct shape of the curves for this substance.

3.7. FORMATION OF STEAM

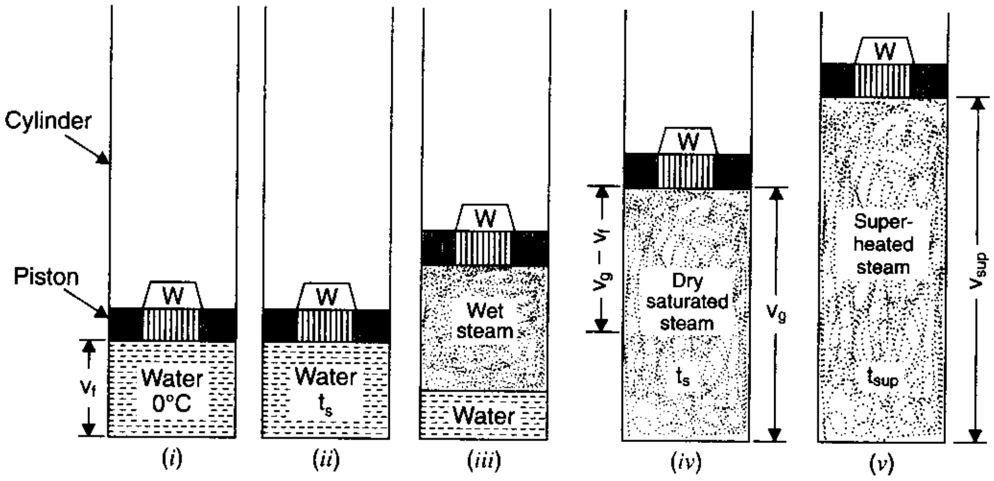
The process of formation of steam is discussed in detail in the following few pages :



C.P. = Critical point

Fig. 3.8

Consider a cylinder fitted with a piston which can move freely upwards and downwards in it. Let, for the sake of simplicity, there be 1 kg of water at 0°C with volume v_f m^3 under the piston [Fig 3.9 (*i*)]. Further let the piston is loaded with load W to ensure heating at constant pressure. Now if the heat is imparted to water, a rise in temperature will be noticed and this rise will continue till boiling point is reached. The temperature at which water starts boiling depends upon the pressure and as such for *each pressure* (under which water is heated) *there is a different boiling point.* This boiling temperature is known as the temperature of formation of steam or *saturation temperature.*



t_s = Saturation temp.
t_{sup} = Temperature of superheated steam
v_f = Volume of water
v_g = Volume of dry and saturated steam
v_{sup} = Volume of superheated steam

Fig. 3.9. Formation of steam.

It may be noted during heating up to boiling point that there will be slight increase in volume of water due to which piston moves up and hence work is obtained as shown in Fig. 3.9 (*ii*). This work, however, is so *small* that is can be *neglected.*

Now, if supply of heat to water is continued it will be noticed that rise of temperature after the boiling point is reached *nil* but piston starts moving upwards which indicates that there is increase is volume which is only possible if steam formation occurs. The heat being supplied does not show any rise of temperature but changes water into vapour state (steam) and is known as *latent heat* or *hidden heat.* So long as the steam is in contact with water, it is called *wet steam* [Fig. 3.9 (*iii*)] and if heating of steam is further progressed [as shown in Fig. 3.9 (*iv*)] such that all the water particles associated with steam are evaporated, the steam so obtained is called *dry and saturated steam.* If v_g m^3 is the volume of 1 kg of dry and saturated steam then work done on the piston will be

$$p(v_g - v_f) \qquad ...(3.1)$$

where p is the constant pressure (due to weight 'W' on the piston).

Again, if supply of heat to the dry and saturated steam is continued at constant pressure there will be increase in temperature and volume of steam. The steam so obtained is called *superheated steam* and it *behaves like a perfect gas*. This phase of steam formation is illustrated in Fig. 3.9 (*v*).

Fig. 3.10 shows the graphical representation of formation of steam.

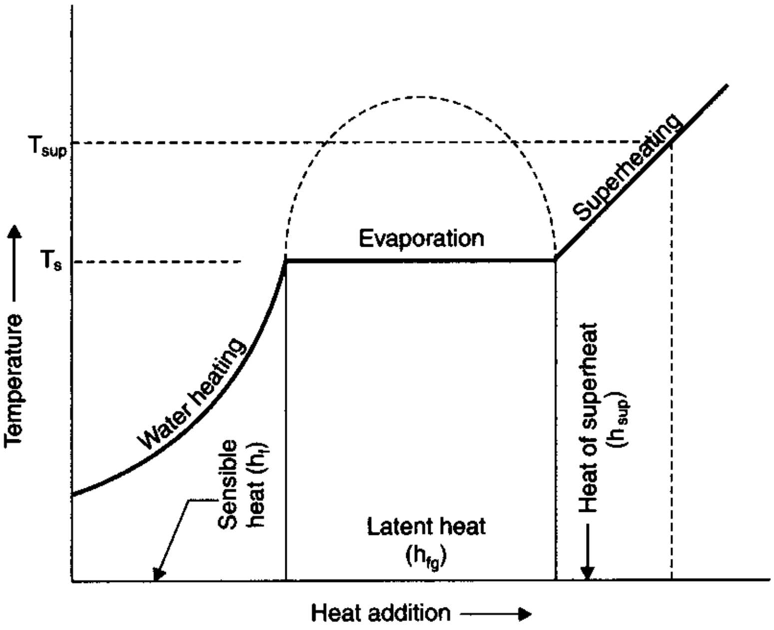


Fig. 3.10. Graphical representation of formation of steam.

3.8. IMPORTANT TERMS RELATING STEAM FORMATION

1. Sensible heat of water (h_f). *It is defined as the quantity of heat absorbed by 1 kg of water when it is heated from 0°C (freezing point) to boiling point.* It is also called total heat (or enthalpy) of water or liquid heat invariably. It is reckoned from 0°C where sensible heat is taken as zero. If 1 kg of water is heated from 0°C to 100°C the sensible heat added to it will be $4.18 \times 100 = 418$ kJ but if water is at say 20°C initially then sensible heat added will be $4.18 \times (100 - 20) = 334.4$ kJ. This type of heat is denoted by letter h_f and its value can be directly read from the steam tables.

Note. The value of specific heat of water may be taken as 4.18 kJ/kg K at low pressures but at high pressures it is different from this value.

2. Latent heat or hidden heat (h_{fg}). *It is the amount of heat required to convert water at a given temperature and pressure into steam at the same temperature and pressure.* It is expressed by the symbol h_{fg} and its value is available from steam tables. *The value of latent heat is not constant and varies according to pressure variation.*

3. Dryness fraction (x). The term dryness fraction is related with wet steam. *It is defined as the ratio of the mass of actual dry steam to the mass of steam containing it.* It is usually expressed by the symbol '*x*' or '*q*'.

If m_s = Mass of dry steam contained in steam considered, and

m_w = Weight of water particles in suspension in the steam considered,

Then,

$$x = \frac{m_s}{m_s + m_w} \qquad \text{...(3.2)}$$

Thus if in 1 kg of wet steam 0.9 kg is the dry steam and 0.1 kg water particles then $x = 0.9$.

Note. No steam can be completely dry and saturated, so long as it is in contact with the water from which it is being formed.

4. Total heat or enthalpy of wet steam (h). *It is defined as the quantity of heat required to convert 1 kg of water at 0°C into wet steam at constant pressure.* It is the sum of total heat of water and the latent heat and this sum is also called **enthalpy.**

In other words,
$$h = h_f + xh_{fg} \qquad ...(3.3)$$

If steam is dry and saturated, then $x = 1$ and $h_g = h_f + h_{fg}$.

5. Superheated steam. When steam is heated after it has become dry and saturated, it is called superheated steam and the process of heating is called *superheating. Superheating is always carried out at constant pressure.* The additional amount of heat supplied to the steam during superheating is called as *'Heat of superheat'* and can be calculated by using the specific heat of superheated steam at constant pressure (c_{ps}), the value of which varies from 2.0 to 2.1 kJ/kg K depending upon pressure and temperature.

If T_{sup}., T_s are the temperatures of superheated steam in K and wet or dry steam, then $(T_{sup} - T_s)$ is called *'degree of superheat'*.

The total heat of superheated steam is given by
$$h_{sup} = h_f + h_{fg} + c_{ps}\,(T_{sup} - T_s) \qquad ...(3.4)$$

Superheated steam behaves like a gas and therefore it follows the gas laws. The value of n for this type of steam is 1.3 and the law for the adiabatic expansion is $pv^{1.3}$ = constant.

The ***advantages*** obtained by using *'superheated'* steam are as follows :

(*i*) By superheating steam, its heat content and hence its capacity to do work is increased without having to increase its pressure.

(*ii*) Superheating is done in a superheater which obtains its heat from waste furnace gases which would have otherwise passed uselessly up the chimney.

(*iii*) High temperature of superheated steam results in an increase in thermal efficiency.

(*iv*) Since the superheated steam is at a temperature above that corresponding to its pressure, it can be considerably cooled during expansion in an engine before its temperature falls below that at which it will condense and thereby become wet. Hence, heat losses due to condensation of steam on cylinder walls etc. are avoided to a great extent.

6. Volume of wet and dry steam. If the steam has dryness fraction of x, then 1 kg of this steam will contain x kg of dry steam and $(1 - x)$ kg of water. If v_f is the volume of 1 kg of water and v_g is the volume of 1 kg of perfect dry steam (also known as specific volume), then volume of 1 kg of wet steam = volume of dry steam + volume of water.

$$= xv_g + (1 - x)v_f \qquad ...(3.5)$$

Note. The volume of v_f at low pressures is very small and is generally neglected. Thus is general, the volume of 1 kg of wet steam is given by, xv_g and density $\frac{1}{xv_g}$ kg/m³.

$$\begin{aligned}
&= xv_g + v_f - xv_f \\
&= v_f + x(v_g - v_f) \\
&= v_f + xv_{fg} && ...[3.5\ (a)] \\
&= v_f + xv_{fg} + v_{fg} - v_{fg} \\
&= (v_f + v_{fg}) - (1 - x)\,v_{fg} \\
&= v_g - (1 - x)v_{fg} && ...[3.5\ (b)]
\end{aligned}$$

7. Volume of superheated steam. As superheated steam behaves like a perfect gas its volume can be found out in the same way as the gases.

If, v_g = Specific volume of dry steam at pressure p,

T_s = Saturation temperature in K,
T_{sup} = Temperature of superheated steam in K, and
v_{sup} = Volume of 1 kg of superheated steam at pressure p,

Then, $$\frac{p \cdot v_g}{T_s} = \frac{p \cdot v_{sup}}{T_{sup}}$$

or, $$v_{sup} = \frac{v_g T_{sup}}{T_s} \quad ...(3.6)$$

3.9. THERMODYNAMIC PROPERTIES OF STEAM AND STEAM TABLES

In engineering problem, for any fluid which is used as working fluid, the six basic thermodynamic properties required are : p (pressure), T (temperature), v (volume), u (internal energy), h (enthalpy) and s (entropy). These properties must be known at different pressure for analysing the thermodynamic cycles used for work producing devices. The values of these properties are determined theoretically or experimentally and are tabulated in the form of tables which are known as '*Steam Tables*'. The properties of wet steam are then computed from such tabulated data. Tabulated values are also available for superheated steam. It may be noted that *steam has only one saturation temperature at each pressure.*

Following are the thermodynamic properties of steam which are tabulated in the form of table :

p = Absolute pressure (bar or kPa) ;
t_s = Saturation temperature (°C) ;
h_f = Enthalpy of saturated liquid (kJ/kg) ;
h_{fg} = Enthalpy or latent heat of vapourisation (kJ/kg) ;
h_g = Enthalpy of saturated vapour (steam) (kJ/kg) ;
s_f = Entropy of saturated liquid (kJ/kg K) ;
s_{fg} = Entropy of vapourisation (kJ/kg K) ;
s_g = Entropy of saturated vapour (steam) (kJ/kg K) ;
v_f = Specific volume of saturated liquid (m^3/kg) ;
v_g = Specific volume of saturated vapour (steam) (m^3/kg).

Also, $h_{fg} = h_g - h_f$ ...... Change of enthalpy during evaporation
$s_{fg} = s_g - s_f$ ...... Change of entropy during evaporation
$v_{fg} = v_g - v_f$ ...... Change of volume during evaporation.

The above mentioned properties at different pressures are tabulated in the form of tables as under :

The internal energy of steam ($u = h - pv$) is also tabulated in some steam tables.

STEAM TABLES

Absolute pressure	*Temperature °C*	*Specific enthalpy kJ/kg*			*Specific entropy kJ/kg K*			*Specific volume m³/kg*	
bar, p	t_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_g
1.0	99.6	417.5	2257.9	2675.4	1.3027	6.0571	7.3598	0.001043	1.6934
50.0	263.9	1154.9	1639.7	2794.2	2.9206	3.0529	5.9735	0.001286	0.00394
100.0	311.1	1408.0	1319.7	2727.7	3.3605	2.2593	5.6198	0.001452	0.01811

3.10. EXTERNAL WORK DONE DURING EVAPORATION

When water is evaporated to form *saturated* steam, its volume increases from v_f to v_g at a constant pressure, and thus external work is done by steam due to increase in volume. The energy for doing the work is obtained during the absorption of latent heat. This work is called **external work of evaporation** and is given by $p(v_g - v_f)$.

i.e., External work of evaporation $= p(v_g - v_f)$ ...(3.7)

As at low pressure v_f is very small and hence neglected, work of evaporation is

$$p \cdot v_g \qquad \text{...(3.8)}$$

In case of *wet* steam with dryness fraction x, work of evaporation will be

$$pxv_g \qquad \text{...(3.9)}$$

3.11. INTERNAL LATENT HEAT

The latent heat consists of true latent heat and the work of evaporation. This true latent heat is called the *internal latent heat* and may also be found as follows :

$$\text{Internal latent heat} = h_{fg} - \frac{pv_g}{J} \qquad \text{...(3.10)}$$

J = 1 in SI units.

3.12. INTERNAL ENERGY OF STEAM

It is defined as the actual energy stored in the steam. As per previous articles, the total heat of steam is sum of sensible heat, internal latent heat and the external work of evaporation. Work of evaporation is not stored in the steam as it is utilised in doing external work. Hence the internal energy of steam could be found by subtracting work of evaporation from the total heat.

In other words,

$$h = \frac{pv_g}{J} + u, \text{ where } u \text{ is internal energy of 1 kg of steam at pressure } p$$

or

$$u = h - \frac{pv_g}{J}$$

In case of wet steam with dryness fraction 'x'

$$u = h - \frac{pxv_g}{J} \qquad \text{...(3.11)}$$

and if steam is superheated to a volume of v_{sup} per kg.

$$h_{sup} = h_f + h_{fg} + c_{ps}\,(T_{sup} - T_s)$$

and

$$u = h_{sup} - \frac{p \cdot v_{sup}}{J} \qquad \text{...(3.12)}$$

3.13. ENTROPY OF WATER

(**Note.** For definition of entropy please refer to chapter 5.)

Consider 1 kg of water being heated from temperature T_1 to T_2 at constant pressure. The change in entropy will be given by,

$$ds = \frac{dQ}{T} = c_{pw} \cdot \frac{dT}{T}$$

Integrating both sides, we get

$$\int_{s_1}^{s_2} ds = \int_{T_1}^{T_2} c_{pw} \frac{dT}{T}$$

$$s_2 - s_1 = c_{pw} \log_e \frac{T_2}{T_1} \qquad \text{...(3.13)}$$

If 0°C is taken as datum, then entropy of water per kg at any temperature T above this datum will be

$$s_f = c_{pw} \log_e \frac{T}{273} \qquad \text{...(3.14)}$$

3.14. ENTROPY OF EVAPORATION

The change of entropy (ds) is given by,

$$ds = \frac{dQ}{T}$$

or $$s_2 - s_1 = \frac{Q}{T}, \text{ where } Q \text{ is the heat absorbed.}$$

When water is evaporated to steam completely the heat absorbed is the latent heat and this heat goes into water without showing any rise of temperature.

Then $$Q = h_{fg}$$

and $$s_{evap.} = \frac{h_{fg}}{T_s} \qquad \text{...(3.15)}$$

However, in case of wet steam with dryness fraction x the evaporation will be partial and heat absorbed will be xh_{fg} per kg of steam. The change of entropy will be $\frac{xh_{fg}}{T_s}$.

3.15. ENTROPY OF WET STEAM

The total entropy of wet steam is the sum of entropy of water (s_f) and entropy of evaporation (s_{fg}).

In other words, $$s_{wet} = s_f + \frac{xh_{fg}}{T_s} \qquad \text{...(3.16)}$$

where s_{wet} = Total entropy of wet steam,

s_f = Entropy of water, and

$\frac{xh_{fg}}{T_s}$ = Entropy of evaporation.

If steam is dry and saturated, *i.e.*, $x = 1$, then

$$s_g = s_f + \frac{h_{fg}}{T_s} \qquad \text{...(3.17)}$$

3.16. ENTROPY OF SUPERHEATED STEAM

Let 1 kg of dry saturated steam at T_s (saturation temperature of steam) be heated to T_{sup}. If specific heat at constant pressure is c_{ps}, then change of entropy during superheating at constant pressure p

$$= c_{ps} \log_e \left(\frac{T_{sup}}{T_s}\right).$$

Total entropy of superheated steam above the freezing point of water.

s_{sup} = Entropy of dry saturated steam + change of entropy during superheating

$$= s_f + \frac{h_{fg}}{T_s} + c_{ps} \log_e \left(\frac{T_{sup}}{T_s}\right) = s_g + c_{ps} \log_e \left(\frac{T_{sup}}{T_s}\right) \qquad ...(3.18)$$

3.17. ENTHALPY-ENTROPY (h-s) CHART OR MOLLIER DIAGRAM

Dr. Mollier, in 1904, conceived the idea of plotting total heat against entropy, and his diagram is more widely used than any other entropy diagram, since the work done on vapour cycles can be scaled from this diagram directly *as a length ; whereas on T-s diagram it is represented by an area.*

A sketch of the *h-s* chart is shown in Fig. 3.11.

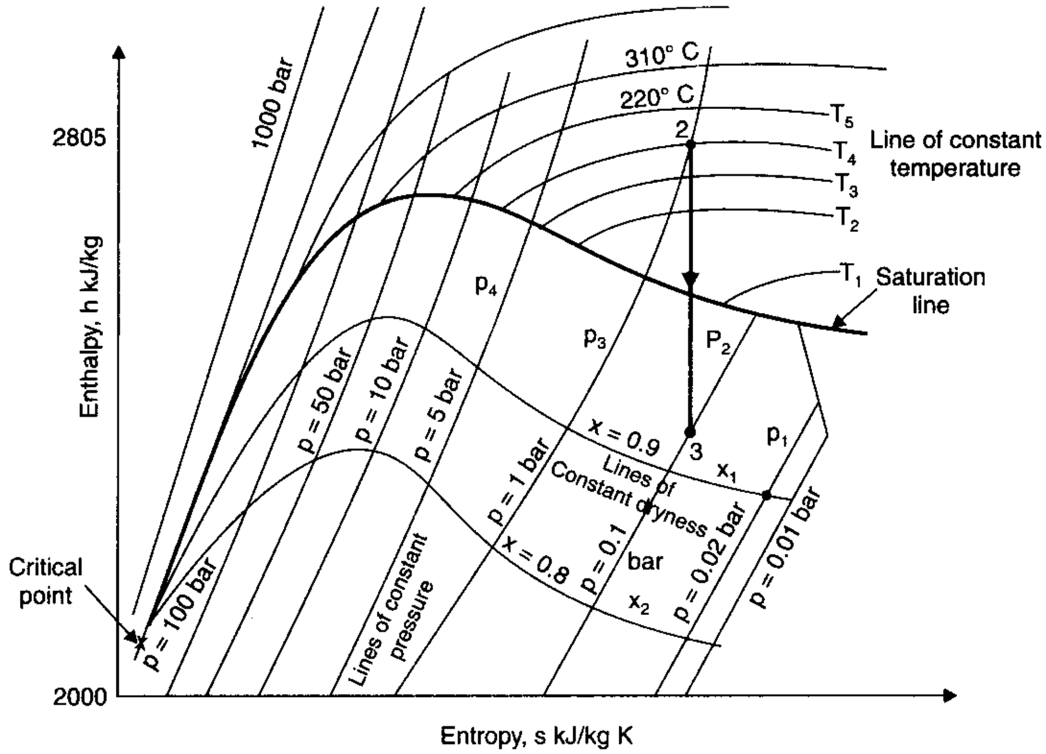


Fig. 3.11. Enthalpy-entropy (*h-s*) chart.

- Lines of constant pressure are indicated by p_1, p_2 etc., lines of constant temperature by T_1, T_2, etc.
- Any two independent properties which appear on the chart are sufficient to define the state (*e.g.*, p_1 and x_1 define state 1 and h can be read off the vertical axis).
- In the superheat region, pressure and temperature can define the state (*e.g.*, p_3 and T_4 define the state 2, and h_2 can be read off).

— A line of constant entropy between two state points 2 and 3 defines the properties at all points during an *isentropic process* between the two states.

Example 3.1. *Calculate the dryness fraction (quality) of steam which has 1.5 kg of water in suspension with 50 kg of steam.*

Solution. Mass of dry steam, m_s = 50 kg

Mass of water in suspension, m_w = 1.5 kg

$\therefore$ **Dryness fraction,** $x = \dfrac{\text{Mass of dry steam}}{\text{Mass of dry steam + mass of water in suspension}}$

$$= \frac{m_s}{m_s + m_w} = \frac{50}{50 + 1.5} = \mathbf{0.971}. \quad \textbf{(Ans.)}$$

☞ **Example 3.2.** *A vessel having a volume of 0.6 m^3 contains 3.0 kg of liquid water and water vapour mixture in equilibrium at a pressure of 0.5 MPa. Calculate :*

(*i*) *Mass and volume of liquid ;*

(*ii*) *Mass and volume of vapour.*

Solution. Volume of the vessel, V = 0.6 m^3

Mass of liquid water and water vapour, m = 3.0 kg

Pressure, p = 0.5 MPa = 5 bar

Thus, specific volume, $v = \dfrac{V}{m} = \dfrac{0.6}{3.0} = 0.2 \text{ m}^3/\text{kg}$

At 5 bar : From steam tables,

$$v_{fg} = v_g - v_f = 0.375 - 0.00109 = 0.3739 \text{ m}^3/\text{kg}$$

We know that, $v = v_g - (1 - x)\, v_{fg}$, where x = quality of the vapour.

$$0.2 = 0.375 - (1 - x) \times 0.3739$$

$$\therefore \quad (1 - x) = \frac{(0.375 - 0.2)}{0.3739} = 0.468$$

or $x = 0.532$

(*i*) **Mass and volume of liquid, $\mathbf{m_{liq.}}$ = ? $\mathbf{V_{liq.}}$ = ?**

$$\mathbf{m_{liq.}} = m(1 - x) = 3.0 \times 0.468 = \mathbf{1.404 \text{ kg}}. \quad \textbf{(Ans.)}$$

$$\mathbf{V_{liq.}} = m_{liq.}\, v_f = 1.404 \times 0.00109 = \mathbf{0.0015 \text{ m}^3}. \quad \textbf{(Ans.)}$$

(*ii*) **Mass and volume of vapour, $\mathbf{m_{vap.}}$ = ? $\mathbf{V_{vap.}}$ = ?**

$$\mathbf{m_{vap.}} = m.x = 3.0 \times 0.532 = \mathbf{1.596 \text{ kg}}. \quad \textbf{(Ans.)}$$

$$\mathbf{V_{vap.}} = m_{vap.}\, v_g = 1.596 \times 0.375 = \mathbf{0.5985 \text{ m}^3}. \quad \textbf{(Ans.)}$$

☞ **Example 3.3.** *A vessel having a capacity of 0.05 m^3 contains a mixture of saturated water and saturated steam at a temperature of 245°C. The mass of the liquid present is 10 kg. Find the following :*

(*i*) *The pressure,* (*ii*) *The mass,*

(*iii*) *The specific volume,* (*iv*) *The specific enthalpy,*

(*v*) *The specific entropy, and* (*vi*) *The specific internal energy.*

Solution. From steam tables, corresponding to 245°C :

$$p_{sat} = 36.5 \text{ bar}, \ v_f = 0.001239 \text{ m}^3/\text{kg}, \ v_g = 0.0546 \text{ m}^3/\text{kg}$$

$$h_f = 1061.4 \text{ kJ/kg}, \ h_{fg} = 1740.2 \text{ kJ/kg}, \ s_f = 2.7474 \text{ kJ/kg K}$$

$$s_{fg} = 3.3585 \text{ kJ/kg K}.$$

(*i*) **The pressure = 36.5 bar** (or 3.65 MPa). **(Ans.)**

(*ii*) **The mass, m :**

Volume of liquid, $V_f = m_f v_f$

$= 10 \times 0.001239 = 0.01239 \text{ m}^3$

Volume of vapour, $V_g = 0.05 - 0.01239 = 0.03761 \text{ m}^3$

∴ Mass of vapour, $m_g = \dfrac{V_g}{v_g} = \dfrac{0.03761}{0.0546} = 0.688 \text{ kg}$

∴ The total mass of mixture,

$\mathbf{m} = m_f + m_g = 10 + 0.688 = \mathbf{10.688\ kg.}$ **(Ans.)**

(*iii*) **The specific volume, v :**

Quality of the mixture,

$$x = \frac{m_g}{m_g + m_f} = \frac{0.688}{0.688 + 10} = 0.064$$

∴ $\mathbf{v} = v_f + x v_{fg}$

$= 0.001239 + 0.064 \times (0.0546 - 0.001239)$ $(\because\ v_{fg} = v_g - v_f)$

$= \mathbf{0.004654\ m^3/kg.}$ **(Ans.)**

(*iv*) **The specific enthalpy, h :**

$\mathbf{h} = h_f + x h_{fg}$

$= 1061.4 + 0.064 \times 1740.2 = \mathbf{1172.77\ kJ/kg.}$ **(Ans.)**

(*v*) **The specific entropy, s :**

$\mathbf{s} = s_f + x s_{fg}$

$= 2.7474 + 0.064 \times 3.3585 = \mathbf{2.9623\ kJ/kg\ K.}$ **(Ans.)**

(*vi*) **The specific internal energy, u :**

$\mathbf{u} = h - pv$

$$= 1172.77 - \frac{36.5 \times 10^5 \times 0.004654}{1000} = \mathbf{1155.78\ kJ/kg.}\ \textbf{(Ans.)}$$

Example 3.4. *Determine the amount of heat, which should be supplied to 2 kg of water at 25°C to convert it into steam at 5 bar and 0.9 dry.*

Solution. Mass of water to be converted to steam, $m_w = 2$ kg

Temperature of water, $t_w = 25°\text{C}$

Pressure and dryness fraction of steam = 5 bar, 0.9 dry

At 5 bar : From steam tables,

$h_f = 640.1$ kJ/kg ; $h_{fg} = 2107.4$ kJ/kg

Enthalpy of 1 kg of steam (above 0°C)

$h = h_f + x h_{fg}$

$= 640.1 + 0.9 \times 2107.4 = 2536.76$ kJ/kg

Sensible heat associated with 1 kg of water

$= m_w \times c_{pw} \times (t_w - 0)$

$= 1 \times 4.18 \times (25 - 0) = 104.5$ kJ

Net quantity of heat to be supplied per kg of water

$= 2536.76 - 104.5 = 2432.26$ kJ

Total amount of heat to be supplied

$$= 2 \times 2432.26 = \mathbf{4864.52\ kJ.}\ \ \textbf{(Ans.)}$$

Example 3.5. *What amount of heat would be required to produce 4.4 kg of steam at a pressure of 6 bar and temperature of 250°C from water at 30°C ? Take specific heat for superheated steam as 2.2 kJ/kg K.*

Solution. Mass of steam to be produced, $m = 4.4$ kg

Pressure of steam, $p = 6$ bar

Temperature of steam, $t_{sup} = 250°C$

Temperature of water $= 30°C$

Specific heat of steam, $c_{ps} = 2.2$ kJ/kg

At 6 bar, 250°C : From steam tables,

$$t_s = 158.8°C,\ h_f = 670.4 \text{ kJ/kg},\ h_{fg} = 2085 \text{ kJ/kg}$$

Enthalpy of 1 kg superheated steam reckoned from 0°C,

$$\begin{aligned} h_{sup} &= h_f + h_{fg} + c_{ps}\,(T_{sup} - T_s) \\ &= 670.4 + 2085 + 2.2(250 - 158.8) \\ &= 2956 \text{ kJ} \end{aligned}$$

Amount of heat already with 1 kg of water

$$= 1 \times 4.18 \times (30 - 0) = 125.4 \text{ kJ}$$

Net amount of heat required to be supplied per kg

$$= 2956 - 125.4 = 2830.6 \text{ kJ}$$

Total amount of heat required

$$= 4.4 \times 2830.6 = \mathbf{12454.6\ kJ.}\ \ \textbf{(Ans.)}$$

☞ **Example 3.6.** *Determine the mass of 0.15 m³ of wet steam at a pressure of 4 bar and dryness fraction 0.8. Also calculate the heat of 1 m³ of steam.*

Solution. Volume of wet steam, $v = 0.15$ m³

Pressure of wet steam, $p = 4$ bar

Dryness fraction, $x = 0.8$

At 4 bar. From steam tables,

$v_g = 0.462$ m³/kg, $h_f = 604.7$ kJ/kg, $h_{fg} = 2133$ kJ/kg

$$\therefore \qquad \text{Density} = \frac{1}{xv_g} = \frac{1}{0.8 \times 0.462} = 2.7056 \text{ kg/m}^3$$

Mass of 0.15 m³ of steam

$$= 0.15 \times 2.7056 = \mathbf{0.4058\ kg.}\ \ \textbf{(Ans.)}$$

Total heat of 1 m³ of steam which has a mass of 2.7056 kg

$$\begin{aligned} &= 2.7056\, h \text{ (where } h \text{ is the total heat of 1 kg of steam)} \\ &= 2.7056\,(h_f + xh_{fg}) \\ &= 2.7056(604.7 + 0.8 \times 2133) \\ &= \mathbf{6252.9\ kJ.}\ \ \textbf{(Ans.)} \end{aligned}$$

Example 3.7. *1000 kg of steam at a pressure of 16 bar and 0.9 dry is generated by a boiler per hour. The steam passes through a superheater via boiler stop valve where its temperature is raised to 380°C. If the temperature of feed water is 30°C, determine :*

(i) The total heat supplied to feed water per hour to produce wet steam.

(ii) The total heat absorbed per hour in the superheater.

Take specific heat for superheated steam as 2.2 kJ/kg K.

Solution. Mass of steam generated, $m = 1000$ kg/h

Pressure of steam, $p = 16$ bar

Dryness fraction, $x = 0.9$

Temperature of superheated steam,

$$T_{sup} = 380 + 273 = 653 \text{ K}$$

Temperature of feed water = 30°C

Specific heat of superheated steam, $c_{ps} = 2.2$ kJ/kg K.

At 16 bar. From steam tables,

$$t_s = 201.4°\text{C} \ (T_s = 201.4 + 273 = 474.4 \text{ K}) \ ;$$

$$h_f = 858.6 \text{ kJ/kg} \ ; \ h_{fg} = 1933.2 \text{ kJ/kg}$$

(*i*) *Heat supplied to feed water per hour* to produce wet steam is given by :

$$\begin{aligned} H &= m\,[(h_f + xh_{fg}) - 1 \times 4.18 \times (30 - 0)] \\ &= 1000\,[(858.6 + 0.9 \times 1933.2) - 4.18 \times 30] \\ &= 1000(858.6 + 1739.88 - 125.4) \\ &= \mathbf{2473.08 \times 10^3\ kJ.} \quad \textbf{(Ans.)} \end{aligned}$$

(*ii*) *Heat absorbed by superheater per hour*

$$\begin{aligned} &= m[(1 - x)\,h_{fg} + c_{ps}\,(T_{sup} - T_s)] \\ &= 1000[(1 - 0.9) \times 1933.2 + 2.2\,(653 - 474.4)] \\ &= 1000(193.32 + 392.92) \\ &= \mathbf{586.24 \times 10^3\ kJ.} \quad \textbf{(Ans.)} \end{aligned}$$

Example 3.8. *Using steam tables, determine the mean specific heat for superheated steam :*

(i) at 0.75 bar, between 100°C and 150°C ;

(ii) at 0.5 bar, between 300°C and 400°C.

Solution. (*i*) **At 0.75 bar.** From steam tables ;

At 100°C, $h_{sup} = 2679.4$ kJ/kg

At 150°C, $h_{sup} = 2778.2$ kJ/kg

$\therefore$ $2778.2 = 2679.4 + c_{ps}\,(150 - 100)$

i.e., $$c_{ps} = \frac{2778.2 - 2679.4}{50} = \mathbf{1.976.} \quad \textbf{(Ans.)}$$

(*ii*) **At 0.5 bar.** From steam tables ;

At 300°C, $h_{sup} = 3075.5$ kJ/kg

At 400°C, $h_{sup} = 3278.9$ kJ/kg

$\therefore$ $3278.9 = 3075.5 + c_{ps}\,(400 - 300)$

i.e., $$c_{ps} = \frac{3278.9 - 3075.5}{100} = \mathbf{2.034.} \quad \textbf{(Ans.)}$$

Example 3.9. *A pressure cooker contains 1.5 kg of saturated steam at 5 bar. Find the quantity of heat which must be rejected so as to reduce the quality to 60% dry. Determine the pressure and temperature of the steam at the new state.*

Solution. Mass of steam in the cooker = 1.5 kg

Pressure of steam, $p = 5$ bar

Initial dryness fraction of steam, $x_1 = 1$

Final dryness fraction of steam, $x_2 = 0.6$

Heat to be rejected :

Pressure and temperature of the steam at the new state :

At 5 bar. From steam tables,

$$t_s = 151.8°\text{C} \; ; \qquad h_f = 640.1 \text{ kJ/kg} \; ;$$
$$h_{fg} = 2107.4 \text{ kJ/kg} \; ; \qquad v_g = 0.375 \text{ m}^3\text{/kg}$$

Thus, the volume of pressure cooker

$$= 1.5 \times 0.375 = 0.5625 \text{ m}^3$$

Internal energy of steam per kg at initial point 1,

$$\begin{aligned} u_1 &= h_1 - p_1 v_1 \\ &= (h_f + h_{fg}) - p_1 v_{g_1} && (\because \; v_1 = v_{g1}) \\ &= (640.1 + 2107.4) - 5 \times 10^5 \times 0.375 \times 10^{-3} \\ &= 2747.5 - 187.5 = 2560 \text{ kJ/kg} \end{aligned}$$

Also, $V_1 = V_2$ (V_2 = volume at final condition)

i.e.,

$$\begin{aligned} 0.5625 &= 1.5[(1 - x_2)\, v_{f2} + x_2 v_{g2}] \\ &= 1.5\, x_2 v_{g2} && (\because \; v_{f2} \text{ is negligible}) \\ &= 1.5 \times 0.6 \times v_{g2} \end{aligned}$$

$$\therefore \qquad v_{g2} = \frac{0.5625}{1.5 \times 0.6} = 0.625 \text{ m}^3\text{/kg.}$$

From steam tables corresponding to 0.625 m³/kg,

$p_2 \simeq$ **2.9 bar**, t_s = **132.4°C**, $h_f = 556.5$ kJ/kg, $h_{fg} = 2166.6$ kJ/kg

Internal energy of steam per kg, at final point 2,

$$\begin{aligned} u_2 &= h_2 - p_2 v_2 \\ &= (h_{f_2} + x_2 h_{fg_2}) - p_2 x v_{g2} && (\because \; v_2 = x v_{g2}) \\ &= (556.5 + 0.6 \times 2166.6) - 2.9 \times 10^5 \times 0.6 \times 0.625 \times 10^{-3} \\ &= 1856.46 - 108.75 = 1747.71 \text{ kJ/kg.} \end{aligned}$$

Heat transferred at constant volume per kg

$$= u_2 - u_1 = 1747.71 - 2560 = -\,812.29 \text{ kJ/kg}$$

Thus, **total heat transferred**

$$= -\,812.29 \times 1.5 = -\,\mathbf{1218.43 \text{ kJ.}} \quad \textbf{(Ans.)}$$

Negative sign indicates that heat has been **rejected.**

☞ **Example 3.10.** *A spherical vessel of 0.9 m³ capacity contains steam at 8 bar and 0.9 dryness fraction. Steam is blown off until the pressure drops to 4 bar. The valve is then closed and the steam is allowed to cool until the pressure falls to 3 bar. Assuming that the enthalpy of steam in the vessel remains constant during blowing off periods, determine :*

(i) The mass of steam blown off ;

(ii) The dryness fraction of steam in the vessel after cooling ;

(iii) The heat lost by steam per kg during cooling.

Solution. Capacity of the spherical vessel, $V = 0.9\ m^3$

Pressure of the steam, $p_1 = 8$ bar

Dryness fraction of steam, $x_1 = 0.9$

Pressure of steam after blow off, $p_2 = 4$ bar

Final pressure of steam, $p_3 = 3$ bar.

(*i*) **The mass of steam blown off :**

The mass of steam in the vessel

$$m_1 = \frac{V}{x_1 v_{g_1}} = \frac{0.9}{0.9 \times 0.24} = 4.167 \text{ kg} \qquad (\because \text{ At 8 bar} : v_g = 0.24 \text{ m}^3/\text{kg})$$

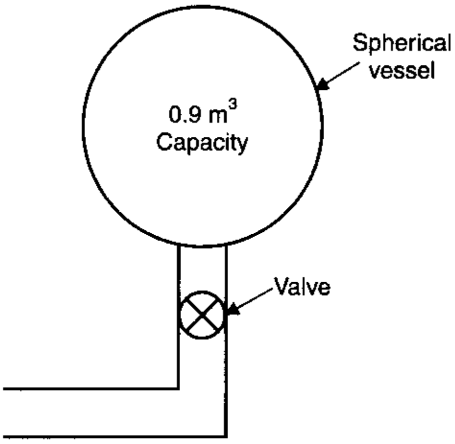


Fig. 3.12

The enthalpy of steam before blowing off (per kg)

$$= h_{f_1} + x_1 h_{fg_1} = 720.9 + 0.9 \times 2046.5 \text{ ...... at pressure } 8 \text{ bar}$$

$$= 2562.75 \text{ kJ/kg}$$

Enthalpy before blowing off = Enthalpy after blowing off

$$\therefore \quad 2562.75 = (h_{f_2} + x_2 h_{fg_2}) \text{ at pressure 4 bar}$$

$$= 604.7 + x_2 \times 2133 \text{ ...... at pressure } 4 \text{ bar}$$

$$\therefore \quad x_2 = \frac{2562.75 - 604.7}{2133} = 0.918$$

Now the mass of steam in the vessel after blowing off,

$$m_2 = \frac{0.9}{0.918 \times 0.462} = 2.122 \text{ kg} \qquad [v_{g_2} = 0.462 \text{ m}^3/\text{kg.......at 4 bar}]$$

Mass of steam blown off, $m = m_1 - m_2 = 4.167 - 2.122$

$= \mathbf{2.045\ kg.}$ **(Ans.)**

(*ii*) **Dryness fraction of steam in the vessel after cooling, x_3 :**

As it is constant volume cooling

$$\therefore \quad x_2 v_{g_2} \text{ (at 4 bar)} = x_3 v_{g_3} \text{ (at 3 bar)}$$

$$0.918 \times 0.462 = x_3 \times 0.606$$

$$\therefore \qquad x_3 = \frac{0.918 \times 0.462}{0.606} = \mathbf{0.699.} \quad \textbf{(Ans.)}$$

(*iii*) **Heat lost during cooling :**

Heat lost during cooling = $m(u_3 - u_2)$, where u_2 and u_3 are the internal energies of steam before starting cooling or after blowing and at the end of the cooling.

$$\therefore \qquad u_2 = h_2 - p_2 x_2 v_{g_2} = (h_{f_2} + x_2 h_{fg2}) - p_2 x_2 v_{g2}$$

$$= (604.7 + 0.918 \times 2133) - 4 \times 10^5 \times 0.918 \times 0.462 \times 10^{-3}$$

$$= 2562.79 - 169.65 = 2393.14 \text{ kJ/kg}$$

$$u_3 = h_3 - p_3 x_3 v_{g_3} = (h_{f_3} + x_3 h_{fg3}) - p_3 x_3 v_{g3}$$

$$= (561.4 + 0.669 \times 2163.2) - 3 \times 10^5 \times 0.699 \times 0.606 \times 10^{-3}$$

$$= 2073.47 - 127.07 = 1946.4 \text{ kJ/kg}$$

∴ Heat transferred during cooling

$$= 2.045\ (1946.4 - 2393.14) = -\ 913.6 \text{ kJ.}$$

i.e., **Heat lost during cooling = 913.6 kJ. (Ans.)**

Example 3.11. *If a certain amount of steam is produced at a pressure of 8 bar and dryness fraction 0.8. Calculate :*

(*i*) *External work done during evaporation.*

(*ii*) *Internal latent heat of steam.*

Solution. Pressure of steam, p = 8 bar

Dryness fraction, x = 0.8

At 8 bar. From steam tables,

$$v_g = 0.240 \text{ m}^3\text{/kg}, \; h_{fg} = 2046.5 \text{ kJ/kg}$$

(*i*) External work done during evaporation

$$= pxv_g = 8 \times 10^5 \times 0.8 \times 0.24 \text{ N-m}$$

$$= \frac{8 \times 10^5 \times 0.8 \times 0.24}{10^3} = \mathbf{153.6\ kJ.} \quad \textbf{(Ans.)}$$

(*ii*) Internal latent heat $= xh_{fg}$ – external work done

$$= 0.8 \times 2046.5 - 153.6$$

$$= \mathbf{1483.6\ kJ.} \quad \textbf{(Ans.)}$$

Example 3.12. *A quantity of steam at 10 bar and 0.85 dryness occupies 0.15 m³. Determine the heat supplied to raise the temperature of the steam to 300°C at constant pressure and percentage of this heat which appears as external work.*

Take specific heat of superheated steam as 2.2 kJ/kg K.

Solution. Pressure of steam, $p_1 = p_2$ = 10 bar

Dryness fraction, x_1 = 0.85

Volume of steam, V_1 = 0.15 m³

Final temperature of steam, t_{sup_2} = 300°C

Specific heat of superheated steam, c_{ps} = 2.2 kJ/kg K

$$\text{Mass of steam} = \frac{V_1}{x_1 v_{g_1}} = \frac{0.15}{0.85 \times 0.194} = 0.909 \text{ kg} \qquad (\because \text{ At 10 bar} : v_g = 0.194 \text{ m}^3/\text{kg})$$

Heat supplied per kg of steam

$$= (1 - x_1)\, h_{fg_1} + c_{ps}\,(300 - 179.9)$$

$$= (1 - 0.85)2013.6 + 2.2 \times 120.1 \qquad \left[\because \; t_s = 179.9°\text{C} \ldots \text{at 10 bar, and } h_{fg} = 2013.6 \text{ kJ / kg}\right]$$

$$= 566.26 \text{ kJ/kg}$$

Total heat supplied

$$= 0.909 \times 566.26 = \mathbf{514.7 \ kJ.} \quad \textbf{(Ans.)}$$

External work done during this process

$$= p\,(v_{sup_2} - x_1 v_{g_1}) \qquad [\because p_1 = p_2 = p]$$

$$= 10 \times 10^5 \left[\left(v_{g_1} \times \frac{T_{sup_2}}{T_{s_1}}\right) - x_1 v_{g_1}\right] \times 10^{-3} \qquad \left[\because \; \frac{v_{g_1}}{T_{s_1}} = \frac{v_{sup_2}}{T_{sup_2}} \; i.e., v_{sup_2} = \frac{v_{g_1} \times T_{sup_2}}{T_{s_1}}\right]$$

$$= 10 \times 10^5 \left[0.194 \times \frac{(300 + 273)}{(179.9 + 273)} - 0.85 \times 0.194\right] \times 10^{-3}$$

$$= \frac{10 \times 10^5}{10^3}\,(0.245 - 0.165) = 80 \text{ kJ/kg}$$

∴ **Percentage of total heat supplied (per kg) which appears as external work**

$$= \frac{80}{566.26} = 0.141 = \mathbf{14.1\%.} \quad \textbf{(Ans.)}$$

Example 3.13. *Find the specific volume, enthalpy and internal energy of wet steam at 18 bar, dryness fraction 0.85.*

Solution. Pressure of steam, $p = 18$ bar

Dryness fraction, $x = 0.85$

From steam tables corresponding to 18 bar pressure :

$h_f = 884.6$ kJ/kg, $h_{fg} = 1910.3$ kJ/kg, $v_g = 0.110$ m^3/kg, $u_f = 883$ kJ/kg, $u_g = 2598$ kJ/kg.

(*i*) **Specific volume of wet steam,**

$$v = x v_g = 0.85 \times 0.110 = \mathbf{0.0935 \ m^3/kg.} \quad \textbf{(Ans.)}$$

(*ii*) **Specific enthalpy of wet steam,**

$$h = h_f + x h_{fg} = 884.6 + 0.85 \times 1910.3$$

$$= \mathbf{2508.35 \ kJ/kg.} \quad \textbf{(Ans.)}$$

(*iii*) **Specific internal energy of wet steam,**

$$u = (1 - x)u_f + x u_g$$

$$= (1 - 0.85) \times 883 + 0.85 \times 2598$$

$$= \mathbf{2340.75 \ kJ/kg.} \quad \textbf{(Ans.)}$$

: 2340.75

Example 3.14. *Find the dryness fraction, specific volume and internal energy of steam at 7 bar and enthalpy 2550 kJ/kg.*

Solution. Pressure of steam, $p = 7$ bar

Enthalpy of steam, $h = 2550$ kJ

From steam tables corresponding to 7 bar pressure :

$h_f = 697.1$ kJ/kg, $h_{fg} = 2064.9$ kJ/kg, $v_g = 0.273$ m^3/kg,

$u_f = 696$ kJ/kg, $u_g = 2573$ kJ/kg.

(*i*) **Dryness fraction, x :**

At 7 bar, $h_g = 2762$ kJ/kg, hence since the actual enthalpy is given as 2550 kJ/kg, the steam must be in the wet vapour state.

Now, using the equation,

$$h = h_f + xh_{fg}$$

$$\therefore \quad 2550 = 697.1 + x \times 2064.9$$

i.e., $$x = \frac{2550 - 697.1}{2064.9} = 0.897$$

Hence, **dryness fraction = 0.897. (Ans.)**

(*ii*) **Specific volume of wet steam,**

$$v = xv_g = 0.897 \times 0.273 = \mathbf{0.2449\ m^3/kg.}\quad \textbf{(Ans.)}$$

(*iii*) **Specific internal energy of wet steam,**

$$u = (1 - x)u_f + xu_g$$
$$= (1 - 0.897) \times 696 + 0.897 \times 2573$$
$$= \mathbf{2379.67\ kJ/kg.}\quad \textbf{(Ans.)}$$

●**Example 3.15.** *Steam at 120 bar has a specific volume of 0.01721 m³/kg, find the temperature, enthalpy and the internal energy.*

Solution. Pressure of steam, $p = 120$ bar

Specific volume, $v = 0.01721$ m³/kg

(*i*) **Temperature :**

First it is necessary to decide whether the steam is wet, dry saturated or superheated.

At 120 bar, $v_g = 0.0143$ m³/kg, which is less than the actual specific volume of 0.01721 m³/kg, and hence the steam is **superheated.**

From the superheat tables at 120 bar, the specific volume is 0.01721 m³/kg at a temperature of **350°C. (Ans.)**

(*ii*) **Enthalpy :**

From the steam tables the specific enthalpy at 120 bar, 350°C,

$$h = \mathbf{2847.7\ kJ/kg.}\quad \textbf{(Ans.)}$$

(*iii*) **Internal energy :**

To find internal energy, using the equation,

$$u = h - pv$$
$$= 2847.7 - \frac{120 \times 10^5 \times 0.01721}{10^3}$$
$$= \mathbf{2641.18\ kJ/kg.}\quad \textbf{(Ans.)}$$

●**Example 3.16.** *Steam at 140 bar has an enthalpy of 3001.9 kJ/kg, find the temperature, the specific volume and the internal energy.*

Solution. Pressure of steam, $p = 140$ bar

Enthalpy of steam, $h = 3001.9$ kJ/kg

(*i*) **Temperature :**

At 140 bar, $h_g = 2642.4$ kJ, which is less than the actual enthalpy of 3001.9 kJ/kg, and hence the steam is **superheated.**

From superheat tables at 140 bar, $h = 3001.9$ kJ/kg at a temperature of **400°C. (Ans.)**

(*ii*) The **specific volume,** v = **0.01722 m³/kg. (Ans.)**

∴ The **internal energy** (specific),

$$u = h - pv = 3001.9 - \frac{140 \times 10^5 \times 0.01722}{10^3}$$

$$= \mathbf{2760.82\ kJ/kg.}\ \textbf{(Ans.)}$$

☞ **Example 3.17.** *Calculate the internal energy per kg of superheated steam at a pressure of 10 bar and a temperature of 300°C. Also find the change of internal energy if this steam is expanded to 1.4 bar and dryness fraction 0.8.*

Solution. At 10 bar, 300°C. From steam tables for superheated steam.

$$h_{sup} = 3051.2 \text{ kJ/kg } (T_{sup} = 300 + 273 = 573 \text{ K})$$

and corresponding to 10 bar (from tables of dry saturated steam)

$$T_s = 179.9 + 273 = 452.9 \text{ K} ; v_g = 0.194 \text{ m}^3\text{/kg}$$

To find $v_{sup.}$, using the relation,

$$\frac{v_g}{T_s} = \frac{v_{sup}}{T_{sup}}$$

$$\therefore \quad v_{\text{sup}} = \frac{v_g \times T_{\text{sup}}}{T_s} = \frac{0.194 \times 573}{452.9} = 0.245 \text{ m}^3\text{/kg.}$$

Internal energy of superheated steam at 10 bar,

$$u_1 = h_{sup} - pv_{sup}$$

$$= 3051.2 - 10 \times 10^5 \times 0.245 \times 10^{-3}$$

$$= \mathbf{2806.2\ kJ/kg.}\ \textbf{(Ans.)}$$

At 1.4 bar. From steam tables ;

$$h_f = 458.4 \text{ kJ/kg}, h_{fg} = 2231.9 \text{ kJ/kg} ; v_g = 1.236 \text{ m}^3\text{/kg}$$

Enthalpy of wet steam (after expansion)

$$h = h_f + xh_{fg}$$

$$= 458.4 + 0.8 \times 2231.9 = 2243.92 \text{ kJ.}$$

Internal energy of this steam,

$$u_2 = h - pxv_g$$

$$= 2243.92 - 1.4 \times 10^5 \times 0.8 \times 1.236 \times 10^{-3}$$

$$= 2105.49 \text{ kJ}$$

Hence change of internal energy per kg

$$u_2 - u_1 = 2105.49 - 2806.2$$

$$= -\ \mathbf{700.7\ kJ.}\ \textbf{(Ans.)}$$

Negative sign indicates **decrease** in internal energy.

Example 3.18. *Find the internal energy of 1 kg of steam at 20 bar when*

(*i*) *it is superheated, its temperature being 400°C* ;

(*ii*) *it is wet, its dryness being 0.9.*

Assume superheated steam to behave as a perfect gas from the commencement of superheating and thus obeys Charle's law. Specific heat for steam = 2.3 kJ/kg K.

Solution. Mass of steam = 1 kg

Pressure of steam, p = 20 bar

Temperature of superheated steam = 400°C ($T_{sup} = 400 + 273 = 673$ K)

Dryness fraction, $x = 0.9$

Specific heat of superheated steam, $c_{ps} = 2.3$ kJ/kg K

(*i*) **Internal energy of 1 kg of superheated steam :**

At 20 bar. From steam tables,

$$t_s = 212.4°\text{C} \; ; \; h_f = 908.6 \text{ kJ/kg} \; ; \; h_{fg} = 1888.6 \text{ kJ/kg}, \; v_g = 0.0995 \text{ m}^3\text{/kg}$$

Now, $h_{sup} = h_f + h_{fg} + c_{ps}(T_{sup} - T_s)$

$= 908.6 + 1888.6 + 2.3(400 - 212.4)$

$= 3228.68$ kJ/kg

Also, $h_{sup} = u + p \, . \, v_{sup}$

or $u = h_{sup} - p \, . \, v_{sup}$

The value of v_{sup} can be found out by Charle's law

$$\frac{v_g}{T_g} = \frac{v_{sup}}{T_{sup}}$$

$$\therefore \quad v_{sup} = \frac{v_g \times T_{sup}}{T_s} = \frac{0.0995 \times 673}{(212.4 + 273)} = 0.1379 \text{ m}^3\text{/kg}$$

Hence internal energy, $u = 3228.68 - 20 \times 10^5 \times 0.1379 \times 10^{-3}$

$=$ **2952.88 kJ/kg. (Ans.)**

(*ii*) **Internal energy of 1 kg of wet steam :**

$$h = h_f + xh_{fg} = 908.6 + 0.9 \times 1888.6 = 2608.34 \text{ kJ/kg}$$

Again $h = u + p \, . \, x \, . \, v_g$

$\therefore \quad u = h - p \, . \, x \, . \, v_g = 2608.34 - 20 \times 10^5 \times 0.9 \times 0.0995 \times 10^{-3}$

$= 2429.24$ kJ/kg

Hence internal energy = 2429.24 kJ/kg. (Ans.)

Example 3.19. *Two boilers one with superheater and other without superheater are delivering equal quantities of steam into a common main. The pressure in the boilers and main is 20 bar. The temperature of steam from a boiler with a superheater is 350°C and temperature of the steam in the main is 250°C.*

Determine the quality of steam supplied by the other boiler. Take $c_{ps} = 2.25$ *kJ/kg.*

Solution. Boiler B_1. 20 bar, 350°C :

Enthalpy, $h_1 = h_{g_1} + c_{ps}(T_{sup} - T_s)$

$= 2797.2 + 2.25(350 - 212.4)$

$= 3106.8$ kJ/kg ...(*i*)

Boiler B_2. 20 bar (temperature not known) :

$h_2 = h_{f_2} + x_2 h_{fg_2}$

$= (908.6 + x_2 \times 1888.6)$ kJ/kg ...(*ii*)

Main. 20 bar, 250°C.

Total heat of 2 kg of steam in the steam main

$= 2[h_g + c_{ps}(T_{sup} - T_s)]$

$= 2[2797.2 + 2.25(250 - 212.4)] = 5763.6$ kJ ...(*iii*)

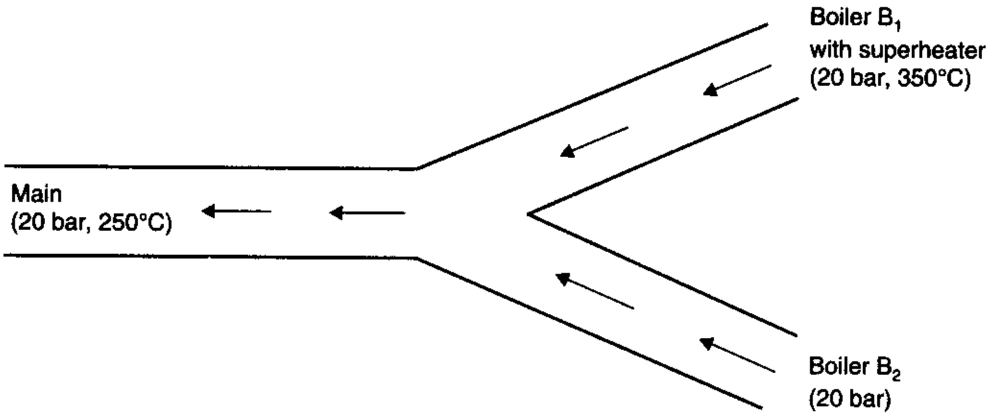


Fig. 3.13

Equating (*i*) and (*ii*) with (*iii*), we get

$$3106.8 + 908.6 + x_2 \times 1888.6 = 5763.6$$

$$4015.4 + 1888.6x_2 = 5763.6$$

$$\therefore \quad x_2 = \frac{5763.6 - 4015.4}{1888.6} = 0.925$$

Hence, **quality of steam supplied by the other boiler = 0.925. (Ans.)**

Example 3.20. *Determine the entropy of 1 kg of wet steam at a pressure of 6 bar and 0.8 dry, reckoned from freezing point (0°C).*

Solution. Mass of wet steam, $m = 1$ kg

Pressure of steam, $p = 6$ bar

Dryness fraction, $x = 0.8$

At 6 bar. From steam tables,

$$t_s = 158.8°\text{C}, \; h_{fg} = 2085 \text{ kJ/kg}$$

Entropy of wet steam is given by

$$s_{wet} = c_{pw} \log_e \frac{T_s}{273} + \frac{xh_{fg}}{T_s} \qquad \text{(where } c_{pw} = \text{specific heat of water)}$$

$$= 4.18 \log_e \left(\frac{158.8 + 273}{273}\right) + \frac{0.8 \times 2085}{(158.8 + 273)}$$

$$= 1.9165 + 3.8700 = 5.7865 \text{ kJ/kg K}$$

Hence, **entropy of wet steam = 5.7865 kJ/kg K. (Ans.)**

Example 3.21. *Steam enters an engine at a pressure 10 bar absolute and 400°C. It is exhausted at 0.2 bar. The steam at exhaust is 0.9 dry. Find :*

(*i*) *Drop in enthalpy ;*

(*ii*) *Change in entropy.*

Solution. Initial pressure of steam, $p_1 = 10$ bar

Initial temperature of steam, $t_{sup} = 400°$C

Final pressure of steam, $p_2 = 0.2$ bar

Final condition of steam, $x_2 = 0.9$

At 10 bar, 400°C. From steam tables,

$$h_{sup} = 3263.9 \text{ kJ/kg} \; ; \; s_{sup} = 7.465 \text{ kJ/kg K}$$

i.e.,
$$h_1 = h_{sup} = 3263.9 \text{ kJ/kg and } s_1 = s_{sup} = 7.465 \text{ kJ/kg K}$$

At 0.2 bar. From steam tables,

$$h_f = 251.5 \text{ kJ/kg} \; ; \; h_{fg} = 2358.4 \text{ kJ/kg} \; ;$$
$$s_f = 0.8321 \text{ kJ/kg K} \; ; \; s_g = 7.9094 \text{ kJ/kg K}$$

Also,
$$h_2 = h_{f_2} + x_2 h_{fg_2} = 251.5 + 0.9 \times 2358.4$$
$$= 2374 \text{ kJ/kg.}$$

Also,
$$s_2 = s_{f_2} + x_2 s_{fg_2}$$
$$= s_{f_2} + x_2 (s_{g_2} - s_{f_2})$$
$$= 0.8321 + 0.9(7.9094 - 0.8321)$$
$$= 7.2016 \text{ kJ/kg K}$$

Hence, (*i*) **Drop in enthalpy,**

$$= h_1 - h_2 = 3263.9 - 2374 = \mathbf{889.9 \text{ kJ/kg.}} \quad \textbf{(Ans.)}$$

(*ii*) **Change in entropy**

$$= s_1 - s_2 = 7.465 - 7.2016$$
$$= \mathbf{0.2634 \text{ kJ/kg K (decrease).}} \quad \textbf{(Ans.)}$$

Example 3.22. *Find the entropy of 1 kg of superheated steam at a pressure of 12 bar and a temperature of 250°C. Take specific heat of superheated steam as 2.1 kJ/kg K.*

Solution. Mass of steam, $m = 1$ kg

Pressure of steam, $p = 12$ bar

Temperature of steam, $T_{sup} = 250 + 273 = 523$ K

Specific heat of superheated steam, $c_{ps} = 2.1$ kJ/kg K

At 12 bar. From steam tables,

$$T_s = 188 + 273 = 461 \text{ K}, \; h_{fg} = 1984.3 \text{ kJ/kg}$$

∴ Entropy of 1 kg of superheated steam,

$$s_{sup} = c_{pw} \log_e \frac{T_s}{273} + \frac{h_{fg}}{T_s} + c_{ps} \log_e \frac{T_{sup}}{T_s}$$
$$= 4.18 \log_e \left(\frac{461}{273}\right) + \frac{1984.3}{461} + 2.1 \times \log_e \left(\frac{523}{461}\right)$$
$$= 2.190 + 4.304 + 0.265$$
$$= \mathbf{6.759 \text{ kJ/kg.}} \quad \textbf{(Ans.)}$$

Example 3.23. *A piston-cylinder contains 3 kg of wet steam at 1.4 bar. The initial volume is 2.25 m^3. The steam is heated until its temperature reaches 400°C . The piston is free to move up or down unless it reaches the stops at the top. When the piston is up against the stops the cylinder volume is 4.65 m^3. Determine the amount of work and heat transfer to or from steam.*

(U.P.S.C. 1994)

Solution. Initial volume per kg of steam $= \frac{2.25}{3} = 0.75$ m^3/kg

Specific volume of steam at 1.4 bar $= 1.2363$ m^3/kg

Dryness fraction of initial steam $= \frac{0.75}{1.2363} = 0.607$

At 1.4 bar, the enthalpy of 3 kg of steam

$$= 3\left[h_f + xh_{fg}\right] = 3\ [\ 458.4 + 0.607 \times 2231.9] = 5439.5 \text{ kJ}$$

At 400°C, volume of steam per kg = $\frac{4.65}{3}$ = 1.55 m^3/kg

At 400°C, when v_{sup} = 1.55 m^3/kg, from steam tables,

Pressure of steam = 2.0 bar

Saturation temperature

$$= 120.2°\text{C},\ h = 3276.6 \text{ kJ/kg}$$

Degree of superheat

$$= t_{sup} - t_s = 400 - 120.2 = 279.8°\text{C}$$

Enthalpy of superheated steam at 2.0 bar,

$$400°\text{C} = 3 \times 3276.6 = 9829.8 \text{ kg}$$

Heat *added during the process*

$$= 9829.8 - 5439.5 = \mathbf{4390.3\ kJ.}\ \ \textbf{(Ans.)}$$

Internal energy of 0.607 dry steam at 1.4 bar

$$= 3 \times 1708 = 5124 \text{ kJ.}$$

Internal energy of superheated steam at 2 bar, 400°C

$$= 3(h_{sup} - pv) = 3(3276.6 - 2 \times 10^2 \times 1.55) = 8899.8 \text{ kJ}$$

$(\because\ 1 \text{ bar} = 10^2 \text{ kPa})$

Change in internal energy = 8899.8 – 5124 = 3775.8 kJ

Hence, **work done** = 4390.3 – 3775.8 = **614.5 kJ. (Ans.)** $(\because\ W = Q - \Delta U)$

3.18. DETERMINATION OF DRYNESS FRACTION OF STEAM

The dryness fraction of steam can be measured by using the following *calorimeters* :

1. Tank or bucket calorimeter
2. Throttling calorimeter
3. Separating and throttling calorimeter.

3.18.1. Tank or Bucket Calorimeter

The dryness fraction of steam can be found with the help of tank calorimeter as follows :

A known mass of steam is passed through a known mass of water and steam is completely condensed. The heat lost by steam is equated to heat gained by the water.

Fig. 3.14 shows the arrangement of this calorimeter.

The steam is passed through the sampling tube into the bucket calorimeter containing *a known* mass of water.

The weights of calorimeter with water before mixing with steam and after mixing the steam are obtained by weighing.

The temperature of water before and after mixing the steam are measured by *mercury thermometer*.

The pressure of steam passed through the sampling tube is measured with the help of *pressure gauge*.

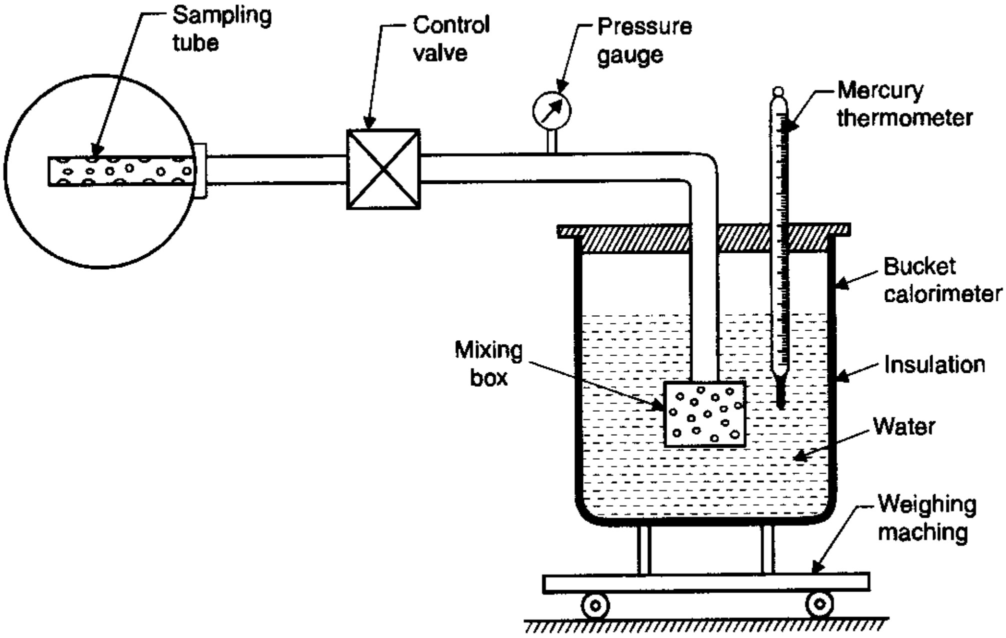


Fig. 3.14. Tank or bucket calorimeter.

Let, p_s = Gauge pressure of steam (bar),
p_a = Atmospheric pressure (bar),
t_s = Daturation temperature of steam known from steam table at pressure $(p_s + p_a)$,
h_{fg} = Latent heat of steam,
x = Dryness fraction of steam,
c_{pw} = Specific heat of water,
c_{pc} = Specific heat of calorimeter,
m_c = Mass of calorimeter, kg,
m_{cw} = Mass of calorimeter and water, kg,
m_w = $(m_{cw} - m_c)$ = Mass of water in calorimeter, kg,
m_{cws} = Mass of calorimeter, water and condensed steam, kg,
m_s = $(m_{cws} - m_{cw})$ = Mass of steam condensed in calorimeter, kg,
t_{cw} = Temperature of water and calorimeter before mixing the steam, °C, and
t_{cws} = Temperature of water and calorimeter after mixing the steam, °C.

Neglecting the losses and *assuming* that the *heat lost by steam is gained by water and calorimeter*, we have

$$(m_{cws} - m_{cw})\,[xh_{fg} + c_{pw}\,(t_s - t_{cws})]$$
$$= (m_{cw} - m_c)c_{pw}\,(t_{cws} - t_{cw}) + m_c\,c_{pc}\,(t_{cws} - t_{cw})$$

$$\therefore \quad m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})\,[m_{cw} - m_c)(c_{pw} + m_c c_{pc}] \qquad ...(3.19)$$

or
$$m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})(m_w c_{pw} + m_c c_{pc})$$

The $m_c c_{pc}$ is known as *water equivalent of calorimeter.*

The value of dryness fraction 'x' can be found by solving the above equation.

The value of dryness fraction found by this method involves some *inaccuracy* since losses due to convection and radiation are *not* taken into account.

The calculated value of dryness fraction neglecting losses is *always less* than the actual value of the dryness.

Example 3.24. *Steam at a pressure of 5 bar passes into a tank containing water where it gets condensed. The mass and temperature in the tank before the admission of steam are 50 kg and 20°C respectively. Calculate the dryness fraction of steam as it enters the tank if 3 kg of steam gets condensed and resulting temperature of the mixture becomes 40°C. Take water equivalent of tank as 1.5 kg.*

Solution. Pressure of steam, $p = 5$ bar

Mass of water in the tank $= 50$ kg

Initial temperature of water $= 20°C$

Amount of steam condensed, $m_s = 3$ kg

Final temperature after condensation of steam $= 40°C$

Water equivalent of tank $= 1.5$ kg

Dryness fraction of steam, x :

At 5 bar. From steam tables,

$$h_f = 640.1 \text{ kJ/kg} \; ; \; h_{fg} = 2107.4 \text{ kJ/kg}$$

Total mass of water, m_w = mass of water in the tank + water equivalent of tank

$$= 50 + 1.5 = 51.5 \text{ kg}$$

Also, heat lost by steam = heat gained by water

$$m_s \, [(h_f + xh_{fg}) - 1 \times 4.18\,(40 - 0)] = m_w[1 \times 4.18\,(40 - 20)]$$

or
$$3[(640.1 + x \times 2107.4) - 4.18 \times 40] = 51.5 \times 4.18 \times 20$$

or
$$3(472.9 + 2107.4x) = 4305.4$$

or
$$472.9 + 2107.4x = 1435.13$$

$$\therefore \quad x = \frac{1435.13 - 472.9}{2107.4} = 0.456.$$

Hence **dryness fraction of steam = 0.456. (Ans.)**

Example 3.25. *Steam at a pressure of 1.1 bar and 0.95 dry is passed into a tank containing 90 kg of water at 25°C. The mass of tank is 12.5 kg and specific heat of metal is 0.42 kJ/kg K. If the temperature of water rises to 40°C after the passage of the steam, determine the mass of steam condensed. Neglect radiation and other losses.*

Solution. Pressure of steam, $p = 1.1$ bar

Dryness fraction of steam, $x = 0.95$

Mass of water in the tank $= 90$ kg

Initial temperature of water in the tank $= 25°C$

Mass of tank $= 12.5$ kg

Specific heat of metal $= 0.42$ kJ/kg K

Final temperature of water $= 40°C.$

Mass of steam condensed, $\mathbf{m_s}$:

Since the radiation losses are neglected,

∴ Heat lost by steam = Heat gained by water

or
$$m_s[(h_f + xh_{fg}) - 1 \times 4.18\,(40 - 0)] = m[1 \times 4.18(40 - 25)]$$

But
$$m = m_1 + m_2$$

where, m_1 = Mass of cold water in the vessel before steam supply, and

m_2 = Water equivalent of vessel $= 0.42 \times 12.5 = 5.25$ kg

At 1.1 bar. From steam tables,

$$h_f = 428.8 \text{ kJ/kg} \; ; \; h_{fg} = 2250.8 \text{ kJ/kg}$$

$$\therefore \quad m_s \, [(428.8 + 0.95 \times 2250.8) - 1 \times 4.18 \times 40]$$
$$= (90 + 5.25) \, [1 \times 4.18 \times (40 - 25)]$$

$$m_s \, [2567.06 - 167.20] = 95.25 \times 62.7$$

i.e., $$2399.86 m_s = 5972.17$$

$$\therefore \quad m_s = 2.488 \text{ kg}$$

Hence, **mass of steam condensed = 2.488 kg. (Ans.)**

3.18.2. Throttling Calorimeter

The dryness fraction of wet steam can be determined by using a throttling calorimeter which is illustrated diagrammatically in Fig. 3.15.

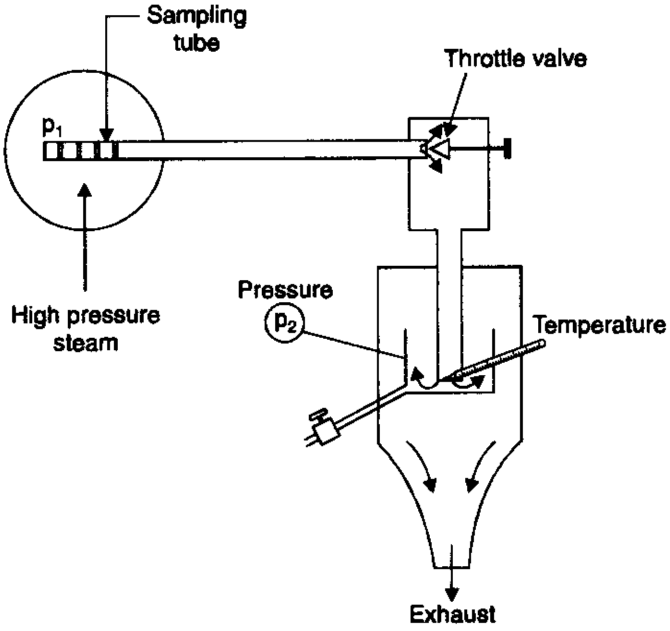


Fig. 3.15. Throttling calorimeter.

The steam to be sampled is taken from the pipe by means of suitable positioned and dimensioned sampling tube. It passes into an insulated container and is throttled through an orifice to atmospheric pressure. Here the temperature is taken and the steam ideally should have about 5.5 K of superheat.

The throttling process is shown on *h-s* diagram in Fig. 3.16 by the line 1-2. If steam initially wet is throttled through a sufficiently large pressure drop, then the steam at state 2 will become superheated. State 2 can then be defined by the *measured pressure and temperature*. The enthalpy, h_2 can then be found and hence

$$h_2 = h_1 = (h_{f_1} + x_1 h_{fg_1}) \text{ at } p_1$$

[where $h_2 = h_{f_2} + h_{fg_2} + c_{ps} \, (T_{sup_2} - T_{s_2})$]

$$x_1 = \frac{h_2 - h_{f_1}}{h_{fg_1}} \qquad \ldots(3.20)$$

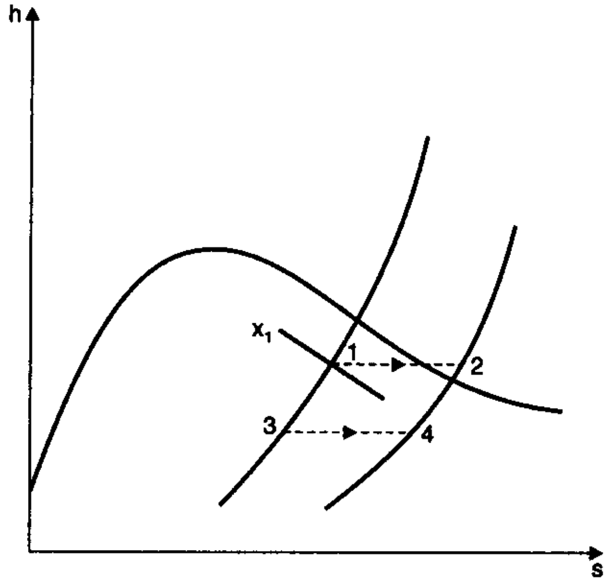


Fig. 3.16. Throttling process.

Hence the dryness fraction is determined and state 1 is defined.

Example 3.26. *A throttling calorimeter is used to measure the dryness fraction of the steam in the steam main which has steam flowing at a pressure of 8 bar. The steam after passing through the calorimeter is at 1 bar pressure and 115°C.*

Calculate the dryness fraction of the steam in the main. Take c_{ps} *= 2.1 kJ/kg K.*

Solution. Condition of steam *before throttling* :

$$p_1 = 8 \text{ bar}, x_1 = ?$$

Condition of steam *after throttling* :

$$p_2 = 1 \text{ bar}, \; t_2 = t_{sup_2} = 115°\text{C}$$

As throttling is a *constant enthalpy* process

$$\therefore \quad h_1 = h_2$$

i.e.,

$$h_{f_1} + x_1 h_{gf_1} = h_{f_2} + h_{fg_2} + c_{p_s}(T_{\text{sup}_2} - T_{s_2}) \quad [\because T_{sup_2} = 115 + 273 = 388 \text{ K}$$

$$T_{s_2} = 99.6 + 273 = 372.6 \text{ K (at 1 bar)}]$$

$$720.9 + x_1 \times 2046.5 = 417.5 + 2257.9 + 2.1(388 - 372.6)$$

$$720.9 + 2046.5\, x_1 = 2707.7$$

$$\therefore \quad x_1 = \frac{2707.7 - 720.9}{2046.5} = 0.97$$

Hence, **dryness fraction of steam in the main = 0.97. (Ans.)**

3.18.3. Separating and Throttling Calorimeter

If the steam whose dryness fraction is to be determined is *very wet* then throttling to atmospheric pressure *may not be sufficient to ensure superheated steam at exit.* In this case it is *necessary to dry the steam partially, before throttling.* This is done by *passing the steam sample from the main through a separating calorimeter* as shown in Fig. 3.17. The steam is made to change direction suddenly, and the water, being denser than the dry steam is separated out. The quantity of water which is separated out (m_w) is measured at the separator, the steam remaining, which *now has a higher dryness fraction*, is passed through the *throttling calorimeter*. With the combined separating and throttling calorimeter it is *necessary* to condense the steam after throttling and measure the amount of condensate (m_s). If a throttling calorimeter only is sufficient, there is no need to measure condensate, the pressure and temperature measurements at exit being sufficient.

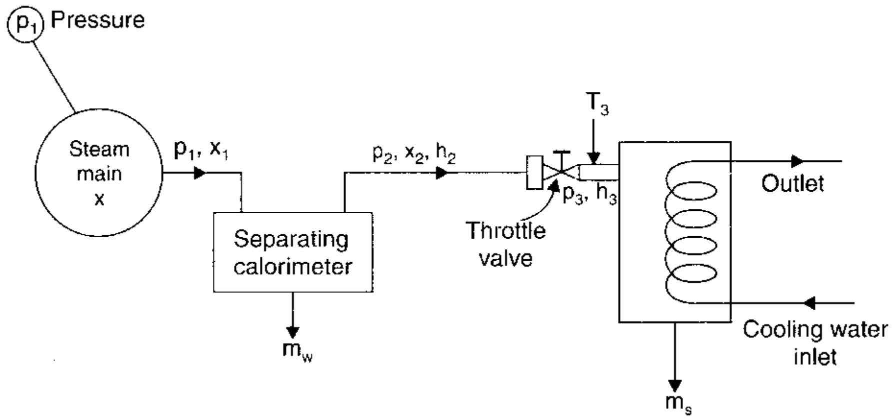


Fig. 3.17. Separating and throttling calorimeter.

Dryness fraction at 2 is x_2, therefore, the mass of dry steam leaving the separating calorimeter is equal to $x_2 m_s$ and this must be the mass of dry vapour in the sample drawn from the main at state 1.

Hence fraction in main, $x_1 = \dfrac{\text{Mass of dry vapour}}{\text{Total mass}} = \dfrac{x_2\, m_s}{m_w + m_s}$.

The dryness fraction, x_2, can be determined as follows :

$$^*h_3 = h_2 = h_{f_2} + x_2 h_{fg_2} \text{ at } p_2 \; [^*h_3 = h_{f_3} + h_{fg_3} + c_{ps}\,(T_{sup_3} - T_{s_3}) \text{ at pressure } p_3]$$

or $$x_2 = \frac{h_3 - h_{f_2}}{h_{fg_2}}$$

The values of h_{f_2} and h_{fg_2} are read from steam tables at pressure p_2. The pressure in the separator is small so that p_1 is approximately equal to p_2.

Example 3.27. *The following observations were taken with a separating and a throttling calorimeter arranged in series :*

Water separated = 2 kg, steam discharged from the throttling calorimeter = 20.5 kg, temperature of steam after throttling = 110°C, initial pressure = 12 bar abs., barometer = 760 mm of Hg, final pressure = 5 mm of Hg.

Estimate the quality of steam supplied.

Solution. Quantity of water separated out, m_w = 2 kg

Steam (condensate) discharged from the throttling calorimeter, m_s = 20.5 kg

Temperature of steam after throttling, t_{sup} = 110°C

Initial pressure of steam, p_1 = 12 bar abs.

Final pressure of steam, $p_3 = 760 + 5 = 765$ mm

$$= \frac{765}{1000} \times 1.3366 \qquad (\because \; 1 \text{ m Hg} = 1.3366 \text{ bar})$$

$$\simeq 1 \text{ bar}$$

From steam tables :

At $p_1 = p_2 =$ **12 bar :** $h_f = 798.4$ kJ/kg, $h_{fg} = 1984.3$ kJ/kg

At $p_3 =$ **1 bar :** $t_s = 99.6$°C, $h_f = 417.5$ kJ/kg, $h_{fg} = 2257.9$ kJ/kg

$t_{sup} = 110$°C (given)

Also $\qquad h_3 = h_2$

$$(h_{f_3} + h_{fg_3}) + c_{ps}(T_{sup_3} - T_{s_3}) = hf_2 + x_2 h_{fg_2}$$

Taking $\qquad c_{ps} = 2$ kJ/kg K, we get

$$417.5 + 2257.9 + 2[(110 + 273) - (99.6 + 273)] = 798.4 + x_2 \times 1984.3$$

$$2696.2 = 798.4 + 1984.3\, x_2$$

$$\therefore \qquad x_2 = \frac{2696.2 - 798.4}{1984.3} = 0.956$$

Now, **quality of steam supplied,**

$$x_1 = \frac{x_2 m_s}{m_w + m_s} = \frac{0.956 \times 20.5}{2 + 20.5}$$

$$= \mathbf{0.87.} \quad \textbf{(Ans.)}$$

☞ **Example 3.28.** *The following data were obtained in a test on a combined separating and throttling calorimeter :*

Pressure of steam sample = 15 bar, pressure of steam at exit = 1 bar, temperature of steam at the exit = 150°C, discharge from separating calorimeter = 0.5 kg/min, discharge from throttling calorimeter = 10 kg/min.

Determine the dryness fraction of the sample steam.

Solution. Pressure of steam sample, $p_1 = p_2 = 15$ bar

Pressure of steam at the exit, $p_3 = 1$ bar

Temperature of steam at the exit, $t_{sup_3} = 150$°C

Discharge from separating calorimeter, $m_w = 0.5$ kg/min

Discharge from throttling calorimeter, $m_s = 10$ kg/min

From steam tables :

At $p_1 = p_2 =$ **15 bar** : $h_{f_2} = 844.7$ kJ/kg, $h_{fg_2} = 1945.2$ kJ/kg

At $p_3 =$ **1 bar and 150°C** : $h_{sup_3} = 2776.4$ kJ/kg

Also, $\qquad h_2 = h_3$

$$h_{f_2} + x_2 h_{fg_2} = h_{sup_3}$$

$$844.7 + x_2 \times 1945.2 = 2776.4$$

$$\therefore \qquad x_2 = \frac{2776.4 - 844.7}{1945.2} = 0.993$$

Now, **quality of steam supplied,**

$$x_1 = \frac{x_2 m_s}{m_s + m_w} = \frac{0.993 \times 10}{10 + 0.5} = \mathbf{0.946.} \quad \textbf{(Ans.)}$$

HIGHLIGHTS

1. A pure substance is a system which is (*i*) homogeneous in composition, (*ii*) homogeneous in chemical aggregation, (*iii*) invariable in chemical aggregation.
2. The triple point is merely the point of intersection of sublimation and vapourisation curves. It must be understood that only on *p-T* diagram is the triple point represented by a point. On *p-V* diagram it is a line, and on a *U-V* diagram it is a triangle.
3. Steam as a vapour does not obey laws of perfect gases unless and until it is highly in super dry condition.
4. *Dryness fraction* is the ratio of the mass of actual dry steam to the mass of steam containing it.

   i.e., Dryness fraction $= \dfrac{m_s}{m_s + m_w}$

   where, m_s = Mass of dry steam contained in steam considered

   m_w = Mass of water particles in suspension in the steam considered.
5. Superheated steam behaves like a gas and therefore, it follows gas laws. The law for adiabatic expansion is $pv^{1.3} = C$.
6. External work of evaporation $= p(v_g - v_f)$

   Internal latent heat $= h_{fg} - \dfrac{pv_g}{J}$

   Internal energy of steam, u :

   (*i*) For wet steam : $u = h - \dfrac{p.x.v_g}{J}$

   (*ii*) For superheated steam : $u = h_{sup} - \dfrac{p.v_{sup}}{J}$. (J = 1, in SI Units)
7. Entropy of water when heated from temperature T_1 to T_2 ;

   $$s_2 - s_1 = c_{pw} \log_e \frac{T_2}{T_1}$$

   If 0°C is taken as the datum then entropy of water at any temperature T, above this datum will be

   $$s_f = c_{pw} \log_e \frac{T}{273}$$

   Entropy of evaporation :

   $$s_{evap.} = \frac{h_{fg}}{T_s} \quad \text{...(when water is evaporated to steam completely)}$$

   $$= \frac{xh_{fg}}{T_s} \quad \text{...(when water is evaporated partially and dryness fraction of steam is } x\text{)}$$

   Entropy of steam :

   $$s_{wet} = s_f + \frac{xh_{fg}}{T_s} \quad \text{...[wet steam } (x < 1)]$$

   $$s_g = s_f + \frac{h_{fg}}{T_s} \quad \text{...[Dry and saturated steam } (x = 1)]$$

   $$s_{sup} = s_f + \frac{h_{fg}}{T_s} + c_{ps} \log_e \frac{T_{sup}}{T_s} \quad \text{...(Superheated steam)}$$

8. Mollier chart/diagram is more widely used than any other entropy diagram, since the work done on vapour cycles can be scaled from this diagram directly as a length, whereas on *T-s* diagram it is represented by an area.

9. *Different processes :*

(*i*) Constant volume heating or cooling

$$x_1 v_{g_1} = x_2 v_{g_2}$$

$$x_1 v_{g_1} = v_{sup_2} = v_{g_2} \cdot \frac{T_{sup_2}}{T_{s_2}}$$

(*ii*) Constant pressure heating or cooling

$$Q = h_2 - h_1$$

(*iii*) Isentropic expansion (non-flow process)

$$W = (u_1 - u_2) \text{ and } s_1 = s_2$$

(*iv*) Throttling

$$h_{f_1} + x_1 h_{fg_1} = h_{f_2} + x_2 h_{fg_2} \qquad \text{...(For wet condition)}$$

$$= h_{f_2} + h_{fg_2} + c_{ps}(T_{sup} - T_{s_2}) \qquad \text{...(For superheated condition)}$$

10. Dryness fraction of steam can determined by the following methods :

(*i*) Bucket calorimeter

(*ii*) Throttling calorimeter

(*iii*) Separating and throttling calorimeter.

OBJECTIVE TYPE QUESTIONS

Choose the correct answer :

1. (*a*) Specific volume of water decreases on freezing
   (*b*) Boiling point of water decreases with increasing pressure
   (*c*) Specific volume of CO_2 increases on freezing
   (*d*) Freezing temperature of water decreases with increasing pressure.
2. (*a*) The slope of vapourisation curve is always negative
   (*b*) The slope of vapourisation curve is always positive
   (*c*) The slope of sublimation curve in negative for all pure substances
   (*d*) The slope of fusion curve is positive for all pure substances.
3. (*a*) The process of passing from liquid to vapour is condensation
   (*b*) An isothermal line is also a constant pressure line during wet region
   (*c*) Pressure and temperature are independent during phase change
   (*d*) The term dryness fraction is used to describe the fraction by mass of liquid in the mixture of liquid water and water vapour.
4. The latent heat of vapourisation at critical point is
   (*a*) less than zero (*b*) greater than zero
   (*c*) equal to zero (*d*) none of the above.
5. (*a*) Critical point involves equilibrium of solid and vapour phases
   (*b*) Critical point involves equilibrium of solid and liquid phases
   (*c*) Critical point involves equilibrium of solid, liquid and vapour phases
   (*d*) Triple point involves equilibrium of solid, liquid and vapour phases.

6. With the increase in pressure

(*a*) boiling point of water increases and enthalpy of evaporation increases

(*b*) boiling point of water increases and enthalpy of evaporation decreases

(*c*) boiling point of water decreases and enthalpy of evaporation increases.

7. With increase in pressure

(*a*) enthalpy of dry saturated steam increases

(*b*) enthalpy of dry saturated steam decreases

(*c*) enthalpy of dry saturated steam remains same

(*d*) enthalpy of dry saturated steam first increases and then decreases.

8. Dryness fraction of steam is defined as

(*a*) mass of water vapour in suspension/(mass of water vapour in suspension + mass of dry steam)

(*b*) mass of dry steam/mass of water vapour in suspension

(*c*) mass of dry steam/(mass of dry steam + mass of water vapour in suspension)

(*d*) mass of water vapour in suspension/mass of dry steam.

9. The specific volume of water when heated at 0°C

(*a*) first increases and then decreases

(*b*) first decreases and then increases

(*c*) increases steadily

(*d*) decreases steadily.

10. Only throttling calorimeter is used for measuring

(*a*) very low dryness fraction upto 0.7

(*b*) very high dryness fraction upto 0.98

(*c*) dryness fraction of only low pressure steam

(*d*) dryness fraction of only high pressure steam.

11. Heat of superheated steam is given by

(*a*) $h_{sup} = h_f + h_{fg} + c_{ps} \log_e \frac{T_{sup}}{T_s}$

(*b*) $h_{sup} = h_f + xh_{fg}$

(*c*) $h_{sup} = h_f + h_{fg}$

(*d*) $h_{sup} = h_f + xh_{fg} + c_{ps} \log_e \frac{T_s}{273}$.

12. Volume of wet steam (per kg) with dryness fraction x is given by

(*a*) $x^3 v_g$

(*b*) xv_f

(*c*) $x^2(v_g - v_f)$

(*d*) $x^2 v_g$

(*e*) none of the above.

13. Internal latent heat is given by

(*a*) $h_{fg} - \frac{pv_g}{J}$

(*b*) $h_g - \frac{pv_g}{J}$

(*c*) $h_{sup} - \frac{pv_f}{J}$

(*d*) $h_{fg} + \frac{pv_g}{J}$

(*e*) none of the above.

14. Entropy of 1 kg of water at T K is given by

(*a*) $c_{pw} \log_e \frac{T}{273}$

(*b*) $c_{pw} \log_e \frac{T_2}{T_1}$

(*c*) $c_{pw} \log_{10} \frac{T}{273}$

(*d*) $c_{pw} \log_e \frac{T_2}{273}$

(*e*) none of the above.

15. Entropy of wet steam (1 kg) is given by

(*a*) $s_f + \frac{xh_{fg}}{T_s}$

(*b*) $s_g + \frac{xh_{fg}}{T_s}$

(*c*) $s_f + \frac{h_{fg}}{T_s}$

(*d*) $s_f + c_{ps} \log_e \frac{T_{sup}}{T_s}$

(*e*) none of the above.

16. In throttling process

(*a*) $h_1^2 = h_2$ (*b*) $h_1 = h_2$

(*c*) $h_1 = h_2 + \frac{h_{fg}}{T_s}$ (*d*) $h_2 = h_1 + \frac{h_{fg}}{T_s}$

(*e*) none of the above.

17. In isentropic process

(*a*) $W = 2(u_2 - u_1)$ (*b*) $W = (u_2 - u_1)^2$

(*c*) $W = u_2 - u_1$ (*d*) $W = (u_2 - u_1)^{1/2}$

(*e*) none of the above.

Answers

1. (*d*) **2.** (*a*) **3.** (*b*) **4.** (*c*) **5.** (*d*) **6.** (*b*) **7.** (*b*)
8. (*c*) **9.** (*b*) **10.** (*b*) **11.** (*a*) **12.** (*e*) **13.** (*a*) **14.** (*a*)
15. (*a*) **16.** (*b*) **17.** (*c*).

THEORETICAL QUESTIONS

1. What is a pure substance ?
2. Draw and explain a *p*-*T* (pressure-temperature) diagram for a pure substance.
3. What is a triple point ?
4. Explain with a neat diagram *p*-V-*T* surface.
5. Does wet steam obey laws of perfect gases ?
6. Describe the process of formation of steam and give its graphical representation also.
7. Explain the following terms relating to steam formation :
   (*i*) Sensible heat of water, (*ii*) Latent heat of steam,
   (*iii*) Dryness fraction of steam, (*iv*) Enthalpy of wet steam, and
   (*v*) Superheated steam.
8. What advantages are obtained if superheated steam is used in steam prime movers ?
9. What do you mean by the following :
   (*i*) Internal latent heat (*ii*) Internal energy of steam
   (*iii*) External work of evaporation (*iv*) Entropy of evaporation
   (*v*) Entropy of wet steam (*vi*) Entropy of superheated steam.
10. Write a short note on Mollier chart.
11. Draw a neat sketch of throttling calorimeter and explain how dryness fraction of steam is determined ; clearly explain its limitations.
12. Describe with a neat sketch a separating-throttling calorimeter for measuring the dryness fraction of steam.

UNSOLVED EXAMPLES

1. Find the specific volume, enthalpy and internal energy of wet steam at 18 bar, dryness fraction 0.9.
   [**Ans.** 0.0994 m³/kg ; 2605.8 kJ/kg ; 2426.5 kJ/kg]
2. Find the dryness fraction, specific volume and internal energy of steam at 7 bar and enthalpy 2600 kJ/kg.
   [**Ans.** 0.921 ; 0.2515 m³/kg, 2420 kJ/kg]
3. Steam at 110 bar has a specific volume of 0.0196 m³/kg, find the temperature, the enthalpy and the internal energy.
   [**Ans.** 350°C ; 2889 kJ/kg ; 2673.4 kJ/kg]

4. Steam at 150 bar has an enthalpy of 3309 kJ/kg, find the temperature, the specific volume and the internal energy. **[Ans.** 500°C ; 0.02078 m^3/kg ; 2997.3 kJ/kg]

5. Steam at 19 bar is throttled to 1 bar and the temperature after throttling is found to be 150°C. Calculate the initial dryness fraction of the steam. **[Ans.** 0.989]

6. Find the internal energy of one kg of steam at 14 bar under the following conditions :
   (*i*) When the steam is 0.85 dry ;
   (*ii*) When steam is dry and saturated ; and
   (*iii*) When the temperature of steam is 300°C. Take c_{ps} = 2.25 kJ/kg K.
   [Ans. (*i*) 2327.5 kJ/kg ; (*ii*) 2592.5 kJ/kg ; (*iii*) 2784 kJ/kg]

7. Calculate the internal energy of 0.3 m^3 of steam at 4 bar and 0.95 dryness. If this steam is superheated at constant pressure through 30°C, determine the heat added and change in internal energy.
   [Ans. 2451 kJ/kg ; 119 kJ ; 107.5 kJ/kg]

8. Water is supplied to the boiler at 15 bar and 80°C and steam is generated at the same pressure at 0.9 dryness. Determine the heat supplied to the steam in passing through the boiler and change in entropy.
   [Ans. 2260.5 kJ/kg ; 4.92 kJ/kg K]

9. A cylindrical vessel of 5 m^3 capacity contains wet steam at 1 bar. The volume of vapour and liquid in the vessel are 4.95 m^3 and 0.05 m^3 respectively. Heat is transferred to the vessel until the vessel is filled with saturated vapour. Determine the heat transfer during the process. **[Ans.** 104.93 MJ]

10. A pressure cooker contains 1.5 kg of steam at 5 bar and 0.9 dryness when the gas was switched off. Determine the quantity of heat rejected by the pressure cooker when the pressure in the cooker falls to 1 bar. **[Ans.** – 2355 kJ]

11. A vessel of spherical shape having a capacity of 0.8 m^3 contains steam at 10 bar and 0.95 dryness. Steam is blown off until the pressure drops to 5 bar. The valve is then closed and the steam is allowed to cool until the pressure falls to 4 bar. Assuming that the enthalpy of steam in the vessel remains constant during blowing off periods, determine :
    (*i*) The mass of steam blown-off,
    (*ii*) The dryness fraction of steam in the vessel after cooling, and
    (*iii*) The heat lost by steam per kg during cooling. **[Ans.** (*i*) 2.12 kg ; (*ii*) 0.78 ; (*iii*) – 820 kJ]

12. Two boilers one with superheater and other without superheater are delivering equal quantities of steam into a common main. The pressure in the boilers and the main is 15 bar. The temperature of the steam from a boiler with a superheater is 300°C and temperature of the steam in the main is 200°C. Determine the quality of steam supplied by the other boiler. **[Ans.** 0.89]

13. A tank of capacity 0.5 m^3 is connected to a steam pipe through a valve which carries steam at 14 bar and 300°C. The tank initially contains steam at 3.5 bar and saturated condition. The valve in the line connecting the tank is opened and the steam is allowed to pass into the tank until the pressure in the tank becomes 14 bar.

    Determine the mass of steam that entered into the tank. **[Ans.** 1.565 kg]