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Department: ME

Subject: BME BT-203

Unit: IV Thermodynamics

TOPIC- 01

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.

THERMODYNAMIC SYSTEMS

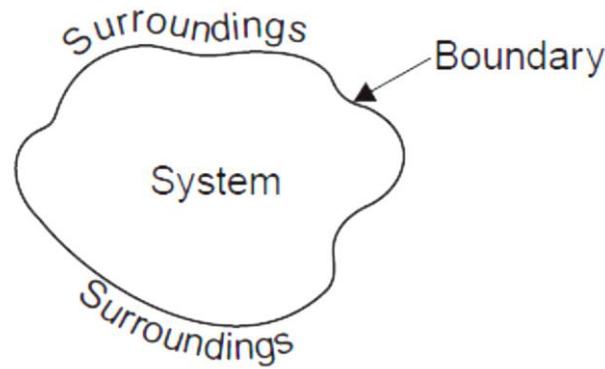
System, Boundary and Surroundings

System. A system is a finite quantity of matter or a prescribed region of space .

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 remnants of the last cylinder charge after the exhaust process



Closed System

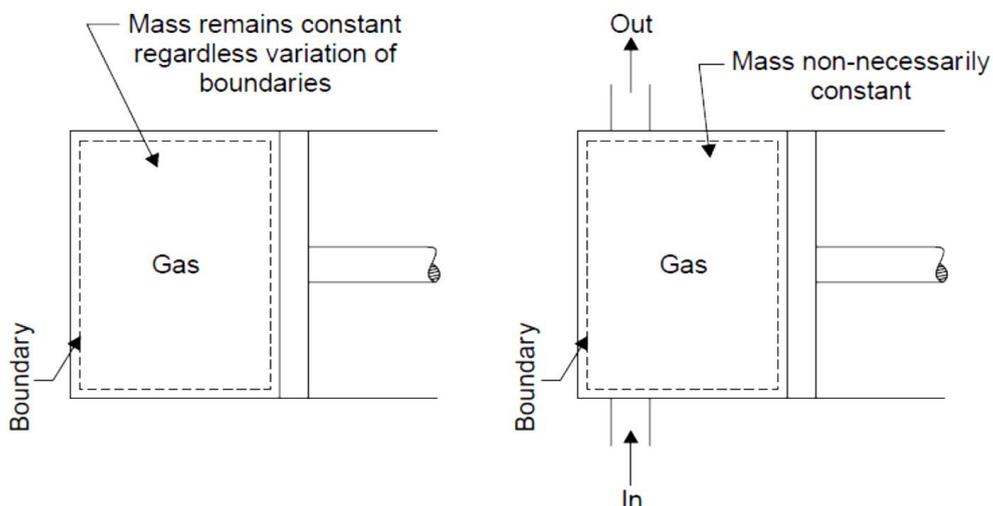
If the boundary of the system is impervious to the flow of matter, it is called a closed system. An example of this system is mass of gas or vapour contained in an engine cylinder, the boundary of which is drawn by the cylinder walls, the cylinder head and piston crown. Here the boundary is continuous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

Open System

An open system is one in which matter flows into or out of the system. Most of the engineering systems are open.

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.



THERMODYNAMIC EQUILIBRIUM

The temperature of the system does not change with time and has same value at all points of the system.

Properties of systems

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:

i . Intensive properties. These properties do not depend on the mass of the system. Examples: Temperature, pressure, density etc.

ii . Extensive properties. These properties depend on the mass of the system. Example: Volume, mass, energy, heat capacity, entropy etc.

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.

PROCES:

A process occurs when the system undergoes a change in a state or an energy transfer at a steady state.

A process may be non-flow in which a fixed mass within the defined boundary is undergoing a change of state. Example: A substance which is being heated in a closed cylinder undergoes a non-flow process. Closed systems undergo non-flow processes.

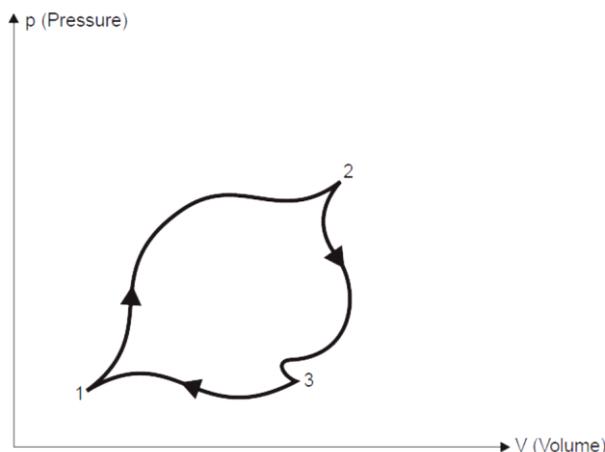
A process may be a flow process in which mass is entering and leaving through the boundary of an open system. In a steady flow process mass is crossing the boundary from surroundings at entry, and an equal mass is crossing the boundary at the exit so that the total mass of the system remains constant.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

Quasi-static process.

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

CYCLE:

Any process or series of processes whose end states are identical is termed a cycle.



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.

PATH FUNCTION:

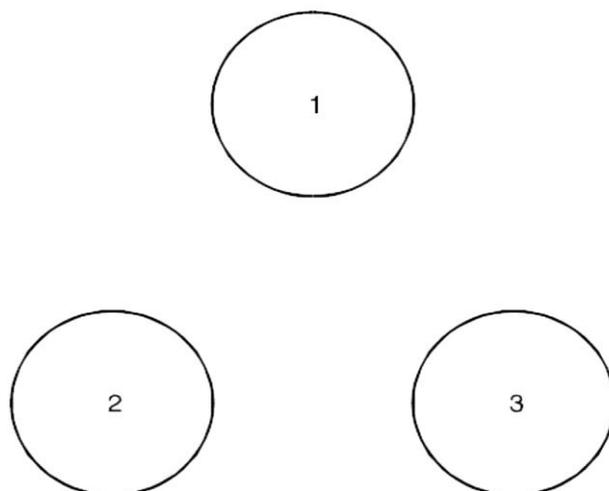
There are certain quantities which cannot be located on a graph by a point but are given by the area or so, on that graph. In that case, the area on the graph, pertaining to the particular process, is a function of the path of the process. Such quantities are called path functions. Examples. Heat, work etc.

TOPIC- 02

LAW OF THERMODYNAMICS:

(1) ZEROTH LAW OF THERMODYNAMICS

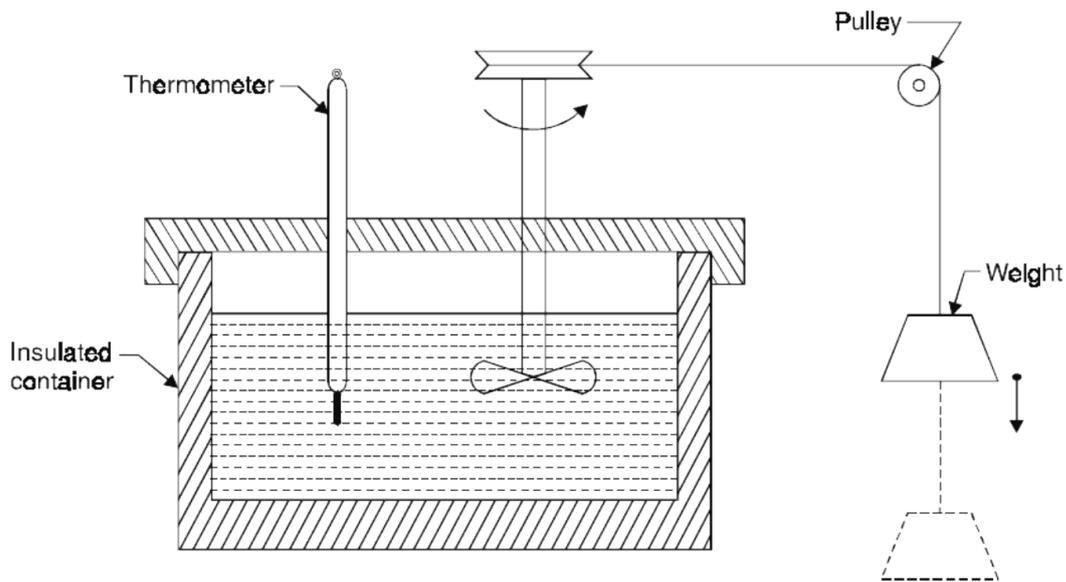
'Zeroth law of thermodynamics' states that if two systems are each equal in temperature to a third, they are equal in temperature to each other.



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.

First law of thermodynamics:

“When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings.



The first law of Thermodynamics cannot be proved analytically, but experimental evidence has repeatedly confirmed its validity, and since no phenomenon has been shown to contradict it, the first law is accepted as a law of nature. It may be remarked that no restriction was imposed which limited the application of first law to reversible energy transformation. Hence the first law applies to reversible as well as irreversible transformations: For non-cyclic process, a more general formulation of first law of thermodynamics is required. A new concept which involves a term called internal energy fulfills this need.

The First Law of Thermodynamics may also be stated as follows :

“Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant”.

Or

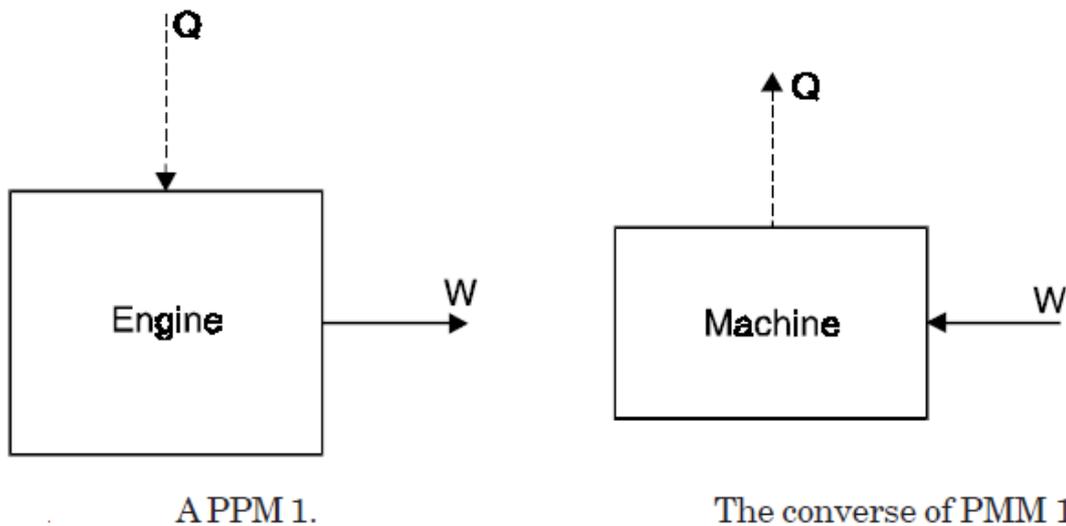
“No machine can produce energy without corresponding expenditure of energy, i.e., it is impossible to construct a perpetual motion machine of first kind”.

The work input to the paddle wheel is measured by the fall of weight, while the corresponding temperature rise of liquid in the insulated container is measured by the thermometer. It is already known to us from experiments on heat transfer that temperature rise can also be produced by heat transfer. The experiments show : (i) A definite quantity of work is always required to accomplish the same temperature rise obtained with a unit amount of heat. (ii) Regardless of returned by heat transfer in opposite direction to the identical state from which it started.

The above results lead to the inference that work and heat are different forms of something more

PERPETUAL MOTION MACHINE OF THE FIRST KIND—PMM 1

The first law of thermodynamics states the general principle of the conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another. There can be no machine which would continuously supply mechanical work without some form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM 1. A PMM 1 is thus impossible.



TOPIC- 03

Second law of thermodynamics:

Clausius Statement

“It is impossible for a self acting machine working in a cyclic process unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature.”

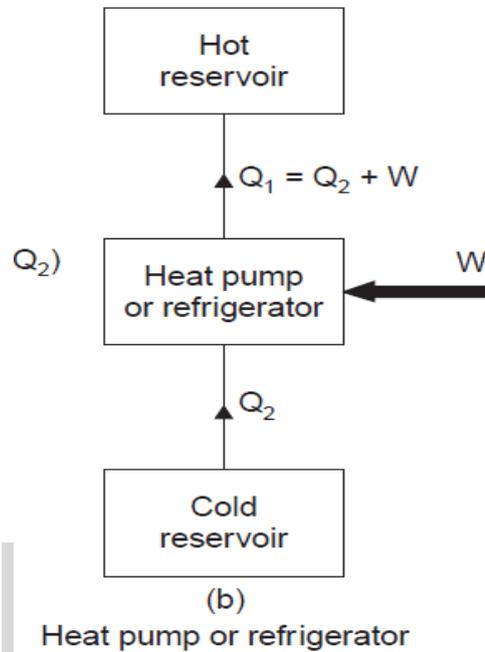
In other words, heat of, itself, cannot flow from a colder to a hotter body.

For a reversed heat engine above Fig. acting as a refrigerator when the purpose is to achieve the maximum heat transfer from the cold reservoir, the measure of success is called the co-efficient of performance (C.O.P.). It is defined by the ratio:

Co-efficient of Performance, (C.O.P.) ref. = Q/W

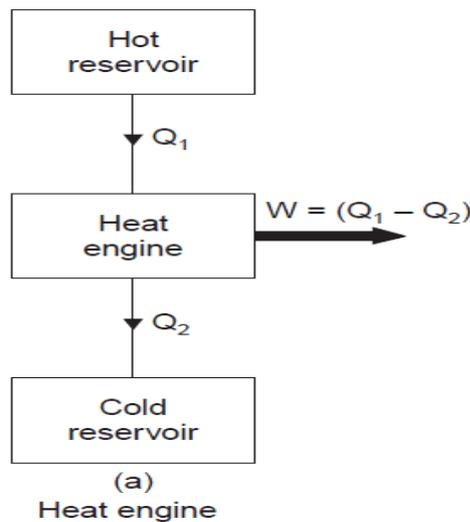
Where, Q_2 = Heat transfer from cold reservoir, and

W = the net work transfer to the refrigerator.



Kelvin-Planck Statement

“It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work”. Although the Clausius and Kelvin-Planck statements appear to be different, they are really equivalent in the sense that a violation of either statement implies violation of other.



A *heat engine* is used to produce the maximum work transfer from a given positive heat transfer. The measure of success is called the *thermal efficiency* of the engine and is defined by the ratio:

$$\text{Thermal efficiency, } \eta_{th} = W/Q_1$$

Where, W = Net work transfer from the engine, and

Q_1 = Heat transfer to engine.

TOPIC- 04

1. Constant volume process (or Isochoric) Process ($v = \text{constant}$).

In a constant volume process the working substance is contained in a rigid vessel, hence the boundaries of the system are immovable and no work can be done on or by the system, other than paddle-wheel work input. It will be assumed that '*constant volume*' implies zero work unless stated otherwise.

Considering mass of the working substance *unity* and applying first law of thermodynamics to the process

$$Q = (u_2 - u_1) + W$$

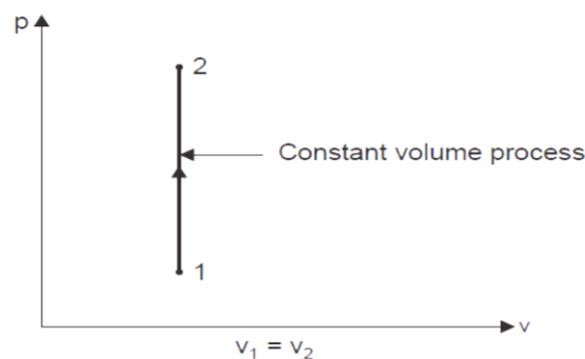
The work done $W = \int_1^2 p dv = 0$ as $dv = 0$.

$$\therefore Q = (u_2 - u_1) = c_v(T_2 - T_1)$$

where c_v = Specific heat at constant volume.

For mass, m , of working substance

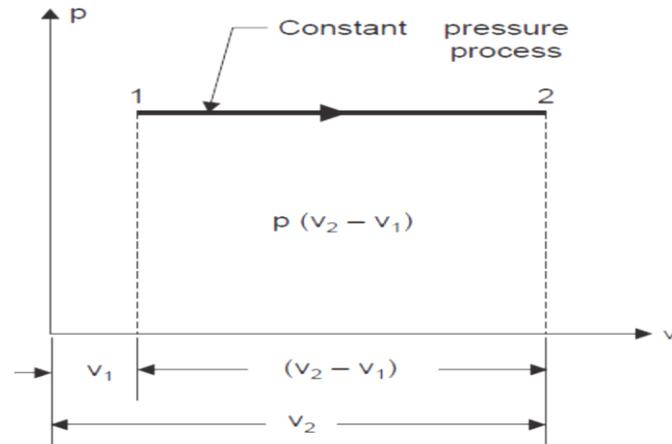
$$Q = U_2 - U_1 = mc_v(T_2 - T_1)$$



2. Reversible Constant Pressure (or Isobaric) Process ($p = \text{constant}$).

It can be seen from Fig. that when the boundary of the system is inflexible as in a constant volume process, then the pressure rises when heat is supplied. Hence for a constant

pressure process, the boundary must move against an external resistance as heat is supplied ; for instance a gas in a cylinder behind a piston can be made to undergo a constant pressure process. Since the piston is pushed through a certain distance by the force exerted by the gas, then the work is done by the gas on its surroundings. Fig. shows the system and states before and after the heat addition at constant pressure.



$$Q = (u_2 - u_1) + W$$

The work done, $W = \int_1^2 p dv = p(v_2 - v_1)$

$$\therefore Q = (u_2 - u_1) + p(v_2 - v_1) = u_2 - u_1 + pv_2 - pv_1$$

$$= (u_2 + pv_2) - (u_1 + pv_1) = h_2 - h_1$$

or $Q = h_2 - h_1 = c_p (T_2 - T_1)$

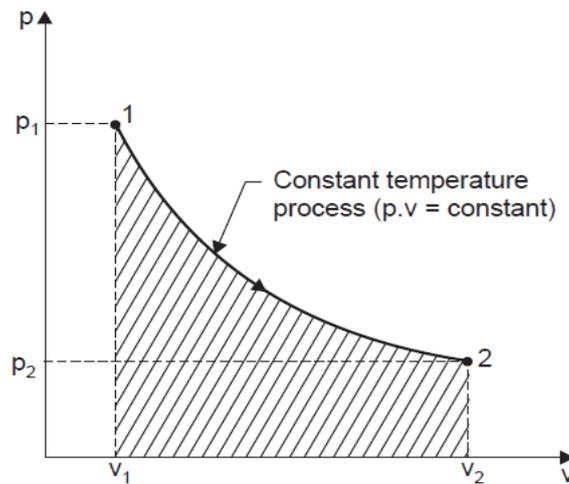
where h = Enthalpy (specific), and

c_p = Specific heat at constant pressure.

For mass, m , of working substance

$$Q = H_2 - H_1 = mc_p (T_2 - T_1)$$

3. Reversible Temperature (or Isothermal) Process ($pv = \text{constant}$, $T = \text{constant}$) :



The constant C can either be written as p_1v_1 or as p_2v_2 , since

$$p_1v_1 = p_2v_2 = \text{constant, } C$$

$$W = p_1v_1 \log_e \frac{v_2}{v_1} \text{ per unit mass of working substance}$$

$$W = p_2v_2 \log_e \frac{v_2}{v_1} \text{ per unit mass of working substance}$$

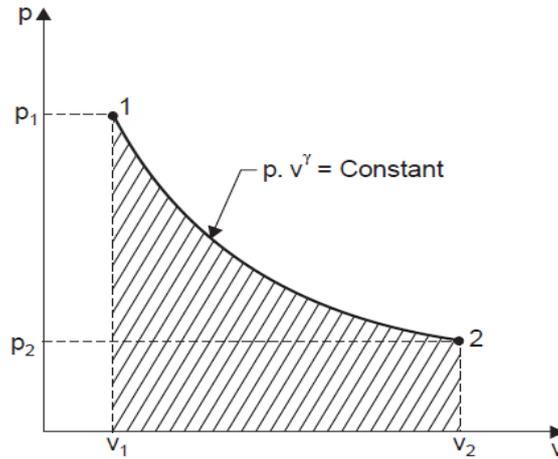
$$\therefore Q = W = p_1v_1 \log_e \frac{v_2}{v_1}$$

For mass, m , of the working substance

$$Q = p_1V_1 \log_e \frac{V_2}{V_1}$$

$$Q = p_1V_1 \log_e \frac{p_1}{p_2} \quad \left[\because \frac{V_2}{V_1} = \frac{p_1}{p_2} \right]$$

4. Reversible Adiabatic Process: ($pv^\gamma=C$)



The work done is given by the shaded area, and this area can be evaluated by integration.

$$W = \int_{v_1}^{v_2} p \, dv$$

Therefore, since $pv^\gamma = \text{constant}$, C , then

$$W = \int_{v_1}^{v_2} C \frac{dv}{v^\gamma} \quad \left[\because p = \frac{C}{v^\gamma} \right]$$

$$\begin{aligned} W &= C \int_{v_1}^{v_2} \frac{dv}{v^\gamma} = C \left[\frac{v^{-\gamma+1}}{-\gamma+1} \right]_{v_1}^{v_2} \\ &= C \left(\frac{v_2^{-\gamma+1} - v_1^{-\gamma+1}}{1-\gamma} \right) = C \left(\frac{v_1^{-\gamma+1} - v_2^{-\gamma+1}}{\gamma-1} \right) \end{aligned}$$

The constant in this equation can be written as $p_1 v_1^\gamma$ or as $p_2 v_2^\gamma$. Hence,

$$W = \frac{p_1 v_1^\gamma v_1^{-\gamma+1} - p_2 v_2^\gamma v_2^{-\gamma+1}}{\gamma-1} = \frac{p_1 v_1 - p_2 v_2}{\gamma-1}$$

$$W = \frac{p_1 v_1 - p_2 v_2}{\gamma-1}$$

$$W = \frac{R(T_1 - T_2)}{\gamma-1}$$

Relationship between T and v, and T and p :

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2} \right)^\gamma$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma - 1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}}$$

TOPIC- 05 Steam engineering

Steam Generator

A steam generator or boiler is usually a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel to water and ultimately to generate steam. Open vessels, generating steam at atmospheric pressure are not considered to be boiler.

Classification of Boilers:

[1] Relative position of hot gas and water

- **Fire tube boiler**

Hot gasses pass through the tubes that are surrounded by water. Horizontal return tubular, vertical tubular, Lancashire, Cochran, Cornish, locomotive fire box, scotch marine etc.

- **Water tube boiler**

The tubes contain water and the hot gases flow outside Babcock and Wilcox Stirling boiler La mont boiler

[2]Method of firing

- **Internally fired boiler**

Lancashire, Locomotive, and Scotch

- **Externally fired boiler**

Babcock and Wilcox

[3]Pressure of steam

- High pressure (>80 kg/cm²)

Babcock and Wilcox Lamont etc

- Low pressure

(<80 kg/cm²) Cochran, Cornish, Lancashire and Locomotive

[4] Method of firing

- Internally fired boiler

Lancashire, Locomotive, and Scotch

- Externally fired boiler

Babcock and Wilcox

[5] Method of circulation of water

- Natural circulation
- Forced circulation

[6] Heat source

- Combustion of solid, liquid, or gas
- Electrical or nuclear energy
- Hot waste gases of other chemical reactions

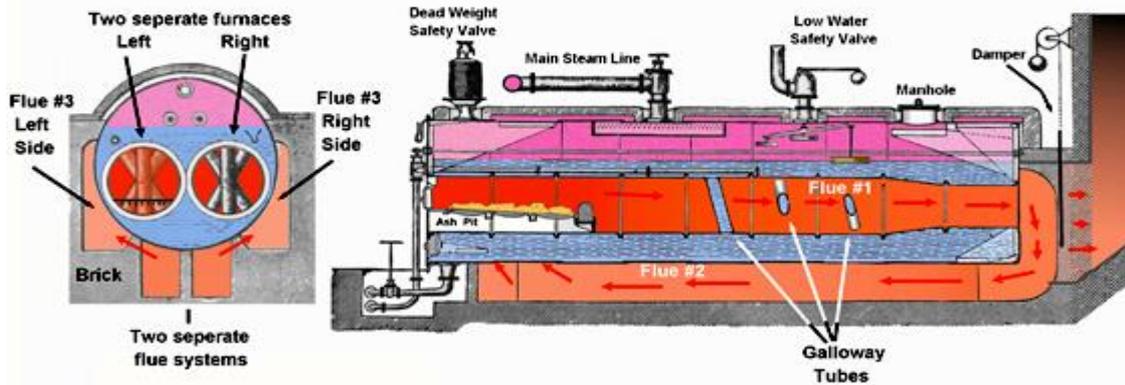
Working principal of boiler:

1. Lancashire boiler

Theory

A Lancashire boiler is a double fire tube boiler, internally fired, horizontal, natural draught, and natural circulation type of boiler. This boiler is very popular and reliable because of simplicity of design and ease of operation. The boiler has good steaming quality, and coal of inferior quality can be used. It has low maintenance and operating cost. This boiler is widely used in sugar mills and chemical industries. This boiler is used where large reservoir of water and steam are required.

Lancashire Boiler cross section views



Its main features and brickwork setting is shown in the figure. Several rings of steel plates we are either welded or riveted to make the cylindrical shell of suitable dimensions. This boiler has two parallel flue pipes throughout the length of boiler. Both the flue tubes, which carry hot gases, lay below the water level. To accommodate a grate of sufficient area and minimum length, these flue tubes are larger in diameter at the front of the shell. to control the gas flow and to control the amount of air entering the grate, dampers are used which are placed in path of flue gases.

Coal is fed to the grates through fire doors. Each of the flue tubes has its own furnace with grates where its combustion takes place and the flue gases rising from the furnaces pass over the fire bridge and traverse along the horizontal path. the hot gases leaving the grate pass up to the back end of the tubes and then travel back from the bottom flue passage to the front of boiler, where the gases bifurcate and pass into the two side flues. Thereafter, the gases in the two side flues enter the common flue and finally discharged to the atmosphere through chimney.

2. Babcock & Wilcox boiler.

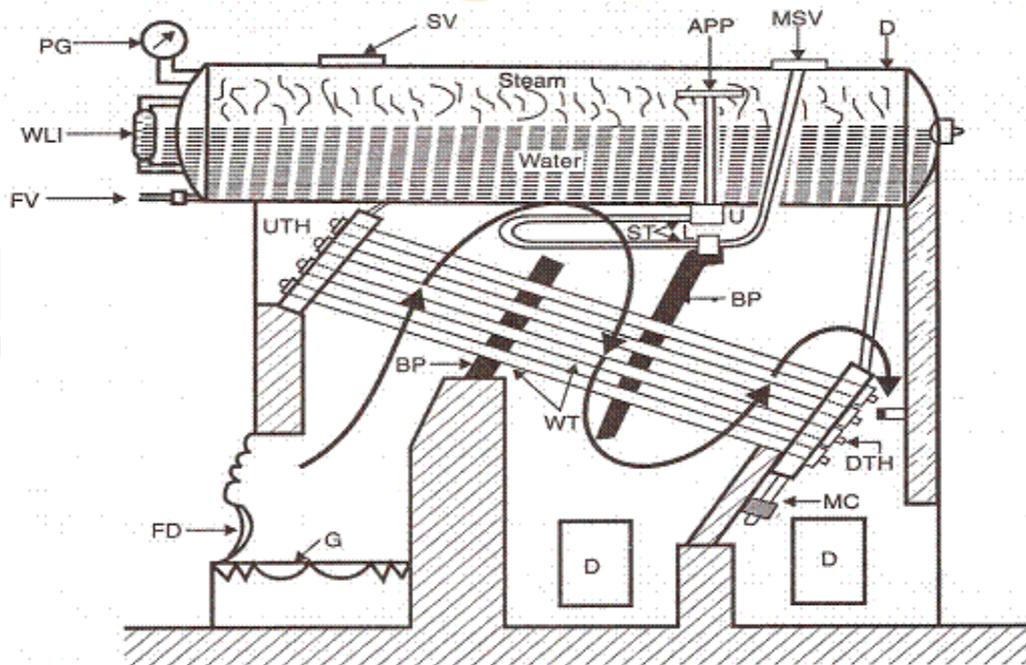
Theory

This is a horizontal, externally fired, water tube, natural circulation type stationary boiler. This boiler is the most common type used in thermal power plants for generation of steam in large quantities. It consists of a high pressure steel drum mounted at the top .from each end of the drum, connections are made with the uptake header and a down take header. The headers are joined to each other by a large number of water tubes which are kept inclined at an angle of about 15degree to the horizontal. The water tubes are straight, solid drawn steel tubes about 10 cm in diameter and are expanded into the bored holes of the headers.

The furnace is located below the uptake header. The coal is fed to the chain grate stoker through the fire door baffles are provided across the water tubes to act as deflectors to the flue gases. The hot gases rise upwards, go down and then rise up again and finally escape to chimney through the smoke chamber. To maintain a uniform velocity of flue gases throughout their travel, the passage of the gases is decreased from furnace to exit.

The circulation of water is maintained by convective currents. The cold water flows from the drum to the rear header and thus cycle is repeated. For getting superheated steam, the steam accumulated in the steam space is sent to the superheated tubes which are arranged above the water tubes. the super heated steam is finally supplied through a steam stop valve and steam pipe.

Evaporative capacity of such boiler ranges from 20,000 to 40,000 kg/hour and operating pressures of 11.5 to 17.5 bar are quite common. the inspection of boiler can be carried out even when the boiler is in operation, draught loss is minimum and replacement of defectives tubes can be made readily.



- | | |
|------------------------------------|-------------------------------|
| <i>D</i> = Drum | <i>PG</i> = Pressure gauge |
| <i>DTH</i> = Down take header | <i>ST</i> = Superheater tubes |
| <i>WT</i> = Water tubes | <i>SV</i> = Safety valve |
| <i>BP</i> = Baffle plates | <i>MSV</i> = Main stop valve |
| <i>D</i> = Doors | <i>APP</i> = Antipriming pipe |
| <i>G</i> = Grate | <i>L</i> = Lower junction box |
| <i>FD</i> = Fire door | <i>U</i> = Upper junction box |
| <i>MC</i> = Mud collector | <i>FV</i> = Feed valve |
| <i>WLI</i> = Water level indicator | |

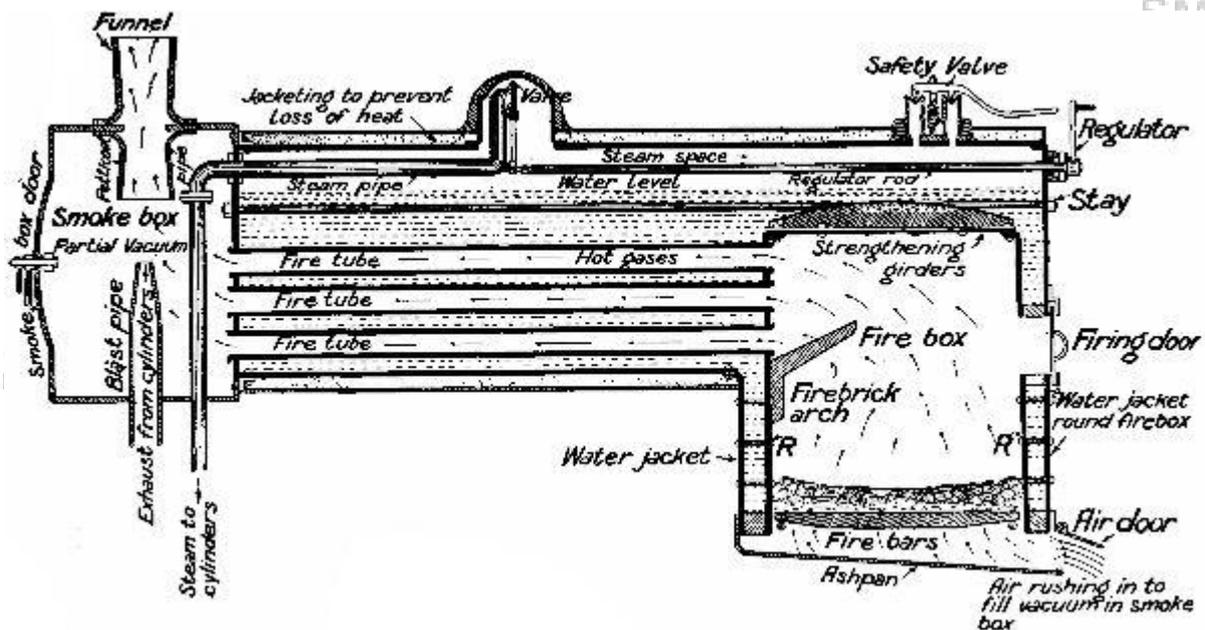
3. Locomotive boiler

Theory

A fire-tube boiler is a type of [boiler](#) in which hot gases from a fire pass through one or more tubes running through a sealed container of water. The [heat energy](#) from the gases passes through the sides of the tubes by [thermal conduction](#), heating the water and ultimately creating [steam](#).

The fire-tube boiler developed as the second of the three major historical types of boilers: low-pressure tank or "haystack" this type of boiler was used on virtually all [steam locomotives](#) in the horizontal "locomotive" form. This has a cylindrical barrel containing the fire tubes, but also has an extension at one end to house the "firebox". This firebox has an open base to provide a large grate area and often extends beyond the cylindrical barrel to form a rectangular or tapered enclosure.

A fire-tube boiler is sometimes called a "smoke-tube boiler" or "shell boiler" or sometimes just "fire pipe".



A locomotive boiler is a fire tube, internally fixed, horizontally, multi tubular boiler. It is mainly employed in locomotives through it may also be used as a stationary boiler. The hot gasses which are generated due to burning of the coal are deflected by an arch of a fire bricks, so that walls of the fire box may be heated properly.

In the locomotive-type boiler, fuel is burnt in a [firebox](#) to produce hot combustion gases. The firebox is surrounded by a cooling jacket of water connected to the long, cylindrical boiler shell. The hot gases are directed along a

series of fire tubes, or flues, that penetrate the boiler and heat the water thereby generating saturated ("wet") steam.

In the locomotive boiler, the saturated steam is very often passed into a [super heater](#), back through the larger flues at the top of the boiler, to dry the steam and heat it to superheated steam.

[Draught](#) for fire tube boilers, particularly in marine applications, is usually provided by a tall partial [vacuum](#). Modern industrial boilers use fans to provide forced or induced draughting of the boiler.

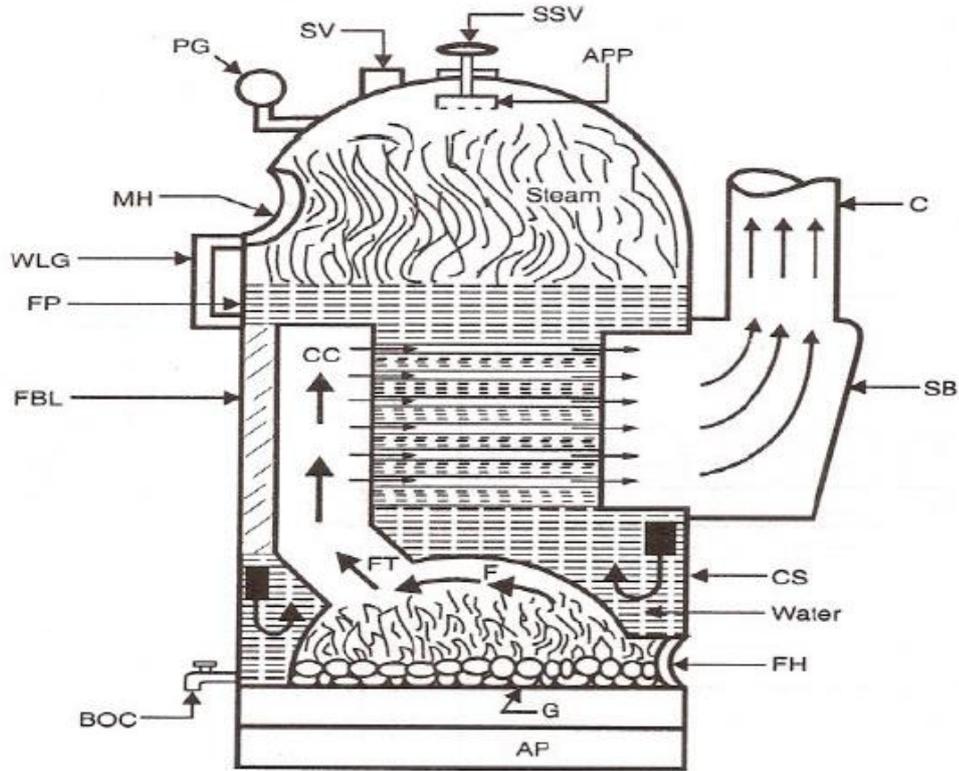
Locomotive-type boilers are also used in [traction engines](#), [steam rollers](#), [portable engines](#) and some other steam road vehicles. The inherent strength of the boiler means it is used as the basis for the vehicle: all the other components, including the wheels, are mounted on brackets attached to the boiler. It is rare to find super heaters designed into this type of boiler, and they are generally much smaller (and simpler) than railway locomotive types.

4. Cochran boiler

It is one of the best types of vertical multi-tubular boiler, and has a number of horizontal fire tubes. It is also a low pressure boiler.

Construction:

Cochran boiler consists of a cylindrical shell with a dome shaped top where the space is provided for steam. The furnace is one piece construction and is seamless. Its crown has a hemispherical shape and thus provides maximum volume of space. Working: the fuel is burnt on the grate and ash is collected and disposed of from ash pit. The gases of combustion produced by burning of fuel enter the combustion chamber through the flue tube and strike against fire brick lining which directs them to pass through number of horizontal tubes, being surrounded by water. After which the gases escape to the atmosphere through smoke box and chimney.



- | | |
|----------------------------------|--------------------------|
| <i>CS</i> = Cylindrical shell | <i>FT</i> = Flue tube |
| <i>CC</i> = Combustion chamber | <i>SB</i> = Smoke box |
| <i>FBL</i> = Fir brick lining | <i>C</i> = Chimney |
| <i>F</i> = Furnace (dome shaped) | <i>FH</i> = Fire hole |
| <i>BOC</i> = Blow off cock | <i>G</i> = Grate |
| <i>SSV</i> = Steam stop valve | <i>AP</i> = Ash pit |
| <i>APP</i> = Antipriming pipe | <i>SV</i> = Safety valve |
| <i>PG</i> = Pressure gauge | <i>MH</i> = Man hole |
| | <i>WLG</i> = Water level |

"WORKING TOWARDS BEING THE BEST"

TOPIC- 06

Boilers mountings & accessories

Introduction

The boiler mountings are added on the boiler for its safe working. While accessories are added on the boiler to improve its performance.

Boiler mountings:-

The boiler mounting are the part of the boiler and are required for proper functioning. in accordance with the Indian boiler regulations of the boiler mounting is essential fittings for safe working of the boiler.

1. Safety valve: - 2 numbers.
2. Water level indicator: - 2 numbers.
3. Pressure gauge: - 1 numbers.
4. Steam stop valve:- 1numbers.
5. Feed check valve.
6. Blow off cock
7. Main hole.
8. Mud hole.
9. Fusible plug.
10. High pressure and low water safety valve on Lancashire and Cornish boiler.

SAFETY VALVE

Safety valves are located on the top the boiler. They guard the boiler against the excessive high pressure of steam inside the drum. If the pressure of the steam in the boiler drum exceed the working pressure, then the safety valve allow to blow off certain quantity of steam to atmosphere. Thus the pressure of steam in the drum falls. The escape of steam makes a audio noise to warn the boiler attendant.

There are 4 types of safety valve.

1. Dead weight safety valve.
2. Spring loaded safety valve.
3. Lever loaded safety valve.
4. High steam& low water safety valve.

Dead weight safety valve

It is very similar to dead weigh (whistle) loaded on pressure cooker& functions in similar way. A gun metal valve resets on gun metal seat. The gun metal seat is mounted on steel steam pipe. The valve is fastened to weight carrier. The total weights in the form of cylindrically disc are placed on the carrier. Therefore the

total weight placed on the carrier is acting downward. This is the weight of cast iron carrier & valve itself.

Spring loaded safety valve

The dead weight safety valve cannot be used on locomotive & marine boiler as the jerks, pitching, rolling may change the load on the valve & it can open frequently under working pressures. The spring loaded safety valve is used on locomotive, marine and high pressure boiler.

Lever loaded safety valve

The body of the valve is fattened on the top of the boiler shell. a gun metal is placed in steam passage formed in the casting. A cast iron lever attached to a fulcrum on one end & loaded by weight on other end keeps the valve on sheets in closed position.

Water level indicator

Water level indicator is located in front of boiler in such a position that the level of water can easily be seen by attendant. Two water level indicators are used on all boilers. a water level consists of a metal tube & a strong glass tube with marking. The upper & lower ends of these tubes are connected to two gun metal hollow pipes.

Fusible plug

It is very important safety device, which protects the fire tube boiler against overheating. It is located just above the furnace in the boiler. During the normal boiler operation, the fusible plug is covered by water & its temp. Does not rise to its melting state. but when the water level falls too low in the boiler, it uncovers the fusible plug. The furnace gases heat up the plug & fusible plug melts, the inner plug falls down.

Feed check valve

The feed check valve is fitted to the boiler, slightly below the working level in the boiler, it is used to supply high pressure feed water to boiler. It also prevents the returning of feed water from the boiler if feed pump fails to work. a feed check consists of two valves: feed valve & check valve.

Steam stop valve

The steam stop valve is located on the highest part of the steam space. It regulates the steam supply to use. The steam stop valve can be operated manually or automatically. A hand operated steam stop valve.

TOPIC- 07

Boiler accessories

The accessories are mounted on the boiler to increase its efficiency. These units are optional on an efficient boiler. with addition of accessories on the boiler the plant accessories also increases. The following accessories used on a modern boiler.

1. Super heater
2. Economiser
3. Air preheated

Super heater It is heat exchanger in which heat of combustion products is used to dry the wet steam & to increase its temp. During superheating the steam, pressure remains constant, its temp & volume increase. basically a super heater consists of a set of small diameter four tubes in which steam flows & takes up the heat from the hot flue gases

Economiser

An economiser is a heat exchanger used for heating the feed water before it enter the boiler the economizer recovers some of waste heat of hot flue gases going to chimney. It helps in improving the boiler efficiency. it is placed in the path of flue gases at the near end of the boiler just before air preheater. The most popular economizer is greens economizer.

Air preheater

The function of an air preheater is similar to economizer. it recovers some portion of the waste heat of hot flue gases going to chimney & transfers same to the fresh air before it enter the combustion chamber. Due to preheating of air, the furnace temp. Increases. it results in rapid combusting of fuel with less soot, smoke & ash.

TOPIC- 08

Comparison between Water Tube and Fire Tube Boilers & Boiler draught

Water Tube Boilers	Fire Tube Boilers
--------------------	-------------------

The water circulates inside the tubes which are surrounded by hot gases from the furnace	The hot gases from the furnace pass through the tubes which are surrounded by water in the shell
It is a high pressure boiler	It cannot handle high pressure
The rate of generation of steam is high	The rate of generation of steam is relatively low
Overall efficiency is up to 90%	Overall efficiency is up to 75%
It is preferred for widely fluctuating loads	It is not preferable for fluctuating loads for a longer time period
The operating cost is high	The operating cost is less
The bursting chances are higher but bursting doesn't produce any destruction to the whole boiler	The bursting chances are less but bursting produces greater risk to the damage of the property
is used for large power plants	It is generally used for supplying steam on a small scale and is not suitable for large power plants

Boiler Draught:

The rate of steam generation in a boiler depends upon the rate at which the fuel is burnt, To burn the fuel rapidly, the continuous supply of fresh air through the grate is required which in turn discharges the products of combustion through the chimney to the atmosphere. Draught is a small pressure difference that causes the flow of air through the bed of fuel on the furnace grate to the chimney.

Object of draught

1. To supply sufficient air for the combustion of fuel.
 2. To push out the hot flue gases from the combustion chamber of the boiler to move through the system.
 3. To discharge the used (spent) flue gases to the atmosphere through chimney.
- of fuel burning is very high, artificial draught is provided. Artificial draught is usually produced by mechanical means such as fans, blower or steam jet. If the draught is produced by a fan, it is called mechanical draught or fan draught and if produced by steam jet it is referred to as steam jet draught. Steam jet draught is used in small installations and locomotives whereas the mechanical draught is preferred in power stations.

(A) Forced draught

In a forced draught system a fan or blower is installed near the base of the boiler or at the entrance of air-preheater. The air is forced to pass through the furnace, flue tubes, economiser, airpreheater, and to the chimney.

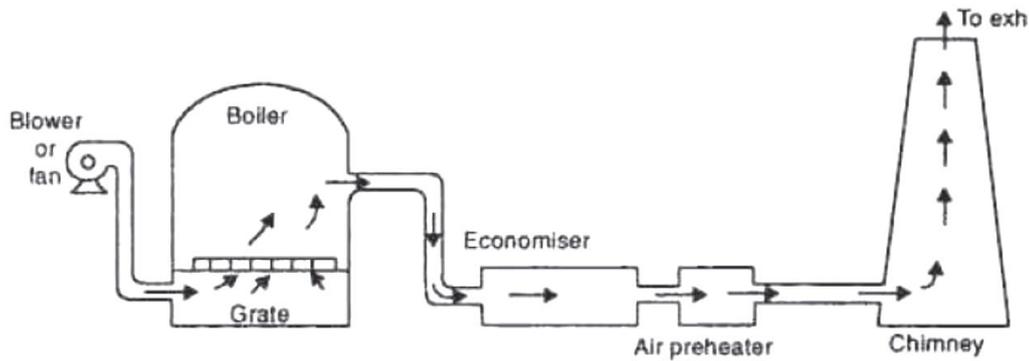


Figure: Forced fan draught

This draught system as shown in Fig. is known as positive draught system or forced draught system because the pressure of air throughout the system is above the atmospheric pressure and air is forced to flow through the system. Chimney used in this system is not for producing draught but just to dispose off the hot gases into the atmosphere.

(B) Induced draught

In the induced draught system a fan or blower is placed at the outlet of an economiser or air-preheater. In this draught system, the air pressure in the furnace is reduced below that of the atmosphere by means of a fan placed at (or near) the bottom of the chimney.

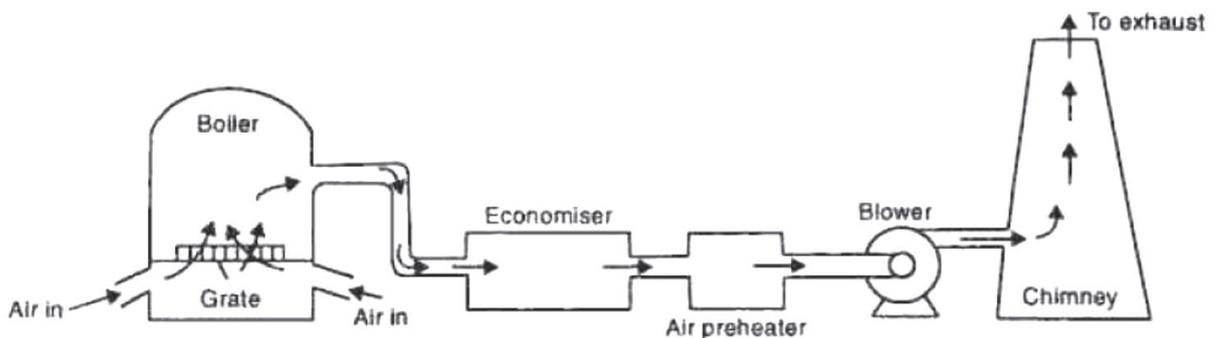


Figure: Induced fan draught

It draws the product of combustion from the furnace and forces them to pass through the chimney. The action of induced draught is similar to the action of the chimney. The arrangement of this system is shown in Fig.

(C) Balanced draught

Balanced draught is a combination of forced and induced draught. It is always better to use a combination of forced and induced draught instead of using either forced or induced draught alone. Here an air fan supplies air at a moderate pressure through the grate and also through the air-preheater.

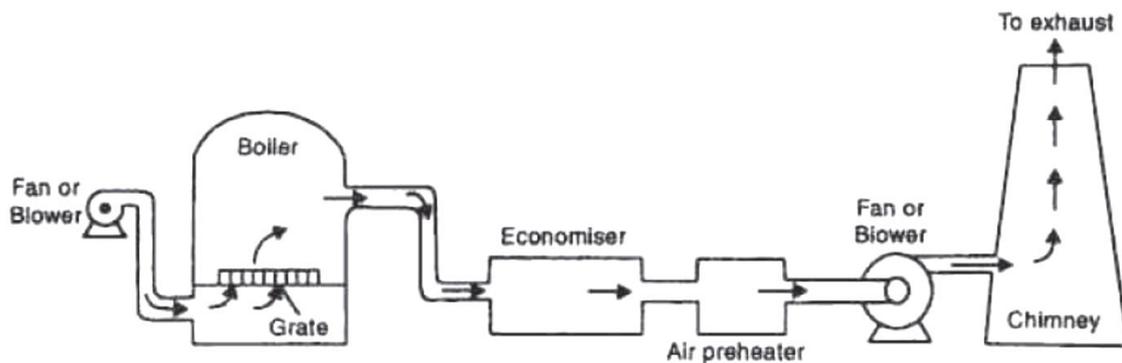


Figure: Balanced draught

An induced draught fan is placed at the bottom of the chimney to draw the flue gases through the flue tubes, economiser air-preheater and discharges them to atmosphere through chimney.

D) Steam Jet draught

The steam jet draught comes under the category of artificial draught. It can also be classified in two categories:

- . Forced steam jet draught
- . Induced steam jet draught

In the forced steam jet draught, the draught is produced by placing the steam jet in the ash pit which is placed under the fire grate of the furnace. In this case, the air will be forced into the furnace by the steam jet and the draught produced will be the forced draught.

The induced steam jet draught is produced when steam jet is directed into chimney from a nozzle placed in chimney. This causes the flow of gases through the fire tubes, ash pit and grate. Lnduced type steam jet draught is used in a locomotive boiler in which the exhaust steam from steam engine is passed through the nozzle to induce the air to pass through the fuel bed, furnace, flues and smoke box, thus creating a partial vacuum in the smoke box.

In case of forced steam jet draught as shown in Fig steam from boiler is throttled by a valve to a pressure of two bar and passed through the nozzles connected to a diffuser pipe. The steam comes out with high velocity from the diffuser and drags the column of air along with it and thus makes way for the fresh air to come inside the furnace.

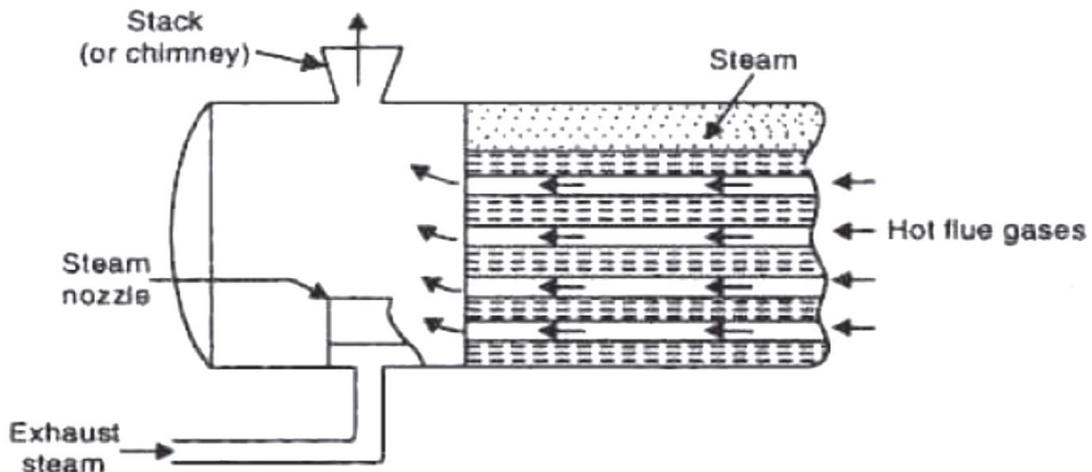


Figure: Steam Jet draught

Advantages of steam jet draught

- . Simple and economical
- . Occupies little space
- . Permits burning of inferior fuel
- . No maintenance

Disadvantages

It can not start until steam at pressure is available

Advantages of Artificial Draught Over the Natural Draught

The artificial draught has the following advantages over the natural draught:

- 1.. Effective control over the combustion
2. High rate of combustion
3. Permits burning of low grade fuel
4. Improves overall thermal efficiency of the plant
5. Reduces the height of chimney as it is only required to discharge the gases high in the atmosphere
6. Low consumption of fuel
7. Prevents smoke formation
8. Independent of atmospheric temperature
9. Enhances the evaporative capacity of boiler
10. It can be regulated as per the requirement of the furnace.

Disadvantage.

1. High installation cost
2. High running and maintenance cost.
3. Permits burning of low grade fuel
4. Improves overall thermal efficiency of the plant
5. Reduces the height of chimney as it is only required to discharge the gases high in the atmosphere

TOPIC- 10

Steam (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*.

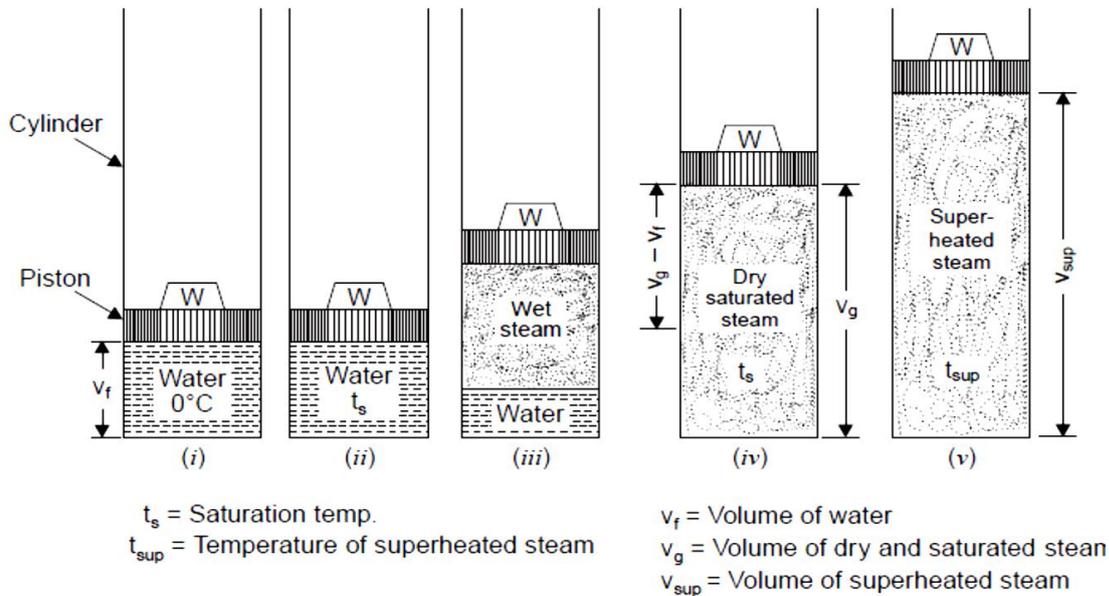
“Homogeneous in composition” means that the composition of each part of the system is the *same* as the composition of *every other part*. “Composition means the relative proportions of the chemical elements into which the sample can be analysed. It does not matter how these elements are combined.

“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. 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.

“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.

FORMATION OF STEAM

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 m³ under the piston Fig. 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*.

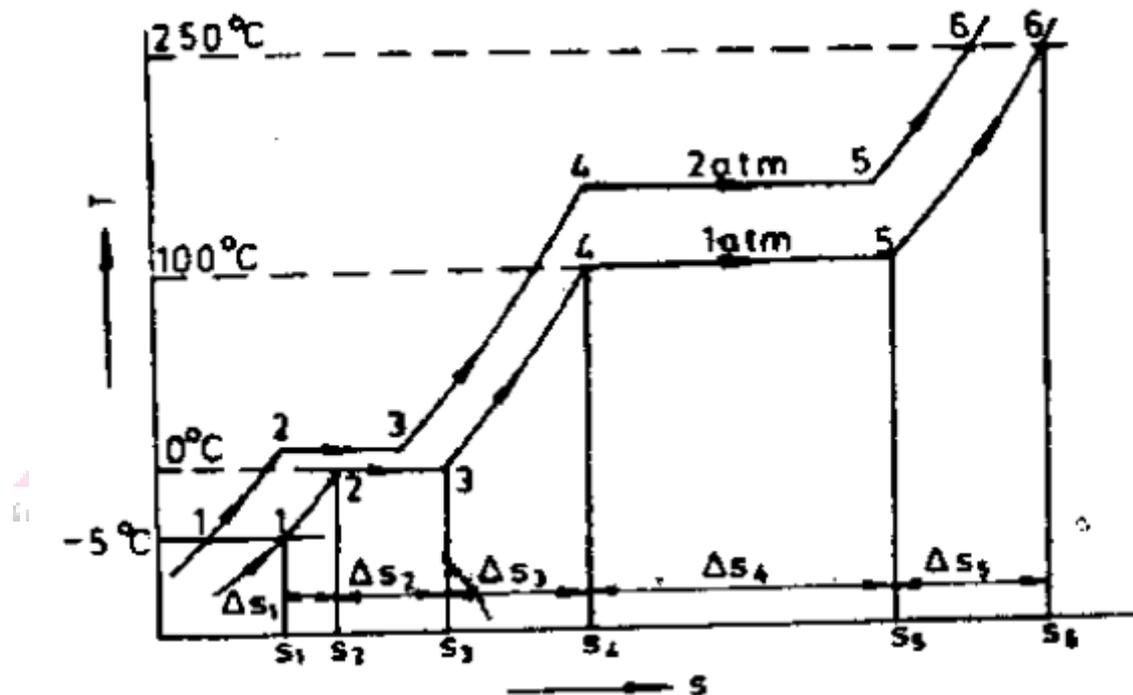


It may be noted during heating up to boiling point that there will be slight increase in volume of water due to which piston moves up and hence work is obtained as shown in Fig. This work, however, is so *small* that it can be *neglected*. Now, if supply of heat to water is continued it will be noticed that rise of temperature after the boiling point is reached *nil* but piston starts moving upwards which indicates that there is increase in 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. and if heating of steam is further progressed as shown in Fig such that all the water particles associated with steam are evaporated, the steam so obtained is called *dry and saturated steam*. If v_g m³ is the volume of 1 kg of dry and saturated steam then work done on the piston will be $p(v_g - v_f) \dots$ 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. Fig. shows the graphical representation of formation of steam.

T-s Diagram for a pure substance:

Consider the heating of 1 kg of ice at -5°C to steam at 250°C . The pressure being maintained at 1 atm. It is observed that the entropy of steam increases in different regimes of heating namely

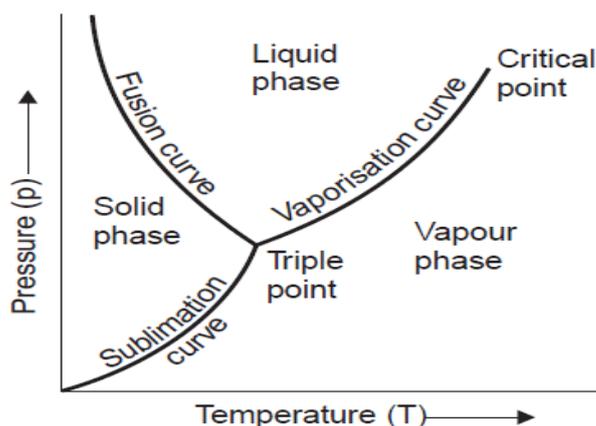
- 1) Entropy increase of ice to saturated freezing temperature
- 2) Entropy increase of ice as it melts into water.
- 3) Entropy increase of water as it is heated from 0°C to 100°C .
- 4) Entropy increase of water as it is vaporized at 100°C absorbing latent heat of vaporization.
- 5) Entropy increase of vapour as it is heated from 100°C to 250°C



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.

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



p-T diagram for a substance such as water.

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 'vaporization 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 vaporization curve is called the steam line, and the fusion curve is called the ice line. The slopes of sublimation and the vaporization curves for all substances are positive. The slope of the fusion curve however may be positive or negative. The fusion curve of most substances has a positive slope. Water is one of the important exceptions.

Triple point

The **triple point** is merely the point of intersection of sublimation and vaporization 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.

Important terms relating steam formation

1. Sensible heat of water (hf). 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.

2. Latent heat or hidden heat (hfg).

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 hfg 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,

$$x = \frac{m_s}{m_s + m_w}$$

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**.

$$h = hf + xhfg$$

If steam is dry and saturated, then $x = 1$

Then $hg = hf + hfg$.

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 (*cps*), the value of which varies from 2.0 to 2.1 kJ/ kg K depending upon pressure and temperature. The total heat of superheated steam is given by

$$h_{sup} = hf + hfg + cps (T_{sup} - T_s)$$

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.

$$= xv_g + (1 - x)v_f$$

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

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.

$$v_{sup} = \frac{v_g T_{sup}}{T_s}$$

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 = $p (v_g - v_f)$ As at low pressure v_f is very small and hence neglected, work of evaporation is

$P. v_g$

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

$$Pxv_g$$

TOPIC- 11

Some solve example on Properties of steam

Q.1 Calculate the internal energy per kg of superheated steam at a pressure of 10 bar and a temperature of of 300°C Also find the change internal energy in this steam if expanded to 1.4 bar and dryness fraction 0.8.

Sol. Given, $p_1 = 10$ bar, $t_{sup} 300^\circ\text{C}$. $P_2 = 1.4$

From steam tables corresponding to a pressure of 10 bar,

$$h_f = 7616 \text{ kJ/kg}$$

$$h_{fg} = 2013,6 \text{ kJ/kg}$$

$$v_g = 0.19430 \text{ m}^3/\text{kg}$$

$$t = 179.9^\circ\text{C}$$

Enthalpy of 1 kg of superheated steam,

$$h_{sup} = h_f + h_{fg} + c_p(t_{sup} - t)$$

$$= 762.6 + 2013.6 + 2.1 (300 - 179.9) \quad (c_p = 2.1$$

kJ/kg for steam)

$$= 3028.41 \text{ kJ/kg}$$

$$V_{\text{sup}} = v_g \frac{T_{\text{sup}}}{T}$$

$$V_{\text{sup}} = 0.1943 \frac{(300 + 273)}{(179.9 + 273)}$$

$$= 0.2458 \text{ m}^3/\text{kg}$$

Internal energy of superheated steam

$$U_{\text{sup}} = h_{\text{sup}} - 100 p_1 V_{\text{sup}}$$

$$= 3028.41 - 100 \times 10 \times 0.2458$$

$$= 2782.61 \text{ kJ/kg Ans}$$

The superheated steam now expands to a pressure of 1.4 bar. From steam tables corresponding to a pressure of 1.4 bar, we find that

$$h_f = 458.4 \text{ kJ/kg,}$$

$$h_{fg} = 2231.9 \text{ kJ/kg,}$$

$$V_g = 1.2363 \text{ m}^3/\text{kg}$$

Internal energy of the expanded steam,

$$U_e = h_f + X h_{fg} - 100 P_2 X V_g$$

$$= 458.4 + 0.8 \times 2231.9 - 100 \times 1.4 \times 0.8 \times 1.2363$$

$$= 2105.45 \text{ kJ/kg}$$

Change in internal energy

$$= U_{\text{sup}} - U_e$$

$$= 2782.61 - 2105.45$$

$$= 677.16 \text{ kJ/kg Ans.}$$

Q.2 Calculate the internal energy of 1 kg of steam at a pressure of 10 bar when steam is

(i) 0.8 dry

(ii) dry and saturated

(iii) Superheated to 250°C.

Sol. Given, $p = 10 \text{ bar}$,

$$T_{\text{sup}} = 250 + 273 = 523 \text{ K.}$$

From steam tables, corresponding to a pressure of 10 bar, we find that

$$h_f = 762.6 \text{ kJ/kg,}$$

$$h_{fg} = 2013.6 \text{ kJ/kg}$$

$$v_g = 0.1943 \text{ m}^3/\text{kg,}$$

$$t_g = 179.88^\circ\text{C, } T_g = 179.88 + 273 = 452.88 \text{ K}$$

(1) Internal energy of 1 kg of steam when it is 0.8 dry

Internal energy for wet steam

$$\begin{aligned} U_{\text{wet}} &= h_f + x h_{fg} - 100 p \times v_g \\ &= 762.6 + 0.8 \times 2013.6 - 100 \times 10 \times 0.8 \times \\ &0.1943 \\ &= 2218.04 \text{ kJ Ans.} \end{aligned}$$

(ii) Internal energy of 1 kg of steam when it is dry and saturated

$$\begin{aligned} \text{Internal energy for dry saturated steam } U_{\text{dry}} &= h_f + h_{fg} - 100 P v_g \\ &= 762.6 + 2013.6 - 100 \times 10 \times 0.1943 \\ &= 2581.9 \text{ kJ Ans.} \end{aligned}$$

(iii) Internal energy of 1 kg of steam when it is superheated to 250°C

Volume of superheated steam

$$V_{\text{sup}} = v_g \frac{T_{\text{sup}}}{T}$$

$$V_{\text{sup}} = 0.1943 \frac{523}{452.88}$$

$$V_{\text{sup}} = 0.2244 \text{ m}^3/\text{kg}$$

Enthalpy of 1 kg of superheated steam

$$\begin{aligned}
 h_{\text{sup}} &= h_f + h_{fg} + c_p (t_{\text{sup}} - t_g) \\
 &= 762.6 + 2013.6 + 2.1 (250 - \\
 &179.88) \\
 &= 2923.452 \text{ kJ} \quad (\text{cp for} \\
 &\text{superheated steam} = 2.1 \text{ kJ/kgK})
 \end{aligned}$$

Internal energy of superheated steam

$$\begin{aligned}
 U_{\text{sup}} &= h_{\text{sup}} - 100 p V_{\text{sup}} \\
 &= 2923.452 - 100 \times 10 \times 0.2244 \\
 &= \mathbf{2699.052 \text{ kJ Ans.}}
 \end{aligned}$$

Question. 3. A spherical shell of capacity 0.10 m³ contains steam and water in equal volume. If the temperature of the steam is 300°C. Determine the mass of water and steam in the container. Also calculate the dryness fraction of the wet steam.

Solution

Total volume of the shell is 0.1 m³

Volume occupied by steam = $V_s = 0.05 \text{ m}^3$

Volume occupied by water = $V_w = 0.05 \text{ m}^3$

From steam tables, at saturation temperature of 300 °C

$v_f = 0.0014 \text{ m}^3/\text{kg}$; $v_g = 0.0217 \text{ m}^3/\text{kg}$

mass of water = $V_w / v_f = 0.05 / 0.0014 = 35.71 \text{ kg}$

mass of steam = $V_s / v_g = 0.05 / 0.0217 = 2.30 \text{ kg}$

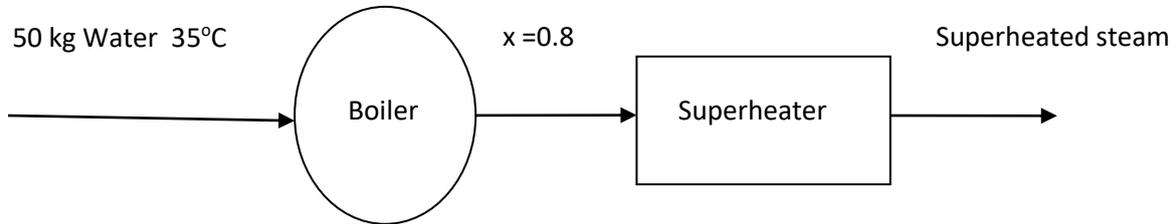
dryness fraction $x = \text{mass of steam} / (\text{mass of steam} + \text{mass of water})$

$$x = 2.30 / 35.71 = 0.06 \text{ Answer}$$

Question 4. Determine the quantity of heat energy required to produce 50 kg of steam at a pressure of 10 bar and dryness fraction 0.8 from water at 35° C. Also calculate the heat added in superheater if the steam is passed

through superheater where its temperature is raised to 250 °C.
 Assume no pressure loss takes place in the superheater. $C_{ps}=2.3 \text{ kJ/kgK}$.

Solution



From steam tables, at saturation pressure of 10 bar

$$T_s=179.9 \text{ }^\circ\text{C}; h_f=762.8 \text{ kJ/kg}; h_{fg}=2015.3 \text{ kJ/kg}; h_g=2778.1 \text{ kJ/kg}$$

Dryness fraction of steam produced in the boiler = $x = 0.8$

Specific enthalpy of wet steam

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

$$h=762.8 + 0.8 \times 2015.3 \text{ kJ/kg} = 2375.04 \text{ kJ/kg}$$

Heat energy added per kg of steam produced = h-enthalpy of water at 35°C

Assume specific heat of water = 4.18 kJ/kg K

$$2375.04 - 4.18 \times 35 = 2228.74 \text{ kJ/kg};$$

Hence heat energy required to produce 50 kg of the steam = $m \times h$

$$= 50 \times 2228.74 = 111437 \text{ kJ Answer}$$

Specific enthalpy of superheated steam = $h_g + C_{ps}(T_{sup} - T_s)$

$$\text{Substituting the values } h_{sup} = 2778.1 + 2.3(250 - 179.9) = 2939.33 \text{ kJ/kg}$$

Heat energy added in the superheater per kg of steam = $h_{sup} - h$

$$= 2939.33 - 2375.04 = 564.29 \text{ kJ/kgK}$$

Total heat energy added in the superheater for 50 kg

$$= 50 \times 564.29 = 28214.5 \text{ kJ. Answer}$$

Question 5. A pressure cooker contains 1 kg of saturated steam at a pressure of 0.4 MPa. Determine the quantity of heat that must be rejected so that the final condition of steam in the cooker is 0.5 dry.

Solution

From steam tables, at saturation pressure of 0.4 MPa = 4 bar

$T_s=143.6\text{ }^\circ\text{C}$; $h_f=604.7\text{ kJ/kg}$; $h_{fg} = 2133.8\text{ kJ/kg}$; $h_{g1}= 2738.5\text{kJ/kg}$; $v_f = 0.001084$; $v_{g1}= 0.463$;

$$v_1 = v_{g1} = 0.463; h_1=h_{g1}$$

Neglecting the volume occupied by water

$v_1 = v_{g1}$ is the initial volume as the steam is saturated, let v_2 be the volume after the heat is removed.

$v_1= v_2$ as the process of cooling is taking place at constant volume.

Since the dryness fraction of steam after cooling = $x = 0.5$ where v_{g2} is the specific volume of steam at condition 2

$$v_2 = x v_{g2} = 0.5 v_{g2} \text{ since } v_1=v_2$$

$$v_1=0.5 v_{g2} ; v_{g2} = 0.926\text{m}^3/\text{kg}$$

from steam tables corresponding to the value of v_{g2} (taking the nearest values)

$T_s=118.6\text{ }^\circ\text{C}$; $h_{f2}=497.8\text{ kJ/kg}$; $h_{fg2}=2206.5\text{ kJ/kg}$; $h_{g2}=2704.3\text{kJ/kg}$

$$h_2 = h_{f2} + x h_{fg2} = 497.8 + 0.5 \times 2206.5 = 1601\text{ kJ/kg};$$

heat energy removed = h_1-h_2

$$2738.5-1601= 1137.5\text{ kJ Answer}$$

Question 6. A vessel of 1 m³ contains wet steam at a pressure of 8 bar and dryness fraction of 0.9. Steam is blown off from the vessel until the pressure drops to 4 bar. Assume that the enthalpy of steam per kg remains constant in the vessel during the blow off. Determine the mass of the steam blown off.

Solution :

Given volume of the vessel $v_1 = 1.0\text{ m}^3$; $x_1 = 0.9$;

From steam tables, at saturation pressure of 8 bar

$$T_s=170.4 \text{ }^\circ\text{C}; h_{f1}=721.1 \text{ kJ/kg}; h_{fg1}=2048 \text{ kJ/kg}; h_{g1}= 2769.1\text{kJ/kg}; v_f = 0.001115; v_{g1}= 0.240;$$

From steam tables, at saturation pressure of 4 bar

$$T_{s2}=143.6 \text{ }^\circ\text{C}; h_{f2}=604.7 \text{ kJ/kg}; h_{fg2}=2133.8 \text{ kJ/kg}; h_{g2}=2738.5\text{kJ/kg}; v_{f2} = 0.001084; v_{g2}=0.463;$$

Neglecting the volume occupied by water

$$\text{The mass of the steam in the vessel} = m_1 = v_1 / x_1 v_{g1} = 1.0 / (0.9 \times 0.24) = 4.629 \text{ kg}$$

Since the enthalpy in the vessel remains same before and after the blow off of the steam

$$h_1 = h_2$$

$$h_{f1} + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2}$$

$$x_2 = 0.918$$

$$\text{Mass of steam present in the vessel after blowing off of the steam} = m_2 = v_1 / x_2 v_{g2} =$$

$$1 / 0.918 \times 0.463 = 2.352 \text{ kg}$$

$$\text{Mass of steam blown off} = m_1 - m_2 = 4.629 - 2.352 = 2.277 \text{ kg} \text{ Answer}$$

Question 7. A sample of steam at a pressure of 10 bar is passed through a throttling calorimeter for measuring the dryness fraction. If the pressure and temperature recorded after the throttling is found to be 1 bar and 120°C. Determine the dryness fraction of steam. Take the value of specific heat of steam = 2.3 kJ/kgK.

Solution:

From steam tables, at saturation pressure of 10 bar

$$T_{s1}=179.9 \text{ }^\circ\text{C}; h_{f1}=762.8 \text{ kJ/kg}; h_{fg1}=2015.3 \text{ kJ/kg}; h_{g1}=2778.1\text{kJ/kg};$$

At saturation pressure of 1 bar

$$T_{s2} = 99.6 \text{ }^\circ\text{C}; h_{g2}=2675.5 \text{ kJ/kg};$$

Let x_1 be the dryness fraction of steam before throttling and h_1 the enthalpy before throttling

$$h_1 = h_{f1} + x_1 h_{fg1} = 762.8 + x_1 2015.3 \text{ kJ/kg};$$

as the temperature after throttling ($T_2 = 120^\circ\text{C}$) is more than the saturation temperature of steam at outlet pressure i.e. T_{s2} steam is superheated. The enthalpy at outlet h_2

$$h_2 = h_{g2} + C_{ps}(T_2 - T_{s2})$$

$$h_2 = 2675.5 + 2.3(120 - 99.6) =$$

$h_1 = h_2$ for throttling process i.e. enthalpy remains constant

$$762.8 + x_1 2015.3 = 2722.42$$

The dryness fraction of steam $x_1 = 0.97$ **Answer**

Ques. 8 In the above example what is the maximum possible moisture that could be measured in percentage, if minimum 5 degree of superheat is required after throttling for the above set setup.

Solution:

Since 5 degree of superheat is required the outlet temperature recorded should be 5°C more than the saturation temperature (T_{s2}) corresponding to the outlet pressure.

$$T_2 = T_{s2} + 5 = 99.6 + 5 = 104.6^\circ\text{C};$$

$$h_2 = h_{g2} + C_{ps}(T_2 - T_{s2})$$

$$h_2 = 2675.5 + 2.3(104.6 - 99.6) = 2687$$

as $h_1 = h_2$ for throttling process

$$762.8 + x_1 \times 2015.3 = 2687;$$

$$x_1 = 0.95.$$

The maximum moisture content which can be measured with the given setup is 5%

