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THERMAL ENGINEERING-II

(THEORY-04)

(ACCORDING TO DIPLOMA SYLLABUS FOR 4TH SEMESTER MECHANICAL ENGG)

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CHAPTER-1 (Performance of I.C engine)

Heat engine: A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work.

It is classified into two types- (a) External combustion engine

(b) Internal combustion engine

External combustion engine: In this engine, the products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle

. Examples: *In the steam engine or a steam turbine plant, the heat of combustion is employed to generate steam which is used in a piston engine (reciprocating type engine) or a turbine (rotary type engine) for useful work.

In a closed cycle gas turbine, the heat of combustion in an external furnace is transferred to gas, usually air which the working fluid of the cycle.

Internal combustion engine: In this engine, the combustion of air and fuels take place inside the cylinder and are used as the direct motive force

Terminology used in IC engine:

1. **Cylinder bore (D):** The nominal inner diameter of the working cylinder.

2. **Piston area (A):** The area of circle of diameter equal to the cylinder bore.

3. **Stroke (L)**: The nominal distance through which a working piston moves between two successive reversals of its direction of motion.

4. **Dead centre**: The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).

Bottom dead centre (BDC): Dead centre when the piston is nearest to the crankshaft.

Top dead centre (TDC): Dead centre when the position is farthest from the crankshaft.

5. **Displacement volume or swept volume (Vs):** The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as, $V_s = A \times L$

6. **Clearance volume (Vc):** the nominal volume of the space on the combustion side of the piston at the top dead centre.

7. **Cylinder volume (V):** Total volume of the cylinder. V= Vs + Vc

8. **Compression ratio (r): (Vs + Vc)/ Vc**

Power and Mechanical efficiency:

BREAK POWER:-

Power developed at the output shaft is known as brake power (b.p.),

b.p.= 2πNT

where, T is Torque in Nm

N is rotational speed in revolutions per second

T=WR W=9.81 × net mass (in kg) applied

R=radius in m

INDICATED POWER:-

power developed in the combustion chamber is known as indicated power (i.p.).

It formsθ the basis for evaluation of combustion efficiency or heat release in the cylinder.

friction power:-

power utilised in overcoming friction is known as friction power (f.p.). **f.p.=i.p.- b.p.**

Mechanical Efficiency= b.p./i.p.=b.p./(b.p.+f.p,)

Mean effective pressure and Torque:

Hypothetical pressure acted upon the piston throughout the power stroke.

$Pm = net\ area\ of\ indicator\ diagram\ length\ of\ indicator\ diagram \times spring\ constan$ Indicated power per cylinder,

i.p.=(PimALN/60) KW

n= number of revolution required to complete one engine cycle (n=1 for two stroke engine, 2 for four stroke engine)

For hit and miss governing, i.p./cylinder= Pim.A.L. × number of working strokes per secondθ Brake power per cylinder

$$b.p.= 2\pi NT /60$$

Then, $T = PbmAL\ n \times 1\ 2\pi$

For same mep, larger engine produces more torque Higher mep,

higher will be the power developed by the engine for a given displacementθ Mep is basis of comparison of relative performance of different enginesθ horsepower of an engine is dependent on its size and speedθ 3.

Specific output: It describes the efficiency of an engine in terms of the brake horsepower.

Specific output=b.p./AL=constant × bmep × rpm

For same piston displacement and bmep an engine running at higher speed will give more output. Increasing speed increase mechanical stressesθ Increasing bmep requires better heat release and more load on engine cylinderθ 4.

Volumetric efficiency: ηv

$Mass\ of\ charge\ actually\ inducted\ Mass\ of\ charge\ inducted\ in\ swept\ volume\ at\ NTP$ Power output is proportional to the amount of air inductedθ ηv of supercharged engine has more than unity due to forced inductionθ ηv can be improved by compressing the induction charge (forced induction) or by aggressive cam phasing in naturally aspirated engines. In the case of forced induction volumetric efficiency can exceed 100%. Modern technique for four-stroke engines, variable valve timing, attempts to changes inθ volumetric efficiency with changes in speed of the engine: at higher speeds the engine needs the valves open for a greater percentage of the cycle time to move the charge in and out of the engine.

Fuel-air ratio (F/A): Ratio of mass of fuel to mass of air in mixture affects the combustion phenomenon, determines the flame propagation velocity, the heat release, maximum temperature and completeness of combustion, unwanted pollutants formation produced in the reaction. stoichiometric mixture- Enough air is provided to completely burn all of the fuel Rich mixtures: lower than stoichiometric; little air present to burn the given quantity of fuel; are less efficient,θ but may produce more power and burn cooler Lean mixtures: higher than stoichiometric; more air than required to burn fuel; are more efficient but mayθ cause higher temperatures, which can lead to the formation of nitrogen oxides. Some engines are designed with features to allow lean-burn. AFR (air-fuel ratio) =1/FARθ Relative fuel-air ratio=actual fuel-air ratio/ stoichiometric fuel-air ratioθ Air-fuel equivalence ratio (λ): ratio of actual AFR to stoichiometry for a given mixture. λ = 1.0 is atθ stoichiometry, rich mixtures λ < 1.0, and lean mixtures λ > 1.0 For pure octane or gasoline fuel the stoichiometric mixture is approximately 15:1, or λ of 1.00 exactly.

Specific Fuel Consumption (sfc): Specific fuel consumption is the indication of efficiency with which the engine develops power from fuel. $sfc = fuel\ consumed\ horse\ power\ developed$ Unit: g/kW.h Basis of comparison of different sizes of engine as per efficient utilization of fuel.

The engine which consumes least amount of fuel can produce high power.

For IC engines, it is of two types:

Indicated Specific Fuel Consumption (ISFC) ISFC = Fuel consumption per unit time / Indicated horse power

Brake Specific Fuel Consumption (BSFC) BSFC = Fuel consumption per unit time / Brake Horse Power:

measure of the efficiency of any prime mover that burns fuel and produces rotational, or shaft power.

Thermal Efficiency (ηth) and Heat Balance: Ratio of engine power output to input power i.e. chemical energy in the form of fuel supply.

Based on power output,

it may be divided into

brake thermal efficiency (ηbth)

indicated thermal efficiency (ηith).

Brake thermal efficiency = b. p. mf × C. V.

Indicated thermal efficiency = i. p. mf × C. V.

Heat balance: In IC engine, total input energy is not fully converted to useful work, energy goes out in various ways.

The heat balance gives the detail of amount of energy wasted in percentage from various parts.

The components of heat balance are brake output, coolant losses, heat going to exhaust, radiation and other losses. 8. Exhaust smoke and other emissions:

Specific weight: Exhaust emissions such as smoke, oxides of nitrogen, unburned hydrocarbons, carbon monoxides etc. are necessary to consider as a performance parameters and components of air pollutions.

It gives the engine bulkiness i.e. weight of the engine in kg for each brake power developed. In aircraft engines, specific weight plays important role

calorific value of fuel:- The calorific value of a fuel is the quantity of heat produced by its combustion – at constant pressure and under "normal" (standard) conditions (i.e. to 0°C and under a pressure of 1,013 mbar)

The unit of calorific value is **kilojoule per kilogram** i.e. KJ/Kg.

Q.1 A four-cylinder, two-stroke cycle petrol engine develops 30 kW at 2500 rpm. The mean effective pressure on each piston is 8 bar and mechanical efficiency is 80%. Calculate the diameter and stroke of each cylinder, if the stroke to bore ratio is 1.5. Also calculate the fuel consumption of the engine, if the brake thermal efficiency is 28%. The calorific value of the fuel is 43900 kJ/kg.

Given A four-cylinder, two-stroke cycle petrol engine

$k = 4$ $\qquad BP = 30$ kW

$N = 2500$ rpm $\qquad n = N$

$\eta_{mech} = 0.8$ $\qquad L = 1.5\,d$

$\eta_{bth} = 0.28$ $\qquad CV = 43900$ kJ/kg

$p_m = 8$ bar $= 800$ kPa

To find

(i) Bore of cylinder,

(ii) Stroke of pistion, and

(iii) Fuel consumption rate (*Bsfc*).

Analysis The mechanical efficiency is given as

$$\eta_{mech} = \frac{BP}{IP}$$

$$\therefore \qquad IP = \frac{30 \text{ kW}}{0.8} = 37.5 \text{ kW}$$

(i) The indicated power is expressed as

$$IP = \frac{p_m L A n k}{60}$$

$$\text{or} \qquad 37.5 = \frac{800 \times (1.5d) \times \left(\frac{\pi}{4} d^2\right) \times 2500 \times 4}{60}$$

$$\text{or} \qquad d^3 = 0.000238 \text{ m}^3$$

$$\text{Bore} \qquad d = 0.062 \text{ m} \quad \text{or} \quad \mathbf{62\ mm}$$

(ii) Stroke $L = 1.5d = \mathbf{93\ mm}$

iii) The brake thermal efficiency is given by

$$\eta_{bth} = \frac{BP}{\dot{m}_f CV}$$

$$\text{or} \qquad \dot{m}_f = \frac{30 \text{ kW}}{0.28 \times (43900 \text{ kJ/kg})}$$

$$= 0.00244 \text{ kg/s} \quad \text{or} \quad 8.78 \text{ kg/h}$$

The brake specific fuel consumption

$$Bsfc = \frac{\dot{m}_f(\text{kg/h})}{BP(\text{kW})} = \frac{8.78}{30}$$

$$= \mathbf{0.293\ kg/kWh}$$

Q.2 The following results refer to a test on a petrol engine:

Indicated power = 30 kW
brake power = 26 kW
Engine speed = 1000 rpm
Bsfc = 0.35 kg/kWh
CV of fuel used = 43900 kJ/kg
Calculate
(a) Indicated thermal efficiency,
(b) Brake thermal efficiency, and
(c) Mechanical efficiency.

Given A petrol engine

$IP = 30$ kW $\quad BP = 26$ kW

$N = 1000$ rpm $\quad Bsfc = 0.35$ kg/kWh

$CV = 43900$ kJ/kg

To find

(i) Indicated thermal efficiency, η_{ith}
(ii) Brake thermal efficiency, η_{bth}
(iii) Mechanical efficiency, η_{mech}

Analysis Fuel consumption rate,

$$\dot{m}_f = Bsfc \times BP$$
$$= 0.35 \times 26 = 9.1 \text{ kg/h} = 2.53 \times 10^{-3} \text{ kg/s}$$

(i) Indicated thermal efficiency (η_{ith}),

$$\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$$
$$= \frac{30}{2.53 \times 10^{-3} \times 43900}$$
$$= 0.27 = \mathbf{27\%}.$$

(ii) Brake thermal efficiency (η_{bth}),

$$\eta_{bth} = \frac{BP}{\dot{m}_f \, CV} = \frac{26}{2.53 \times 10^{-3} \times 43900} = 0.234 = \mathbf{23.4\%.}$$

(iii) Mechanical efficiency (η_{mech}),

$$\eta_{mech} = \frac{BP}{IP} = \frac{26}{30} = 0.867 = \mathbf{86.7\%.}$$

Q.3 A two-stroke, Diesel engine developsa brake power of 420 kW. The engine consumes 195 kg/h of fuel and air–fuel ratio is 22:1. Calorific value of the fuel is 42000 kJ/kg. If 76 kW of power is required to overcome the frictional losses, calculate

(a) Mechanical efficiency,

(b) Air consumption,

(c) Brake thermal efficiency.

Ans:-

To find

(i) Mechanical efficiency, η_{mech}

(ii) Air consumption, and

(iii) Brake thermal efficiency, η_{bth}

(i) Mechanical efficiency (η_{mech})

Indicated power,

$$IP = BP + FP = 420 + 76 = 496 \text{ kW}$$

$$\eta_{mech} = \frac{BP}{IP} = \frac{420}{496} = 0.8467$$

$$= \mathbf{84.67\%.}$$

(ii) Fuel consumption rate,

$$\dot{m}_a = \dot{m}_f \times \frac{A}{F} = (195 \text{ kg/h}) \times \frac{22}{1}$$

$$= 4290 \text{ kg/h} \quad \text{or} \quad \mathbf{71.5 \text{ kg/min}}$$

(iii) The brake thermal efficiency of an engine is expressed as

$$\eta_{bth} = \frac{BP}{\dot{m}_f \times CV}$$

$$= \frac{420 \text{ kW}}{\left(\frac{195}{3600} \text{ kg/s}\right) \times (42000 \text{ kJ/kg})}$$

$$= 0.1846 \quad \text{or} \quad \mathbf{18.46\%}$$

QNA Chapter -1

Q.1 What is Relative efficiency ?

It is the ratio of actual thermal efficiency to air standard efficiency of the engine. It is sometimes referred as efficiency ratio. It is expressed as

$$\eta_{Relative} = \frac{\text{Brake thermal efficiency}}{\text{Air standard efficiency}}$$

Q.2. What is Mechanical efficiency ?

It is the ratio of the brake power and indicated power.

$$\eta_{mech} = \frac{BP}{IP}$$

It can also be expressed as

It can also be expressed as

$$\eta_{mech} = \frac{\text{Brake thermal efficiency}}{\text{Indicated thermal efficiency}}$$

$$= \frac{\eta_{bth}}{\eta_{ith}} \quad \ldots($$

Q.3. Define Air-Fuel Ratio (A/F) ?

It is the ratio between the mass of the air and mass of the fuel supplied to the engine. It is expressed as

$$A/F = \frac{\dot{m}_a \text{ (mass flow rate of air)}}{\dot{m}_f \text{ (mass flow rate of fuel)}}$$

Q.4 What do you mean by Calorific Value ?

The term 'calorific value' is most commonly used in conjunction with the combustion of fuel. The calorific value of a fuel is defined as the amount of heat energy liberated by complete combustion of unit quantity of a fuel. It is also called heating value of the fuel and it can also be considered as an absolute value of enthalpy of combustion

Q.5 Define Specific Fuel Consumption ?

It is defined as the ratio of the mass of fuel consumed per hour per unit power output (BP). It is also designated as Bsfc (brake specific fuel consumption). It is a parameter which decides the economical power production from an engine

CHAPTER-2(Air Compressor)

Function of a compressor:-

The function of a compressor is to take a definite quantity of fluid (usually a gas, often air) and deliver it at a required pressure.

An air compressor is a pneumatic device that **converts power (using an electric motor, diesel or gasoline engine, etc.) into potential energy stored in pressurized air (i.e., compressed air)**

Reciprocating type – low mass flow rate (kg/s) and high pressure ratio

Rotary type – high mass rate but low pressure ratio.

Industrial use of compressor air:-

Heavy-duty industrial air compressors are capable of operating at higher pressure levels than commercial units. Consequently, they rely on higher horsepower motors and heavier-duty components. Typical industrial air compressor uses include spraying crops and ventilating silos in agricultural facilities, running pneumatic machinery in manufacturing plants, operating laundry presses in dry cleaners and various processes in food and beverage manufacturing, oil and gas operations and more.

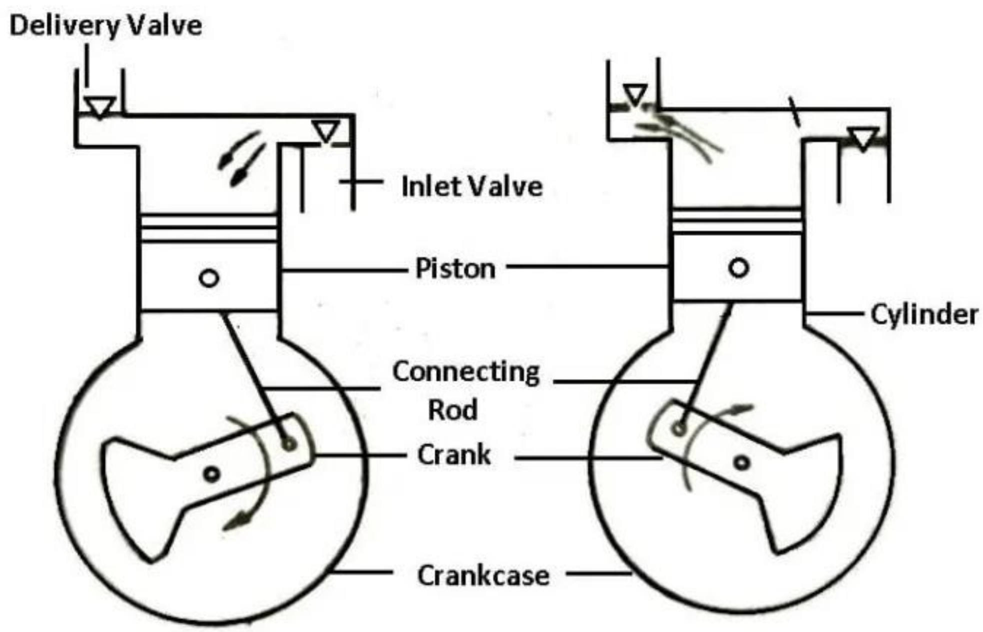
Classify air compressor:-

The four most common types of air compressors you will see are:

- Rotary Screw Compressor.
- Reciprocating Air Compressor.
- Axial Compressor.
- Centrifugal Compressor.

. Reciprocating Air Compressor

- A reciprocating air compressor is a type of positive displacement compressor that uses a piston. The piston is driven by the crankshaft to transfer the high-pressure gases into the cylinder.



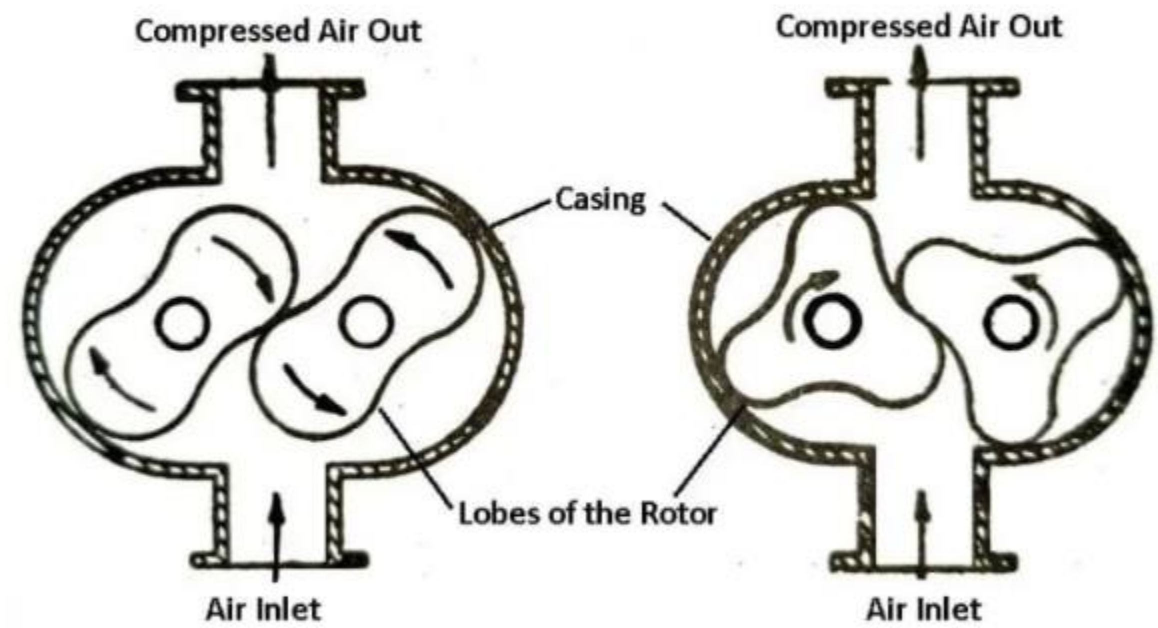
Reciprocating Air Compressor

- In these types of air compressors, initially, the gas enters from the suction manifold. This gas is flowing through a compression cylinder where it gets compressed by an attached piston. It is driven in a reciprocating motion by the application of a crankshaft, and it is released.
- A typical reciprocating compressor is commonly used in automotive industries to generate 5 to 30 horsepower. A large type of reciprocating compressor creates up to 1000 horsepower that equals 750 KW, and it is used in the large petroleum industry.

When compared to a regular diaphragm compressor, it has a longer lifespan and requires quiet maintenance because of continuous use. A reciprocating compressor is used in gas pipelines, chemical plants, air conditioning, and refrigeration plants.

Rotary Air Compressor:-

A rotary air compressor, which is the simplest compressor, consists of two rotors with lobes rotating in an air-tight casing that has an inlet and outlet ports. Its action resembles that of a gear pump.



Rotary Air Compressor

There are many designs of a wheel, but they generally have two or three lobes. The lobes are made that they provide an air-tight joint at their point of contact.

Mechanical energy is provided from one external source to one of the rotors, while the second gear is driven in advance. As the rotors rotate, the air at atmospheric pressure is trapped in the pockets formed between the lobes and casing.

The rotary motion of the lobes delivers the entered air into the receiver. Thus greater flow of air in the receiver increases its pressure. Finally, the air is delivered from the receiver at high pressure.

Centrifugal Air Compressor:-

A centrifugal blower compressor is a common type, has a rotor (or impeller), in which several types of curved vanes are arranged symmetrically. The rotor revolves in an air-tight casing with inlet and outlet points.

These types of air compressors, the casing for the compressor is so designed that the kinetic energy of the air is converted into pressure energy before it leaves the casing as shown in the figure. Mechanical energy is given to the rotor from an external source.

As the rotor rotates, it absorbs air through its eye, increases its pressure due to centrifugal force, and pushes air to flow across the diffuser. The air pressure increases further during its flow on the diffuser.

Finally, the air at high pressure is delivered to the receiver. It would remain interesting to know that air enters the impeller radially and discharge the vane axially.

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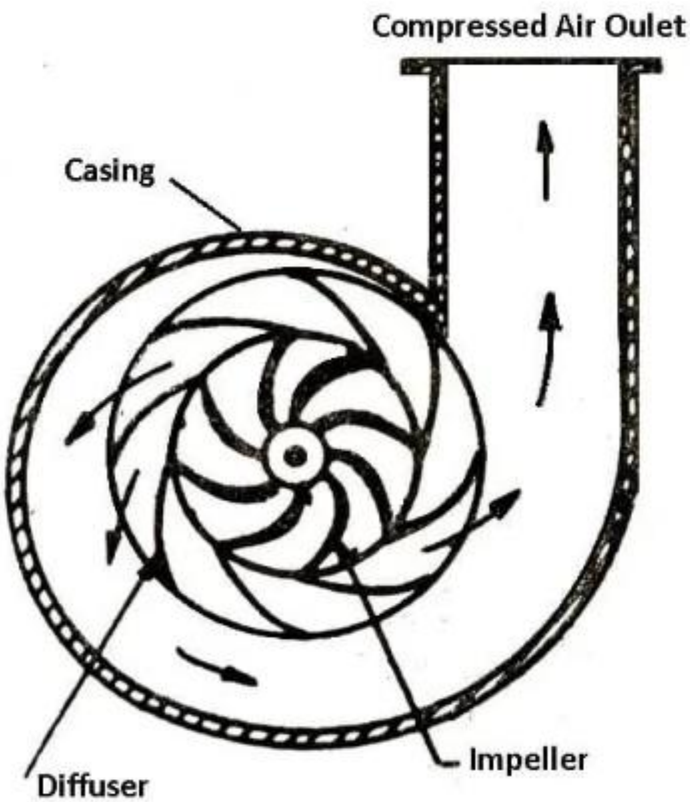
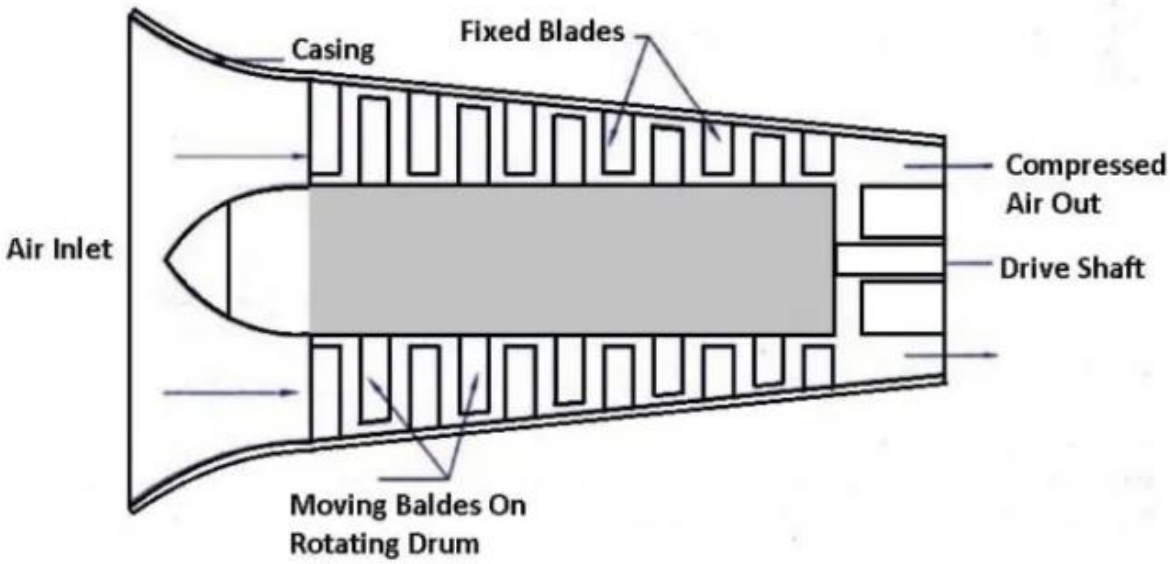


Centrifugal Air Compressor

Axial Air Compressor:-

An axial-flow compressor, in its simplest form, has a number of rotating blades attached to a revolving drum. The drum rotates inside an air-tight casing to which are fixed stator blade rows as shown in the figure



Axial Flow Air Compressor

The blades are produced of an aerofoil section to lower the loss created by turbulence and boundary separation. Mechanical energy is given to the rotating shaft, which turns the drum.

The air comes from the left side of the compressor. As the drum begins to rotate, air flows through the arranged stator and rotor. As the air flows from one set of stators and rotors to another, it gets compressed.

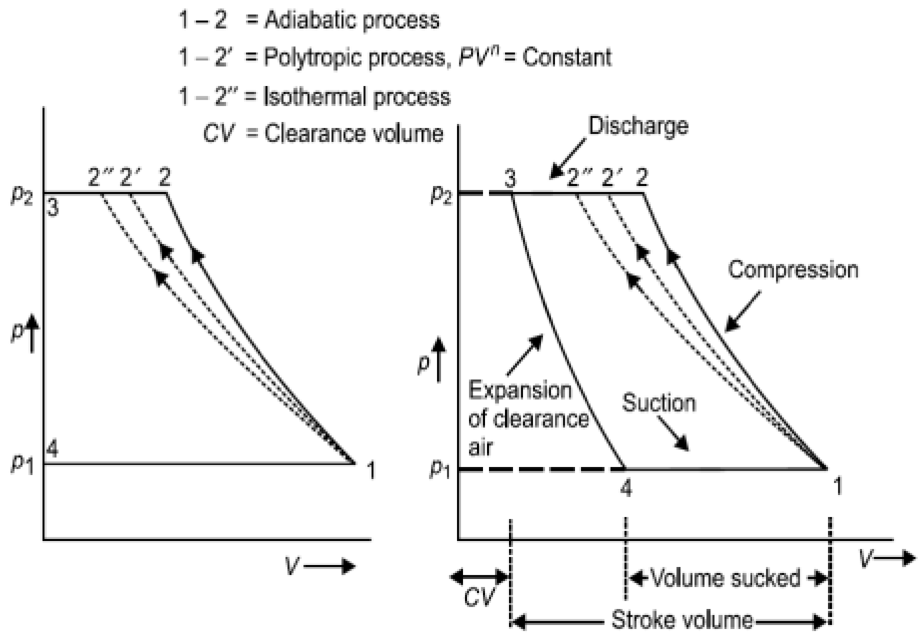
Thus successive compression of the air, in all the sets of stator and rotor, the air is delivered at high pressure at the outlet point.

Thermodynamic Analysis of Reciprocating Compressor

Compression of air in compressor may be carried out in three different ways of thermodynamic processes such as isothermal compression, polytropic compression or adiabatic compression. Figure (2) shows the thermodynamic cycle involved in compression. Clearance volume is provided in reciprocating compressor. Purpose of clearance volume in cylinder is twofold. One is to accommodate valve mechanism and another one is to prevent collision of piston with cylinder head. On p-V diagram process 4–1 shows the suction process followed by compression during 1–2, discharge process 2–3 and expansion of clearane air 3-4 (if clearance volume is provided). Fig. (2) Compression cycle on p-V diagram

(a) without clearance volume

(b) with clearance volume



(a) (b)

Fig. (2) Compression cycle on p-V diagram (a) without clearance volume (b) with clearance volume

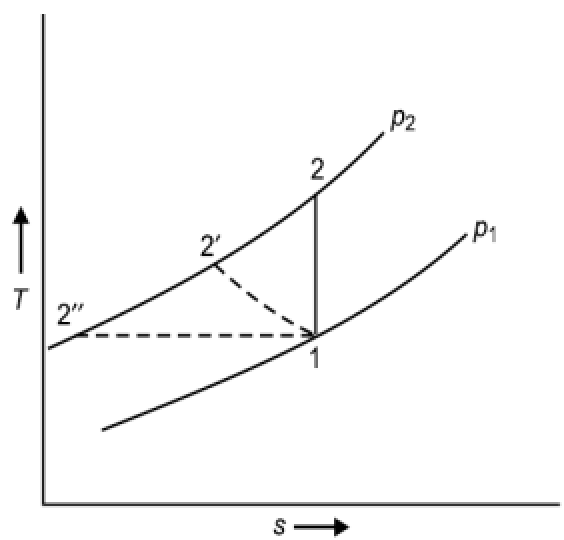


Fig. (3) Compression process on T-S diagram.

Compression Work, $\boldsymbol{WC}$ (without clearance volume)- Assuming compression process follow polytropic process i.e. $pV\ n$ = C

$$W_c = \text{Area on } p\text{-}V \text{ diagram}$$

$$= \left[p_2V_2 + \left(\frac{p_2V_2 - p_1V_1}{n-1}\right)\right] - p_1V_1$$

$$= \left(\frac{n}{n-1}\right)[p_2V_2 - p_1V_1]$$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\frac{p_2V_2}{p_1V_1} - 1\right]$$

$$W_c = \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$\boxed{W_c = \left(\frac{n}{n-1}\right)(mRT_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]}$$

or,

$$\boxed{W_c = \left(\frac{n}{n-1}\right) mR\,(T_2 - T_1)}$$

In case of compressor having isothermal compression process, $n=1$ i.e. $p_1V_1 = p_2V_2$

$$W_{c,\ \text{iso}} = p_2V_2 + p_1V_1 \ln r - p_1V_1$$

$$W_{c,\ \text{iso}} = p_1V_1 \ln r, \text{ where } r = \frac{V_1}{V_2}$$

In case, compressor follow adiabatic compression process, $n = \gamma$

$$\boxed{W_{c,\ \text{adiabatic}} = \left(\frac{\gamma}{\gamma-1}\right) mR\,(T_2 - T_1)}$$

$$W_{c,\ \text{adiabatic}} = mC_p\,(T_2 - T_1)$$

$$\boxed{W_{c,\ \text{adiabatic}} = m\,(h_2 - h_1)}$$

Hence isothermal efficiency

$$\eta_{iso} = \frac{p_1 V_1 \ln r}{\left(\frac{n}{n-1}\right)(p_1 V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]}$$

Compression Work, WC (with clearance volume)-

With clearance volume the cycle is represented on Fig. (2-b). The work done for compression of air polytropically can be given by the area enclosed in cycle 1–2–3– 4

$$W_{c,\text{ with CV}} = \text{Area}1234$$

$$= \left(\frac{n}{n-1}\right)(p_1 V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] - \left(\frac{n}{n-1}\right)(p_4 V_4)\left[\left(\frac{p_3}{p_4}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(p_1 V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] - \left(\frac{n}{n-1}\right)(p_1 V_4)\cdot\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$(\because\ p_1 = p_4 \ \&\ p_2 = p_3)$$

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right) p_1 \cdot \left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] \cdot (V_1 - V_4)$$

This $(V_1 - V_4)$, say V_d, is actually the volume of air inhaled in the cycle and delivered subsequently.

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right) p_1 V_d \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Assuming air behaves as a perfect gas. Now temperature and pressure can be related as

$$\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} = \frac{T_2}{T_1} \qquad \text{And} \qquad \left(\frac{p_4}{p_3}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3} \Rightarrow \left(\frac{p_1}{p_2}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3}$$

Substituting,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_4)\left[\frac{T_2}{T_1} - 1\right]$$

Ideally there shall be no change in temperature during suction and delivery i.e. $T_1 = T_4$ & $T_2 = T_3$. Above equation can be written as

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_1)\left[\frac{T_2 - T_1}{T_1}\right]$$

Or,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)(m_1 - m_2)\,R(T_2 - T_1)$$

Where $(m_1 - m_2)$ indicates the mass of air sucked or delivered. For unit mass of air delivered the work done per kg of air can be given as,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right)R(T_2 - T_1), \text{ per kg of air}$$

Thus from above expressions it is obvious that the clearance volume reduces the effective swept volume i.e. the mass of air handled but the work done per kg of air delivered remains unaffected.

Power required to run the compressor

For single acting compressor,

$$\text{Power required} = \left[\left(\frac{n}{n-1}\right)p_1(V_1 - V_4)\left\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right\}\right] \times N$$

$$\text{for double acting compressor, power} = \left[\left(\frac{n}{n-1}\right)p_1(V_1 - V_4)\left\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right\}\right] \times 2N$$

The terminology of reciprocating compressor

Bore:- The bore is the diameter of the circular opening at its end

Stroke:- The stroke, on the other hand, is the depth of the hole

FAD (Free Air Delivery) :- It is the actual quantity of compressed air converted back to the inlet conditions of the compressor.

it is a standardized measure of the capacity of an air compressor

VOLUMETRIC EFFICIENCY::-

Volumetric efficiency of compressor is the measure of the deviation from volume handling capacity of compressor.

Mathematically, the volumetric efficiency is given by the ratio of actual volume of air sucked and swept volume of cylinder.

$$\text{Overall volumetric efficiency} = \frac{\text{Volume of free air sucked in cylinder}}{\text{Swept volume of LP cylinder}}$$

$$(\text{Volumetric efficiency})_{\text{free air condition}} = \frac{\text{Volume of free air sucked in cylinder}}{(\text{Swept volume of LP cylinder})_{\text{free air condition}}}$$

1.A single stage reciprocating compressor takes 1m^3 of air per minute at 1.013 bar and 15^{o}C and delivers it at 7 bar. Assuming that the law of compression is $P_v^{1.35}$= constant, and the clearance is negligible, calculate the indicated power?

Solution

Volume of air taken in, $V_1 = 1\ m^3/\ min$

Intake pressure, $p_1 = 1.013$ bar

Initial temperature, $T_1 = 15 + 273 = 288$ K

Delivery pressure, $P_2 = 7$ bar

Law of compression: $P_V^{1.35} = \text{constant}$

Indicated power I.P.:

Mass of air delivered per min.,

$$m = \frac{p_1 v_1}{RT_1} = \frac{1.013 \times 10^5 \times 1}{287 \times 288} = 1.266 kg / \min$$

Delivery temperature, $T_2 = T_1 \left(\frac{p2}{p1} \right)^{(n-1/n)}$

$$= 288 \left(\frac{7}{1.013} \right)^{(1.35-1)/1.35} = 475.2K$$

Indicated work $= \frac{n}{n-1} mR(T_2 - T_1) kJ / \min$

$$= \frac{1.35}{1.35-1} \times 1.226 \times 0.287(475.2 - 288 = 254 kJ / \min$$

i.e., Indicated power I.P $= \frac{254}{60} = 4.23 kW.(Ans)$

2.An air compressor cylinder has 150mm bore and 150mm stroke and the clearance is 15%. It operates between 1 bar, 27°C and 5 bar. Take polytrophic exponent n=1.3 for compression and expansion processes find?

i. **Cylinder volume at the various salient points of in cycle.**
ii. **Flow rate in m³/min at 720 rpm and .**
iii. **The deal volumetric efficiency.**

Given

$D = 150\times10^{-3}m$ $\quad$ $P_2 = 5\times10^5\ N/m^2$

$L = 150\times10^{-3}\ m$ $\quad$ $T_1 = 27+273 = 300K$

$V_c = 0.15V_s$ $\quad$ $N = 720rpm$

$P_1 = 1\times10^5\ N/m^2$ $\quad$ $pv^n = C n=1.3$

Find

i. V_1, V_2, V_3, V_4
ii. FAD (V_a)
iii. η_v

Solution

$V_1 = V_c + V_s$

$$V_s = \frac{\pi}{4}D^2L.N = \frac{\pi}{4}(0.15)^2\times.0.15\times720 = 1.9085m^3/\min$$

$V_c = 0.15\ V_s$

$= 0.15\times1.9085$

$V_c = 0.2862\ m^3/min$

$V_1 = V_c + V_s$

$= 0.2862 + 1.9085$

$V_1 = 2.1948$

m^3/min

$P_1V_1^n = P_2V_2^n$

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{1/n}$$

$V_4 = 0.98674\ m^3/min$

$\therefore$ Volumetric efficiency (η_v) = $1+k-k\left(\frac{P^2}{P_1}\right)^{1/n}$

k= Clearance Raito = $\frac{V_c}{V_s} = \frac{0.2862}{1.9085}$

K =0.1499

$\therefore\ \eta_v = 1+0.1499 - 0.1499\left[\frac{5}{1}\right]^{1/1.3}$

$\eta_v = 0.633 = 63.3\%$

$\eta_v = 63.3\%$

∴WKT

$\eta_v = \frac{FAD}{V_s}$

$\therefore FAD = \eta_v \times V_s$

$= 0.633 \times 1.9085$

FAD = 1.2083 m^3/min

3.Calcute the diameter and stroke for a double acting single stage reciprocating air compressor of 50kW having induction pressure 100 kN/m^2 and temperature 150°C. The law of compression is $PV^{1.2}$ = C and delivery pressure is 500 kN/ m^2. The revolution/sec =1.5 and mean piston speed in 150 m/min. Clearance is neglected.

Given:

Double acting single stage

Compressor

IP = 50kW

$P_1 = 100\times10^3$ N/m^2

$T_1 = 15 + 273 = 288K$

$PV^{1.2} = C \quad \therefore n=1.2$

$P2 = 500\times10^3$ N/m^2

N = 1.5 rps = 1.5×60 rpm

2LN = 150m/min (Double acting)

Find

i. D and L

Solution

For double acting compressor average piston speed = 2LN

$\therefore$ 2LN = 150 m/min

$$\therefore L = \frac{150}{2\times1.5\times60} = 0.833m$$

L = 0.833 m

To Find D

IP = W.N_w

where

N_w = Number of working stroke

For Double acting $N_w = 2N$

For single acting $N_w = N$

$\therefore N_w = 2\times1.5\times60 = 180$ rpm

$$\therefore \text{W.D/cycle} = \frac{n}{n-1}p_1V_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}-1\right]$$

$$=\frac{1.2}{1.2-1}\times 100\times 10^3\left(\frac{\pi}{4}D^2\times 0.833\right)\times\left[\left(\frac{(500)}{100}\right)^{\frac{0.2}{1.2}}-1\right]$$

$W= 120764.2D^2$ N-m

$$\therefore \text{IP}=\frac{W.N_w}{60}$$

$$50\times 10^3=\frac{1207642D^2\times 180}{60}$$

$D^2 = 0.1380$

D=0.371 m

QNA Chapter-2

Q.1 Work of air compressor ?

An air compressor is a machine which takes in atmospheric air, compresses it with the help of some mechanical energy and delivers it at higher pressure.

Q.2. Write four Industrial use of Compressed air ?

Ans:- Compressed air has wide applications in industriesas well as in commercial equipment. It is used in

1. Air refrigeration and cooling of large buildings,

2. Driving pneumatic tools in shops like drills, riveters, screw drivers, etc.

3. Driving air motors in mines, where electric motors and IC engines cannot be used because of fire risks due to the presence of inflammable gases, etc.

4. Cleaning purposes

Q 3 . Write the Classification of Air compressor ?

The compressors are mainly classified as

(i) Reciprocating compressors,

(ii) Rotary compressors.

Q.4 Define the term Pressure Ratio?

Pressure Ratio :- It is defined as the ratio of absolute discharge pressure to absolute suction pressure.

Q.5 Define Free-air delivered ?

It is the discharge volume of the compressor corresponding to ambient conditions

Long questions :-

Q.1 A single-cylinder, double-acting, reciprocating air compressor receives air at 1 bar; 17°C, compresses it to 6 bar according to the law $pV^{1.25}$= constant. The cylinder diameter is 500 mm. The average piston speed is 150 m/min at 250 rpm. Calculate the power required in kW for driving the compressor. Neglect clearance

Q.2 A single-acting, single-cylinder reciprocating air compressor is compressing 30 kg/min. of air from 110 kPa, 30°C to 600 kPa and delivers it to a receiver. Law of compression is is $pV^{1.25}$ = constant Mechanical efficiency is 80%. Find the power input to compressor, neglecting losses due to clearance, leakages and cooling

Q.3 A single-acting, single-cylinder reciprocating air compressor has a cylinder diameter of 200 mm and a stroke of 300 mm. Air enters the cylinder at 1 bar; 27°C. It is then compressed polytropically to 8 bar according to the law $pV^{1.3}$ = constant. If the speed of the compressor is 250 rpm, calculate the mass of air compressed per minute, and the power required in kW for driving the compressor

CHAPTER-3(Properties of Steam)

Difference between Vapor and Gas

Usually, a vapour phase consists of a phase with two different substances at room temperature, whereas a gas phase consists of a single substance at a defined thermodynamic range, at room temperature. Thus, this is defined as the key differences between Vapor and Gas. You can find the major differences in the table below.

Difference between Vapor and Gas	
Vapour	Gas
Vapour is a mixture of two or more different phases at room temperature, these phases are liquid and gaseous phase.	Gas usually contains a single thermodynamic state at room temperature.
Vapour has a collection of particles without any definite shape when observed under a microscope.	Gas does not a definite shape when it is observed under a microscope.
Vapour consists of random molecules and atoms moving randomly about.	Gas also consists of random molecules and atoms moving about randomly.
Vapour is not a state of matter, unlike gases.	Gases are a state of matter.
Vapours of water are around us all the time at temperatures below the boiling point of water.	Gases are usually formed above its critical temperature, but below critical pressure.

FORMATION OF STEAM AND ITS PROPERTIES:-

Introduction:-

Steam, which is gaseous form of pure water, is an excellent working medium in various thermodynamic systems because of its following properties:

1) It can carry large quantities of heat

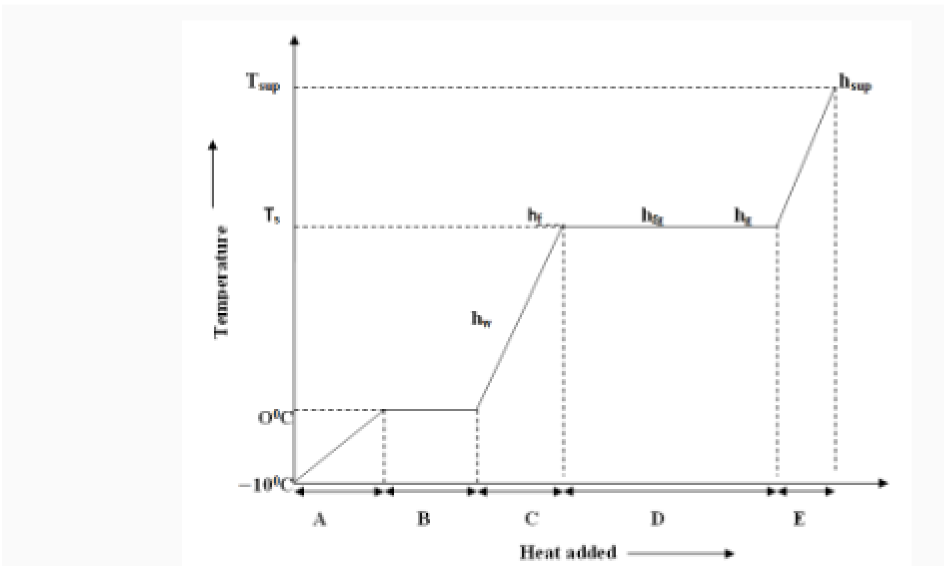
2) It is produced from water which is cheap and readily available

3) It can be used for heating purposes after its duty as working agent is completed.

4) It can be used purely as a heating medium in food processing Industries because of a fast, easily controllable and hygienic method of heating.

Formation of Steam:-

In general, steam can be formed by boiling water in a vessel. But to use it effectively as a working or heating medium, it has to produce in a closed vessel under pressure. Steam formed at a higher pressure has higher temperature and can be made to flow easily through insulated pipes from steam generator to point of use. A simple arrangement of formation of steam at constant pressure



A = Sensible Heat taken by Ice

B= Latent Heat of Fusion

C = Sensible Heat taken by Water

D = Latent Heat of evaporation

E = Sensible Heat taken by Steam

h_w = Specific enthalpy of water

h_f = Specific enthalpy of saturated water

h_{fg} = Latent heat of evaporation

h_g = Specific enthalpy of dry saturated steam

h_{sup} = Specific enthalpy of super heated steam

Temperature enthalpy curve of formation of steam at constant pressure

Consider 1 kg of ice at temperature -10^{0}C which is below the freezing point. Let it be heated at constant pressure P. The temperature of ice starts increasing until it reaches the melting temperature of ice i.e., 0^{0}C and during this course ice absorbs its sensible heat. On further addition of heat, ice starts melting, its temperature remains constant at 0^{0}C and it absorbs latent heat of fusion and converts completely into water at 0^{0}C.

On further addition of heat, the temperature of water starts rising until it reaches the boiling temperature or saturation temperature corresponding to pressure P. This heat absorbed by water in sensible heat.

Note: Saturation temperature or boiling temperature increases with increase in pressure

After the boiling temperature is reached, it remains constant with further addition of heat and vaporization take place. The water absorbs its latent heat and converts into dry saturated steam remaining at same saturation temperature. The intermediate stage of water and dry saturated steam is wet steam, which is actually a mixture of steam and water.

If further the heat is added, the temperature of this dry saturated steam starts rising from saturation temperature and it converts into superheated steam. This heat absorbed is again the sensible heat. The total rise in temperature of superheated steam above the saturation temperature is called degree of superheat. We must know here that the saturation temperature, latent heat and other properties of steam remain same at constant pressure but varies with the variation of pressure.

22.2.1 Advantages of superheated steam

1) The superheated steam can be considerably cooled during expansion in an engine cylinder, before its temperature falls so low as to cause condensation on cylinder walls which is a direct heat loss.

2) The temperature of superheated steam being higher, it gives a high thermal efficiency in heat engine.

3) It has high heat content and so high capacity of doing work. Thus it results in an economy in steam consumption.

Enthalpy of Steam:-

_To find out the total heat content or enthalpy of any state of water/ steam we have to add all types of heat added i.e., sensible and latent to convert the water to that state starting from some initial state or datum which is assumed as a zero enthalpy point or where the heat content is taken as zero. Generally in engineering calculations the datum is water at 0^0C where it is considered as having zero heat content or zero enthalpy. Enthalpy of one kg of water or steam is called as specific enthalpy.

Specific enthalpy of un-saturated water (h_w)

__It is simply the amount of heat required to raise the temperature of one kg of water from 0 °C to its actual temperature which is below its saturation temperature. It can be calculated by multiplying actual temperature of unsaturated water with its specific heat which is considered equal to 4.187 kJ/ kg/ K. It is denoted as h_w.

$$h_w = C_w . t$$

Specific enthalpy of saturated water (h_f):-

_It is the quantity of heat required to raise the temperature of one kg of water at 0^0C to its boiling point or saturation temperature corresponding to the pressure applied. It is denoted as h_f. It can be calculated by multiplying the specific heat of water to the total rise in temperature. The specific heat Cp_w of water may be approximately taken as constant i.e., 4.187 kJ/kg K, but in actual it slightly increases with increase in saturation temperature or pressure.

Latent heat of steam (h_{fg}):-

Latent heat of steam at a particular pressure may be defined as the quantity of heat in kJ required to convert one kg of water at its boiling point (saturated water) into dry saturated steam at the same pressure. It is usually denoted by L or h_{fg}. It decreases with increase in pressure or saturation temperature.

Wet and dry steam:-

_Wet steam is that steam in which the whole of water has not vaporized but the un-vapourized water is present in the form of mist/fog suspended in completely vaporized water or steam. Due to this mist the wet steam is visible. However the dry steam i.e., in which the vaporization is complete is invisible or colorless. Any steam which is completely dry and present at saturation temperature is called dry saturated steam

Dryness fraction:-

This term refers to quality of wet steam. It is defined as the ratio of the weight of dry steam actually presents to the weight of total wet steam which contains it. It is denoted by x

$$x = \frac{W_d}{W_d + W}$$

W_d = Weight of dry steam in 1 kg of wet steam,

W = Weight of water in suspension in 1 kg of wet steam

Dryness fraction is zero for saturated water and one for dry saturated steam.

Wetness fraction:-

It is the ratio of the weight of water/ moisture in suspension in a wet steam sample to the total weight of wet steam. It is calculated by subtracting x from 1

$$wetness\ fraction, (1 - x) = \frac{W}{W_d + W}$$

Specific enthalpy of wet steam (h_{ws}):-

It may be defined as the quantity of heat required to convert 1 kg of water at 0^0C into wet steam of a given quality and at constant pressure. It may be denoted by h_{ws}. It is equal to the sum of specific enthalpy of saturated water and latent heat of dry fraction of steam. So

$$h_{ws} = h_f + x\, h_{fg}.$$

Specific enthalpy of dry saturated steam (h_g):-

t may be defined as the quantity of heat required to convert 1kg of water at 0^0C into dry saturated steam at given constant pressure. It may be denoted by h_g. It is equal to the sum of specific enthalpy of saturated water and latent heat corresponding to given saturation pressure and temperature. Thus

$$h_g = h_f + h_{fg}$$

Specific enthalpy of superheated steam (h_{sup}):-

It is defined as the quantity of heat required to convert 1kg of water at 0^0C into the superheated steam at given temperature and pressure. It may be denoted as h_{sup} and is equal to the sum of specific enthalpy of dry saturated steam and product of specific heat of superheated steam (C_s) to degree of superheat.

$$h_{sup} = h_g + C_s(t_{sup} - t_s)$$

Where, h_g and t_s are the specific enthalpy of dry steam and saturation temperature at corresponding pressure and C_S & t_{sup} are specific heat of superheated steam and temperature of superheated steam at the same pressure.

$$C_S = \frac{h_{sup} - h_g}{t_s - t}$$

The superheated steam behave like the perfect gas and law of expansion has been found to be $pv^{1.3}$ = constant.

Specific Volume of Water/Steam:-

The volume of a unit mass of water/steam is known as its specific volume

Specific volume of saturated water (v_f):-

It is defined as volume of 1kg of water at saturation temperature corresponding to the given pressure. It is denoted by v_f. It can be calculated experimentally. It slightly increases with increase in saturation temperature and hence the pressure. The reciprocal of sp-volume is equal to density.

Specific volume of dry saturated steam (v_g):-

It is defined as volume of 1kg of dry saturated steam corresponding to the given pressure. It is denoted by v_g and can be calculated experimentally. As dry saturated steam is a gas, its specific volume decreases with increase in pressure or the saturation temperature.

Specific volume of wet steam of quantity x:-

It is the volume of 1kg of wet steam and is denoted as

$$v_{ws} = x.v_g + (1-x)\, v_f$$

At low pressure the value of v_f is very small as compared to v_g; so the term $(1-x)\, v_f$ may be neglected. Then volume of 1kg of wet steam = $x.v_g$

Specific volume of Superheated Steam (v_{sup}):-

It is the volume of 1kg of superheated steam and can be determined by assuming that the steam behaves as a perfect gas i.e., obeys the gas laws. It is denoted by v_{sup}

Let P = pressure under which steam is superheated.

t_{sup} =temperature of superheated steam

v_g = Specific volume of dry saturated steam

t_s = saturation temperature at pressure P.

Since, P = constant

Entropy of Steam

Specific entropy of saturated water (s_f):-

The specific entropy of saturated water at a particular pressure P and saturation temperature T_S is given as the change in entropy during conversion of one kg of water at 0^0C into saturated water at that pressure. The water at freezing point 0^0C or 273 K is considered as datum where, absolute entropy is taken as zero. If C_W is specific heat of water then the change in entropy of 1kg water during temperature change from 273 K to T K is given as

$$s_w = C_W \log_e \frac{T}{273}$$

As the Initial entropy at 273 K is zero, so this change in entropy above 273 K is taken as entropy of water at temperature T. In case of Saturated Water, T= T_S.

Change in specific entropy during evaporation, (S_{fg}):-

During evaporation heat added = h_{fg} = Latent heat of water

Temperature remains constant during evaporation and is equal to saturation Temperature T_S.

Specific entropy of dry saturated steam (s_g):-

It is the entropy of one kg of dry saturated steam and is given as the sum of entropy of 1kg of saturated water and entropy change during evaporation. It is denoted by s_g.

Thus $s_g = s_f + s_{fg}$

Specific entropy of wet steam:-

It is the sum of specific entropy of dry saturated steam and entropy change during superheating from saturation temp T_S to superheated temp T_{sup}.

Change in entropy during superheating

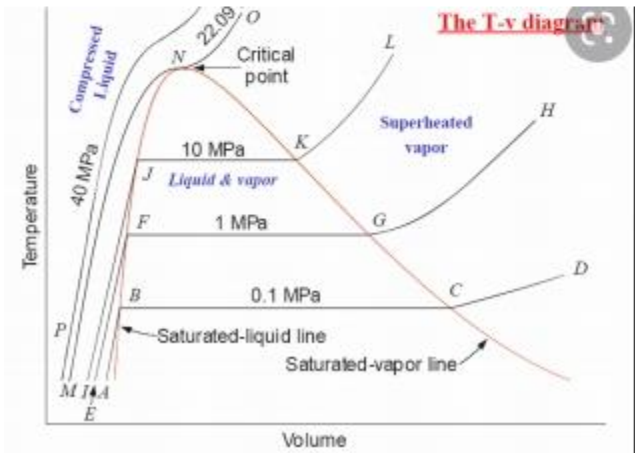
$$= C_{sup} \log_e \frac{T_{sup}}{T_s} \quad where, C_{sup} = Sp. heat\ of\ super\ heated\ steam$$

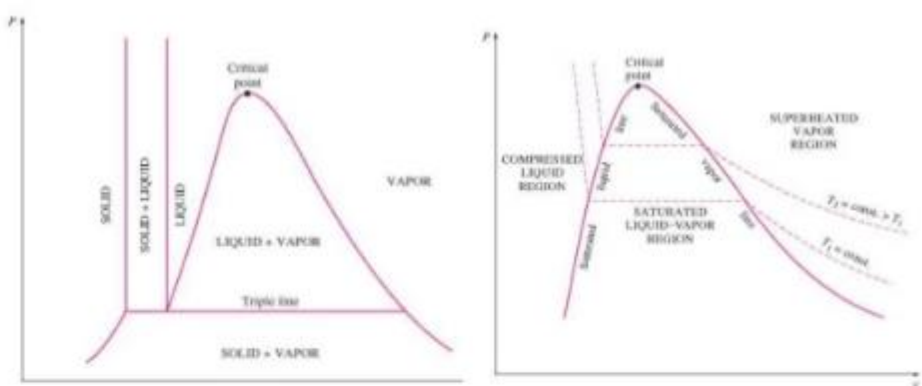
Total specific entropy of superheated steam

$$s_{sup} = s_g + c_{sup} \log_e \frac{T_{sup}}{T_s}$$

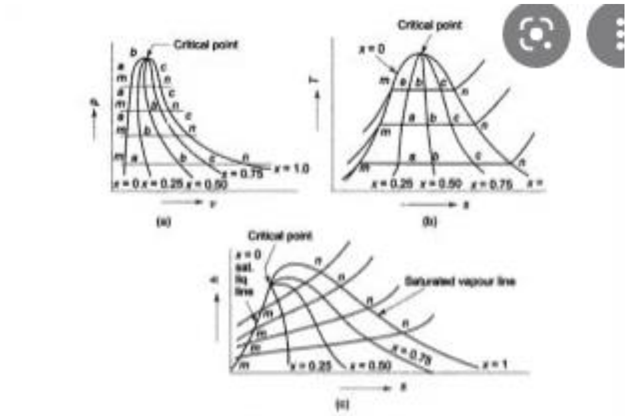
$$= s_f + \frac{h_{fg}}{T_s} + C_{sup} \log_e \frac{T_{sup}}{T_s}$$

Representation on P-V, T-S, H-S, & T-H diagram.





P-V diagram



Constant quality lines

Q.1 Calculate volume, density, enthalpy, and entropy of 2 kg of steam at 80°C and having a dryness fraction of 0.85.

Given Wet steam

$m = 2$ kg $\quad T = 80°C \quad x = 0.85$

To find

(i) Volume, (ii) Density,

(iii) Enthalpy, ad (iv) Entropy.

Properties of water At 80°C;

$p_{sat} = 47.39$ kPa $\quad v_f = 0.001029$ m^3/kg

$v_g = 3.40715$ m^3/kg $\quad h_f = 334.88$ kJ/kg

$h_{fg} = 2308.77$ kJ/kg·K $\quad s_f = 1.0752$ kJ/kg·K

$s_{fg} = 6.5369$ kJ/kg·K

(i) At 80°C, the specific volume of steam;

$$v = (1-x)v_f + x v_g \approx x v_g$$
$$= 0.85 \times 3.40715 = 2.896 \text{ m}^3/\text{kg}$$

For $m = 2$ kg;

$$V = m\,v = 2 \times 2.896 = \mathbf{5.792\ m^3}$$

(ii) The density of steam;

$$\rho = \frac{1}{v} = \frac{1}{2.896} = \mathbf{0.345\ kg/m^3}$$

(iii) Specific enthalpy of steam;

$$h_{wet} = h_f + x\,h_{fg} = 334.88 + 0.85 \times 2308.77$$
$$= 2297.33 \text{ kJ/kg}$$

Total enthalpy

$$H = m\,h_{wet} = 2 \times 2297.33 = \mathbf{4594.66\ kJ}$$

(iv) Specific entropy of steam;

$$s_{wet} = s_f + x\,s_{fg} = 1.0752 + 0.85 \times 6.5369$$
$$= 6.631 \text{kJ/kg}\cdot\text{K}$$

Total entropy

$$S = m\,s_{wet} = 2 \times 6.631 = \mathbf{13.26\ kJ/K}$$

Q.2 Calculate volume, density, enthalpy, and entropy of 2 kg of water at 2 bar and 80°C. ?

To find

(i) Volume, (ii) Density,

(iii) Enthalpy, ad (iv) Entropy.

Assumption The specific heat of water as 4.187 kJ/kg·K.

Properties of water At $T = 80°C$

$$p_{sat} = 47.39 \text{ kPa}$$
$$v_f = 0.001029 \text{ m}^3\text{/kg}$$

Analysis At 80°C, water pressure is 2 bar, thus it is compressed liquid.

(i) At 80°C, the specific volume of water

$$v_f = 0.001029 \text{ m}^3\text{/kg}$$

For $m = 2$ kg;

$$V = m\,v_f = 2 \times 0.001029 = \mathbf{0.002058\ m^3}$$

(ii) The density of water

$$\rho = \frac{1}{v_f} = \frac{1}{0.001029} = \mathbf{971.82\ kg/m^3}$$

(iii) The enthalpy of water

$$H = m C_{pw} (T_{water} - 0)$$
$$= 2 \times 4.187 \times (80°C - 0) = \mathbf{669.92\ kJ}$$

(iv) Entropy of water

$$S = m C_{pw} \ln\left(\frac{T_{water} + 273}{0 + 273}\right)$$
$$= 2 \times 4.187 \times \ln\left(\frac{80 + 273}{0 + 273}\right) = \mathbf{2.152\ kJ/K}$$

QNA Chapter-3

Q.1 Write Difference between gas and steam ?

The main difference between steam and gas is that the steam state of a substance in which evaporation is not compete from its liquid state .Gas is a state in which there is complete vaporization of the liquid .It is a gaseous state .

Q.2 . Define Vaporisation ?

It is the process that involves change of phase from liquid to vapour, when the latent heat of phase change is supplied to saturated water.

Q.3 What is Evaporation ?

It is the process of vapour generation only at the free surface of the liquid. The molecules at the free surface extract their latent heat of phase transformation from the surrounding medium and break away as vapour from the liquid surface and escape to the surrounding atmosphere

Q.4 Define Triple Point ?

A locus on the p–T diagram, where all three phases of water coexist. Q.5 What is Critical Point ? Ans:- A locus on the saturation curve, where saturation liquid line and saturated vapour line meet

Long Questions

Q.1 Identify the type of steam in the following three cases, using the steam tables and giving necessary calculations supporting your claim. 5 kg of steam at 8 bar with an enthalpy of 5538.0 kJ at a temperature of 170.4°C

Q.2 . Calculate volume, density, enthalpy, and entropy of 5 kg of water at 2 bar and 80°C. ? Hint – See Solution no 2 of ch.3 Q.3 Calculate volume, density, enthalpy, and entropy of 2 kg of steam at 80°C and having a dryness fraction of 0.85.

CHAPTER-4(Steam Generator)

Steam Generator:-

A boiler is a closed vessel in which fluid (generally water) is heated. The fluid does not necessarily boil. The heated or vaporized fluid exits the boiler for use in various processes or heating applications, including water heating, central heating, boiler-based power generation, cooking, and sanitation

The equipment used for producing steam is called **Boiler** or Steam Generator. Or it is also defined as " A closed vessel in which steam is produced from water by the combustion of fuel."

The steam generated is used for:

- Power generation
- Heating
- Utilization in industries like chemical industries, sugar mills, etc.

Classification & types of Boiler:-

The boilers may be classified as follows:

1. Horizontal, Vertical and Inclined Boilers
2. Externally Fired and Internally Fired
3. Fire-tube boiler and Water-tube boiler.
4. Natural circulation and Forced Circulation
5. High Pressure and Low-Pressure boilers
6. Stationary and Portable boilers
7. Single tube and Multitube boilers.

The explanation of the above types of boilers is as follows.

1. Horizontal, Vertical, and Inclined Boilers:

- If the axis of the boiler is horizontal, then the boiler is of *horizontal type*.
- If the axis of the boiler is vertical, then it is called a *vertical boiler.*
- If the axis of the boiler is inclined, then it is called an *inclined boiler.*

The parts of a horizontal boiler can be inspected and repaired easily. But, it occupies more space and the vertical boiler occupies less floor area.

2. Externally Fired and Internally Fired Boilers

- The boiler is known as **externally fired boiler** if the fire is outside the shell.

For example, Babcock and Wilcox Boiler.

- In the case of internally fired boilers, the furnace is located inside the boiler shell.

For example, Cochran, Lancashire boiler, etc.

3. Fire-tube boiler and Water-tube boiler:

- In the fire tube boilers, the hot gases are inside the tubes and the water surrounds the tubes.

For Example, Cochran, Lancashire boiler, etc.

- In the water tube boilers, the water is inside the tubes and hot gases around them

For example, Babcock and Wilcox Boiler.

4. Natural circulation and Forced Circulation:

- In forced Circulation type of boilers, the circulation of water is done by a forced pump.

For example, Lamont Boiler, Benson Boiler, etc.

- In the natural circulation type of boilers, the circulation of water in the boiler takes place due to the natural convection currents produced by the application of heat.

Ex: Lanarkshire, Babcock and Wilcox boiler.

5. High Pressure and Low-Pressure boilers:

High-Pressure Boilers:

The boilers which produce steam at pressures of 80 bar and above are called high-pressure boilers.

For example, Babcock and Wilcox, Lamont, Benson boilers.

Low-Pressure Boilers:

The boilers which produce steam at a pressure below 80 bar are called low-pressure boilers.

For example, Cochran, Lancashire, and locomotive boiler.

6. Stationary and Portable Boilers:

- Primarily, the boilers are classified as either stationary or mobile(marine and Locomotives)

Stationary boilers are used for power plant steam for Central station utility power plants.

Portable Boilers:

Portable or mobile boilers include the locomotive type and other small units for temporary usage at sites(Just as in small coal-field pits).

7. Single tube and Multi-tube Boilers:

- If a fire tube is just one, then it is called a Single tube boiler.

For example, Cornish, Simple Vertical Boiler.

- If fire tubes are more than one, they are called as Multi-tub

Important terms of Boiler

Shell :-

The shell of a boiler consists of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell ends are closed with the end plates.

Setting:-

The primary function of setting is to confine heat to the boiler and form a passage for gases. It is made of brickwork and may form the wall of the furnace and the combustion chamber. It also provides support in some types of boilers (e.g., Lancashire boilers).

Grate:-

It is the platform in the furnace upon which fuel is burnt and it is made of cast iron bars. The bars are so arranged that air may pass on to the fuel for combustion. The area of the grate on which the fire rests in a coal or wood fired boiler is called grate surface.

Furnace:-

It is a chamber formed by the space above the grate and below the boiler shell, in which combustion takes place. It is also called a fire box.

Water space and steam space :-

The volume of the shell that is occupied by the water is termed water space while the entire shell volume less the water and tubes (if any) space is called steam space.

Mountings:-

The items such as stop valve, safety valves, water level gauges, fusible plug, blow-off cock, pressure gauges, water level indicator etc. are termed as mountings and a boiler cannot work safely without them.

Accessories:-

The items such as superheaters, economisers, feed pumps etc. are termed as accessories and they form integral part of the boiler. They increase the efficiency of the boiler.

Water level :-

The level at which water stands inthe boiler is called water level. The space above the water level is called steam space.

Foaming :-

Formation of steam bubbles on the surface of boiler water due to high surface tension of the water.

Scale :-

A deposit of medium to extreme hardness occurring on water heating surfaces of a boiler because of an undesirable condition in the boiler water.

Blowing off :-

The removal of the mud and other impurities of water from the lowest part of the boiler (where they usually settle) is termed as 'blowing off'. This is accomplished with the help of a blow off cock or valve.

Lagging:-

Blocks of asbestos or magnesia insulation wrapped on the outside of a boiler shell or steam piping.

Refractory:- A heat insulation material, such as fire brick or plastic fire clay, used for such purposes as lining combustion chambers.

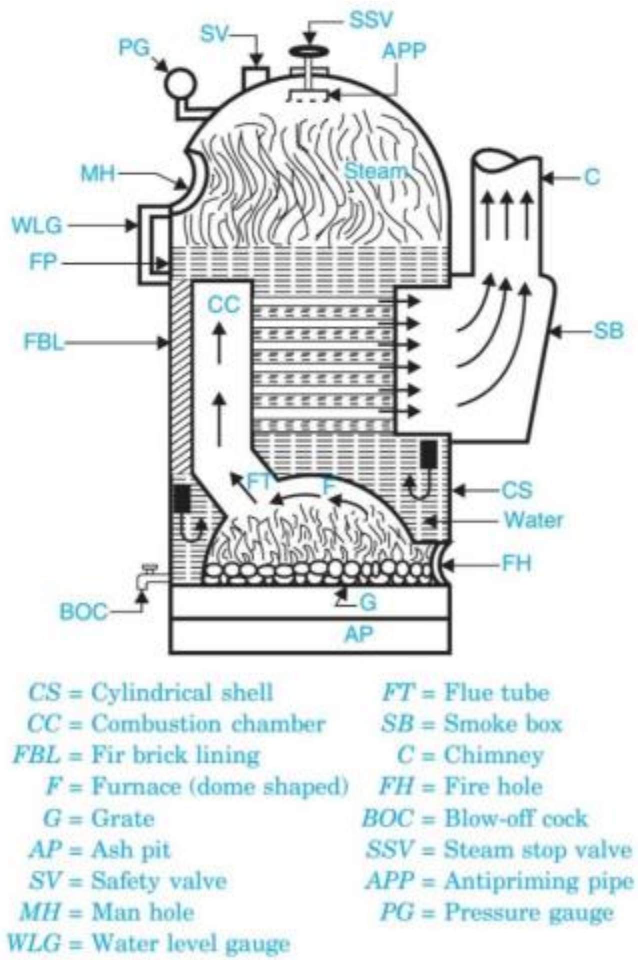
Difference Between Fire Tube Boiler and Water Tube Boiler

FIRE TUBE BOILER	WATER TUBE BOILER
Hot flue gases flow inside the tube and the water outsides the tubes.	Water flows inside the turbine and hot flue gases outside the tube.

FIRE TUBE BOILER	WATER TUBE BOILER
These boilers are generally internally fired.	These boilers are generally extra really fired.
The boiler pressure limited to 20 bar.	The boiler pressure is limited to up to 100 bar.
The fire-tube boiler has a lower rate of steam production.	A higher rate of steam production.
Not suitable for larger power plants.	Suitable for larger power plants.
Involves lesser risk of explosion due to low pressure.	The risk of the explosion is higher due to high boiler pressure.
For a given power, it occupies large floor space.	For a given power, it occupies small floor space.
This boiler is difficult to construct.	Simple in construction.

Description & Working of Common boilers (Cochran ,Lancashire ,Babcock & Wilcox Boiler)

Cochran Boiler :-



Cochran Boiler

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

• 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. 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.

• A number of hand-holes are provided around the outer shell for cleaning purposes.

The various boiler mountings shown in Fig. above are :

- Water level gauge
- Safety valve,
- Steam stop valve
- Blow off cock
- Manhole
- Pressure gauge.

Lancashire boiler:-

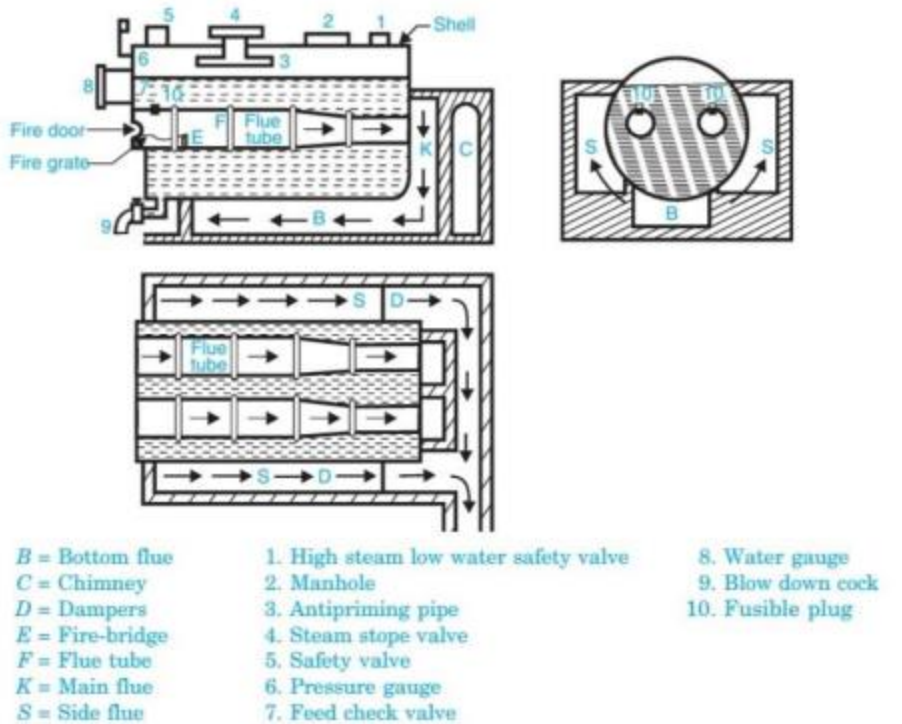
• This boiler is reliable, has simplicity of design, ease of operation and less operating and maintenance costs.

• It is commonly used in sugar-mills and textile industries where along with the power steam and steam for the process work is also needed.

• In addition this boiler is used where larger reserve of water and steam are needed

• The Lancashire boiler consists of a cylindrical shell inside which two large tubes are placed.

• The shell is constructed with several rings of cylindrical from and it is placed horizontally over a brick work which forms several channels for the flow of hot gases.



Lancashire boiler

- These two tubes are also constructed with several rings of cylindrical form.
- They pass from one end of the shell to the other and are covered with water.
- The furnace is placed at the front end of each tube and they are known as furnace tubes.
- The coal is introduced through the fire hole into the grate.
- There is low brickwork fire bridge at the back of the gate to prevent the entry of the burning coal and ashes into the interior of the furnace tubes.

• The combustion products from the grate pass up to the back end of the furnace tubes and then in downward direction. Thereafter they move through the bottom channel or bottom flue up to the front end of the boiler where they are divided and pass up to the side flues.

• Now they move along the two side flues and come to the chimney flue from where they lead to the chimney.

• To control the flow of hot gases to the chimney, dampers (in the form of sliding doors) are provided.

• As a result the flow of air to the grate can be controlled.

Babcock and wilcox water tube boiler :-

• The water tube boilers are used exclusively, when pressure above 10 bar and capacity in excess of 7000 kg of steam per hour is required.

• Babcock and Wilcox water tube boiler is an example of horizontal straight tube boiler and may be designed for stationary or marine purposes.

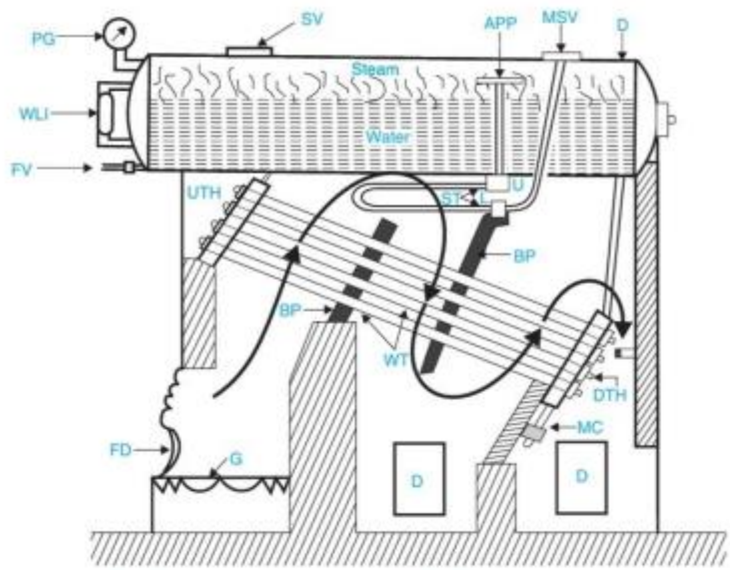
• Fig. above shows a Babcock and Wilcox boiler with longitudinal drum.

• It consists of a drum connected to a series of front end and rear end headers by short riser tubes.

• To these headers are connected a series of inclined water tubes of solid drawn mild steel.

• The angle of inclination of the water tubes to the horizontal is about 15° or more.

• A hand hole is provided in the header in front of each tube for cleaning and inspection of tubes.



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

Babcock and wilcox water tube boiler

• A feed valve is provided to fill the drum and inclined tubes with water the level of which is indicated by the water level indicator.

• Through the fire door the fuel is supplied to grate where it is burnt.

• The hot gases are forced to move upwards between the tubes by baffle plates provided.

• The water from the drum flows through the inclined tubes via down take header and goes back into the shell in the form of water and steam via uptake header.

• The steam gets collected in the steam space of the drum.

• The steam then enters through the anti priming pipe and flows in the superheater tubes where it is further heated and is finally taken out through the main stop valve and supplied to the engine when needed.

• At the lowest point of the boiler is provided a mud collector to remove the mud particles through a blow-down cock.

• The entire boiler except the furnace are hung by means of metallic slings or straps or wrought iron girders supported on pillars.

• This arrangement enables the drum and the tubes to expand or contract freely.

• The brickwork around the boiler encloses the furnace and the hot gases.

Boiler Draught :-

Boiler Draught:-

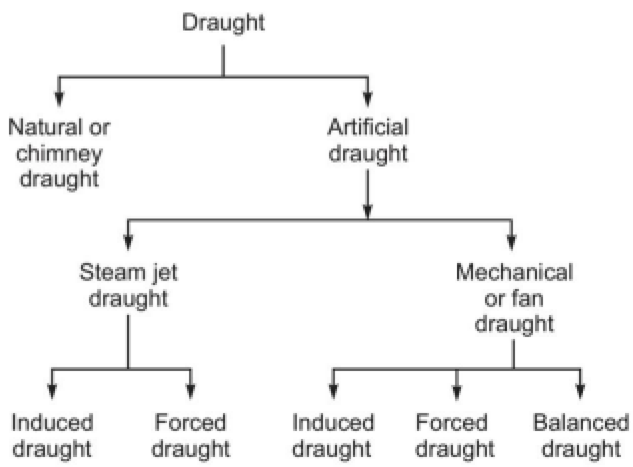
The boiler draught may be defined as the small pressure difference which causes the continuous flow of gases inside the boiler. In other words, the draught is a small pressure difference between the air outside the boiler and gases within the furnace or chimney.

Function of Draught :-

It forces a sufficient quantity of air into the furnace for proper combustion of fuel.

It circulates the hot flue gases through the flue tubes, superheater, economiser, air preheater etc.

It discharges the hot flue gases to the atmosphere through the chimney



Draught produced by a fan or blower may be of three types:

(a) induced

(b) forced

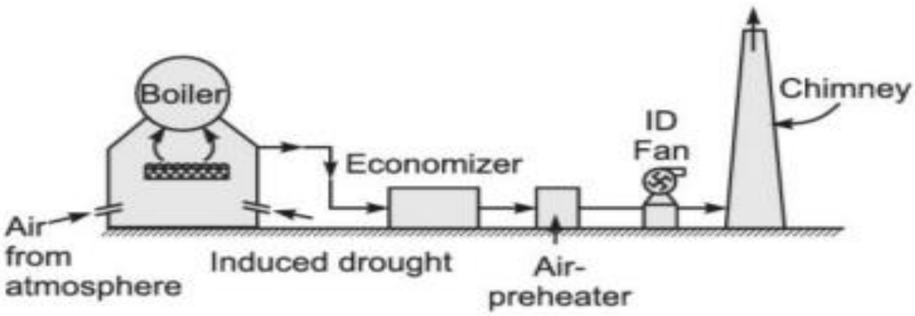
(c) balanced draught.

Induced draught :-

The fan is placed near the base of the chimney as shown in Fig.

The fan draws the flue gases from the furnace. So the pressure above the fuel bed is reduced below the atmospheric pressure.

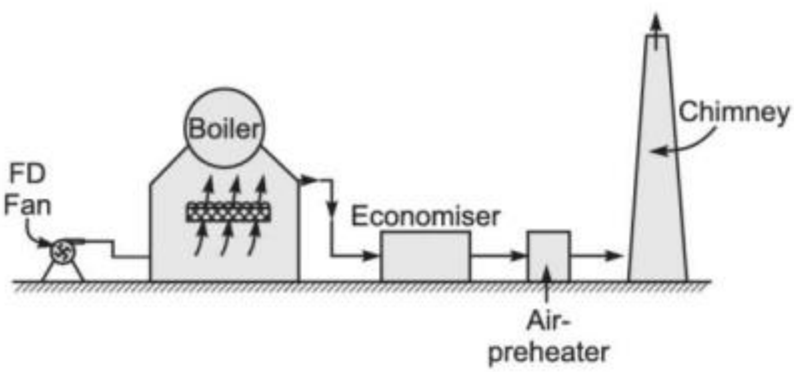
The fresh air rushes to the furnace and after combustion, the flue gases get discharged through the chimney in the atmosphere..



Forced Draught :-

The fan or blower is located near or at the base of the boiler grate to force atmospheric air on to the furnace under pressure.

This pressure helps in circulation of flue gases through components of the boiler and then through chimney to atmosphere. It is shown in above Fig.

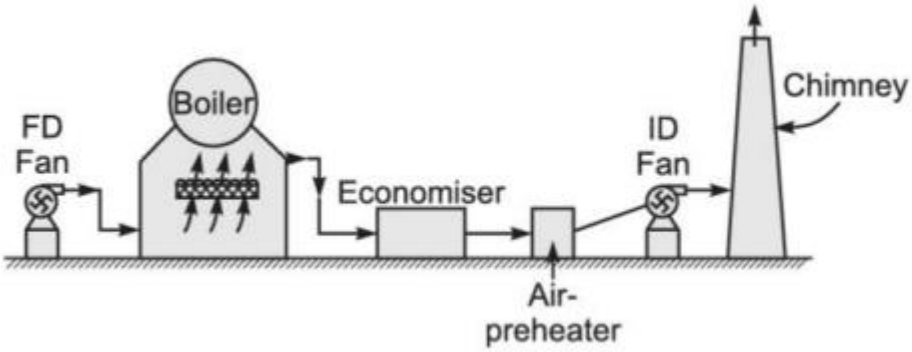


Balanced draught :-

A combination of induced and forced draught in a boiler is known as a balanced draught.

A forced draught fan located near the grate supplies air under the pressure through the furnace and an induced draught fan located near the chimney base, draws in flue gases through the economiser, air preheater, etc., and discharges them into the atmosphere through a chimney.

Figure above illustrates the balanced draught system.



Boiler mounting & Accessories:-

The boiler mountings are the different fittings and devices which are mounted on a boiler shell for proper functioning and safety. These form an integral part of the boiler.

(a) Mountings for Safety :-

1. Safety valve

2. Water-level indicator

3. Fusible plug

(b) Mountings for Control :-

4. Pressure gauge

5. Steam stop valve

6. Feed check valve

7. Blow off cock

Safety valve :-

Safety valves are located on the top of the boiler.

They guard the boiler against the excessive high pressure of steam inside the drum.

If the pressure of steam in the boiler drum exceeds the working

pressure then the safety valve allows to blow-off a certain quantity of steam to the atmosphere, and thus the pressure of steam falls in the drum

The escape of steam makes an audible noise as alarm to warn the boiler attendant. There are four types of safety valves.

1. Dead-weight safety valve

2. Spring-loaded safety valve 3. Level-loaded safety valve

4. High steam and low water safety valve

QNA Chapter-4

Q. What is boiler ?

Ans:- In simple a boiler may be defined as a closed vessel in which steam is produced from water by combustion of fuel.

Q. Define Fire tube and water tube ?

Ans:- Fire tube In the fire tube boilers, the hot gases are inside the tubes and the water surrounds the tubes. Examples : Cochran, Lancashire and Locomotive boilers. Water tube In the water tube boilers, the water is inside the tubes and hot gases surround them. Examples : Babcock and Wilcox, Stirling, Yarrow boiler etc.

Q.3 Define Single-tube and multi-tube boilers ?

Ans:- The fire tube boilers are classified as single-tube and multi-tube boilers, depending upon whether the fire tube is one or more than one. The examples of the former type are cornish, simple vertical boiler and rest of the boilers are multi-tube boilers.

Q.4 What is Grate ?

Ans:- It is the platform in the furnace upon which fuel is burnt and it is made of cast iron bars. The bars are so arranged that air may pass on to the fuel for combustion.

The area of the grate on which the fire rests in a coal or wood fired boiler is called grate surface.

Long question

Q .1 Description & Working of Cochran Wilcox Boiler ?

Q.2 Description & Working of Lancashire Boiler ?

Q.3 Short notes on Boiler Draught ?

Q.4 Short notes on Boiler mounting & Accessories ?

CHAPTER-5 (Steam Power Cycle)

Carnot cycle with vapour

When we think of a power cycle of maximum efficiency, the Carnot cycle immediately conjures up in our mind.

It is a cycle, which has maximum efficiency, operating between given temperature limits and its efficiency is independent of properties of working fluid.

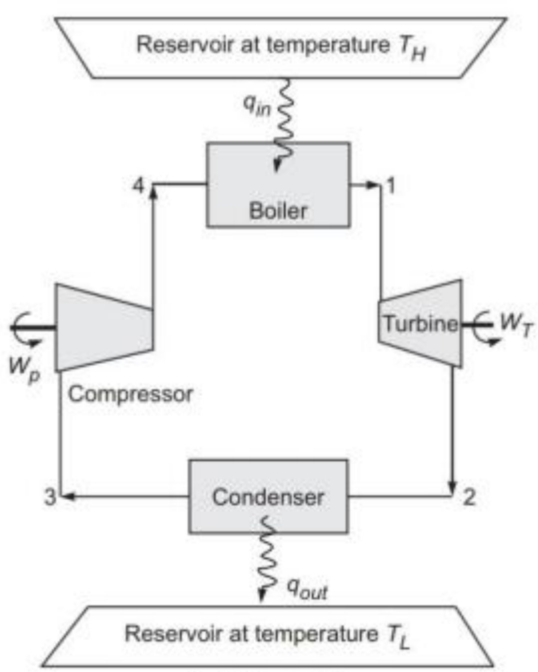
A Carnot vapour power cycle is executed within saturation dome of a pure substance. It uses a two phase fluid as the working medium .

Figure (a) gives the arrangement of components in the cycle,

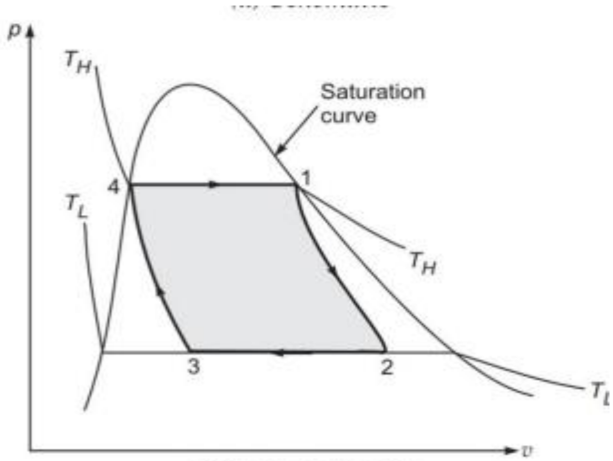
(b) shows Carnot vapour power cycle on p–v coordinates,

(c) on T –s coordinates, and

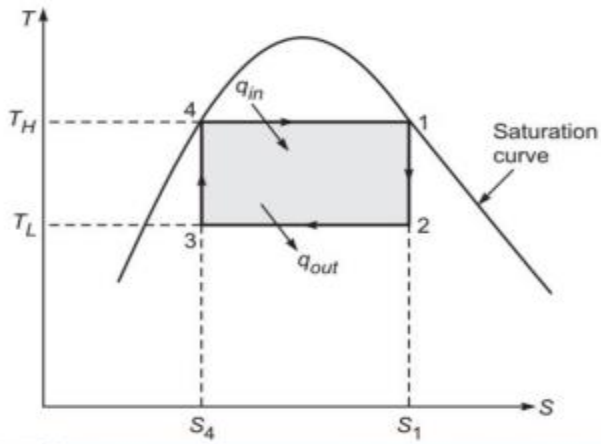
(d) on h –s coordinates. The boundary of the region in which liquid and vapour are both present (the vapour dome) is also indicated

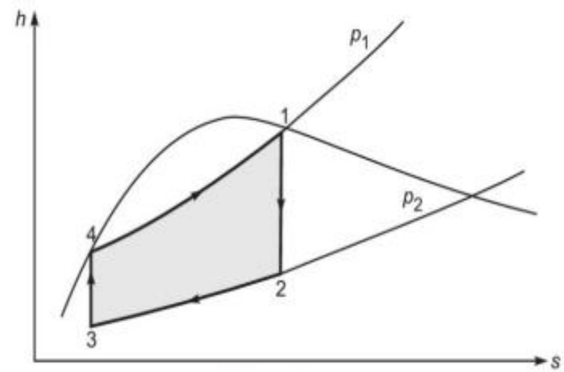


(a) Schematic



(b) p–v as diagram





(d) h–s diagram

Figure (a) gives the arrangement of components in the cycle ,

Figure (b) shows carnot vapour power cycle on p-v coordinates ,

Figure (c) on T-s coordinates . The four processes in the cycle are as follows :-

<u>1.Reversible Adiabatic Expansion 1-2</u>

Saturated steam expands in the turbine .

The temperature lowers from TH to TL .The state 2 is reached in the wet region

2.Controlled Condensation 2-3

During this process ,the condensation starts from state 2 and stops at state 3 and the heat qL per unit mass is rejected in the condenser to the sink at TL.

3.Reversible Adiabatic copression3-4

The mixture of liquid and vapour is compressed to the saturation liquid state 4 at boiler pressure .

4.Reversible Isothermal heat addition 4-1

During this process , a quantity of heat qH per unit mass is added in the boiler from heat source at the temperature TH .

Derive work & efficiency of the cycle

Isothermal heat addition to a vapourising fluid in the boiler;

$$Q_{in} = T_H (s_1 - s_4)$$

Isothermal heat rejected by the working substance in the condenser;

$$Q_{out} = T_L (s_1 - s_4)$$

The net work done of the cycle; $W_{net} = q_{in} - q_{out}$

$= T_H (s_1 - s_4) - T_L (s_1 - s_4)$

$= (T_H - T_L)(s_1 - s_4)$

The thermal efficiency of the cycle;

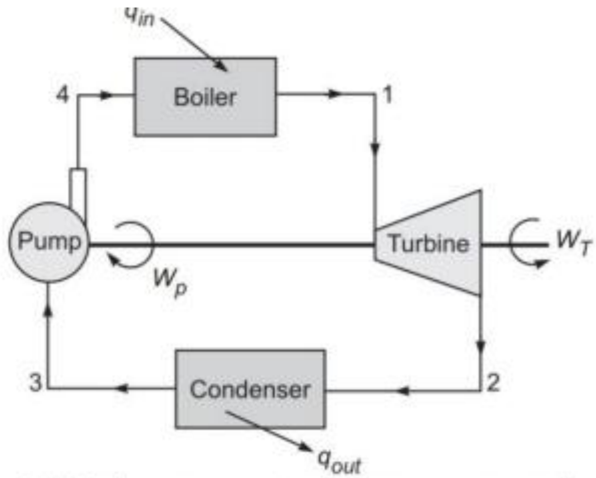
$$\eta_{Carnot} = \frac{w_{net}}{q_{in}} = \frac{(T_H - T_L)(s_1 - s_4)}{T_H(s_1 - s_4)}$$

$$= 1 - \frac{T_H}{T_L}$$

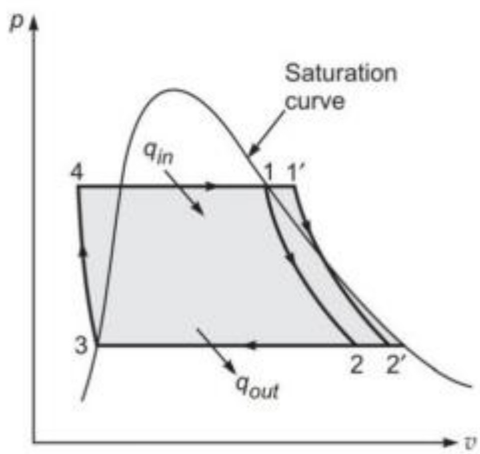
Rankine Cycle :-

Many of the practical difficulties associated with the Carnot vapour power cycle are eliminated in Rankine cycle. The steam coming out of the boiler is usually in superheated state, and expands in the turbine. After expanding in the turbine, the steam is condensed completely in the condenser

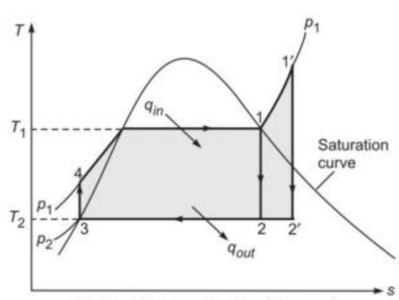
Representation in P-V ,T-S ,&h-s diagram :-



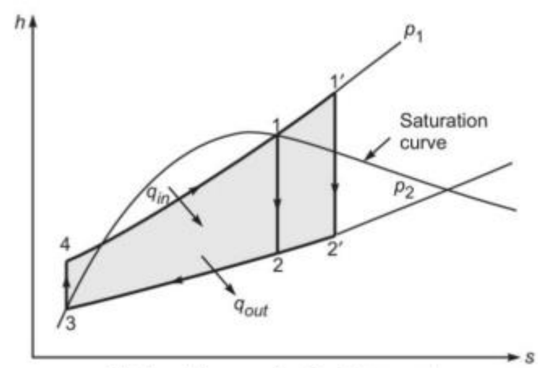
(a) Basic components of vapour power cycle



(b) p–v diagram for Rankine cycle



(c) T–s diagram for Rankine cycle



(d) h–s diagram for Rankine cycle

–

Process 1-2 :- Isentropic expansion of the working fluid in turbine from boiler pressure to condenser pressure . Process 2-3 :- Heat rejection from the working fluid at constant pressure in the condenser till the fluid reaches the saturated liquid state 3 .

Process 3-4 :- Isentropic compression of the working fluid in the pump to the boiler pressure at the state 4 in the compressed liquid region .

Process 4-1:- Heat addition to working fluid at constant pressure in the boiler from state 4 to 1.

Derive work & efficiency of the cycle

We assume 1 kg of working substance in the cycle and applying steady flow energy equation to each component in the cycle. If changes of kinetic and potential energy are neglected then the steady-flow energy equation reduces to

$$q - w = \triangle h$$

For isentropic compression (q = 0) in the pump (process 3– 4);

wP = h4 – h3 Taking pump work negative;
then wp = h4 – h3 where h3 is hf enthalpy of liquid at condenser pressure p2.
h4 is the enthalpy of water at state 4,
calculated as h4 = h3 + wp
Then the isentropic compression work wp is obtained as

$$w_p = \int_{p_2}^{p_1} v\,dp = v(p_1 - p_2)$$

where vf is the specific volume of liquid at condenser pressure p2

For constant-pressure heat addition process in the boiler (w = 0): q2–3 = qin = h1 – h4

For isentropic expansion process 1–2 in the turbine (q = 0): wT = h2 – h1 or wT = h1 – h2

For isentropic expansion process 1–2 in the turbine (q = 0): wT = h2 – h1

or wT = h1 – h2

For constant-pressure heat removal process 2–3 in the condenser (w = 0):

q2–3 = qout = h3 – h2 Taking negative sign for heat rejection, then qout = h2 – h3 .

The thermal efficiency of any power cycle is expressed as h =Net work done in the cycle /Heat supplied in the cycle =wnet/qin

For Rankine cycle, wnet = wT – wp

= (h1 – h2) – vf (p1 – p2) For a thermodynamic cycle, the net work is also equal to net heat transfer;

wnet = qin – qout = (h1– h4) – (h2 – h3)

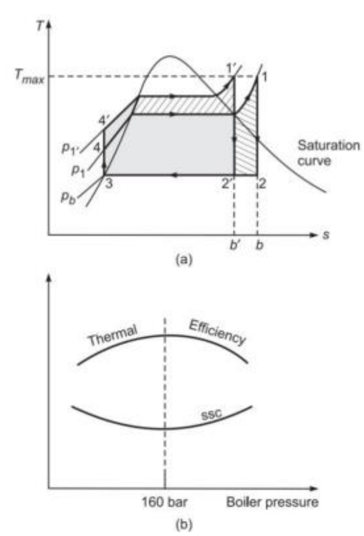
Efficiency of Rankine cycle can be expressed as :

$$\eta_{Rankine} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{h_2 - h_3}{h_1 - h_4} .$$

Effect of Various end conditions in Rankine Cycle :-

By Increase in Boiler pressure :-



(a)
(b)

By increasing the boiler pressure ,the mean temperature of heat addition increase , and thus raises the thermal efficiency of the cycle .fig (a) illustrates the effect of boiler pressure on Rankine cycle efficiency .

Effect due to Increase in Boiler pressure:-

1) Turbine work (WT) increase

2) Pump work (WP) increase

3) Net Work = WT - WP increase

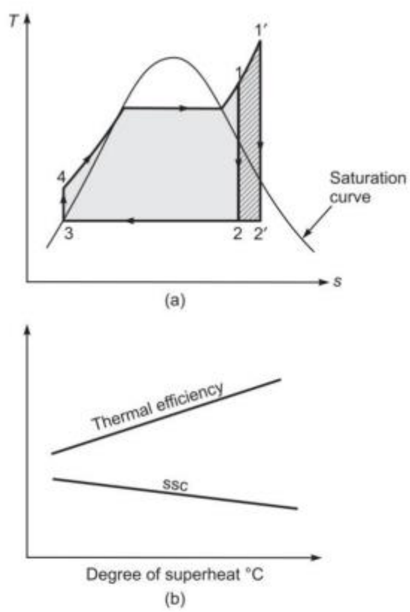
4) Efficiency increase

5) Heat rejection (QR) decrease

6) Heat addition (QS) cannot say

Super heating :-

Superheating of steam increases the mean temperature of heat addition . The effect of superheated steam on performance of the Rankine cycle is shown in below fig.



Effect of superheating :-

1) Turbine work (WT) increase

2) Pump work (WP) remain constant

3) Net Work = WT - WP increase

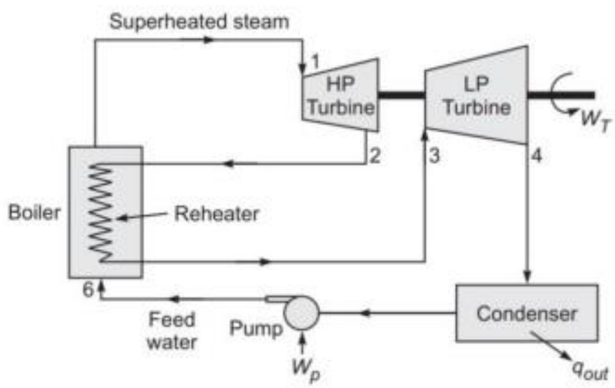
4) Efficiency increase

5) Heat rejection (QR) increases

6) Heat addition (QS) increases

Reheating of Cycle:-

In this process heat is added to the steam .The reheated steam then further expands in the next stage of the turbine .Due to reheating , the work output of the turbine increases ,thus improving the thermal efficiency



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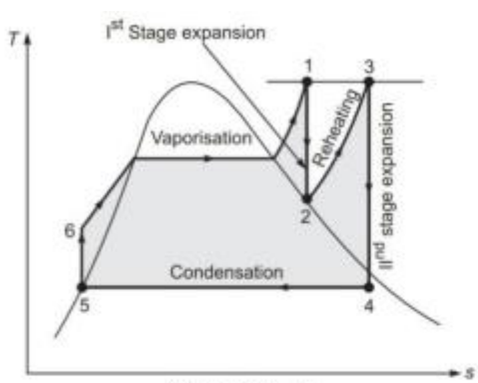
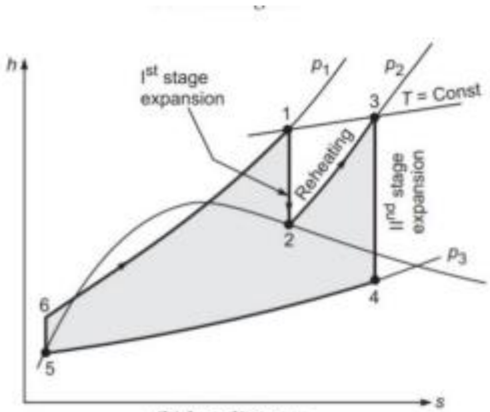


(a) T–s diagram



(b) h–s diagram

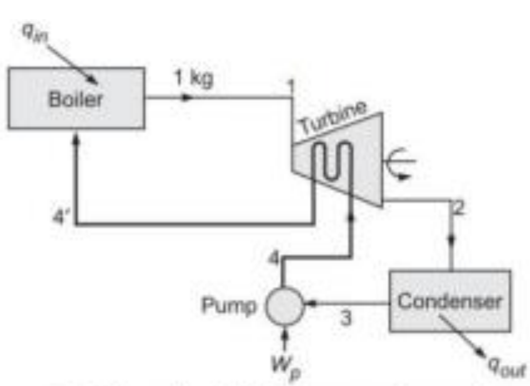
Effect of Reheating of steam :-

1) Turbine work (W_T) =(h_1 –h_2) +(h_3 –h_4) increases
2) Pump work (W_P) = h_6 –h_5 increases
3) Net Work = W_T - W_P increases

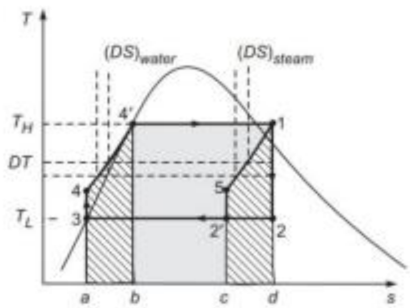
4) Heat supplied =(h1 –h6) +(h3 –h2) increases

Regenerative Cycle :-

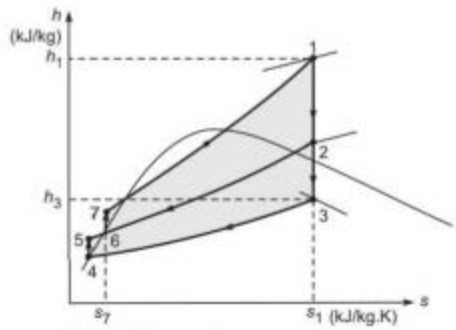
In a simple Rankine cycle , a significant amount of heat is added for sensible heating of compressed liquid coming out the pump .The mean temperature at which sensible heat added is much lower than source temperature . Thus , the efficiency of the Rankine cycle is much lower than that of carnot vapour power cycle . The efficiency of Rankine cycle can be improved by heating the feed water regeneratively .



(a) Schematic of ideal regenerative cycle



(b) Ideal regenerative cycle on T–s plot



Then $\quad q_{in} = h_1 - h_{4'} = T_H (s_1 - s_{4'})$

and $\quad q_{out} = h_{2'} - h_3 = T_L (s_{2'} - s_3)$

Since $s_1 - s_{4'} = s_{2'} - s_3$

$$\therefore \quad \eta_{Reg} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_L}{T_H}$$

Thus efficiency of an ideal regenerative cycle is thus equal to efficiency of the carnot cycle .

Q .1 A steam power plant operates on the Carnot cycle using dry steam at 17.5 bar. The exhaust takes place at 0.075 bar into condenser. The steam consumption is 20 kg/min. Calculate: The efficiency of the cycle ?

Given :- A steam power plant operating on Carnot cycle p1 = 17.5 bar , p2 = 0.075 bar mS= 20 kg/min

To Find :- (i) Power developed, and (ii) Thermal efficiency of the cycle.

Analysis Properties of steam At boiler pressure from Table A-12 P1 = 17.5 bar = 1750 kPa TH = 205.76°C = 478.77 K h4 = hf = 878.48 kJ/kg h1 = hg = 2796.43 kJ/kg

At condenser pressure from Table A-12, P2 = 0.075 bar = 7.5 kPa TL = 40.29°C = 3l3.3 K

The heat supplied in the cycle Qin = h1 – h4 = 2796.43 – 878.48 = 1917.95 kJ/kg

The Carnot efficiency is given as =

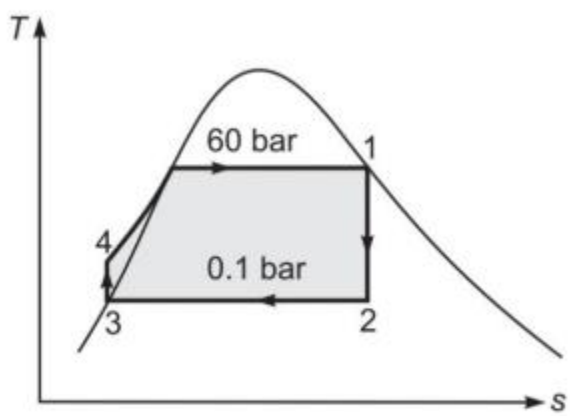
$$\eta_{Carnot} = \frac{w_{net}}{q_{in}} = \frac{(T_H - T_L)(s_1 - s_4)}{T_H(s_1 - s_4)}$$

$$= 1 - \frac{T_H}{T_L}$$

=1-(313.3/478.77)

= 0.3456 or 34.56%

Q 2.A steam power plant has boiler and condenser pressures of 60 bar and 0.1 bar, respectively. Steam coming out of the boiler is dry and saturated. The plant operates on the Rankine cycle. Calculate thermal efficiency ?



Given :- Rankine cycle with dry saturated steam

P1 = 60 bar = 6000 kPa,

P2 = 0.1 bar = 10 kPa

To find :-

Thermal efficiency of steam power plant.

Analysis Properties of steam at principal states State 1:

Dry saturated steam; from Table A-13

$P1 = 6000$ kPa,

$h1 = 2785.10$ kJ/kg

$S1 = 5.8891$ kJ/kg ◊ K

State 2 :

Wet steam;

$P2 = 10$ kPa

$hf2 = 191.81$ kJ/kg

$hfg2= 2392.82$ kJ/kg

$Sf2 = 0.6492$ kJ/kg ◊ K

$Sfg2 = 7.5010$ kJ/kg ◊ K

State 3:

Saturated liquid; $P3 = 0.1$ bar = 10 kPa

$h3 = hf3 = 191.81$ kJ/kg $vf3 = 0.001010$ m3/kg

State 4: Compressed liquid; $p4 = 6000$ kPa,

The state 2, after isentropic expansion can be defined by equating entropy at states 1 and 2;

$s1 = s2 = (sf + x\ sfg)$@ 10 kPa 5.8891

$= 0.6492 + x\ (7.5010)$

or $x = (5.8891 - 0.6492)/ 7.5010$

$= 0.698$

Specific enthalpy at the state 2

h2 = (hf2+ x hfg2)@ 10 kPa = 191.81 + 0.698 x 2392.82 = 1863.34 kJ/kg

The pump work:- wp = vf (p1 – p2)

= 0.001010 x (6000 – 10) = 6.05 kJ/kg

Enthalpy at the state 4; h4 = h3 + wp

= 191.81 + 6.05 = 197.86 kJ/kg.

Rankine cycle efficiency =

$$\eta_{Rankine} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{h_2 - h_3}{h_1 - h_4} .$$

=1-(1863.34-191.81)/(2785.10-197.86)

= 0.353 or 35.35%

QNA CHAPTER-5

Q.1 What is thermal efficiency of any steam power cycle ?

Thermal Efficiency- The thermal efficiency of any power cycle is expressed

$$\eta_{th} = \frac{\text{Net work done in the cycle}}{\text{Heat supplied in the cycle}}$$

$$= \frac{w_{net}}{q_{in}} ..$$

2.What do you understand by steam rate ?

It is also called specific steam consumption .It relates the power output to amount of steam necessary to produce it .It is the amount of steam required to produce 1kWh(3600kj) of power .

Q3. What do you understand by heat rate ?

- It is the amount of heat required by a power plant to produce 1 kWh of power

$$\text{Heat rate} = \frac{(\text{Heat input in kJ/s}) \times (3600 \text{ s/h})}{\text{Net power output in kW}}$$

$$= \frac{3600}{\eta_{th}} (\text{kJ/kWh})$$

Q4.What is Back Work Ratio ?

-Back Work Ratio is defined as ratio of pump work input to the work developed by the turbine .

$$r_{bw} = \frac{\text{Pump work}}{\text{Turbine work}} = \frac{w_p}{w_T}$$

Q.5 What is Work Ratio ?

:-The work ratio for a power plant is defined as ratio of the net work output of the cycle to the work developed by the turbine .

$$r_w = \frac{\text{Net work output of the cycle}}{\text{Turbine work}}$$

$$= \frac{w_{net}}{w_T} = 1 - bwr$$

Q.1 A steam power plant operates on the Carnot cycle using dry steam at 15 bar. The exhaust takes place at 0.065 bar into condenser. The steam consumption is 5000 gm/min. Calculate: The efficiency of the cycle ?

Q.2 A steam power plant has boiler and condenser pressures of 70 bar and 0.5 bar, respectively. Steam coming out of the boiler is dry and saturated. The plant operates on the Rankine cycle. Calculate thermal efficiency ?

Q.3 An steam power plant operates on a theoretical reheat cycle. The steam from boiler at 150 bar and 550°C expands through the high-pressure turbine. It is reheated at constant pressure of 40 bar to 550°C and expands through the low pressure turbine to a condenser pressure of 0.1 bar. Draw T –s and h –s diagrams and find

(a) quality of steam at turbine exhaust,

(b) Thermal efficiency of the cycle,

(c) Steam rate in kg/kWh.

CHAPTER-6(Heat transfer)

Modes of Heat Transfer(Conduction ,Convection , Radiation)

Conduction:- When temperature gradient exists in a medium which may be a solid, fluid or gas, then there is an energy transfer from high temperature region to low temperature region. This energy transfer as heat is called heat conduction.

Convection:- In contrast, heat convection refers to heat transfer that will occur between a surface and the adjacent moving medium, liquid or gas, when they are at different temperatures. It involves the combined effects of conduction and fluid motion.

Radiation:- If there is no fluid motion, then the heat is transferred between a solid and its adjacent fluid by pure conduction. The third mode of heat transfer is thermal radiation.

All surfaces at finite temperature emit energy in the form of electromagnetic waves or (photons) as result of the changes in electron configuration of the atoms or molecules. This mode of heat transfer does not require the presence of a material medium. The energy transfer by radiation is fastest and it can also travel in vacuum

Fourier law of heat conduction and thermal Conductivity (K)

The rate of heat conduction through a medium depends on its geometry, thickness and material of the medium as well as temperature difference.

The Fourier law states that the rate of heat conduction per unit area (heat flux) is directly proportional to temperature gradient

$$\frac{\dot{Q}}{A} \propto \frac{dT}{dx}$$

or $$q = \frac{\dot{Q}}{A} = -k\frac{dT}{dx}$$

$$\dot{Q} = -kA\frac{dT}{dx}$$

or $$q = \frac{Q}{A} = -k\frac{dT}{dx}$$

$$\dot{Q} = -kA\frac{dT}{dx}$$

where q = heat flux (W/m^2)

$\dot{Q}$ = rate of heat transfer, W

A = area normal to direction of heat flow, m^2

$\frac{dT}{dx}$ = temperature gradient °C/m, slope of temperature curve on T–x diagram

k = constant of proportionality, called *thermal conductivity* of material, W/m °C or W/m·K

The minus sign is inserted to make natural heat flow a positive quantity. According to the second law of thermodynamics, heat always flows in the direction of decreasing temperature. Thus the temperature gradient dT/dx becomes negative..

Thermal conductivity:-

➢ The thermal conductivity is a property of a material and is defined as the ability of the material to conduct heat through it.

➢ It can also be defined as the rate of heat transfer through a unit thickness of material per unit area per unit temperature difference.

➢ The thermal conductivity of a material is a measure of how fast heat will flow in that material. A large value of thermal conductivity

➢ indicates that the material is a good heat conductor and a low value indicates that the material is a poor heat conductor or an insulator.

➢ The thermal conductivity is measured in watts per meter per degree Celsius or Watt metre per kelvin, when heat flow rate is expressed in watts.

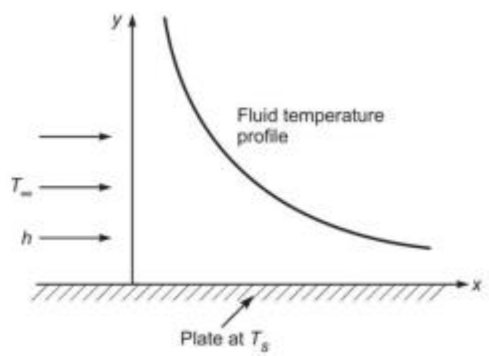
Newton's law of cooling:-

➢ The convection heat transfer comprises of two mechanisms. The first is the transfer of energy due to random molecular motion (diffusion)

➢ The second is the energy transfer by bulk motion of the fluid. The molecules of fluid are moving collectively or as aggregates and thus carry energy from a high temperature region to a low-temperature region.

➢ If the fluid motion is artificially induced by a pump, fan or a blower that forces the fluid over a surface to flow, the heat transfer is said to be forced convection.

➢ If the fluid motion is set up by buoyancy effects resulting from density difference caused by temperature difference in the fluid, the heat transfer is said to be by free (or natural) convection.



Temperature Profile in Convection

The Newton's law of cooling is the governing equation of convection heat transfer. It states that the rate of heat transfer is directly proportional to temperature difference between a surface and fluid or mathematically

$$\frac{\dot{Q}}{A}\ (\mathrm{W/m^2}) \propto (T_s - T_\infty)\ (^\circ\mathrm{C})$$

or $$\frac{\dot{Q}}{A} = h(T_s - T_\infty)$$

where, T_s = surface temperature, °C

T_∞ = fluid temperature, °C

h = constant of proportionality, is called the heat transfer coefficient.

The heat transfer coefficient is measured in W/m2 K or W/m2 °C. The value of the heat transfer coefficient depends on the properties of fluid as well as fluid flow conditions

Radiation heat transfer.(Stefan–Boltzmann Law & Kirchhoff's Law):-

Radiation heat transfer : Stefan–Boltzmann Law

When energy propagates in the form of electromagnetic waves from a high-temperature region to a low-temperature region, the form of energy transfer is referred as thermal radiation. Stefan–Boltzmann law governs the radiation heat transfer. It states that the rate of radiation heat transfer per unit area from a black surface is directly proportional to fourth power of the absolute temperature of the surface and is given by

$$\frac{\dot{Q}}{A} \propto (T^4)$$

or

$$\frac{\dot{Q}}{A} = \sigma T_s^4$$

where T_s = absolute temperature of surface K

σ = constant of proportionality, called *Stefan Boltzmann Constant* and has value of 5.67×10^{-8} W/m² K⁴

The heat flux emitted by a real surface is less than that of black surface and is given by

$$\frac{\dot{Q}}{A} = \sigma \varepsilon (T_s^4)$$

where, = Ɛ a radiative property of the surface is called the emissivity .

The net rate of radiation heat exchange between a real surface and its surrounding is

$$\frac{\dot{Q}}{A} = \sigma \varepsilon (T_s^4 - T_\infty^4) \quad ..$$

where, T_∞ = surrounding temperature K

T_s = surface temperature, K

The three other radiation laws, Planck's law, Wein's law and Kirchhoff's law, are also used in radiation heat transfer.

Kirchhoff's Law :- It states that at thermal equilibrium, the ratio of the spectral emissive power to spectral absorptivity for all bodies is constant

$$\frac{E_{\lambda 1}}{\alpha_{\lambda 1}} = \frac{E_{\lambda 2}}{\alpha_{\lambda 2}} = \frac{E_{\lambda 3}}{\alpha_{\lambda 3}} = \frac{E_{\lambda b}}{\alpha_{\lambda b}} = C$$

Since $\alpha_{\lambda b} = 1$

$$\frac{E_{\lambda 1}}{E_{\lambda b}} = \alpha_{\lambda 1}$$

or $E_{\lambda 1} = \alpha_{\lambda 1}$

Similarly, for other bodies, it can be shown that at thermal equilibrium, the energy emitted by a surface must be equal to energy absorbed by the surface. Hence, spectral emissivity is equal to spectral absorptivity at thermal equilibrium. This law is applicable when the radiation properties are independent of wavelength (for gray bodies) or when incident and emitted radiation have the spectral distribution.

Black body Radiation , Definition of Emissivity ,Absorptivity ,& Transmissibility :-

Black body Radiation:-

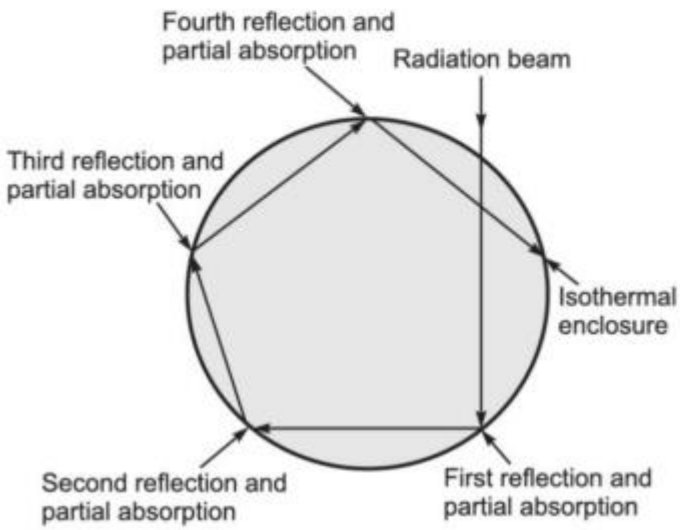
It is an ideal surface having the following properties:

1. A black body absorbs all incident radiation from all directions at all wavelengths.

2. At any temperature and wavelength, nobody can emit energy more than a black body.

3. Although the radiation emitted by a black body depends upon wavelength and temperature, it is independent of direction.

4. A black body neither reflects nor transmits any amount of incident radiation. Consider a radiation beam entering the cavity of an enclosure as shown in Fig. bellow . It experiences many reflections within the enclosure and almost entire beam is absorbed by the cavity and the black body behaviour is experienced.



Definition of Emissivity :-

It is the ratio of radiation heat flux emitted by a real surface at a temperature T, over all wavelengths into hemispherical space, to that which would have been emitted by a black body at same temperature. Mathematically

$$\varepsilon = \frac{E}{\int_0^\infty E_{b\lambda}\, d\lambda} = \frac{E}{E_b}$$

For real surfaces, the emissive power

$$E = \varepsilon E_b = \varepsilon \sigma T^4$$

Absorptivity:- A black body absorbs all incident radiation, hence its absorptivity is considered unity. But real surfaces do not absorb all energy incident on it. The total or average or hemispherical absorptivity a is defined as fraction of radiation energy incident on the surface from all directions, over entire wavelength spectrum, that is absorbed by the surface.

Mathematically,

$$\alpha = \frac{Ga}{G}$$

where, Ga = Energy absorbed by the surface, W/m2 G = Irradiation, W/m2

Transmissibility:-

_When a radiation beam is incident on a semitransparent surface, a part is reflected, a part is absorbed and the remaining is transmitted. Hence, transmissivity is the fraction of incident energy transmitted through the surface.

Mathematically

$$\tau = \frac{G\tau}{G}$$

and for average properties:

$$\alpha + \rho + \tau = 1$$

QNA CH.6

Short Question

Q.1 What is Conduction ?

ANS :- When temperature gradient exists in a medium which may be a solid, fluid or gas, then there is an energy transfer from high temperature region to low temperature region. This energy transfer as heat is called heat conduction.

Q.2 What is Radiation ?

Ans:- Thermal radiation refers to the heat energy emitted by the bodies because of their temperatures. All bodies at a temperature above absolute zero temperature emit thermal radiation. For example, the energy emitted by sun travels through space and reaches the earth surface. The energy transfer by radiation does not require any medium between hot and cold surfaces. In fact, the radiation heat transfer is more effective in vacuum

Q.3 Define Thermal conductivity ?

Ans:- The thermal conductivity is a property of a material and is defined as the ability of the material to conduct heat through it.

Q.4 What is Convection ?

Ans:- In contrast, heat convection refers to heat transfer that will occur between a surface and the adjacent moving medium, liquid or gas, when they are at different temperatures. It involves the combined effects of conduction and fluid motion.

Long Question

Q.1 Write a short notes on Black body Radiation ?

Q.2 Define Fourier law of heat conduction ?

Q .3 Short notes on Newton's law of cooling ?

Q.4 Write down the Stefan–Boltzmann Law and Kirchhoff's Law?