LECTURE NOTES

ON

THERMAL ENGINEERING II

Complied By

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MECHANICAL ENGINEERING

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CONTENT

Performance of I.C Engine

Chapter-1

Mechanical Efficiency :-

Mechanical Efficiency is a measure of how well a machine converts input energy, work, and power into output energy, work and power.

The efficiency of an ideal machine is 100% because the input work = The output work

Real machine do not achive efficiency of 100% because heat may be lost from the system due to the friction between the moving part.

Equation :-

Mechanical efficiency

$$ME = \frac{\text{output work (J)}}{\text{Input work (J)}} \times 100\% = ME(J)$$

Mechanical Advantage (MA) :-

Mechanical advantage tells how many times a machine multiple force.

$$MA = \frac{\text{output force}}{\text{Input force}}$$

Indicated Thermal Efficiency (η_{ith}) :-

It is defined as the ratio

Between indicated power to the fuel energy per Secound.

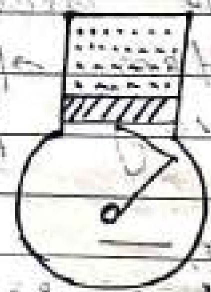
$$\eta_{ith} = \frac{\text{Indicated power}}{\text{Fuel Energy}}$$

$$= \frac{I.P}{m_f/sec \times \text{Calorific volume of fuel}}$$

$$\eta_{ith} = \frac{I.P}{m_f \times CV}$$

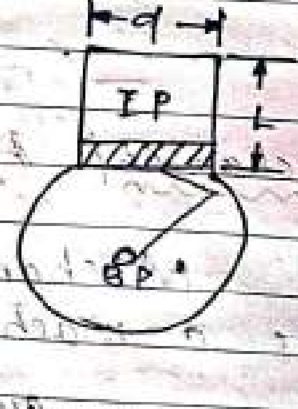
m_f = Mass of fuel Supplied kg/sec

Cv = Calorific value (KJ/kg)



Indicated Power (I.P) -

The indicated power is the power actually developed by the engine cylinder.



Indicated power

$$I.P = \frac{P_m \times L.A.n.K}{60} \text{ Watts}$$

Where,

P_m = Mean effective pressure.

L = Length of Stroke in meters.

A = Area of the piston in m^2
N = Speed of the engine in r.p.m
n = Number of working strokes per minute.
$n = N$ (For two stroke engine)
$n = N/2$ (For Four stroke engine)

$$I.P = \frac{100 \times P_m \times L \times A \times n}{60} \text{ KW}$$ (For single cylinder engine)

$$I.P = \frac{100 \times K \times P_m \times L \times A \times n}{60} \text{ KW}$$ (For multi cylinder engine)

Where,
K = Number of cylinder.

Brake Power (B.P) :-

The brake power is the power obtained at the engine flywheel and is measured with the help of dynamometer.

Brake power $B.P = \frac{2\pi N T}{60}$ (Watt)

Where,
N = rpm of crank shaft of engine
T = Torque at crank shaft.

$\boxed{\text{Torque } T = F \times R}$

F = Tangential force on crank pin (N)
R = Radius of crank pin (m)

Brake Thermal Efficiency (η_{bth}) –

It may be defind as the ratio of heat equivalent to brake power to the heat energy supplied by the fuel during a specific period of time.

So, brake thermal efficiency,

$$\eta_{bth} = \frac{\text{Heat equivalent to B.P per minute}}{\text{Heat energy supplied by fuel}}$$

$$= \frac{B.P \times 60}{m_f \times C_v}$$

Where,

M_f = Mass of fuel supplied to the engine per minute.

C_v = Calorific value.

Relative Efficiency (η_{rel}) –

Relative efficiency or efficiency ratio is the ratio of thermal efficiency of an actual cycle to that ideal cycle. The efficiency ratio is a very useful critirion which indicates the degree of devlopement of engine.

$$\eta_{rel} = \frac{\text{Actual thermal efficiency}}{\text{Air-Standard efficiency}}$$

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Air-Standard Efficiency —

The air standard efficiency is also known as "Thermodynamic efficiency". It is mainly function of compression ratio and other parameters. It gives the uper limit of the efficiency obtained from an engine.

For engine working on otto cycle, the air standard efficiency,

$$\eta_{otto} = 1 - \frac{1}{r^{\gamma - 1}}$$

Where,

r = Compression ratio
γ = Adiabatic index

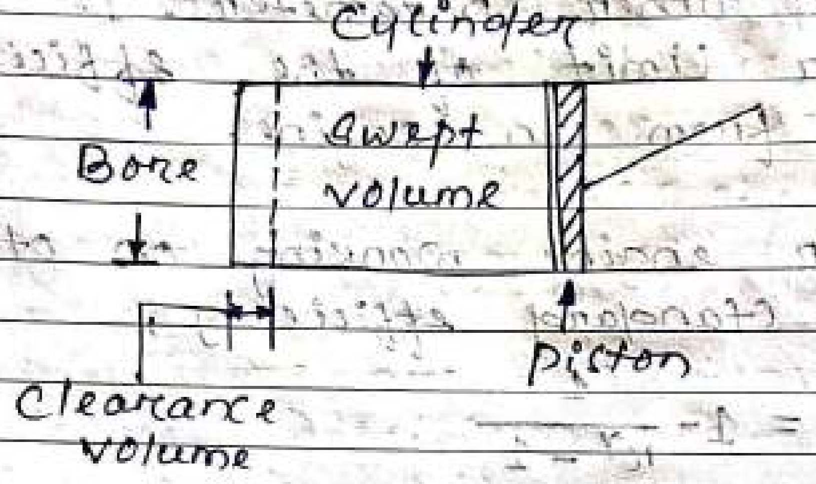
Volumetric Efficiency (η_{vol}) —

The volumetric efficiency is measure of the success with air supply and thus the charged is indeced into the engine cylinder. It is very important parameter, since it indicate the breathing capacity of the engine.

$$\eta_{vol} = \frac{\text{Volume of air at suction stroke}}{\text{Swept volume of the engine cylinder}}$$

Swept volume –

Swept volume is the total volume covered by the piston inside the cylinder.



Mean Effective Pressure (P_m) –

Mean effective pressure is the avarage presure inside the cylinder of an internal combustion engine based on the Calculated or measured power output. It increases as manifold pressure increases. For any particular engine operating at a given speed and power output, there will be a specific indicated mean effective pressure. They are derived from indicated and brake power respectively.

Indicated power can shown to be

$$I.P = \frac{P_m L A n K}{60 \times 1000}$$

then, the indicated mean effective pressure can be written as

$$P_{im} = \frac{6000 \times IP}{L A n K}$$

Similarly, the brake mean effective Pressure ~~can be written as~~ is given by

$$P_{bm} = \frac{6000 \times bP}{L A n K}$$

Where,

IP = Indicated power (KW)

P_{im} = Indicated mean effective pressure (N/m^2)

L = Length of the Stroke (m)

A = Area of the piston (m^2)

N = Speed in revolutions per minute (rpm)

n = Number of power strokes

$N/2$ for 4-stroke engines

N for 2-stroke engines.

K = Number of Cylinder.

Another way of Specifying the indicated mean effective pressure P_{im} is from the knowledge of engine indicator diagram (P-V diagram). In this case, P_{im} may be defing as

$$P_{im} = \frac{\text{Area of the indicator diagram.}}{\text{Length of the indicator diagram.}}$$

Calorific value of fuel :-

The calorific value of or net value of a solid or liquid may be define as the amount of heat given out by the complete combustion of 1 K.g. of fuel. It is expressed interm of KJ/Kg of fuel. The calorific value of gases is expressed in terms of kg/m^3.

There are two types of fuel
- Higher calorific value - gross.
- Net or lower calorific value.-

Overall Efficiency -

It is the ration of work obtained at the crankshaft in a given time to the energy supplied by the fuel during the same time.

Let,

m_f = Mass of fuel consumed in kg per hour.

C = Calorific value of fuel in KJ/Kg of fuel.

$\therefore$ Energy supplied by the fuel per minute

$$= \frac{m_f \times C}{60} \text{ KJ}$$

and work obtained at the crankshaft per minute,

$= B.P \times 60$ KJ ($\because$ B.P is in KW and 1 KW = 1 KJ/s)

$\therefore$ Overall efficiency $\eta_0 = \dfrac{B.P \times 60 \times 60}{m_f \times C}$

$= \dfrac{B.P \times 3600}{m_f \times C}$

Mechanical Efficiency

It is the ratio of brake power to indicated power. Mathematically,

Mechanical efficiency $\eta_m = \dfrac{B.P}{I.P}$

Indicated thermal efficiency –

It is the ratio of the heat equivalent to one KW hour to the heat in the fuel per I.P. hour. Mathematically,

Thermal efficiency $\eta_t = \dfrac{\text{Heat equivalent to one KW Hour}}{\text{Heat in fuel per I.P. hour}}$

$= \dfrac{3600}{\dfrac{m_f \times C}{I.P}} = \dfrac{I.P \times 3600}{m_f \times C}$

Problems

Question no. 1 - A gas engine has piston diameter of 150 mm, length of stroke 400 mm and mean effective pressure 5.5 bar. The engine makes 120 explosions per minute. Determine the mechanical efficiency of the engine, ~~of the engine~~ if its Brake power is 5 KW.

Data Given,

$D_p = 150\,mm$ (Diameter of piston)

$= 0.15\,m$

$L = 400\,mm$

$= 0.4\,mm$

$P_m = 5.5\,bar$

$n = 120$

Brake power $= 5\,KW$

We know the area of piston,

$$A = \frac{\pi}{4}(0.15)^2 = 0.0177\,m^2$$

and indicated power,

$$I.P = \frac{100\,P_m L A n}{60}$$

$$= \frac{100 \times 5.5 \times 0.4 \times 0.0177 \times 120}{60}$$

$$= 7.79\,KW$$

We know that mechanical efficiency of the engine,

$$\eta_m = \frac{B.P}{I.P} = \frac{5}{7.79} = 0.642 \text{ or } 64.2\%$$

Ans

Question no. 2 – A four cylinder two stroke cycle petrol engine devlops 23.5 KW brake power at 2500 r.p.m. The mean effective pressure on each piston is 8.5 bar and the mechanical efficiency is 85%. Calculate the diameter and stroke of each cylinder, assuming the length of stroke equal to 1.5 times the diameter of cylinder.

Data Given;

Brake power = 23.5 KW

$K = 4$ (Number of cylinder)

$n = 2500$ r.p.m

Mean effective pressure $P_m = 8.5$ bar

$\eta_m = 85\% = 0.85$

D_c = Diameter of cylinder

L = Length of stroke = $1.5D$

We know that the area of cylinder

$$A = \frac{\pi}{4}(D_c)^2 = 0.7855(D_c)^2$$

and number of working strokes per minute, $n = N = 2500$ ($\because$ Engine works on two stroke cycle)

We know that indicated power,

$$I.P = \frac{B.P}{\eta_m} = \frac{23.5}{0.85} = 27.65\ KW$$

Mechanical Efficiency

$$\eta_m = \frac{\text{Brake Power}}{\text{Indicated power}}$$

$$\Rightarrow \text{Indicated power} = \frac{\text{Brake Power}}{\text{Mechanical Efficiency}}$$

We also know that indicated power (I.P)

$$I.P = \frac{100 K P_m L A n}{60}$$

$$\Rightarrow 27.85 = \frac{100 \times 4 \times 8.5 \times 1.5 D \times 0.7855 D^2 \times 2500}{60}$$

$$\Rightarrow 27.85 = 166918.75 (D^2)^3$$

$$\therefore D^3 = \frac{27.647}{166918.75}$$

$$= 0.00016563$$

$$D = \sqrt{0.00016563}$$

$$= 0.012$$

Length of Stroke $L = 1.5 D$

$= 1.5 \times D = 1.5 \times 0.012 = 0.018 = 18\ mm$

Ans

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Question no. 3 :- An engine uses 6.5 Kg of oil per hour of calorific value 30000 KJ/Kg. If the Brake power B.P of the engine is 22 KW and mechanical efficiency 85 %, Calculate :-

1. Indicated thermal efficiency
2. Brake thermal efficiency
3. Specific fuel consumption in kg/B.P/h.

<u>Data Given</u>,

Mass of fuel supplied $m_f = 6.5$ Kg/h.
Calorific value $C = 30000$ KJ/Kg.
Brake power $B.P = 22$ KW,
Mechanical efficiency $\eta_m = 85\% = 0.85$

1. Indicated thermal efficiency

We know indicated power,

$$I.P = \frac{B.P}{\eta_m} = \frac{22}{0.85} = 25.88 \text{ KW}$$

$\therefore$ Indicated thermal efficiency,

$$\eta_i = \frac{I.P \times 3600}{m_f \times C}$$

$$= \frac{2.588 \times 3600}{6.5 \times 30000}$$

$$= 0.48 \text{ or } 48\% \text{ Ans}$$

2. Brake thermal efficiency

We know brake thermal efficiency,

$$\eta_b = \frac{B.P \times 3600}{m_f \times C}$$

$$= \frac{22 \times 3600}{6.5 \times 30000}$$

$= 0.406$ or 40.6% Ans

3. Specific fuel consumption

We know that Specific fuel consumption

$$= \frac{m_f}{B.P} = \frac{6.5}{22} = 0.295 \text{ Kg/B.P./h}$$

Ans

Question no. 4 – The diameter and stroke length of a single cylinder two stroke gas engine, working on the constant volume cylinder, are 200 mm and 300 mm respectively with clearance volume 2.78 litres.

When the engine is running at 135 r.p.m, the indicated mean effective pressure was 5.2 bar and the gas consumption 8.8 m^2/hour. If the Calorific value of the gas used is 16350 KJ/m3, find

1. Air standard efficiency
2. Indicated power developed by the engine

3. Indicated thermal efficiency of the engine.

Data Given,

Diameter of the cylinder $D_c = 200\,mm$
$= 0.2\,m$
Length of the Stroke $L = 300\,mm$
$= 0.3\,m$
Clearance volume $V_c = 2.78$ Litres
$= 0.00278\,m^3$,
Speed of engine $N = 135$ r.p.m
Mean effective pressure $P_m = 5.2$ bar
Mass of fuel supplied $m_f = 8.8\,m^3/h$.
Calorific value $C = 16350\,KJ/m^3$

1. Air Standard efficiency

We know that area of the cylinder,

$$A = \frac{\pi}{4}(D_c)^2 = \frac{\pi}{4}(0.2)^2 = 0.03192\,m^2$$

$\therefore$ Stroke volume, V_s = Area of cylinder × Length of Stroke

$= 0.03192 \times 0.3$
$= 0.009926\,m^3$

and compression ratio, $r = \dfrac{\text{Total volume of cylinder}}{\text{Clearance volume}}$

$$r = \frac{V_c + V_s}{V_c}$$

$$= \frac{0.00278 + 0.009426}{0.00278}$$

$$= 4.4$$

We know that air standard efficiency

$$\eta_{ase} = 1 - \frac{1}{r^{\gamma-1}}$$ (γ is the specific heat ratio of air usually taken as 1.4)

$$= 1 - \frac{1}{(4.4)^{1.4-1}}$$

$$= 1 - 0.553$$

$$= 0.447 \text{ or } 44.7\% \quad \underline{\text{Ans}}$$

2. Indicated power developed by the engine

We know that the indicated power developed by the engine,

$$I.P = \frac{100\, p_m L A n}{60}$$

$$= \frac{100 \times 5.2 \times 0.3 \times 0.03142 \times 135}{60} \text{ kW}$$

... ($n = N$, for two stroke cycle engine)

$$= 11.03 \text{ kW} \quad \underline{\text{Ans}}$$

3. We know that indicated thermal efficiency,

$$\eta_i = \frac{I.P \times 3600}{m_f \times C}$$

$$= \frac{11.03 \times 3600}{8.8 \times 16350}$$

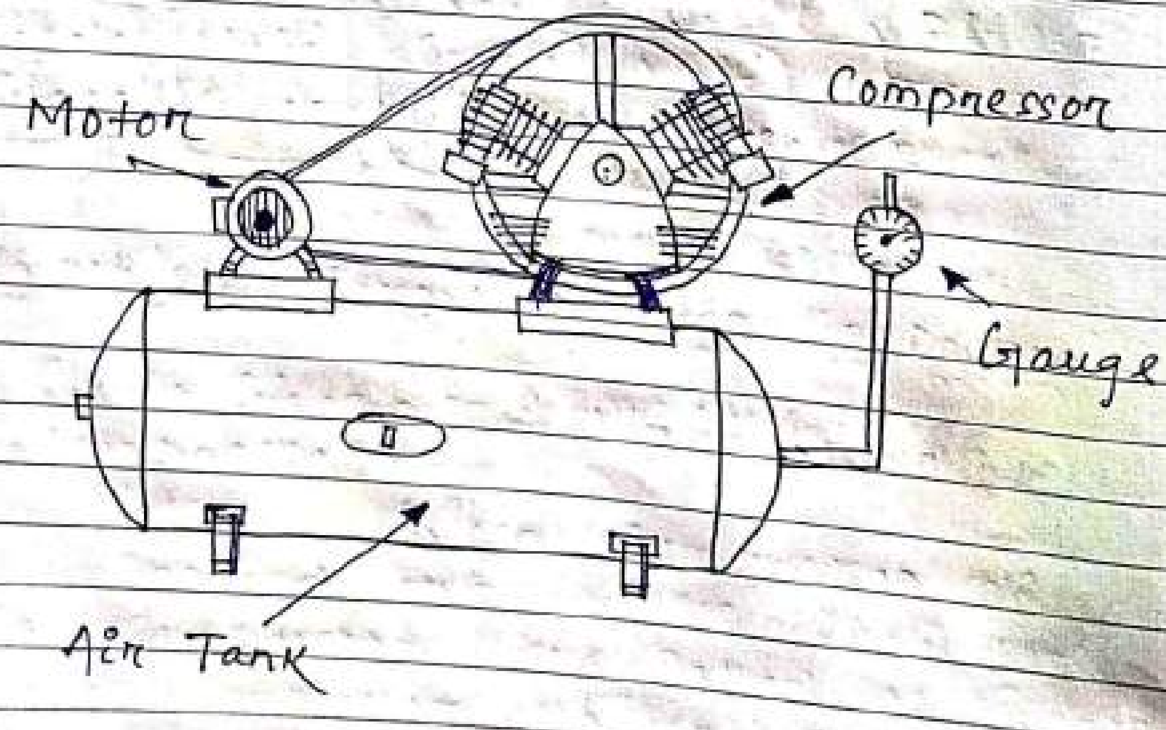
$$= 0.276 \text{ or } 27.6\% \text{ Ans}$$

AIR COMPRESSOR

Chapter-2

Function of air compressor:-

An air compressor is a machine to compress the air and to raise its pressure. The air compressor sucks air from the atmosphere, compresses it and then delivers the same under a high pressure to a storage vessel. From the storage vessel, it may be conveyed by the pipeline to a place where the supply of compressed air is required. Since the compression of air requires some work to be done on it, therefore a compressor must be driven by some prime mover.



Industrial use of Compressor air—

The compressed air is used for many purposes such as for operating pneumatic drills, riveters, road drills, paint spraying, in starting and super-charging of internal combustion engines, in gas turbine plants, jet engines and air motors, etc.

It is also utilised in the operation of lifts, rams, pumps and a variety of other devices.

In industry, compressed air is used for producing blast of air in blast furnaces and bessemer converters.

Classification of Air Compressor—

The air compressor may be classified in many ways, but the following are important from the subject point of view—

1. According to working—

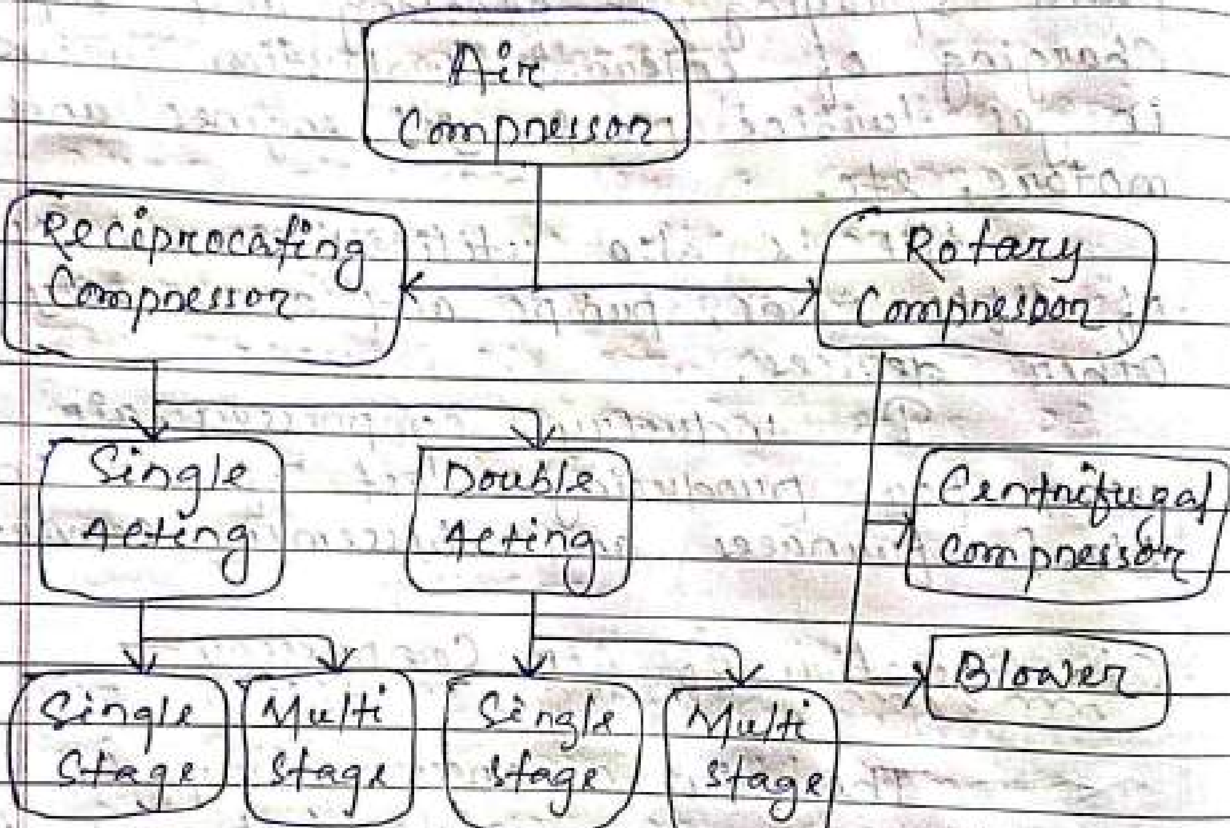
   (a) Reciprocating compressor
   (b) Rotary compressor

2. According to Action—

   (a) Single acting compressor.
   (b) Double acting compressor.

3. According to number of stages

(a) Single stage compressor
(b) Multi-stage compressor.



Important Terms of Air Compressor

* Single Stage and Multi stage compressor —
When compressor of air is carried out in one cylinder, the compressor is called as single stage compressor, When compression of air is carried out in more than one cylinder, the compressor is called as Multi stage compressor.

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* Single acting and Double acting compressor —

When suction, compression and delivery of compressed air is done on one side of the piston, the compressor is called as single acting compressor. When suction, compression and delivery of compressed air is done on both sides of the piston, the compressor is called as Double acting compressor.

* Inlet pressure —

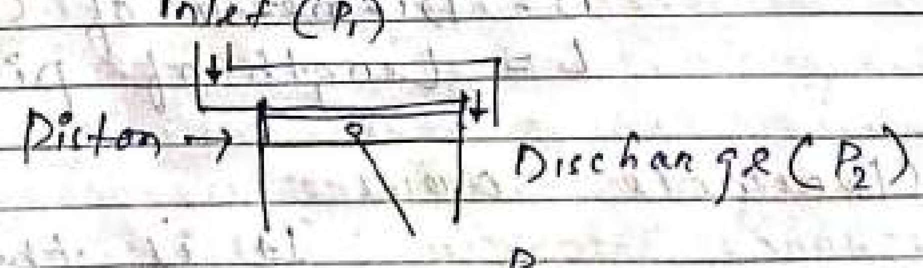
It is the absolute pressure of air at the inlet of a compressor.

* Discharge pressure —

It is the absolute pressure of air at the outlet of a compressor.

* Compression ratio or pressure ratio —

It is the ratio of discharge pressure to the inlet pressure. Since the discharge pressure is always more than the inlet pressure, therefore the value of compression ratio is more than unity.



Pressure Ratio = $r_p = \frac{P_2}{P_1}$

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* Compressor Capacity – It is the volume of air delivered by the compressor, and is expressed in m^3/min or m^3/s.

* Free air delivery – It is the actual volume delivered by a compressor when reduced to the normal temperature and pressure condition. The capacity of ~~air~~ a compressor is generally given in terms of free air delivery.

* Swept volume – It is the volume of air sucked by the compressor during its suction stroke. Mathematically, the swept volume or displacement of a single acting air compressor is given by

$$V_s = \frac{\pi}{4} \times D^2 \times L$$

Where,
D = Diameter of cylinder bore
L = Length of piston stroke

* Clearance Volume – It is the space left in the cylinder when the

piston reaches its top dead centre. The ratio of clearance volume to swept volume is called as clearance ratio.

* Bore and Stroke length–

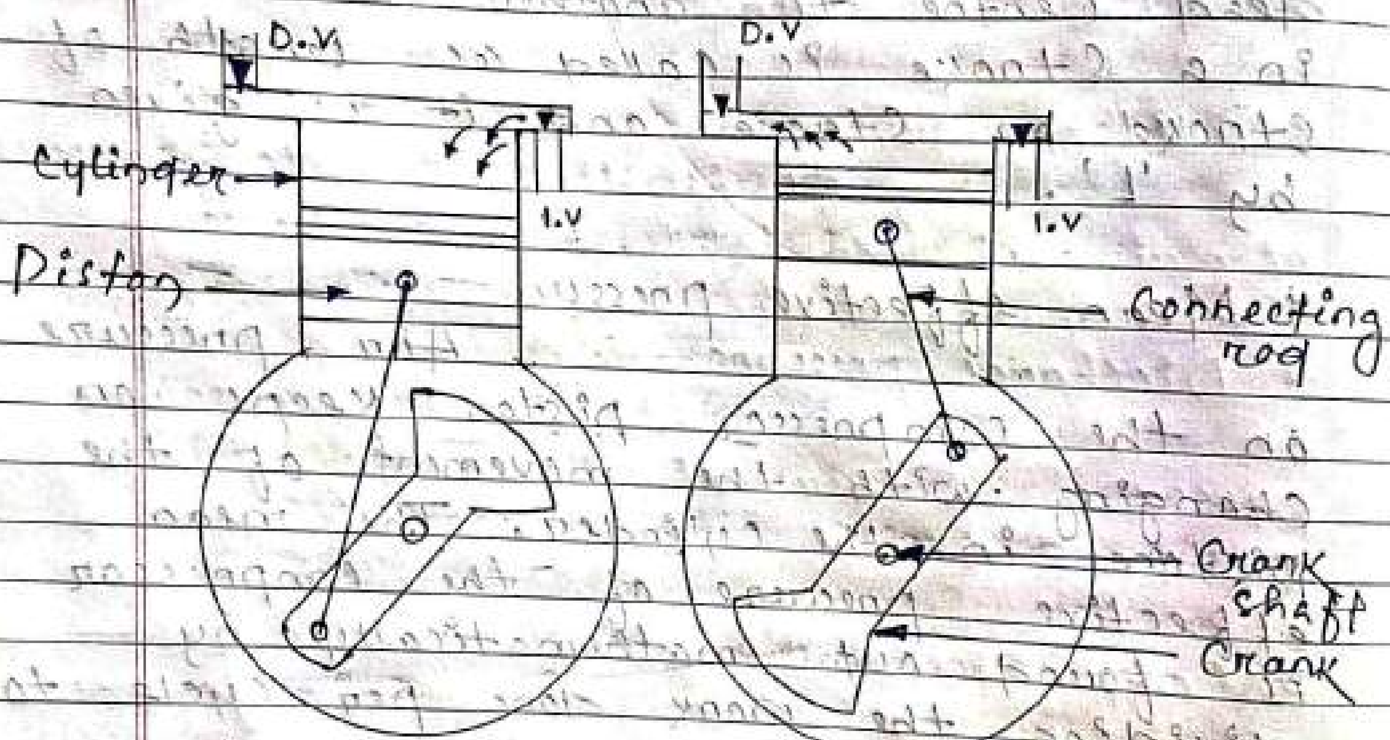
~~Internal diameter~~ The cylinder internal diameter is called as bore and it is given by 'D'. The distance by which the piston moves from one dead centre to another dead centre in a stroke is called as length of stroke or "stroke" and it is given by 'L'.

* Mean effective pressure–

Air pressure on the compressor piston keeps on changing with the movement of the piston in the cylinder. The mean effective pressure of the compressor is found out mathematically by dividing the work done per cycle to the stroke volume.

Parts and working principle of Reciprocating Air compressor–

A Reciprocating air compressor, consists of a cylinder, piston, inlet and discharge valves. From the geometry of compressor, we find that when the piston moves downwards (or in other words, during outward or suction stroke), the pressure inside the cylinder fall below the atmospheric pressure. Due to this pressure difference, the inlet valve (I.V) gets opened and the air sucked into the cylinder, at inlet pressure until the piston completes the outward stroke.



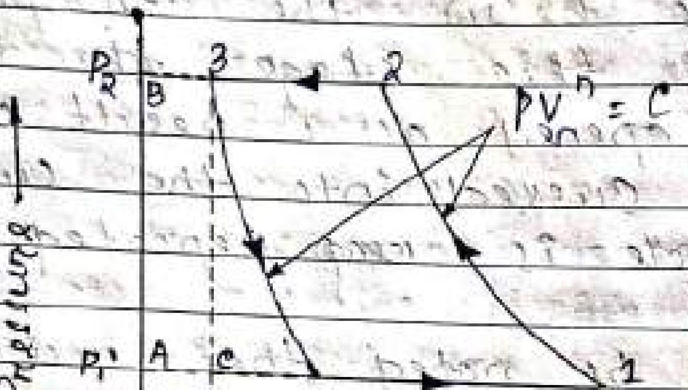
(Suction Stroke) (Delivery Stroke)

Now when the piston move upward (or in the other words, during inward or delivery stroke), the pressure inside the cylinder goes on increasing till it reaches the discharge pressure. At this stage, the discharge valve (D.V) gets opened and air is delivered to the container. At the end of delivery stroke, a small quantity of air, ~~contained~~ at high pressure, is left in the clearance space. As the piston starts its suction stroke, the air contained in the clearance space expands till its pressure falls below the atmospheric pressure. At this stage, the inlet valve gets opened as a result of which fresh air is sucked into the cylinder, and the cycle is ~~rep~~ repeated.

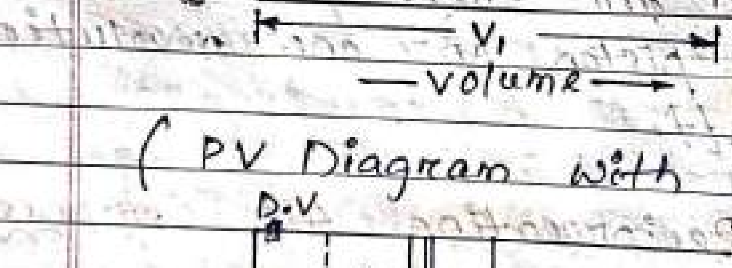
It may be noted that reciprocating air compressor, the suction, compression and delivery of air takes place in two strokes of the piston or one revolution of the crankshaft.

Workdone by Reciprocating Air Compressor with clearance volume –

The entire volume of the air, in the compressor cylinder, is compressed by the inward stroke of the piston. But in actual practice, it is not ~~desirable~~ ~~to allow the piston head~~ possible to reduce the clearance volume to zero, for mechanical reasons. Moreover, it is not desirable to allow the piston head to come in contact with the cylinder head. In addition to this, the passage leading to the inlet and outlet valves always contribute to clearance volume. In general, the clearance volume is expressed as some percentage of the piston displacement.



(PV Diagram with clearance volume)



Now consider a reciprocating air compressor with clearance volume.

Let,

P_1 = Initial pressure of air (Before compression)

V_1 = Initial volume of air (Before compression)

T_1 = Initial temperature of air (Before compression)

P_2, V_2, T_2 = Corresponding values for the final conditions (at the delivery point).

r = Pressure ratio (P_2/P_1)

V_c = Clearance volume (volume at point 3)

V_s = Stroke volume = $V_1 - V_c$

n = Polytropic index for compression and expansion.

The P-V diagram of a single stage single acting reciprocating air compressor with clearance volume (V_c) is shown fig. We know that during return stroke, the air is compressed by its major part, compression stroke 1-2. This compression continues, till the pressure P_2 in the cylinder is sufficient to force open the delivery valve at 2. After that, no more compression takes place with the inward movement of the piston. Now during the remaining part of compression stroke, compressed air is delivered till the piston reaches at 3. At this stage, there will be some air (equal to clearance volume) left in the clearance space of the cylinder at pressure P_2.

After that air in the clearance space

reject heat from the air in the small time available during compression.

3. Sometimes, the temperature of air, at the end of compression, is too high. It may be heat up the cylinder head or burn the lubricant oil.

Advantages of Multistage Compression

1. The work done per Kg of air is reduced in multistage compression with intercooler as compared to single stage compression for the same delivery pressure.

2. It improves the volumetric efficiency for the given pressure ratio.

3. The size of the two cylinder (high pressure and low pressure) may be adjusted to suit the volume and pressure of the air.

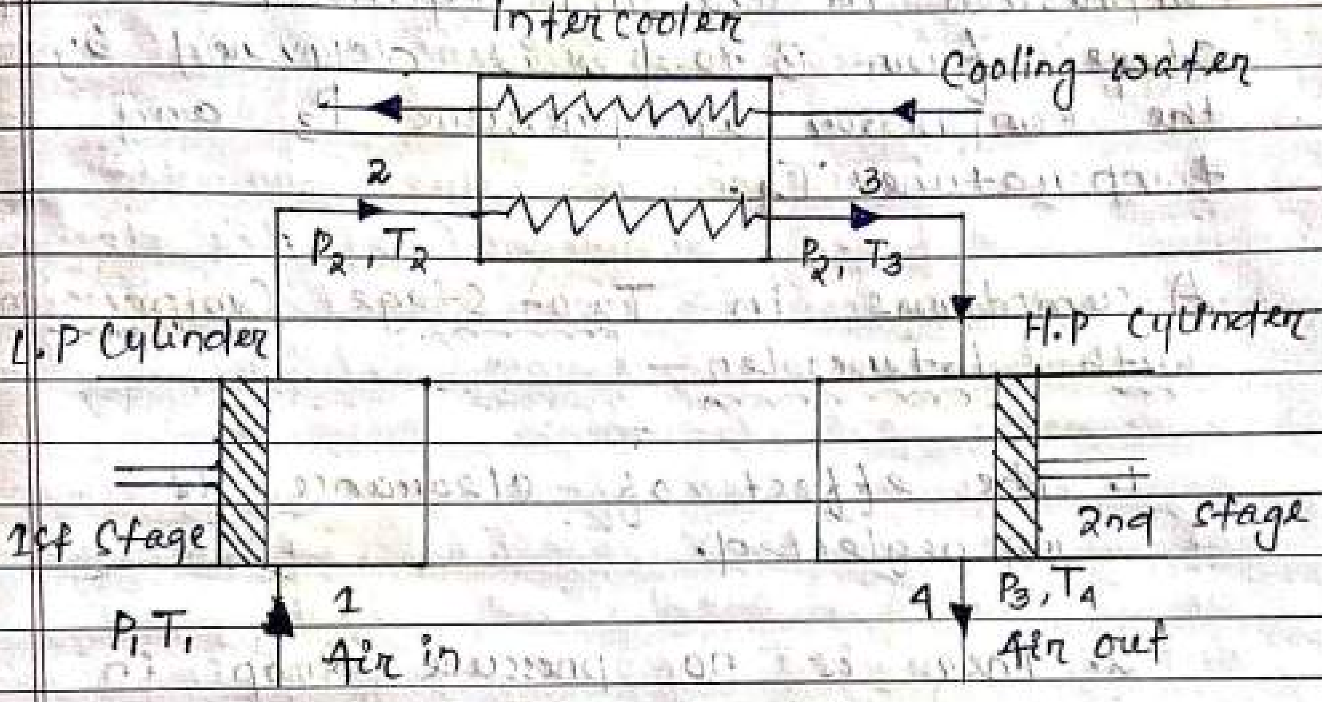
4. It reduces the leakage loss considerably.

5. It gives more uniform torque, and hence a smaller size flywheel is required.

6. It provides effective lubrication because of lower temperature range.

7. It reduces the cost of compressor.

Two-Stage Reciprocating Air Compressor with Intercooler



First of all, the fresh air is sucked from the atmosphere in the low pressure (L.P.) cylinder during its suction stroke at intake pressure P_1 and temperature T_1.

The air, after compression in the L.P cylinder (First Stage) from 1 to 2, is delivered to the intercooler at pressure P_2 and temperature T_2.

Now the air is cooled in the intercooler from 2 to 3 at constant pressure P_2 and from temperature T_2 to T_3.

After this, the air is sucked in

the high pressure (H.P) cylinder during its suction stroke.

Finally, the air, after further compression in the H.P cylinder (second stage) from 3 to 4, is delivered by the compressor at pressure P_3 and temperature T_4.

Assumptions in Two-stage Compression with Intercooler –

1. The effect of clearance is neglected.

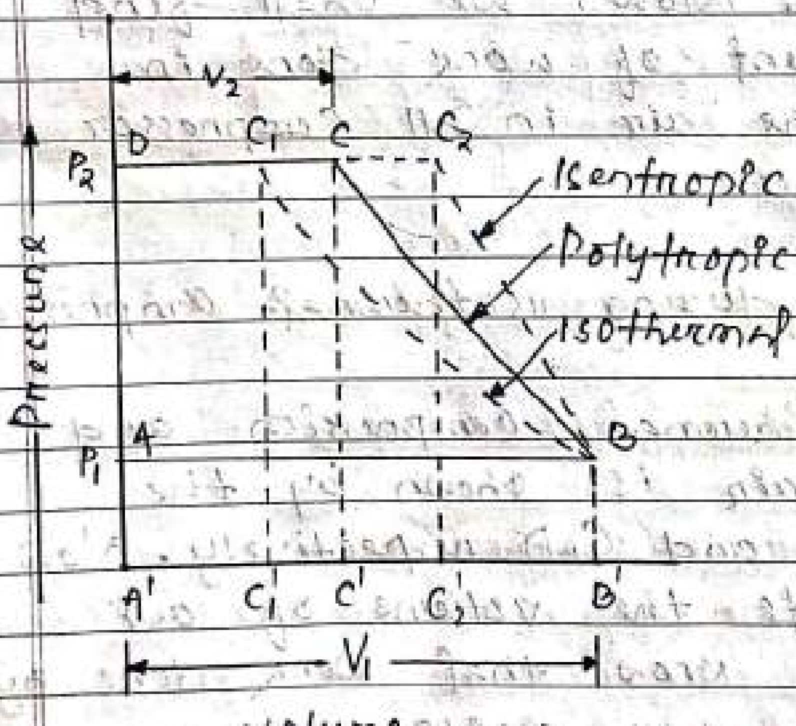
2. There is no pressure drop in the intercooler.

3. The compression in both the cylinder (L.P and H.P) is polytropic.

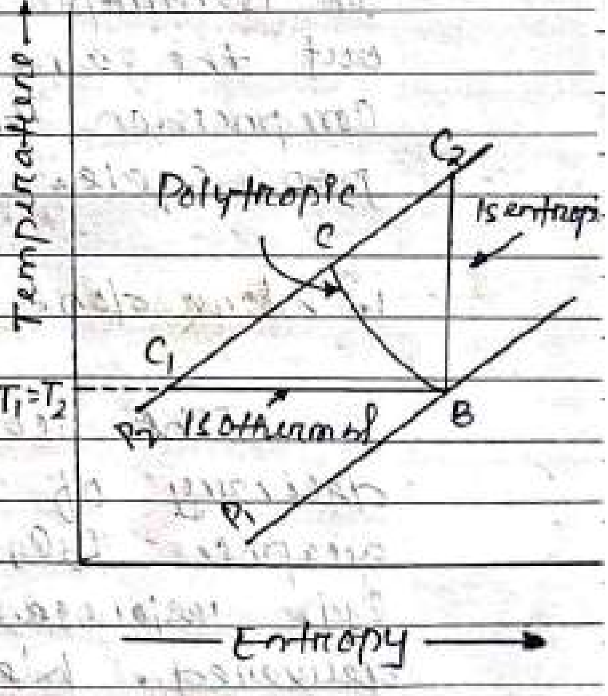
4. The suction and delivery of air takes place at constant pressure.

Workdone by a Single Stage Reciprocating Air Compressor without Clearance volume –

The P-V and T-s diagrams of a single acting single stage reciprocating air compressor without clearance volume is shown in fig. We know that during return stroke, the air is compressed by its major part at constant temperature. The compression continues till the pressure (P_2) in the cylinder is sufficient to force open delivery valve at C. After that no more compression takes place with the inward movement of the piston. Now during the remaining part of compression stroke, the compressed air is delivered till the piston head reaches the cylinder end. After that, the air is sucked from the atmosphere during the suction stroke AB at pressure P_1.



(P-V diagram without clearance volume)



(T-S diagram)

Let,

P_1 = Initial pressure of air (before compression)

V_1 = Initial volume of air (before compression)

T_1 = Initial temperature of air (before compression)

P_2, V_2, T_2 = Corresponding values for the final conditions (at the delivery point)

r = Pressure ratio (P_2/P_1)

As a matter fact, the compression of air may be isothermal, polytropic or isentropic. Now, we shall find out the amount of work done in compression the air in all compressor per cycle,

1. Work done during isothermal compression -

The isothermal compression and delivery of air is shown by the graphs BC_1 and C_1D respectively. Now C_1D represents the volume of air delivered. We know that work done by the compressor per cycle,

W = Area ABC_1D

= Area $A'DC_1C_1'$ + Area $C_1BB'C_1'$ − Area $A'ABB'$

$$= P_2V_2 + 2.3\, P_2V_2 \log\left(\frac{V_1}{V_2}\right) - P_1V_1$$

$$= 2.3\, P_1V_1 \log\left(\frac{V_1}{V_2}\right) = 2.3\, P_1V_1 \log\left(\frac{P_2}{P_1}\right)$$

$$= 2.3\, P_1V_1 \log r = 2.3\, mRT_1 \log r$$

2. Work done during polytropic compression (PV^n = constant)

The polytropic compression is shown by the line BC in fig. Now CD represents the volume of air delivered V_2. We know that work done on the air per cycle,

$$W = \text{Area } ABCD$$

$$= \text{Area } A'DCC' + \text{Area } CBB'C' - \text{Area } A'ABB'$$

$$(W) = P_2V_2 + \frac{P_2V_2 - P_1V_1}{n-1} - P_1V_1$$

$$= \frac{(n-1)P_2V_2 + P_2V_2 - P_1V_1 - (n-1)P_1V_1}{n-1}$$

$$= \frac{n}{n-1}(P_2V_2 - P_1V_1) \quad \text{--- (i)}$$

$$= \frac{n}{n-1} \times P_1V_1\left(\frac{P_2V_2}{P_1V_1} - 1\right) \quad \text{--- (ii)}$$

We also know that for polytropic compression

$$P_1V_1^n = P_2V_2^n$$

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

Substituting the value of V_2/V_1 in equn. (ii),

$$W = \frac{n}{n-1} \times P_1V_1 \left[\frac{P_2}{P_1}\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} - 1\right]$$

$$= \frac{n}{n-1} \times P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} \times mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \quad \text{.....(iii)}$$

The equation (i) may also be written as:

$$W = \frac{n}{n-1} \times P_2V_2\left(1 - \frac{P_1V_1}{P_2V_2}\right)$$

$$= \frac{n}{n-1} \times P_2V_2 \left[1 - \frac{P_1}{P_2}\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}\right]$$

$$= \frac{n}{n-1} \times P_2V_2 \left[1 - \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}\right]$$

$$= \frac{n}{n-1} \times mRT_2\left(1 - \frac{T_1}{T_2}\right)$$

$$= \frac{n}{n-1} \times mR\left(T_2 - T_1\right) \quad \text{.......(iv)}$$

2. Work done during is isentropic compression-

(i) The isentropic compression is shown by the curve BC_2 in fig. In this case, the volume of air delivered V_2 is represented by the line C_2D.

The work done on the air per cycle during isentropic compression may be worked out in the similar way as polytropic compression. The polytropic index n is changed to isentropic index γ in the previous results:-

$\therefore$ Work done on the air per cycle;

$$W = \frac{\gamma}{\gamma-1} \times P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{\gamma}{\gamma-1} \times mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{\gamma}{\gamma-1} \times mR(T_2 - T_1)$$

Power Required to Drive a Single acting Reciprocating Air Compressor -

We have already obtained in the last article the expressions for the work done (W) per cycle during isothermal, polytropic and isentropic compression. The power required to drive the compressor may be obtained from the usual relation,

$$P = \frac{WN_w}{60} \text{ watts}$$

If N is the speed of the compressor in r.p.m., then number of working strokes per minute,

$N_w = N$ ..... (For single acting compressor)

$= 2N$ ..... (For double acting compressor)

1. Isothermal power = $\frac{W(\text{in isothermal compression}) N_w}{60}$

2. Isentropic power = $\frac{W(\text{in isentropic compression}) N_w}{60}$ Watts

3. Indicated power = $\frac{W(\text{in Polytropic compression}) N_w}{60}$ Watts

Simple Problems

Question no.1 - A single stage reciprocating air compressor is required to compress 1 kg of air from 1 bar to 4 bar. The initial temperature is 27°C. Compare the work required in the following cases -

1. Isothermal compression, 2. Compression with $pv^{1.2}$ = Constant, 3. Isentropic compression.

Data Given,

$m = 1\,kg$, $P_1 = 1$ bar, $P_2 = 4$ bar

$T_1 = 27°C = 27 + 273 = 300K$, $n = 1.2$

1. Work required for isothermal compression

We know that work required by the compressor,

$$W = 2.3\, P_1 V_1 \log\left(\frac{P_2}{P_1}\right) = 2.3\, mRT_1 \log\left(\frac{P_2}{P_1}\right)$$

$$= 2.3 \times 1 \times 287 \times 300 \log\left(\frac{4}{1}\right) = 119230 J$$

$= 119.23 kJ$ Ans

2. Work required for polytropic compression -

$$W = \frac{n}{n-1} \times mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{1.2}{1.2-1} \times 1 \times 287 \times 300 \left[\left(\frac{4}{1} \right)^{\frac{1.2-1}{1.2}} - 1 \right]$$

$$= 134320 \text{ J}$$

$$= 134.32 \text{ KJ} \quad \underline{\text{Ans}}$$

3. Work required for isentropic compression

We know that work required by the compressor,

$$W = \frac{\gamma}{\gamma-1} \times mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

$$= \frac{1.4}{1.4-1} \times 1 \times 287 \times 300 \left[\left(\frac{4}{1} \right)^{\frac{1.4-1}{1.4}} - 1 \right]$$

$$= 146630 \text{ J}$$

$$= 146.63 \text{ KJ}$$

Question no.2 - Determine the size of the cylinder for a double acting air compressor of 40 KW indicated power, in which air is drawn in at 1 bar and 15°C and compressed ~~air~~ according to the law $pv^{1.2}$ = constant, to 6 bar. The compressor runs at 100 r.p.m. with average piston speed of 152.5 m/min. Neglect clearance.

Data Given ;

$1. P = 40 KW = 40 \times 10^3 W$,

$P_1 = 1 bar = 1 \times 10^5 N/m^2$,

$T_1 = 15^\circ C = 15 + 273 = 288 K$

$n = 1.2$, $P_2 = 6$ bars , $N = 100$ r.p.m

Avarage piston speed $= 152.5$ m/min.

Let,

D = Diameter of the cylinders in metres

L = Length of the stroke in metres

We know the avarage piston speed ,

$2LN = 152.5$

$L = 152.5/2N$

$= 152.5/2 \times 100$

$= 0.7625$ m Ans

Volume of air before Compression ,

$V_1 = \frac{\pi}{4} \times D^2 L$

$= \frac{\pi}{4} \times D^2 \times 0.7625 = 0.6 D^2 m^3$

and workdone by the Compressor ,

$$W = \frac{n}{n-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{1.2}{1.2-1} \times 1 \times 10^5 \times 0.6 D^2 \left[\left(\frac{6}{1} \right)^{\frac{1.2-1}{1.2}} - 1 \right] N\text{-}m$$

$$= 125310 \, D^2 \, N\text{-}m$$

Since the compressor is double acting, therefore number of working strokes per minute,

$$N_W = 2N = 2 \times 100 = 200$$

We know that indicated power (I.P)

$$40 \times 10^3 = \frac{W \times N_W}{60}$$

$$= \frac{125310 D^2 \times 200}{60}$$

$$= 417.7 \times 10^3 D^2$$

$D^2 = 0.096$ or $D = 0.31\,m$ or $310\,mm$ **Ans**

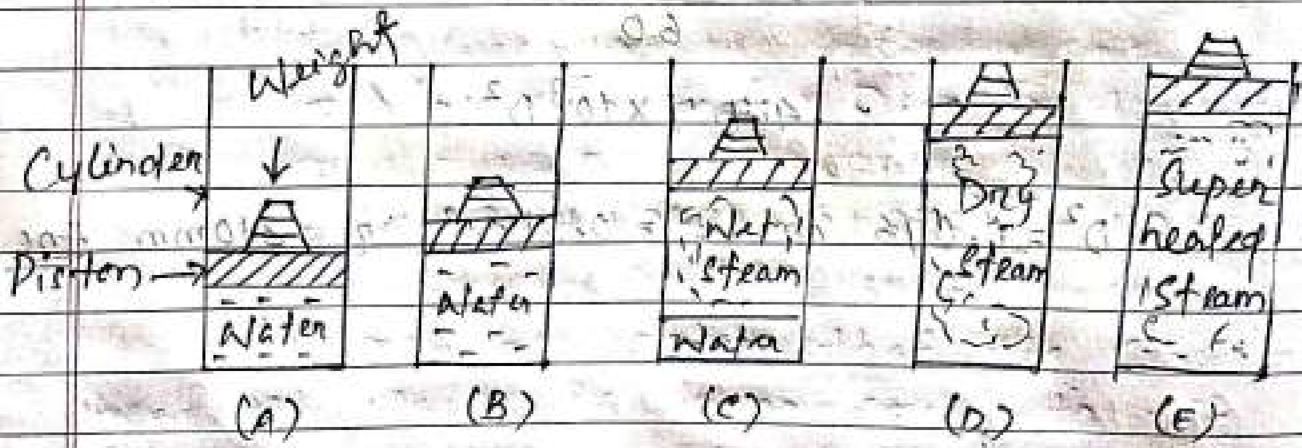
PROPERTIES OF STEAM

Chapter-3

Steam is a vapour of water, and is invisible when pure and dry. It is used as the working substance in the operation of steam engines and steam turbines.

1. Steam does not obey laws of perfect gases, until it is perfectly dry. When the dry vapour is heated further, it becomes superheated vapour which behaves, more or less, like a perfect gas.

Formation of Steam at a constant pressure from water—



1. Wet Steam—

When the steam contains moisture or particles of water in suspension, it is said to be wet steam. It means that the evaporation of water is not complete, and the whole of the latent heat has not been absorbed.

2. Dry Saturated Steam -

When the wet steam is further heated, and it does not contain any suspended particles of water, it is known as dry saturated steam. The dry saturated steam has absorbed its full latent heat and behaves practically in the same way as a perfect gas.

3. Superheated Steam -

When the dry steam is further heated at a constant pressure, thus raising its temperature, it is said to be superheated steam. Since the pressure is constant, therefore the volume of superheated steam increase.

4. Dryness fraction or Quality of wet Steam

It is the ratio of the mass of actual dry steam, to the mass of same quantity of wet steam, and is generally denoted 'x'. Mathematically,

$$x = \frac{m_g}{m_g + m_f} = \frac{m_g}{m}$$

Where,

m_g = Mass of actual dry steam,
m_f = Mass of water in suspension

m = Mass of wet steam = $m_g + m_f$

5. Sensible heat of water —

It is the amount of heat absorb by 1 kg of water, when heated at a constant pressure, from the freezing point (0°C) to the temperature of formation of steam, i.e. saturation temperature. The sensible heat also known as liquid heat.

The specific heat of water at constant pressure is usually taken as 4.2 KJ/Kg K. Therefore heat absorbed by 1 kg of water from 0°C to t°C or sensible heat.

$$= \text{Mass} \times \text{Sp. heat} \times \text{Rise in temperature}$$

$$= 1 \times 4.2[(t+273)-(0+273)] = 4.2\ KJ/Kg$$

It may be noted that the sensible heat of water is taken equal to the specific enthalpy of water. It is usually denoted by h_f in steam tables and its value may be determined for any given pressure in KJ/Kg.

6. Latent heat of vaporisation -

It is the amount of heat absorb to evaporate 1 kg of water, at its boiling point or saturation temperature without change of temperature. It is denoted by h_{fg} and its value depends upon the pressure. The heat of vaporisation of water or latent heat of steam is 2257 KJ/Kg at atmospheric pressure.

7. Enthalpy or total heat of steam -

It is amount of heat absorbed by water from freezing point to saturation temperature plus the heat absorb during evaporation.

∴ Enthalpy or total heat of steam

= Sensible heat + Latent heat

It is denoted by h_g and its value for the dry saturated steam may be read directly from the steam tables. The expressions for the enthalpy of wet steam, dry steam and superheated steam are as follows -

(i) Wet steam - The enthalpy of wet steam is given by

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

Where x is the dryness fraction of steam.

(ii) Dry steam – We know that in case of dry steam, $x = 1$

$$\therefore h = h_g = h_f + h_{fg}$$

(iii) Superheated steam – If we further add heat to the dry steam, its temperature increases while pressure remaining constant. This increase in temperature shows the superheat stage of the steam. Thus, the total heat required for the steam to be superheated is →

h_{sup} = Total heat for dry steam + Heat for superheated steam

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

$$= h_g + C_p(t_{sup} - t)$$

Where,

C_p = Mean specific heat at constant pressure for superheated steam.

t_{sup} = Temperature of superheated steam

t = Saturation temperature at the given constant pressure.

Notes –

1. The difference ($t_{sup} - t$) is known as degree of Superheat.

2. The value of C_p for steam lies between 1.67 KJ/Kg K to 2.5 KJ/Kg K.

3. Specific volume of steam – It is the volume occupied by the steam per unit mass at a given temperature and pressure, and is expressed in m^3/kg.

Difference between gas and vapour –

GAS	VAPOUR
1. A gas is a state of matter.	1. A vapour is a state between liquid and gas.
2. While changing into gas, the particles of liquid gain kinetic energy due to heat, to overcome the force of attraction between the particles.	2. While changing into vapour only a fraction of particles at the surface of liquid have higher kinetic energy to break free the force of attraction between the particles.
3. A liquid change into gas due to boiling.	3. A liquid change into vapour due to evaporation.

4. A liquid change into gas at a fixed temperature, as the boiling point of liquid is constant at atmospheric pressure.	4. A liquid change into vapour at any temperature below boiling point, as evaporation takes place at any temperature below its boiling point.
5. A gas contains particles only in one state. ex- Gaseous state.	5. A vapour contains particles at both of its state. ex- Gaseous and liquid.
6. Changing into gas boiling is a fast process.	6. Changing into vapour evaporation is a slow process.

Charles law -

The volume of an ideal gas is directly proportional to the absolute temperature at constant pressure.

The volume of gas increases as the temperature increase.

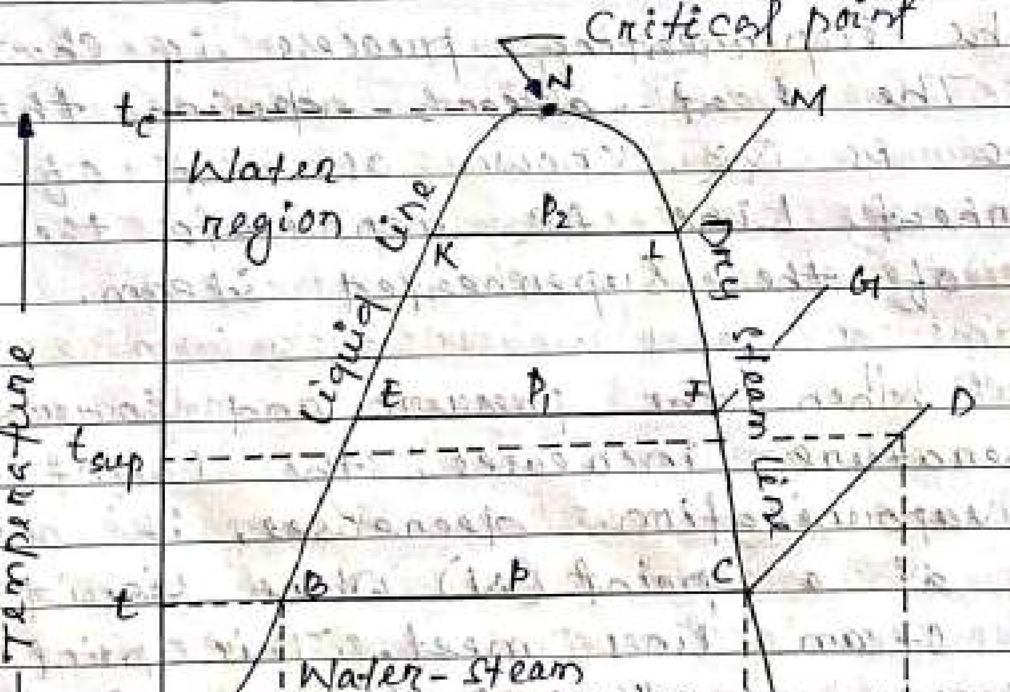
Boyle's law -

The pressure exerted by a gas is inversely proportional to the volume occupied by it at a constant mass and temperature.

The volume of gas increases as the pressure decreases.

Temperature vs. Total heat Graph during Steam Formation –

The process of steam formation, as discussed above, may also be represented on the graph, whose abscissa represents the total heat and the vertical ordinate represents the temperature. The point A represents the initial condition of water at 0°C and pressure p (in bar) as shown in figure ABCD shows the relation betⁿ temperature and heat at a Specific pressure of p (in bar).



During the formation of the super-heated steam, from water at freezing point, the heat is absorb in the following three stages —

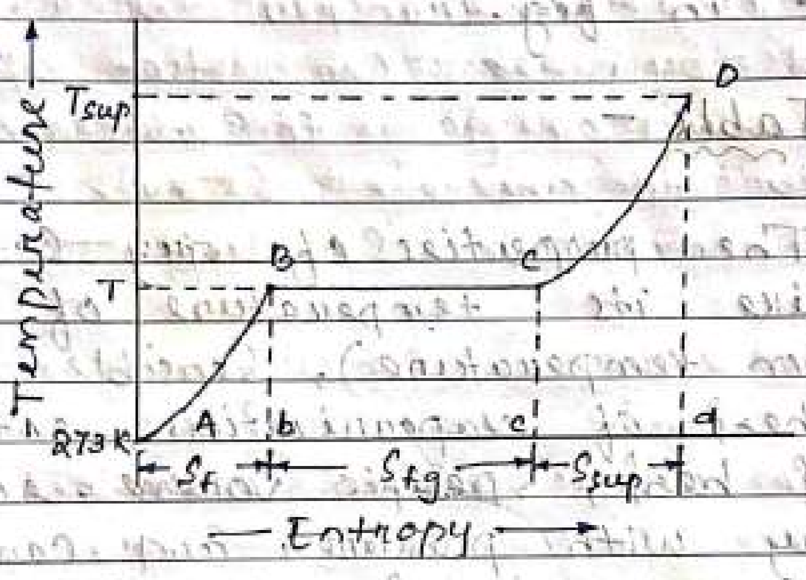
1. The heating of water up to boiling temperature or saturation temperature (t) is shown by AB in fig. The heat absorb by the water is AP, known as sensible heat or liquid heat or total heat of water.

2. The change of state from liquid to steam is shown by BC. The heat absorb during this stage is PQ, known as latent heat of vapourisation.

3. The superheating process is shown by CD. The heat absorb during this stage is QR, known as heat of superheat. Line AR represents the total heat of the superheated steam.

When the pressure and saturation temperature increases, the latent heat of vapourisation decreases, it becomes zero at a point (N) where liquid and dry steam lines meet. This point N is known as the critical point and at this point, the liquid and vapour phase merge, and become identical in every respect. The temperature corresponding to critical point N is known as critical temperature and the pressure is known as critical pressure. For steam, the critical temperature is 374.15°C and critical pressure is 212.2 bar.

Temperature - Entropy (T-S) Diagram for Water and Steam



Now consider 1 kg of water being heated at a constant pressure (p). We know that when heat is added to the water, its entropy will increase. If we plot a graph between temperature and entropy we shall find that the entropy increases along logarithmic curve with the increase in temperature, till the boiling temperature (T) corresponding to the pressure (p) is reached. It is shown by the graph AB. The corresponding increase in entropy (S_f) is given by the line AB as shown fig.

On further heating, we find that the water starts evaporating and receives heat at constant temperature (T). The entropy goes on increases, till the entire latent heat required to evaporate 1 kg of water has been supplied. The increase in entropy (S_{fg}) during evaporation is given by the line bc in fig.

Steam Table -

The properties of dry saturated steam like its temperature of formation (saturation temperature), sensible heat, latent heat of vapourization, enthalpy or total heat, specific volume, entropy etc, vary with pressure, and can be found by experiment only. These properties have been carefully determined, and made a available in a tabular from known as steam tables.

Mollier Chart -

Its a graphical representation of the steam tables, in which the enthalpy (h) is plotted along the ordinate and the entropy (s) along abscissa. First of all, enthalpy and entropy of water and dry saturated steam, for any particular pressure, are obtained from the steam tables.

STEAM GENERATOR

Chapter-04

Introduction–

A boiler is a steam generator which is used to convert steam from water by heating it.

A steam generator or boiler, usually, a closed vessel made of steel. It's function is to transfer the heat produced by the combustion of fuel (solid, liquid or gas) to water, and ultimatly to generate steam. The steam produced may be supplied.–

* To an external combustion engine i.e. steam engine and turbines.
* At low pressure for industrial process work in cotton mills, sugar factories, breweries etc.
* For producing hot water.

Important Terms for steam boilers –

Through there are many terms used in steam boilers, yet the following are important –

1. Boiler Shell – It is made up of steel plates bent into cylindrical form and riverted or welded together. The end of shell are closed by means of end plates. A boiler shell

classmate
Date
Page

Should have sufficient capacity to contain water and steam.

2. Combustion chamber — It is the space, generally below the boiler shell, meant for burning fuel in order to produce steam from the water contained in the shell.

3. Grate — Its a platform, in the combustion chamber, upon which fuel (coal or wood) is burnt. The grate, generally, consists of cast iron bars which are spaced apart so that air (required for combustion) can pass through them. The surface area of the grate, over which the fire takes place, is called grate surface.

4. Furnace — It is the space, above the grate and below the boiler shell, in which the fuel is actually burnt. The furnance is also called fire box.

5. Heating Surface — It is the part of boiler surface, which is exposed to the fire (or hot gases from the fire).

6. Mountings — These are fittings which are mounted on the boiler for its proper functioning. They include water

level indicator, pressure gauge, safety valve etc. It may be noted that a boiler cannot function safely without the mountings.

7. Accessories — These are the devices, which from an integral part of a boiler, but are not mounted on it. They include superheater, economiser, feed pump etc. It may be noted that the accessories help in controlling and running the boiler efficiently.

Classification of steam boilers —

1. According to the contents in the tube —
   (a) Fire tube or smoke tube boilers.
   (b) Water tube boilers.

2. According to the position of the furnance —
   (a) Internally fired boilers
   (b) Externally fired boilers.

3. According to the axis of the shell —
   (a) Vertical boilers
   (b) Horizontal boilers.

4. According to the number of tubes —
   (a) Single tube boilers.

(b) Multi-tubular boilers.

5. According to the method of circulation of water and steam —
   (a) Natural circulation boilers.
   (b) Forced circulation boilers.

6. According to the use —
   (a) Stationary boilers.
   (b) Mobile boilers.

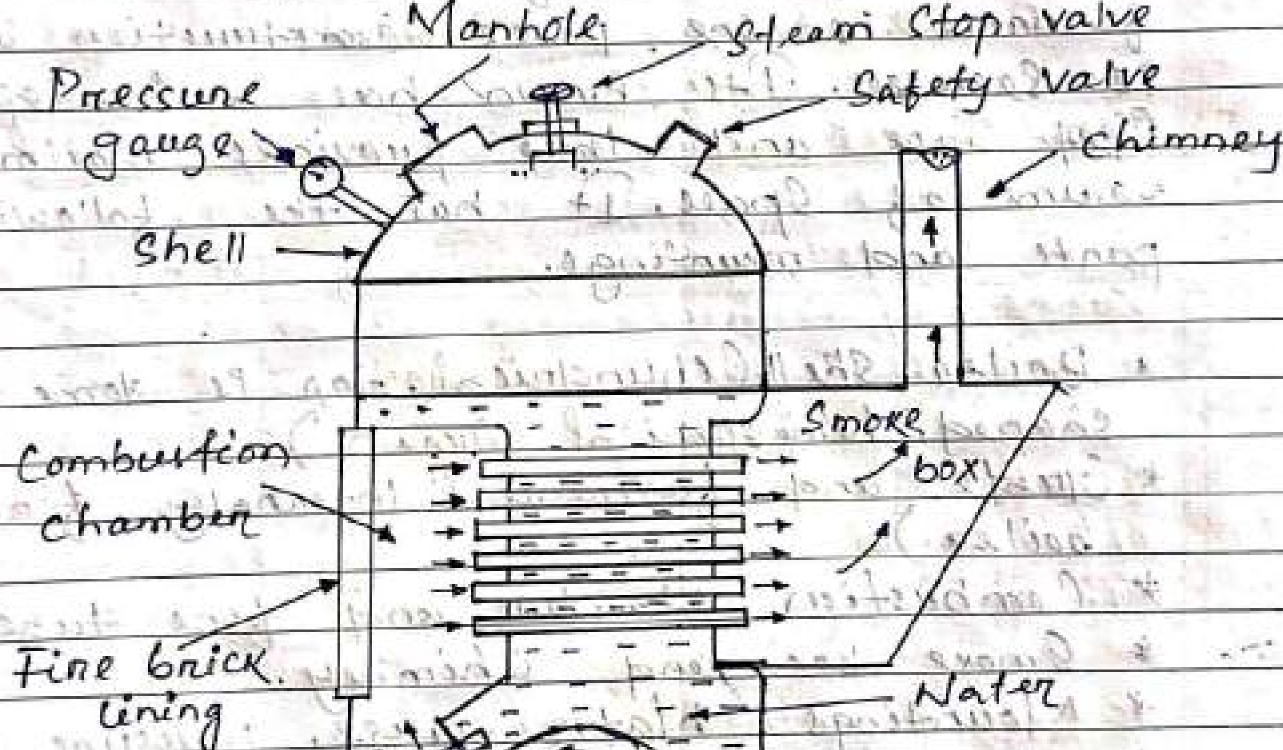
Comparison between Fire tube & Water tube boiler —

Water tube boiler	Fire tube boiler
1. The water circulates inside the tubes which are surrounded by hot gases from the furnance.	1. The hot gases from the furnance pass through the tubes which are surrounded by water.
2. It generates steam of a higher pressure upto 165 bar.	2. It can generate steam only upto 24.5 bar.
3. The rate of generation of steam is high upto 450 tonnes per hour.	3. The rate of generation of steam is low upto 9 tonnes per hour.
4. For a given power, the floor area required	4. The floor area required more. i.e

for generation of steam is less i.e about 5 m^2 per tonne per hour of steam generation.	about 8 m^2 per tonne per hour of steam generation.
5. Overall efficiency with economiser is upto 90 %.	5. Its overall efficiency is only 75 %.
6. It can be transported and erected easily as its various parts can be separated.	6. The transportation and erection is difficult.
7. It is preferred for widely fluctuating loads.	7. It can also cope reasonably with sudden increase in load but for a shorter period.
8. The direction of water circulation is well defined.	8. The water does not circulate in a definite direction.
9. The operating cost is high.	9. The operating cost is less.
10. The bursting chances are more.	10. The bursting chances are less.

11. The bursting does not produce any destruction to the whole boiler.	11. The bursting produces greater risk to the damage of the property.
12. It is used for large power plants.	12. It is not suitable for large plants.

Cochran Boiler or Vertical Multitubular Boiler—



cochran boiler

Cochran boiler is a vertical multi-tubular fire tube boiler. It produces steam of low pressure from the heat exchange between water and flue gas. It has steam capacity upto 3500 Kg/hr.

Construction of Cochran boiler –

It consist of a cylindrical shell with a dome shaped top where the space is provided for steam. The furnance is one piece construction and is seamless. Its crown has a hemispeerical shape and thus provides maximum volume of space. It has the following parts and mountings.

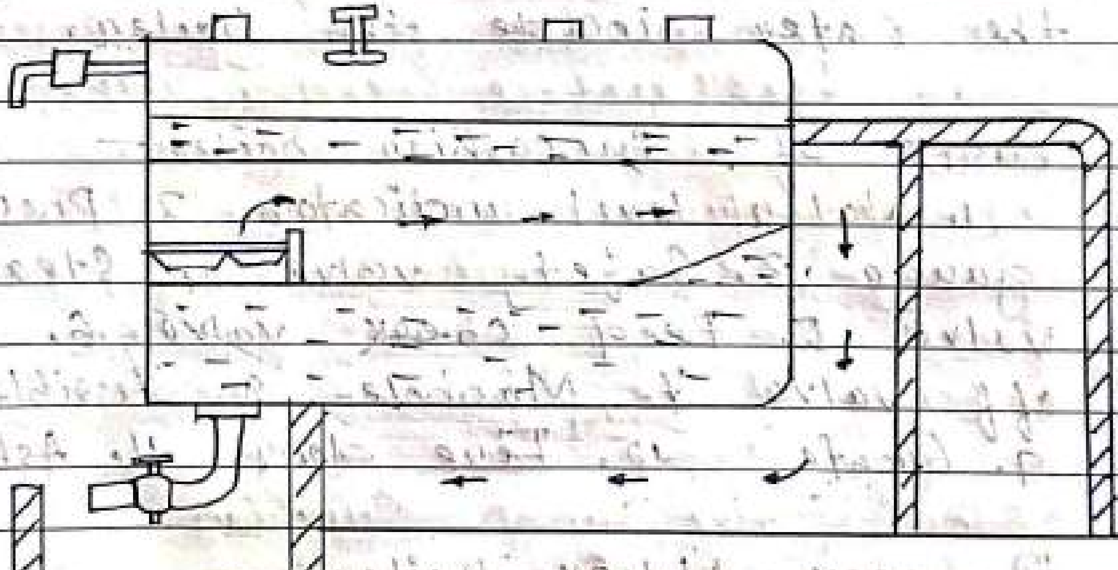
* Boiler shell (cylindrical, top is dome shaped, hemisperical crown).
* Grate and furnance (Internally fired boiler)
* Combustion chamber and fire tubes.
* Smoke box and chimney.
* Mountings – Water gauge, pressure gauge, fusible plug, feed check valve, steam stop valve, safety valve and blow off cock.

Working of Cochran boiler –

When the fuel burns inside

the fire box / Furnance. flue gas produces and flow into the Combustion chamber after striking through the fire brick linings. Then the flue gases passes through the fire tubes to exchange heat with water surrounding to them. Then the flue gas is collected in a smoke box and escape to the atmosphere through chimney. In this way the steam produces at the top of the boiler shell and collected.

· Lancashire Boiler:-



It is a stationary, Fire tube, internally fired, horizontal and natural circulation boiler. It is used where working pressure and power required are moderate. These boilers have a cylindrical shell of 1.75 m to 2.75 m diameter. Its length varies from 7.25 m to 9 m. It has two internal flue tubes having diameter about 0.4 times that of shell. This type of boiler is set in work brick work forming external flue so that part of the heating surface is on the external shell.

Lancashire boiler work on the principle of the heat exchanger. The heat is a transfer from exhaust gases to the water through convection. It is a natural circulation boiler that uses natural current to flow the water inside the boiler.

Parts of Lancashire boiler –
1. Water level indicator 2. Pressure gauge 3. Safety valve 4. Steam stop valve 5. Feed check valve 6. Blow off valve 7. Manhole 8. Fusible plug 9. Grate 10. Fire door 11. Ash pit.

Babcock Wilcox Boiler –

It is a horizontal inclined tube, Water tube boiler, In this boiler high pressure steam produces from the heat exchange between water and hot flue gases.

Safe operation such as: Steam stop valve, Safety valve, water level indicator, pressure gauge, thermometer, fusible plug, feed check valve, blow-off cock, man hole etc.

Working—

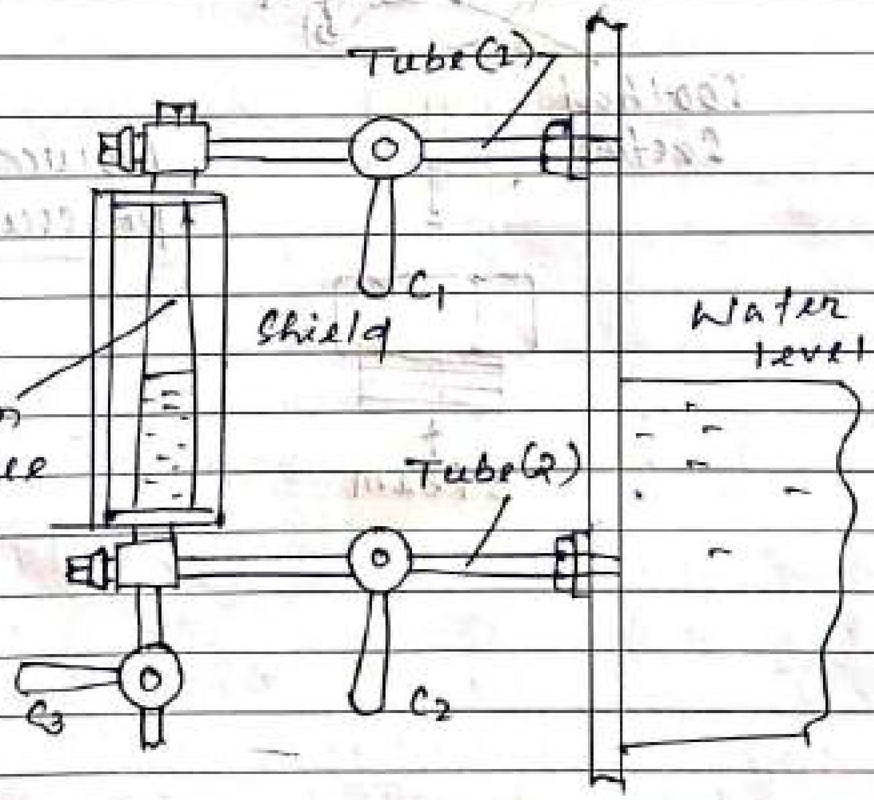
Fuel is supplied to grate through fire door where it is burnt. The hot gases are forced to move upwards between the tubes by baffle plates provided. The water from the drum flows through the inclined tubes via down take header and goes back into the shell in the form of water and steam via uptake header. The steam goes collected in the steam space of the drum. The steam then enters through the anti-priming pipe and flows in the super heater tubes where it is further heated and is finally taken out through the main stop valve and supplied to the steam turbine or steam engine when needed.

Boiler Mountings—

These are the fitting and devices which are necessary for the operation and safety of a boiler. Through there are many ~~toy~~ types of boiler mountings, yet the followinge are important from the Subject point of view.

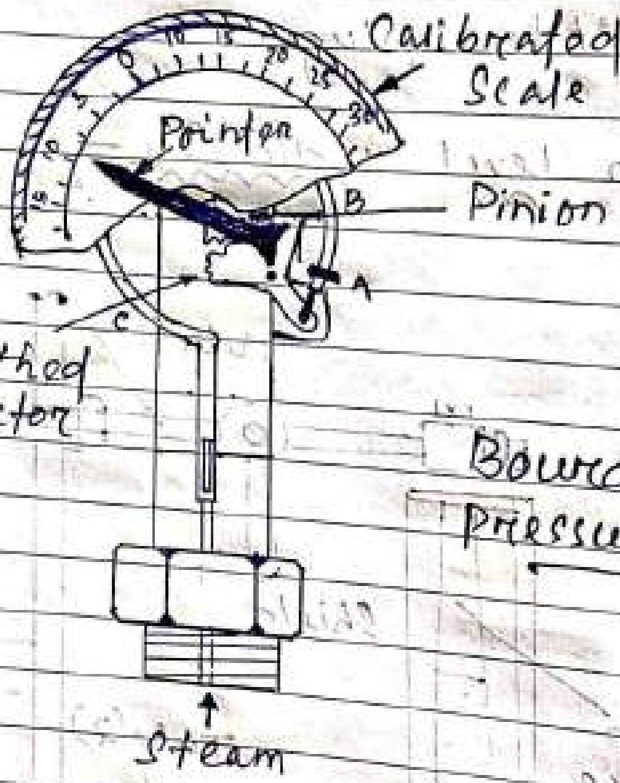
1. Water level indicator
2. Pressure gauge
3. Safety Valve
4. Steam Stop valve
5. Blow-off cock
6. Feed cheack valve
7. Fusible plug.

1. Water level indicator –



It is an important fitting, which indicates the water level inside the boiler to an observer. In the working of a steam boiler and for the proper functioning of the water level indicator, the steam and water cocks are opened and the drain cock is closed. In this case, the handles are placed in a vertical position.

Pressure gauge-

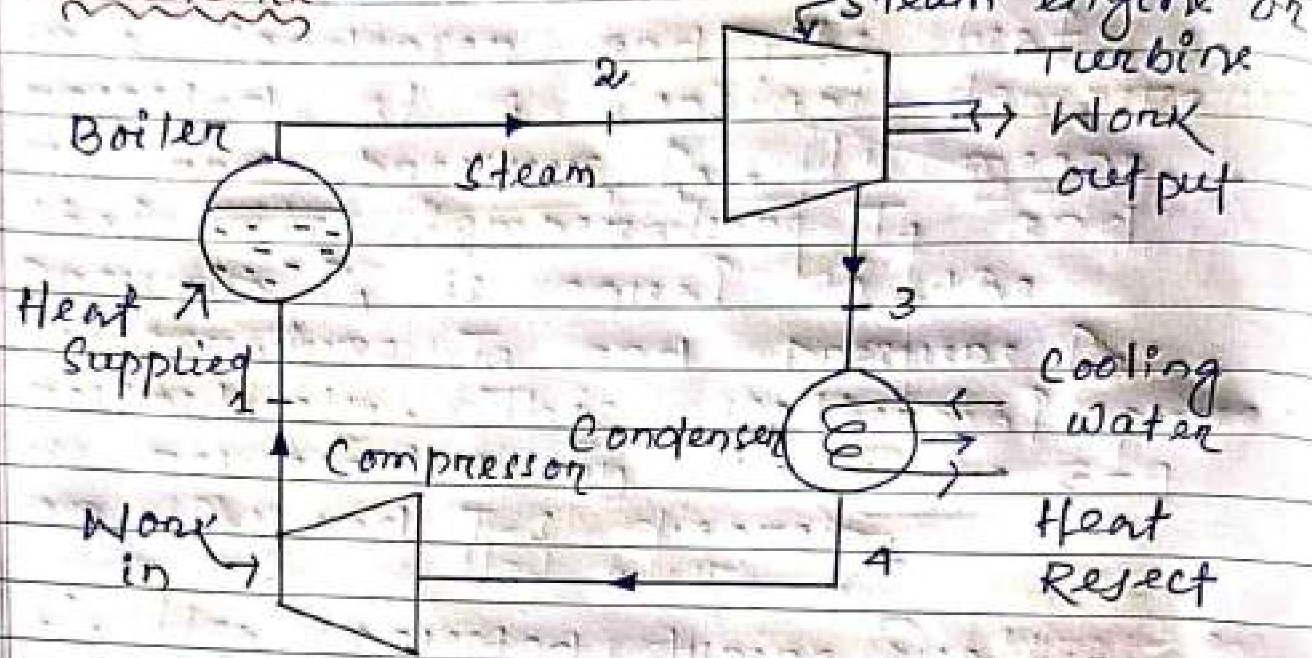


Bourden type pressure gauge

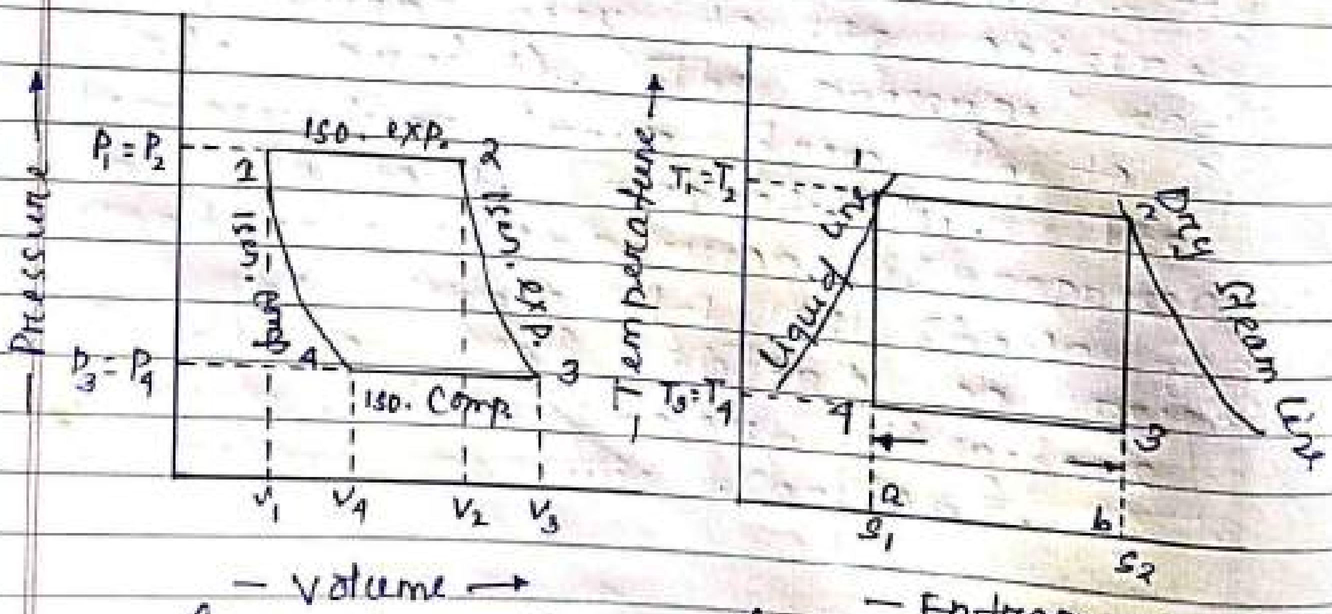
Steam Power Cycles

Chapter-05

Carnot cycle with steam as working substance —



The schematic diagram of a Carnot cycle using steam as the working substance is represented on P-V and T-S diagram as shown fig.



(P-V Diagram) (T-S diagram)

Consider 1 kg of saturated water at pressure P_1 and absolute temperature T_1, as represented by point 1 Fig. The cycle is completed by the following four processes.

1. Process 1-2 - The saturated water at point 1 is isothermally converted into dry saturated steam, in a boiler, and the heat is absorbed at a constant temperature T_1 and pressure P_1. The dry state of steam is represented by point 2. Entropy increases from S_1 to S_2 and dry steam is collected at state 2.

∴ Heat absorbed during isothermal process (area 1-2-b-a)

Q_{1-2} = Change in entropy x Absolute temperature

$= (S_2 - S_1) = T_1 = T_1(S_2 - S_1)$

2. Process 2-3 - The dry steam at point 2 now expands isentropically in a steam engine or turbine. The pressure and temperature falls from P_2 to P_3 and T_2 to t_3 respectively. Since no heat is supplied or rejected during this process, therefore no change of entropy. The isentropic expansion is represented by the curve 2-3 as shown fig.

3. Process 3-4 - The wet steam at point 3 is now isothermally condensed in a condenser and the heat rejected at a constant temperature T_3 and pressure $P_3 = P_4$ means that the temperature T_4 and pressure P_4 is equal to the temperature T_3 and pressure P_3 respectively. This isothermal process is represented by the curve 3-4 on P-v and T-s diagram.

∴ Heat rejected during isothermal compression (area 3-4-a-b),

$$Q_{3-4} = (S_2 - S_1)\ T_3 = T_3(S_2 - S_1)$$

4. Process 4-1 - The wet steam at point 4 is finally compressed isentropically in a compressor, till it return back to its original state (point 1). The pressure and temperature raise from P_4 to P_1 and T_4 to T_1 respectively. The isentropic compression is represented by the curve 4-1 as shown fig. Since no heat absorb or rejected during this process, therefore entropy remains constant.

We know that work done during the cycle

$$= \text{Heat absorbed} - \text{Heat rejected}$$

$$= (S_2 - S_1) T_1 - (S_2 - S_1) T_3 = (S_2 - S_1)(T_1 - T_3)$$

Efficiency of Carnot cycle -

$$\text{Efficiency } \eta_{Carnot} = \frac{\text{Workdone}}{\text{Heat supplied}}$$

$$= \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

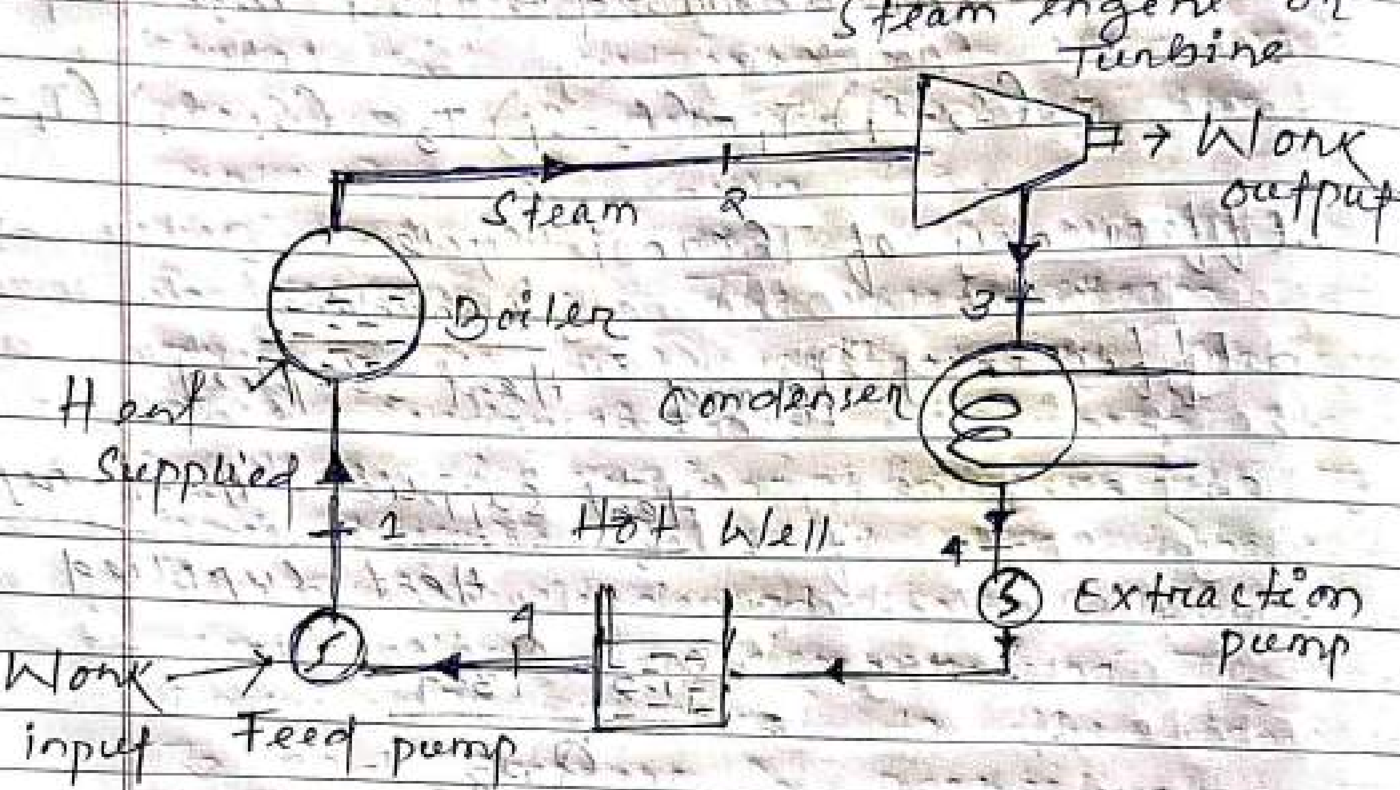
$$= \frac{Q_{1-2} - Q_{3-4}}{Q_{1-2}}$$

$$= \frac{T_1 (S_2 - S_1) - T_3 (S_2 - S_1)}{T_1 (S_2 - S_1)}$$

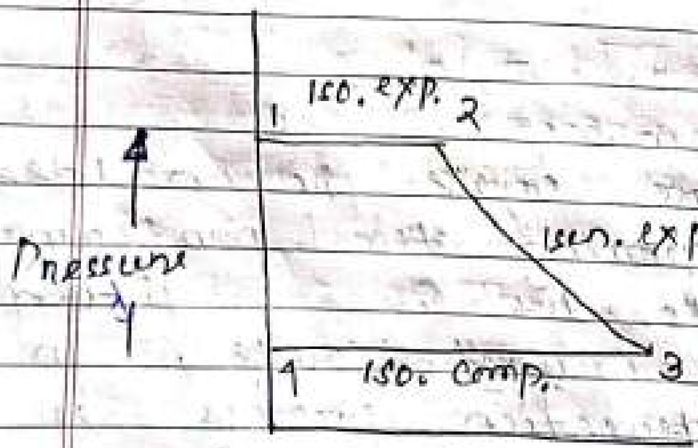
$$= \frac{T_1 - T_3}{T_1} = 1 - \frac{T_3}{T_1}$$

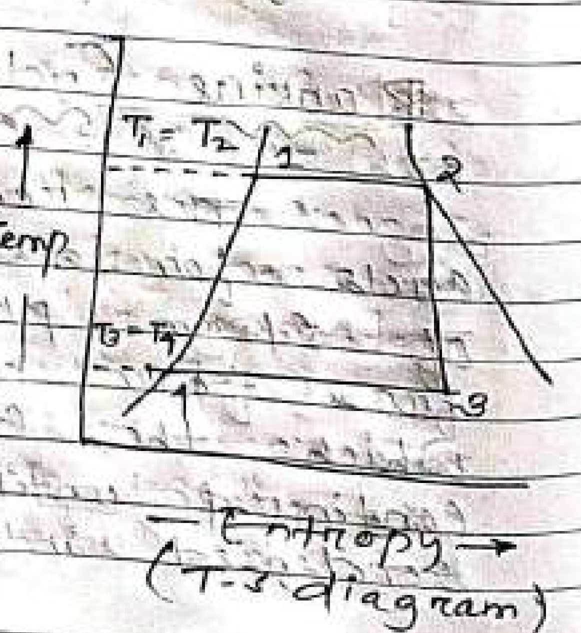
Rankine Cycle -

The rankine cycle is an ideal cycle for comparing the performance of steam plants. It is modified ~~form~~ form of Carnot cycle, in which the condensation process is continued until the steam is condensed into water. The schematic diagram of a steam engine or a turbine plant is shown fig.



A rankine cycle, using steam as a working substance, is represented on P-V and T-s diagrams as shown fig.





Consider 1 kg of Saturated water at pressure P_1 and absolute temperature T_1 as represented by point 1. The cycle is completed by following four process.

1. Process 1-2 – The saturated water at point 1 is isothermally converted into dry saturated steam in a boiler, and the heat is absorbed at a constant temperature T_1 and pressure P_1. The dry state of steam is represented by point 2. This means that the temperature T_2 and pressure P_2 is equal to temperature T_1 and pressure P_1 respectively. This isothermal process is represented by curve 1-2 on p-v and T-s diagram.

We know that the heat absorbed during isothermal process by water during its conversion into dry steam is its latent heat of vaporisation ($h_{fg1} = h_{fg2}$), corresponding to a pressure P_1 and P_2

$$(\because P_1 = P_2)$$

2. Process 2-3 – The dry saturated steam at point 2, now expands isentropically in an engine or turbine. The pressure and temperature falls from P_2 to P_3 and T_2 to T_3 respectively

with a dryness fraction x_3. Since no heat is supplied or rejected during this process, therefore there is no change of entropy. The isentropic expansion is represented by the curve 2-3 as shown fig.

3. Process 3-4 - The wet steam at point 3 is now isothermally condensed in a condenser and the heat is rejected at constant temperature T_3 and pressure P_3 until the whole steam is condensed into water. It means that the temperature T_4 and pressure P_4 is equal to the temperat T_3 and pressure P_3 respectively. The isothermal compression is represented by curve 3-4 on P-V and T-S diagrams in fig.

The heat rejected by steam is its latent heat (equal to $x_3 h_{fg_3}$).

4. Process 4-1 - The water at point 4 is now warmed in a boiler at constant volume from temperature T_4 to T_1. Its pressure also raise from P_4 to P_1. This warming operation is represented by the curve 4-1 on P-V and T-S diagram in fig. The heat absorbed by the water during this operation is equal to the

Sensible heat or liquid heat corresponding to the pressure P_1 equal to Sensible heat at point 1 minus Sensible heat at point 4.

∴ Heat absorbed during warming operation 4-1

$$= h_{f_1} - h_{f_4} = h_{f_2} - h_{f_3}$$

and heat absorbed during the complete cycle

= Heat absorbed during isothermal operation 1-2 + Heat absorbed during warming operation 4-1

$$= h_{fg_2} + (h_{f_2} - h_{f_3})$$

$$= h_{f_2} + h_{fg_2} - h_{f_3}$$

$$= h_2 - h_{f_3}$$

We know that heat rejected during the cycle

$$= h_3 - h_{f_4} = h_{f_3} + x_3 h_{fg_3} - h_{f_4} = x_3 h_{fg_3}$$

Workdone during the cycle

= Heat absorbed - Heat rejected

$$= (h_2 - h_{f_3}) - x_3 h_{fg_3}$$

$$= h_2 - (h_{f_3} + x_3 h_{fg_3}) = h_2 - h_3$$

and efficiency (also called Rankine efficiency);

$$\eta_R = \frac{\text{Work done}}{\text{Heat absorbed}} = \frac{h_2 - h_3}{h_2 - h_{f_3}}$$

The terms efficiency ratio, work ratio and Specific steam consumption –

Efficiency Ratio – It is the ratio of thermal efficiency to Rankine cycle efficiency or actual cycle efficiency to ideal cycle efficiency.

$$\text{Efficiency ratio} = \frac{\text{Thermal efficiency}}{\text{Rankine Efficiency}}$$

$$\text{Thermal efficiency} = \frac{3600 \times P}{m(h_2 - h_{f_3})}$$

Where,

P = power devloped in KW
m = Mass of Steam Supplied

Work Ratio = It is the ratio of net work done to the turbine work.

$$\text{Work ratio} = \frac{\text{Turbine work} - \text{Compression work}}{\text{Turbine Work}}$$

Specific Steam Consumption –

It is defing

as the mass of steam supplied to the turbine to developed unit power output. It is also known as steam rate or flow of steam.

Specific steam consumption $= \frac{3600}{h_2 - h_3}$ kg/kWh

Question no. 1 – A power plant is supplied with dry saturated steam at a pressure of 16 bar and exhaust at 0.2 bar. Using steam tables, find the efficiency of the carnot cycle.

Data Given,

$P_1 = 16$ bar $\quad P_2 = 0.2$ bar

From steam table, corresponding to a pressure of 16 bar, we find that

$$T_1 = 201.4^\circ C = 201.4 + 273 = 474.4 K$$

and corresponding to a pressure of 0.2 bar, we find that

$$T_3 = 60.1^\circ C = 60.1 + 273 = 333.1 K$$

We know that efficiency of carnot cycle,

$$\eta_{carnot} = \frac{\text{Heat absorbed} - \text{Heat rejected}}{\text{Heat absorbed}}$$

$$= \frac{T_1 - T_3}{T_1}$$

$$= \frac{471.1 - 333.1}{471.1}$$

$= 0.298$ or 29.8% Ans

Question no. 2 - In a carnot cycle, heat is supplied at 350°C and is rejected at 25°C. The working fluid is water which while receiving heat, evaporate from liquid at 350°C to steam at 350°C. From steam table, the entropy change for this process is 1.438 KJ/Kg K.

If the cycle operates on a stationary mass of 1kg of water, find the heat supplied, work done and heat rejected per cycle. What is the pressure of water during heat reception?

Data Given,

$T_1 = 350°C = 350 + 273 = 623 K$

$T_3 = 25°C = 25 + 273 = 28 K$

Change in entropy

$s_2 - s_1 = 1.438$ KJ/Kg K

Heat supplied per cycle

We know that heat supplied per cycle,

$= T_1 (s_2 - s_1) = 623 \times 1.438 = 895.87$ KJ/Kg

Work done per cycle,

We know that work done per cycle

$$= (S_2 - S_1)(T_1 - T_3)$$

$$= 1.438\ (623 - 298)$$

$$= 467.35\ KJ/Kg$$

Heat Rejected per cycle,

We know that heat rejected per cycle,

$$= T_3 (S_2 - S_1) = 298 \times 1.438 = 428.52\ KJ/Kg$$

pressure of water during heat reception -

The pressure of water during heat reception is the formation pressure of steam corresponding to 350°C. From steam tables, corresponding to 350°C, the pressure is 165.35 bar Ans

HEAT TRANSFER

Chapter-6

Heat transfer is the movement of thermal energy, or heat, between physical systems with different temperatures. It's a fundamental process in thermodynamics and occurs naturally whenever a temperature difference exists.

Method of heat transfer -

The heat transfer may be broadly defind as the transmission of heat energy from one region to another due to the temperature difference between these two region.

The following methods of heat transfer, from one body to another, are important from the subject point of view -

1. Conduction -

→ Conduction is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it.

→ In solids, the heat is conducted by the lattice vibration and by transport of free electrons.

→ In cases of gases, the molecules are in a continous random motion exchanging energy and momentum. When

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a molecular from the high temperature region collide with a molecule from the low temperature region. it loses energy by collisions.

→ In liquids, the mechanism of heat is nearer to that of gases, However, the molecules are more closely spaced and intermolecular forces comes into play.

2. Convection:-

Convection is the transfer of heat within a fluid by mixing of one portion of the fluid with another.

→ Convection is possible only in a fluid medium.

→ The heat flow depends on the properties of the material of the surface.

3. Radiation-

Radiation is the transfer of the heat through space or matter by means other than condition or convection.

→ All bodies radiate heat, so a transfer of heat by radiation occurs because hot body emits more heat than it receives and a cold body receives more heat than it emits.

Fourier's Law of heat Conduction —

Fourier's Law states that, "The rate of flow of heat through a simple homogeneous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change of temperature with respect to the length of the path of the heat flow".

Mathematically, it can be represented by the equation, —

$$Q \propto A \cdot \frac{dT}{dx} = KA \times \frac{dT}{dx}$$

Where,

Q = Amount of heat flow through the body in a unit time.

A = Surface area of heat flow. It is taken at right angles to the direction of flow.

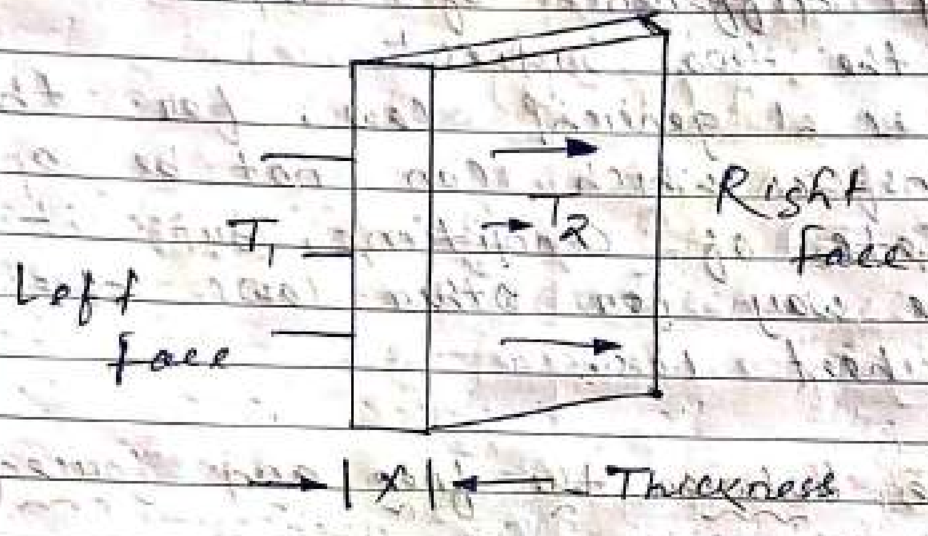
dT = Temperature difference on the two faces of the body.

dx = Thickness of the body through which the heat flows. It is taken along the direction of heat flow.

K = Constant of proportionality known as thermal conductivity of the body.

Heat Transfer by Conduction through a slab -

Consider a solid slab having one of its face (say left) at a higher temperature and the other (say right) at a lower temperature as shown fig.



Heat transfer through a slab.

Let, T_1 = Temperature of the left face (Higher temperature) in K.

T_2 = Temperature of the righ face (Lower temperature) in K.

x = Thickness of the slab.

A = Area of the slab.

K = Thermal conductivity of the body.

t = Time through which the heat flow has taken place.

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Newton's Law of Cooling - It is an important law in the field of heat transfer which states, "Heat transfer from a hot body to a cold body is directly proportional to the surface area and difference of temperatures between the two bodies".

It is a general law, for the heat transfer which can not be applied to all sets of conditions, But it paved the way for other laws dealing in the heat loss.

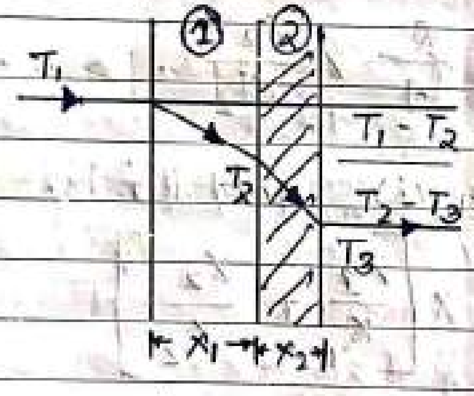
Difference between the free and forced convection -

Free Convection	Forced convection
Free or Natural is the process of heat transfer which occurs due to movement of the fluid particles by density changes associated with temperature differential in a fluid.	Forced convection is the process of heat transfer in which the motion of fluid generated by external sources like pump, fan, suction device etc.
When there is density difference among the heated and cooled layers of fluid, the	When the fluid is forced by means of external sources to flow in a device

fluid layers flow freely. | for heat transfer, it is said to be forced convection.

Heat transfer by conduction through a composite wall -

Consider a composite wall consists of two different materials through which the heat (i.e.,) being transferred by conduction.



Let,

x_1 = Thickness of first material

K_1 = Thermal conductivity of first material.

x_2 = Thickness of second material

K_2 = Thermal conductivity of second material.

T_1, T_3 = Temperature of the two outer surfaces.

T_2 = Temperature at the section point.

A = Surface area of the wall.

Now assuming T_1 to be higher than T_2, the heat will flow from left to right. Under steady condition, the rate of heat flow through section 1 is equal to that through section 2. We know that heat flowing through section 1,

$$Q = \frac{K_1 A (T_1 - T_2)}{x_1}$$

$$(T_1 - T_2) = \frac{Q}{A} \times \frac{x_1}{K_1} \quad \text{--- (i)}$$

Similarly for section 2,

$$(T_2 - T_3) = \frac{Q}{A} \times \frac{x_2}{K_2} \quad \text{--- (ii)}$$

Adding equation (i) and (ii),

$$(T_1 - T_3) = \frac{Q}{A} \times \left[\frac{x_1}{K_1} + \frac{x_2}{K_2}\right]$$

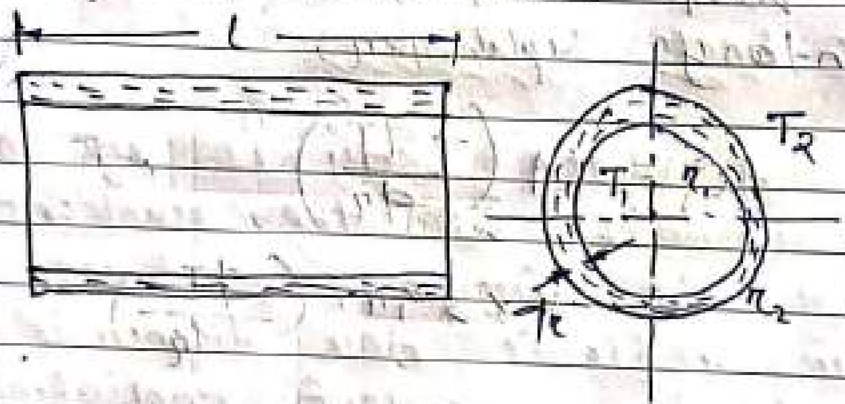
$$Q = \frac{A(T_1 - T_3)}{\frac{x_1}{K_1} + \frac{x_2}{K_2}} = \frac{(T_1 - T_3)}{\frac{x_1}{K_1 A} + \frac{x_2}{K_2 A}}$$

$$= \frac{(T_1 - T_3)}{\sum \frac{x}{KA}}$$

Radial Heat transfer by conduction through a thick cylinder :-

The heat transfer through boiler tubes or refrigerator pipings are the examples of conduction of heat transfer radially through the walls of hollow thick cylindrical pipes.

Consider a thick pipe of length l carrying steam or a hot liquid at a higher temperature.



Let,

T_1 = Inside (Higher) temperature of liquid.

T_2 = Outside (Lower) temperature of the surroundings,

r_1 = Inside radius of the pipe

r_2 = Outside radius of the pipe

$\therefore (r_2 - r_1)$ = Thickness of the pipe.

This thick pipe may be imagined to consist of a large number of thin concentric cylinder of increasing radius.

Now consider any thin imaginary cylinder of infinitesimal thickness (dr) at a distance (r) from the axis of the pipe. Let temperature drop across the thickness be dT.

We know that the surface area of this imaginary cylinder,

$$A = 2\pi r l$$

and heat conduction through this elementary cylinder,

$$Q = KA\left(\frac{-dT}{dr}\right)$$

$$= -K \times 2\pi r l\left(\frac{dT}{dr}\right)$$

Stefan Boltzmann Law -

According to Stefan Boltzman's Law, the emissive power of a black body is directly proportional to absolute temperature to the fourth power.

i.e $= E_b = \sigma A T^4$

Where: E_b = total emissive power of a black body,

σ = Stefan Boltzmann Constant $= 5.67 \times 10^{-8}\ W/m^2 K^4$

A = Surface area of heat radiation
T = Absolute Temperature

Kirchoff's law -

The law States that at any temperature, the ratio of total emissive power (E) to the total absorptivity (a) is a constant for all Substances, which are in thermal equilibrium with their environment.

Kirchhoff's law also states that, the emissivity of a body is equal to its absorptivity when the body remains in thermal equilibrium with its Surroundings.

Total emissive power and emissivity -

Total emissive power (E) - The emissive power is defined as the total amount of radiation emitted by a body per unit area and time. It is expressed in W/m^2.

According to Stefan boltzmann's law, the emissive power of a black body is directly proportional to absolute temperature to the fourth power. i.e $E_b = \sigma A T^4$

Emissivity (ϵ) It is defined as the ability of the Surface of a body to radiate heat. It is also defined as the ratio of the emissive power of a body to the emissive power of a black body ~~at~~ ~~standing~~ of equal temperature.

$$i.e., \epsilon = \frac{E}{E_b}$$

Where,
E = emissive power of a body,
E_b = emissive power of a black body

Black body Radiation –

A black body is an object that absorbs all the radiant energy reaching its surface. A black body neither reflects nor transmits any part of the incident radiation but absorbs all of it. For a black body: absorptivity $(\alpha) = 1$, Reflectivity $(\rho) = 0$ and Transmittivity $(\tau) = 0$. It emits maximum amount of thermal radiations at all wavelengths at any specified temperature. The radiation emitted by a black body is independent of direction. It absorbs all the incident radiation falling on it and does not transmit or reflect regardless of wavelength and direction.

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Black body -

A black body is one which neither reflects nor transmits any part of the incident radiation but absorbs all of it.

For a black body: absorptivity $(\alpha) = 1$
Reflectivity $(\rho) = 0$
Transmittivity $(\tau) = 0$

White body -

It is all the incident radiation falling on the body are reflected, it is called a 'white body'.

For a white body: Absorptivity $(\alpha) = 0$
Reflectivity $(\rho) = 1$
Transmittivity $(\tau) = 0$

Grey body -

If the radiative properties, α, ρ, τ of a body are assumed to be uniform over the entire wavelength Spectrum, then such body called grey body.

Absorptivity (α) - It is the ratio of amount of heat absorbed to total incident radiation.

Reflectivity (ρ) - It is the ratio of amount of heat reflected to total incident radiation.

Transmittivity (τ) - It is the ratio of amount of heat transmitted to total incident radiation.