UTKALMANI GOPABANDHU INSTITUTE OF ENGINEERING, ROURKELA

Lecture Note

Sub:- Thermal Engineering-II (Th-4)

Semester :- 4th

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DEPARTMENT OF
MECHANICAL ENGINEERING

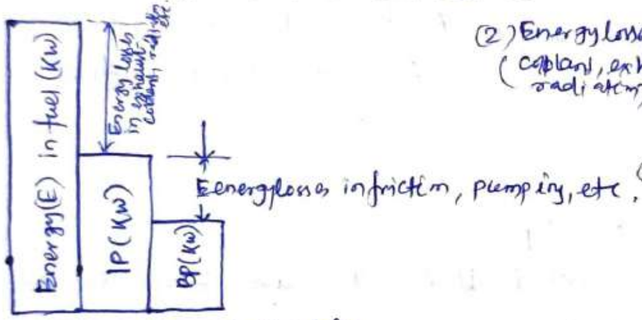
Theory - 4   Thermal Engineering - II

1. Performance of I.C Engine

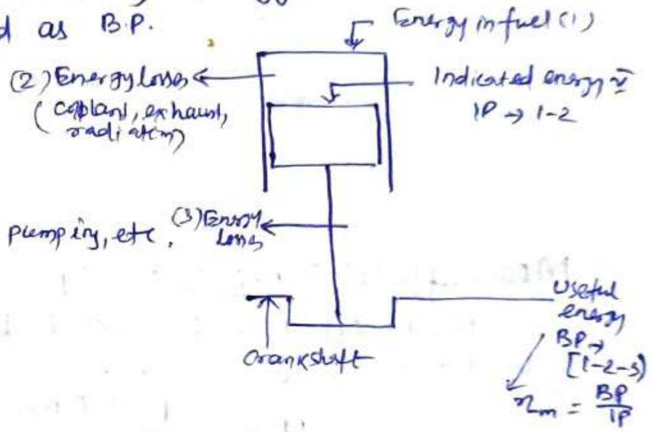
According to 1st law of thermodynamics energy can neither be created nor destroyed. It can only be converted from one form to other. There must be energy balance of I/P and O/P.

IC Engine :→ chemical energy (fuel burns in air converting) convert into heat (into heat)

The whole of this energy cannot be utilized for driving the piston as there are losses to the exhaust, to the coolant and to radiation. The remaining energy converted to power is called indicated power (IP). (The heat energy which is converted to power is called (IP)). This is utilised to drive the piston. The energy applied to the piston passes through connecting rod to the crank shaft. In this transmission there are energy losses due to friction, pumping losses, valve mechanism, feed pump, ignition system etc. The sum of all these losses expressed in units of power is termed as frictional power (F.P). The remaining energy is the useful mechanical energy and is termed as B.P.



Energy Distribution



$\eta_m = \frac{BP}{IP}$

IP

$$IP = \frac{K P_m L A n}{60} \text{ (KW)}$$

K → No. of cylinder

L → length of stroke

A → c/s area of piston

$= \frac{\pi}{4} d^2$, d → cylinder bore ≈ Dia of piston

P_m → Mean effective pressure inside the cylinder during combustion (KPa) (this is not the peak pr.)

n → No. of working stroke per minute

= N for 2-stroke cycle

$= \frac{N}{2}$ for 4-stroke cycle

BP

N - RPM of crankshaft

T → Torque at crankshaft

= F R → crank radius

F → Tangential force on crank pin

$$BP = \frac{2\pi N T}{60} \text{ (W)}$$

$$= \frac{2\pi N (F \cdot R)}{60} \text{ (W)}$$

FP

$$FP = IP - BP$$

Indicated Thermal Efficiency (η_{ith})

η_{ith} is the ratio of energy in the indicated power to the input fuel energy

$$\eta_{ith} = \frac{IP \text{ [KJ/s]}}{\text{Energy in fuel per sec [KJ/s]}}$$

$$= \frac{IP \text{ (KJ/sec)}}{\text{mass of fuel/sec (Kg/sec)} \times \text{Calorific value of fuel (KJ/kg)}}$$

Brake thermal efficiency (η_{bth}) - is the ratio of energy in the brake power to the I/p fuel energy.

$$\eta_{bth} = \frac{b.P}{\text{mass of fuel in sec} \times \text{Calorific value of fuel}}$$

Mechanical Efficiency (η_m). is the ratio of brake power (delivered power) to the indicated power (power provided to the piston)

$$\eta_m = \frac{bP}{iP} = \frac{bP}{bP + fP}$$

$$fP = iP - bP$$

It can also be defind as the ratio of the brake thermal efficiency to the indicated thermal efficiency.

Relative Efficiency or Efficiency Ratio (η_{rel}) is the ratio of thermal efficiency of actual cycle to that of the ideal cycle.

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

Mean effective pressure (P_m)

Mean effective pressure is the average pressure inside the cylinder of an IC engine.

$$IP = \frac{P_m L A n K}{60}$$

$n \rightarrow \frac{N}{2}$ for 4-stroke engine
$\rightarrow N$ for 2-stroke engine

Force on piston $= P_m \times A \times 10^5$ N (bar)

Workdone per working stroke = Force × length of stroke
$= P_m \times A \times 10^5 \times L$ N-m

Workdone per second = Workdone per stroke × No. of working stroke persec

$$= P_m \times L \times A \times 10^5 \times \frac{N}{60} \times K \quad \text{N-m/sec or J/s}$$

$$= \frac{P_m L A N K \times 10^5}{60 \times 1000} \text{ KW}$$

$$IP = \frac{P_m L A N K}{6} \times 10 \text{ KW}$$

If K is the no. of cylinder

$$IP = \frac{n P_m L A N K}{6} \times 10 \text{ KW}$$

Air-fuel ratio - It is ratio of mass of air to mass of fuel in the Air-fuel mixture

$$= \frac{\dot{m}_a}{\dot{m}_f}$$

Specific fuel Consumption (sfc) -

It is the mass of fuel consumed per KW developed per hour. $\frac{\text{Fuel Consumption per unit time}}{\text{Power}}$ $\left(\frac{Kg}{KW\text{-}hr}\right)$

$sfc = \frac{\dot{m}_f}{BP} \quad \frac{Kg}{KW \cdot h}$

bsfc

isfc on the basis of bp and ip.

Thermal Efficiency

It is the ratio of indicated work done to energy supplied by the fuel.

$\eta_{th}(F) = \frac{IP}{\dot{m}_f \times C}$ (Based on IP)

$\eta_{th}(B) = \frac{BP}{\dot{m}_f \times C}$ (Based on BP)

$\dot{m}_f \rightarrow$ mass of fuel used in kg/sec

$C \rightarrow$ C.V of fuel (lower)

Calorific value of Fuel (CV) . (Heating value / Heat of Combustion)

CV is the thermal energy released per unit ~~mass~~ quantity of fuel when the fuel is burned completely and the products of combustion cooled back to the initial temperature of combustible mixture. Unit - KJ/Kg

It is defined as the amount of heat energy released during complete combustion of unit mass of fuel. (KJ/kg)

Air standard efficiency

$\eta_{ase} = 1 - \frac{1}{r^{\gamma-1}}$ (Petrol engine)

$= 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\rho^{\gamma}-1}{\gamma(\rho-1)}\right]$ (Diesel engine)

$r \rightarrow$ Compression Ratio $= \frac{V}{V_C} = \frac{V_C + V_S}{V_C}$ → Total vol. of cylinder

$\gamma \rightarrow$ Ratio of specific heat

$\rho \rightarrow$ Cut~~off~~ ratio

$V_C \rightarrow$ Clearance volume

$V_S \rightarrow$ swept volume $= \frac{\pi}{4} d^2 \times L$

Volumetric efficiency

It is the ratio of actual volume of charge admitted during suction stroke to the clearance ~~swept~~ volume of the piston.

$\eta_v = \frac{v_a}{v_c}$

$P v_a = m_a R T$

$P = 1.013 \times 10^5 \ N/m^2$

$R = 281 \ J/kg$

$T =$

$\frac{v_3}{v_2} \rightarrow$ cutoff Ratio

Speed of piston $= 2LN$

Torque, $T = W \times L$ (load × length of brake) N-m

Power of single stage compressor

$P = IP = \frac{W N_w}{60}$ watt

$W \rightarrow$ compression work (isothermal / Polytropic / adiabatic)

$N_w \rightarrow$ No of working cycle

$N_w = N$ (single acting)

$N_w = 2N$ (Double acting)

$N \rightarrow$ speed of compressor

$n =$ No of working stroke per min

$= N \rightarrow$ 2 stroke

$= \frac{N}{2} \rightarrow$ 4 stroke

$\gamma = \frac{C_p}{C_v} = 1.4$

Overall efficiency = Brake Thermal Efficiency.

Ch-2 Air Compressor

→ A Compressor is a mechanical device that is used to compress ~~gases~~ the atmospheric air, ~~and~~ compress it ~~raise its pressure~~ and delivers the high pressure air.

→ High pressure air delivers to storage tank and conveyed by the pipeline wherever is required.

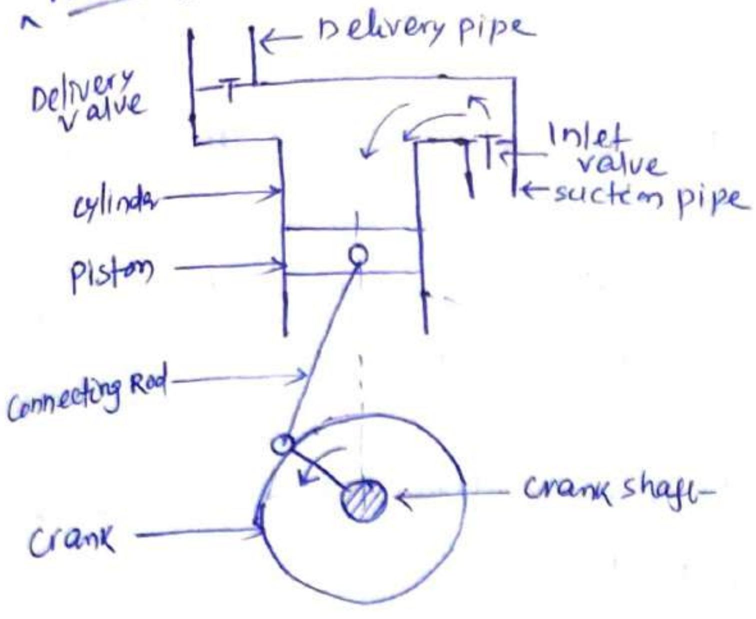
Industrial use of ~~Air~~ compressed air

→ operating pneumatic drill, hammer, riveters, etc.
→ operating pneumatic Brakes in locomotives
→ Starting IC engine
→ Paint spraying
→ operating gas turbine
→ ~~Sup~~ super charging of IC engine
→ Air conditioning of air craft and large building.
→ operating Air motor
→ cleaning of w/s machines, generators, automobile vehicles, etc.
→ compressed air used in blast furnaces.

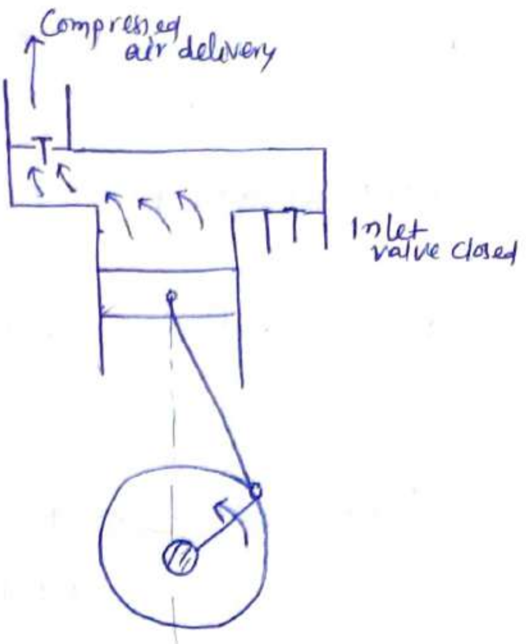
Classification of Air Compressors

- Air Compressor
  - Reciprocating Compressor
    - Single acting ~~stage~~
      - Single stage
      - Multi ~~double~~ stage
    - Double acting ~~stage~~
      - Single stage
      - Multi stage
  - Rotary Compressor
    - Blower type
      - Roots blower
      - vane blower
    - Centrifugal type

Construction and
Working principle of Air Compressor



Suction stroke



Delivery stroke

→ It consists of piston which reciprocates in a cylinder driven through a connecting rod and crank

→ There are inlet valve and delivery valve mounted in the cylinder head.

Working.

→ During downward motion of the piston the pressure inside the cylinder falls below atmosphere. So suction valve/inlet valve opens due to difference of pressure.

→ So that air is sucked into the cylinder through suction pipe.

→ During admission of air the delivery valve remains closed.

→ Now the piston move upward and the pressure inside cylinder gradually increases.

→ When the pressure becomes larger than atmospheric pressure, the suction valve / inlet valve closes.

→ When the pressure in the cylinder is greater than that in the delivery pipe, the delivery valve opens due to difference of pressure. and the air is delivered through delivery pipe.

→ ~~As the~~ Once again the piston begins to move down and the delivery valve closes; the inlet valve opens and the cycle is repeated.

Technical Term Used in Reciprocating Compressor.

Inlet pressure/ suction pressure - It is the absolute pressure of air at inlet to compressor

Discharge pressure - It is the absolute pressure of air at outlet of compressor.

pressure ratio/ Compression ratio - It is the ratio of the discharge pressure to the inlet pressure/suction pressure

Compressor capacity - It is the volume of air delivered by the compressor.

free air delivered - It is the actual volume delivered by a compressor when reduced to the normal pressure and temperature condition.

swept volume - It is the volume through which piston moves in one stroke.

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

D → cylinder Bore
L → stroke length.

Single stage and multi stage compressor -

In single stage compressor compression of air from initial pressure to the final pressure is carried in one one cylinder

In multi stage compressor pressure increase is carried out in more than one cylinder.

Sing acting and Double acting Compressor

In single acting compressor, suction, compression and delivery of air caused on one side of piston only.

In Double acting compressor, suction, compression and delivery of air caused on both side of the piston.

volumetric Efficiency - It is defind as that ratio of actual volume of air sucked into the cylinder to the swept volume.

Workdone of single acting single stage compressor (Without clearance)

$P_1 \rightarrow$ pressure of air at the begining of compression

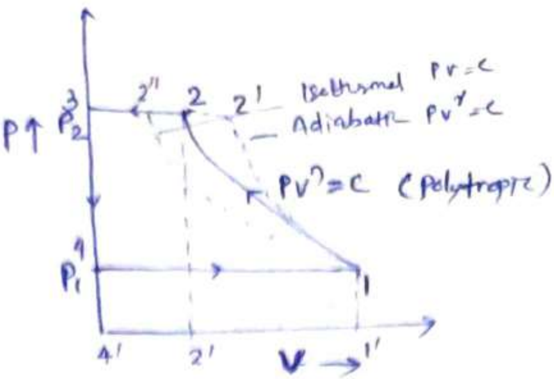
$P_2 \rightarrow$ pressure of air at the end of compression

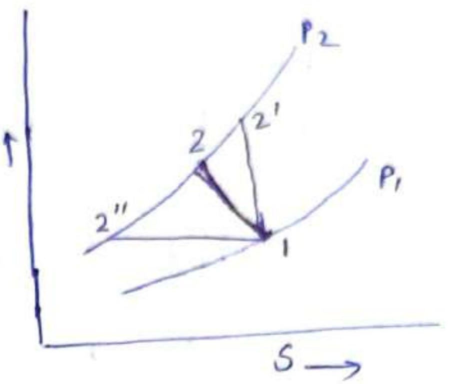
$T_1 \rightarrow$ Abs temp of air at the begining of compression

$T_2 \rightarrow$ Abs temp of air at the end of compression

$V_1 \rightarrow$ vol of air at begining of compression

$V_2 \rightarrow$ vol of air at the end of compression.





For polytropic compression

Workdone = Area 1-2-3-4-1

= Area 2-3-4'-2'-2
+ Area 1-2-2'-1'-1
− Area 1-4-4'-1'-1

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

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

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

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

For ~~Adiabatic~~ ~~$W = \frac{\gamma}{\gamma-1}(P_2V_2 - P_1V_1)$~~

For reversible adiabatic process $P_1V_1^\gamma = P_2V_2^\gamma$

In process 1-2

$$P_1V_1^n = P_2V_2^n \Rightarrow \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{1/n}$$

$\Rightarrow$ ~~$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)$~~

∴ Equn (1) becomes,

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

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

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

$\frac{P_2}{P_1} \rightarrow$ pressure ratio / Compression ratio

For Isentric compression

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

For Isothermal compression

For Isothermal process 1-2 $P_1V_1 = P_2V_2$

$$W = P_2V_2 + P_2V_2 \log_e \frac{V_1}{V_2} - P_1V_1$$

$$= P_2V_2 \log_e \frac{V_1}{V_2}$$ or ~~$P_2V_2 \ln \frac{V_1}{V_2}$~~

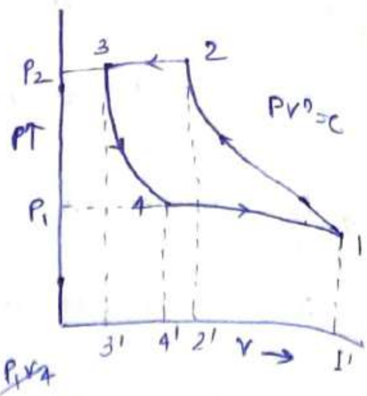
$P_1V_1 \ln \frac{P_2}{P_1}$

$$= 2.3\, P_2V_2 \log \frac{V_1}{V_2}$$

$\gamma > n > 1$

Isothermal work gives min work
Adiabatic work gives max^m work
Polytropic work lies in between the above two

Workdone of single stage Compressor (with clearance)



W = Area 1-2-3-4 =
Area 2-3-3'-2'-2 + Area 1-2-2'-1'-1
− Area 3-4-4'-3'-3 − Area 1-4-4'-1'-1

$= (P_2V_2 - P_2V_3) + \frac{n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$
$- \frac{n}{n-1} P_1V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] - (P_1V_1 - P_1V_4)$

$= nP_2V_2 - nP_2V_3 + P_2V_2 + P_2V_3 - nP_1V_1 + nP_1V_4 + P_1V_1 - P_1V_4$

$= P_2(V_2 - V_3) + \frac{P_2V_2 - P_1V_1}{n-1} - \frac{P_3V_3 - P_4V_4}{n-1} - P_1(V_1 - V_4)$

$= \left(P_2V_2 + \frac{P_2V_2}{n-1}\right) - \left(P_1V_1 + \frac{P_1V_1}{n-1}\right) - \left(P_2V_3 + \frac{P_3V_3}{n-1}\right) + \left(P_1V_4 + \frac{P_4V_4}{n-1}\right)$

$= P_2V_2 \times \frac{n}{n-1} - P_1V_1 \times \frac{n}{n-1} - P_2V_3 \times \frac{n}{n-1} + P_1V_4 \times \frac{n}{n-1}$

$= \frac{n}{n-1}(P_2V_2 - P_1V_1) - \frac{n}{n-1} \times P_2V_3 + \frac{n}{n-1} \times P_1V_4$

$= \frac{n}{n-1} \times P_1V_1 \left(\frac{P_2V_2}{P_1V_1} - 1\right) - \frac{n}{n-1}(P_2V_3 - P_1V_4)$

$= \frac{n}{n-1} \times P_1V_1 \left(\frac{P_2V_2}{P_1V_1} - 1\right) - \frac{n}{n-1} P_1V_4 \left(\frac{P_2V_3}{P_1V_4} - 1\right)$ ——— (1)

For polytropic process 1-2, $P_1V_1^n = P_2V_2^n$ and 3-4, $P_3V_3^n = P_4V_4^n$

from equ^n (1)

$\therefore W = \frac{n}{n-1} P_1V_1 \left\{\frac{P_2}{P_1} \times \left(\frac{P_2}{P_1}\right)^{-1/n} - 1\right\} - \frac{n}{n-1} \times P_1V_4 \left\{\frac{P_2}{P_1} \times \left(\frac{P_2}{P_1}\right)^{-1/n} - 1\right\}$

$= \frac{n}{n-1} P_1V_1 \left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right\} - \frac{n}{n-1} \times P_1V_4 \left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right\}$

$= \frac{n}{n-1}(P_1V_1 - P_1V_4) \left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right\} = \frac{n}{n-1} \times P_1(V_1 - V_4) \left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right\}$

Now, $V_1 - V_4$ is the volume of air actually drawn in during a cycle $= V$ (say)

Then $P_1V = mRT_1$

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

where

$m \rightarrow$ mass of air actually admitted into compressor in every cycle

$R \rightarrow$ characteristics gas constant of air.

Volumetric efficiency. It is defind as the ratio of actual volume of air sucked into the cylinder during a cycle to the swept volume

$\eta_v = \frac{V_1 - V_4}{V_1 - V_3} = \frac{V_1 - V_4}{V_1 - V_c}$ $V_3 = V_c \rightarrow$ Clearance volume.

For polytropic process 3-4, $P_3V_3^n = P_4V_4^n \Rightarrow P_3V_c^n = P_4V_4^n \Rightarrow V_4 = V_c\left(\frac{P_2}{P_1}\right)^{1/n}$

$\eta_v = \frac{V_1 - V_c \times (P_2/P_1)^{1/n}}{V_1 - V_c} = \frac{V_1 + (V_c - V_c) - V_c \times (P_2/P_1)^{1/n}}{V_1 - V_c} = \frac{(V_1 - V_c) + V_c - V_c(P_2/P_1)^{1/n}}{V_1 - V_c}$

$= \frac{V_1 - V_c}{V_1 - V_c} + \frac{V_c}{V_1 - V_c} - \frac{V_c(P_2/P_1)^{1/n}}{V_1 - V_c} = 1 + C - C(P_2/P_1)^{1/n}$

$C \rightarrow$ clearance factor / clearance ratio

Workdone of two stage compressor (without clearance)

- → size of cylinder too large
- → Due to compression there is rise in temp' of air. It is difficult to reject heat from air in small time available during compression.
- → Sometime the temp' of air at the end of compression is too high. It may heat up the cylinder head or burn the lubricating oil.

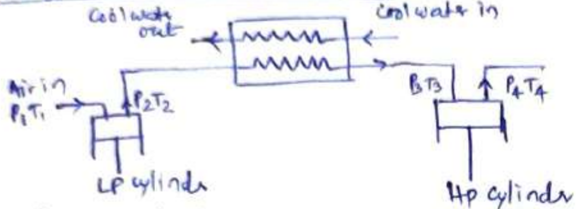
Multistage compression
In single stage compressor for producing high pressure air it suffers following drawback ⟵

To overcome above difficulties two or more cylinders are provided in series with intercooling arrangement between them. Such an arrangement is known as multistage compression.

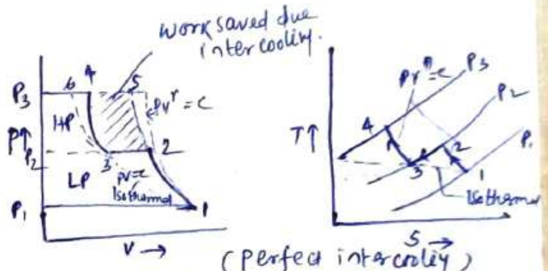
Advantages of multistage compression →

- → It improves volumetric efficiency
- → It gives uniform torque
- → It provides effective lubrication because of lower temp range.
- → It reduces cost of compressor.
- → It reduces leakage loss.
- → Less power is reqd to operate compressor of given pressure ratio.

Consider two stage compression with intercooler:



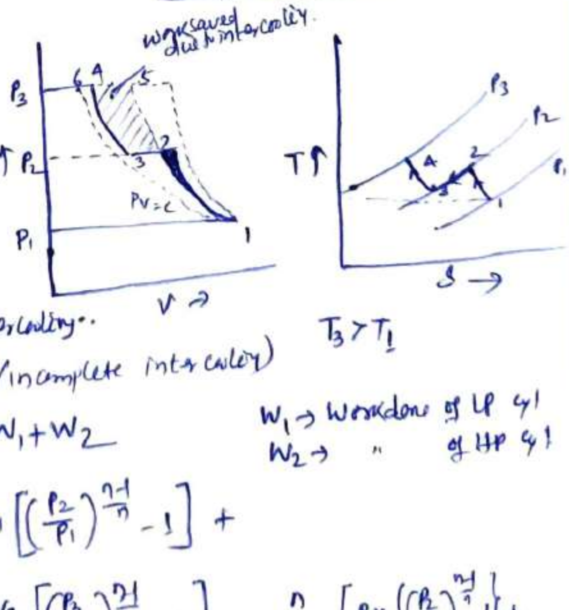
Let P_1 → pressure of air entering the LP cyl
V_1 → stroke vol of LP cyl
P_2 → pr of air leaving the LP cyl or entering the HP cyl
V_2 → stroke vol of HP cyl
P_3 → pr of air leaving the HP cyl
n → polytropic index for both the cyl



For perfect intercooling or complete intercooling $T_3 = T_1$ (Atm air temp')
Work saved due to intercooling is area 2-5-4-3-2

Incomplete Intercooling

Work saved due to incomplete intercooling 2-3-4-5-2



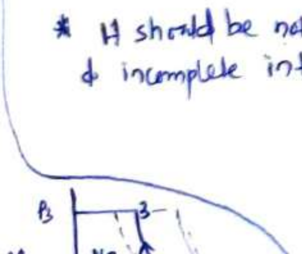
$T_3 > T_1$

* It should be noted that work saved is due to incomplete intercooling is less than due to complete intercooling.

Workdone (imperfect/incomplete intercooling)

$$W = W_1 + W_2$$

W_1 → Workdone of LP cyl
W_2 → " of HP cyl



$$= \frac{n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} P_2V_2 \left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right] = \frac{n}{n-1}\left[P_1V_1\left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right\} + P_2V_2\left\{\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right\}\right]$$

Workdone (Complete intercooling)

For perfect intercooling point 2 lies on isothermal curve

$\therefore P_1V_1 = P_2V_2$

Now $W_1 = \frac{n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$, $W_2 = \frac{n}{n-1} P_2V_2 \left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]$

$$W = W_1 + W_2 = \frac{n}{n-1} P_1V_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

ch. 3. properties of steam

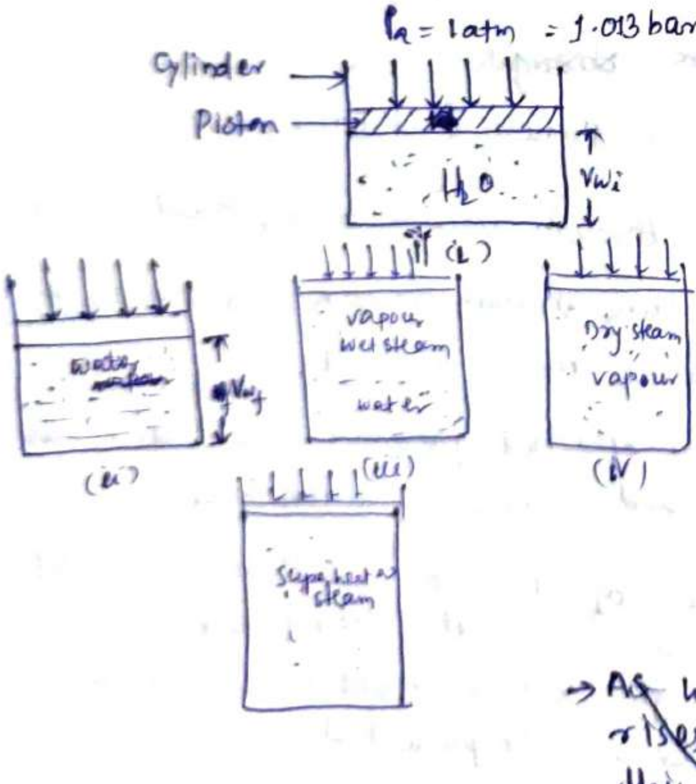
Difference between Gas and vapour

Gas	vapour (Steam is a vapour of water)
→ A gas is a completely evaporated liquid	→ A vapour is a partially evaporated liquid.
→ A gas cannot be liquified by application of pressure alone because it's temp^r is above it's critical temp^r.	→ A vapour can be liquified by application of pressure alone, because it's temp^r is below it's critical temp^r.
→ A gas obeys all gas law of a perfect gas.	→ A vapour (steam) does not obey gas laws.

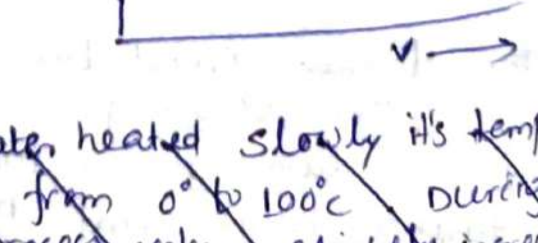
pure substance → A pure substance is a substance of constant chemical composition throughout it's mass.
→ It is a one component system
→ It may exist in one or more phases. water

Formation of steam from water at constant pressure (1 atm) and water at 0°C.

consider 1 kg of H_2O at 0°C contained in a cylinder-piston machine.



If we heat the water, at constant P it will be converted into steam. ~~the state changes of water~~ State changes are given below.



→ ~~As water heated slowly it's temp^r rises from 0° to 100°C. During this process volume slightly increases~~

→ Fig. i shows heating of water at 0°C under constant pressure.
→ Due to heating temp^r of water increases and reaches a temp^r of 100°C of water and volume of water increases slightly i.e. V_f. It will cause the piston to move slightly

→ When boiling point reached the tempr remains constant and water evaporates, thus piston moves up against constant pressure. At this stage sp. volume of steam increases, as shown in fig-III. At this stage steam will have some water particle and it termed as wet steam. This process will continue till the whole water converted into steam.

→ on Further heating water particle in suspension will be converted into steam. The entire steam in such a state as dry steam is dry saturated steam.

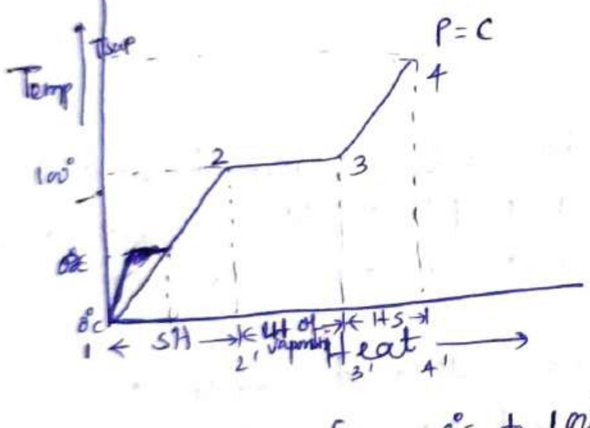
→ On further heating, tempr of steam starts rising. This steam is termed as superheated steam.

Representation on P-V, T-S, T-H and H-S Diagram

sp heat of ice = 2.1 kJ/kgK

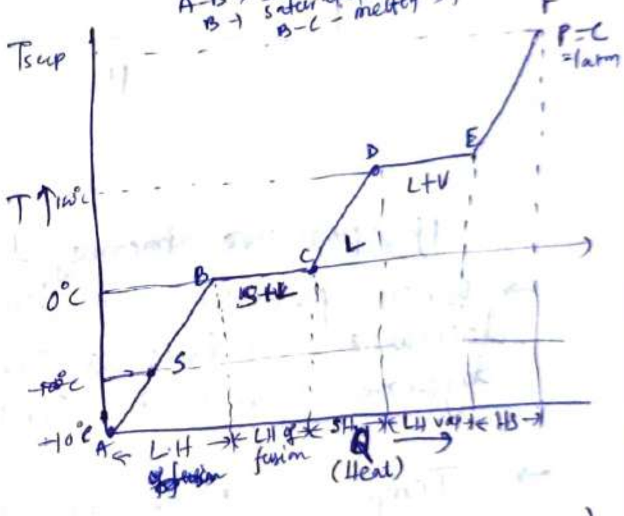
phase changes Diagram during steam formation.

water – steam



ice – steam

A → solid state
A-B → solid warming
B → saturated solid
B-C – melting = fusion process
C-D → liq. heating process
D → saturated liq. state
DE → vaporization process
E → saturated vap. state
EF → superheating process



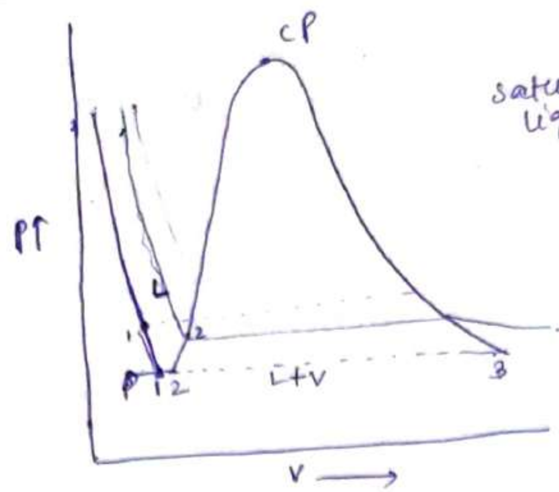
→ Heating of water from 0°C to 100°C (i.e. boiling tempr or saturation tempr) is shown by 1-2. Heat absorbed during this process called sensible heat.

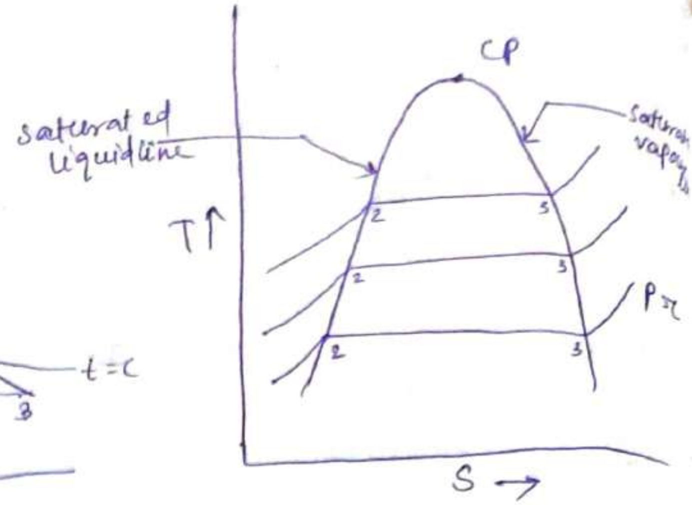
→ Change of state from Liquid to steam is shown by 2-3. Heat absorbed during this stage is called LH of vaporisation.

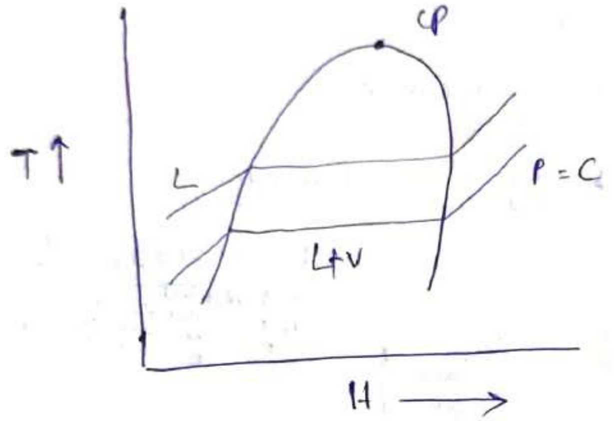
→ Super heating process is shown by 3-4. Heat absorbed during this stage is called heat of superheat.

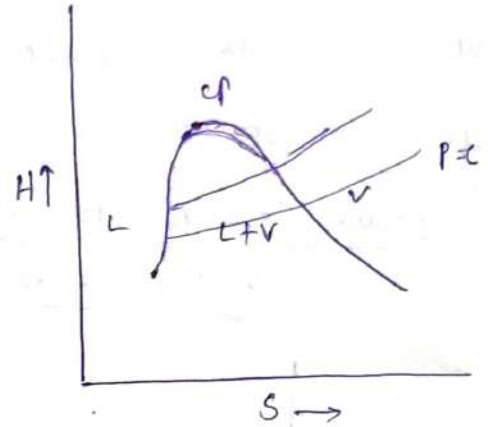
→ Line 1-4' represents total heat of superheated steam.

P-V, T-S, T-H, H-S Diagram -









If ~~pressure~~ increased

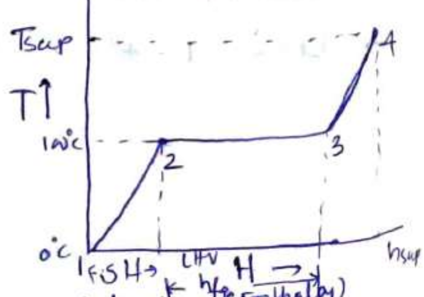
→ When pressure and sat. temp^r increases latent heat of vaporisation decreases. It becomes zero at a point where liquid line and dry steam lines meet. This point is known as critical point.

→ Temp^r and pressure corresponding to that point is called critical temp^r and critical pressure.

→ For steam $P_{cr} = 221.2$ bar, $T_{cr} = 374.15°C$

Important term and properties of steam -

Wet steam - When steam contains water particle, it is said to be wet steam. Here whole latent heat has not been absorbed in process 1-2.



Dry Steam / Dry saturated steam

When wet steam further heated and does not contain any water particle in suspension is called dry saturated steam. point 3 indicated dry saturated steam.

superheated steam. When dry steam is further heated at constant pr thus raising it's tempr, it is said to be superheated steam. point 4 indicated superheated steam at temp t_{sup}. It behaves as perfect gas.

Sensible heat (h_f) - It is defined as quantity of heat absorbed of water of 1kg when it is heated from 0°C water to boiling point 100°C.

It is denoted as h_f (sensible heat or enthalpy of ~~heat~~ liquid)

Sensible heat added = $m c_w dT$

$= 1 \times 4.2 [(100+273) - (0+273)] = -- KJ/kg$

Sp. heat of water = $c_w = 4.2\ KJ/kg \cdot K$

Latent heat of vaporisation (h_{fg})

It is the quantity of head required to convert from mass of water at sat. tempr to dry saturated ~~tempr~~ steam at same tempr.

$P \uparrow h_{fg} \downarrow$

~~Total enthalpy~~
~~$h = h_f$~~

Dryness fraction or Quality of steam (x).

It is the ratio of mass of actual dry steam to mass of same quantity of wet steam.

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

$m_g \rightarrow$ mass of actual dry steam
$m_f \rightarrow$ mass of water suspension
$m \rightarrow$ mass of wet steam

x varies from 0 to 1.
water starts boiling, $x = 0$

Total heat or Enthalpy of steam = sensible heat + latent heat

for wet steam, $h = h_f + x h_{fg}$

Dry steam, $h = h_g = h_f + h_{fg}$ (for dry steam $x = 1$)

Enthalpy of superheated steam

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

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

$(t_{sup} - t_{sat})$ is known as degree of superheat.

$c_p \rightarrow 1.67\ KJ/kg \cdot K$ to $2.5\ KJ/kg \cdot K$

Specific volume.

$m = m_f + m_g$
$V = V_f + V_g$

$m v = m_f v_f + m_g v_g$
$= (m - m_g) v_f + m_g v_g$
$\Rightarrow v = \left(1 - \frac{m_g}{m}\right) v_f + \frac{m_g}{m} v_g$
$= (1 - x) v_f + x v_g$

$= 1 - x v_f + x v_g$
$= v_f + x(v_g - v_f)$
$v = x v_f + x v_{fg}$

Entropy

Similarly, Entropy, $s = s_f + x s_{fg}$

Entropy for super heated steam, $S_{sup} = S_{sat\,dry} + C_p \ln \frac{T_{sup}}{T_{sat}}$

Steam Table.

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

There are two important steam table, one in terms of absolute pressure and other in terms of tempr.

Mollier Diagram / Mollier Chart.

It is a graphical representation of steam table in which enthalpy is plotted along ordinate and entropy along abscissa.

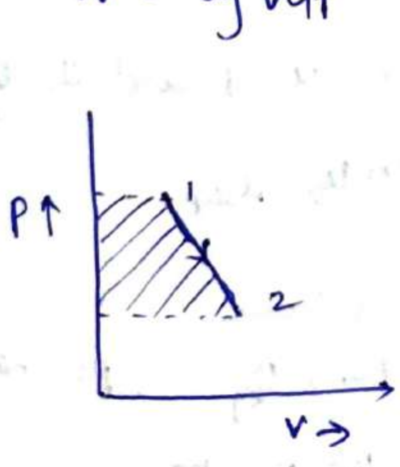
Flow process and Non Flow process of vapour

Flow process

→ It is related to opensystem in which both mass and energy transfer takesplace

→ mass enter the system and laves after enhancing energy.

→ $W = -\int v\,dp$



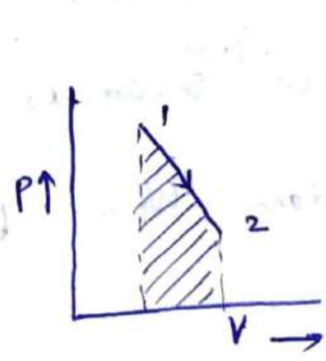
→ Ex - Steam turbine

Non flow process

→ It is a related to closed system in which mass transfer is not possible. Only energy transfer takes place.

→ Energy crosses the boundary in form of heat & work

→ $W = \int p\,dV$



capydea

Ch. 4. Steam Generators

Simple Boiler - Boiler may be defind as a closed vessel in which steam is produced from water by combustion of fuel.

Classification of Boiler -

1. According to the axis of the shell - Ex - Lanchashire, Locomotive, Babcock and ...
   a - Horizontal boiler
   b - vertical boiler — Ex - Cochran boiler
   c - Inclined boiler

→ If the axis of the boiler is horizontal, the boiler is called horizontal.
→ If the axis of the boiler is vertical, the boiler is called vertical boiler. → If the axis is inclined, it is known as inclined boiler.

2 - According to the relative position of water and flue gases
   a - Fire Tube boiler
   b - Water Tube boiler

→ In the fire tube boiler the hot gases are inside the tube and water scurrounds the tubes. Ex- Cohran boiler, Lanchashire boiler and Locomotive boilers.

→ In the water tube boiler, the water is inside the tube and the hot gases scurround them.
Ex. Babcock and Wilcox, stirling, etc.

3. According to the position of furnace
   a. Externally fired boiler
   b- Internally fired boiler

→ The boiler is known as externally fired if the fire is outside the shell. Ex. Babcock and wilcox, stirling boiler, etc.
→ The boiler is known as internally fired, if the furnace is located inside the shell. Ex- cochran, Lanchashire, etc.

4. According to circulation of water and steam
   a. Natural circulation
   b. Forced circulation

→ In natural circulation boiler, circulation of water in the boiler takes place due to natural convection.
Ex. Lanchashire, Babcock and Wilcox, Benson boiler, etc.

→ In forced circulation type of boiler, the circulation of water is done by a forced pump.
Ex. Velox, Lamont, Benson boiler, etc.

5. According to pressure

a. High pressure Boiler
b. Low pressure Boiler

→ The boiler which produces steam at a pressure of 80 bar and above is called high pressure boiler. Ex Babcock Wilcox, Lamont, etc

→ The boiler which produces steam at a pressure of below 80 bar is called low pressure boiler. Ex. Cochran, Lancashire, Locomotive.

6. According to the use

a- stationary use
b- portable use

→ The boiler which are used in power plant and industrial process work are called stationary because they do not move from one place to another.

→ The boiler which moves from one place to another is called portable steam boiler. Ex. Marine Boiler, Locomotive boiler.

7. According to number of tubes

a- Single Tube boiler
b- Multi Tube boiler

→ In single tube steam boiler there is only one fire tube or water tube. Ex- Simple vertical boiler, Cornish boiler.

→ In multi tube steam boiler there are two or more ~~than one~~ fire tube or water tube. Ex Cochran, Lancashire, Locomotive, etc.

~~8. According to the source of heat~~

~~solid fuel~~
~~gaseous fuel~~
~~liquid fuel~~

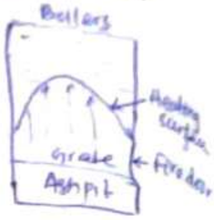
Important Terms of Boiler

→ Boiler Shell - The boiler shell consists of hollow cylindrical body made up of steel plates riveted or welded together.

Furnace - It is a chamber where fuel is burnt and to produce heat. This heat is utilised in generating steam in the boiler.

Grate - It is a space on which fuel is burnt. It is made of CI bars. The bars are so arranged that the air may pass on to the fuel for combustion. The area on which fuel (coal & wood) rests is called grate surface of the grate

Heating surface - Heating surface is the surface of boiler which is exposed to hot gases on one side and water on the other.



Water space and steam space

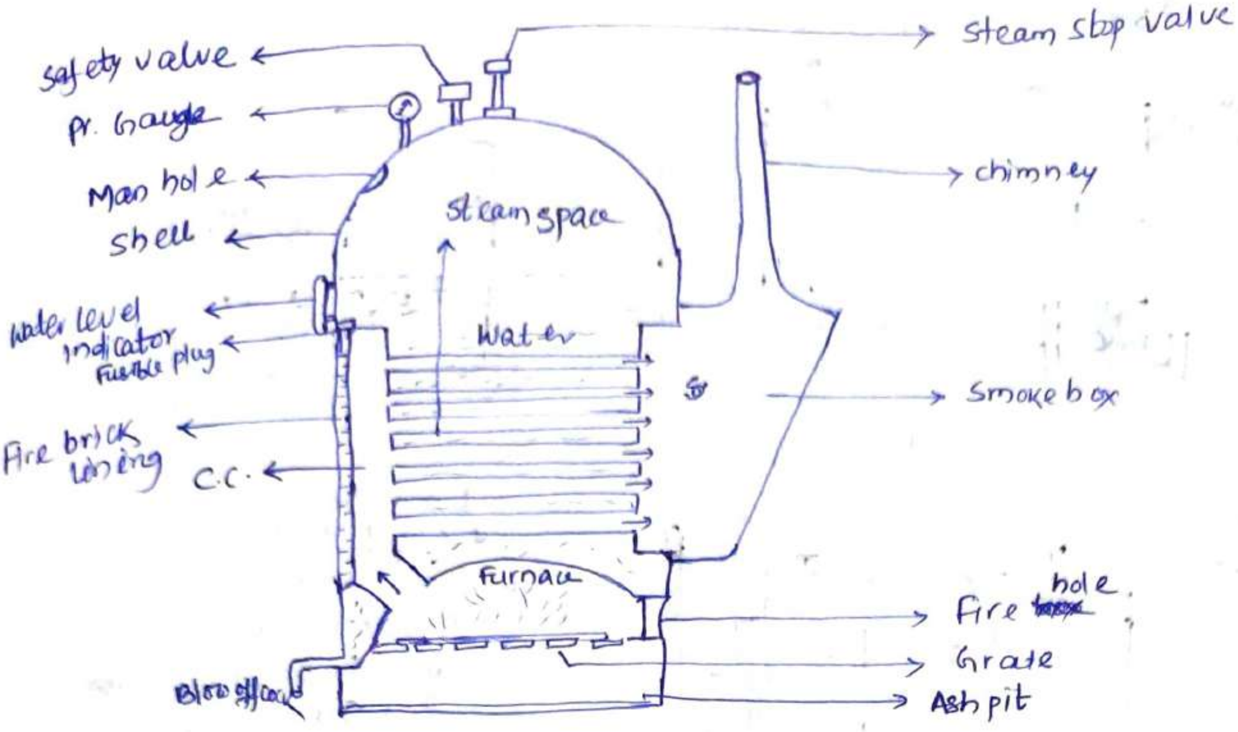
→ The volume of the shell that is occupied by water is called water space .and remaining space is ~~occupied~~ called
→ steam space.

Flue gases. Flue gases are ~~those~~ hot gases produced due to combustion of fuel. in the boiler furnace.

Comparison between Fire tube and water tube boiler

Firetube boiler	Water tube boiler
→ Hot gases passes through tube which are surrounded by water	→ The water circulates inside tubes which are surrounded by hot gases.
→ It is ~~an~~ Internally fired type of boiler.	→ It is an externally fired type of boiler
→ Rate of steam production is lower	→ Rate of steam production is higher
→ It generates steam at ~~steam~~ pressure upto 24 bar.	→ It generates steam at pressure upto 165 bar.
→ Construction is difficult	→ Construction is simple
→ Transportation is difficult	→ Transportation is simple.
→ Operating cost is less	→ operating cost is high
→ Bursting chances is less	→ Bursting chances is high.
→ It require less skill for efficient and economic working	→ It require more skill and careful attention.
→ It is not suitable for large power plant	→ It is used for large power plant
→ overall efficiency is upto 75%	→ over all efficiency with economiser is upto 90%.

Cochran Boiler



→ It is a vertical fire tube boiler.

→ It consists of no. of horizontal tube called flue tube which are fitted to a vertical cylindrical shell which has hemispherical top.

→ Boiler furnace is also hemispherical.

→ Furnace and CC connected through a short pipe.

→ The fuel introduce into the furnace through fire hole.

→ The fuel burns on grate inside furnace and ashes falls into ashpit.

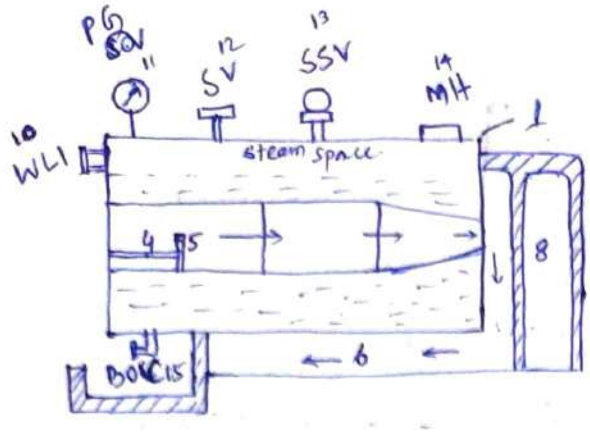
→ The flue gases passes from furnace to CC and then flow through horizontal tube to box called smoke box.

→ From smoke box the flue gases escape to atmosphere through chimney.

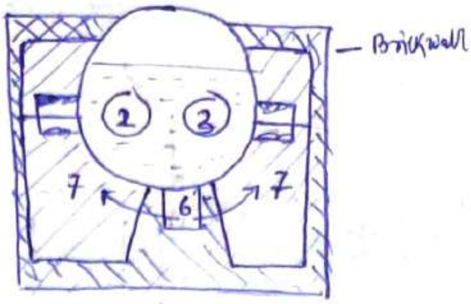
→ The continuous flow of flue gas through flue tube, the water which surrounds them becomes more and more heated. Thus steam is generated and collects in the steam space

Lancashire Boiler

Increase velocity flow

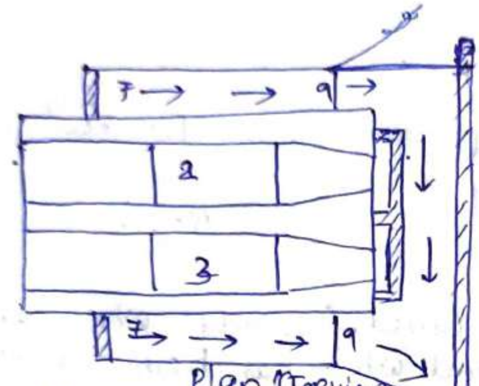


F.V



Side

Bottom flow 6



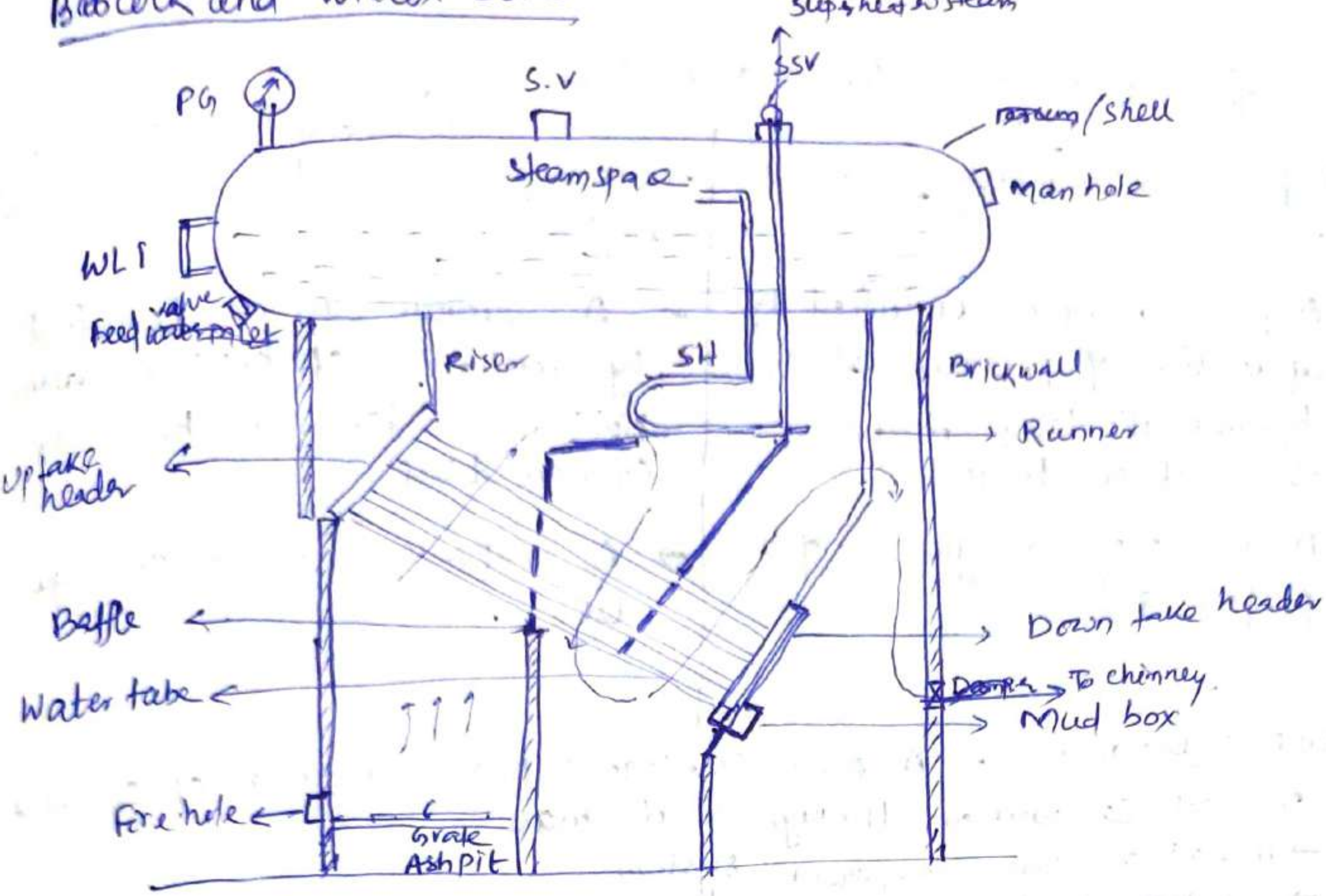
Plan (Topview)

1 → Shell
2,3 → Flue tube
4 → Fire Grate
5 → Brick Arch
6 → Bottom tube path
7 → Side flue path
8 → Main flue
9 → Damper

Construction and working

- It is a fire tube horizontal boiler. → length - 8 to 10 mtr, Dia - 3-4 mtr
- Boiler consists of cylindrical shell + contains two tubes 2 and 3 called flue tube → cylindrical shell is placed over brick structure. are placed affront solid
- 4 is Fire grate, over which fuel is burnt. ~~at~~
- Brick Arch 5 deflects flue gases upword.
- Hot flue gases after leaving the ~~b~~ flue tube pass down to Bottom tube 6 and reach front end of boiler where they become divided and flow through side flue path 7.
- The flue gases then enter the main flue 8 which leads to chimney.
- Damper 9 is provided to regulate the mass flow rate ~~of generation of steam~~. of flue gases.
- ~~Spring loaded Safety Valve and Steam stop valve is mounted as~~ → Due to this flue gases path the water in the shell is heated from bottom by bottom flue from side by side flue and centre through flue tube
- Due to continous flow of flue gases steam generated from water and collected in the steam space within the boiler.

Babcock and Wilcox Boiler



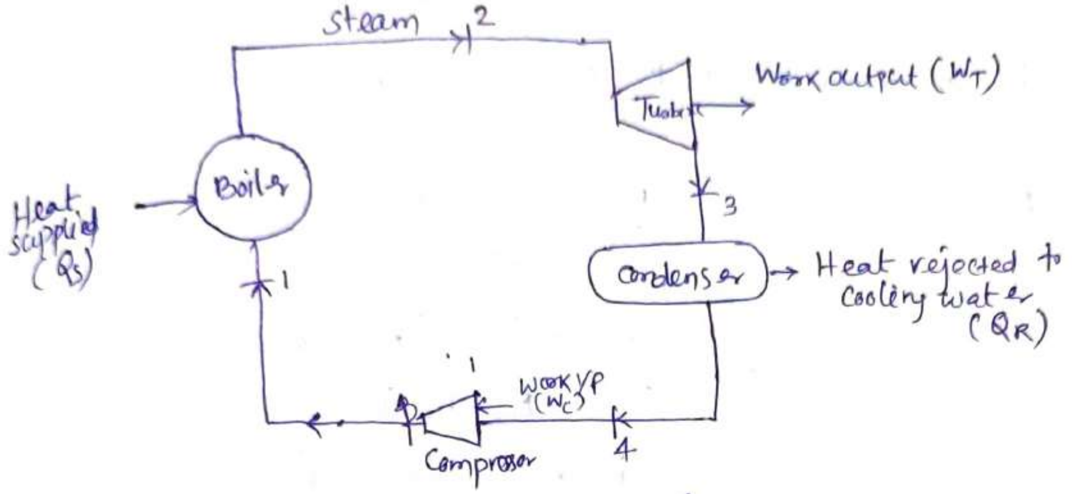
Construction and Working

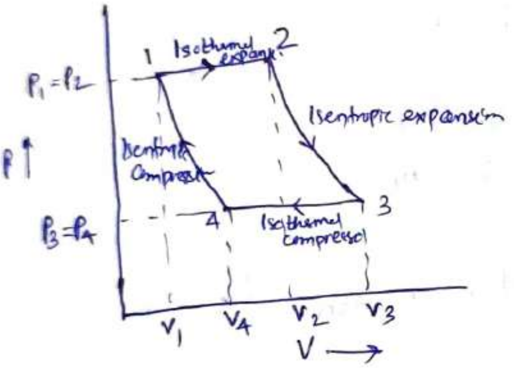
- → It consist of inclined water tube, steam and water drum, a mud box and a super heater.
- → The drum connected with uptake and down take header by short riser tube. Header are connected to series of inclined water tube.
- → Baffle plates are provided inorder to make circulation of hot gases in sine wave form.
- → ~~Damper is provided to regulate draught.~~
- → Feed water feed into boiler shell through feed check valve.
- → Due to gravity water passes through vertical tube, header and fill up inclined tube.
- → The water comes down to water tube through runner and rises up through riser.
- → Hot gases produced in the furnace move upward.
- → The baffle plates make flow of hot gases in sine wave as move downward and then upward over the water tube.
- → ~~The damper~~ Control ~~the flow~~ of flue gases. Due to continous flow of steam generated from water and again the steam passes through a superheater where it further heated and becomes superheated.

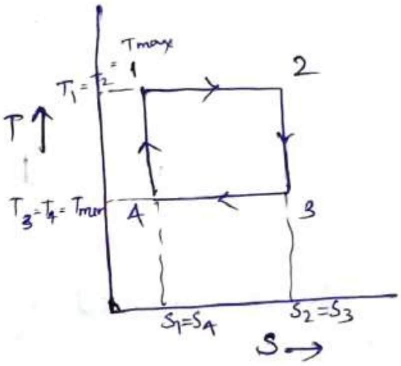
5. Steam power cycle

Carnot cycle with vapour.

- In the carnot vapour cycle, steam or any other vapour is used as working substance in place of a perfect gas.
- Components and arrangement of carnot vapour cycle is shown in fig and same is represented on P-V diagram.







process (1-2) - This is isothermal heat addition in the boiler. Isothermal process having $T_1 = T_2 =$ Constant. This is also constant pressure process saturated water at point 1 is isothermally converted into dry saturated steam in boiler.

process (2-3) - This is reversible adiabatic expansion of steam in the turbine. The dry steam at point 2 expands adiabatically in the steam turbine develops work (W_T).

process (3-4) - This is isothermally heat rejection in the condenser. Condenser converts steam into water at constant pressure and tempr.

process (4-1) - This is reversible adiabatic compression process. steam and water enters into compressor in which pressure increases from P_4 to P_1 and compressor consumes power W_C. thus complete the cycle.

Efficiency of Carnot vapour cycle

consider 1 kg of working substance

Work developed by turbine, $W_T = h_2 - h_3$

Work input during compression, $W_C = h_1 - h_4$

Net work developed, $W_{net} = W_T - W_C$

$= (h_2 - h_3) - (h_1 - h_4)$

Heat supplied in Boiler, $Q_s = h_2 - h_1$

$$\text{Efficiency}, \eta = \frac{\text{Net work developed}}{\text{Heat supplied}}$$

$$= \frac{(h_2 - h_3) - (h_1 - h_4)}{(h_2 - h_1)}$$

$$= \frac{(h_2 - h_1) - (h_3 - h_4)}{(h_2 - h_1)}$$

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

But heat rejected by condenser, $Q_R = h_3 - h_4$

$$\therefore \boxed{\eta = 1 - \frac{Q_R}{Q_s}}$$

Entropy, $ds = \frac{dQ}{T}$ so, $Q_R = T_{min}($
$Q_s =$

$$\therefore \eta = 1 - \frac{T_{min}(s_3 - s_4)}{T_{max}(s_2 - s_1)}$$

But process (2-3) and (4-1) are isentropic, $s_2 = s_3$ and $s_1 = s_4$

$$\therefore \eta = 1 - \frac{T_{min}(s_3 - s_4)}{T_{max}(s_3 - s_4)}$$

$$\Rightarrow \boxed{\eta = 1 - \frac{T_{min}}{T_{max}}}$$

$T_{max} \rightarrow$ Max^m temp^r of cycle

$T_{min} \rightarrow$ Min^m temp^r of cycle

Limitations of Carnot cycle

- It is not possible to operate the cycle on reversible processes.
- No compressor or pump can handle saturated vapour
- It is very difficult to locate point 4 from which adiabatic compression is to be started to arrive at the initial state point 1.
- Net workdone during a cycle is not high

Importance of Carnot cycle.

- Although Carnot cycle cannot be used in actual practice, it is the mother cycle on the basis of which Rankine cycle has been developed.
- Carnot cycle has the highest thermal efficiency

Rankine cycle

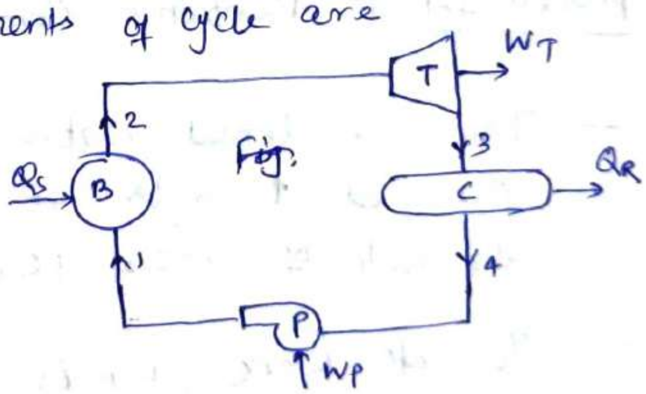
- Rankine cycle is the modification of Carnot cycle
- It is an ideal cycle

In this cycle condensation of steam is continued untill is all water. This water can be easily handle by feed pump.

The heat energy of the fuel is converted into mechanical work or power in steam turbine power plant

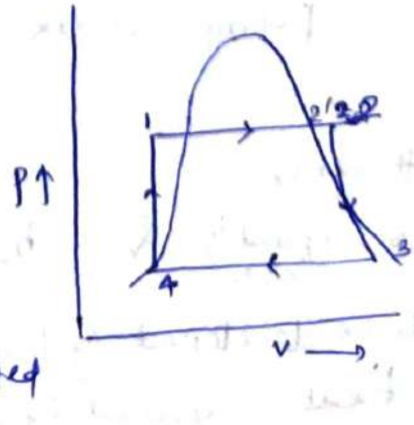
The main four components of cycle are

1. Boiler
2. Turbine
3. Condenser
4. Feed pump



Process 1-2 - Constant pressure heat addition process in boiler

- The water is heated at constant pressure P_1 in the boiler until the saturation temp^n is reached.
- Saturated water is converted into saturated steam at constant pressure.
- During $2'$-2 process is superheated in super heater.
- Heat supplied, $Q_s = h_2 - h_1$



process 2-3 . Isentropic expansion in the turbine

- High pressure and high temp superheated, dry saturated & wet steam generated in the boiler at P1 and T1 is supplied to the steam turbine.
- This steam expands isentropically into steam turbine upto the condenser pressure.
- Steam turbine develops mechanical work, W_T due to expansion of steam.
- Turbine work, $W_T = h_2 - h_3$

process 3-4 (Constant pressure heat rejection in condenser)

- The exhaust steam from turbine enters into condenser, where it is condensed at constant pressure by circulating cooling water in the tube.
- The heat rejected by exhaust steam is Q_R

Heat rejected, $Q_R = h_3 - h_4$

process 4-1 (Isentropic compression in the pump (pumping process).

- The condensed water coming from condenser is pumped to boiler at boiler pressure with the help of feed pump.
- To do work, W_P is supplied to feed pump.

pump work, $W_P = h_1 - h_4$

Efficiency

Heat supplied by boiler $Q_S = h_2 - h_3$

Work developed by turbine, $W_T = h_2 - h_3$

Heat rejected by condenser, $Q_R = h_3 - h_4$

work supplied ~~to~~ feed pump, $W_P = h_1 - h_4$

Net work developed, $W_{net} = W_T - W_P$

$$= (h_2 - h_3) - (h_1 - h_4)$$

$$\eta = \frac{\text{Net work developed}}{\text{Heat supplied in boiler}}$$

$$= \frac{(h_2 - h_3) - (h_1 - h_4)}{h_2 - h_1}$$

$$= \frac{(h_2 - h_1) - (h_3 - h_4)}{h_2 - h_1}$$

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

$$= 1 - \frac{Q_R}{Q_S}$$

Ch. 6

Heat Transfer

Heat Transfer means transmission of heat energy from one region to another due to difference of tempr between these two region.

Modes of Heat Transfer

There are three modes of heat transfer from one region to another

1. Conduction
2. Convection
3. Radiation

Conduction – It is defined as transfer of heat energy because of tempr difference between parts of a system.

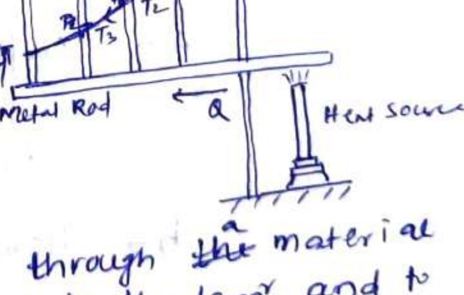
Heat conduction may takes place through solid, liq and gases. Thermal energy transfer by means of electrons which are free to move through lattice structure of the mat.

Convection is the process of heat transfer during which heat energy is carried from one part of fluid to another part by actual movement of heated mass of the fluid.

The motion of the fluid is caused by the differences in density which results from tempr difference.

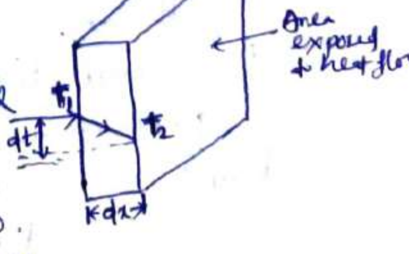
Radiation is the process of heat transfer between two bodies situated at some distance apart without using any medium.

It is due to radiation that solar heat reaches the earth.



Fourier's law of Heat Conduction

It states that rate of heat transfer through the material is proportional to the gradient in the tempr and to the area.



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

Q → Quantity of heat conducted through a wall in unit time

A → Area exposed to heat flow i.e. at right angle to direction of heat flow.

dt → Tempr difference betn two sides of wall.

dx → Thickness of wall

$\frac{dT}{dx}$ → Tempr gradient

$$\therefore \quad Q = KA \frac{dT}{dx}$$

constant of proportionality known as Thermal Conductivity.

Thermal conductivity (K)

$$Q = KA\frac{dT}{dx} = KA\frac{T_1 - T_2}{dx}$$

K → Thermal conductivity of the slab

$$\Rightarrow K = \frac{Q \cdot dx}{A(T_1 - T_2)}$$

$$\text{Unit} \rightarrow \frac{\frac{KJ}{hr} \times m}{m^2 \times {}^\circ C} = \frac{KJ}{m \cdot hr \cdot {}^\circ C}$$

KJ per metre per hour per °C.

If Q in KJ/s the unit will be ~~KJ per sec~~ KW/mK

* Thermal conductivity is the ability of material ~~to~~ conduct Conduct heat.

Newton's Laws of Cooling.

Heat transfer from hot body to cold body is directly proportional to the surface area and difference of tempr between two bodies.

$$Q \propto A(T_1 - T_2)$$

$$\Rightarrow Q = hA(T_1 - T_2) \quad KJ/h$$

A → Surface Area in m^2

$T_1 - T_2$ → Difference betn surface tempr of solid ~~and~~ ~~tp~~ and fluid in °C.

h → heat transfer Co-efficient in $\frac{KJ}{m^2/h/K}$

Stefan-Boltzman law

It states that amount of radiant energy emitted per unit time from unit area of black surface is proportional to the fourth power of it's absolute tempr.

$$E_b \propto T^4$$

$$E_b = \sigma_b T^4$$

E_b → Emissive radiation heat energy per unit time

T → Absolute tempr at which emission takes place, K.

σ_b → Boltzman constant $= 5.78 \times 10^{-8}$

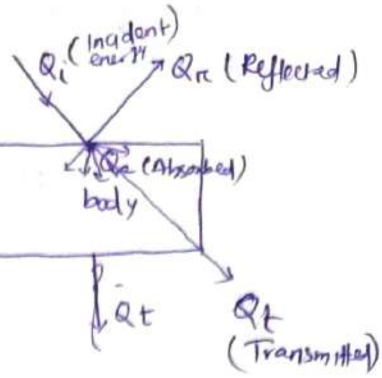
Absorptivity, Reflectivity and Transmissibility

Let $Q_i \rightarrow$ incident radiation energy

$Q_a \rightarrow$ radiation energy absorbed by the body

$Q_r \rightarrow$ radiation energy reflected by the body

$Q_t \rightarrow$ radiation energy transmitted by the body.



By Conservation of energy principle total sum must be equal to the incident radiation.

$$Q_i = Q_a + Q_r + Q_t$$

$$\Rightarrow 1 = \frac{Q_a}{Q_i} + \frac{Q_r}{Q_i} + \frac{Q_t}{Q_i}$$

$$\Rightarrow \boxed{\alpha + \beta + \gamma = 1}$$

$\frac{Q_a}{Q_i} \rightarrow$ Absorptivity of body : Absorptivity of a body is the ratio of radiation heat absorbed by the body to the total radiation heat received by the body.

$\frac{Q_r}{Q_i} \rightarrow$ Reflectivity of body : Reflectivity of a body is the ratio of radiation heat reflected by the body to the total radiation received by the body.

$\frac{Q_t}{Q_i} \rightarrow$ Transmissibility of body : Transmissibility of a body is the ratio of radition heat transmitted by the body to the total radiation received by the body.

Classification of solid on the basis of their Radiation properties

Black body

A black body absorbs all radiation heat energy received by it. Where $\beta = 0, \gamma = 0$, so $\alpha = 1$ i.e. Absorptivity of black body $= 1$.

similarly white body
$\alpha = 0, \gamma = 0, \beta = 1$

Transparent body
$\alpha = 0, \beta = 0, \gamma = 1$

opaque body
$\gamma = 0, \alpha + \beta = 1$