A LECTURE NOTE
ON
TH.4 THERMAL ENGG-II
SEMESTER -4

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Sr. Lecture Mechanical Engineering

Mechanical Engineering

GOVT. POLYTECHNIC, MALKANGIRI

Thermal Engg. II

Content :-

1. Performance of I.C. engine
   - 1.1. Define mechanical efficiency, Indicated thermal efficiency, Relative Efficiency, brake thermal efficiency, overall efficiency Mean effective pressure and specific fuel consumption
   - 1.2. Define air-fuel ratio and calorific value of fuel.
   - 1.3 Workout problems to determine efficiencies and specific fuel consumption.
2. Air Compressor
   - 2.1 Explain functions of compressor & industrial use of compressor air
   - 2.2. classify air compressor & principle of operation
   - 2.3. Describe the parts and working principle of reciprocating air compressor
   - 2.4 Explain the terminology of reciprocating Air compressor such as bore, stroke, pressure ratio, free air delivered & volumetric efficiency
   - 2.5 Derive the W.D. of single stage & 2-stage compressor with and without clearance
   - 2.6 solve simple problems (without clearance only)
3. Properties of steam
   - 3.1 Difference between gas & vapours
   - 3.2 Formations of steam
   - 3.3 Representation on P-V, T-S, H-S & T-H diagram
   - 3.4 Defn & properties of steam
   - 3.5 Use of steam table & mollier chart for finding unknown properties
   - 3.6 Nonflow and flow process of gas
   - 3.7 P-V, T-S & H-S diagram
   - 3.8 determination the changes in properties & solve simple numerical.

4. Steam Generator

4.1 Classification & type of Boiler

4.2 Important terms for Boiler

4.3 Comparison between fire tube and water tube boiler

4.4 Description & working of common boiler (cochran, Lancashire, Babcock & Wilcox boiler)

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5. Steam Power cycles

5.1 Carnot cycle with vapour

5.2 Derive work & efficiency of the cycle

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5.3.1 Representation in P-V, T-S, h-S diagram

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5.3.3 Effect of various end conditions in Rankine cycle

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6.5 Black body radiation, def^n on emissivity, absorptivity & transmissibility.

Books

Thermal Engineering → Mahesh M Rathore (TMH)

Engg. Thermodynamics → P.K. Nag (TMH)

Thermal Engg. → R.S. Khurmi (S. Chand)

1. Performance of I.C. Engine

Srinila Nayak

1.1

Performance of I.C. Engine

↓ 3 parameter

- Power developed
  - Indicated power (IP)
  - Brake power (BP)
  - Friction power (FP)
- Efficiency
  - Indicated thermal efficiency (η_{ith})
  - Brake thermal eff. (η_{bth})
  - Mechanical eff. (η_m)
  - Relative eff. (η_{rel})
  - Volumetric eff. (η_{vol})
  - Overall efficiency
- Air & fuel consumption
- Mean effective pressure
  - Fuel consumption ($\dot{m}_f$)
  - Specific fuel consumption (sfc)
  - Air consumption ($\dot{m}_a$)
  - Air-fuel ratio (A/F)
- Mean piston speed

* An engine is selected for a particular application on the basis of its power output and rated speed. Therefore, certain measurements and calculations are required to judge the performance of an engine.

Engine performance is an indication of the degree of success of an engine performs its assigned task i.e. conversion of chemical energy of the fuel into useful work.

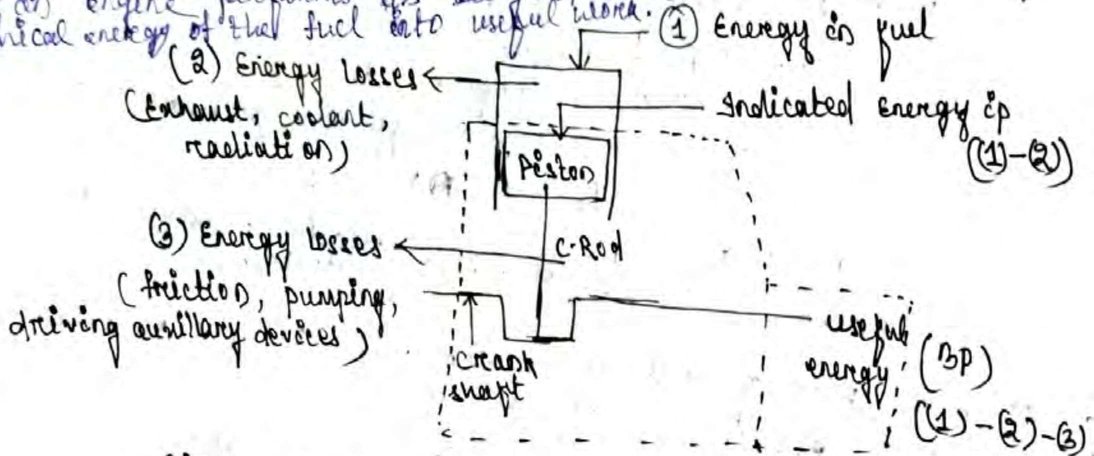
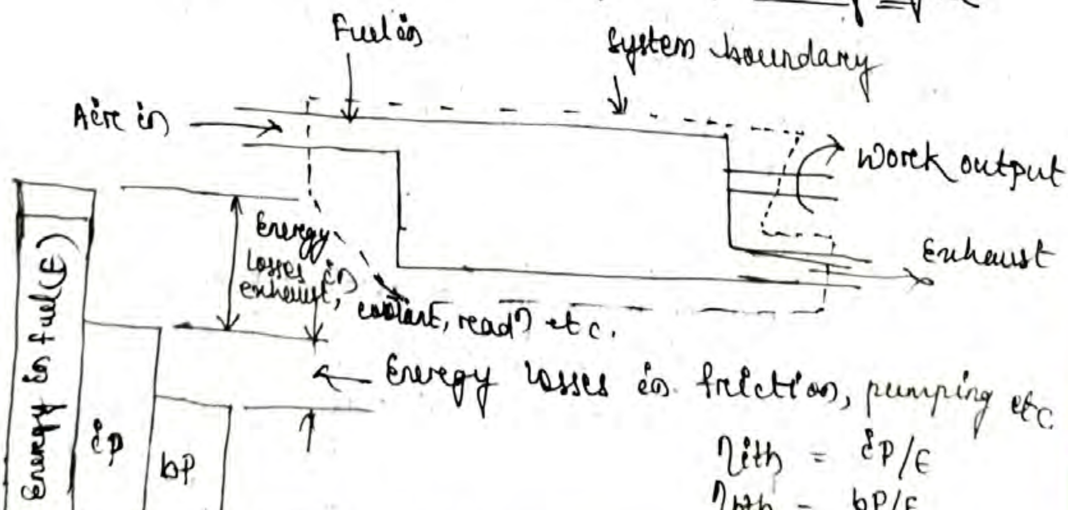


Fig:- Energy flows through reciprocating engine



Energy Distribution

$\eta_{ith} = ip/E$

$\eta_{bth} = bp/E$

$\eta_m = bp/ip$

Indicated power :- (IP)

→ It is defined as the rate of work done on the piston or the power actually developed by the engine cylinder because of burning of charge inside the cylinder.

→ It is evaluated from an indicator diagram obtained from the engine.

$$\text{Indicated power } IP = \frac{P_m \times A \times L \times n \times K}{60} \text{ (kW)}$$

where K = No. of cylinders

P_m = Indicated mean effective pressure obtained from indicator diagram (KPa)

L = stroke length (m)

$A = \pi/4\, d^2$, d = bore = cross-sec. area of cylinder (m)

n = no. of working stroke/min = N (for 2-stroke engine), N/2 (for 4-stroke engine)

Brake power :- (BP)

→ It is the net power available at the engine shaft for external use.

→ Usually, it is measured by brake or dynamometer (prony brake, rope brake)

→ Brake power BP = brake load (F) × vel. of brake drum $\left(\frac{\pi R N}{60}\right)$

$$BP = \frac{2\pi NT}{60\times10^3} \text{ (kW)}$$

where F = braking force, R = effective radius of brake drum

T = F·R. = torque

N = speed of engine in rpm

BP = Brake mean effective pressure × swept vol. rate

$$= \frac{P_{mb} \times A L n K}{60} \text{ (kW)}$$

where P_{mb} = Brake mean effective pressure (KPa)

n = No. of working stroke/min

Friction power :- (FP)

It is the part of indicated power which is used to overcome the frictional effects within the engine.

→ F.P. includes power required to operate the fuel pump, lubrication pump, valves, etc.

→ FP is the difference betn IP and BP.

$$\boxed{FP = IP - BP}$$

Brake thermal efficiency :- (η_{bth})

The power output of an engine is obtained from the combustion of charge

$$\eta_{bth} = \frac{\text{Brake power}}{\text{Energy supply rate}} = \frac{BP}{\dot{m}_f \times CV}$$

$\dot{m}_f$ = Mass flow rate of the fuel (kg/s)

CV = Calorific value of fuel (KJ/kg)

Indicated thermal efficiency (η_{ith})

It is defined as the ratio of indicated power to heat supply rate.

$$\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$$

Mechanical efficiency (η_{mech})

It is the ratio of brake power and indicated power.

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

$$\eta_{mech} = \frac{\eta_{bth}}{\eta_{ith}}$$

$$= \frac{P_{mb}}{P_{mi}}$$

Relative efficiency (η_{rel}) :-

It is the ratio of actual thermal efficiency to air standard efficiency of the engine.

It is also defined as efficiency ratio.

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

Overall efficiency :- (η_o)

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

$$\eta_o = \frac{BP}{m_f \times C.V.}$$

Volumetric efficiency :- (η_{vol})

It is defined as the ratio of mass of the actual air inducted into the cylinder to the mass of air corresponding to swept volume.

$$\eta_{vol} = \frac{\text{Actual mass flow rate of charge}}{\text{Density} \times \text{Swept vol./sec.}}$$

$$= \frac{\dot{m}_a}{\rho_a \times \left(\frac{\pi}{4} d^2 L\right) \frac{n}{60}}$$

$n = N$ (for 2-stroke)

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

$$= \frac{\text{vol. of air inducted}}{\text{Swept vol. of cylinder}} = \frac{V_a}{V_s}$$

Mean effective pressure :-

⇒ It is defined as average pressure which if acted on the piston (inside the cylinder of engine as IC) during the entire power or expansion stroke would produce the same workoutput as the net work output from the actual cyclic process.

$$W.D./cycle = P_m \times \text{Piston area} \times \text{stroke}$$

$$= P_m \times A \times L \times K$$

$$P_m = \frac{W.D./cycle}{A \times L \times K}$$

$$= \frac{W.D.\ \text{per cycle}}{\text{swept vol.}}$$

$$W.D./minute = P_m \times A \times L \times n \times K$$

* For any particular engine, operating at a given speed and power output, there will be a specific indicated mean effective pressure and a corresponding brake mean effective pressure.

$$P_{im} = \frac{60000 \times IP}{ALnK}$$

$$P_{bm} = \frac{60000 \times BP}{ALnK}$$

* Indicated mean eff. pressure can also be derived from indicator diagram.

$$P_{im} = \frac{\text{Area of Indicator diagram}}{\text{length of Indicator diagram}} \times K$$

length of indical diagram = Total vol − Clearance volume
K = indicator spring const.

Specific fuel consumption :-

⇒ It is an important parameter that reflects how good the engine performance is.

⇒ It is defined as the ratio of mass of fuel consumed per hour per unit power developed.

⇒ It is inversely proportional to thermal efficiency of engine.

$$sfc = \frac{\text{Fuel consumption per unit time}}{\text{power}}$$

<u>Unit</u> :- kg/kWhr.

⇒ Specific fuel consumption based on brake power (BP) is called brake specific fuel consumption (Bsfc)

$$BSFC \text{ or } sfc = \frac{\dot{m}_f}{BP} \ kg/kWh$$

* Specific fuel consumption based on indicated power (IP) is called indicated specific fuel consumption (Isfc)

$$Isfc = \frac{\dot{m}_f}{IP} \quad (kg/kWh)$$

* Fuel consumption :- $\dot{m}_f$ (kg/h)

$$\dot{m}_f = \frac{V_{fuel} \times \rho_{fuel} \times 3600}{\Delta t}$$

V_{fuel} = vol. of fuel in m^3 used in time Δt

ρ_{fuel} = density of fuel

Δt = Time (sec)

1.2 Air fuel ratio (A/F) :-

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

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

* A mixture that contains just enough air for complete combustion of all the fuel in the mixture is called a chemically correct or stoichiometric fuel-air ratio.
Mixture having more fuel than that stoichiometric mixture called as rich mixture and mixture that contains less fuel (excess air) is called a lean mixture.

* Equivalence ratio (ϕ) = $\frac{\text{Actual A/F ratio}}{\text{Stoichiometric A/F ratio}}$

$\phi > 1$ (lean mixture)

$\phi < 1$ (Rich mixture)

* Theoretically correct (stoichiometric) A/F = 15
but for petrol engine A/F ranges from 12 to 19
& Diesel engine A/F ranges from 20 to 60.

Calorific Value (CV) :-

Calorific value of a fuel is defined as the amount of heat energy liberated/released by complete combustion of unit quantity of a fuel. It is also called as heating value of fuel and it can also be considered as absolute value of enthalpy of combustion.

Unit :- KJ/kg or KJ/kmol (for solid and liquid fuel)
KJ/m³ (Gaseous fuel)

Higher Calorific value (HCV) :-

When combustion products are cooled to reactant's temp^n, the water vapour resulting from combustion gets condensed and heat of its vapourisation is recovered. The heating value so obtained is called higher calorific value (HCV) or gross calorific value.

Lower calorific value (LCV) :-

The amount of heat released by complete combustion of unit quantity of fuel, when water vapour in the products of combustion is not condensed and remains in vapour forms

⇒ It is obtained by deducting the heat necessary to form the vapour from hydrogen.

Lower calorific value (LCV) = $HCV - m_v h_{fg}$

m_v = mass of water vapour formed per kg of fuel

h_{fg} = heat of vapourisation of water at $25°C$ and 1 atm

= 2441.5 KJ/kgk

$$CV \text{ of fuel in KJ/kg} = \frac{CV \text{ of fuel in KJ/kmol}}{M.W. \text{ of fuel (kg/kmol)}}$$

1.3 Problems.

1Q) A four cylinder, 2-stroke petrol engine develops 30 kW at 2500 rpm. MEP on each piston is 8 bar and mech. eff. is 80%, calculate diameter and stroke of each cylinder, if stroke to bore ratio is 1.5. Calculate fuel consumption of the engine if brake thermal eff. is 28%. C.V. of fuel is 43900 KJ/kg.

Ans :- Data

K = 4, n = N (2-stroke) = 2500 rpm

B.P = 30 kW, MEP = 8 bar = 800 kPa, η_m = 80% = 0.8

l/d = 1.5

$$\eta_m = \frac{BP}{IP} \Rightarrow IP = \frac{BP}{\eta_m} = \frac{30}{0.8} = 37.5 \text{ kW}$$

$$IP = \frac{P_m \times A \times L \times N}{60} = \frac{8 \times 100 \times \frac{\pi}{4} d^2 \times 1.5d \times 25}{60}$$

⇒ d = 0.062 m

L = 1.5 × 0.062 = 93 mm = 0.093 m

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

$$\Rightarrow 0.28 = \frac{30}{\dot{m}_f \times 43900}$$

$$\Rightarrow \dot{m}_f = 0.00244 \text{ kg/s} = 8.78 \text{ kg/h}$$

Brake specific fuel consumption $B_{sfc} = \frac{\dot{m}_f}{BP}$

$$= \frac{8.78}{30}$$

$$= 0.293 \text{ kg/kwh}$$

2) (a) The following results refer to a test on petrol engine

Indicated power = 30kw

Brake power = 26 kw

Engine speed = 1000 rpm

Bsfc = 0.35 kg/kwh

cv of fuel = 43900 kJ/kg

calculate (a) η_{ith} (b) Brake thermal efficiency (c) Mech. efficiency [2019-W]

Ans :— IP = 30kw, BP = 26 kw, N = 1000 rpm,

Bsfc = 0.35 kg/kwh, cv = 43900 kJ/kg

$$Bsfc = 0.35$$

$$\therefore Bsfc = \frac{\dot{m}_f}{BP}$$

$$\Rightarrow \dot{m}_f = Bsfc \times BP = 0.35 \times 26$$

$$= 9.1 \text{ kg/h}$$

$$\eta_{ith} = \frac{IP \times 3600}{\dot{m}_f \times CV} = \frac{30 \times 3600}{9.1 \times 43900}$$

$$= 0.27$$

$$\eta_{bth} = \frac{BP \times 3600}{\dot{m}_f \times CV} = \frac{26 \times 3600}{9.1 \times 43900}$$

$$\eta_m = \frac{BP}{IP} = 0.867 \qquad = 0.234$$

Sunita Nayak

2. Air Compressor

Susmita nayak

2.1

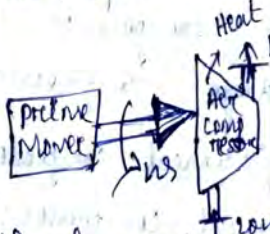
An air compressor is a device which takes in atmospheric air, compresses it with add of some mechanical energy and delivers the same at higher pressure. It is also called air pump.

Or

* Compressor is a device which is used to increase the pressure of atmospheric air from low pressure to high pressure by using some external energy.

→ Air compressor increases the pressure of air by decreasing its specific volume using mechanical means. Thus compressed air carries an immense potential of energy.

→ This compressed air is used for many purposes such as for operating pneumatic drills, paint spraying, in refrigeration plants, in gas turbine plants, air motors, production of bottled gases, air brakes for vehicles etc.



The compressor receives energy input from a prime mover. Some part of this energy is used to overcome the frictional effect, some part is lost in form of heat and remaining part is used to compress air to a high pressure.

Industrial use of compressed air :—

Compressed air has wide applications in industries as follows

→ In pump sets for oil and gas transmission line

→ For driving pneumatic tools in shops like drills, rivetters, etc

→ For driving air motors in mines

→ For cleaning purposes in automobile service station

→ For producing blast of air in blast furnaces

→ For spray painting in paint industries

→ Air Refrigeration and cooling of buildings

→ For inflating automobiles and aircraft tyres

→ For supercharging of I.C. engine

→ In vehicle to operate air brakes.

→ Operating lifts, crains, hoists and to operate pump.

→ For Metallurgical and chemical processes

2.2.

Classification :—

Air compressor can broadly be classified as :—

- Compressor
  - Positive displacement type
    - Reciprocating
      - Single acting
      - Double Acting
    - Rotary
      - Roots Blower
      - Vane type
  - dynamic compressor
    - Centrifugal
    - Axial

* According to no. of stages they (Air compressor) can also be classified as

→ single stage compression

→ Multiple stage compression

* **Positive displacement compressors :—**

Positive displacement compressors causes movement by trapping a fixed amount of air, and then after compressing the same trapped air, it forced the same to discharge pipe.

⇒ It can be of 2 type :—

① **Rotary compressor :—**

This compressor is usually consist of a bladed wheel or impeller that spins inside a circular housing

⇒ The gas is compressed by the rotating action of roller inside the /wheel inside the housing

⇒ This handles a large mass of gas and also are used for low and medium pressures.

② **Reciprocating compressor :—**

⇒ This is used to produce high pressure gas.

⇒ It uses the displacement of piston in the cylinder for compression.

⇒ It handles low mass of gas and high pressure ratio.

2.3 Reciprocating air compressor :-

A reciprocating air compressor is a positive displacement type compressor, which takes in air or gas during suction stroke at low pressure in a piston-cylinder arrangement and then compresses it to high pressure in a piston-cylinder arrangement. External work must be supplied to the compressor to achieve required compression. After compression, the compressed high pressure air is delivered to a storage vessel. From the storage vessel, the compressed air is supplied to the place where it is required.

Construction :-

Fig shows a sectional view of single stage (single acting) air compressor.

* It consist of cylinder, piston, crank, connecting rod, inlet and delivery valves.

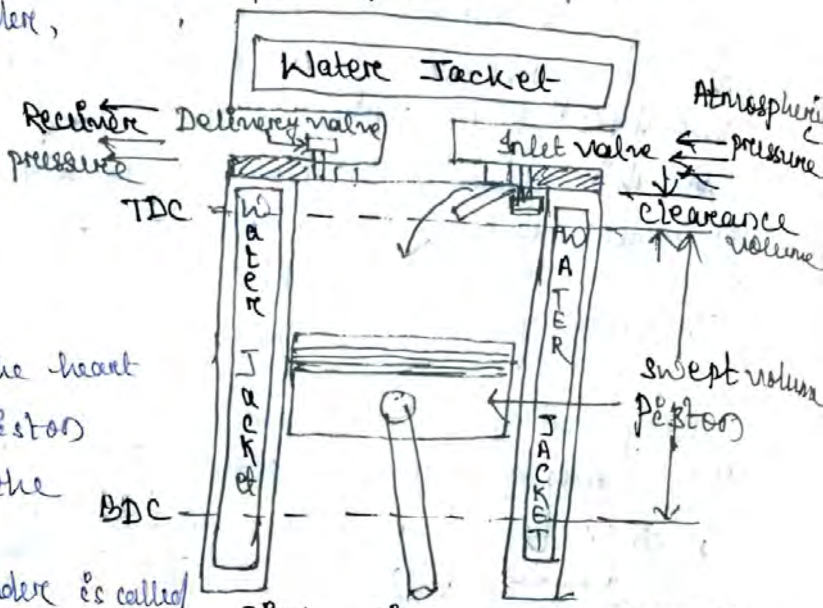


Fig :- single stage Reciprocating air compressor

cylinder :-

The cylinder is the heart of compressor. Piston reciprocates in the cylinder.

→ Top cover of cylinder is called cylinder head.

→ cylinder head consists of spring-loaded inlet and delivery valves, which are operated by a small pressure difference across them.

→ cylinder is surrounded by water jacket or metallic fins for proper cooling of air during compression.

Piston :-

The piston fitted with piston rings, reciprocates in the cylinder.

→ Piston rings seal the gap between piston and cylinder wall.

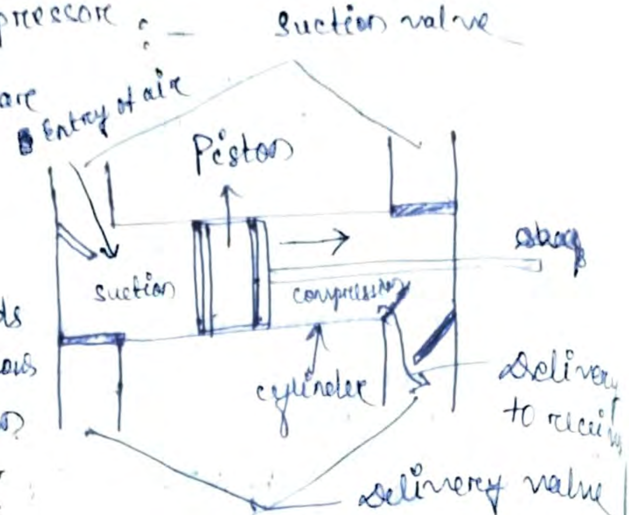
Crank :- It is a rotating member.

→ The prime mover (electric motor or engine) drives the crank shaft, the crank rotates and converts rotary motion into reciprocating motion of piston with the help of connecting

Connecting rod :-

It is a link between the piston and crank. ~~transmits power developed on the piston to crank shaft through a~~

* Double acting air compressor :-



Its construction is similar to single acting air compressor except there two inlet and two delivery valves on two ends of cylinder inorder to allow air entry and delivery on two sides of the piston.

→ So this when piston compress the air on its one side, it creates suction on the other side. Thus, suction and compression of air take place on two sides of the piston simultaneously.

* Reciprocating air compressor may be of two types based on the action of air on piston

① Single acting :- It is a compressor that has one discharge per revolution of crankshaft. and operations take place on one side of piston during a cycle of one revolution of crankshaft.

② Double acting :- It is a compressor that complets two discharge strokes per revolution of crankshaft. Operations are carried out on both side of piston.

* Further it also can be classified into two types

① Single stage :- In this compression of gas to final delivery pressure is carried out in one cylinder only

② Multi stage :- In this air is compressed in several stages instead of compressing the air fully in a single cylinder. The pressure of air is increased in each stage.

* This compressed air system also consist of following arrangement

Intake air filter :- They prevent dust from entering the compressor.

Interstage cooler :- These are placed between consecutive stages of multistage compressor. They reduce the temp of compressed air, before it enters next stage of compression.

After coolers :- They remove heat of compression and moisture in air by reducing the temp^re in a water-cooled heat exchanger, after compression is completed.

Air dryers :- The remaining traces of moisture, after an after-cooler are removed by using air dryers, for using compressed air in instruments.

Air receivers :- These are cylindrical tanks into which the compressed air is discharged after final stage of compression from the air compressor. It act as storage tank.

control valves/check valve :- The cylinder valves control the flow of air through the cylinder, these valve act as check valve.

Working principle of single-Acting single stage air compressor :-

* As the piston moves in a downward stroke from TDC to BDC, any residual compressed air left in the cylinder from the previous cycle expands first.
  On further movement of piston, the pressure in the cylinder falls below the atmospheric pressure. Due to this pressure difference, the inlet valve gets opened and fresh air is entered into the cylinder until piston reaches BDC.
* As piston begins its return stroke from BDC to TDC, the pressure in the cylinder increases, and closes the inlet valve. During compression stroke, as air pressure reaches slightly more than pressure of compressed air acting outside the delivery valve, the delivery valve opens and compressed air is discharged from the cylinder to storage tank.
* At the end of delivery stroke, the piston once again moves downward, and a small quantity of air left in clearance space expands till the cylinder pressure falls below atmospheric pressure.
  At this stage delivery valve closes and inlet valve opens for next cycle.
* This cyclic operation consisting suction, compression and delivery of air take place with 2 stroke of piston and one revolution of crank

1.1 Terminology :—

Bore :- The nominal inner diameter of the working cylinder is called bore. It is designated as 'd'.

Stroke :- The nominal distance through which a working piston moves between ~~TDC~~ TDC to B.D.C. or betⁿ two successive reversals of its dirⁿ of motion is called stroke. It is designated by 'L'.

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

Free air delivered (FAD) :-

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

i.e. the volume of air delivered by compressor under the compressor intake conditions.

Volumetric efficiency (η_v) :-

It is the ratio of actual volume of FAD at standard atmospheric condition in one delivery stroke (Actual air intake) to the swept volume (theoretical air intake) by piston during the stroke.

$$\eta_v = \frac{\text{Actual mass of air sucked per stroke}}{\text{Mass of air corresponding to swept volume at atmospheric condⁿ of pressure \& temp.}}$$

$$= \frac{\text{Actual vol. of air sucked / Effective swept vol.}}{\text{piston displacement vol. / swept vol.}}$$

Induction volume flow rate / volume flow rate (m^3/s)

$\dot{V}$ = volume inducted per cycle × No. of induction per revolution × No. of rev. per second

$$= \frac{\pi}{4} d^2 \times L \times \frac{N}{60} \quad \text{(For single acting Reciprocating compressor)}$$

$$= \frac{\pi}{4} d^2 \times L \times \frac{2N}{60} \quad \text{(For double acting reciprocating compressor)}$$

Capacity of Compressor :-

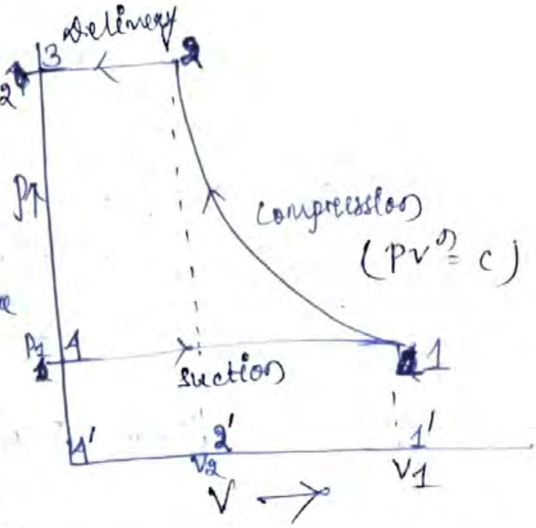
The actual quantity of air delivered per unit time at atmospheric condition.

Piston Speed :- It is the linear speed of the piston measured in m/min. Piston = 2LN

2.5 Work done of a single stage reciprocating air compressor without clearance :—

→ The cyclic operation of reciprocating air compressor comprises of three processes :—

1. Suction stroke (4–1)
2. Compression (1–2)
3. Delivery (2–3)



P-V diagram for single stage compressor without clearance

Process 4–1 Suction stroke

Inlet valve opens, while exhaust valve is closed. Atmospheric air enters into the cylinder at constant pressure P_1.

Process 1–2 Compression

Both intake and exhaust valve closed. The air is compressed from pressure P_1 to P_2 according to polytropic law $PV^n = C$.

Process 2–3 Delivery or Discharge or Exhaust process

The Entake valve closed while exhaust valve opens. The compressed air is pushed out of the cylinder at constant pressure P_2 through delivery / exhaust valve.

Analysis :—

Indicated work per cycle :—

Theoretical P–V diagram for single stage single acting reciprocating air compressor without clearance is shown in above figure.

* The net work done per cycle is equal to the area under the P-V diagram.

Indicated work done on the air per cycle

= Area under the curve 1-2-3-4-1

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

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

Area under 1-2 = $-\int P\,dV$

$= \frac{P_2V_2 - P_1V_1}{n-1}$ (During compression process 1-2 process follows $PV^n = C$)

Area under 2-3 = P_2V_2 (Flow work during discharge at const. pressure P_2)

Area under 4-1 = P_1V_1 (Flow work during suction at const. pressure P_1)

∴ Total indicated work input to compressor

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

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

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

Assuming air as perfect gas and applying characteristic gas equation :-

$PV = M_aRT$ where M_a = Mass of air inducted into cylinder per cycle

R = universal gas constant

$$W_{in} = \frac{n}{n-1} M_aR(T_2 - T_1) \quad (\text{KJ/cycle})$$

Other Expression :-

$$W_{in} = \frac{n}{n-1} M_aRT_1\left(\frac{T_2}{T_1} - 1\right)$$

$$= \frac{n}{n-1} M_aRT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] (\text{KJ/cycle})$$

$\left(\because \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right) \right.$

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

V_1 = vol. inducted per cycle

Mean Effective Pressure (P_m) :-

It is a hypothetical average pressure, which if acted on the piston during the entire compression stroke will require the same power input as required during actual cycle.

* Net work input in a cycle

$$W_{in} = P_m \times \text{Swept vol.}$$

$$\Rightarrow P_m = \frac{W_{net}}{V_s}$$

From an indicator diagram the P_m can be obtained as

$$P_m = \frac{\text{Area of indicator diagram } (mm^2)}{\text{length of indicator diagram } (mm)} \times \text{spring const } (kPa/mm)$$

$$= \frac{a}{l} \times K$$

Indicated power

W.D. on air per unit time is called indicated power.

$$I.P. = \text{Work input/cycle} \times \text{No. of cycle per unit time}$$

$$= \frac{W_{in} \times N \times K}{60}$$

$$= \frac{P_{mi} \times A \times L \times N \times K}{60} \; (kW)$$

W_{in} = Indicated work input/cycle

P_{mi} = Indicated mean effective pressure (kPa)

L = stroke length (m)

A = $\frac{\pi}{4} d^2$ cross-sectional area of bore

N = no. of rot^n/minute

K = no. of suction per revolution of crank

= 1 (single acting Reciprocating compressor)

= 2 (double acting ")

Brake Power :- Actual power input to compressor is more than indicated power as some work is required to overcome irreversibilities and frictional effects.

$$BP = IP + \text{Friction power (FP)}$$

$$\eta_m = IP/BP \qquad \text{Motor power} = \frac{BP/\text{shaft power}}{\eta_m \text{ of motor and drive}}$$

Work done of a single stage reciprocating air compressor with clearance :—

Clearance volume :— It is the space kept in the cylinder when the piston reaches its topmost position (TDC).

* It is provided :—
  - → to avoid the piston striking the cylinder head
  - → To accomodate the valve's actuation inside the cylinder as suction and delivery valves are located in clearance volume.

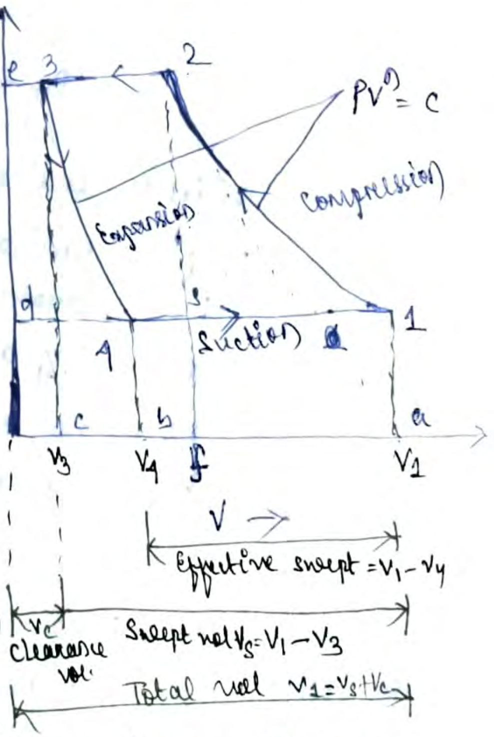
* Ratio of clearance volume to swept volume is defined as clearance ratio or percentage clearance. It vary from 4% to 10%.

* Compressor should have smallest possible clearance volume because compressed air kept in clearance volume reduces the suction capacity.

Effects of clearance volume :— With increase in clearance volume
* volumetric efficiency decreases as vol. of air takes is less than swept volume per stroke
* More power require to run compressor
* Max^m compression pressure is controlled by clearance vol.

Indicated compression work with Clearance :—

* Fig. shows the indicator diagram for reciprocating compressor with clearance.



Stroke 1 (3–1) :— The piston withdraws, causing the air in the clearance volume to expand i.e. expansion stroke 3–4. This expansion continues till the pressure in the cylinder falls below atmospheric pressure P_1 (at 4) and force to open the inlet valve at 4. After that fresh air is drawn into cylinder during suction stroke 4–1 at pressure P_1.

Stroke 2 (1–3) :— The piston moves inward i.e. from (BDC to TDC) compressing the air in the cylinder, till pressure P_2 is sufficient to open the delivery valve at 2. After that no more compression take place and during remaining part of compression stroke, compressed air is delivered as delivery valve opens till piston reaches at 3.

⇒ Both expansion and compression are supposed to follows $pV^n = c$ law.

* The total area of indicator diagram represent the work of compressor on the air.

Indicated workdone is given by the area 1-2-3-4-1 on p.v. diagram.

Indicated work = Area 1-2-3-4-1

= Area f-2-3-c + Area a-1-2-f
− Area b-4-3-c − Area b-a-1-4

$$= P_2(V_2 - V_3) + \frac{P_2V_2 - P_1V_1}{n-1} - \frac{P_2V_3 - P_1V_4}{n-1} - P_1(V_1 - V_4)$$

Indicated work = Area (1-2-e-d) − Area (3-e-d-4)

$= W_c - W_e$

W_c = workdone during compression following $pV^n = c$

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

W_e = workdone by gas during expansion following by $pV^n = c$

$$W_e = \frac{n}{n-1} P_4V_4 \left[\left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} P_1V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \quad \left(\because \begin{array}{l} P_3 = P_2 \\ P_4 = P_1 \end{array}\right)$$

Net workdone / cycle W_n $= \frac{n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] - \frac{n}{n-1} P_1V_4 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

$$= \frac{n}{n-1} P_1(V_1 - V_4) \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$W_{in} = \frac{n}{n-1}(m_1 - m_4)RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Volumetric Efficiency :-

It is defined as the ratio of actual volume of air sucked into the compressor (at atm pressure & temp) to the piston displacement volume.

$$\eta_{vol} = \frac{\text{Effective swept volume}}{\text{Piston displacement volume/swept volume}}$$

$$= \frac{V_1 - V_4}{V_1 - V_3}$$

$$= \frac{V_s + V_c - V_4}{V_s + V_c - V_c} = \frac{V_s + V_c - V_4}{V_s}$$ [V_c = clearance vol, V_s = swept vol]

$$= 1 + \frac{V_c}{V_s} - \frac{V_4}{V_s} \times \frac{V_c}{V_c}$$

$$= 1 + \frac{V_c}{V_s} - \frac{V_c}{V_s} \times \frac{V_4}{V_c}$$

$$= 1 + c - c\left(\frac{V_4}{V_3}\right)$$ [∵ clearance ratio $c = \frac{V_c}{V_s}$]

$$\frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{\frac{1}{n}} = \left(\frac{P_2}{P_1}\right)^{1/n} = \frac{V_1}{V_2}$$

$$\therefore \eta_{vol} = 1 + c - c\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}\right]$$

$$\boxed{\eta_{vol} = 1 + c - c\left(\frac{V_1}{V_2}\right)}$$

* η_v decreases with increase in pressure ratio and with increase in clearance.

η_v decreases because of following factor :—

1. Too large clearance volume
2. Obstruction at inlet valve.
3. High speed of compressor :- with high speed ↑ P↓ T↑ ...
4. Heated cylinder wall.
5. Increase in pressure ratio :- $\frac{P_{2max}}{P_1} = \left(1 + \frac{1}{c}\right)^n$ ← Max^m pressure ratio attained

Free air delivery (FAD) :-

The volume of compressed air corresponding to atmospheric condition is known as free air delivery (FAD).

Unit :- m^3/min

* FAD is less than compressor displacement vol. due to :-
  - → Obstruction at inlet valve
  - → Re-expansion of high pressure air in clearance vol.
  - → Hot cylinder walls of compressor.

* Air is sucked at a pressure & temp^r lower than that of free air.

$$\frac{P_f V_f}{T_f} = \frac{P_1 (V_1 - V_4)}{T_1}$$ (f denote free (ambient cond^n), 1 " actual suction cond^n)

FAD $$V_f = \frac{P_1 T_f}{P_f T_1} (V_1 - V_4)$$

η_{vol} w.r.t. FAD :-

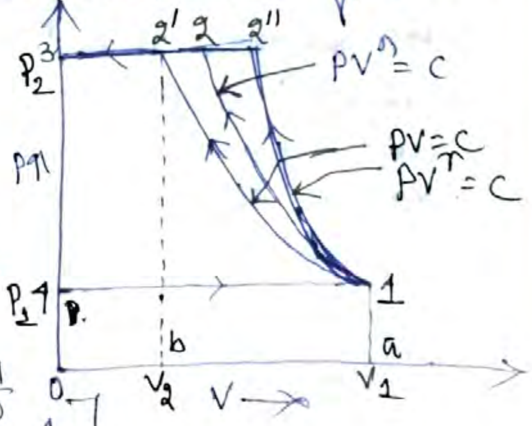
$$\eta_{vol} = \frac{V_f}{V_1 - V_c} = \frac{P_1 T_f}{P_f T_1} \left(\frac{V_1 - V_4}{V_1 - V_c}\right)$$

$$= \frac{P_1 T_f}{P_f T_1} \left[1 + c - c\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}\right]$$

Minimizing Compression work :-

between same pressure levels (P_1 and P_2)

* compression process can be executed in 3 types i.e.
  1. Isentropic compression 1 - 2'',
  2. Polytropic compression (1-2)
  3. Isothermal compression (1-2')



(1) Polytropic compression :- (1-2)

The indicated compression work per cycle for a polytropic process 1-2 is :-

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

(2) Isentropic compression (1-2'') :-

$$W_{iso} = \frac{\gamma}{\gamma - 1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

(3)

(3) Isothermal Processes (1-2'):-

Indicated work input for isothermal compression

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

= Area a-1-2'-b + Area b-2'-3-0 - Area a-1-4-0

$$W_{iso} = -\int_{V_1}^{V_2} P\,dV + P_2V_2 - P_1V_1 \qquad (1)$$

For an isothermal process;

$$PV = C$$

$$\Rightarrow P = \frac{C}{V}$$

$$-\int_{V_1}^{V_2} P\,dV = P_1V_1 \ln\left(\frac{V_1}{V_2}\right) \qquad (2)$$

For isothermal process :- $P_2V_2 = P_1V_1$ — (3)

Putting value of eq(2) & eq(3) in eq(1) :-

~~$W_{iso} = P_1V_1 \ln(\frac{V_1}{V_2})$~~

$$W_{iso} = P_1V_1 \ln\left(\frac{V_1}{V_2}\right) + P_2V_2 - P_2V_2$$

$$= P_1V_1 \ln\left(\frac{V_1}{V_2}\right)$$

$$= P_1V_1 \ln\left(\frac{P_2}{P_1}\right)$$

V_1 = vol. of air inducted per cycle.

* The area of indicator diagram under P-V diagram is the measure of compression work.

From diagram, it is shown that the area with isentropic compression is max^m. So it requires max^m work input.

whereas the area of indicator diagram for isothermal compression is minimum. Thus compressor with isothermal compression will require minimum work input.

Adiabatic efficiency:-

It is defined as the ratio of isentropic work input to actual work input.

$$\eta_{adiabatic} = \frac{\text{W isentropic input}}{\text{Actual W input}}$$

Compressor efficiency:- It is defined as ratio of isothermal work input to indicated work input.

$$\eta_{comp} = \frac{\text{Isothermal work input}}{\text{Indicated work input}}$$

Isothermal efficiency:

It is defined as ratio of isothermal work input to actual work input during compression.

$$\eta_{iso} = \frac{\text{Isothermal work input}}{\text{Actual work input}}$$

Methods for improving isothermal eff. :-

The compression of gas requires min^m work input for isothermal process. and it is only possible if all heat generated during compr^n is dissipated to cooling medium around the cylinder wall to keep temp^re constant throughout process.

* Various methods are adopted to reduce temp^r of gas during compression and to keep it more closely to isothermal compression :-

1. Water spray
2. Water Jacketing
3. External fins
4. Inter cooler
5. By suitable cylinder proportion :- Large surface to volume ratio, cylinder large bore and short piston stroke.

Multi-stage Compression :-

Compressor requires minimum work input with isothermal compression. But the delivery temp^r increases with increase in pressure ratio and volumetric efficiency decreases as pressure ratio increases.

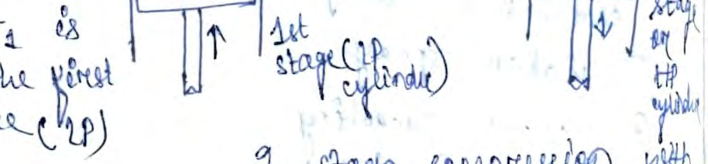
The vol. eff. can be improved by carrying out the comp in more than one cylinders with intercooling bet^n stages for same compression ratio. compression of air in 2 or more cylinders in series is called multistage compr.

Adv :-

1. Gas can be compressed to a sufficiently high pressure.
2. cooling of air is more efficient with intercoolers.
3. Power input to compressor can be reduced by cooling.
4. Pressure ratio of each stage reduced by multistaging.
5. vol. eff. increases as pressure ratio decreases.
6. Low working temp^r helps to sustain better lubrication.

Workdone in 2-stage compressor with intercooler

Figure shows a schematic diagram for 2-stage compression.



2-stage compression with inter cooler

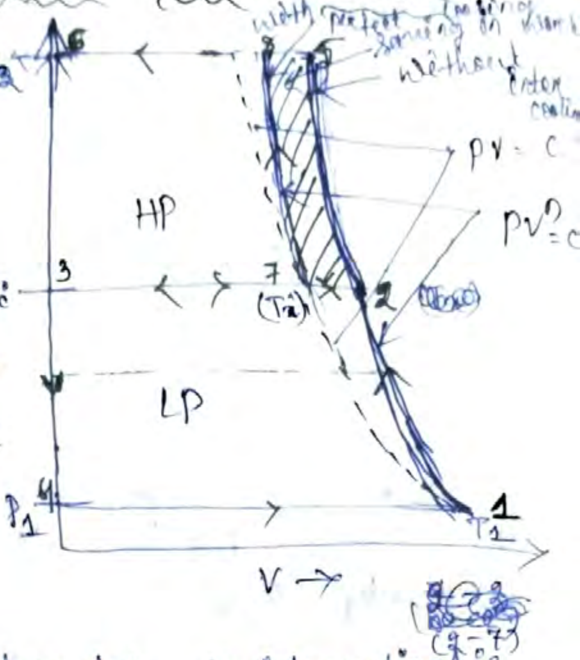
→ The air at P_1 and T_1 is first drawn into the first stage or low pressure (LP) cylinder.

→ It is partially compressed to some intermediate pressure, P_i and temp^r T_i.

→ The low pressure cylinder then discharge the air to an intercooler which ideally cools the air to its initial temp^r (T_1). The process of cooling air is called intercooling process.

⇒ The cooler air then enters the second stage or high pressure (HP) cylinder and is compressed to final delivery pressure P_2 and temp^r T_2.

Workdone of 2-stage compressor without clearance :-



Indicator diagram is shown in figure $p \sim v$ diagram.

cycle 1-2-3-4-1 represents 1st stage compression cycle.

Air is discharged from P_1 LP cylinder at intermediate pressure P_i & T_{xi}.

$$\frac{T_{xi}}{T_1} = \left(\frac{P_{xi}}{P_1}\right)^{\frac{n-1}{n}}$$

The air is cooled in intercooler. If intercooling is perfect or complete, air will enter HP cylinder at the same tempr at which it enters LP cylinder i.e. the exiting tempr (T_{xi}) of gas from intercooler will be same as the original inlet tempr T_1.

So $T_{xi} = T_1$. (for perfect cooling)

→ 2nd stage compression cycle in HP cylinder is shown by 7-8-6-3-7.

* Area 1-2-5-6-4-1 represents the single stage compression cycles from initial pressure P_1 to delivery pressure P_2.

The shaded area 7-2-5-8-7 represent saving in comp work

Total indicator work :-

$$W_{in} = W_{LP} + W_{HP}$$

$$= \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_{xi}}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} P_{xi} V_7 \left[\left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 1\right]$$

delivery tempr $T_8 = T_{xi}\left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}}$. If ($T_{xi} = T_1$, $P_i V_7 = P_1 V_1$)

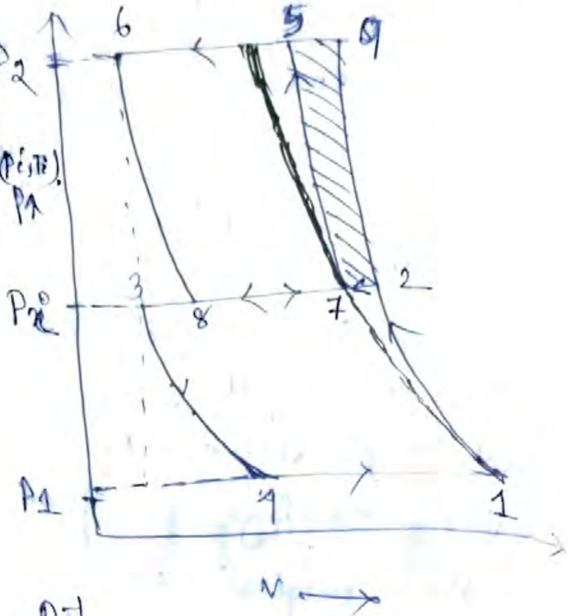
$$= T_1 \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}}$$

$$= \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_{xi}}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 1\right]$$

$$W_{in} = \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 2\right] \quad (\text{kJ}/[illegible])$$

$$m_a = \frac{P_1 V_1}{R T_1} = \frac{P_i V_7}{R T_1}$$

Workdone in 2-stage compressor with clearance :-



1-2-3-4-1 represent 1st stage compression cycle in LP cylinder compressing air from (P_1, T_1) to (P_i, T_7). 2-7 represent perfect intercooling so $T_i = T_1$.

7-5-6-8-7 represent 2nd stage compression cycle in HP cylinder delivering the air at P_2 pressure and Temp^e T_5.

$$\frac{T_i}{T_1} = \left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}}$$

$$\frac{T_2}{T_i} = \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}}$$

Total indicator work

$$W_{in} = W_{LP} + W_{HP}$$

$$= \frac{n}{n-1} P_1 (V_1 - V_4) \left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} P_i (V_7 - V_8) \left[\left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 1\right]$$

∵ $T_1 = T_i$, $P_1 (V_1 - V_4) = P_i (V_7 - [illegible]$

$$= \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 2\right] \quad \text{kJ}/[illegible]$$

$$m_a = \frac{P_4 V_4}{RT_4} = \frac{P_1(V_1 - V_4)}{RT_1} = \frac{P_2(V_5 - V_8)}{RT_1}$$

Condition for Min^m compression work :-

Intermediate pressure (P_i) influences work to be done on gas. It has optimum value for min^m comp. work
Total work per kg of air is given by :-

$$W_{in} = \frac{n}{n-1} RT_1 \left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 2 \right]$$

In this equ^n P_1, T_1, P_2 are fixed. So optimum value of P_i for min^m work input can be obtained by applying cond^n as

$$\frac{d(W_{in})}{dP_i} = 0$$

$$\Rightarrow \frac{n}{n-1} RT_1 \frac{d}{dP_i}\left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} - 2 \right] = 0$$

$$\Rightarrow \left(\frac{1}{P_1}\right)^{\frac{n-1}{n}} \frac{n-1}{n} (P_i)^{\frac{n-1}{n} - 1} + (P_2)^{\frac{n-1}{n}} \times (P_i)^{\frac{1-n}{n} - 1} \times \left(\frac{-n+1}{n}\right) = 0$$

$$\Rightarrow \left(\frac{1}{P_1}\right)^{\frac{n-1}{n}} (P_i)^{\frac{-1}{n}} - (P_2)^{\frac{n-1}{n}} \times (P_i)^{\frac{1-2n}{n}} = 0$$

$$\Rightarrow (1/P_1)^{\frac{n-1}{n}} \cdot (P_i)^{\frac{-1}{n}} = (P_2)^{\frac{n-1}{n}} (P_i)^{\frac{1-2n}{n}}$$

$$\Rightarrow \frac{(P_i)^{\frac{-1}{n}}}{(P_i)^{\frac{1-2n}{n}}} = (P_1 P_2)^{\frac{n-1}{n}}$$

$$\Rightarrow (P_i)^{\frac{2(n-1)}{n}} = (P_1 P_2)^{\frac{n-1}{n}}$$

$$\Rightarrow P_i^2 = P_1 P_2$$

$$\Rightarrow \boxed{P_i = \sqrt{P_1 P_2}} \quad \text{or} \quad \frac{P_i}{P_1} = \frac{P_2}{P_i} = \sqrt{\frac{P_2}{P_1}}$$

* For min^m compression work, intermediate pressure (P_i) is the geometric mean of suction and discharge pressure.

For min^n compression work :-

pressure ratio in LP stage = Pressure ratio in HP stage

$$\frac{T_i}{T_1} = \left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}}$$

$$\frac{T_2}{T_i} = \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}} \Rightarrow \frac{T_2}{T_1} = \left(\frac{P_2}{P_i}\right)^{\frac{n-1}{n}}$$

$(\because T_1 = T_i)$

As $\frac{P_i}{P_1} = \frac{P_2}{P_i}$

$$\frac{T_i}{T_1} = \frac{T_2}{T_1}$$

$$\Rightarrow T_2 = T_i$$

Also work required in L.P. compressor = Work required in HP compressor

So intermediate pressure that produce min^n work also result in equal pressure ratio in 2-stages, equal discharge temp^{re} and equal work for 2-stages.

* For 2-stage compression, min^n work :-

putting eq (2) in eq (1) :-

$$W_{in} = \frac{2n}{n-1} m_a R T_1 \left[\left(\frac{P_i}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$= 2 \times$ power required for one stage

$$\boxed{W_{in} = \frac{2n}{n-1} m_a R T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{2n}} - 1\right]}$$

Heat rejected in intercooler $Q_2 = C_p(T_i - T_1)$

Note

For N-stage compressor :-
optimum pressure ratio per stage is

$$\frac{P_2}{P_1} = \left(\frac{P_d}{P_s}\right)^{\frac{1}{N}}$$

(P_d, P_s are discharge & suction pressure respectively)

Min^m work of compression for N-stage :-

$$W_{min} = \frac{N n m R T_1}{n-1}\left[\left(\frac{P_d}{P_s}\right)^{\frac{n-1}{Nn}} - 1\right]$$

Conditions required for min^m compression work :-

* Pressure ratio of each stage should be same
* Air after compression in each stage cooled to initial temp^r of air intake.
* Work input to each stage same.

Formulae

* $\eta_v = \frac{\text{Actual mass of air/stroke}}{\text{Mass of air corresponding to swept vol. at atm cond}^n} = 1 + C - C\left(\frac{V_1}{V_2}\right)$ ← $\left(\frac{P_2}{P_1}\right)^{1/n}$

* Induction vol. / vol. flow rate (m^3/s) :-

$$\dot{V} = \frac{\pi}{4} d^2 \times L \times \frac{N}{60} \quad (\text{for single acting})$$

$$= \frac{\pi}{4} d^2 \times L \times \frac{2N}{60} \quad (\text{for double acting})$$

* Piston speed $v = 2LN$ m/min

* Work input $W_c = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

$$= \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} m_a R T_1 \left[\left(\frac{T_2}{T_1} - 1\right)\right]$$

Chapter - 3

Properties of Steam

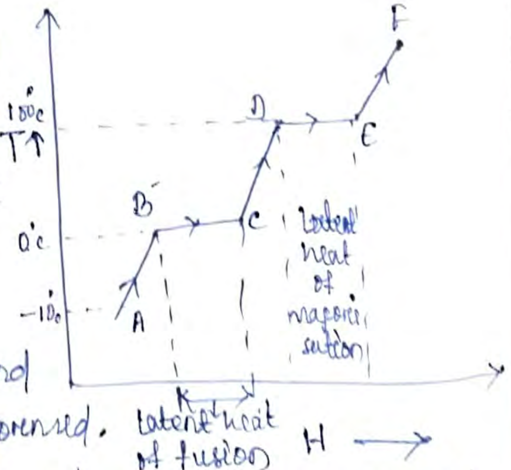
3.1 Difference betn gas and vapour :—

Gas	Vapor
⇒ Gas phase consists of a single thermodynamic state i.e. gaseous state at room temperature.	⇒ Vapour is a mixture of two or more different phases at room tempr.
→ Gases are a state of matter.	⇒ Vapour is not a state of matter.
→ Gas is a substance which has not and will not experience a phase change.	⇒ vapour is a substance which has experienced a phase change
→ Gas is formed above critical tempr below critical the pressure of a substance.	⇒ vapour is formed below critical tempr boiling point of substance.

Formation of steam :—

Consider a cylinder fitted with a frictionless piston, which may be loaded to any desired pressure.
The cylinder contains 1 kg of ice at −10°c under 1 atm pressure at the state A.

Process A-B :—
when any amount of heat is added to ice, its tempr rises till it reaches 0°c. The vol. of ice increases upon heating.



Process B-C :—
→ Ice begins to melt at 0°c and a two phase mixture is formed.
→ At state C melting process ends and ice melts to water without change in pressure and tempr.
→ There is a decrease in volume.
→ This phase transformation from solid to liquid is called melting or fusion of ice.

Process C-D :-

When heat is added to liquid water,

(i) Temp^r of water rises with heat supply and keeps on rising until it reaches boiling point temp^r, pt D.

(ii) There is a decrease in specific volume of water, when its temp^r rises from 0°c to 4°c and thereafter specific vol. increases with temp^r with increase in temp^r till it reaches saturation temp^r.

⇒ Piston moves up during this process.

Process D-E :-

→ After water reaches saturation temp^r, any addition of heat causes the phase change process from saturated water to saturated vapour.

⇒ During this phase change process :-

(i) There exist two phase mixture of water and vapour called wet steam.

(ii) The temp^r of the mixture remains constant

(iii) specific vol. of vapour increases.

⇒ At state E, all water has been vapourised and this state of steam is called dry saturated steam.

⇒ Phase change from liquid to vapour is called vaporisation.

Process E-F :-

Once steam becomes dry and saturated, it behaves as an ideal gas and its temp^r and vol. start increasing with further supply of heat. This steam is called superheated steam.

Terminology :-

Saturation temp^r :- It is the temp^r at which a pure substance starts to evaporate at a given pressure.

Saturation pressure :-

It is the pressure at which a pure substance starts to evaporate at a given temp^r.

Steam :- It is the gaseous phase of water

Saturated steam :- steam is about to condense.

Wet steam :- It is the mixture of dry steam and water particles as moisture.

Dry saturated steam :- saturated vapour, which is free from moisture.

Superheated steam :-

When the dry saturated steam is further heated at const pressure, then the steam existing at higher temperature than its saturation temperature is called superheated steam.

Degree of superheat :-

It is the temperature rise of superheated steam above its saturation temp^r.

Critical point :-

A locus on the saturation curve, where saturation liquid line and saturated vapour line meet.

Triple point :-

It is the locus, where all three phases of water coexist.

Dryness fraction :-

It is the ratio of mass of actual dry saturated steam to total mass of steam considered.

Dryness fraction $x = \frac{m_g}{m_g + m_w}$

m_g = Mass of dry and saturated steam

m_w = mass of water in suspension

3.3 P–v diagram

Figure shows the P–v diagram for the process of phase transformation from liquid water to vapour at different pressures.

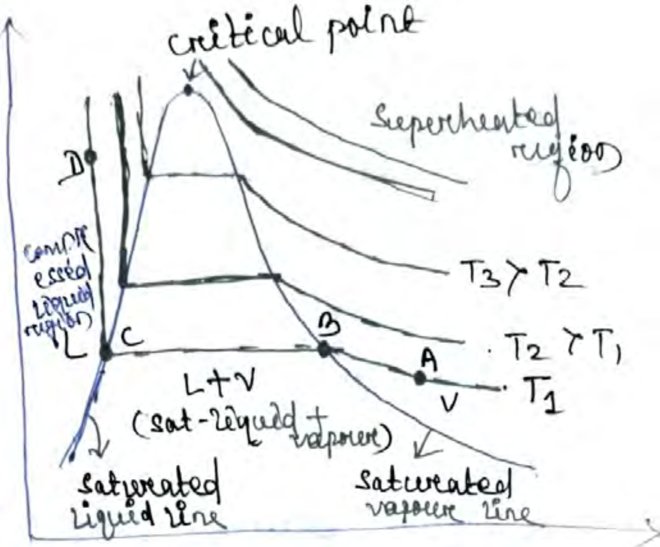


Fig:- P–v diagram for water

- P–v diagram is constructed by following consideration :–

(i) All saturated liquid lines are connected by a solid line, called saturated liquid line.

(ii) All saturated vapour states are connected by another solid line, called, saturated vapour line.

(iii) The saturated liquid line and saturated vapour line meet at critical point and form vapour dome.

(iv) Region located right to the saturated vapour line is called superheated vapour region.

(v) Region located left to the saturated liquid line is called compressed liquid region.

(vi) The region under the dome involves equilibrium between saturated liquid and saturated vapour and is called wet vapour region.

Observation :– P–v diagram shows that :–

→ Constant temperature lines (Isotherms) on this diagram have a downward trend.

→ consider ABCD, as a isotherm on P–V diagram.

→ the vapour state A is compressed slowly and isothermally, pressure will raise until there is saturated vapour at point B.

→ If compression is continued, condensation takeplace, and BC represent this condensation process where pressure and temp^re remain constant.

→ A very large pressure is needed to compress the liquid so CD is almost vertical.

⇒ As tempʳ increases, liquid-vapour transition (L) decreases and becomes zero at critical point.

→ Above critical point, a liquid upon heating suddenly flashes into vapour, or vapour upon cooling suddenly condenses into liquid.

→ The isotherm passing through critical point is called critical isotherm and corresponding tempʳ is known as critical temp (T_c). The pressure and volume at critical point are known as critical pressure (P_c) and critical volume (v_c)

For water :- P_c = 221.2 bar

T_c = 374.15 °C

v_c = 0.00317 m³/kg

→ Above critical point, isotherms are continuous curves approach equilateral hyperbolas.

T-S diagram

The tempʳ-entropy (T-S) diagram for steam is shown in figure with following observations:

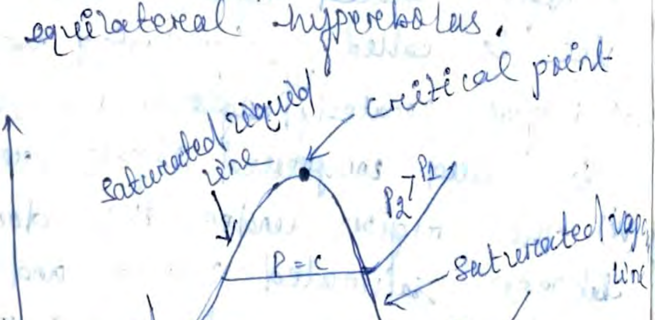


Fig :- T-S diagram for water & steam

→ The absolute tempʳ data is plotted along the ordinate and the specific entropy data is plotted along the abscissa.

⇒ The diagram has three regions. These are separated by saturated liquid line and saturated vapour line

The saturated liquid line represents completely wet steam i.e. having dryness fraction $x = 0$ and the saturated vapour line represent completely dry steam having dryness fraction $x = 1$.

* The three regions are compressed liquid region left to the saturated liquid line, superheated vapour region right to saturated vapour line and wet vapour region between these two lines.

* The two saturation line meet at critical point.

⇒ In compressed liquid region, the constant pressure lines almost coincide with the saturated liquid line.

⇒ In saturated liquid-vapour mixture region (wet steam region), the constant pressure lines and constant temp^r lines are horizontal and parallel to each other.

⇒ In superheated vapour region, the constant volume lines are steeper than the constant pressure lines.

H-S diagram :— or Mollier diagram :—

⇒ The enthalpy-entropy diagram is referred as Mollier diagram.

⇒ It is most commonly used to obtain the properties of steam.

⇒ The use of a Mollier chart eliminates the complex calculation work and very useful in solving the problems. It is also convenient to use.

⇒ In H-S diagram, The specific enthalpy data is plotted along the ordinate and specific entropy data is plotted along abscissa.

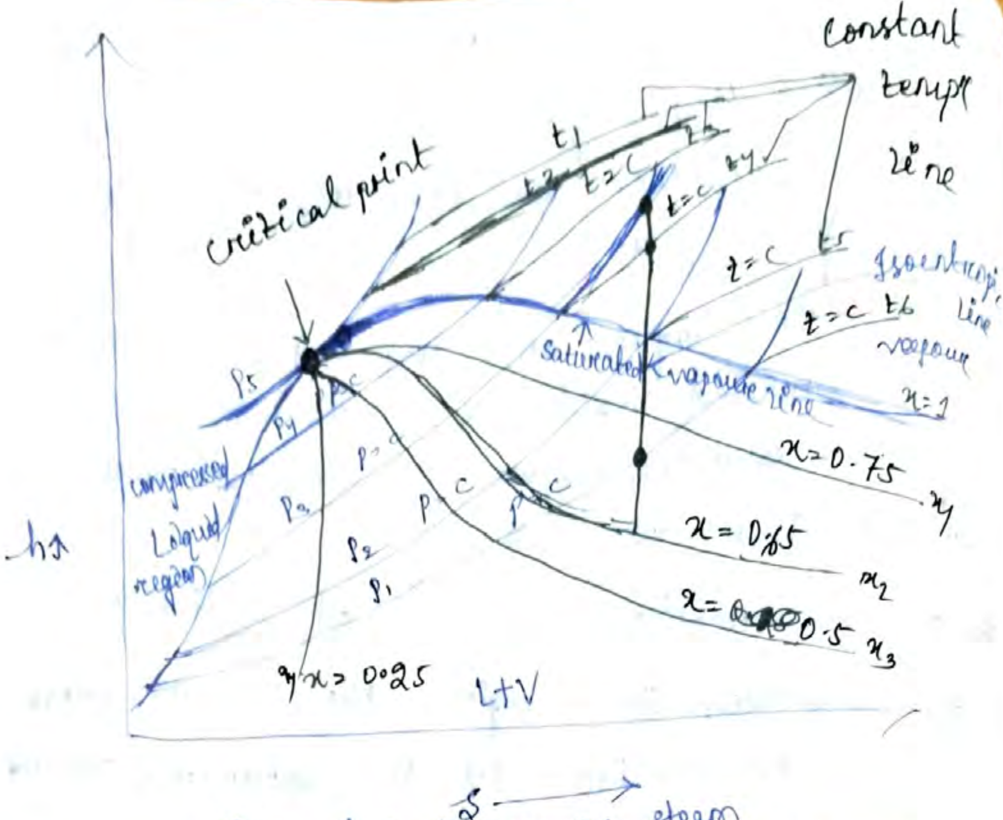


Fig :- h-s diagram for steam

→ A schematic h-s diagram is shown in figure. constant pressure lines P_1, P_2, P_3, P_4 - - , constant tempr line t_1, t_2, t_3, t_4 - - , const. dryness fraction lines x_1, x_2, x_3 - - are drawn in this diagram ;

=> The diagram consists of following features:-

* constant pressure lines are drawn in both wet steam region and superheated steam region. These lines are straight in wet steam region. These are curved slightly upwards in superheated region. constant pressure lines diverge from one another and the critical isobar is a tangent at the critical point.

* The constant tempr lines are straight and almost horizontal in superheated region

* Dryness fraction lines are drawn only in wet steam region, below the saturated vapour line. These lines represent the condition of wet steam and these are parallel to the saturation line.

* The constant volume lines are drawn in both wet steam region and superheated region.

These lines are straight in wet steam region and curved above the saturation curve. These lines are steeper than constant pressure region.

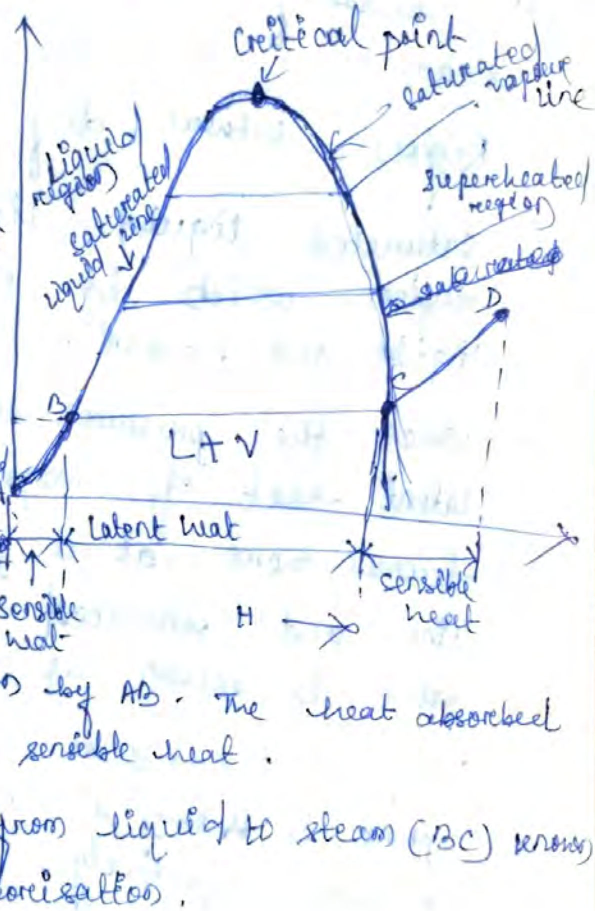
* Isentropic lines are represented by vertical lines as there is no change in entropy.

* As pressure increases h_{fg} decreases and at critical pressure it becomes zero.

T – H diagram :-

T-H diagram is shown in figure for steam formation.

⇒ During the formation of the superheated steam, from water at freezing point, the heat is absorbed in the following three stages and ABCD shows relation bet^n Temp^r & heat at a specific pressure p as:



1. The heating of water upto boiling temp^r or saturation temp^r is shown by AB. The heat absorbed by water is known as sensible heat.
2. The heat absorbed for change of state from liquid to steam (BC) known as latent heat of vaporisation.
3. Superheating state (CD) is obtained by absorbing heat of superheat.

The graph T – H is drawn by plotting data of temp^r along ordinate and Total heat along abscissa, conducting the steam formation process for different pressure.

The graph has following feature :-

→ Line passing through saturated liquid state is known as saturated liquid line which forms the boundary line between water and steam.

→ Line passing through dry steam points is known as dry saturated steam line, which forms the boundary line betⁿ wet and superheated steam.

→ Region between dry saturated vapour line and saturated liquid line is called wet steam region which is mixture of saturated liquid and vapour.

→ When the pressure and saturation tempʳ increases latent heat of vaporisation decreases, it becomes zero, at a point where saturated liquid line and saturated vapour line meet. This point is known as critical point.
Tempʳ and pressure corresponding to critical point is known as critical tempʳ and critical pressure respectively.

3.4 Properties of steam :-

Enthalpy changes during formation of steam :-

Latent heat of fusion :-

It is defined as the quantity of heat, required to convert 1kg of ice into water at constant temperature.

Enthalpy of saturated water :- (h_f)

It is defined as amount of heat absorbed by 1kg of water during its heating from 0° to saturation tempʳ at given pressure.

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

It is defined as an amount of heat energy required to convert 1 kg of saturated water into dry and saturated steam keeping pressure and tempr constant.

→ h_{fg} is directly obtained from steam tables.

Enthalpy of steam or Total heat (h_g) :-

It is the sum of enthalpy of saturated water and enthalpy of vaporisation.

It is defined as the amount of heat required to convert 1 kg of water at 0°C into dry and saturated steam at a given pressure.

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

Enthalpy or Total heat of steam :-

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

∴ Enthalpy or total heat of steam = sensible heat + latent heat

(i) Wet Steam :-

Enthalpy of wet steam is given by :-

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

x = dryness fraction of steam

(ii) Dry steam :- In dry steam $x = 1$

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

(iii) Superheated steam :-

It can be defined as the amount of heat required to convert 1 kg of water at 0°C into superheated steam at constant pressure. h_{sup} = Total heat for dry steam + Heat for superheated steam

$$= h_g + C_{ps}(t_{sup} - t_{sat})$$

Specific volume of steam :— (v_s)

It is the volume occupied by the steam per unit mass at a given temp^r and pressure.

Unit :- m^3/kg

* For dry and saturated steam, the specific volume is designated as v_g.

specific vol. during evaporation is noted as v_{fg}.

(i) Wet steam :-

$$v_{wet} = v_f + x\,v_{fg} = v_f + x(v_g - v_f)$$
$$= x v_g + (1-x) v_f$$
$$v_{wet} \approx x v_g \quad (v_f \text{ at low pressure is very small})$$

(ii) Dry steam :- $x = 1$

Sp. vol. of 1 dry steam $= v_g \ (m^3/kg)$

(iii) Superheated steam :—

Superheated steam behaves like a perfect gas and superheating is carried at constant pressure.

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

$$\Rightarrow v_{sup} = v_g \times \frac{T_{sup}}{T_{sat}} \ (m^3/kg)$$

where, v_g = specific volume of dry and saturated steam

v_f = Specific volume of moisture

v_{fg} = Specific volume change of steam during evaporation $= v_g - v_f$

T_{sup} = Temp^r of superheated steam (K)

T_{sat} = Temp^r of dry and saturated steam (K)

Entropy change of steam :-

Entropy change of wet steam :-

It is the sum of entropy of saturated water (s_f) and entropy of evaporation.

$$s_{wet} = s_f + x\,s_{fg} \ (kJ/kg\,K)$$

Entropy change of dry and saturated steam :-

It is the sum of entropy of saturated water (S_f) and entropy of evaporation.

$$S_g = S_f + S_{fg}$$

It can be directly obtained from steam tables.

Entropy change of superheated steam :-

Entropy change during superheating of 1kg of dry steam from Tsat to Tsup at constant pressure

$$S_{sup} = S_f + S_{fg} + C_{ps} \ln\left(\frac{T_{sup}}{T_{sat}}\right)$$
$$= S_g + C_{ps} \ln\left(\frac{T_{sup}}{T_{sat}}\right)$$

Internal energy of steam :—

Internal energy of steam is actually heat energy stored in steam above freezing point temp^r of water.

$$u = h - pv$$

dry steam :- $u_g = h_g - P v_g$

wet steam :- $u_{wet} = (h_f + x h_{fg}) - P(x v_g)$

$$= x u_{fg}$$

Superheated steam :- $u_{sup} = h_g + C_{ps}(T_{sup} - T_{sat}) - P v_g \times \frac{T_{sup}}{T_{sat}}$

3.5 Steam table :—

⇒ The properties of steam are arranged in the steam tables as functions of pressure and temperature.

⇒ Properties of steam like its temperature of formation (saturation temp^r), sensible heat, latent heat of vaporisation, enthalpy or total heat, specific volume, specific entropy, specific internal energy etc vary with pressure, and can be found by experiments only

These properties have been carefully determined and made available in a tabular form known as steam tables. Steam table gives the properties on per kg basis.

→ These experimentally determined thermodynamic properties are presented in 3 different forms of table as:

1. Temperature Entry table :- In this table, temp is chosen as an independent variable and properties of coexisting liquid and vapour phases are presented for saturated water/steam.

2. Pressure entry steam table :-

In this table, pressure is chosen as an independent variable and other properties are presented against it for saturated water/steam.

3. Superheated steam table :-

In this table, pressure and tempr are two independent variables and properties of superheated steam can be obtained against these variable.

Use of steam table :-

→ Steam table give the values of properties for different pressure and tempr, ~~these values~~ corresponding to 1 kg of dry and saturated steam.

→ These values may also be used to determine the corresponding values for wet steam.

3.6 Thermodynamic process :-

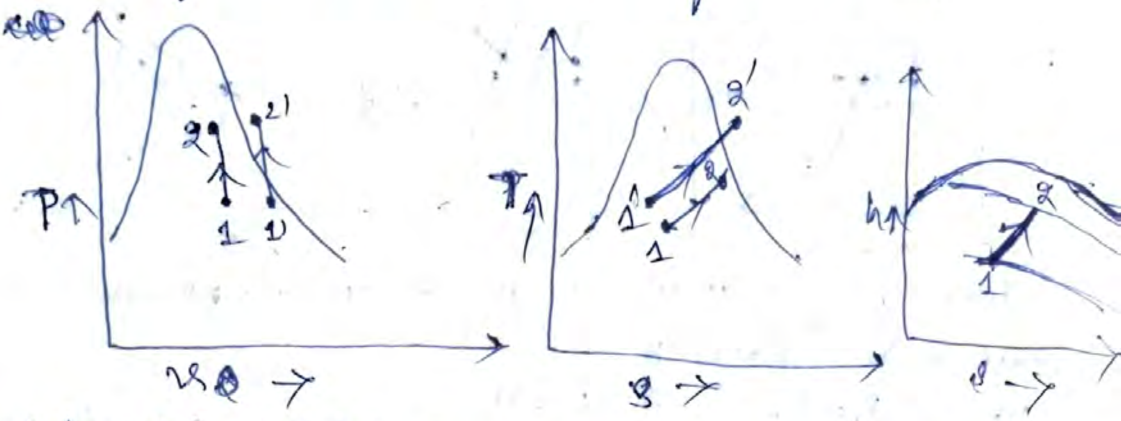
Various thermodynamic processes for vapour are :-

(i) constant volume process
(ii) constant pressure process
(iii) constant tempr process
(iv) Reversible adiabatic or Isentropic process
(v) Polytropic process
(vi) Throttling process

Constant volume process (Isochoric process) :-

In this process volume of steam before and after the process is constant.

* consider 1 kg of wet steam being heated at constant volume from initial state 1 to final state 2.



Let P_1 = Initial pressure of wet steam (bar)

v_{g1} = specific volume of dry saturated steam corresponding to P_1

x_1 = dryness fraction of steam at state 1.

P_2, v_{g2}, x_2 = corresponding values for state 2 of 1 kg of wet steam.

Initial vol. of steam $v_1 = x_1 v_{g1}$

Final volume at final state 2 is $v_2 = x_2 v_{g2}$ (if steam is wet condition)

$v_2 = v_{g2}$ (if steam is dry saturated)

$= v_{sup}$ (if steam is superheated)

$v_1 = v_2 \Rightarrow x_1 v_{g1} = x_2 v_{g2}$

$\Rightarrow x_2 = x_1 \dfrac{v_{g1}}{v_{g2}}$

Workdone :- $W_{1-2} = \int P\,dV$

$= 0$ ($\because$ const vol. process $V_1 = V_2$)

change in internal energy :-

$u_1 = h_1 - 100 P_1 v_1 = h_1 - 100 P_1 x_1 v_{g1}$ (KJ)

$u_2 = h_2 - 100 P_2 v_2$ (KJ)

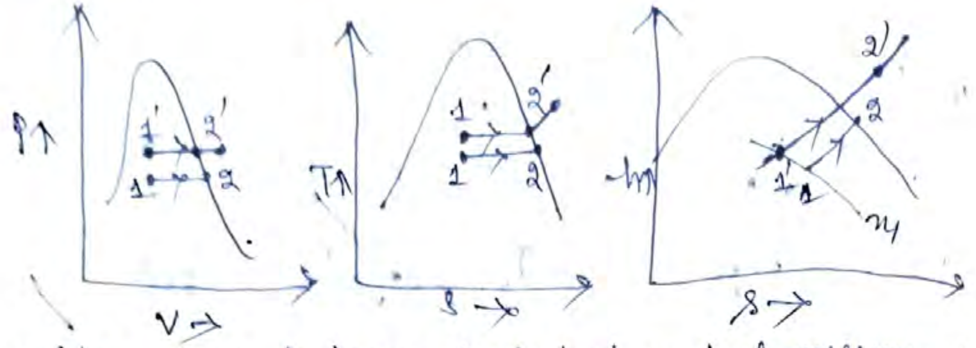
$du = u_2 - u_1$

Heat transferred :- $q_{1-2} = du + W_{1-2}$

$q_{1-2} = du = u_2 - u_1$

Constant pressure Process (Isobaric process) :-

In this process, pressure of steam before and after the process is constant.



consider 1 kg of steam heated at constant pressure from state 1 to state 2.

Let $P_1 = P_2 = P$ (bar)

x_1, x_2 = initial and final dryness fraction of the respectively

v_1, v_2 = spe. vol. of steam at initial and final state respectively

$v_1 = x_1 v_{g}$ ($\because v_{g1} = v_{g2} = v_g$ as pressure constant)

$v_2 = x_2 v_g$. (of wet steam)

$= v_g$ (of dry saturated steam)

$= v_{sup}$ (superheated steam)

Workdone :- $w_{1-2} = P \times 10^{2} (v_2 - v_1)$ KJ/kg

$= 100 P (v_2 - v_1)$

change in internal energy :-

$u_1 = h_1 - 100 P_1 v_1$

$u_2 = h_2 - 100 P_2 v_2$

$du = u_2 - u_1$ KJ/kg

Heat transferred :-

$q_{1-2} = du + w_{1-2}$

$= (u_2 - u_1) + 100P (v_2 - v_1)$

$= (h_2 - 100Pv_2) - (h_1 - 100Pv_1) + 100P(v_2 - v_1)$

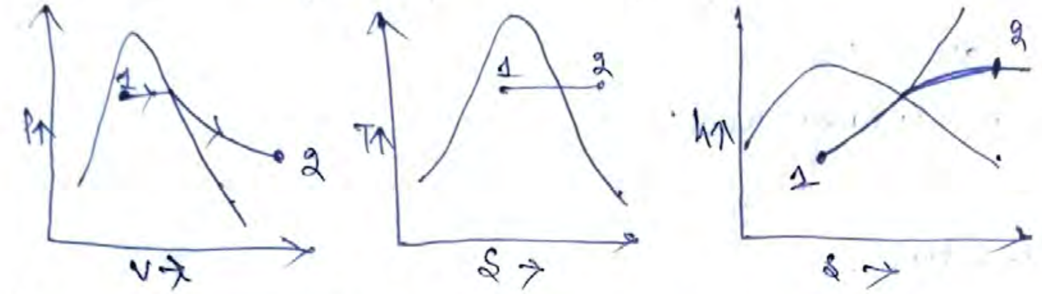
$= (h_2 - h_1)$ KJ/kg

$\therefore$ Heat transferred is equal to change in enthalpy

Constant tempr process (Isothermal process) :-

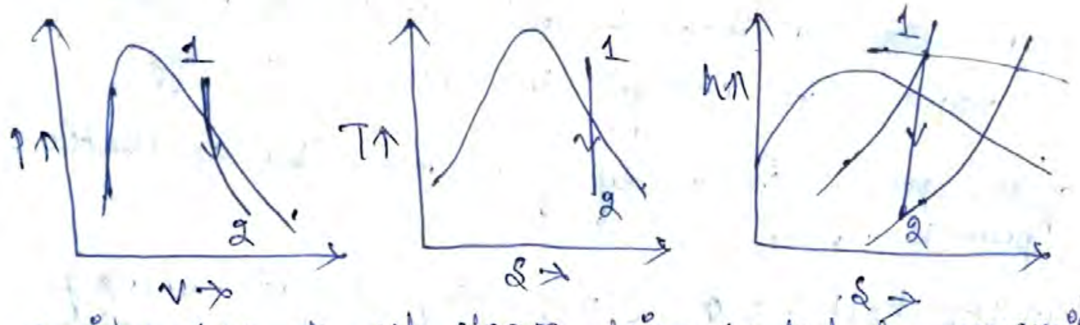
Isothermal process of wet steam will be same as isobaric process.
But for superheated steam, it behaves like a perfect gas. So it follow gas law.

$$\frac{PV}{T} = \text{const} \Rightarrow PV = \text{constant.}$$



Reversible adiabatic / Isentropic process :-

⇒ In this process there is no heat transfer and entropy remains constant.



consider 1 kg of wet steam being heated by reversible adiabatic process from state 1 to final state 2.

Let P_1, v_{g_1}, x_1 = Initial pressure, specific volume of dry saturated steam and dryness fraction of steam at state 1

P_2, v_{g_2}, x_2 = corresponding values for final condition of the steam

s_1, s_2 = specific entropy at state 1 & 2 respectively.

Initial entropy $s_1 = s_{f1} + x_1 s_{fg1}$

Final entropy of steam $s_2 = s_{f2} + x_2 s_{fg_2}$

$$s_1 = s_2$$

$$\Rightarrow s_{f1} + x_1 s_{fg_1} = s_{f2} + x_2 s_{fg_2}$$

Change in internal energy :-

$u_1 = h_1 - 100 P_1 v_1$

$v_1 = x_1 v_{g1}$

$u_2 = h_2 - 100 P_2 v_2$

$v_2 = x_2 v_{g2}$ (for wet steam)

$= v_{g2}$ (for dry saturated steam)

$= v_{sup}$ (for superheated steam)

$du = u_2 - u_1$

Heat transferred :-

$$q_{1-2} = 0$$

Work done :-

$$q_{1-2} = du + w_{1-2}$$

$$\therefore w_{1-2} = -du$$

$$= u_1 - u_2$$

$\therefore$ For reversible adiabatic process workdone is equal to change in internal energy.

If the process is steady flow reversible adiabatic process then

$h_1 + q_{1-2} = h_2 + w_{1-2}$ (neglecting kinetic energy, potential energy)

$\Rightarrow w_{1-2} = h_1 - h_2$ $(\because q_{1-2} = 0)$

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

Ans :- Given :- $m = 2\,kg$, $T = 80°c$, $x = 0.85$

At 80°c :-

$P_{sat} = 47.39\,kPa$, $v_f = 0.001029\,m^3/kg$,
$v_g = 3.40715\,m^3/kg$, $h_f = 334.88\,KJ/kg$,
$h_{fg} = 2308.77\,KJ/kgK$, $s_f = 1.0752\,KJ/kg$,
$s_{fg} = 6.5369\,KJ/kgK$

Volume :- $v = x v_g$

$= 0.85 \times 3.40715$

$= 2.896\,m^3/kg$

$V = mv = 2 \times 2.896 = 5.792\,m^3$

density :- $\rho = \frac{1}{v} = \frac{1}{2.896} = 0.345\,kg/m^3$

specific enthalpy :-

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

$= 334.88 + (0.85 \times 2308.77)$

$= 2297.33\,KJ/kg$

$H = m h_{wet}$

$= 2 \times 2297.33 = 4594.66\,KJ$

Specific entropy :-

$s_{wet} = s_f + x s_{fg}$

$= 1.0752 + (0.85 \times 6.5369)$

$= 6.631\,KJ/kgK$

Total entropy $S = m s_{wet} = 2 \times 6.631$

$= 13.26\,KJ/K$

Q) ~~calculate~~ A vessel contains 2 kg of steam at pressure 8 bar. Find amount of heat transfer as to reduce the quality of steam in vessel to be 70%.

Ans :- $m = 2\,kg$, $P_1 = 8\,bar$, $x_2 = 0.7$

From steam tables :-

At 8 bar $h_{g1} = 2767.5\ kJ/kg$,

$v_{g1} = 0.24\ m^3/kg$

volume $V = 2 \times v_{g1}$

$= 2 \times 0.24 = 0.48\ m^3$

Initial internal energy per kg of steam

$u_1 = h_{g1} - 100\,P_1\,v_{g1}$

$= 2767.5 - (100 \times 8 \times 0.24)$

$= 2575.5\ kJ/kg$

* The volume occupied by steam = volume of vessel

$\Rightarrow m \times x\, v_{g2} = V$

$\Rightarrow 2 \times 0.7 \times v_{g2} = 0.48$

$\Rightarrow v_{g2} = 0.343\ m^3/kg$

For $v_{g2} = 0.343\ m^3/kg$, $P_2 = 5.5\ bar$ (From steam table)

$h_{f2} = 655.8\ kJ/kg$, $h_{fg2} = 2095.9\ kJ/kg$

$u_2 = h_2 - 100\,P_2\,x_2\,v_{g2}$

$u_2 = (h_{f2} + x_2\,h_{fg}) - 100\,P_2\,x_2\,v_{g2}$

$= (655.8 + 0.7 \times 2095.9) - (100 \times 5.5 \times 0.7 \times 0.343)$

$= 1991\ kJ/kg$

Heat ~~applied~~ rejected $= u_1 - u_2$

$= 2575.5 - 1991$

$= 584.5\ kJ/kg$

Total heat rejected $= 2 \times 584.5$

$= 1169\ kJ$.

Chapter - 4 Steam Generator

4.1

Steam boiler or steam generator :—

A steam boiler or steam generator is a closed vessel in which water is heated, vaporised and converted into steam at a pressure higher than atmospheric pressure.

⇒ The heat energy required for steam generation is produced by burning of fuel in the furnace.

Use of steam :-

⇒ Heat content of steam is large and thus it is suitable for heating process in many industries like textile mills, chemical industries.

⇒ It is also used for power generation in thermal power plant.

⇒ Steam is also used for heating buildings and producing hot water in winter.

⇒ It is also used for cooking items.

Classification of Boiler :—

Boilers can be classified according to following criteria:

1. According to the contents in the tube :—

According to contents in tube, boilers may be divided into:-

(a) Fire tube boiler (b) Water tube boiler

(a) Fire tube boiler :— In fire tube boilers, the hot combustion gases pass through the boiler tubes which are surrounded by water.

Ex :- Cochran boiler, Lancashire boiler, Locomotive boilers etc.

(b) Water tube boiler :- In this boiler, water is contained inside the tube which are surrounded by hot gases from outside.

Ex :- Babcock and wilcox boiler, stirling boiler, Lamont boiler, Benson boiler etc.

2. **According to position of the furnace :—**

According to this, boilers are classified as :-
(a) Internally fired boiler (b) Externally fired boiler

(a) Internally fired boiler :-
The furnace is located inside the shell of boiler.
Most of fire tube boilers are internally fired boiler

(b) Externally fired boiler :—
The furnace is located outside the boiler shell.
Most of water tube boilers are externally fired.

3. **According to position of boiler :-**

Boilers may be classified as :—
(a) Horizontal boiler (b) Vertical boiler (c) Inclined boiler

4. **According to number of tubes :—**

(a) Single tube boiler :- There is only one fire tube or water tube.
Ex :- Simple vertical boiler.

(b) Multiple tube boiler :- There are two or more fire tube or water tube.
Ex :- Cochran boiler, Babcock & wilcox boiler

5. **According to water circulation arrangement :—**

(a) Natural circulation :—
Water circulates in the boiler due to density difference of hot and cold water.
Ex :- Babcock and wilcox boiler, Lancashire boiler

(b) Forced circulation :-
A water pump forces the water along its path, thereby steam generation rate increases.
It is used in high pressure boiler.
Ex :- Lamont boiler, Benson boiler.

6. According to use :-

(a) Stationary boiler :- These are used in power plant for power generation.

(b) Portable or mobile boiler :- These boiler move from one place to another and used for temporary uses at the sites. These are locomotive and marine boiler.

(c) Locomotive boiler :- They produce steam to drive railway engines.

Marine boiler :- These are used on ships.

7. According to pressure of steam generated :-

Low pressure boiler :- Boiler produce steam at a pressure of 15 - 20 bar.

Medium pressure boiler :- It has steam at a pressure from 20 bar to 80 bar.

High pressure boiler :- It produce steam more than 80 bar pressure.

Supercritical boiler :- These boiler produce steam at a pressure greater than critical pressure.

Subcritical boiler :- These produce steam at a pressure less than critical pressure.

8. According to source of heat :-

Steam boiler may be classified according to the source of heat supplied for producing steam. These source may be combustion of solid, liquid or gaseous fuel, hot waste gases, electrical energy etc. ~~or nuclear~~

4.2 Important terms for boiler :-

Important terms for boiler are described as follows:

Boiler shell :- Shell of boiler consists of ~~one sheet~~ one or more steel plates bent into cylindrical form and riveted or welded together. End of the shell are closed by means of end plates.

Combustion chamber :-

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

Grate :-

It is the space located below the furnace and consist of cast-iron bars upon which fuel is burned. The air can pass through the spaces between the bars and the ash can fall down through these spaces.

Furnace :-

It is the space above the grate and below the boiler shell, in which fuel is actually burnt, and flue gases are generated. Furnace is also called as fire box.

Heating surface :-

It is the surface of the boiler which is exposed to hot flue gases on one side, water on other side.

Water space :-

The space of boiler shell occupied by water is called water space.

Steam space :-

The entire space of boiler shell which is not occupied by the water is called steam space.

Mountings :-

These are the fittings which are mounted on the boiler for its proper functioning. They include water level indicator, pressure gauge, safety valve etc.

Accessories :-

These are integral part of boiler, but are not mounted on it. They include superheater, economiser, feed pump etc.

Fire tube Boiler	Water-tube Boiler
→ The hot flue gases pass through tubes and water surrounds them.	→ water passes through the tubes and hot flue gases su[rround] them.
→ It can generate steam only upto 20bar.	→ The working pressure is high enough, upto 250 bar
→ The rate of steam generation is low i.e. upto 9 tonnes per hour.	→ The rate of steam genera[tion] is high; upto 450 tonnes per hour.
→ It requires more floor area for a given output.	→ It requires less floor area for a given output.
→ They are bulky and difficult to transport	→ They are light in weight hence transportation is not a problem.
→ Overall efficiency is upto 75%.	→ Overall efficiency with economiser is 90%.
→ water doesnot circulate in a definite direction.	→ water circulation direction is well defined.
→ less initial cost, but cost per unit is more.	→ Initial cost is very high, but cost per unit is low.
→ operating cost is less.	→ Operating cost is high.
→ less skill is required for efficient operation.	→ skilled operators are required.
→ Bursting chances are less.	→ Bursting chances are more.
→ load fluctuations cannot be handled.	→ load fluctuations are easily handled.
→ It is used for small industry i.e. in process industry	→ Use in large industry i.e. in large power plant

4.4

Cochran Boiler :—

Cochran boiler is a vertical, multi tubular, fire tube boiler, having a number of horizontal flue tubes.

→ It is the modification of a simple vertical boiler with increase in the heating surface area.

→ The flue gases from the furnace are passed through a number of small tubes surrounded by water.

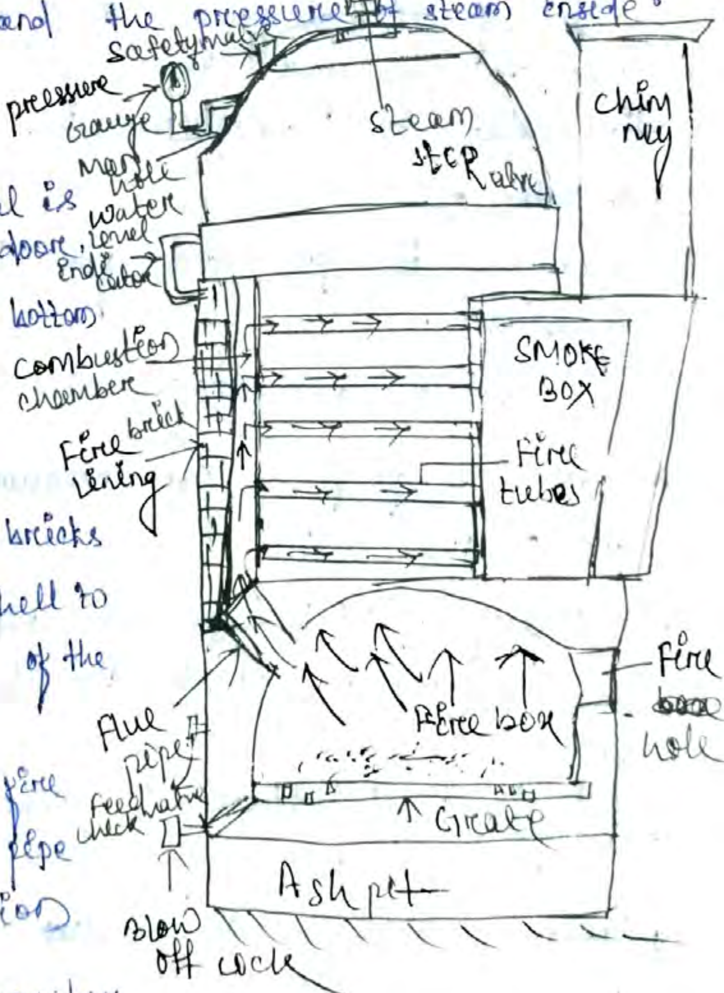
*Construction :—

Cochran boiler consist of following parts:-

Shell :— The main body of the boiler is known as a shell.

→ It is cylindrical in nature with a hemispherical crown, where space is provided for steam.

→ This hemispherical top gives a higher volume to area ratio which increases the steam capacity and strength to withstand the pressure of steam inside the boiler.



Grate :—
This is the area, where the coal is fed through the fire door. It is placed at the bottom of the furnace.

Combustion chamber:-
It is lined with fire bricks on the side of the shell to prevent overheating of the boiler.

→ Hot gases enter the fire tubes from the flue pipe through the combustion chamber.

→ The combustion chamber is connected to the furnace or firebox.

Fig:- Cochran Boiler

Fire tubes :-

There are various horizontal fire tubes whose one is connected to the furnace and other to the chimney. It helps to exchange heat from flue gases water surrounded around it.

Fire hole :-

A small hole is provided at the bottom of the combustion chamber to place fuel is known as fire hole.

Fire box / Furnace :-

Fire box is hemispherical, for resisting intense heat. Fire box and combustion chamber connected through a short pipe called as flue pipe.

Smoke box :- It is used to collect the flue gases from combustion chamber.

Chimney :-

chimney is attached to the smoke box, which is used to transfer the flue gases coming from fire tube to environment.

Man hole :-

manhole is provided for inspection and cleaning of boiler.

Other boiler mountings and accessories attached are:

* Pressure gauge :- It measures the pressure of steam inside the boiler.
* safety valve :- It blow off the extra steam when steam pressure inside the boiler reaches above safety level.
* water level indicator :- The position of water level is indicated by this.
* Steamstop valve :- It is ~~the~~ used to transfer steam to the desired location when it is required.
* Blow off valve :- It is used to blow off the impurities present in boiler water.

Working :-

- First the coal is placed on grate through fire hole. Then air is entered into the combustion chamber and fuel is burnt.
- Then hot flue gases pass through flue pipe to combustion chamber.
- This flue gases further moves into the fire tubes and then as the water is surrounded by the fire tubes, exchange of heat take place. By this water is vaporised by absorbing the heat from flue gas and converted into steam.
  The generated steam is collected in the steam space above the water. This steam is then taken for use through steam stop valve.
- The flue gases further move to the chimney, through smoke box and are then discharged to atmosphere through chimney.

Specification of Cochran Boiler :-

Shell diameter = 1m to 3 m
Height = 2m to 6 m
Steam capacity = 3600 kg/h approx.
Tubes diameter = 6 cm
Working pressure = 11 bar (limited) to maximum
Efficiency = 70 to 75%.

Lancashire Boiler :-

It is a horizontal, internally fired, natural circulation, stationary fire tube boiler.

→ It is widely used boiler due to its good steam generation capacity.

→ These boiler used for power generation at a moderate pressure of 15 bar.

Construction :-

The boiler consist of :-

* Long cylindrical external shell :- This is supported by refractory brick masonry.
The shell is usually 2 to 3 m in diameter and 7 to 9 m long.

* Flue tubes :-
It has two large horizontal and parallel flue gas tubes pass through the shell.

* A fire grate called furnace is provided at one end of the flue tubes on which solid fuel is burnt.
At the end of fire grate there is a brick arch to deflect the flue gases upwards.
The hot flue gases, after leaving the internal flue tubes pass down to the bottom tube.
These flue gases move to the front of the boiler where they divide and flow into the side flues.
The flue gases then enter the main flue, which leads them to chimney.

* Damper :-
Dampers are located at the end of side flues to control the flow of gases. They regulate the combustion rate as well as steam generation rate.

* Boiler also provided with mountings as ~~valves~~ like pressure gauge, water level indicators, steam stop valve, safety valve, low water and high steam safety valve, man-hole on top of shell for cleaning purpose. Low water and high steam ~~valve~~ safety alarm gives alarm i.e. an audio signal for low water level and high steam pressure.

Blow off cock and feed check valve are provided in front of the boiler, fusible plug is provided to prevent overheating of the boiler..

Working :-

* The fuel is burnt at the grating and the hot gases travel through the internal flue tubes followed by flue passage. ~~The flue gases then~~

* The flue gases then collected in the chamber before they lead to atmosphere through chimney.
* Hot flue gases transfer its heat to water during its long passage. The water is converted into steam and collected in steam space in the shell and then taken out through steam stop valve for use.

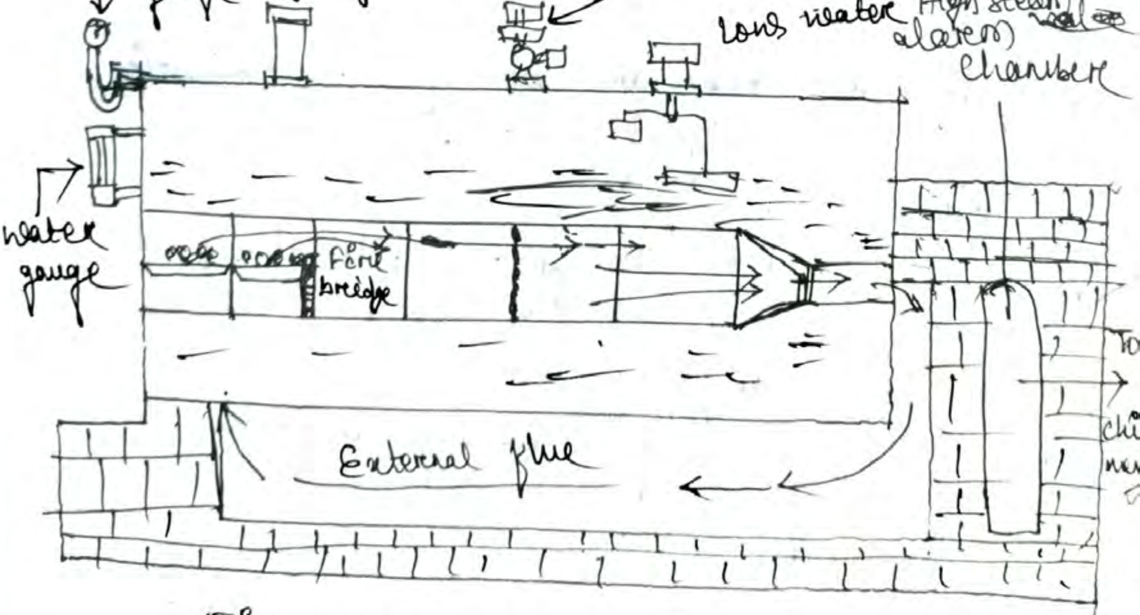


Fig Lancashire Boiler

Babcock and Wilcox Boiler :-

It is a multi tubular, stationary type water tube boiler. In this water is circulated inside the tubes and hot gases flow over the tube.

* It is a natural circulation, high pressure, externally fired water tube boiler.

Construction :-

A horizontal steam and water drum :-

This is the main part of boiler.

It is supported by steel structure.

* It contains water and steam.

All safety and control devices are mounted over the boiler drum.

Steel tubes / water tubes :-

The front end of the boiler is connected to the uptake header (water box) by a short tube and the rear end is connected to the downtake header by a long tube.

* In between the headers, a no. of small diameter steel tubes are fitted at an angle of 5° to 15° with the horizontal to promote water circulation.
* These steel tubes are arranged in combustion chamber in a zigzag manner.

Combustion chamber :-

It is the space above the grate, below the front end of drum where combustion of fuel take place.

* This is enclosed by brickwork.
* Doors are provided in it for cleaning, inspection and repairing.

* **Baffle :-**

The fire brick baffles, two in number, are provided to deflect the hot flue gases.

Superheater

Superheater is placed between the drum and water tubes. It increases the temperature of saturated steam to required superheated temperature by absorbing the heat from hot gases, before discharging it from steam stop valve.

Damper :-

Dampers are provided at the rear end of combustion chamber to regulate the fresh air supply for maintaining proper combustion of fuel.

Safety and control devices :-

* These are safety valve, pressure gauge, water-level indicator, feed check valve, steam stop valve, blow off cock, fusible plug and man hole.
* Mud box is used to collect the mud present in water.

Working principle :-

* First the water is pumped by a feed pump and enters the drum through feed check valve upto the prescribed level.
* When combustion takes place above the grate, the products of hot gases comes out and rush through each compartment of combustion chamber. The front portion of tube has highest temp^r and the rear portion has lowest.
* As hot gases comes in contact with the water tube, water is heated inside the tubes, it becomes lighter and rises up in the tube and thereby flow from downtake header to uptake header.
* Due to continuous heat supply, some of water converts into steam. By this natural circulation of water from drum to water tube and water tube to drum, steam is produced.

* The generated steam is moved upward, due to density difference and through uptake header, it gets collected at the upper side of drum, above water space.
* In order to remove all the water particle from steam, it is finally passed through the superheater tubes for its superheating. The superheated steam then available for use.

Features :-

→ Operating pressure = 11.5 bar to 20 bar
→ Efficiency high.
→ Easy to repair, ~~maintanance~~ maintenance and cleaning.
→ Steam generation rate is high i.e. 20 ton/h.

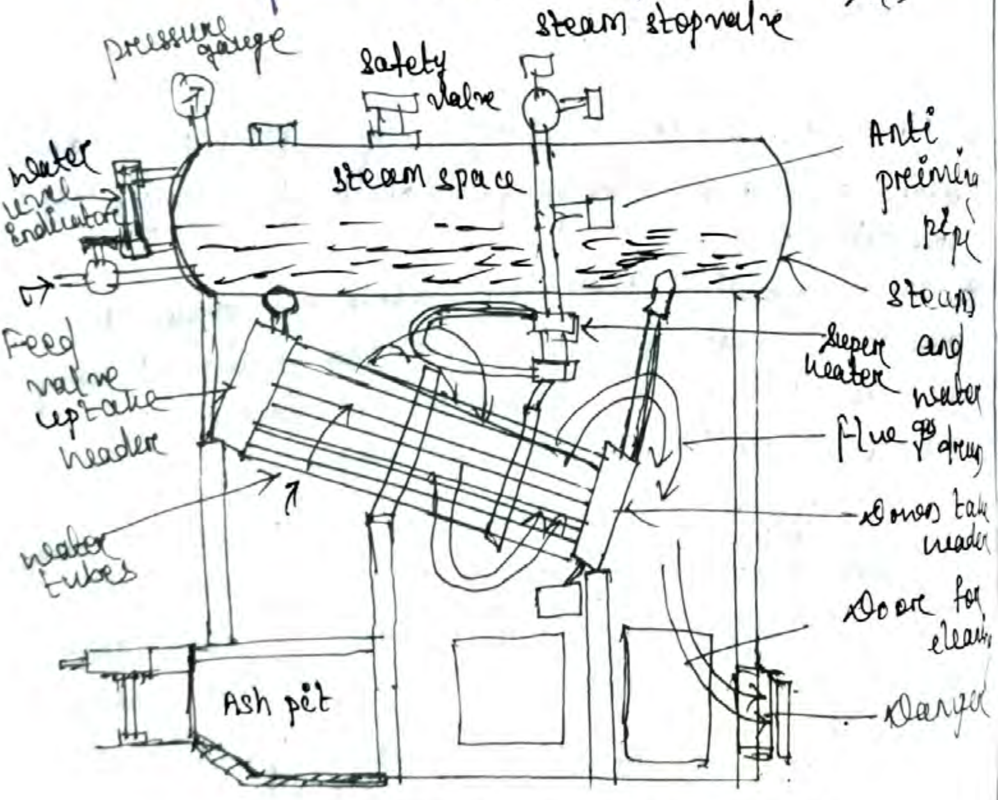


Fig :- Babcock and Wilcox boiler

4.5 Boiler draught :-

→ Boiler draught may be defined as the small pressure difference which causes the continuous flow of gases inside the boiler.

Or

The draught is a small pressure difference between the air outside the boiler and gases within the furnace or chimney.

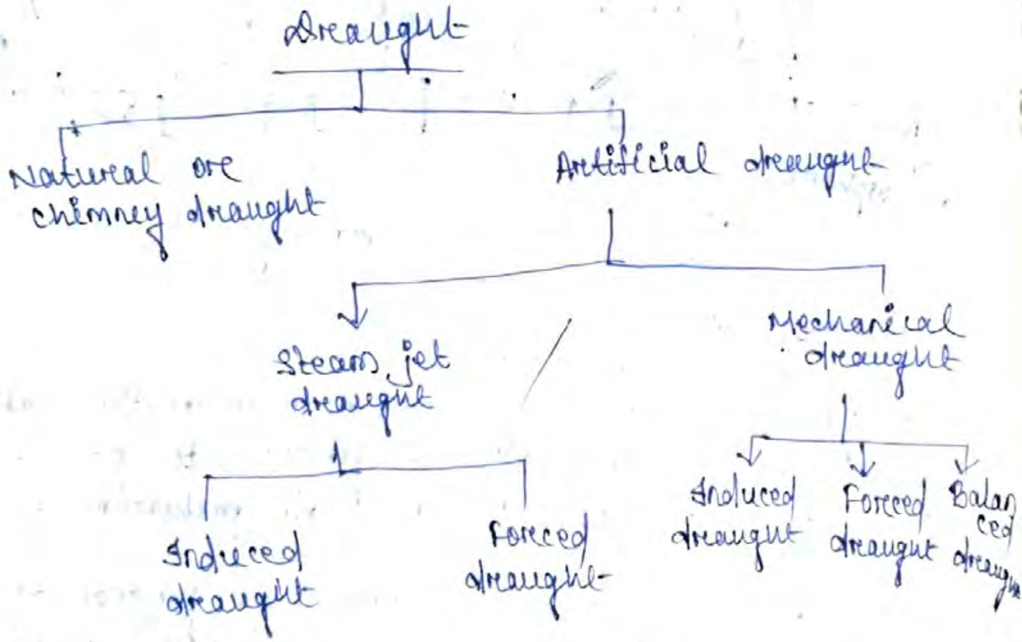
Function

→ It provide an adequate / sufficient quantity of air for fuel combustion

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

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

Classification :-



Natural draught

→ The draught obtained by use of a chimney is called natural or chimney draught.

→ Chimney carries the products of combustion to such a height that they will not be harmful to surroundings.

→ Draught is produced due to the density difference between the hot gases inside the chimney and cold air outside it.

Mechanical draught :-

Artificial draught produced by a fan or a blower is known as mechanical draught.

They are of 3 types :—
(1) Induced (2) Forced (3) Balanced draught

(1) Induced draught :-

→ In induced draught fan or blower is placed near base of chimney.
→ The fan draws the flue gases from the furnace. So the pressure above the fuel bed is reduced below atmospheric pressure.
→ The fresh air rushes into the furnace and after combustion, the flue gases get discharged through the chimney to the atmosphere.

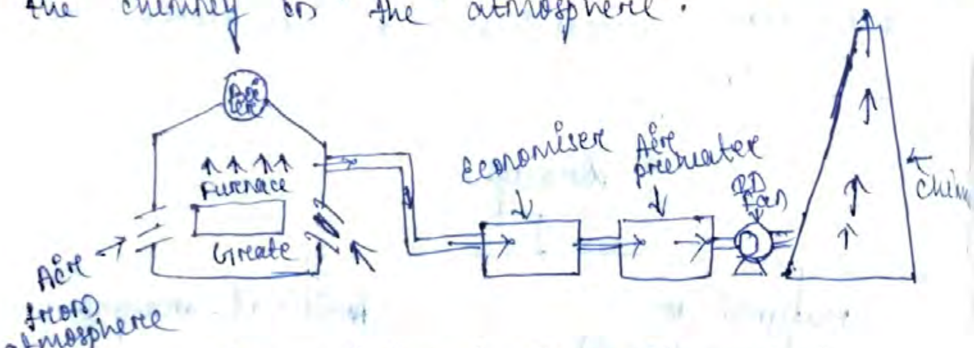


Fig :- Induced draught

(2) Forced draught :-

→ The fan or blower is located near or at the base of the boiler grate and air is forced to pass through the furnace, economiser, air preheater and to chimney.
→ This draught system is known as forced draught system or positive draught system because the gases and air is forced to flow through the system under pressure.
→ This pressure helps in circulation of flue gases through components of the boiler and then through chimney to atmosphere.

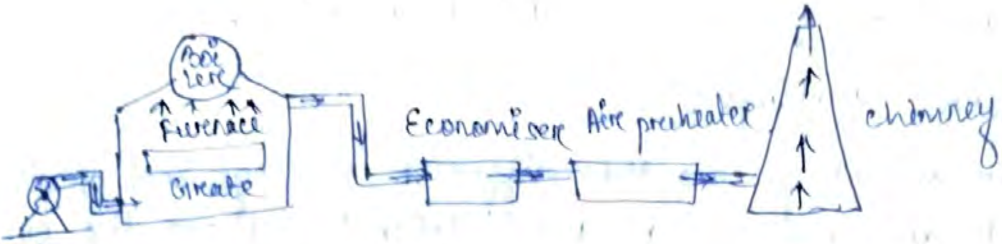


Fig:- Forced draught

(3) Balanced draught :-

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

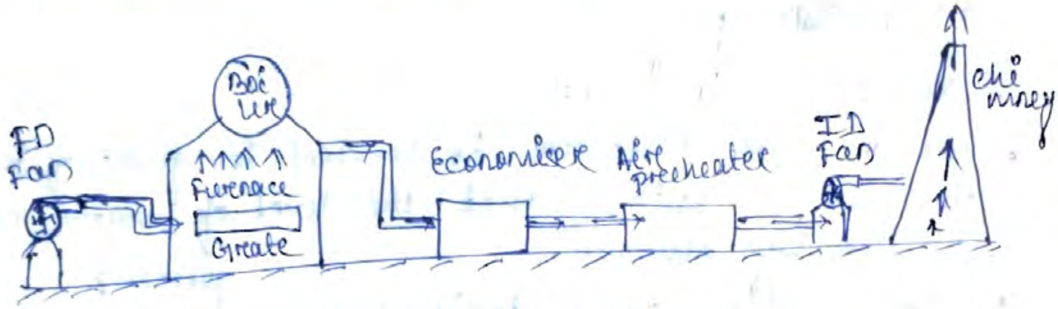


Fig:- Balanced draught

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

4.6 Boiler mountings and accessories :-

Boiler mountings :-

⇒ Boiler mountings are the different fittings and devices which are mounted on the boiler shell for its proper functioning and safety.

⇒ These are essential part of the boiler without which boiler cannot function safely.

⇒ Boiler mountings are of following types :-

1. water level indicator 2. Pressure gauge 3. safety valve 4. stop valves 5. Blow off cock 6. feed check valve 7. Fusible plug

1. water level indicator :-

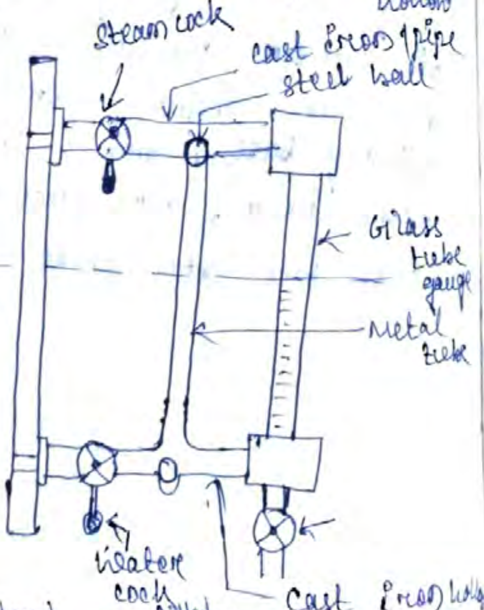
* water level indicator is located in front of the boiler in such a position that the level of water can easily be seen by observer.
* Two water level indicators are generally used on all boilers
* It is a safety device upon which safe working of the boiler depends.

Working principle :-

⇒ water tube indicator consist of a vertical hard glass tube with marking and metal tube.

⇒ Upper and lower ends of these tubes are connected to two gunmetal hollow pipes.

⇒ Upper pipe has steam cock and lower pipe has water cock. Also another drain cock fitted with water level indicator, is used to ensure that water and steam cock are clear.



2. Pressure Gauge :-

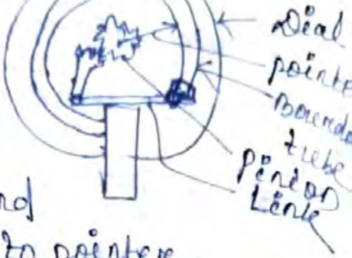
Pressure gauges are used to measure the pressure of steam inside boiler.

⇒ It is fitted in front of the boiler so that operator can read it conveniently.

→ commonly used gauge is Buordon pressure gauge.

Working principle:-

Bourdon tube pressure gauge consists of a elliptical spring tube. One end of the tube is closed and connected by levers and gears to pointer.



→ When fluid pressure acts on tube, it tries to change its cross-section from elliptical to circular. By this the lever end of the tube moves out. The tube movement is magnified by the mechanism and given to pointer to move over a circular scale indicating the pressure.

3. Safety valve :-

→ These are the devices attached in the boiler for preventing explosions due to excessive internal pressure of steam.

→ A steam boiler usually provided with two safety boiler.

→ Safety valve prevent the boiler pressure from rising above its normal working pressure by automatically opening the valve, thus allowing the excess steam to escape into the atmosphere until the pressure comes down to its normal pressure.

→ Safety valve ensures safety to a boiler from being damaged due to excessive steam pressure.

→ Safety valves commonly used are :-

(i) dead weight safety valve, (ii) lever safety valve, (iii) spring loaded valve (iv) high alarm steam and low water safety valve

4. Steam Stop valve :-

→ Steam stop valve is located on the highest part of the steam space.
→ It regulates the steam supply for use.
→ It control the flow of steam from the boiler and to stop it completely when required.

5. Blow off cock valve :-

→ The function of blow off cock valve is to discharge mud and other sediments deposited at the bottom of the boiler, while the boiler is in operation.
→ It also used to drain off the boiler water.
→ It is ~~located~~ mounted at the lowest part of boiler.
→ When it is open, water under the pressure rushes out, thus carrying sediments and mud.

6. Feed check valve :-

→ Feed check valve is fitted to the boiler, slightly below the working level in the boiler.
→ It is used to supply high pressure feed water to boiler.
→ It prevent the returning of feed water from boiler if feed pump fails to work as it is a non-return valve.
→ Feed check valve consist of two valves :- Feed valve and check valve.

7. Fusible plug :-

→ It is a very safety device which protects the fire tube boiler against heating.
→ It is located just above the furnace in boiler.
→ The plug is made up of tin or lead alloy, which has low melting point.

→ Function of fusible plug is to put off the fire in the furnace of boiler when water level falls below an unsafe level and thus avoid explosion, which may take place due to overheating of the tubes and shell.

Boiler accessories :-

→ These are the devices which are used as integral part of the boiler and help in running efficiently.

→ These are optional on an efficient boiler. These are not mounted directly on boiler and required to improve the efficiency of boiler.

Essential boiler accessories are :-

1. Economiser 2. Superheater 3. Air preheater

4. Feed pump 5. Steam separator

1. Economiser :-

→ An economiser is a heat exchanger used for heating the feed water before it enters the boiler.

→ The economiser recovers the heat of hot flue gases going to chimney for heating of feed water, thus helps to improve the boiler efficiency.

→ Economiser is placed in the path of flue gases at the rear end of the boiler just before the airpreheater.

→ Each economiser consist of generally vertical tubes equipped with a safety valve, drain valve, release valve, pressure gauge and thermometers.

2. Superheater :-

→ It is a heat exchanger, used to increase the tempr of saturated steam without raising its pressure.

→ It is generally an integral part of boiler, and is placed in the path of hot flue gases from furnace. The heat released by these hot gases, is used in superheating the steam.

→ A Superheater consists of set of small diameter 'U' tubes in which steam flows and takes up heat from hot gases, to increase steam tempr about saturation tempr.

3. Air preheater :-

→ An air preheater is used to recover heat from the exhaust flue gases, going to chimney.

→ It is installed between the economiser and chimney.

→ The air required for the purpose of combustion is drawn through the air preheater where its temp^r is raised. It is then passed through the ducts to the furnace.

→ Due to preheating of air, temp^r of furnace increases. It results in rapid combustion of fuel and also low grade of fuel can be used.

4. Feed pump :-

Feed pump is required to deliver the water at a pressure higher than that in the boiler.

→ The pressure of steam inside a boiler is high. So the pressure of feed water has to be increased proportionately before it is made to enter the boiler.

→ Feed pump may be of reciprocating type or rotary type.

→ The rotary pumps are driven by steam turbines or electric motors.

5. Steam Separator :-

→ Steam separator is used to separate any water particles present from the steam and to improve the quality of steam going to the units.

→ It is installed very close to units on main steam pipes.

—— × ——

5. Steam Power Cycle

5.1 A power cycle continuously converts heat into shaft work, in which a working fluid repeatedly performs a succession of processes.

* In steam power cycle the working fluid is water, which undergoes a change of phase. In one part of cycle working fluid exists in vapour phase and during another part liquid phase exist.

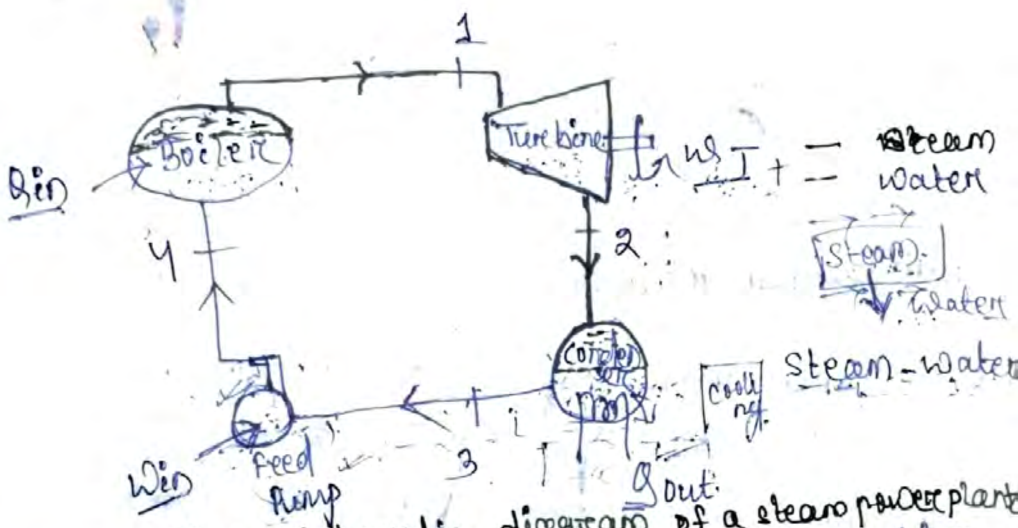


Fig :- schematic diagram of a steam power plant

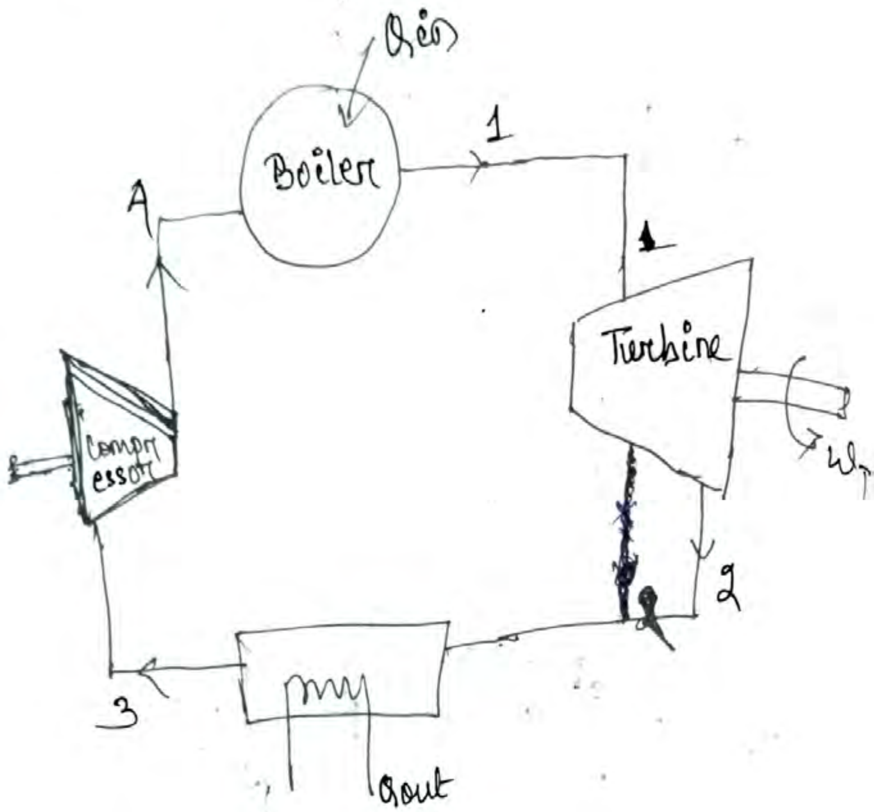
4-1 Boiler :- Heat energy released by combustion of fuel in furnace is utilized to vaporize water into steam, in boiler.

1-2 Turbine :- The steam produced in boiler is expanded in a steam turbine to obtain useful work

2-3 :- Condenser :- vapour leaving the steam turbine is condensed in a condenser.

3-4 :- Feed pump :- The condensed liquid is pumped back into the boiler to its initial state constituting a cycle.

5.1 Carnot Vapour Cycle :—



Steam Power plant on Carnot cycle

* A carnot vapour cycle is executed within the saturation dome of a pure substance. It uses a two phase fluid as working medium.
* The cycle is completed by following 4 processes cycle:-

1. Process 4-1: (Rev. Isothermal heat addition):
In this process, heat is added at a constant temperature T_1 and pressure P_1, thereby converting the saturated liquid (state 4) into dry and saturated steam (state 1) in boiler.

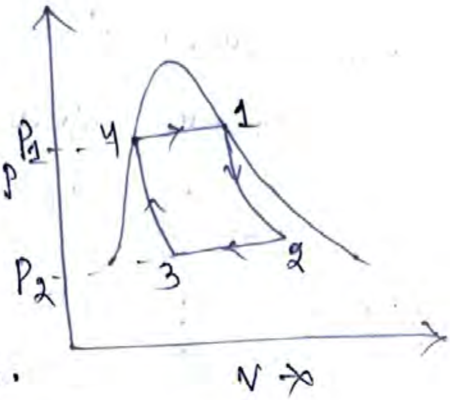
Heat added $Q_{in} = Q_{4-1} = h_1 - h_4 = h_g - h_f$

2. Process: 1-2 Rev. adiabatic expansion
Saturated steam at point 1 expands isentropically in the turbine. The pressure during this process

falls from P_1 to P_2 and temp^n from T_1 to T_2.
→ state 2 is reached in the wet region.

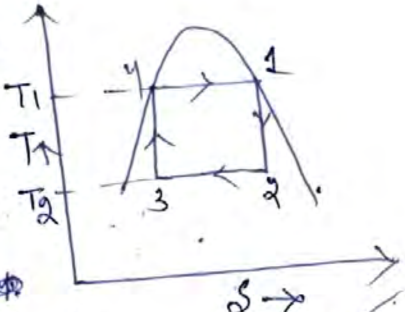
3. Controlled Condensation (2-3) :-

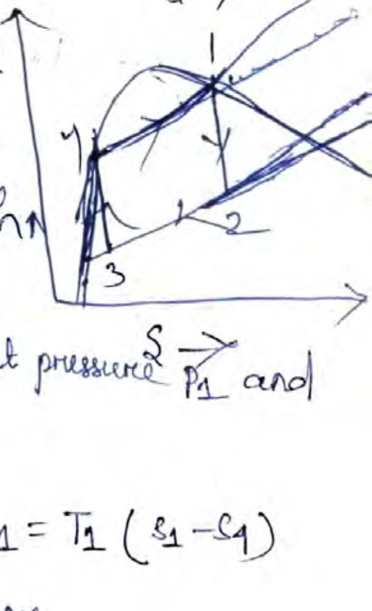
Wet steam at point 2 is now isothermally condensed in a condenser and heat is rejected at constant temp^n T_2 & pressure P_2.
condensation starts from point 2 and stops at state 3.



4. Reversible adiabatic compression (3-4):-

Wet steam at point 3 is finally compressed isentropically in a compressor till it returns back to its original state 4.





Analysis of Carnot vapour cycle :-

Consider 1 kg of saturated water at pressure P_1 and temp^n T_1.

Isothermal heat addition $Q_{in} = Q_{4-1} = T_1 (s_1 - s_4)$

Isothermal heat rejected in condenser

$$Q_{out} = Q_{2-3} = T_2 (s_2 - s_3)$$
$$= T_2 (s_1 - s_4)$$

Net work done of cycle :-

$$W_{net} = Q_{in} - Q_{out}$$
$$= T_1(s_1 - s_4) - T_2 (s_1 - s_4)$$
$$= (s_1 - s_4)(T_1 - T_2)$$

$$\eta = \frac{W_{net}}{Q_{in}} = \frac{(T_1 - T_2)(s_1 - s_4)}{T_1 (s_1 - s_4)} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

Q) A steam power plant operates on carnot cycle using dry steam at 17.5 bar. The exhaust takes place at 0.075 bar into condenser. Steam consumption is 20 kg/min. Determine

(a) Power developed

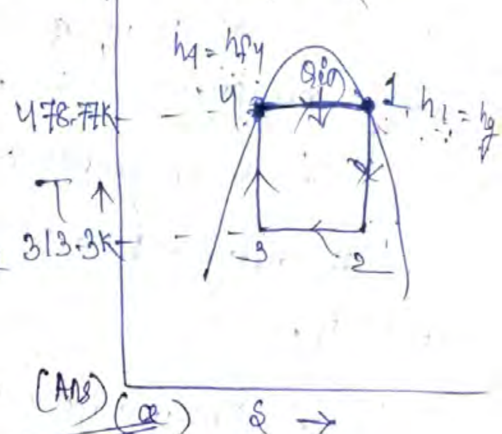
(b) η of cycle

Ans :— $P_1 = 17.5$ bar, $P_2 = 0.075$ bar

$\dot{m}_s = 20$ kg/min $= \frac{20}{60} = 0.33$ kg/s

At $P_1 = 17.5$ bar $T_1 = 205.76°C = 478.77$ K

$P_2 = 0.075$ bar $T_2 = 40.29°C = 313.3$ K



$\eta = 1 - \frac{T_2}{T_1}$

$= 1 - \frac{313.3}{478.77}$

$= 0.3456$

$= 34.56\%$ (Ans) (a)

(b) Power $= W_T - W_C$

$= Q_{in} - Q_{rej}$

$Q_{in} = h_1 - h_4$

$= h_g - h_f$ (pressure P_1)

$= 2796.43 - 878.48$

$= 1917.95$ kJ/kg

$\eta = \frac{W_{net}}{Q_{in}}$

$\Rightarrow W_{net} = \eta \times Q_{in} = 0.3456 \times 1917.95$
$= 662.84$ kJ/kg

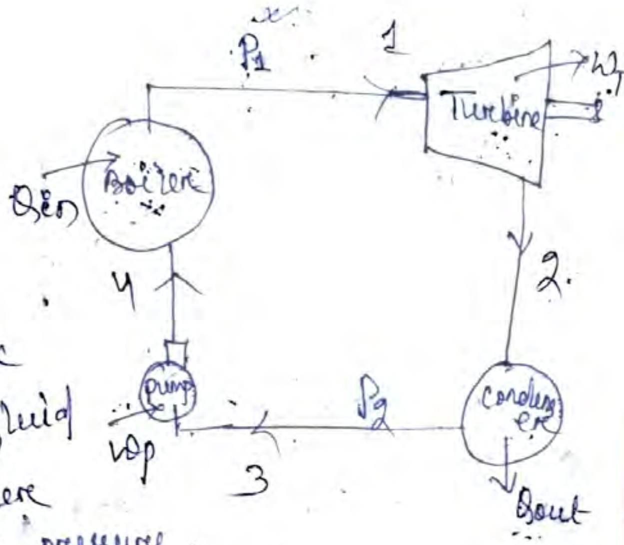
$\therefore$ Net power $= W_s \times \dot{m}_s$
$= 662.84 \times \frac{20}{60}$
$= 220.95$ kJ/s $= 220.95$ kW (Ans)

Rankine cycle :-

Rankine cycle is an ideal cycle for comparing the performance of steam power plant.

→ It is modified form of carnot cycle, which eliminates the practical difficulties associated with carnot cycle.

→ In this cycle two isothermal processes of carnot cycle are replaced by two constant pressure process.



→ The cycle consists of following 4 internally reversible processes.

Process 1-2 :- Isentropic expansion of working fluid in turbine from boiler pressure to condenser pressure.

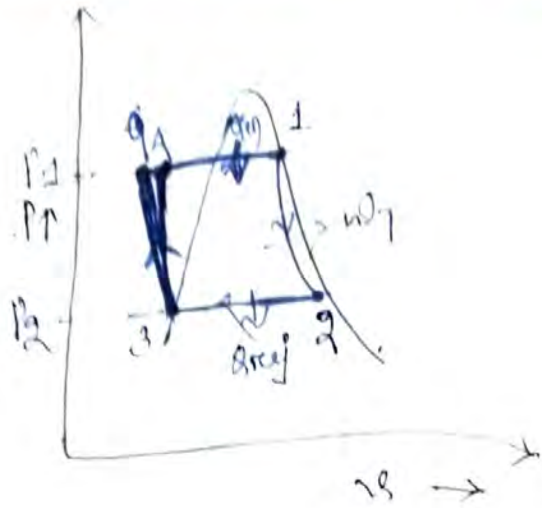
Process 2-3 :- Heat rejection from the working fluid at constant pressure in condenser till fluid reaches saturated liquid state 3.

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

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

Analysis :- consider 1 kg of working fluid :-

Applying steady flow energy equation to turbine, boiler, condenser and pump :—



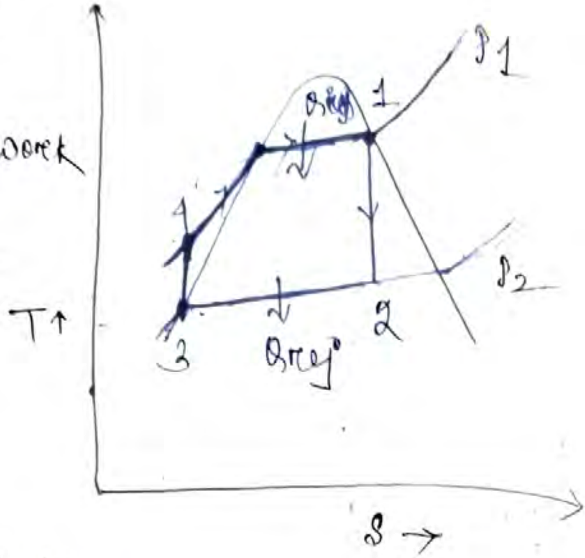
(i) Boiler :— (4-1)

$Q_{in} = h_1 - h_4$

(ii) Turbine :- (1-2)

$W_T = h_1 - h_2$

W_T = Turbine work



(iii) condenser

$Q_{rej} = -(h_3 - h_2)$

$= h_2 - h_3$

$= h_2 - h_{f3}$

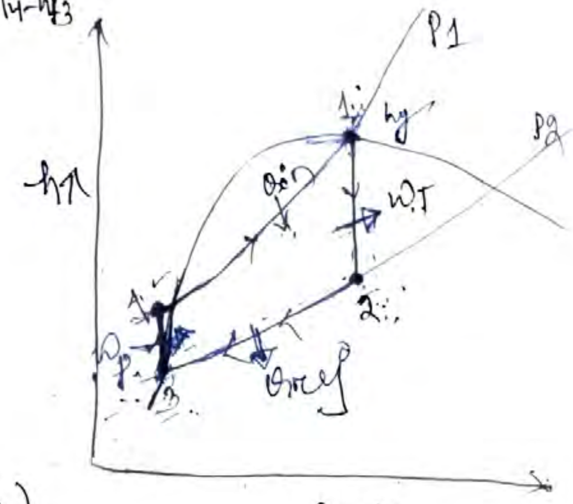
(iv) Feed pump :-

$h_3 = h_4 - W_p$

$\Rightarrow W_p = (h_4 - h_3) = h_4 - h_{f3}$

~~$W_p = h_3 - h_4$~~

~~$= h_{f3} - h_4$~~



$W_p = \int_{P_2}^{P_1} v\,dp$

$= v_{f3}(P_1 - P_2)$

$\therefore h_4 - h_{f3} = v_{f3}(P_1 - P_2)$

$\Rightarrow h_4 = v_{f3}(P_1 - P_2) + h_3$

$\eta = \dfrac{\text{Net work done}}{\text{Heat supplied}} = \dfrac{W_{net}}{Q_{in}}$

$W_{net} = W_T - W_p$

$= (h_1 - h_2) - v_f(P_1 - P_2)$

$= (h_1 - h_2) - (h_4 - h_{f3})$

$Q_{in} = h_1 - h_4$

$\therefore \eta = \dfrac{W_T - W_p}{Q_{in}} = \dfrac{Q_{in} - Q_{rej}}{Q_{in}}$ [* For 1st law: $\because \Sigma W_{net} = Q_{in} - Q_{rej}$ $\Rightarrow W_T - W_p = Q_{in} - Q_{rej}$]

$= \dfrac{(h_1 - h_4) - (h_2 - h_{f3})}{h_1 - h_4}$

$= 1 - \dfrac{h_2 - h_{f3}}{h_1 - h_4}$

How to solve problems :-

Method

Usually given data in a question are :-
Boiler pressure P_1,
condenser pressure P_2,
and condition of steam enter to turbine :- wet / dry saturated / super heated steam)

Methods to follow :- (Procedure)

① For h_1 :- Find h_1, s_1 (From steam table using data given in question for pressure P_1)

② For h_2 :- $S_1 = S_2$

$\Rightarrow s_1 = s_{f2} + x s_{fg2}$ (Find value of s_2, s_{fg2} from steam table for pressure P_2)

$\Rightarrow x = \dfrac{s_1 - s_{f2}}{s_{fg2}}$

$\therefore h_2 = h_{f2} + x h_{fg2}$ (Find h_{f2}, h_{fg2} from steam table for pressure P_2)

③ For h_3 :- $h_3 = h_{f3}$ (Find value of h_{f3} from steam table for pressure P_2)

④ For h_4 :- $W_p = v_{f3}(P_1 - P_2)$ (Find v_{f3} from steam table for pressure P_2)

$W_p = h_4 - h_3$

$\Rightarrow h_4 = W_p + h_3$ (Put value of W_p & h_3 from above)

$\therefore W_{net} = W_T - W_p = (h_1 - h_2) - W_p$

$\eta = \dfrac{Q_{in} - Q_{rej}}{Q_{in}} = 1 - \dfrac{Q_{rej}}{Q_{in}} = 1 - \dfrac{h_2 - h_3}{h_1 - h_4}$

Reheat cycle :-

Efficiency of Rankine cycle can be improved by increasing the pressure and temp^r of steam entry into turbine. But if the steam expands in turbine completely in a single stage then steam coming out the turbine is wet.
Wet steam causes erosion of turbine blade and increases internal losses. This will ultimately reduce the efficiency & life of turbine.

→ To overcome this, reheating of steam is done.

* In reheat cycle, steam is expanded in no. of stages. After each stage of expansion, steam is reheated in boiler. Then it expands in the next stage of turbine and is finally exhausted to ~~turbine~~ condenser.

Adv :-

→ It increases workdone through turbine
→ Increase efficiency of cycle.
→ Reduces the erosion of blades
→ Reduce specific steam consumption.

Reheat Rankine cycle :-

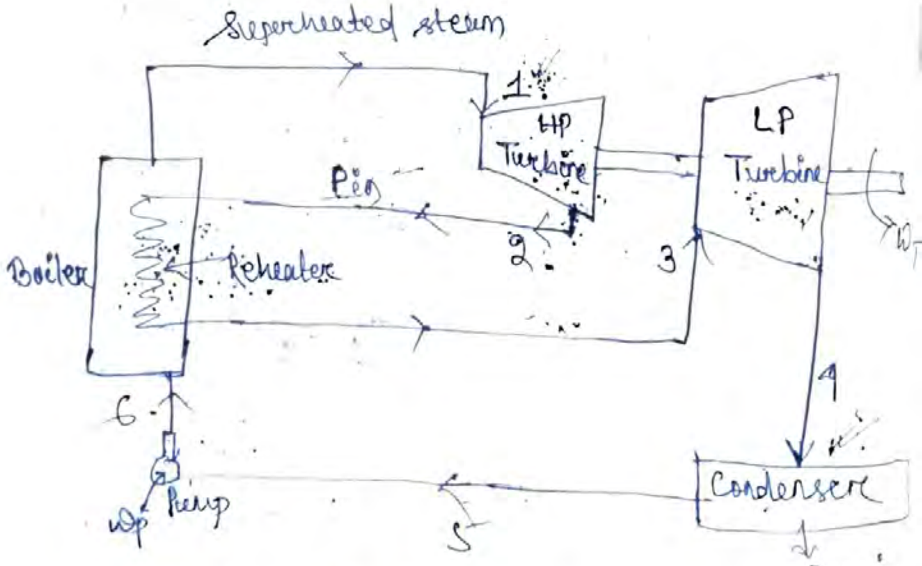
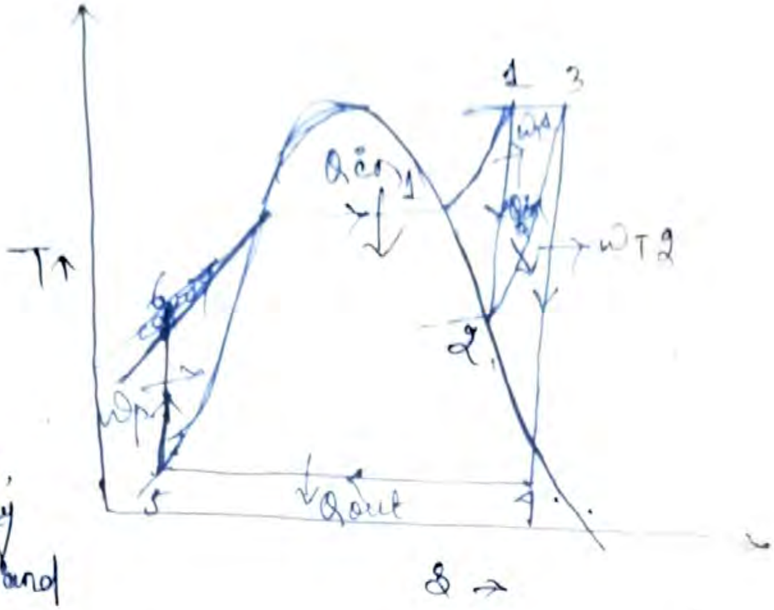


Fig :- Reheat process

→ Steam at state 1 enters in first stage of turbine and expands isentropically to state 2.

→ The quality of steam at state 2, is either just dry or slightly wet and



then it is taken back in the boiler and is reheated to original superheated temperature $T_3 (= T_1)$ at constant pressure P_{in}.

→ Then this reheated steam at state 3 enters the next stage turbine and further expands to back pressure P_2 at state 4.

Consider 1kg of working fluid :-

→ Amount of heat added during reheating

$$Q_{reheat} = h_3 - h_2$$

Total heat supplied in 2 stages

$$Q_{in} = (h_1 - h_6) + (h_3 - h_2)$$

For isentropic expansion in two stages, total W.D.

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

Pump work $W_p = h_6 - h_5$

$$= -\int v\,dp = v_{f5}(P_1 - P_2)$$

$W_{net} = W_T - W_p$ (However pump work is very small in comparison to W_T so it is neglected in most of cases)

Heat rejected in condenser :-

$$Q_{out} = h_4 - h_5$$

$$\eta = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{h_4 - h_5}{(h_1 - h_6) + (h_3 - h_2)}$$

Regenerative cycle :-

Efficiency of Rankine cycle can be improved by heating the feed water regeneratively. It is achieved by regenerative cycle.

Regeneration with single open feed water heater

The steam (at pressure P_1) enters the turbine at point 1.

Let a small amount of wet steam (m_1 kg) is extracted at state 2 from turbine at pressure; $(1-m_1)$ kg of steam per kg flow through the remaining part of the turbine during expansion from 2-3, condensation from 3-4 and pumping from 4-5.

⇒ $(1-m_1)$ kg of steam enters in feed water heater and mixed with m_1 kg. of steam blows from the turbine at state 2. After mixing, the mass of liquid becomes 1 kg at the state 6 and it is pumped to boiler pressure at state 7.

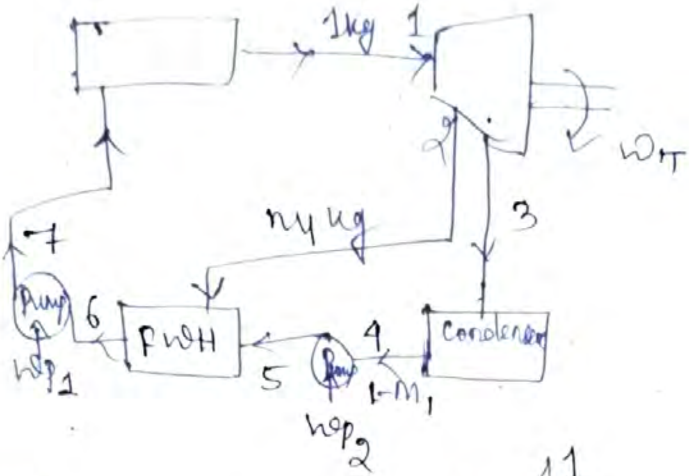
Applying SFEE to process 2-6 :-

$$(1-m_1)h_5 + m_1 h_2 = h_6$$

$$\Rightarrow m_1 = \frac{h_6 - h_5}{h_2 - h_5}$$

$$\eta_{reg} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{(1-m_1)(h_3-h_4)}{h_1-h_7}$$

Turbine work :-



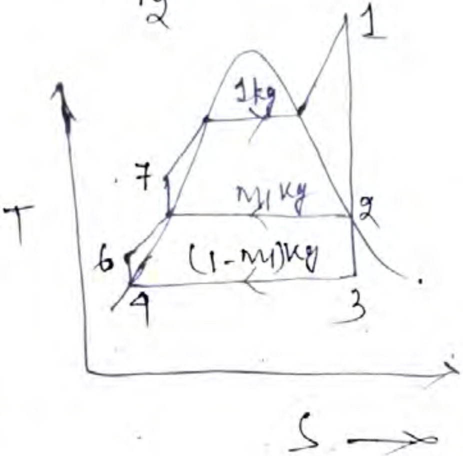
Turbine work :-

$W_T = (h_1 - h_2) +$

$(1 - m_1)(h_2 - h_3)$

$W_P = (h_7 - h_6) +$

$(1 - m_1)(h_5 - h_4)$



$W_{net} = W_T - W_P$

$= (h_1 - h_2) + (1 - m_1)(h_2 - h_3) -$

$[(h_7 - h_6) + (1 - m_1)(h_5 - h_6)]$

6. Heat transfer

6.1 Modes of heat transfer

Heat transfer defined as the transmission of the energy from one region to another due to tem. difference between these two regions.

Following are the methods of heat tran

① **Conduction** :- It is a process of heat trans from one particle of the body to another in the direction of fall of tempr. The particles remain in fixed position relative to each other.

② **Convection** :- It is a process of heat trans from one particle of the body to another by convection current. In this case, particles of the body move relative to each other.

③ **Radiation** :- It is a process of heat transfer from a hot body to a cold body, in a straight line, without affecting the intervening medium.

6.2 Fourier law of heat conduction :-

It states that the rate of heat conduction through a medium depends on its geometry, thickness and material of the medium as well as tempr diff

* states that the rate of heat conduction per unit area is directly proportional to temp^r gradient.

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

$$\Rightarrow \frac{Q}{A} = -K\frac{dT}{dx}$$

$$\Rightarrow Q = -KA\frac{dT}{dx}$$

K = Thermal conductivity of a material

* Thermal conductivity is defined as the ability of the material to conduct heat.

* It also defined as the rate of heat transfer through a unit thickness of material per unit area per unit temp^r difference.

Unit :- W/mK

Newton's Law of Cooling :-

It is the governing equation of convection heat transfer.

* It states that the rate of heat transfer is directly proportional to temp^r difference between a surface and fluid.

Mathematically $\frac{\dot{Q}}{A} \propto (T_s - T_\infty)$

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

T_s = surface temp^r (°c)

T_∞ = fluid temp^r

h = const of proportionality called as heat transfer co-efficient.

Unit of h :- W/m^2K

6.4 :- Radiation

Stefan Boltzmann law

This law governs the radiation heat transfer.

→ It states that the rate of radiation heat transfer per unit area from a black surface is directly proportional to 4th power of the absolute tempr of the surface and is given by

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

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

T_s = Absolute tempr of surface (K)

σ = const. of proportionality, called Stefan Boltzmann constant and has value $5.67 \times 10^{-8}\ W/m^2K^4$

Kirchoff's law :—

It states that at thermal equilibrium, the ratio of the spectral emissive power to absorptivity for all bodies is constant

or $$\frac{E}{\alpha} = C$$

Black body radiation :-

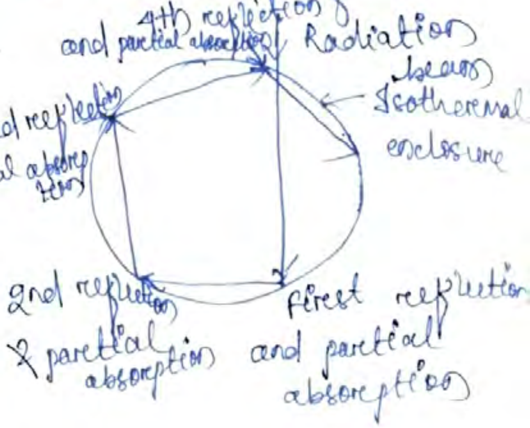
It is an ideal surface having the following properties :-

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

2. At any temp^r and wavelengths, no body can emit energy more than a black body.

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

* Consider a radiation beam entering a cavity of an enclosure



It experiences many reflections within the enclosure and almost entire beam is absorbed by the cavity and black body behaviour is experienced.

Emissivity :-

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

$$\varepsilon = \frac{E}{E_b} \Rightarrow E = \varepsilon E_b = \varepsilon \sigma T^4$$

Absorptivity :-

It is defined as fraction of radiation energy incident on the surface from all directions, over entire wavelength spectrum, that is absorbed by the surface.

Mathematically $\alpha = \frac{G_a}{G}$

G_a = Energy absorbed by the surface (W/m^2)

G = Irradiation, W/m^2

Reflectivity :-

It is defined as the fraction of radiation energy incident on a surface from all directions over all wavelengths, that is reflected.

$$\rho = \frac{G_r}{G}$$

Transmissivity :-

It is defined as the fraction of incident energy transmitted through the surface.

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

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