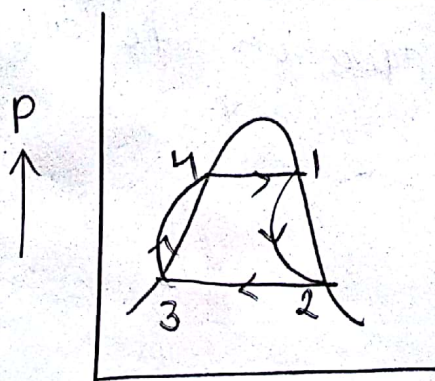
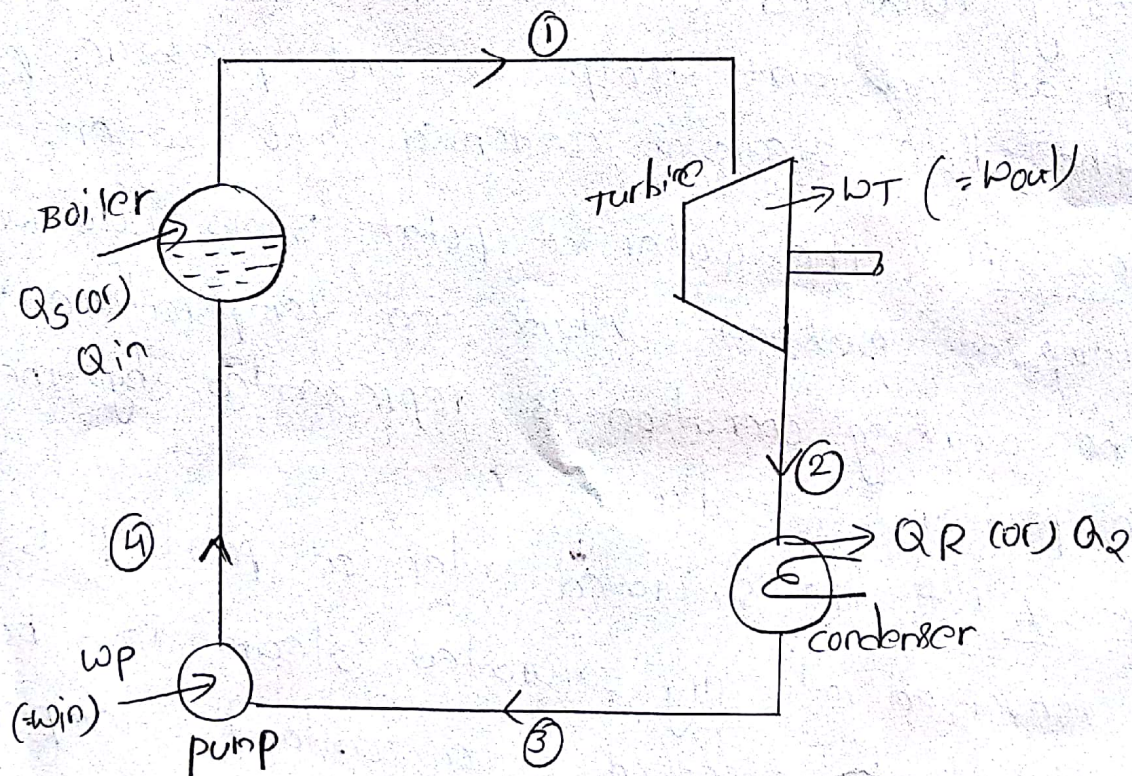
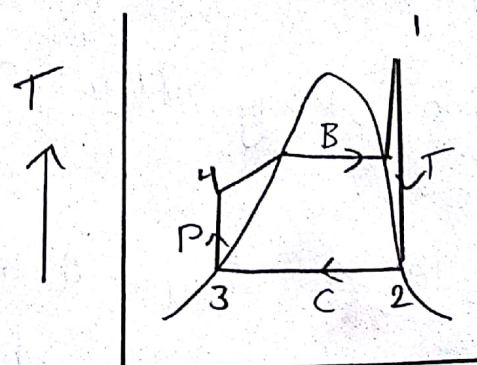


Basic concepts :

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



$P-v$ diagram



$T-s$ diagram

Consider a cycle of saturated water at pressure P_1 and absolute temp T_1 , as represented by point 1 in fig. the cycle is completed by the following four processes.

1. process 1-2: - the dry saturated steam at point 1, now expands isentropically in an engine or turbine. The pressure and temp falls from P_1 to P_2 and T_1 to T_2 respectively with a dryness fraction x .

2. process 2-3: - the wet steam at point 2 is now isothermally condensed in a condenser and heat is rejected at constant temp T_2 and pressure P_2 until the whole steam is condensed into water.

3. process 3-4: - the water at point 3 is now warmed in a pump at constant volume and temperature T_3 to T_4 . the warming operation is represented by the curve 3-4 on $p-v$ and $T-s$ dia.

4. process 4-1: - the saturated water at point 4 is isothermally converted into dry saturated steam in boiler, and the heat is absorbed at a constant temperature. the dry state of steam is represented by point 1.

Applying steady flow energy equation to all the components.

for boiler: - $h_{f4} + Q_1 = h_1$

$$Q_1 = h_1 - h_{f4}$$

for turbine:-

$$h_1 = w_T + h_2$$

$$w_T = h_1 - h_2$$

for condensor:-

$$h_2 = Q_2 + h_{f3}$$

$$Q_2 = h_2 - h_{f3}$$

for pump:-

$$h_{f3} + w_P = h_{f4}$$

$$w_P = h_{f4} - h_{f3}$$

Now the efficiency of Rankine cycle is given by

$$\eta_R = \frac{w_{net}}{Q_s} = \frac{\text{net work done}}{\text{heat supplied}}$$

$$\eta_R = \frac{w_T - w_P}{Q_s} = \frac{(h_1 - h_2) - (h_{f4} - h_{f3})}{(h_1 - h_{f4})}$$

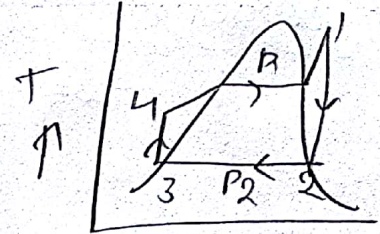
the feed pump term $(h_{f4} - h_{f3})$ being a small quantity in comparison with turbine work. w_T is usually neglected,

$$\eta_{\text{Rankine}} = \frac{h_1 - h_2}{h_1 - h_{f4}}$$

- ① In a power plant cycle, the steam supply is at 15 bar and dry and saturated. The condensor pressure is 0.4 bar. calculate the Rankine η of the cycle, neglect pump work.

Sol:- Given data:-

pressure $P_1 = 15 \text{ bar}$,
 $P_2 = 0.1 \text{ bar}$,



$\rightarrow s$
T-s diagram

from steam tables corresponding to a pressure of 15 bar, we find that

$$h_g = 2789.9 \text{ kJ/kg}, \quad s_g = 6.4406 \text{ kJ/kg}\cdot\text{K}$$

$$t_g = 198.3^\circ\text{C}$$

and corresponding to a pressure of 0.1 bar, we find that

$$s_f = 1.0261 \text{ kJ/kg}\cdot\text{K}, \quad t_s = 75.9^\circ\text{C}$$

$$s_{fg} = 6.6448 \text{ kJ/kg}\cdot\text{K}$$

$$h_f = 317.7 \text{ kJ/kg}$$

$$h_{fg} = 2319.2 \text{ kJ/kg}$$

$$\eta_{\text{Ran}} = \frac{h_1 - h_2}{h_1 - h_{f4}}$$

$$s_1 = s_2$$

$$s_2 = s_{f2} + x_2 s_{fg2}$$

$$s_1 = s_{f2} + x_2 s_{fg2}$$

$$6.4406 = 1.0261 + x_2 \times 6.6448$$

$$x_2 = 0.815$$

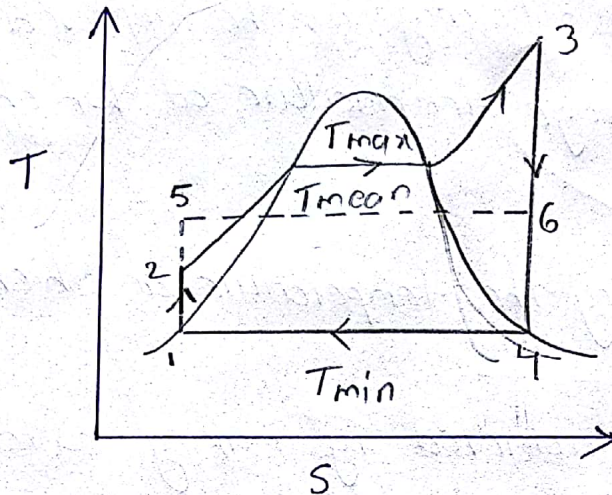
$$h_2 = h_{f2} + x_2 h_{fg2}$$

$$h_2 = 317.7 + (0.815) \times 2319.2$$

$$\therefore h_2 = 2207.8 \text{ kJ/kg}$$

$$\eta_R = \frac{2789.9 - 2207.8}{2789.9 - 317.7} = 0.2354 \times 100 = 23.54\%$$

Mean temperature of heat addition: →



If T_m is the mean temperature of heat addition as shown in fig. so that the area under curve 2-3 is equal to area under curve 5-6, then heat added,

$$Q_1 = H \cdot A = (h_3 - h_2) = T_m (s_3 - s_2)$$

$$T_m = \frac{h_3 - h_2}{s_3 - s_2}$$

$$\text{If } Q = \text{heat rejected} = (h_4 - h_1) = T_{min} (s_4 - s_1) = T_{min} (s_3 - s_2)$$

$$\eta_{\text{rankine}} = 1 - \frac{Q_2}{Q_1}$$

$$= 1 - \frac{T_{min} (s_3 - s_2)}{T_m (s_3 - s_2)}$$

$$\therefore \eta_{\text{rankine}} = 1 - \frac{T_{min}}{T_m}$$

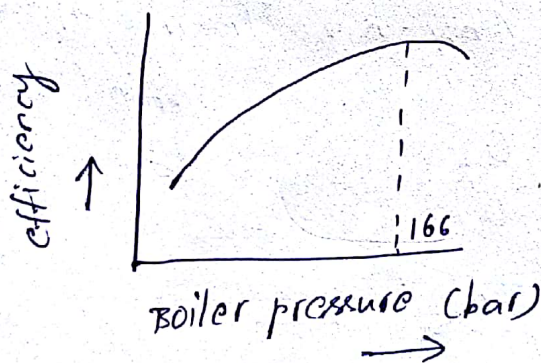
Effect of operating conditions on Rankine cycle efficiency:-

The Rankine cycle efficiency can be improved by:

- (i) Increasing the average temperature at which heat is supplied.
- (ii) Decreasing/reducing the temperature at which heat is rejected.

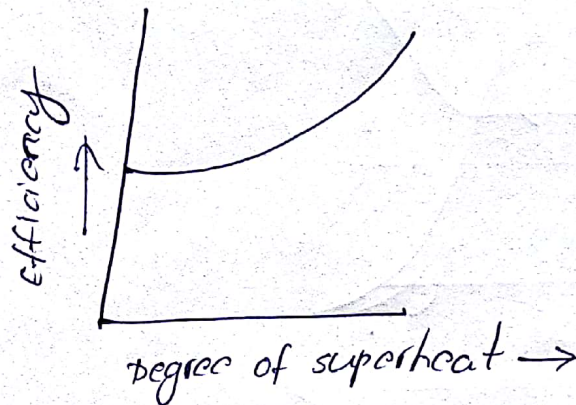
This can be achieved by making suitable changes in the conditions of steam generation (or) condensation, as discussed below.

1. Increasing boiler pressure:- It has been observed that by increasing the boiler pressure (other factors remaining the same) the cycle tends to rise and reaches a maximum value at a boiler pressure of about 166 bar.



2. super heating:- All other factors remaining the same, if the steam is superheated before allowing it to expand the Rankine cycle efficiency may be increased. The use of superheated steam also ensures longer turbine blade life because of the absence of

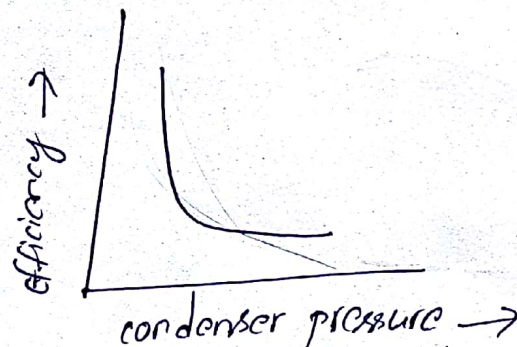
erosion, from high velocity water particles that are suspended in wet vapour.



(b)

3) Reducing condenser pressure:

The thermal efficiency of the cycle can be amply improved by reducing the condenser pressure (hence by reducing the temperature at which heat is rejected), especially in high vacuums. But the increase in efficiency is obtained at the increased cost of condensation apparatus.



The thermal efficiency of the Rankine cycle is also improved by the following methods.

- ci) By regenerative feed heating
- ci) By reheating of steam
- cii) By water extraction
- civ) By using binary vapour.

2) the steam consumption of a steam engine is 20 tonnes per shift of 8 hrs. when developing 220 kW. Dry and saturated steam enters the engine at 10 bar pressure and leaves it at 0.1 bar pressure. estimate the Rankine η & thermal η of engine?

Sol:- mass of steam $m_s = \frac{20}{8} = 2.5 \text{ t/h} = 2500 \text{ kg/hr}$,

$P = 220 \text{ kW}$, $P_1 = P_2 = 10 \text{ bar}$, $P_3 = P_4 = 0.1 \text{ bar}$.

from steam tables, at a pressure of 10 bar,

$h_1 = h_g = 2776.2 \text{ kJ/kg}$, $s_1 = 6.583 \text{ kJ/kg K}$,

at 0.1 bar, we find that,

$h_{f4} = 191.8 \text{ kJ/kg}$, $h_{fg} = 2393 \text{ kJ/kg}$,

$s_f = 0.649 \text{ kJ/kg K}$, $s_{fg} = 7.502 \text{ kJ/kg K}$.

Rankine η : $\eta_R = \frac{h_1 - h_2}{h_1 - h_{f4}}$

$$h_2 = h_{f2} + x_2 h_{fg2}$$

$$s_1 = s_{f2} + x_2 s_{fg2}$$

$$6.583 = 0.649 + x_2 (7.502)$$

$$x_2 = 0.791$$

$$h_2 = 191.8 + (0.791) \times 2393 = 2084.7 \text{ kJ/kg}$$

$$\eta_R = \frac{2776.2 - 2084.7}{2776.2 - 191.8} = 0.267 \times 100 = 26.7\%$$

Thermal efficiency of engine:

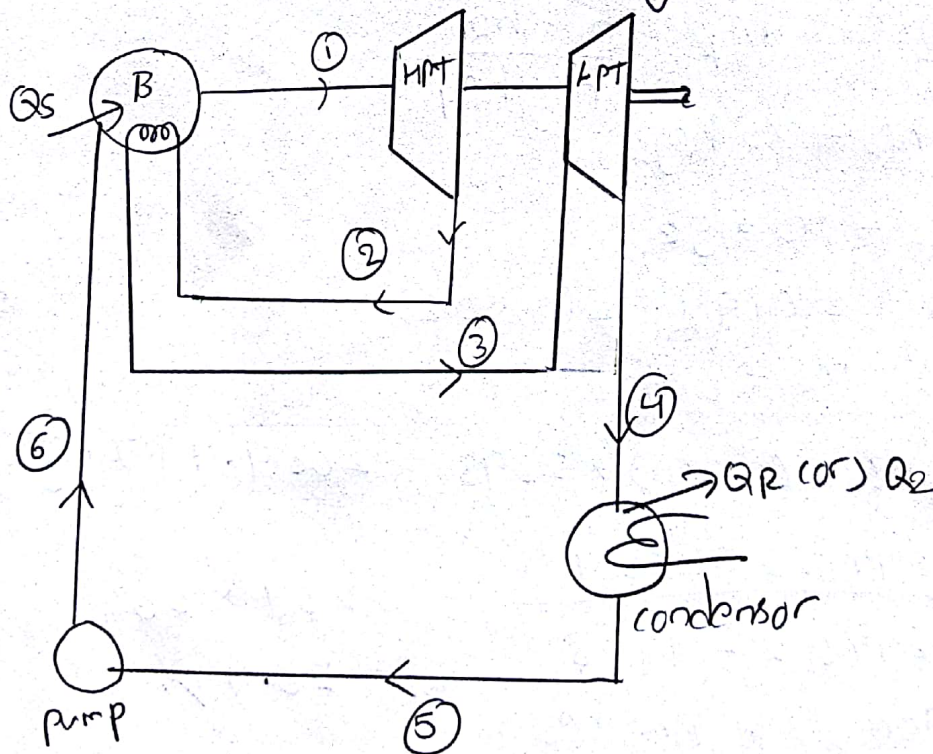
$$\eta_{th} = \frac{3600 \times P}{m_s (h_1 - h_{f4})} = \frac{3600 \times 220}{2500 (2776.2 - 191.8)}$$

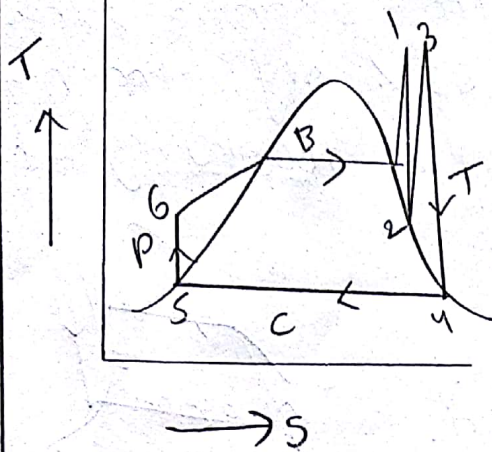
$$\eta_{th} = 0.1226 \times 100 = 12.26\%$$

→ Reheat cycle :-

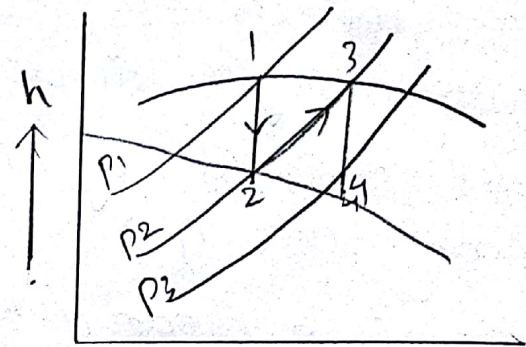
The efficiency of the ordinary Rankine cycle can be improved by increasing the pressure and temperature of steam entering into the turbine. A little consideration will show that, that the increase in the initial steam pressure will increase the expansion ratio, and steam will become quite wet at the end of expansion, the wet steam causes erosion of the turbine blades and increases internal losses. Thus will reduce the blade η of the turbine.

The above difficulty may be overcome by reheating of the steam. The schematic diagram of the process is shown in fig.





T-s diagram



h-s diagram

1st stage: (high pressure turbine)

steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it's reheated at constant pressure usually to the inlet temperature of the 1st turbine stage

2nd stage: (low pressure turbine)

steam then expands isentropically in the 2nd stage (hpt) to the condenser pressure.

$$\text{total work done} = w_T - w_P$$

$$= (h_1 - h_2) + (h_3 - h_4) \text{ kJ/kg}$$

$$\text{heat supplied} = (h_1 - h_{f6}) + (h_3 - h_2) \text{ kJ/kg}$$

$$\therefore \eta = \frac{w_D}{Q_S} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f6}) + (h_3 - h_2)}$$

1) steam at 100 bar and 500°C enters the ideal engine that has one stage of reheat. the steam is exhausted from the engine at 0.07 bar and 85% dry. the net work developed by the engine is 1600 kJ/kg of steam. find η ?

Sol:- from steam tables, at 100 bar and 500°C, $h_1 = 3374.6$ kJ/kg.

$$x = 0.85$$

$$w_{net} = 1600 \text{ kJ/kg}$$

find $\eta = ?$

$$\eta = \frac{w_{net}}{(h_1 - h_{f6}) + (h_3 - h_2)}$$

$$w_{net} = (h_1 - h_2) + (h_3 - h_2)$$

$$\Rightarrow (h_3 - h_2) = w_{net} + (h_2 - h_1)$$

$$= 1600 + 2211.2 - 3374.6$$

$$= 436.6 \text{ kJ/kg}$$

At 0.07 bar.

$$h_{f5} = 163.8 \text{ kJ/kg}$$

$$h_u = h_{f4} + x_4 h_{fg4}$$

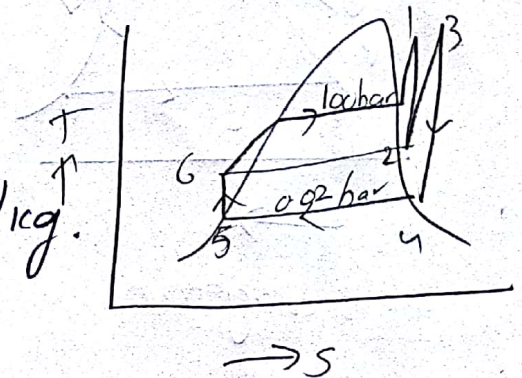
$$h_4 = 163.8 + (0.85) \times 2409.2$$

$$h_4 = 2211.2 \text{ kJ/kg}$$

$$\eta = \frac{1600}{(3374.6) - 163.38 + 436.6} = \frac{1600}{3647.82} = 0.4386$$

$$\eta = 0.4386 \times 100$$

$$\therefore \eta = 43.86\%$$



2) Steam at a pressure of 15 bar and 250°C is first expanded through a turbine to a pressure of 4 bar. It is then reheated at a constant pressure to the initial temp of 250°C and is finally expanded to 0.1 bar. Using Mollier chart, find the work done per kg of steam flowing through the turbine and the amount of heat supplied during the process of reheat.

Also find the work output when the expansion is direct from 15 bar to 0.1 bar without any reheat. Assume all expansion processes to be isentropic.

Sol:- Given :-

$$P_1 = 15 \text{ bar}, T_1 = 250^\circ\text{C},$$

$$P_2 = 4 \text{ bar}, T_2 = 250^\circ\text{C},$$

$$P_3 = 0.1 \text{ bar}.$$

The reheating of steam is represented on the Mollier chart as shown in fig. From the chart, we find that,

$$h_1 = 2930 \text{ kJ/kg}, h_2 = 2660 \text{ kJ/kg},$$

$$h_3 = 2965 \text{ kJ/kg}, h_4 = 2345 \text{ kJ/kg}$$

$$\text{and } h_5 = 2130 \text{ kJ/kg}.$$

From steam tables, at 0.1 bar pressure,

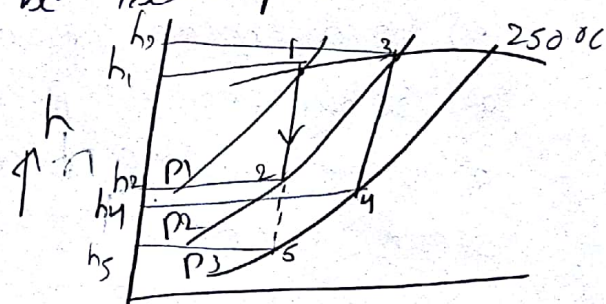
$$h_f = 191.8 \text{ kJ/kg}.$$

1) work done per kg of steam.

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

$$= (2930 - 2660) + (2965 - 2345)$$

$$W = 890 \text{ kJ/kg}.$$



2) heat supplied during the process of reheat

$$Q = h_3 - h_2 = 2965 - 2660$$

$$Q = 305 \text{ kJ/kg}$$

3) work done when the expansion is direct from 15 bar to 0.1 bar. which is shown in h-s diagram.

$$\text{work output} = h_1 - h_5$$

$$= 2930 - 2130$$

$$= 800 \text{ kJ/kg}$$

3) In a thermal plant, the steam is supplied at a pressure of 30 bar and temp of 300°C to the high pressure side of steam turbine where it is expanded to 5 bar. the steam is then removed and reheated to 300°C at a constant pressure. It is then expanded to the low pressure side of the turbine to 0.5 bar. find the η of the cycle with and without reheating.

Sol:- Given $p_1 = 30 \text{ bar}$, $p_2 = 5 \text{ bar}$, $p_3 = 0.5 \text{ bar}$.
 $T_1 = 300^\circ\text{C}$, $T_2 = 300^\circ\text{C}$,

η of cycle with reheating :-

using moiler chart :-

$$h_1 = 2990 \text{ kJ/kg}, h_2 = 2625 \text{ kJ/kg}$$

$$h_3 = 3075 \text{ kJ/kg}, h_4 = 2595 \text{ kJ/kg}$$

$$h_5 = 2280 \text{ kJ/kg}$$

from steam tables, at 0.5 bar,

$$h_f = 340.6 \text{ kJ/kg}$$

$$\eta_R = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f6}) + (h_3 - h_2)}$$

$$\eta_R = \frac{(2990 - 2625) + (3075 - 2595)}{(2990 - 340.6) + (3075 - 2625)}$$

$$\eta_R = \frac{845}{3099.4} = 0.273 = 27.3\%$$

η of cycle without reheating:-

$$\eta = \frac{h_1 - h_5}{h_1 - h_{f5}} = \frac{2990 - 2280}{2990 - 340.6} = 0.268 = 26.8\%$$

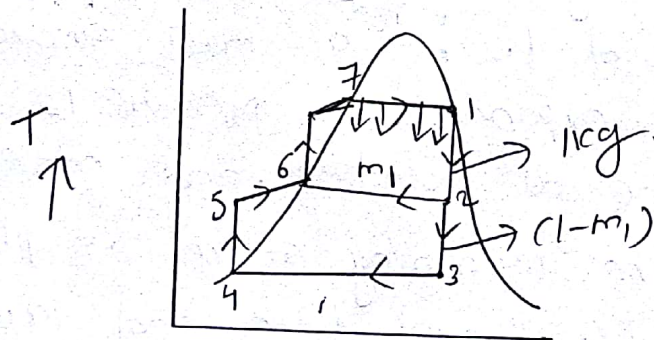
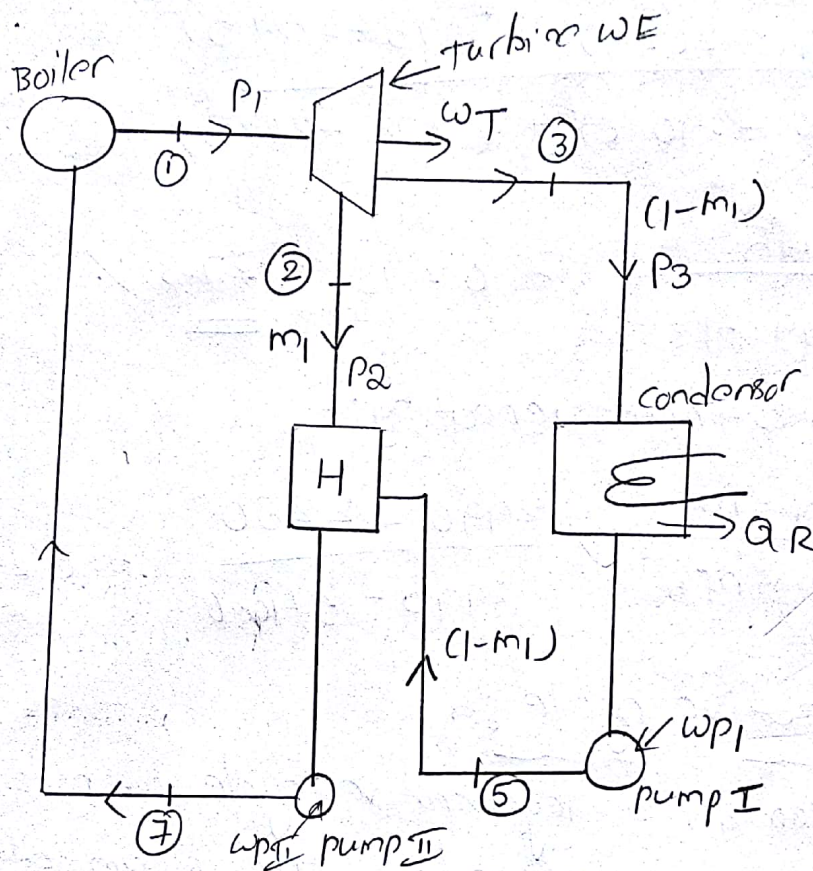
→ Regenerative cycle :-

consider a regenerative cycle with single feed water heater as shown in fig. the steam at pressure P_1 enters the turbine at point 1. let a small amount of wet steam after partial expansion at pressure P_2 be drained from the turbine at point 2 and enters the feed water heater. the remaining steam at pressure P_3 is further expanded in the turbine and leaves at point 3 as shown in the Moiler diagram.

this steam is then condensed in the condensor. the condensate from the condensor, is pumped into the feed water heater, where it is mixed up with the steam extracted from the turbine. the proportion of steam extracted is just sufficient to cause the steam leaving the feed water heater

to be saturated.

now consider 1kg of steam entering the turbine at point 1.



1-2 → Expansion of 1kg of steam

2-3 → Expansion of $(1-m_1)$ kg of steam

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

$$w_P = w_{P1} + w_{P2} = (1-m_1)(h_5 - h_4) + 1(h_7 - h_6)$$

$$Q_s = \text{from 1 to 7} = 1 \times (h_1 - h_7)$$

$$\eta = \frac{w_T - w_P}{Q_s}$$

$$\eta = \frac{(1 \times (h_1 - h_2) + (1 - m_1)(h_2 - h_3))}{(1 \times (h_2 - h_1) + (1 - m_1)(h_5 - h_4) + 1 \times (h_7 - h_1))}$$

$$\therefore \eta = \frac{(h_1 - h_2) + (1 - m_1)(h_2 - h_3)}{(h_1 - h_7)}$$

Mean temperature of heat addition:

$$\text{w.k.T } T ds = dh - v dp$$

as 1 to 2 isobaric process
 $dp = 0$

$$\text{for regeneration :- } T m_1 (s_1 - s_7) = h_1 - h_7$$

$$\Rightarrow T m_1 = \frac{h_1 - h_7}{s_1 - s_7}$$

$$\text{without regeneration :- } T m_1 = \frac{h_1 - h_5}{s_1 - s_5}$$

w.k.T. heat lost by the bleed steam $\frac{s_1 - s_5}{s_1 - s_7}$ = heat gained by the feed water.

$$m_1 (h_2 - h_7) = (1 - m_1) (h_7 - h_4)$$

$$m_1 h_2 - m_1 h_7 = h_7 - h_4 - m_1 h_7 + m_1 h_4$$

$$m_1 (h_2 - h_4) = h_7 - h_4$$

$$\therefore m_1 = \frac{h_7 - h_4}{h_2 - h_4}$$

1) In a regenerative cycle, having one feed water heater, the dry saturated steam is supplied from the boiler at a pressure of 30 bar and the condenser pressure is 1 bar. The steam is bled at a pressure of 5 bar. Find the amount of bled steam per kg of steam supplied and the η of cycle?

What would be the η without regenerative feed heating, also find the percentage η due to regeneration.

sol: - $P_1 = 30 \text{ bar}$, $P_3 = 1 \text{ bar}$, $P_2 = 5 \text{ bar}$,

from Mollier diagram:-

At 30 bar, $h_1 = 2800 \text{ kJ/kg}$.

At 5 bar, $h_2 = 2460 \text{ kJ/kg}$.

At 1 bar, $h_3 = 2220 \text{ kJ/kg}$.

sensible heat of water at 1 bar,

$$h_f = 417.5 \text{ kJ/kg}.$$

Amount of bleed steam per kg of steam supplied,

$$m = \frac{h_1 - h_4}{h_2 - h_4} = \frac{2800 - 417.5}{2460 - 417.5} = 0.109 \text{ kg}.$$

η of the cycle:-

$$\eta = \frac{(h_1 - h_2) + (1 - m_1)(h_2 - h_3)}{h_1 - h_f}$$

$$= \frac{(2800 - 2460) + (1 - 0.109)(2460 - 2220)}{2800 - 417.5}$$

$$\therefore \eta = \frac{553.84}{2159.9} = 0.256 = 25.6 \%$$

η of cycle with out regenerative feed heating

$$\eta = \frac{h_1 - h_3}{h_1 - h_{f3}} = \frac{2800 - 2220}{2800 - 417.5} = 0.243 = 24.3 \%$$

$$= \frac{0.256 - 0.243}{0.243} = 0.0535 \times 100 = 5.35 \%$$

Fuels :-

A fuel, in general term may be defined as the substance containing mostly carbon and hydrogen which, on burning with oxygen in the atmospheric air, produces a large amount of heat. The amount of heat generated is known as calorific value of the fuel.

The main components of a fuel are carbon and hydrogen, it is also known as hydrocarbon fuel.

→ classification of fuels :-

The fuels may be classified as the following general forms:

1. solid fuels
2. Liquid fuels
3. Gaseous fuels,

Again they are further subdivided into the following two types.

- a) natural (or) primary fuels
- b) prepared (or) secondary fuels.

→ solid fuels:-

The solid fuels are wood, peat, lignite, brown coal, bituminous coal and anthracite coal. The prepared solid fuels are wood charcoal, coke, briquetted coal and pulverised coal.

1) wood:- It was extensively used as a fuel. It consists of mainly carbon and hydrogen. The wood is converted into coal when burnt in the absence of air. The average calorific value of wood is 19700 kJ/kg .

2) peat:- It is a spongy humid substance found in boggy land. It may be regarded as the 1st stage in the formation of coal. Its average calorific value is 23000 kJ/kg .

3) lignite:- It represents the next stage of peat in the coal formation, and is an intermediate variety b/w bituminous coal and peat. It contains 40% moisture and 60% of carbon. Calorific value of lignite is 25000 kJ/kg .

4) Bituminous coal:- It represents the next stage of lignite in the coal formation and contains very little moisture (4 to 6%) and 75 to 90% of carbon. Calorific value of coal is 33500 kJ/kg .

5) Anthracite coal:- It represents the final stage in the coal formation, and contains 90% (or) more carbon with very little volatile matter. Calorific value is 36000 kJ/kg .

6) wood charcoal: - It is made by heating wood with a limited supply of air to a temp absence of air in a closed vessel. this process is known as carbonization of coal. calorific value is 85% higher than coal.

7) coke: - It is produced when coal is strongly heated continuously for 42 to 48 hrs in the absence of closed vessel.

→ liquid fuels: - Almost all the commercial liquid fuels are derived from natural petroleum. The liquid fuels consists of hydrocarbons. the natural petroleum may be separated into petrol or gasoline, paraffin oil or kerosine, fuel oils and lubricating oils by boiling the crude oil.

the following are the liquid fuels are important from the subject point of view.

1. kerosine or paraffin oil or gasoline: - It is the ^{heavier} lightest and most less volatile fuel than the petrol, and is used as heating and lighting fuel.

2) petrol or gasoline: - It is the lightest and most volatile fuel than the petrol, mainly used for light petrol engines. It is distilled at a temp from 65° to 220°C .

3) heavy fuel oils: - the liquid fuels distilled after petrol and kerosine are known as heavy fuel oils. They are distilled at a temp of 345°C to 470°C .

→ Gaseous fuels: The natural gas, usually, found in (or) near the petroleum fields, under the earth's surface. It contains of marsh gas or methane (CH_4) together with small amounts of other gases such as ethane (C_2H_6), carbon dioxide (CO_2) and carbon monoxide (CO).

The following are the prepared gases, which are used as fuels, are important. from

1. coal gas: It is also known as town gas. It is obtained by the combustion of coal and consists of mainly of hydrogen, carbon monoxide and various hydrocarbons.

Its calorific value is 25000 kJ/m^3 .

2) producer gas: It is obtained by the partial combustion of coal, coke, anthracite coal (or) charcoal in a mixed air - steam blast. Its manufacturing cost is low, and has a calorific value of about 5000 to 6700 kJ/m^3 .

3. water gas: It is a mixture of hydrogen and carbon monoxide and is made by passing steam over incandescent coke. As it burns with a blue flame, it is also known as blue water gas.

4. Mond gas: It is produced by passing air and a large amount of steam over waste coal at about 650°C . It is used for power generation and heating.

5. Blast furnace gas: - It is a by-product in the production of pig iron in the blast furnace. It has low heating value of about 3750 kJ/m^3 .

6. Coke oven gas: - It is a by product from coke oven, and is obtained by the carbonisation of bituminous coal.

→ Calorific value of fuels: - The calorific value or heat value of a solid or liquid fuel may be defined as the amount of heat given out by the complete combustion of 1 kg of fuel. It is expressed in terms of kJ/kg of fuel.

→ Combustion of fuels :-

The combustion of fuel may be defined as a chemical combination of oxygen, in the atmosphere air, and hydro-carbons. It is usually, expressed both qualitatively and quantitatively by equations known as chemical equations.

→ Atoms and Molecules :-

The atoms are made up of minute and chemically indivisible particles known as atoms.

The smallest quantity of a substance, which can exist by itself, in a chemically recognizable form, is known as molecule.

symbols with atomic mass and molecular mass: -

substance	symbol	Atomic mass	molecular mass
Hydrogen	H ₂	1	2
oxygen	O ₂	16	32
Nitrogen	N ₂	14	28
Carbon	C	12	-
sulphur	S	32	-
Carbon monoxide	CO	-	28
Methane	CH ₄	-	16
Acetylene	C ₂ H ₂	-	26
Ethylene	C ₂ H ₄	-	28
Ethane	C ₂ H ₆	-	30
Carbon dioxide	CO ₂	-	44

→ combustion equations of solid fuels:-

1) When carbon burns in sufficient quantity of oxygen, carbon dioxide is produced along with a release of large amount of heat.



$$1 \text{ mol} + 1 \text{ mol} = 1 \text{ mol}$$

$$12 \text{ kg} + 32 \text{ kg} = 44 \text{ kg.}$$

$$1 \text{ kg} + \frac{8}{3} \text{ kg} = \frac{11}{3} \text{ kg.}$$

It means that 1 kg of carbon requires $\frac{8}{3}$ kg of oxygen for its complete combustion, and produces $\frac{11}{3}$ kg of carbon dioxide gas.

2) If sufficient oxygen is not available, the combustion of carbon is incomplete. It then produces carbon monoxide instead of carbon dioxide.



$$2\text{mol} + 1\text{mol} = 2\text{mol}$$

$$2 \times 12 \text{ kg} + 2 \times 16 \text{ kg} = 2 \times 28 \text{ kg}$$

$$1 \text{ kg} + \frac{4}{3} \text{ kg} = \frac{7}{3} \text{ kg}$$

3) If carbon monoxide is burnt further, it is converted into carbon dioxide. Thus,



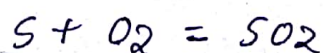
$$2\text{mol} + 1\text{mol} = 2\text{mol}$$

$$2 \times 28 \text{ kg} + 2 \times 16 = 2 \times 44 \text{ kg}$$

$$1 \text{ kg} + \frac{4}{7} \text{ kg} = \frac{11}{7} \text{ kg}$$

It means that 1 kg of carbon monoxide requires $\frac{4}{7}$ kg of oxygen, and produces $\frac{11}{7}$ kg of carbon dioxide.

4) When sulphur burns with oxygen, it produces sulphur dioxide. This is represented by following chemical equation



$$1\text{mol} + 1\text{mol} = 1\text{mol}$$

$$32 \text{ kg} + 2 \times 16 \text{ kg} = 64 \text{ kg}$$

$$1 \text{ kg} + 1 \text{ kg} = 2 \text{ kg}$$

It means that 1 kg of sulphur requires 1 kg of oxygen for complete combustion and produces 2 kg of sulphur dioxide.

→ conversion of volumetric Analysis into mass Analysis :-

① The volumetric analysis of a gas is CO_2 14%, CO 1%, O_2 5% and N_2 80%. find the fuel gas composition by mass.

Sol:- Given $\text{CO}_2 = 14\% = 0.14 \text{ m}^3$, $\text{CO} = 1\% = 0.01 \text{ m}^3$, $\text{O}_2 = 5\% = 0.05 \text{ m}^3$, $\text{N}_2 = 80\% = 0.8 \text{ m}^3$,

the volumetric analysis may be converted into mass analysis by completing the table as follows.

constituent	volume in m^3 of the gas (a)	molecular mass (b)	proportional mass (c) = (a) × (b)	Mass in kg per of the gas (d) = (c) / Σ (c)	% by mass = (d) × 100
CO_2	0.14	44	6.16	$\frac{6.16}{30.44} = 0.202$	20.2 %
CO	0.01	28	0.28	$\frac{0.28}{30.44} = 0.009$	0.9 %
O_2	0.05	32	1.60	$\frac{1.60}{30.44} = 0.053$	5.3 %
N_2	0.80	28	22.40	$\frac{22.40}{30.44} = 0.736$	73.6 %
total	1.00		$\Sigma c = 30.44$	1.0000	100.0

the fuel gas composition, by mass is given in the last column.

$\text{CO}_2 = 20.2\%$, $\text{CO} = 0.9\%$, $\text{O}_2 = 5.3\%$, $\text{N}_2 = 73.6\%$
= .

For obtaining, 1 kg of oxygen, amount of air required,

$$= \frac{100}{23} = 4.35 \text{ kg.}$$

theoretical (or) minimum air required for complete combustion of 1 kg of fuel.

$$= \frac{100}{23} \left[\left(\frac{8}{3} C + 8 H_2 + S \right) - O_2 \right] \text{ kg.}$$

1) A producer gas, used as a fuel, has the following volumetric composition.

H_2 28%, CO 12%, CH_4 2%, CO_2 16%, N_2 42%.

find the volume of air required for complete combustion of 1 m^3 of this gas. Air contains 21% by volume of oxygen.

Sol. Given $H_2 = 28\% = 0.28 \text{ m}^3$, $CO = 12\% = 0.12 \text{ m}^3$,
 $CH_4 = 2\% = 0.02 \text{ m}^3$, $CO_2 = 16\% = 0.16 \text{ m}^3 \Rightarrow N_2 = 42\% = 0.42 \text{ m}^3$

$$\text{Theoretical air required} = \frac{100}{21} \left[(0.5 CO + 0.5 H_2 + 2 CH_4 + 3 CO_2 H_4) - O_2 \right] \text{ m}^3$$

$$= \frac{100}{21} \left[(0.5 \times 0.12 + 0.5 \times 0.28 + 2 \times 0.02 + 3 \times 0.16) - 0 \right] \text{ m}^3$$

$$= 1.143 \text{ m}^3$$

→ conversion of mass analysis into volumetric analysis:-

A fuel gas has the following percentage composition by mass. $\text{CO}_2 = 13.3\%$, $\text{CO} = 0.95\%$, $\text{O}_2 = 8.35\%$, $\text{N}_2 = 77.4\%$, convert this into volumetric analysis.

Sol:- Given $\text{CO}_2 = 13.3\%$, $\text{CO} = 0.95\%$, $\text{O}_2 = 8.35\%$, $\text{N}_2 = 77.4\%$.

The mass analysis may be converted into volumetric analysis by completing the table as shown.

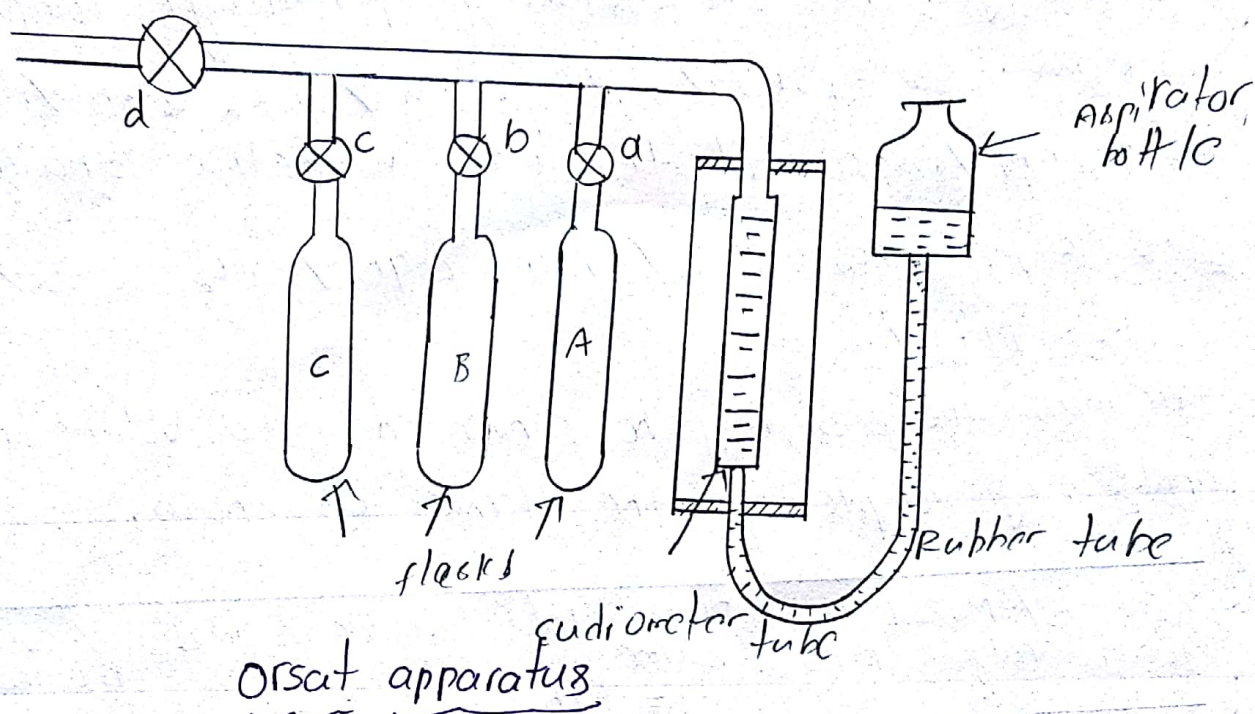
constituent	% Mass analysis (a)	Molecular Mass (b)	Proportional Volume $c = a/b$	Volume in m^3 of flue gas $d = c/\Sigma c$	% volumetric analysis $= (d) \times 100$
CO_2	13.3	44	$\frac{13.3}{44} = 0.302$	$\frac{0.302}{3.357} = 0.090$	9.0
CO	0.95	28	$\frac{0.95}{28} = 0.034$	$\frac{0.034}{3.357} = 0.010$	1.0
O_2	8.35	32	$\frac{8.35}{32} = 0.261$	$\frac{0.261}{3.357} = 0.078$	7.8
N_2	77.4	28	$\frac{77.4}{28} = 2.76$	$\frac{2.76}{3.357} = 0.822$	82.2
Total	100.0		$\Sigma c = 3.357$	1.000	100.0

The flue gas composition by volume, is given in the last column,

$\text{CO}_2 = 9\%$, $\text{CO} = 1\%$, $\text{O}_2 = 7.8\%$, $\text{N}_2 = 82.2\%$

==.

→ flue gas Analysis by orsat apparatus :-



The flask A contains caustic soda (NaOH) and is used to absorbing carbon dioxide in the sample of the flue gas.

The flask B contains caustic soda (NaOH) and pyrollic acid, which absorbs oxygen from the sample of the flue gas.

The flask C contains a solution of cuprous chloride (Cu_2Cl_2) in hydrochloric acid (HCl). It absorbs carbon monoxide (CO) from the sample of the flue gas.

To check the combustion of boilers, it is considered essential to determine the constituents of the flue gases. Such an analysis is carried out with the help of orsat apparatus as shown in fig.

It contains a graduated measuring glass tube and three flasks A, B, C each containing different chemicals for absorbing carbon dioxide, carbon monoxide, and oxygen. An aspirator bottle containing water is connected to the bottom of the eudiometer tube by means of a rubber tube. It can be moved up and down, at will, for producing a suction (or) pressure effect on the sample of the flue gas.

The sample of the flue gas to be analysed is first sucked in the eudiometer tube, and its volume is noted. It contains usually 100cm^3 of gas. By manipulating the level of aspirator tube, the flue gas can, in turn, be forced into either of the flasks A, B, C by opening the cocks a, b, c. The flue gas is left there for some times and then sucked back into tube. The percentage of each gas present in the sample to be read on the eudiometer tube.

Adiabatic flame temperature:

In a given combustion process, that takes place adiabatically and with no work or changes in kinetic energy or potential energy involved, the temperature of the products is referred to as the 'adiabatic flame temperature'. With the assumptions of no work and no changes in kinetic energy or potential energy, this is the maximum temperature that can be achieved for the given reactants because any heat transfer from the reacting substances and any incomplete combustion would tend to lower the temperature of the products.

The following points are worth noting:

(i) The maximum temperature achieved through adiabatic complete combustion varies with help of reaction and percent of theoretical air supplied.

(ii) For a given fuel and fuel pressure and temperature of the reactants, the maximum adiabatic flame temperature that can be achieved is with a 'stoichiometric' mixture.

(iii) The adiabatic flame temperature can be controlled by the amount of excess air that is used. This is important, for example, in gas turbines, where the maximum permissible temperature is determined by

metallurgical considerations in the turbine, and close control of the temperature of the products is essential.

UNIT - II

BOILERS

Introduction:-

A steam generator or boiler is, usually, a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel (solid, liquid, or gaseous) to water and ultimately to generate steam.

IMPORTANT TERMS OF BOILER:-

1) BOILER SHELL:-

It is made up of steel plates bent into cylindrical form and riveted or welded together. The ends of the shell are closed by means of end plates. A boiler shell should have sufficient capacity to contain water and steam.

2) COMBUSTION CHAMBER:-

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

3) GRATE:-

It is a platform in the combustion chamber, upon which fuel is burnt. It consists of cast iron bars which are spaced apart so that air can pass through them. The surface area of the grate, over which the fire takes place, is called grate surface.

It is the space, above the grate and below the boiler shell, in which the fuel is actually burnt. It is also called as firebox.

5. Heating Surface

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

6. MOUNTINGS

These are the fittings which are mounted on the boiler for its proper functioning. They include water level indicator, pressure gauge, safety valve, etc. It may be noted that a boiler cannot function safely without the mounting.

7. ACCESSORIES

These are the devices, which form an integral part of a boiler, but are not mounted on it. They include Superheater, economiser, feed pump etc. They help in controlling and running the boiler efficiently.

- 1) The power Required and the working pressure.
- 2) The rate at which the steam is to be generated.
- 3) The Geographical position of power house.
- 4) The fuel and water available.
- 5) The type of fuel to be used.
- 6) The probable permanency of the station.

CLASSIFICATION OF STEAM BOILERS:-

(1) ACCORDING TO THE CONTENTS IN THE TUBE:-

(a) Fire tube & smoke tube Boiler

(b) water tube Boiler.

In fire tube steam Boilers, the flame and hot gas, produced by the combustion of fuel, pass through the tubes which are surrounded by water. The heat is conducted through the walls of the tubes from the hot gases to the surrounding water.

ex: Simple vertical Boiler, Cochran Boiler, Lancashire, Cornish, Scotch marine, Locomotive and vertical Boiler.

In water tube steam boiler, the water is contained inside the tubes which are surrounded by flame, and hot gas from outside.

ex: Babcock and Wilcox, Stirling, Lamont, Benson, Yarrow, Loeffler Boilers.

2) ACCORDING TO POSITION OF FURNACE

- (a) Internally fired (b) Externally fired.

In internally fired steam Boilers, the furnace is located inside the Boiler shell; Most of the fire tube steam Boilers are internally fired.

In externally fired Boilers, the furnace is arranged underneath in a brick-work setting. Water steam

Boilers are always Externally fired.

3) ACCORDING TO AXIS OF THE SHELL:-

- (a) VERTICAL (b) HORIZONTAL

In vertical Boilers, the axis of the Shell is vertical.

Ex: Simple vertical Boiler, Cochran Boiler.

In horizontal Boiler, the axis of the Shell is horizontal.

Ex: Lancashire, Locomotive, Babcock & Wilcox

4) ACCORDING TO NUMBER OF TUBES:-

- (a) SINGLE TUBE

- (b) MULTITUBULAR BOILER.

In Single tube boilers, there is only one fire

water tube. Simple vertical and Cornish boiler are

Single tube boilers.

In multitubular boiler, there are two or more fire

water tubes.

Ex: Lancashire, Locomotive, Cochran, Babcock & Wilcox

(a) Natural Circulation (b) Forced Circulation

In natural circulation Boilers, the circulation of water is by natural convection currents, which are set up during the heating of water. In most of boilers, there is a natural circulation of water.

In forced circulation boiler, there is a forced circulation of water by a centrifugal pump driven by some external power. It is made in high pressure

Boilers such as La-Mont, Benson, Loeffler, and Velcon

6) ACCORDING TO USE:-

(a) STATIONARY (b) MOBILE

The stationary Boilers are used in power plants, and in industrial process work. These are called stationary because they do not move from one place to another.

The mobile steam Boilers are those which move from one place to another. These are locomotive and marine Boilers.

7) ACCORDING TO SOURCE OF HEAT:-

The sources may be the combustion of solid, liquid or gaseous fuel, hot water gases or by products of other chemical process, electrical energy or nuclear energy.

A Cochran boiler is considered to be one of the most efficient type of such boilers. It is an improved type of simple vertical boiler.

The boiler consists of an cylindrical shell and a fire box of hemispherical. The hemispherical crown of the boiler shell gives maximum space and strength to withstand the pressure of steam inside the boiler. The hemispherical crown of fire box is also advantageous for resisting intense heat. The firebox and combustion chamber connected through a short pipe. The flue gases from the combustion chamber flow to the smoke box through a number of smoke tubes, which have 62.5mm external dia and are in 165 in number. The gases from the smoke box pass to the atmosphere through a chimney. The combustion chamber is lined with fire bricks on the shell side. A manhole near the top of the crown on the shell is provided for

cleaning.

At the bottom of the fire box, there is a grate and the coal is fed through the fire hole, which contains the oil burner.

→ It is a Stationary, fire tube, internally fired, horizontal and natural circulation boiler. It is used where working pressure and power required are moderate. These boilers have a cylindrical shell

of 1.75m to 2.75m Dia.

→ Its length varies from 7.25m to 9m. It has two internal fire tubes having diameter about 0.4 times that of shell. This type of boiler is set in brick work forming external fire, so that part of heating surface is on the external shell.

→ This boiler consists of a long cylindrical external shell built of steel plates, in sections riveted together.

→ It has two long internal fire tubes, which are reduced in diameter at the back end to provide access to the lower part of the boiler.

→ A fire grate also called furnace, is provided at the one end of the fire tubes in which

solid fuel is burnt.

→ At the end of the fire grate, there is Bore arch to deflect the flue gases upwards. The hot flue gases, after leaving the internal fire tubes pass down to

to the bottom tube and move to the front of the boiler where they divide and flow into the side flue.

→ The flue gases then enter the main flue which leads them to chimney.

→ The damper is fitted at the end of side flues to control the draught and thus regulate the rate of generation of steam. These dampers are operated by chain passing over a pulley at the front of the boiler.

→ The stop valve supplies steam to the engine as required. A high steam and low water safety valve is also provided.

→ A perforated feed pipe controlled by a feed valve is used for feeding water uniformly. When the boiler is strongly heated, the steam generated carries a large quantity of water in the steam space, known as priming. An anti-priming pipe is provided to separate out water as far as possible.

CORNISH BOILER:-

→ It is similar to the Lancashire boiler in all respects, excepts there is only one fire tube in Cornish Boiler instead of two in Lancashire

Boiler.

→ The Diameter of Cornish Boiler is generally 1m to 2m and its length varies from 5m to 7.5m.

→ The Diameter of flue tube may be about 0.6 times that of shell.

→ The Capacity & working pressure is low.

LOCOMOTIVE BOILER:

→ It is a multi tubular, horizontal, internally fired and mobile Boiler. The principal feature of this Boiler is to produce steam at high rate.

→ It consists of a shell or barrel having 1.5m Diameter and 4m in length.

→ The coal is fed into the fire box through the fire door and burns on grate.

→ The flue gases from the grate are deflected by a Brick arch, and thus whole of the fire box is properly heated. There are about 157 tubes or flue tubes of (47.5mm Dia) and 24 tubes

24 thick & Superheated tubes $\phi 130 \text{ mm}$ (11)

→ The flue gases after passing through these tubes enter a Smoke Box and are then lead to atmosphere through a chimney.

→ The Barrel contains water around the tubes, which is heated up by the flue gases and gets converted into steam.

→ A stop valve or regulator is provided inside a cylindrical Steam Dome, which is operated by a regulator Shaft from the engine room by a Driver.

→ The heater is divided into two portions. one is Superheated steam chamber and other is Saturated steam chamber.

→ The steam pipe leads to the steam from the regulator to the Saturated steam chamber.

→ It then leads the steam to the Superheated tubes and after passing through these tubes, the steam returns back to the Superheated steam chamber.

→ This steam now flows through the steam pipe to the cylinder on each side.

By opening the Smoke Box.

→ The ash from grate is collected in ash pan and is discharged out from time to time by opening it with the help of Dampers.

BABCOCK AND WILCOX BOILER:

→ It is a straight tube, stationary type water tube boiler. It consists of a steam and water drum. It is connected by a short tube with uptake header & riser at the back end.

→ The water tubes (100 mm Diameter) are inclined to the horizontal and connects the uptake header to the downtake header.

→ Each row of the tubes is connected with two headers and there are plenty of such rows.

The headers are curved when viewed in the direction of tube in that one tube is not in space of other. and hot gas can pass properly after heating all tubes.

→ The headers are provided with hand holes in the front of the tubes and are covered with caps.

→ There is a slow moving automatic change over which the coal is fed from the hopper.
→ A fire bricks baffle causes hot gases to move upwards and downwards and again upwards before leaving the chimney.

→ The dampers are operated by a chain which passes over a pulley to the front of a Boiler to Regulate the Draught.

→ The Boiler is Suspended on steel girders and Surrounded in all the four sides by fire Brick walls.

→ The Doors are provided for a man to enter the Boiler for repairing and cleaning.

→ Water Circulates from the Drum into the header and through the tubes to header and again to the Drum. Water continues to Circulate like this till it is Evaporated.

→ A steam Superheater Consists of a large number of tubes and Contains two boxes: one is Superheated Steam Box and other Saturated Steam Box.

→ The steam generated above the water level in the Drum flows in the drypipe and through the inlet tube into the Superheated Box.

Saturated Steam Box.

→ The steam, During its passage through tubes, gets further heated and becomes Superheated

→ Now the steam is taken through the outlet pipe to the stop valve.

LAMONT BOILER:

→ This is a modern high pressure water tube Steam Boiler working on a Forced Circulation.

→ The Circulation is maintained by a Centrifugal pump Driven by a Steam turbine, using Steam from the Boiler.

→ The forced Circulation causes the feed water to Circulate through the water walls and drums Equal to ten times the mass of steam Evaporated. This prevents the tube from being overheated.

→ The feed water passes through the economiser to an evaporating Drum. It is then drawn to the circulating pump through the tube.

→ The pump delivers the feed to the headers, at a pressure above the Drum pressure. The header distributes water through Nozzles into the generating tubes acting in Parallel.

- The water and steam from the tubes enter into the Drum.
- The steam in the drum is then drawn through the Superheater.

LOG FLER BOILER:-

→ This is the water tube boiler using a forced circulation.

→ Its main principle of working is to evaporate the feed water by means of superheated steam from the Superheater.

→ The hot gases from the furnace are used for super heating.

→ The feed water from the economiser tubes is forced to mix with superheated steam in the evaporating Drum.

→ The Saturated Steam, thus formed, is drawn from the evaporating drum by a steam circulating pump. This steam passes through the tubes of the Combustion Chamber walls and then enters the Super heater.

→ From the Superheater, about one third of the super heated steam passes to the turbine and the remaining two thirds is used to evaporate the feed water in the evaporating Drum.

BENSON BOILER:

www.FirstRanker.com

www.FirstRanker.com

→ It is a high pressure, Downless, water tube steam boiler using forced circulation. In this boiler the feed water enters at one end and discharges superheated steam at the other end.

→ The feed pump increases the pressure of water to supercritical pressure (i.e., above critical pressure of 225 bar) and thus the water directly transforms into steam without boiling.

→ The feed water passes through the economiser to the water cooled walls of the furnace. The water receives heat by radiation and the temperature rises to almost critical temperature.

→ It then enters the evaporator and may of superheated.

→ Finally, it passed through superheater to obtain desired superheated steam.

→ The Benson Boiler is also known as light-weight boiler as there is no large water and steam drum. The thermal efficiency upto 90% may be achieved. The average operating pressure and capacity of this boiler is 250 bar and 135 ton/hr. It can be started with in 15 minutes.

1) The initial cost is low. There is no water (17)

Steam Drum).

2) Since there is no pressure limit, so SuperCritical pr. may be employ.

3) High pressure avoids the Bubble formation in the tubes which increase heat transfer rate.

4) It is a light-weight Boiler.

5) The Boiler can be started within 15 minutes.

SCOTCH MARINE BOILER:-

The marine steam Boiler of the Scotch & tank type are used for marine works, particularly, due to their compactness efficiency in operation and their ability to use any type of water. It does not require Brick work setting and external flues.

It has a Drum of diameter from 2.5m to 3.5 meters placed horizontally. These steam boilers may be single ended or double ended. The length of a single ended steam Boiler may be up to 3.5 meters while for double ended up to 6.5 meters.

A single ended Boiler has one to four furnaces which enter from front end of the Boiler. A double ended boiler has furnaces on both of its ends, and may have furnaces from two to four in each end.

The furnaces are generally corrugated for strength. Each furnace has its own combustion chamber. There are five flat plates in the combustion chamber, which require staying, i.e., the top plate, back plate, two side plates and the tube plates. There are a no. of smoke of tubes placed horizontally. The front and back plates of shell are strengthened by longitudinally stays.

The combustion chamber walls form the best heating surface. The furnace tubes, smoke tubes and the combustion chamber, all being surrounded by water, give a very large heating surface area in proportion to the cubical size of boiler. The level of water is maintained a little above the combustion chamber. The flue gases, from the combustion chamber are forwarded by draught through the smoke tubes, and finally up the chimney.

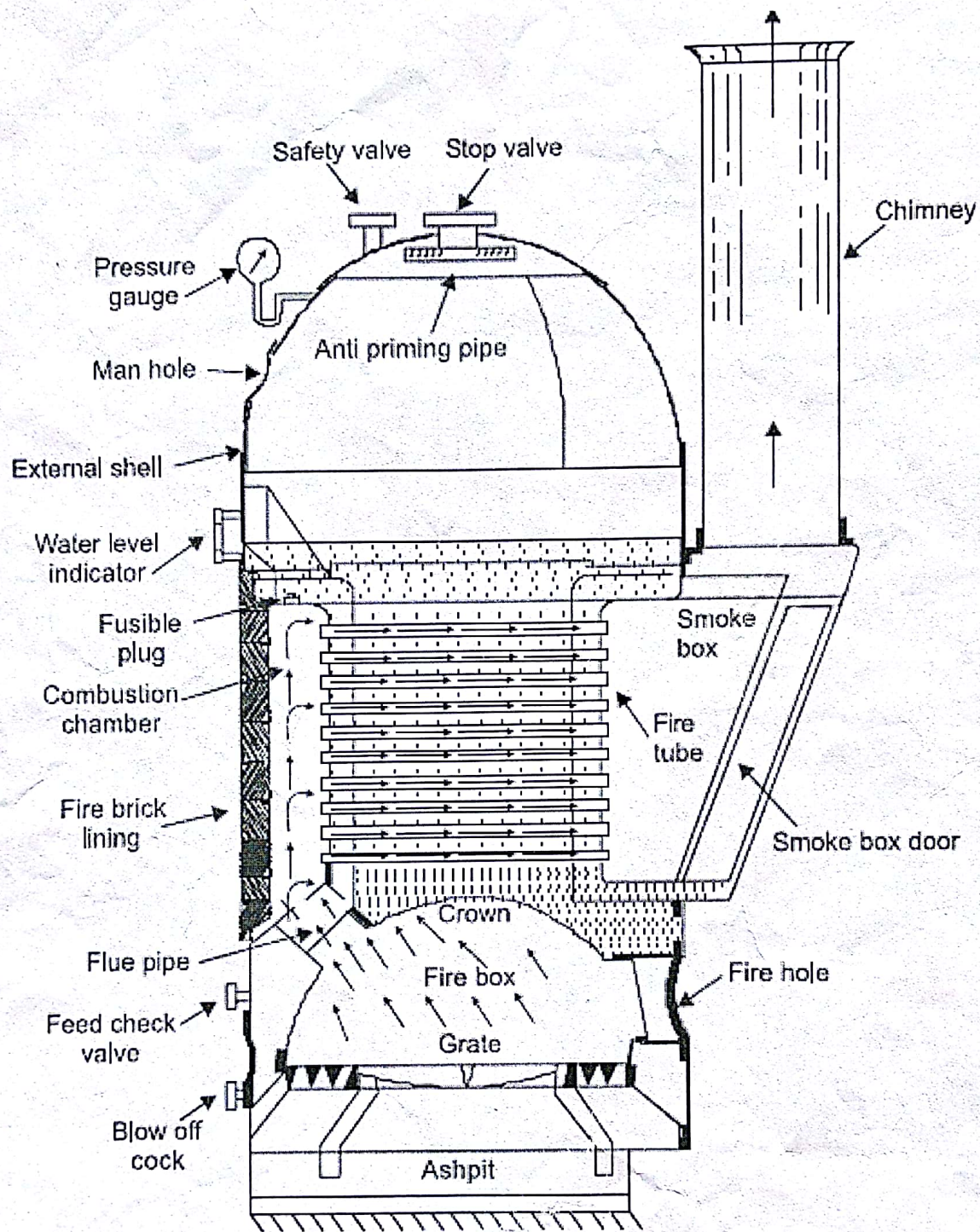
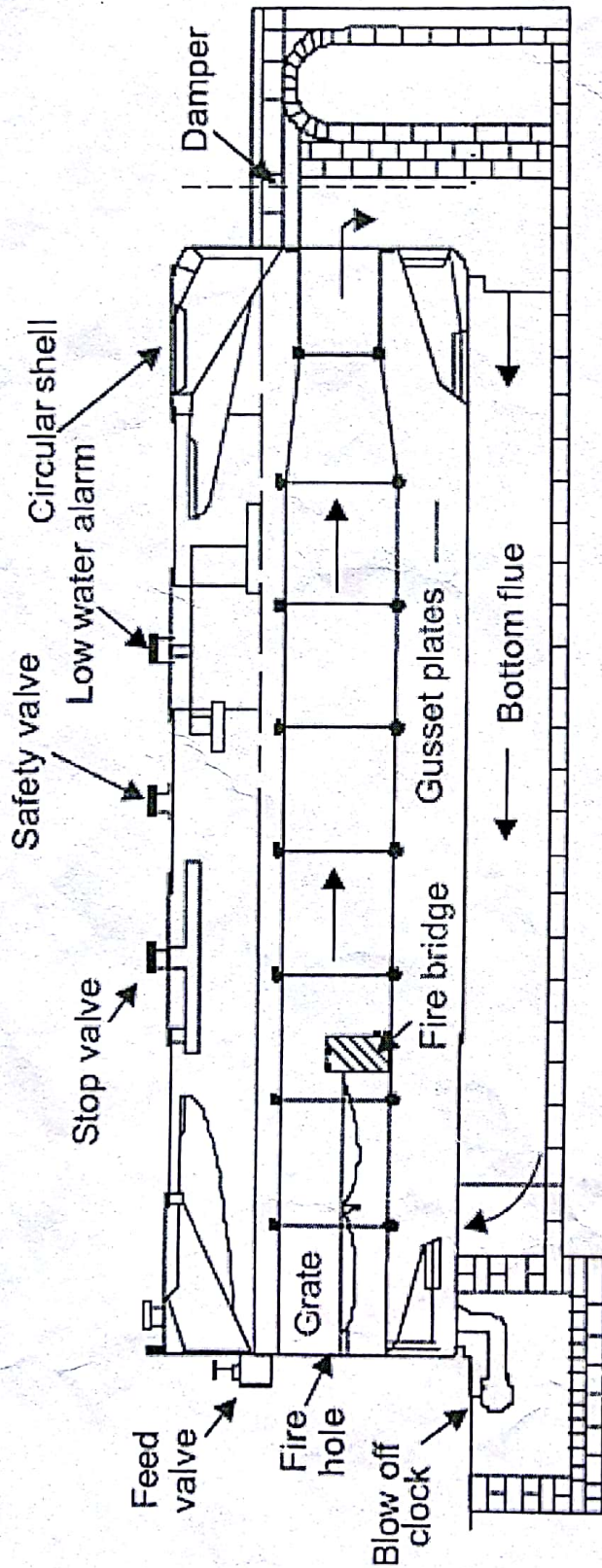
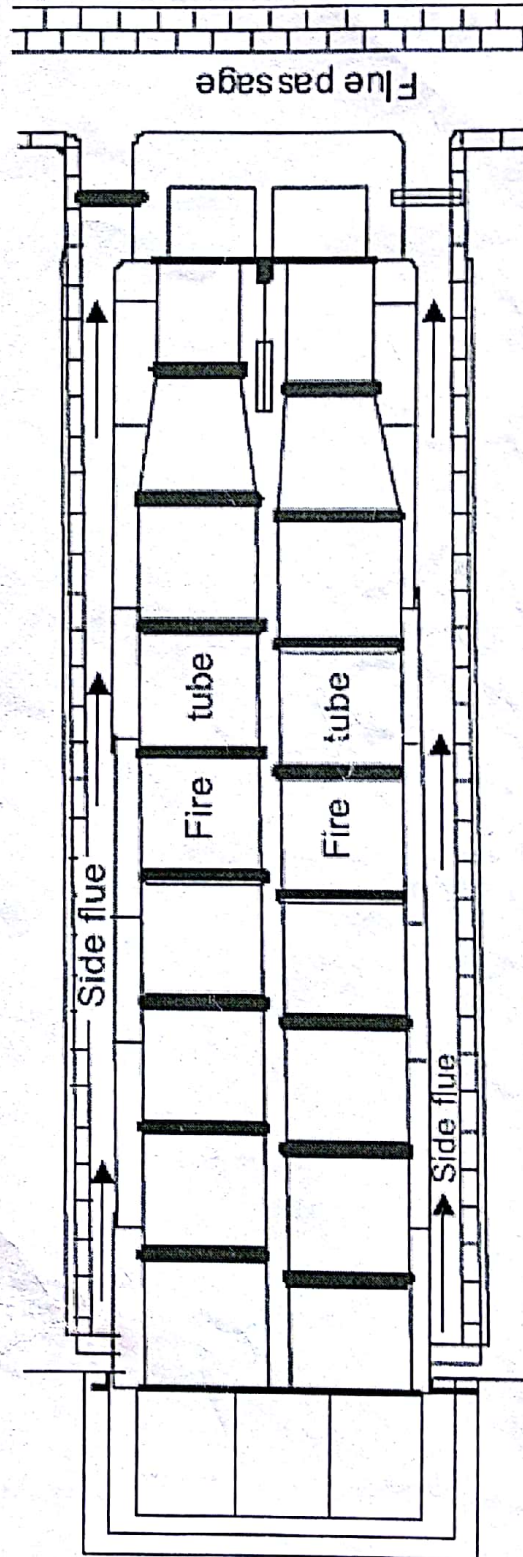


Fig. 11.7 Cochran boiler

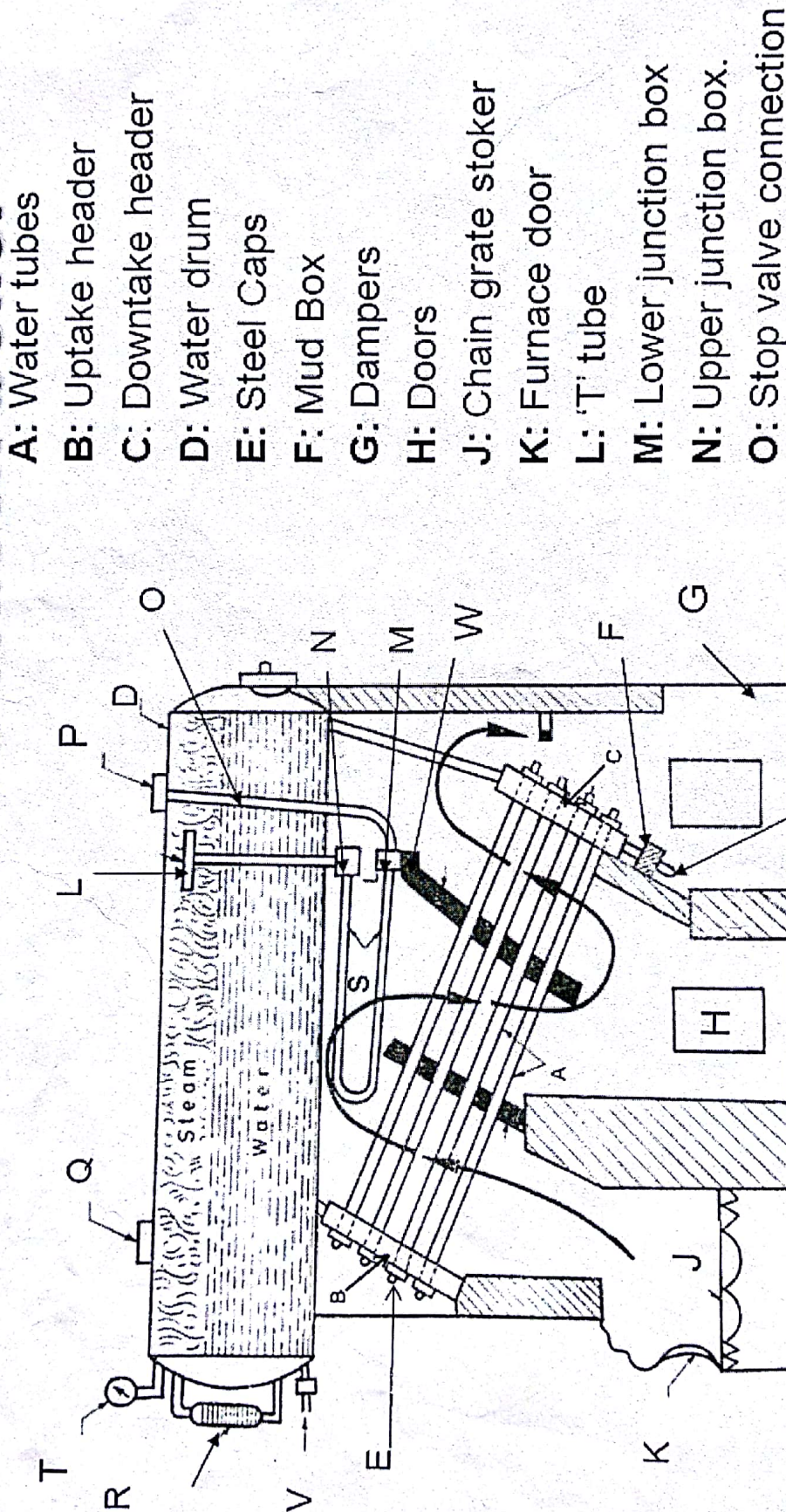


(a) Front view of Lancashire boiler



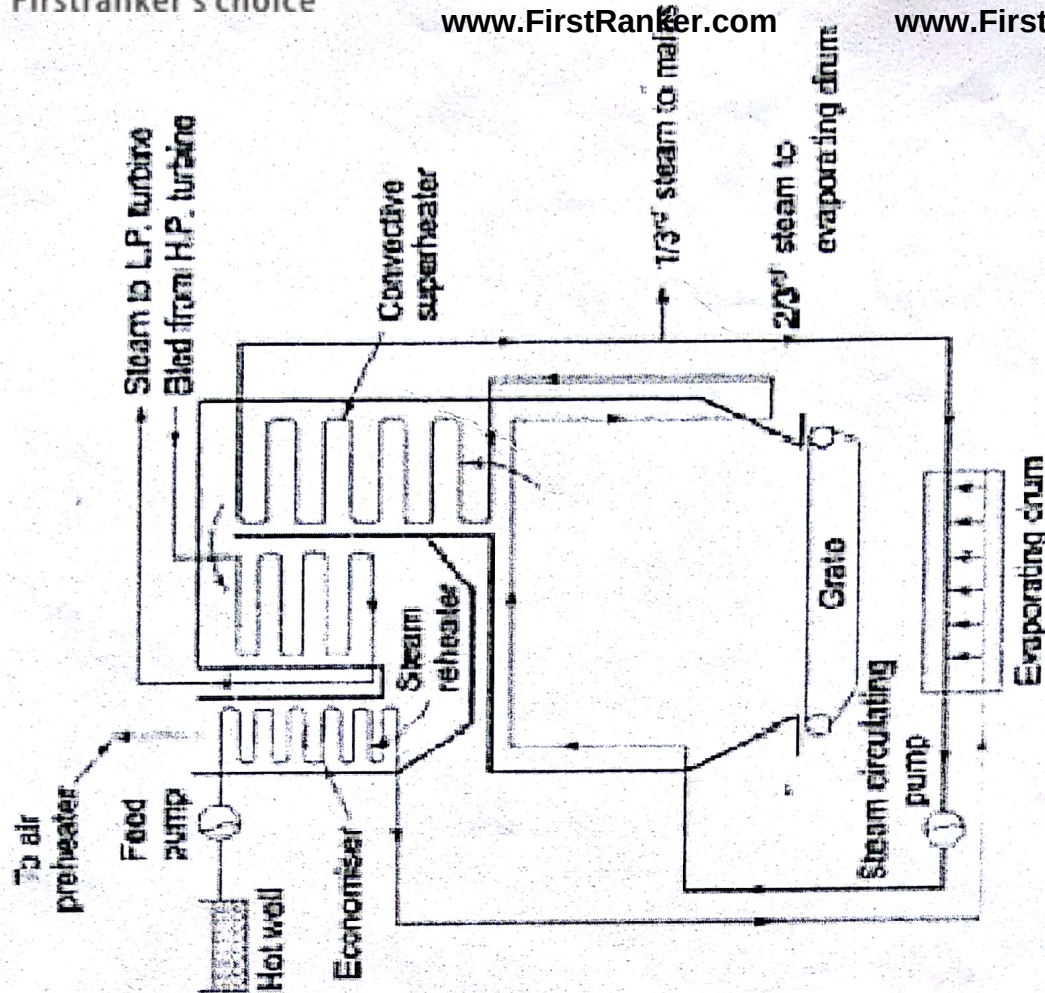
(b) Top view of Lancashire boiler

Babcock and Wilcox boiler

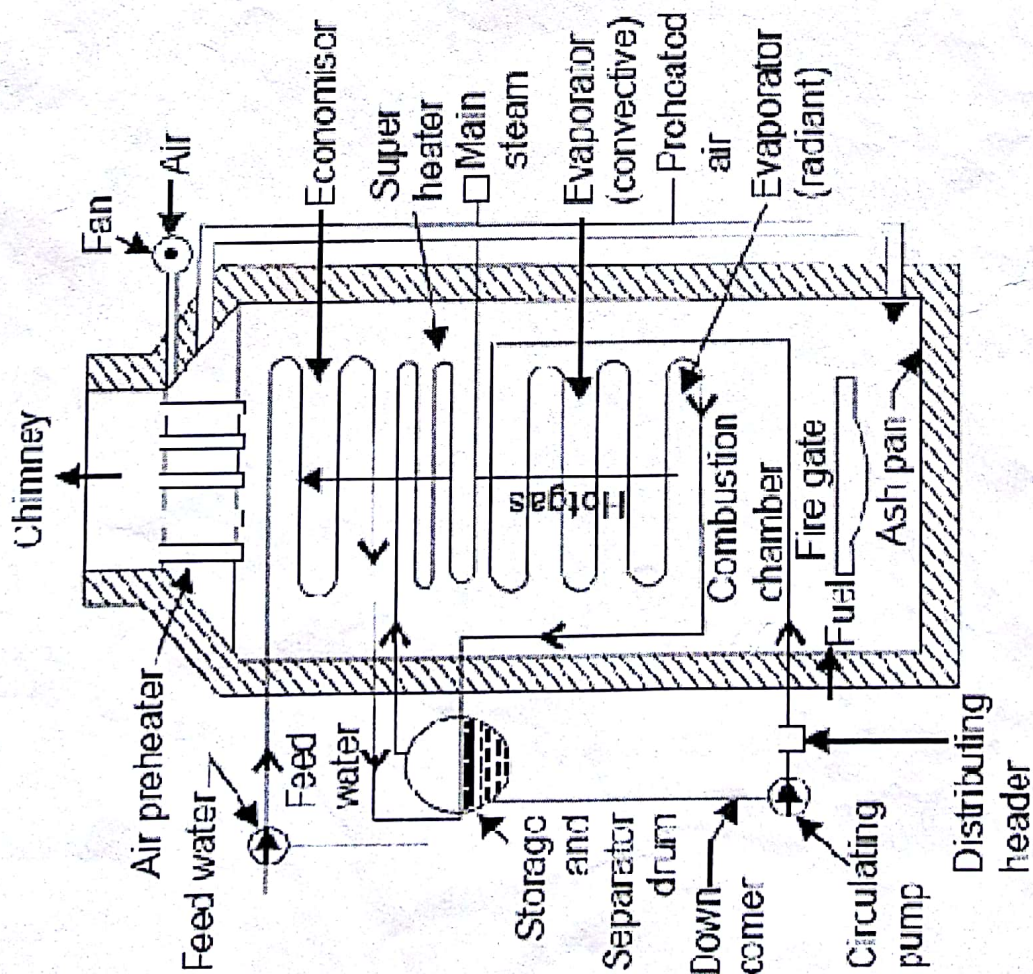


P: Stop valve, **Q:** Safety valve, **R:** Water-level indicator, **S:** Superheater,

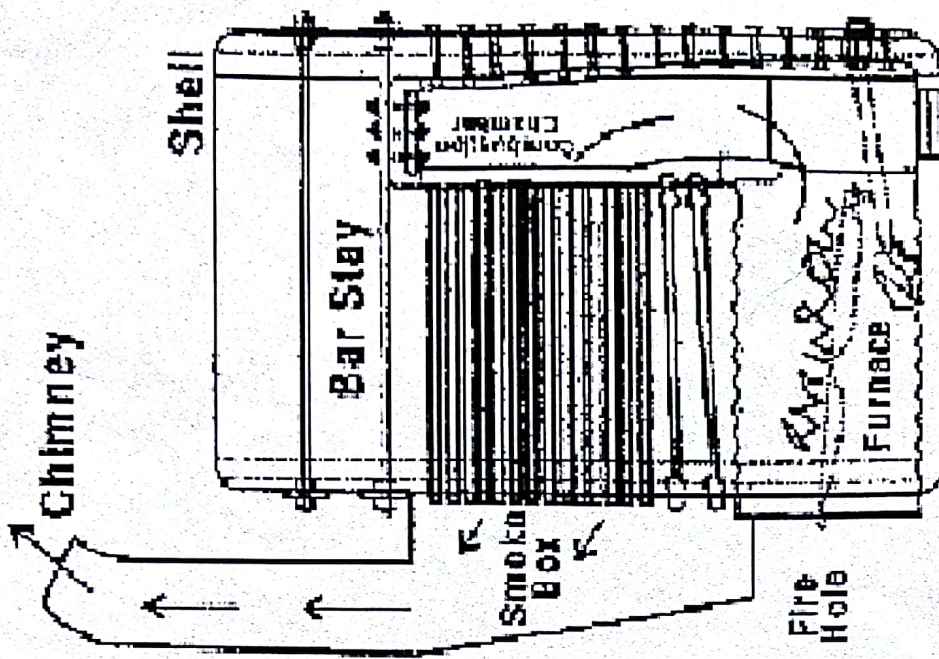
T: Pressure gauge, **V:** Feed check valve, **W:** Baffles, **X:** Blowoff valve



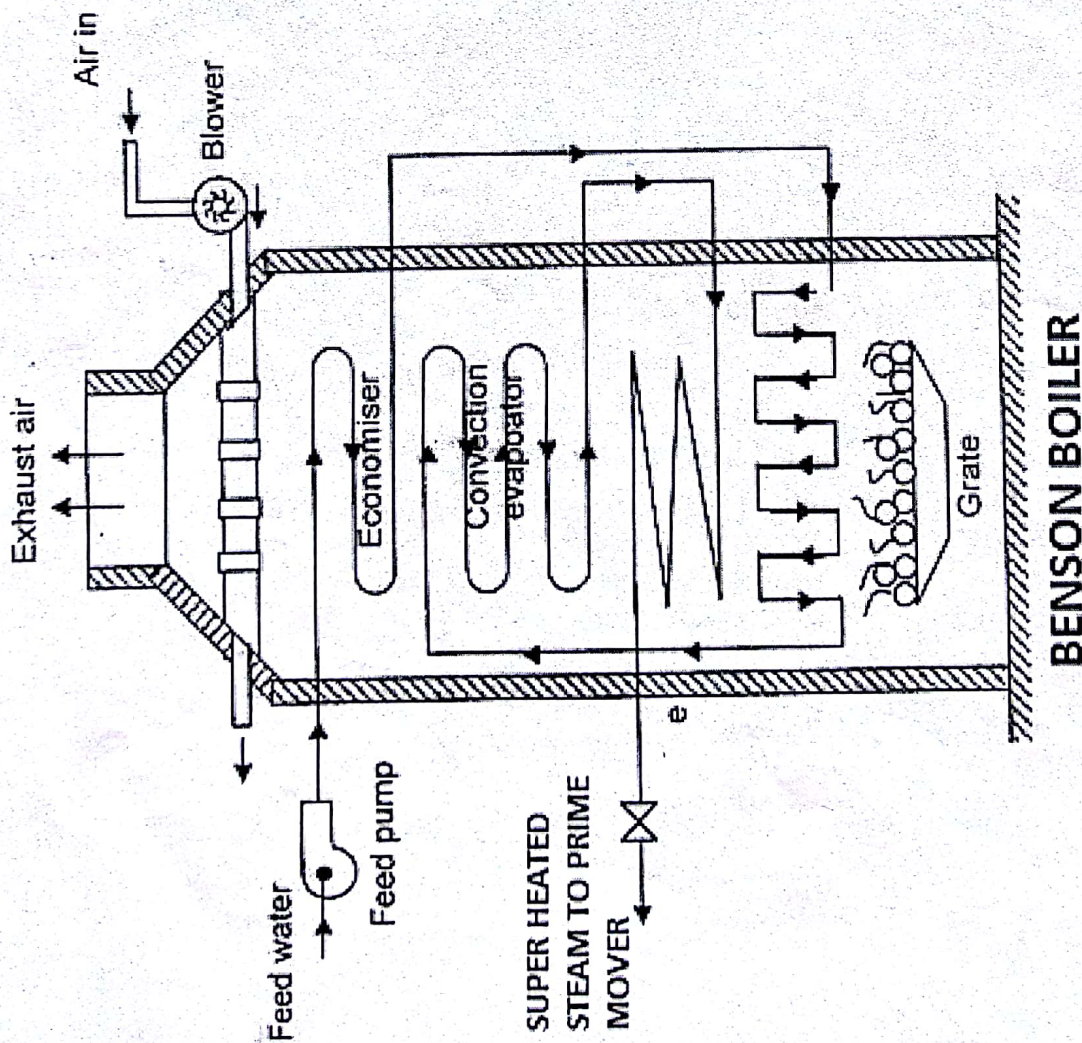
LOEFFLER BOILER



LA-MONT BOILER



SCOTCH MARINE BOILER



BENSON BOILER

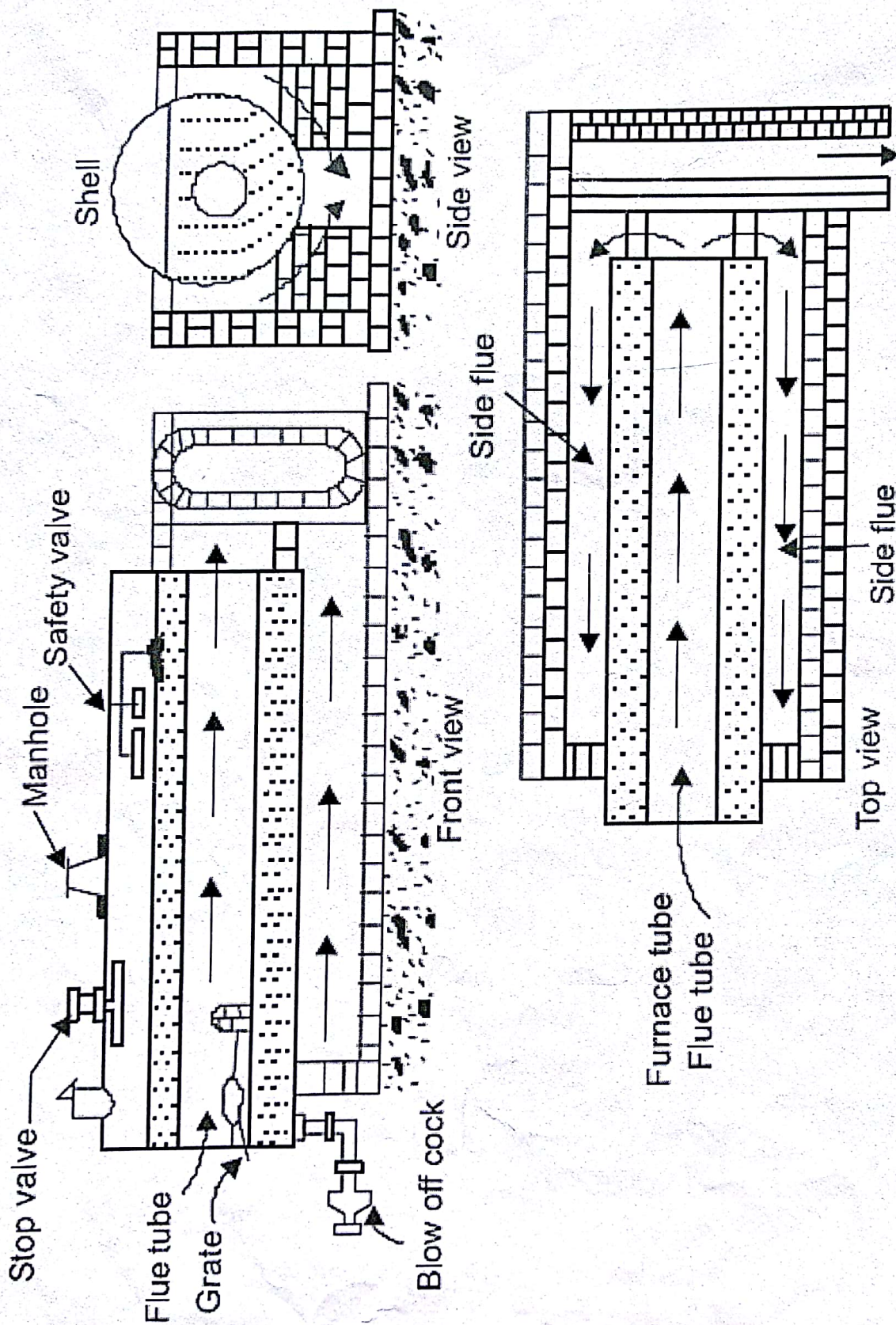
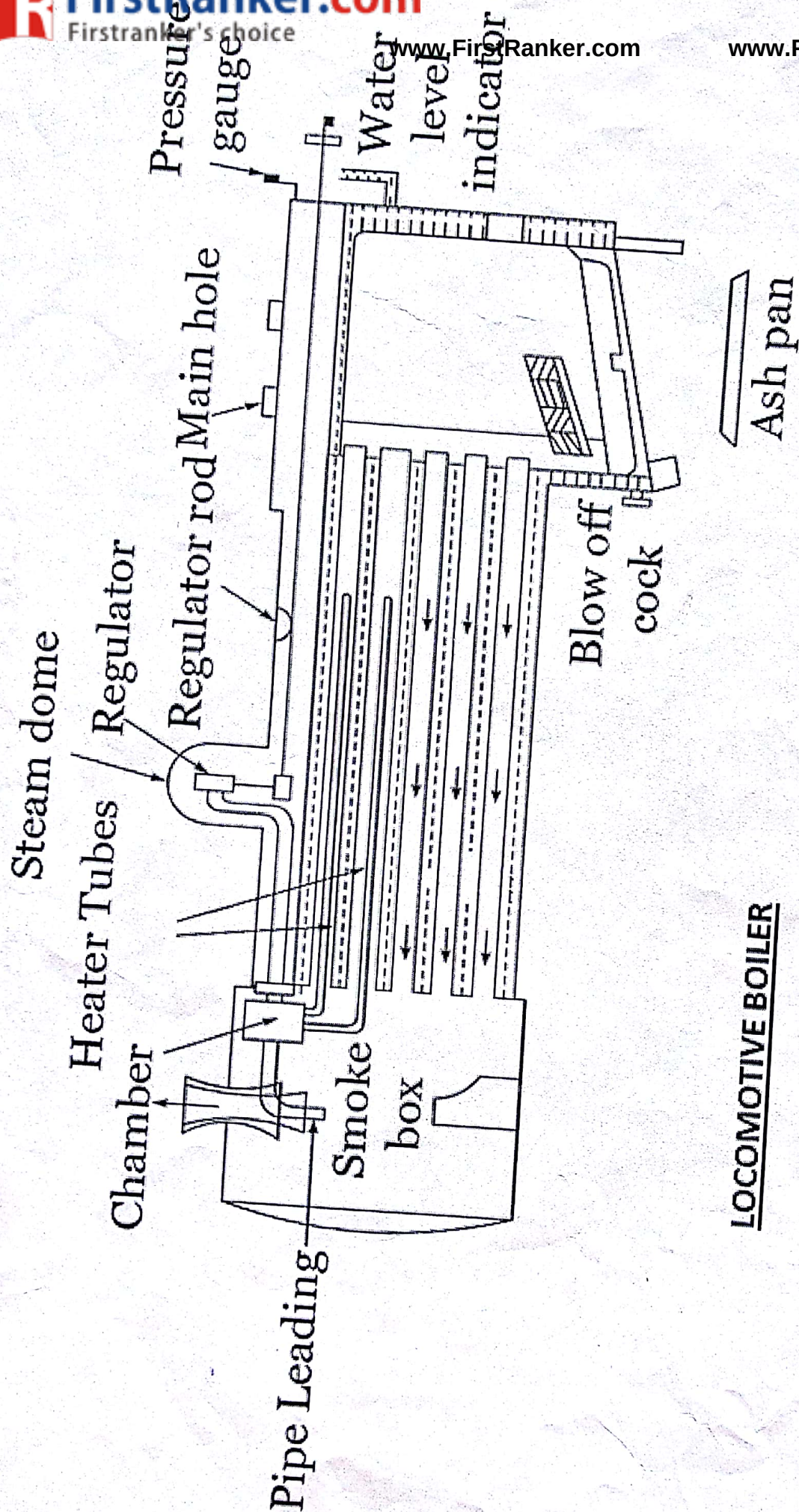
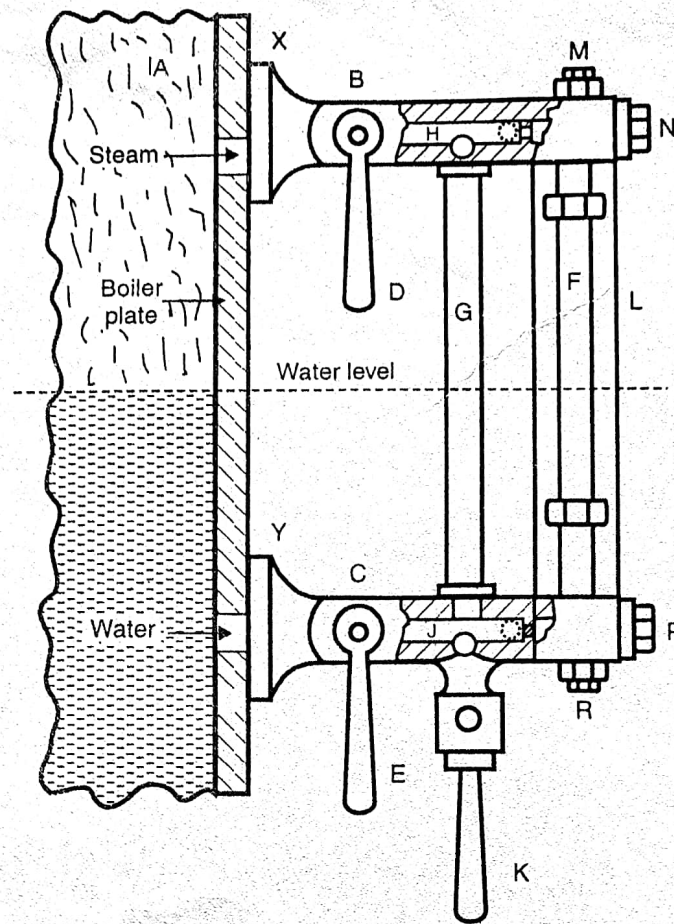


Fig. 11.9 Cornish boiler



LOCOMOTIVE BOILER

BOILER MOUNTINGS



- | | |
|---|-----------------------------------|
| <i>A</i> = End plate of boiler | <i>H</i> and <i>J</i> = Two balls |
| <i>B</i> and <i>C</i> = Hollow gun metal castings | <i>K</i> = Drain cock |
| <i>D</i> and <i>E</i> = Cocks | <i>L</i> = Guard glass |
| <i>F</i> = Gauge glass | <i>M, N, P, R</i> = Screwed caps |
| <i>G</i> = Hollow metal column | <i>X, Y</i> = Flanges |

Fig. 2.1 Water Level Indicator

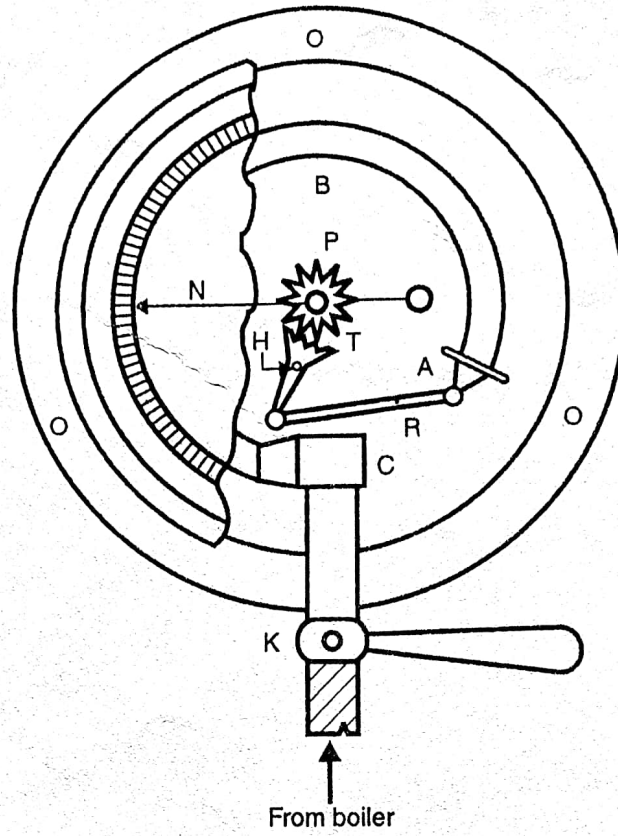


Fig. 2.2 Pressure Gauge

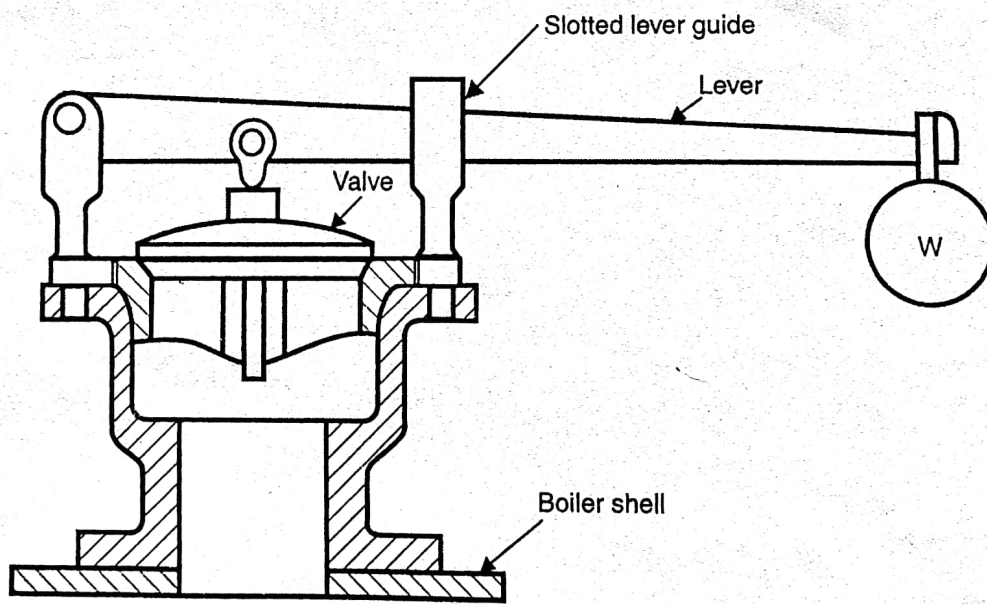
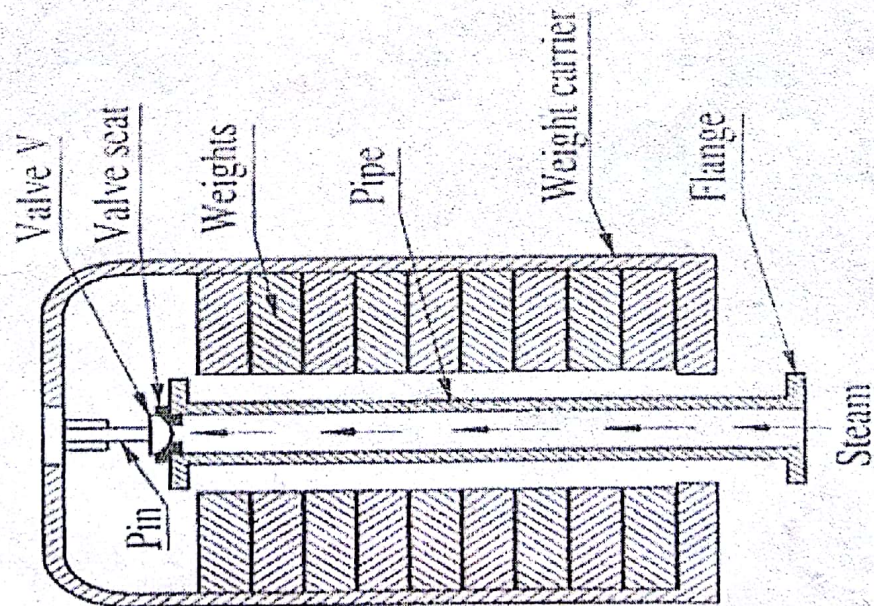
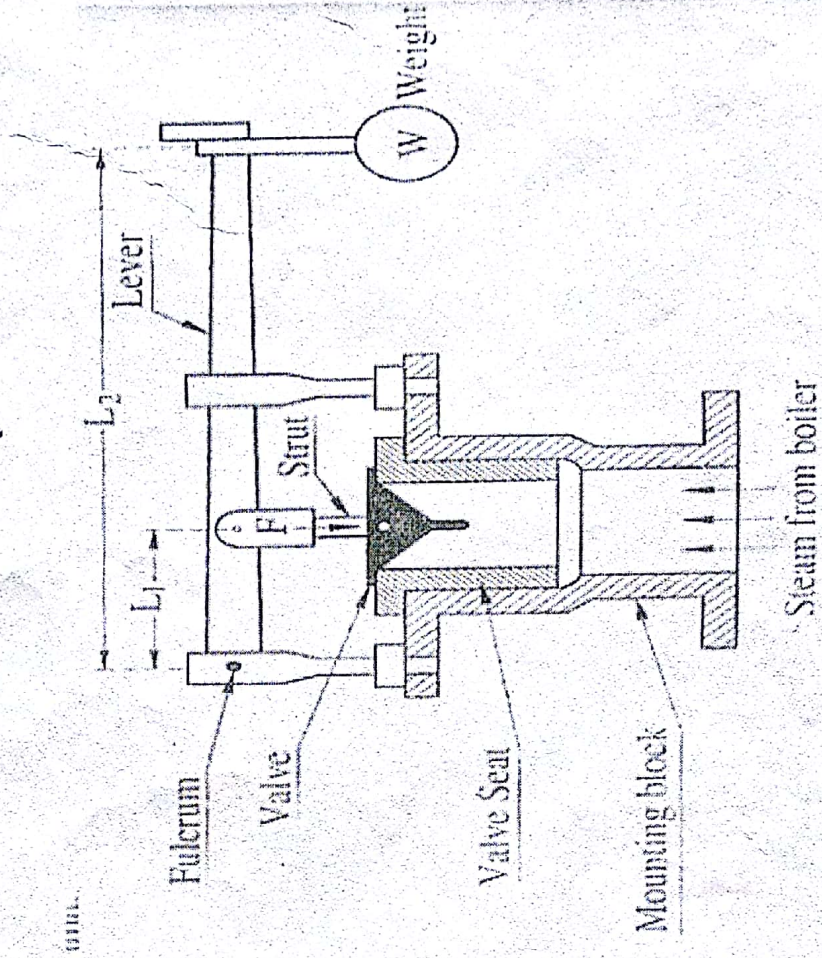


Fig. 2.3 Lever Safety Valve

Dead weight safety valve

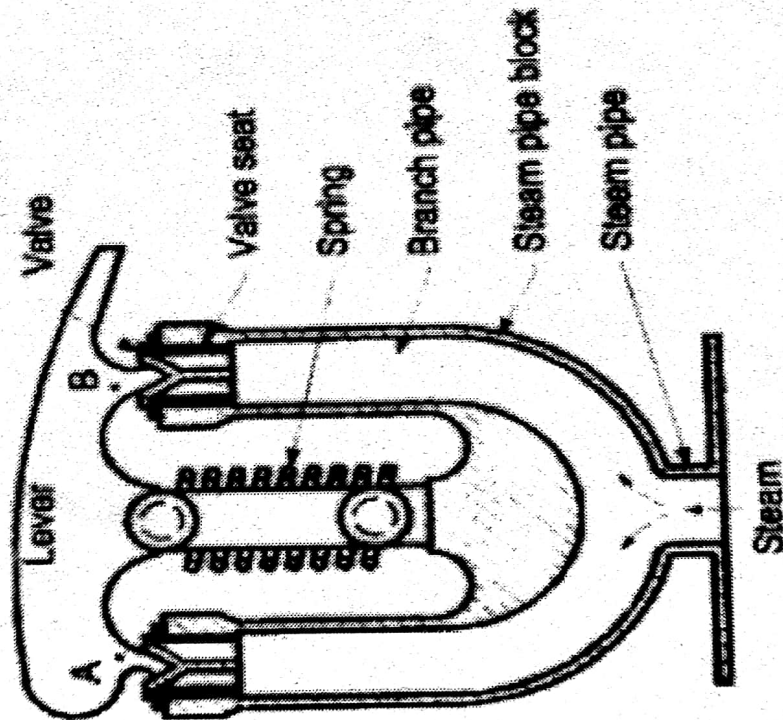


Lever safety valve

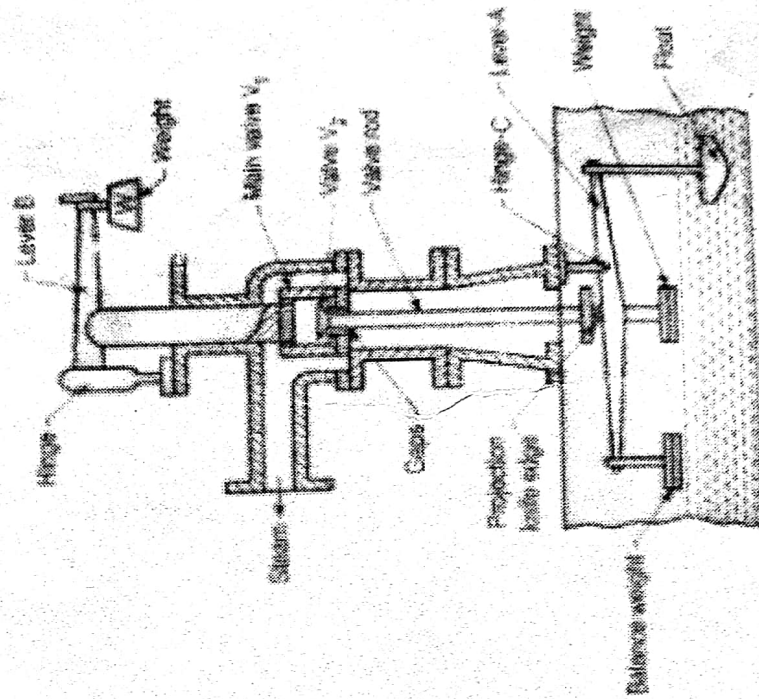


SAFETY VALVES

SPRING LOADED SAFETY VALVE



HIGH STEAM AND LOW WATER SAFETY VALVE



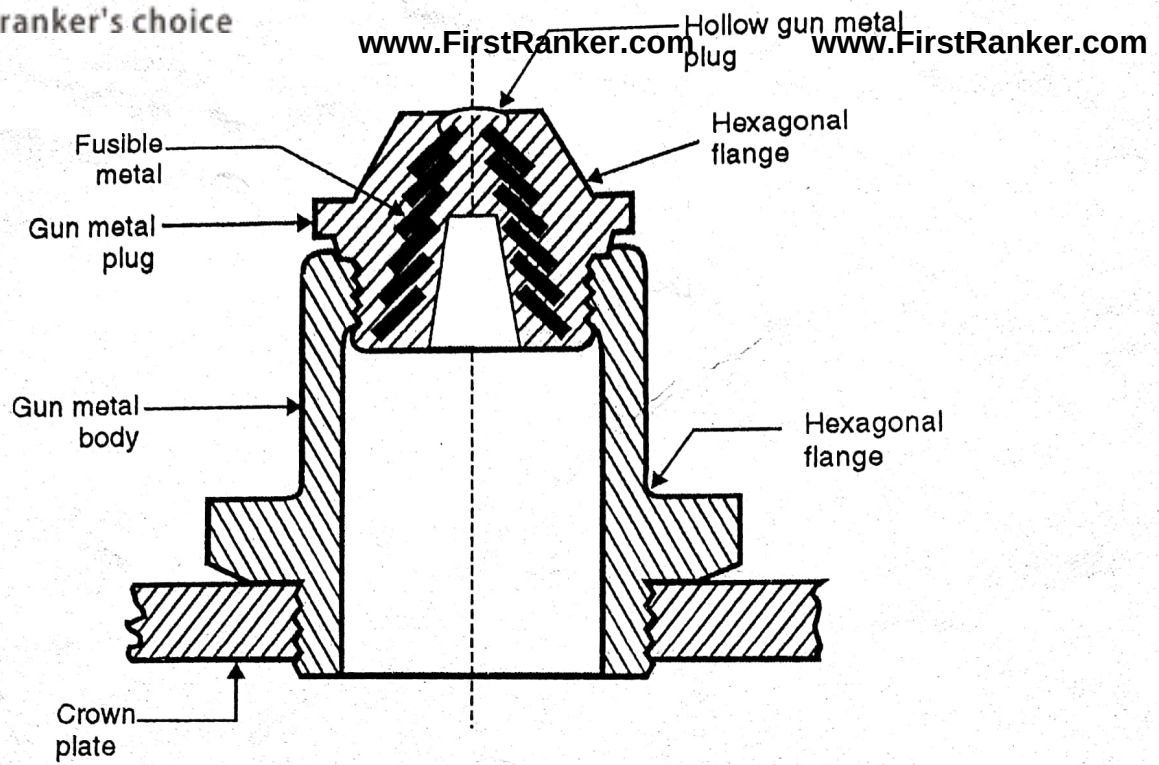


Fig. 2.4 Fusible Plug

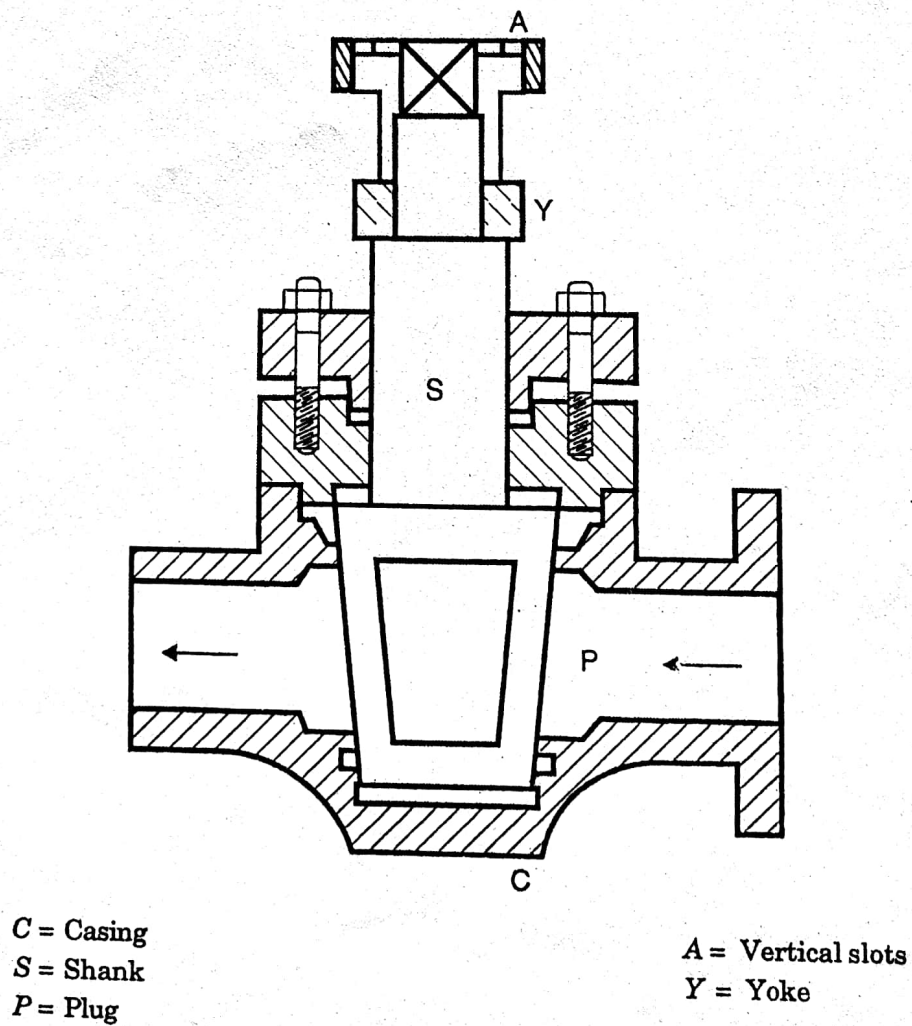
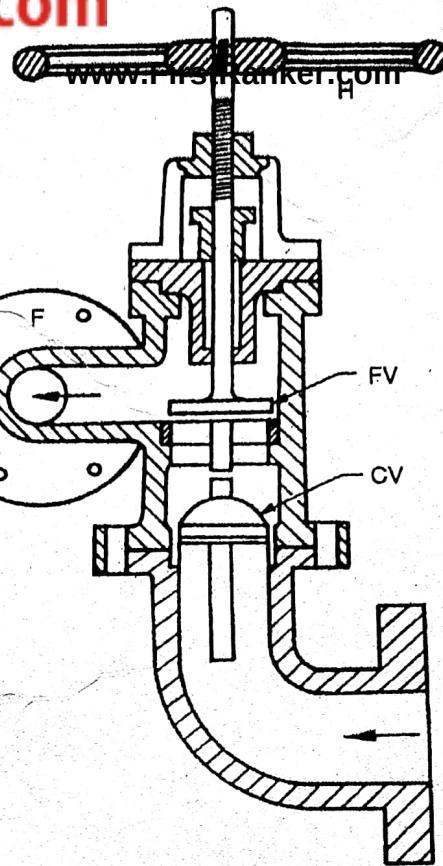


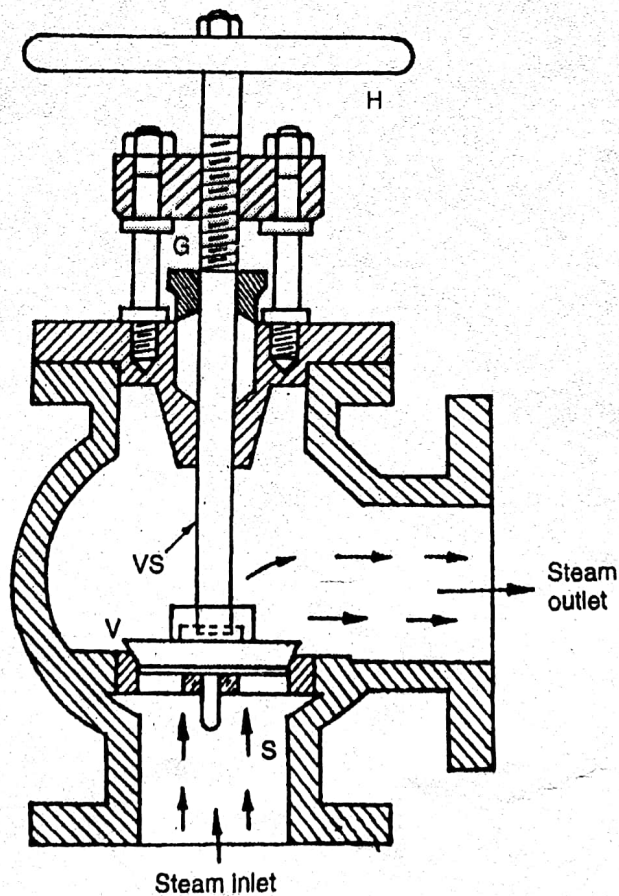
Fig. 2.5 Blow off Cock



FV = Feed check valve
CV = Check valve

F = Flange
H = Hand wheel

Fig. 2.6 Feed Check Valve

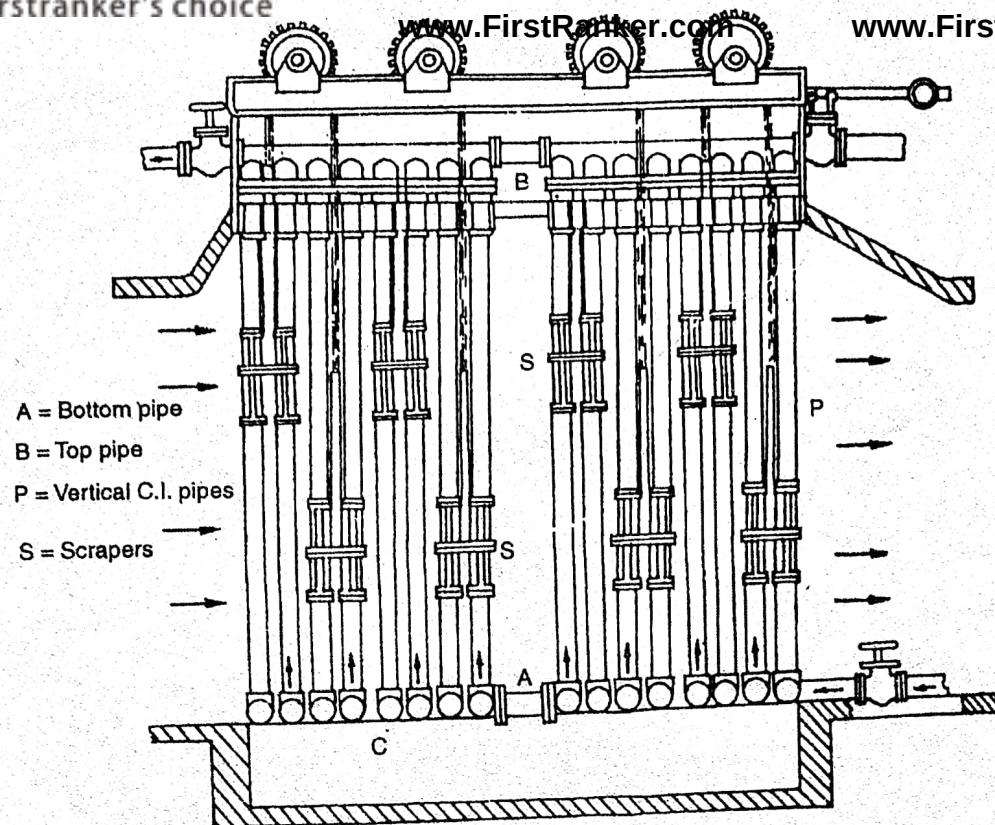


H = Hand wheel
VS = Valve spindle
G = Gland

V = Valve
S = Valve seat

Fig. 2.7 Steam Stop Valve

BOILER ACCESSORIES

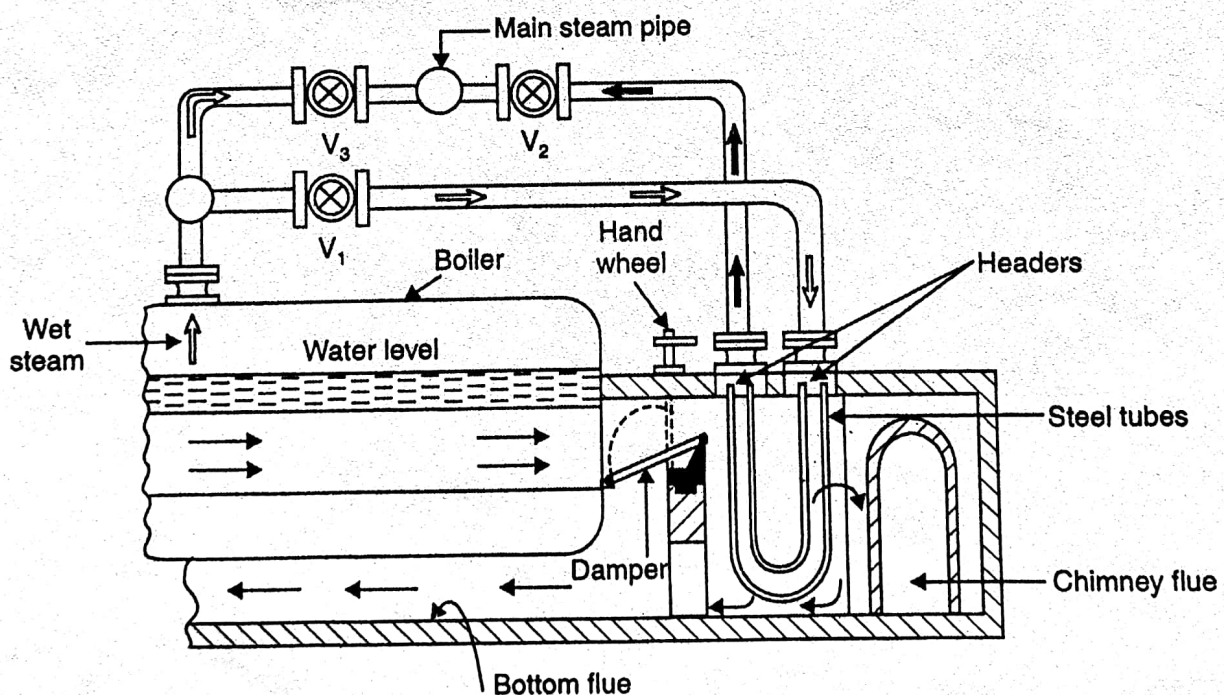


A = Bottom pipe
B = Top pipe
P = Vertical C.I. pipes
S = Scrapers

A = Bottom pipe
B = Top pipe

P = Vertical C. I. pipes
S = Scrapers

Fig. 2.8 Economizer



→ Flue gases
⇒ Wet steam
⇒ Superheated steam

Fig. 2.9 Super Heater

UNIT-III

STEAM NOZZELS

AND STEAM

TURBINES

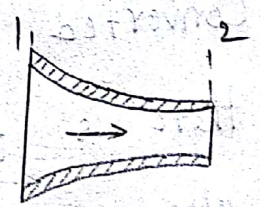
A Steam nozzle is a passage of varying cross-sections which converts heat energy of steam into kinetic energy.

The main use of steam nozzle in steam turbines, is to produce a jet of steam with a high velocity. The smallest section of nozzle is called throat.

Types of steam nozzles!:-

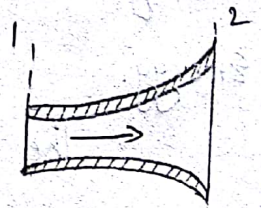
1. Convergent nozzle!:-

When the cross-section of nozzle decreases continuously from entrance to exit, it is called a convergent nozzle.



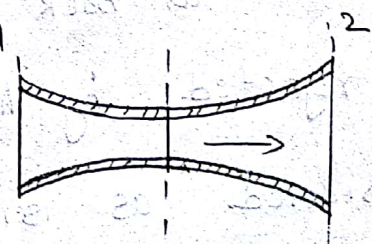
2. Divergent nozzle!:-

When the cross-section of a nozzle increases from entrance to exit, it is called a divergent nozzle.



3. Convergent - Divergent nozzle!:-

When the cross-section of a nozzle first decreases from its entrance to throat, and then increases from its throat to exit, it is called a convergent-divergent nozzle.



This type of nozzle is used these days in

Flow of steam through convergent-divergent nozzle:-

The steam enters the nozzle with a high pressure, but with a negligible velocity. In the converging portion, there is a drop in the steam pressure with a rise in its velocity. There is also a drop in enthalpy or total heat of steam, which is not utilised for external work, but is portion, converted into kinetic energy. In the divergent portion, there is further drop of steam pressure with a rise in velocity and enthalpy drop, which is converted to kinetic energy.

The pressure at which the steam leaves the nozzle, is known as back pressure. More over, there is no heat supplied or rejected by the steam during flow. Therefore, it is considered as isentropic flow, and the corresponding expansion is considered as isentropic expansion.

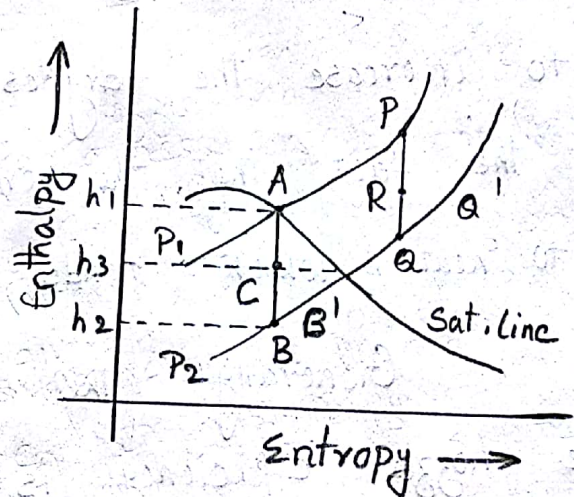
Friction in nozzle or nozzle efficiency:-

When the steam flows through a nozzle, some loss in its enthalpy or total heat takes place due to friction between the nozzle surface and the flowing

steam. This can be best understood with the help of $h-s$ diagram or mollier diagram.

Locate a point A for the initial conditions of the steam. It is a point, when saturation line meets the initial pressure P_1 line.

Draw a vertical line through A to meet the final pressure line. This is done as the flow is isentropic. The heat drop $h_1 - h_2$ is known isentropic heat drop.



Due to friction, the actual heat drop is less than $(h_1 - h_2)$. Let this heat drop be shown as AC.

As the expansion of steam ends at pressure P_2 , therefore final condition of steam is obtained by drawing a horizontal line through C to meet the P_2 line at B'.

Now the actual expansion of heat steam is expressed by the curve AB' (adiabatic expansion) instead of AB (isentropic expansion).

The actual heat drop is known as useful heat drop.

Coefficient of nozzle or nozzle efficiency is defined as the ratio of useful heat drop to the isentropic heat drop.

$$K = \frac{AC}{AB} = \frac{h_1 - h_3}{h_1 - h_2}$$

Note!:-

The dryness fraction of Steam at B' is greater than at B. It is thus obvious, that the effect of friction is to increase the dryness fraction of Steam. This is due to the fact that the energy lost in friction is transferred into heat, which tends to dry or superheat the Steam.

Generally the friction losses are of 15%. So the nozzle efficiency is $= 100 - 15 = 85\%$.

$$= 0.85$$

Velocity of Steam flowing through a nozzle:-

Consider a unit mass flow of Steam through a nozzle.

Let v_1 = Velocity of the Steam at nozzle entrance in m/s

V_2 = Velocity of Steam at any section in m/s

h_1 = Enthalpy of Steam at entering nozzle (kJ/kg)

h_2 = Enthalpy of Steam at section (kJ/kg)

We know that for a Steady flow process in a nozzle,

$$h_1 + \frac{1}{1000} \left[\frac{v_1^2}{2} \right] = h_2 + \frac{1}{1000} \left[\frac{v_2^2}{2} \right] + \text{losses}$$

Neglecting losses;

$$\frac{1}{1000} \left[\frac{v_2^2}{2} - \frac{v_1^2}{2} \right] = h_1 - h_2$$

$$V_2 = \sqrt{v_1^2 + 2000(h_1 - h_2)}$$

h_d = Enthalpy drop during expansion = $h_1 - h_2$

$$\Rightarrow V_2 = \sqrt{v_1^2 + 2000 h_d}$$

$\therefore v_1 \ll v_2$ So v_1 is neglected compared to v_2

$$\Rightarrow V_2 = \sqrt{2000 h_d}$$

$$V_2 = 44.72 \sqrt{h_d}$$

Considering friction losses;

$$V_2 = 44.72 \sqrt{k h_d}$$

When k is nozzle efficiency.

Example 1:-

1. Dry Saturated steam at 10 bar is expanded isentropically in a nozzle to 0.1 bar using steam tables only. find the dryness fraction of the steam at exit. Also find the velocity of steam leaving the nozzle when (i) initial velocity negligible and (ii) initial velocity of steam is 135 m/s

Solution:- Given data

$$P_1 = 10 \text{ bar} ; P_2 = 0.1 \text{ bar}$$

Dryness fraction of steam at exit = x_2

At $P_1 = 10$ bar, using steam tables.

$$S_1 = S_{g1} = 6.583 \text{ kJ/kg.K}$$

at $P_2 = 0.1$ bar

$$S_{f1} = 0.649 \text{ kJ/kg.K}$$

and

$$S_{fg2} = 7.502 \text{ kJ/kg.K}$$

Since the expansion is isentropic, so entropy of steam at inlet (S_1) = entropy at exit (S_2)

$$6.583 = S_{f2} + x_2 S_{fg2}$$

$$6.583 = 0.649 + (x_2 \times 7.502)$$

$$x_2 = 0.791$$

ii) Velocity of steam.

$$\text{at } P_1 = 10 \text{ bar, } h_1 = h_{g1} = 2776.2$$

$$\text{at } P_2 = 0.1 \text{ bar}$$

$$h_{f2} = 191.8 \text{ kJ/kg} \quad \& \quad h_{fg2} = 2392.9$$

$$h_2 = h_{f2} + x_2 h_{fg2}$$

$$= 191.8 + (0.791)(2392.9)$$

$$= 2084.6 \text{ kJ/kg.}$$

$$V_2 = 44.72 \sqrt{h_d}$$

$$h_d = h_1 - h_2 = 691.6 \text{ kJ/kg.}$$

$$V_2 = \sqrt{V_1^2 + 2gh} = \sqrt{135^2 + 2 \times 9.81 \times 691.6}$$

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$$V_2 = 1176 \text{ m/s}$$

(ii)

$$V_2 = \sqrt{V_1^2 + 2gh}$$

$$= \sqrt{135^2 + 2 \times 9.81 \times 691.6}$$

$$V_2 = 1184 \text{ m/s}$$

Mass of Steam discharged through Nozzle -

The flow through nozzle is isentropic

$$P V^n = \text{Constant}$$

$$\text{Gain in kinetic energy} = \frac{V_2^2}{2} \quad (\because V_1 \ll V_2)$$

Heat drop = Work done during Rankine cycle

$$= \frac{n}{n-1} (P_1 V_1 - P_2 V_2)$$

Gain in kinetic energy is equal to heat drop.

$$\frac{V_2^2}{2} = \frac{n}{n-1} [P_1 V_1 - P_2 V_2]$$

$$= \frac{n}{n-1} (P_1 V_1) \left[1 - \frac{P_2 V_2}{P_1 V_1} \right] \rightarrow (1)$$

$$\therefore P_1 V_1^n = P_2 V_2^n \rightarrow (2)$$

$$\Rightarrow V_2 = V_1 \left[\frac{P_2}{P_1} \right]^{-1/n}$$

$$\Rightarrow \frac{V_2^2}{2} = \frac{n}{n-1} \times P_1 V_1 \left[1 - \frac{P_2}{P_1} \cdot \left(\frac{P_2}{P_1} \right)^{-1/n} \right]$$

$$= \frac{n}{n-1} \times P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]$$

$$\Rightarrow v_2 = \sqrt{2 \times \frac{n}{n-1} \times P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]}$$

Volume of Steam flowing per second = Cross sectional Area $\times$ velocity of Steam

$$= A v_2$$

Volume of 1kg of Steam i.e; specific volume of Steam at pressure $P_2 = v_2 \text{ m}^3/\text{kg}$.

Mass of Steam, $m = \frac{\text{Volume of Steam flowing per second}}{\text{volume of 1kg of Steam at } P_2}$

$$m = \frac{A v_2}{v_2} = \frac{A}{v_2} \sqrt{2 \times \frac{n}{n-1} \times P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]}$$

from (2) equation.

$$m = \frac{A}{v_1} \left[\frac{P_2}{P_1} \right]^{1/n} \sqrt{\frac{2n}{n-1} \times P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]}$$

$$m = A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{P_2}{P_1} \right)^{2/n} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]}$$

$$m = A \sqrt{\frac{2n}{n-1} \times \frac{A}{v_1} \left[\left(\frac{P_2}{P_1} \right)^{2/n} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]}$$

Condition for maximum discharge through a nozzle:

P_1 = initial pressure of Steam, N/m^2

P_2 = Pressure of Steam at throat, N/m^2

V_1 = volume of steam at (P_1)

V_2 = volume of 1kg of steam at (P_2) , m^3

A = Cross - Sectional area of nozzle at throat, m^2

$$m = A \sqrt{\frac{2\eta}{n-1} \times \frac{P_1}{V_1} \left[\left(\frac{P_2}{P_1} \right)^{2/\eta} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right]}$$

By differentiating with respect to P_2/P_1 and considering remaining terms as constants.

$$\frac{d}{d(P_2/P_1)} \left[\left(\frac{P_2}{P_1} \right)^{2/\eta} - \left(\frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right] = 0$$

$$\Rightarrow \frac{2}{\eta} \left[\frac{P_2}{P_1} \right]^{\frac{2}{\eta}-1} - \frac{n+1}{n} \left[\frac{P_2}{P_1} \right]^{\frac{n+1}{n}-1} = 0$$

$$\frac{2}{\eta} \left[\frac{P_2}{P_1} \right]^{\frac{2-\eta}{\eta}} = \frac{n+1}{n} \left[\frac{P_2}{P_1} \right]^{1/n}$$

$$\left(\frac{P_2}{P_1} \right)^{\frac{2-\eta}{\eta}} \cdot \left(\frac{P_2}{P_1} \right)^{-1/n} = \frac{n+1}{n} \times \frac{n}{2}$$

$$\left(\frac{P_2}{P_1} \right)^{\frac{1-\eta}{\eta}} = \frac{n+1}{2}$$

$$\frac{P_2}{P_1} = \left(\frac{n+1}{2} \right)^{\frac{-\eta}{n-1}}$$

$$\frac{P_2}{P_1} = \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}}$$

The ratio P_2/P_1 is known as critical pressure ratio and the pressure P_2 at the throat is known as critical pressure.

Substituting

P_2/P_1

m

$$\Rightarrow m_{\max} = A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1} \right)^{\frac{n+1}{n-1}} \right]}$$

$$= A \sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1} \left[\left(\frac{2}{n+1} \right)^{\frac{2}{n-1}} \right] \left[1 - \frac{2}{n+1} \right]}$$

$$m_{\max} = A \sqrt{\frac{2n}{n+1} \cdot \frac{P_1}{v_1} \cdot \left(\frac{2}{n+1} \right)^{\frac{2}{n-1}}}$$

So the discharge depends up on the area of the throat and initial conditions and independent of the exit conditions of the steam.

This is true for gases also.

Values for maximum discharge through a nozzle:

When steam is initially dry saturated

$$n = 1.135$$

$$\Rightarrow m_{\max} = 0.637 \cdot A \cdot \sqrt{P_1/v_1}$$

When the steam is initially superheated

$$n = 1.3$$

$$\Rightarrow m_{\max} = 0.666 A \sqrt{P_1/v_1}$$

for gases $n = 1.4$

$$\Rightarrow m_{\max} = 0.685 A \sqrt{P_1/v_1}$$

Values for critical Pressure Ratio.

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$$P_2 / P_1 = \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}}$$

When Steam is initially Saturated, $n = 1.135$

$$\frac{P_2}{P_1} = \left(\frac{2}{1.135+1} \right)^{\frac{1.135}{1.135-1}} = 0.577$$

$$\frac{P_2}{P_1} = 0.577 \quad \text{or}$$

$$P_2 = 0.577 P_1$$

When Steam is initially Superheated, $n = 1.3$

$$\frac{P_2}{P_1} = 0.546 \quad \text{or} \quad P_2 = 0.546 P_1$$

When the Steam is initially wet

It has been experimentally found that

$$P_2 / P_1 = 0.582$$

for Gases, $n = 1.4$

$$P_2 / P_1 = 0.528 \quad \text{or} \quad P_2 = 0.528 P_1$$

Physical Significance of Critical Pressure Ratio.

Consider two vessels A and B Connected by a Convergent nozzle. Let Vessel A Contains Steam at a high Pressure and Steady pressure (P_1) and vessel B Contains Steam at another pressure (P_2)

Let pressure P_1 in the vessel B be made equal to the pressure (P_2) in the vessel A. In this case, there will be flow of steam through nozzle. Now if pressure P_2 in vessel B is gradually reduced, the discharge through nozzle will increase. As P_2 approaches the critical value, the rate of discharge will also approach its maximum value. If P_2 further reduced it will not increase rate of discharge.

We know that,

$$V_2 = \sqrt{\frac{2n}{n-1} \times P_1 V_1 \left(1 - \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right)} \rightarrow (1)$$

and the critical pressure ratio for max. discharge

$$\frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \quad (\text{or})$$

$$\left(\frac{P_2}{P_1}\right)^{\frac{n}{n-1}} = \frac{2}{n+1}$$

Substituting in (1)

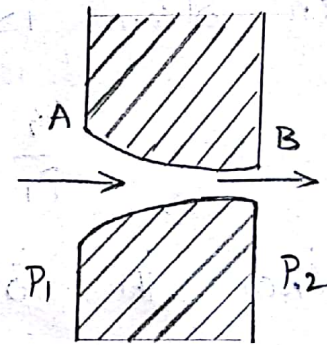
$$V_2 = \sqrt{\frac{2n}{n-1} P_1 V_1 \left[1 - \frac{2}{n+1}\right]}$$

$$V_2 = \sqrt{\frac{2n}{n+1} \cdot \frac{P_1}{\rho_1}}$$

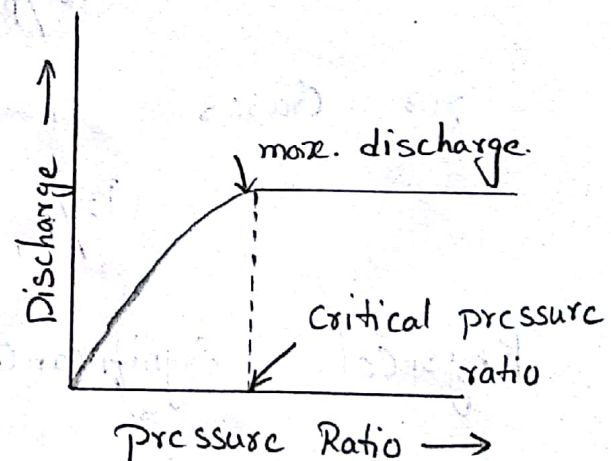
$$\left[\because \text{Volume} = \frac{1}{\text{Density}}\right]$$

We also know that,

$$P_1 V_1^n = P_2 V_2^n$$



Nozzle section



$$\begin{aligned} \frac{P_1}{\rho_1^n} &= \frac{P_2}{\rho_2^n} \\ \Rightarrow \frac{1}{\rho_1} &= \frac{1}{\rho_2} \left[\frac{P_2}{P_1} \right]^{1/n} \\ \frac{P_1}{\rho_1} &= \frac{P_1}{\rho_2} \left[\frac{P_2}{P_1} \right]^{1/n} \\ &= \frac{P_2}{\rho_2} \times \left[\frac{P_1}{\rho_2} \right] \left[\frac{P_2}{P_1} \right]^{1/n} \\ &= \left(\frac{P_2}{\rho_2} \right) \left(\frac{P_2}{P_1} \right)^{\frac{1-n}{n}} \\ &= \left(P_2 / \rho_2 \right) \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}} \times \frac{1-n}{n} \\ P_1 / \rho_1 &= \left(P_2 / \rho_2 \right) \left(\frac{n+1}{2} \right) \\ \hline V_2 &= \sqrt{2 \left(\frac{n}{n+1} \right) \frac{P_2}{\rho_2} \left(\frac{n+1}{2} \right)} \\ V_2 &= \sqrt{\gamma \cdot P_2 / \rho_2} \end{aligned}$$

This is the value of velocity of sound in the medium at pressure P_2 and is known as Sonic velocity.

- Notes:-
1. The critical pressure gives the velocity of steam at the throat equal to velocity of sound
 2. The flow in the convergent portion of the nozzle is sub-sonic and in the divergent portion it is super sonic.
 3. To increase the velocity of steam above sonic velocity (supersonic) by expanding steam below the critical pressure, the divergent portion for the nozzle is necessary.

Diameters of throat and exit for maximum discharge :-

Consider Convergent - divergent nozzle

Let

P_1 = Initial pressure of steam

h_1 = Enthalpy of steam at inlet

P_2, P_3

h_2, h_3 = Corresponding values at throat & outlet

x_2 = dryness fraction at throat

V_2 = velocity of steam at throat

v_{g2} = Specific volume of steam at

throat corresponding to pressure P_2
(from steam tables)

A_2 = Area of throat

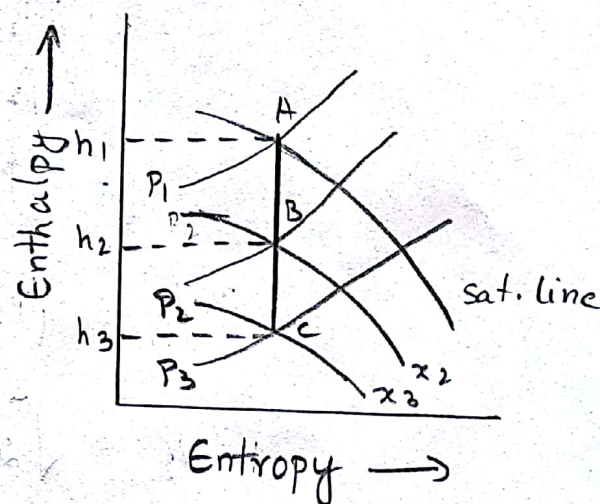
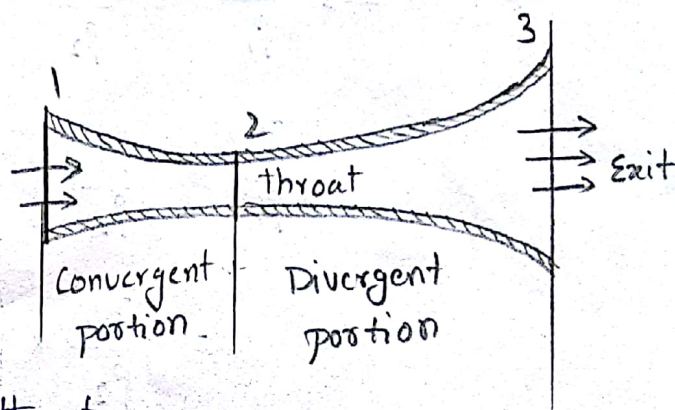
x_2, v_3, v_{g3}, A_3 = Corresponding values at exit,

m = mass of steam discharged.

Locate a point A for initial conditions of steam.

It is the point where the saturation line meets the initial pressure (P_1) line. Now draw a vertical line through point A to meet the critical pressure line P_2 at B and outlet pressure line at (C) P_3 .

Now find the values of h_1, h_2, h_3, x_2 and x_3 from



Consider the flow from inlet to throat,

$$\text{Enthalpy or heat drop} = h_{d2} = h_1 - h_2$$

$$\text{Velocity of Steam at throat} = v_2 = 44.72 \sqrt{h_{d2}}$$

mass of Steam discharged per second = m

$$m = \frac{\text{volume of Steam flowing at throat}}{\text{volume of 1kg of Steam at } P_2}$$

$$m = \frac{A_2 v_2}{v_2} = \frac{A_2 v_2}{x_2 v_{g2}} \quad [\because v_2 = x_2 v_{g2}]$$

Similar for exit conditions.

$$m = \frac{A_3 v_3}{x_3 v_{g3}}$$

Supersaturated flow or Metastable flow through nozzle:-

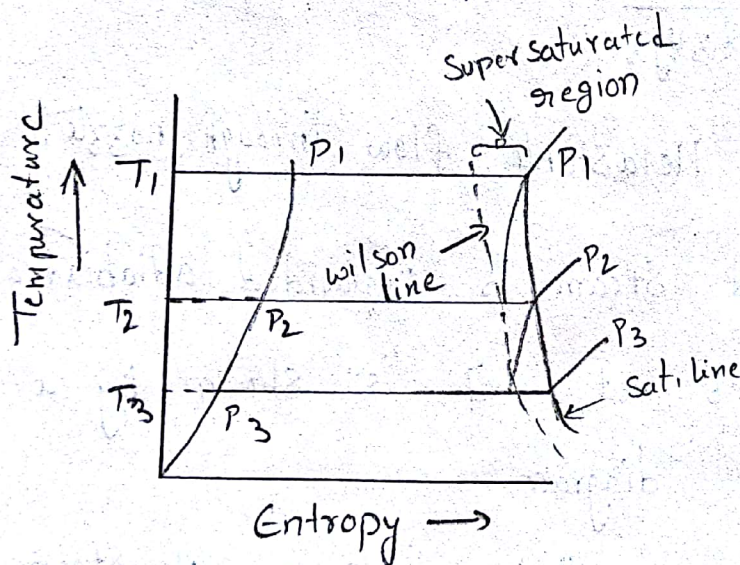
When dry saturated steam is expanded adiabatically or isentropically, it becomes wet and is shown by a vertical line on mollier diagram.

We have discussed that expansion of steam in an ideal nozzle is isentropic, which is accompanied by condensation process. If the steam is initially superheated, the condensation should start after it had become dry saturated. This is possible when the steam is processed through some distance in the nozzle and

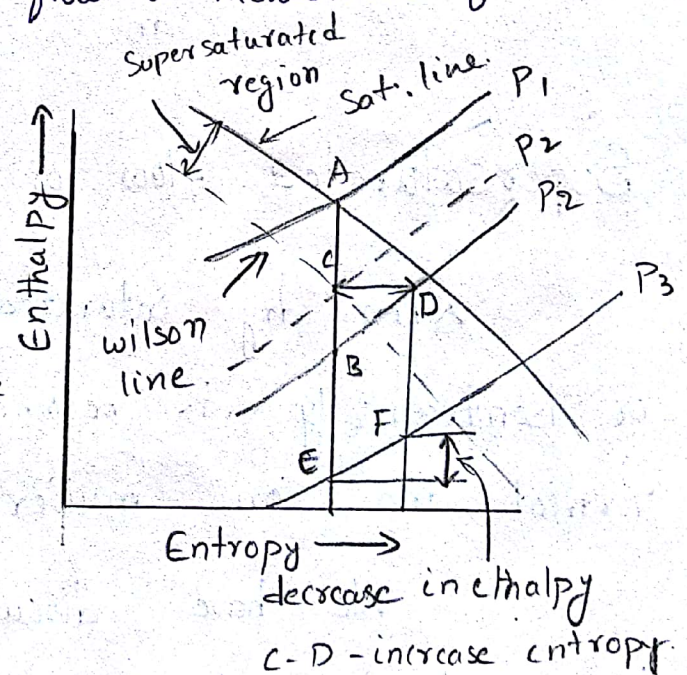
in a short interval of time. But in practice view, the

Steam has a great velocity. Thus the phenomenon of Condensation does not take place at the expected rate. As a result of this, equilibrium between the liquid and vapor phase is delayed and the steam continues to expand in a dry state.

The steam is such a set of conditions, is said to be Super Saturated or in metastable state. It is also called Super cooled steam, as its temperature at any pressure is less than the saturation temperature corresponding that pressure. The flow of super saturated steam, through the nozzle is called Super saturated flow or metastable flow.



(a) T-S diagram



(b) h-s diagram

Experiments of Super saturated flow of steam have shown that there is a limit to which the super saturated flow is possible. This limit is represented by Wilson line on T-S and h-s diagrams respectively. It may be

fraction line. beyond this wilson line, there is no supersaturation. The steam suddenly condenses and restores its normal equilibrium state.

h-s diagram is shown the isentropic expansion of steam in a nozzle. The point A represents the position of initial dry saturated steam at pressure P_1 . The line AC represents the isentropic expansion of steam in supersaturated region. The metastable state (point C) is obtained by drawing a vertical line through A to meet the wilson line. At C, the steam condenses suddenly. The line CD represents the condensation of steam at constant enthalpy. The point D is obtained by drawing horizontal line through C to meet the throat pressure (P_2) of the nozzle. The line DE represents the isentropic expansion of steam in divergent portion.

Notes:- 1. The same theory is applicable, if the steam is initially superheated.
2. The difference of super saturated temperature and saturation temperature at that pressure is known as degree of under cooling. Mathematically, degree of under cooling is

$$\text{Degree of under cooling} = T_2 - T_2'$$

3. The ratio of pressure corresponding to temperatures

known as degree of super saturation.

$$= \frac{\text{Pressure corresponding to } T_2}{\text{Pressure corresponding to } T_2'}$$

$$\text{degree of Super saturation} = P_2 / P_2'$$

4. On Super saturated flow, some relations are.

$$i, \quad v = \frac{0.0023 (h - 1943)}{P}$$

$$ii, \quad P v^{1.3} = \text{Constant}$$

$$iii, \quad P / T^{1.313} = \text{Constant} \Rightarrow \boxed{P / T^{1.313} = \text{Const}}$$

Effect of Super saturation:-

1. Since the Condensation doesnot take place during Super saturated expansion, so the temperature, at which the Super saturation occurs will be less than that Saturation temperature corresponding to pressure.

So the density of Steam will be more than for the equilibrium conditions, which gives the increases in mass of Steam discharged.

2. The Super saturation increases the entropy and Specific volume of Steam.

3. The Super saturation reduces the heat drop that for thermal equilibrium. Hence the exit velocity of steam is reduced.

4. The Supersaturation increases dryness fraction of Steam.

Problem! The dry saturated steam is expanded in a nozzle from pressure of 10 bar to a pressure of 5 bar. If the expansion is supersaturated, find 1. degree of under cooling 2. degree of Super saturation.

Sol! Given data

$$P_1 = 10 \text{ bar}$$

$$P_2 = 5 \text{ bar}$$

$$T_1 = 179.9^\circ\text{C} = 452.9 \text{ K} \quad \text{from steam tables}$$

T_2' = Temperature at which supersaturation occurs

$$P_1/T_1^{13/3} = \frac{P_2}{(T_2')^{13/3}} \Rightarrow T_2' = T_1 \left(P_2/P_1 \right)^{3/13} = 0.852 T_1$$

$$T_2' = 385.9 \text{ K} = 112.9^\circ\text{C}$$

$$T_2 = 151.9^\circ\text{C}$$

$$\text{degree of under cooling} = T_2' - T_2$$

$$= 39^{\circ}\text{C}$$

$$P_2' = 1.584 \text{ bar} \quad \text{from steam tables}$$

Degree of supersaturation

$$\frac{P_2}{P_2'} = 3.16$$

In a Steam turbine the force exerted on the blades is due to the velocity of Steam. This is due to the fact that the curved blades by changing the direction of Steam receive a force or impulse. The action of Steam in this case is said to be dynamic. In general, a Steam turbine, essentially, consists of.

1. The nozzle in which heat energy of high pressure Steam is converted into kinetic energy.

2. The blades which change the direction of Steam issuing from the nozzle, so that a force acts on the blades due to change of momentum and propel them.

Advantages of Steam turbines over Reciprocating Steam Engines:-

1. A Steam turbine may develop higher speeds and a greater Steam range is possible.
2. The efficiency of Steam turbine is higher.
3. The Steam Consumption is less.
4. Since all the moving parts are enclosed in a casing, the Steam turbine is comparatively safe.
5. A Steam turbine requires less space and lighter foundations, as there are little vibrations.

7. The applied torque is more uniform to the driven shaft.
8. A Steam turbine requires less attention during running more over, the repair costs are generally less.

Classification of Steam turbine.

1. According to mode of Steam action.
 - i, Impulse turbine
 - ii, Reaction Turbine
2. According to direction of Steam flow.
 - i, Axial flow turbine
 - ii, Radial flow turbine.
3. According to the exhaust condition of the Steam.
 - i, Condensing turbine
 - ii, Non-Condensing turbine.
4. According to pressure of Steam.
 - i, High pressure turbine
 - ii, Medium pressure turbine
 - iii, Low pressure turbine.
5. According to no. of Stages.
 - i, Single Stage turbine
 - ii, Multi Stage turbine.

Note: The first impulse turbine was devised by Giovanni Branca in 1629

Named after the Swedish engineer De-laval,
who devised this turbine in 1881

A de-level turbine is the simplest type of impulse steam turbine; and is commonly used. It has the following main components.

1. Nozzle:- It is a circular guide mechanism, which guides the steam to flow at the designed direction and velocity. It also regulates the flow of the steam. The nozzle is kept very close to the blades, in order to minimise the losses due to windage.

2. Runner and blades:-

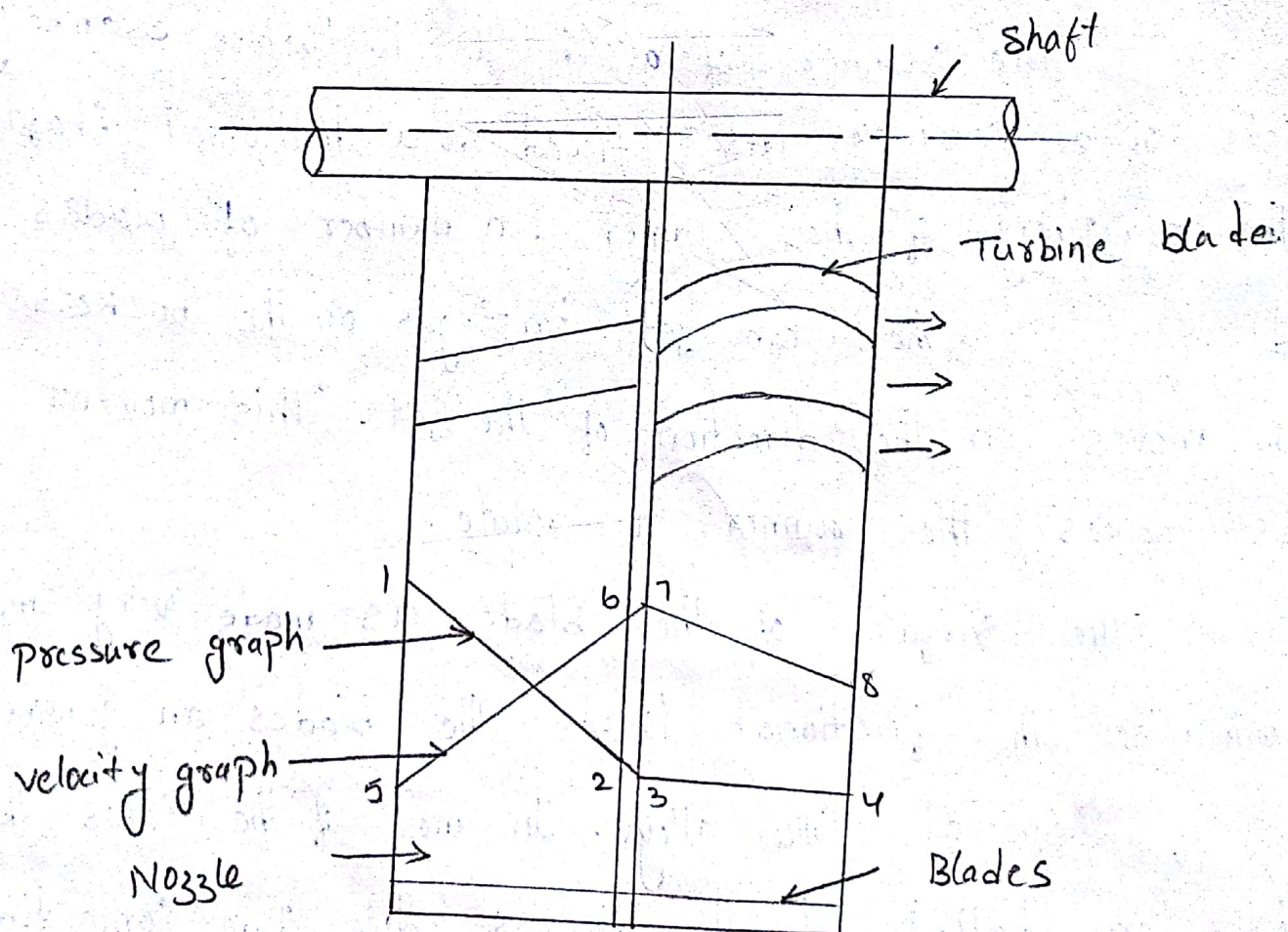
The runner of a de-level turbine essentially consists of a circular disc fixed to a horizontal shaft. On the periphery of the runner, a number of blades are fixed. The steam jet impinges on the buckets, which moves in the direction of the jet. This moment of blades makes the runner to rotate.

The surface of the blades is made very smooth to minimise the frictional losses. The blades are generally made of special steel alloys. In most of the cases the blades are bolted to the runner disc. But sometimes the blades and disc are cast as a single unit.

It is an air-tight metallic case, which contains the turbine runner and blades. It controls the movement does not permit it to move into the space. more over, it is essential to safe guard the runner against any accident.

Pressure and velocity of Steam In an impulse Turbine!

The pressure of steam jet is reduced in the nozzle and remains constant while passing through the moving blade. The velocity of steam increased in the nozzle and is reduced while passing through the moving blades.



The diagram represents the pressure and velocity graphs of the steam in a simple turbine while it flows in the nozzle and moving blades. The pressure graph 1-2-3-4 represents steam pressure at entrance of the nozzle, exit of the nozzle, entrance & exit of the moving blades respectively. Similarly, velocity graph 5-6-7-8 represents the velocity of steam at entrance, exit of nozzle, entrance of the blades, and exit of the blades respectively.

Velocity triangles for moving blade of an impulse turbine

The steam jet after leaving the nozzle impinges on one end of the blade. The jet then glides over the inside surface of the blade and finally leaves from the other edge. It may be noted that the jet enters and leaves the blades tangentially for shockless entry and exit.

Consider a steam jet entering a curved blade after leaving the nozzle at C. Now let in the jet glides over the inside surface and leaves at D.

The velocity triangles at inlet and outlet tips of the moving blade.

Let V_{bl} = linear velocity of moving blade.

v = Absolute velocity of steam entering the blade,

v_r = Relative velocity of jet to moving blade. It

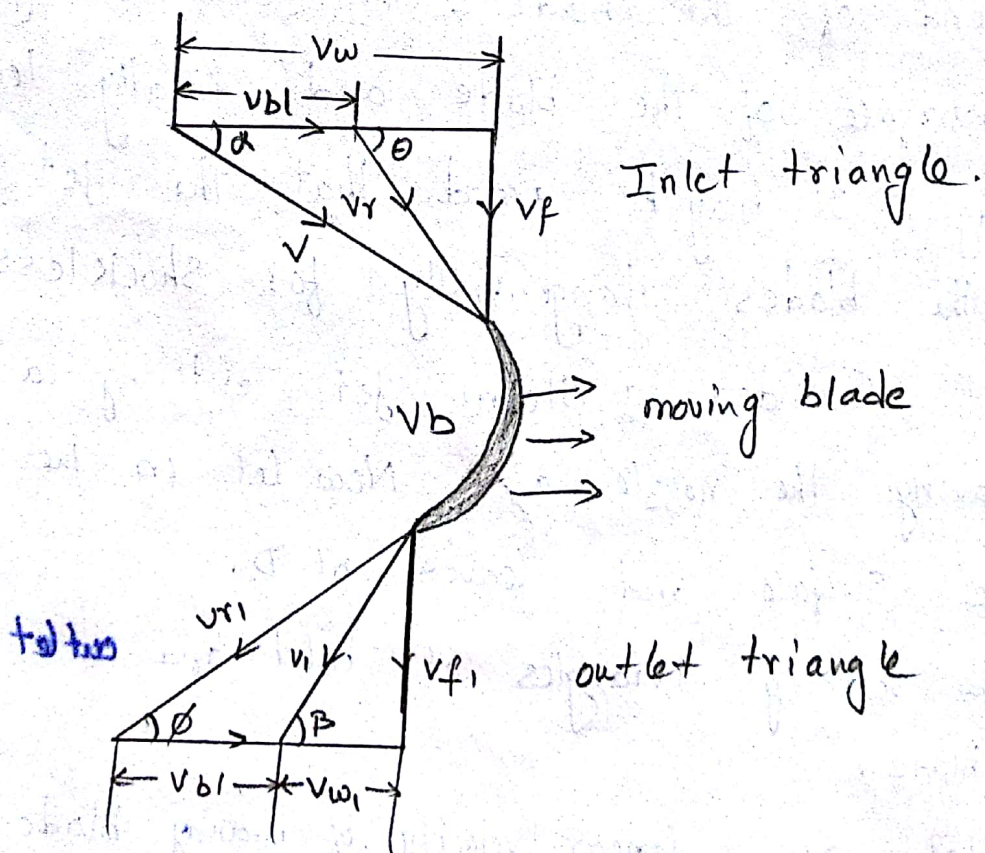
v_f = Velocity of flow at entrance of moving blade. It is the vertical component of v .

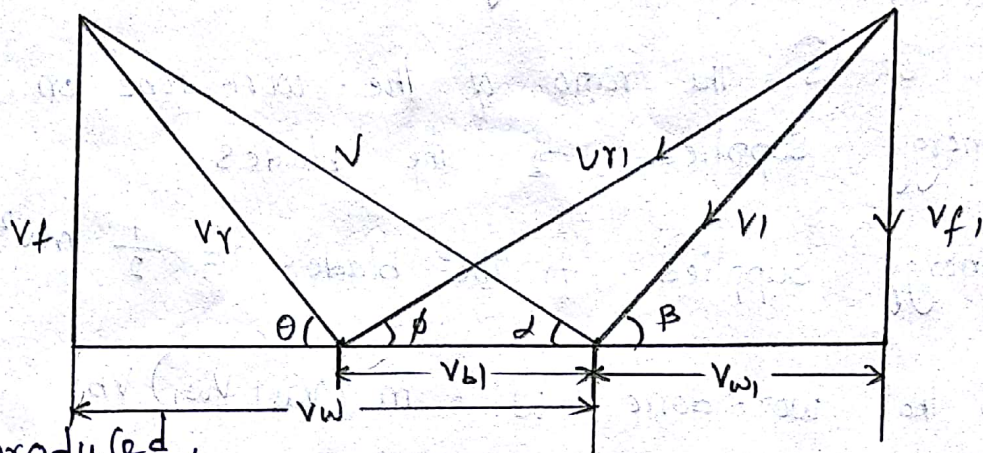
v_w = Whirl velocity at entrance of blade. It is the horizontal component of v .

θ = Angle which the relative velocity of jet to the moving blade (v_r)

α = Angle with the direction of motion of blade at which the jet enters the blade.

$v_1, v_{r1}, v_{f1}, v_{w1}, \phi, \beta$ = Corresponding values at exit of the moving blade:





Power produced,

m = mass of the steam flowing through turbine, kg/sec,

$v_w + v_{w1}$ = change in whirl velocity, m/s

F_x = mass of steam / sec $\times$ change in whirl velocity

$$= m (v_w - (-v_{w1}))$$

$$F_x = m (v_w + v_{w1})$$

Power = work done = force $\times$ Distance / sec

$$= m (v_w + v_{w1}) \times v_{bl} \text{ N-m/sec}$$

$$P = m (v_w + v_{w1}) v_{bl} W$$

The axial thrust on the wheel which is due to the difference of velocity of flow at inlet & outlet is

$$\text{Axial thrust, } F_y = m (v_{f1} - v_f) N$$

Note! The relation b/w inlet and outlet velocity triangle

unless given is

$$v_r = v_{r1}$$

$$\eta_b = \frac{\frac{m/2 (v^2 - v_1^2)}{www.FirstRanker.com}}{\frac{mv^2}{2}}$$

$$\therefore \eta_b = \frac{v^2 - v_1^2}{v^2}$$

2. Gross or Stage efficiency:

It is the ratio of the work done on the blades per kg of steam to the total energy supplied per stage per kg of steam

h_1 = Enthalpy or total heat of steam before expansion through nozzle in kJ/kg of steam

h_2 = Enthalpy after expansion through nozzle in kJ/kg of steam.

Enthalpy or heat drop in nozzle ring of an impulse wheel,

$$h_d = h_1 - h_2$$

Total energy supplied per stage = $1000 (h_1 - h_2)$ J/kg.

Work done per kg of steam, $w = (v_w + v_{w1}) v_{bl}$ J/kg.

Gross efficiency

$$\eta_s = \frac{(v_w + v_{w1}) v_{bl}}{1000 (h_1 - h_2)}$$

3. Nozzle efficiency:

It is the ratio of energy supplied to the blades per kg of steam to the total energy supplied per stage per kg of steam.

$$\eta_n = \frac{v^2}{2000 h d}$$

Effect of friction on Combined velocity triangle:

We have assumed that the inner side of the curved blade offers no resistance to the steam jet. But in actual practice, some resistance is always offered by the blade surface to the gliding steam, whose effect is to reduce the relative velocity of jet. i.e., to make $v_{r1} \neq v_r$. The ratio of v_{r1} to v_r is known as blade velocity coefficient or coefficient of velocity or friction factor.

i.e., $k = v_{r1} / v_r$

Note 1. As v_{r1} decreasing, the work done per kg of steam also decreases.

2. The value of k varies from 0.15 to 0.85 depending upon the shape of the blades.

Condition for maximum efficiency:

We know that, $\eta_b = \frac{2(v_w + v_{w1})v_{b1}}{v^2 - v_{r1}^2}$

It may be noted that the blowing efficiency will be maximum when v_1 is minimum. From Combined velocity triangle, the value of v_1 is minimum, when β is equal to 90° . It may also be noted that for maximum efficiency, v_{w1} is zero.

$$\Rightarrow \eta_{max} = \frac{2(v_w)(v_b)}{v^2}$$

We know that in De-laval turbine $\theta = \phi$, considering

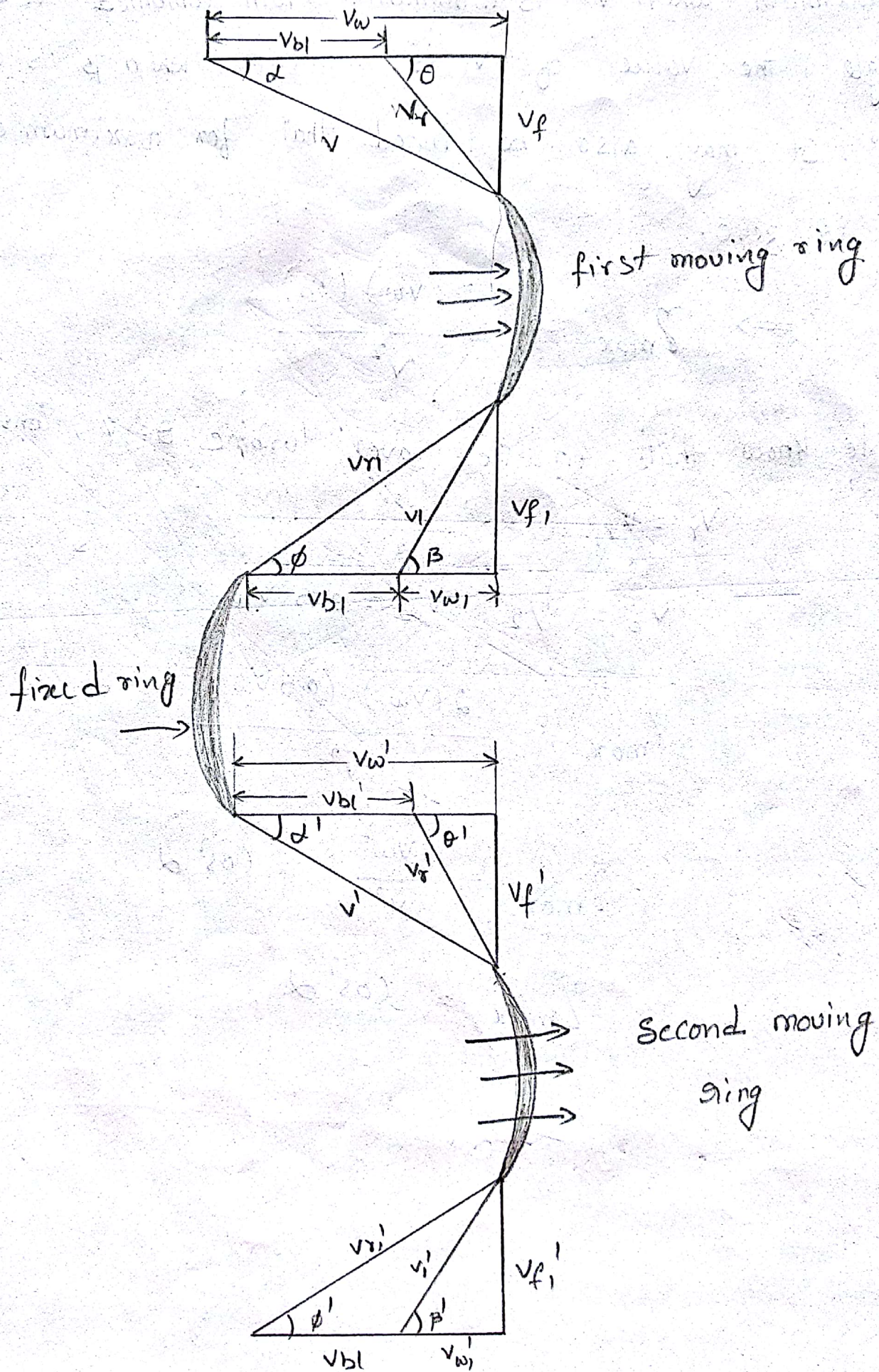
$$v_r = v_{r1}$$

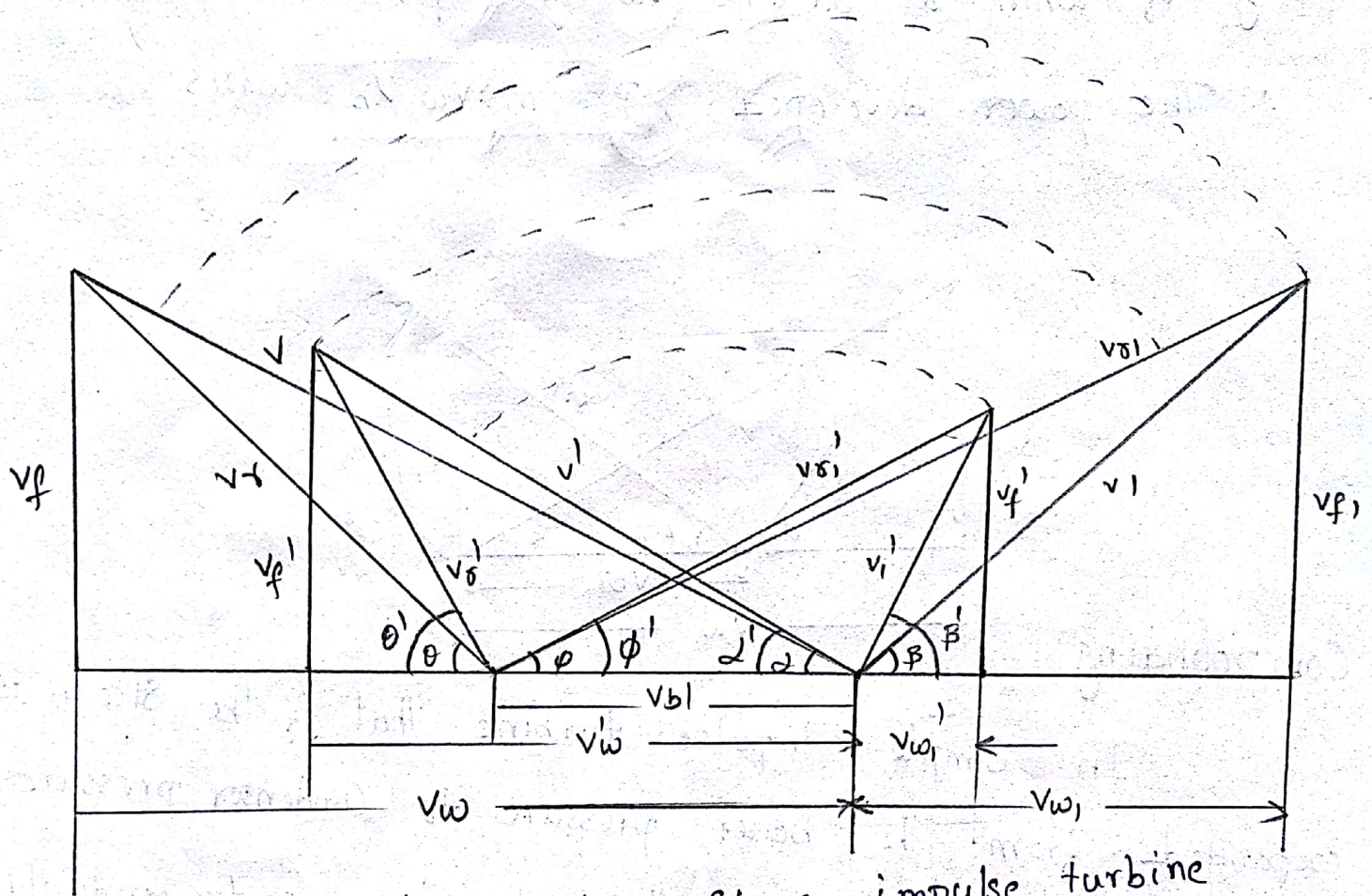
$$v_b = \frac{1}{2} v_w = 0.5 v_w$$

$$\eta_{max} = \frac{2(v_w)(0.5 v_w)}{v^2}$$

$$\boxed{\eta_{max} = \frac{v_w^2}{v^2} = \cos^2 \alpha}$$

$$\boxed{\eta_{max} = \cos^2 \alpha}$$





Power developed by two stage impulse turbine

$$P = m (v_w + v_{w_1} + v'_w + v'_{w_1}) v_{bl}$$

Blade efficiency, $\eta_b = \frac{m (v_w + v_{w_1} + v'_w + v'_{w_1}) v_{bl}}{m v^2 / 2}$

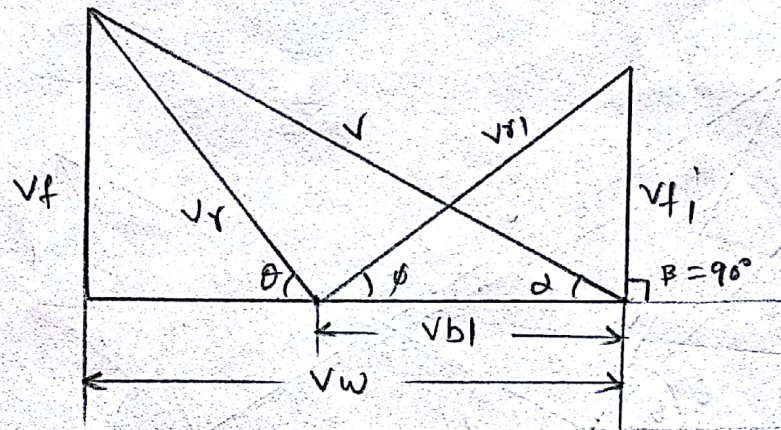
$$\eta_b = \frac{2 (v_w + v_{w_1} + v'_w + v'_{w_1}) v_{bl}}{v^2}$$

Combined velocity triangle for axial discharge!

Some times, the steam leaves the blade at its exit tip at 90° to the direction of the blade motion.

such a case, the turbine is said to have an axial discharge. It may be noted that in such a turbine, velocity of whirl at outlet (v_w) is equal to zero.

∴ The power developed, $P = m v_w V_b$ watts



Compounding:

In simple impulse turbine that if the steam is expanded from the boiler pressure to Condenser pressure in one stage the speed of the rotor becomes tremendously high which crops up practical complications. There are several methods of reducing this speed to lower value. all these methods utilise a multiple system of rotor in series, keyed on a common shaft using and the steam pressure or jet velocity is absorbed in stages as the steam flows over the blades.

This is known as compounding

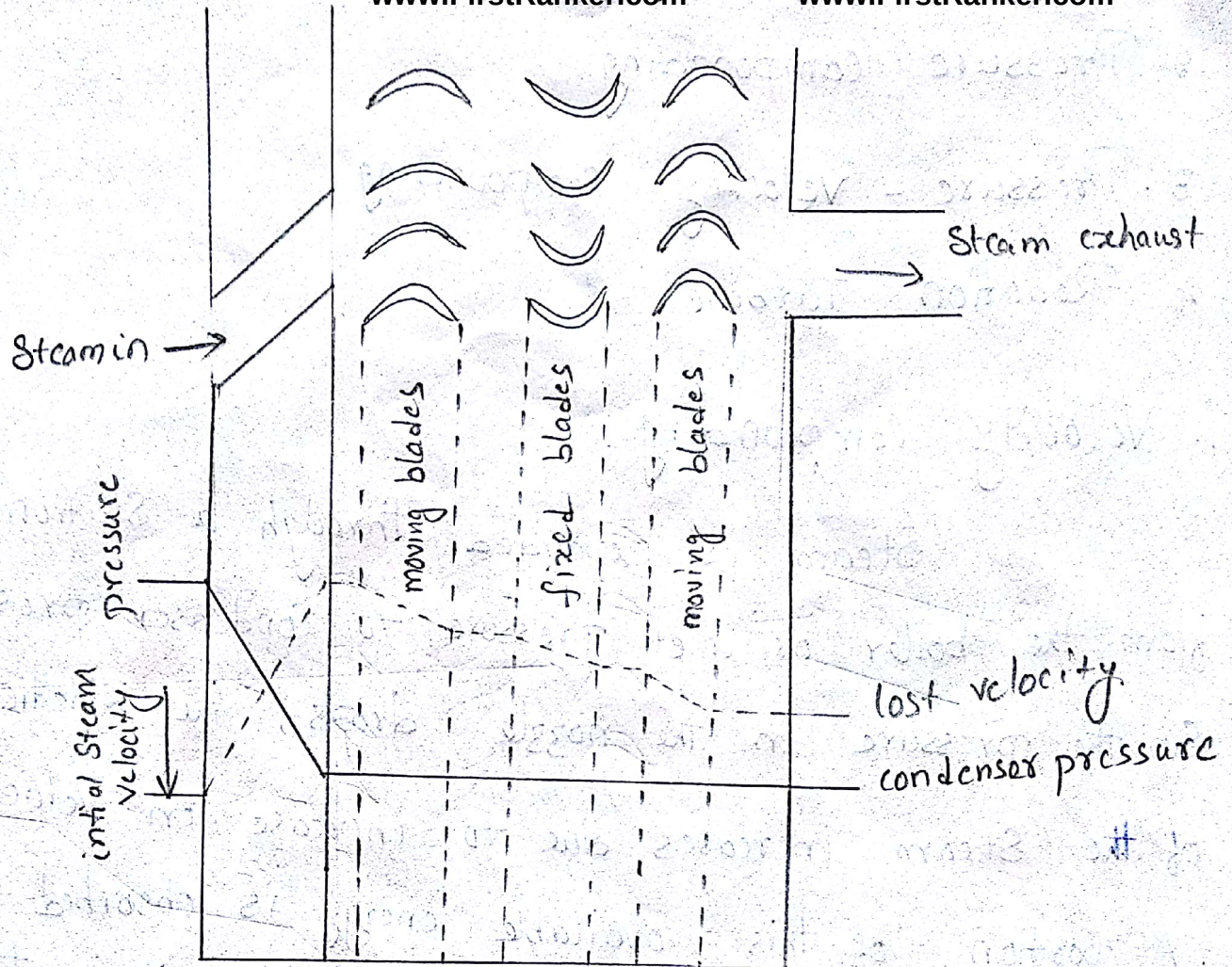
The different methods of compounding are.

1. Velocity Compounding
2. Pressure Compounding
3. Pressure - velocity Compounding
4. Reaction Turbine

1. Velocity Compounding:

Steam is expanded through a stationary nozzle from the boiler or inlet pressure to condenser pressure. So the pressure in the nozzle drops, the kinetic energy of the steam increases due to increase in velocity.

A portion of this available energy is absorbed by a row of moving blades. The steam then flows through the second row of blades which are fixed. The function of these fixed blades is to re-direct the steam flow without altering its velocity to the following next row, moving blades. Where again work is done on them. Through this method has advantage that the initial cost is low due to lesser number of stages yet its efficiency is low.



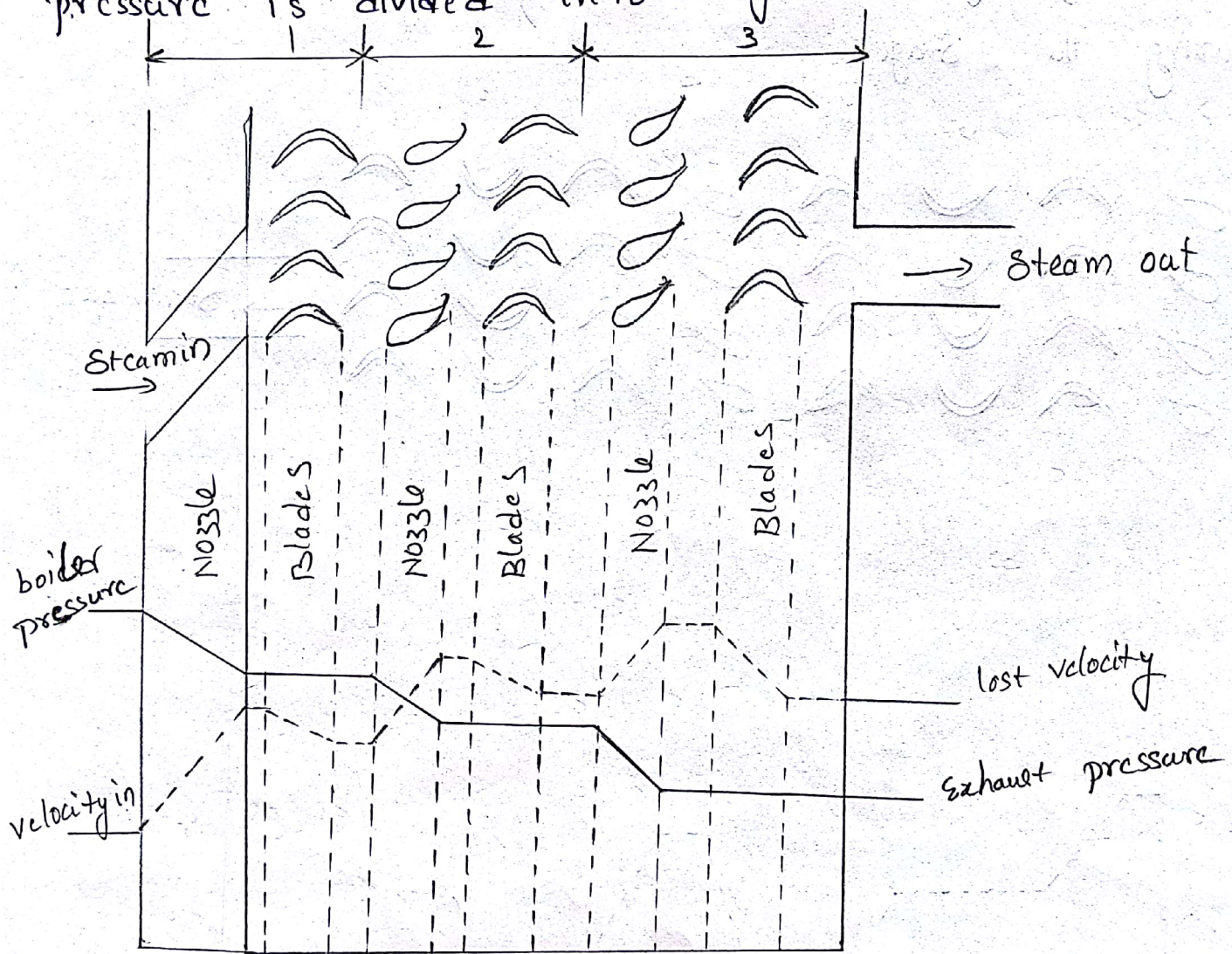
2. Pressure Compounding:

The Steam at boiler pressure enters the first set of nozzles and expands partially. The kinetic energy of the steam at boiler thus obtained is absorbed by the moving blades. The steam then expands partially in the second set of nozzles where its pressure again falls and the velocity increases. The kinetic energy so obtained is absorbed by the second ring of moving blades.

This is repeated in stage 3 and steam finally

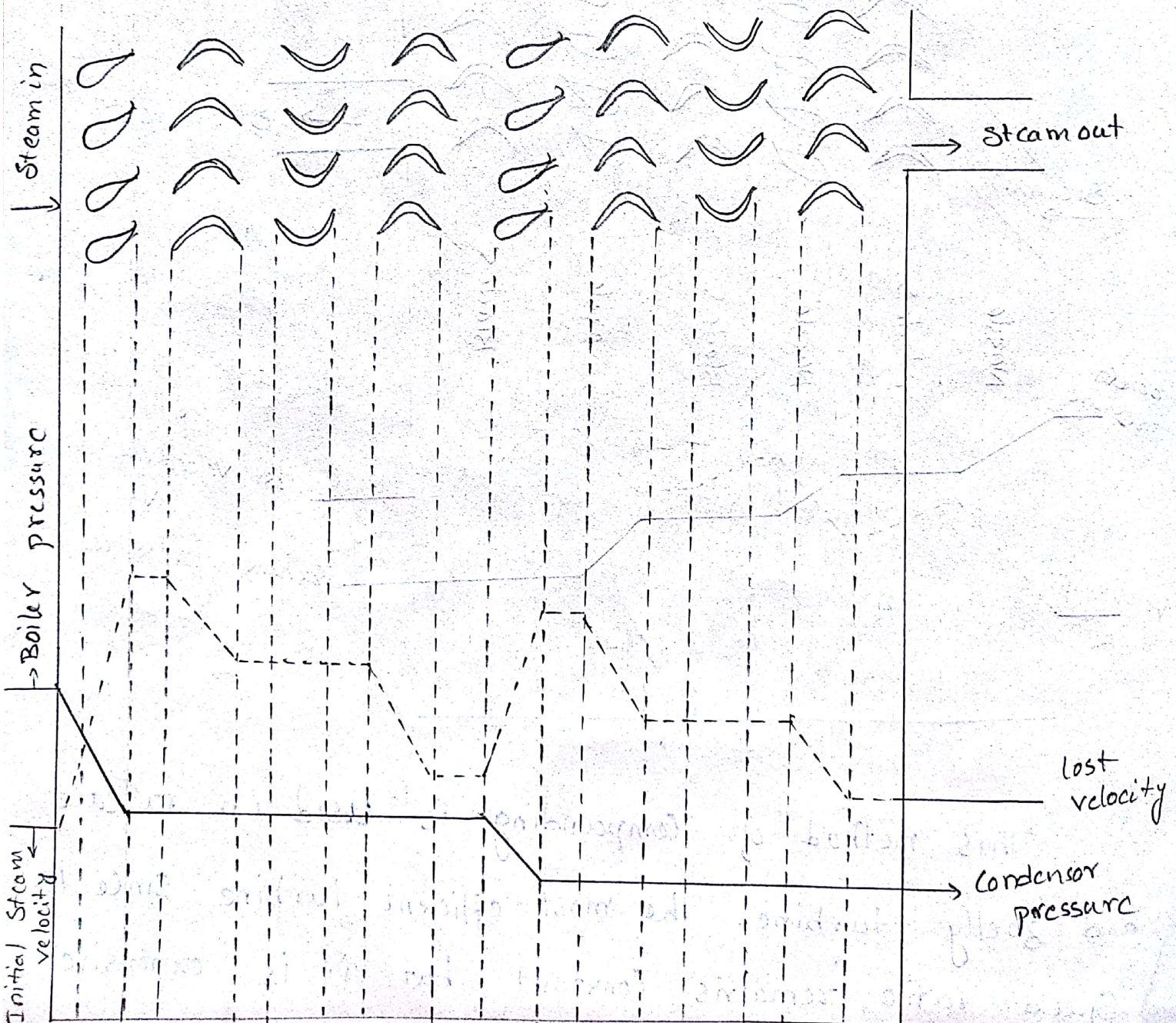
the turbine at low velocity and pressure. The number of stages depends on the number of rows of nozzles through which the steam must pass.

This method of compounding is the combination of two previously discussed methods. The total drop in steam pressure is divided into stages.



This method of compounding is used in rateau and goelly turbine. The most efficient turbine since the speed ratio remains constant but it is expensive owing to a large number of stages.

This method of compounding is the combination of two previously discussed method. The total drop in steam pressure is divided in to stages and the velocity obtained in each stage is also compounded. The rings of nozzles are fixed at the beginning of each stage and pressure remains constant during the stage.



UNIT-IV REACTION TURBINES AND STEAM CONDENSERS

In a reaction turbine the steam enters the wheel under the pressure and flows over the blades. The steam while gliding, propels the blades and make them to move. As a matter of fact, the turbine runner is rotated by the reactive forces of steam jets. The backward motion of the blades is similar to the recoil of a gun. It may be noted that an absolute reaction turbine is rarely used in actual practice.

Parson's Reaction Turbine:-

The components of parson's reaction turbine are.

1. Casing:-

It is an air-tight metallic case, in which the steam from the boiler, under a high pressure and temperature, is distributed around the fixed blades in the casing. The casing is designed in such away that the steam enters the fixed blades with a uniform velocity.

2. Guide mechanism:-

It is a mechanism, made up with the help of guide blades, in the form of a wheel

These guide blades are also called fixed blades. The guide blades are properly designed in order to:

- allow the steam to enter the runner without shock. This is done by keeping the relative velocity at inlet of the runner tangentially to the blade angle.
- allow the required quantity of the steam to enter the turbine this is done by adjusting the openings of the blades.

The guide blades may be opened or closed by rotating the regulating shaft, thus allowing the steam to flow according to the need. The regulating shaft is operated by means of a governor whose function is to govern the turbine (i.e. to keep the speed constant at varying loads).

3. Turbine runner:-

It consists of runner blades fixed to a shaft or rings, depending upon the type of turbine. The blades fixed to the runner, are properly designed in order to allow the steam to enter and leave the runner without shock. The surface of the turbine runner is made very smooth to minimise the frictional losses. The turbine runner is generally cast in one piece. But some times, it is made up of separate steel plates welded together.

4. Draft tube:

The Steam, after passing through the runner, flows into the Condenser through a tube called draft tube. It may be noted that if this tube is not provided in the turbine, then the Steam move freely and will cause Steam eddies.

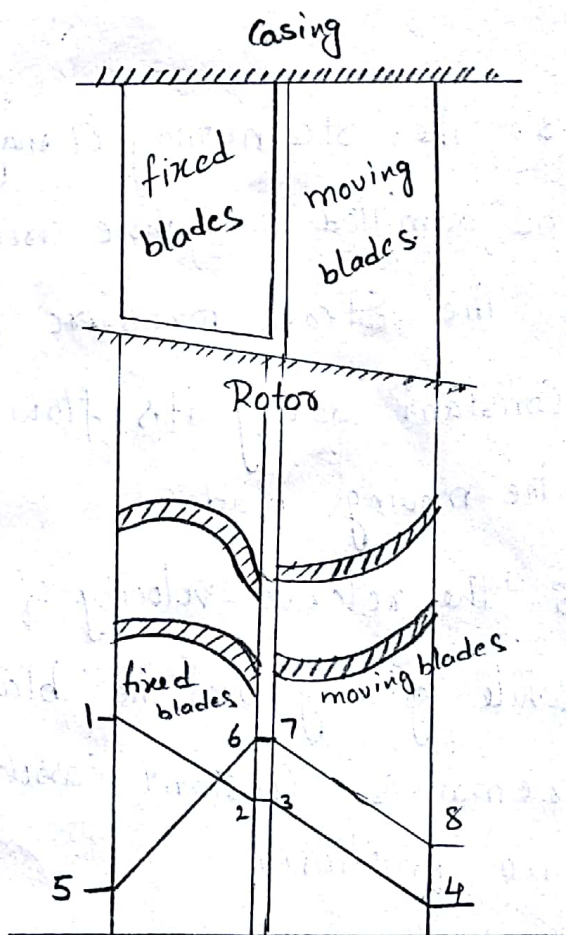
Pressure and velocity of Steam in a reaction Turbine:-

The pressure in a reaction turbine is reduced in the fixed blades as well as in moving blades.

The velocity of Steam is increased in the fixed blades and is reduced while passing through the moving blades.

The pressure graph 1-2-3-4 represents Steam at inlet, outlet of fixed blades, entrance & exit

of moving blades respected points 5-6-7-8 represents velocity graph.



Impulse turbine

1. The Steam flows through the nozzles & impinges on moving blades
2. The Steam impinges on buckets with kinetic energy
3. The Steam may or may not be admitted over whole circumference
4. The Steam pressure remains Constant during its flow through the moving blades
5. The relative velocity of Steam while gliding over the blades remains Constant (assuming no friction)
6. The blades are symmetrical
7. The no. of stages required are less for same power developed.

Reaction turbine

1. The Steam flows first through guide mechanism and then through moving blades.
2. The Steam guides over the moving ^{vanes} must be with pressure & kinetic energy
3. The Steam must be admitted over the whole circumference.
4. The Steam pressure is reduced during its flow through the moving blades.
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6. The blades are not symmetrical
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moving blades of a reaction turbine?

The steam enters at the one end of the moving blades from the guide mechanism. The jet then glides over the inside surface of the blades and finally leaves from the other end. It may be noted that the jet enters and leaves the blades tangentially for shockless entry and exit.

V_b = linear velocity of moving blade (AB)

V = Absolute velocity of steam entering the moving blade (BC)

V_r = Relative velocity of jet to the moving blade (AC)

It is the vectorial difference of V_b & V .

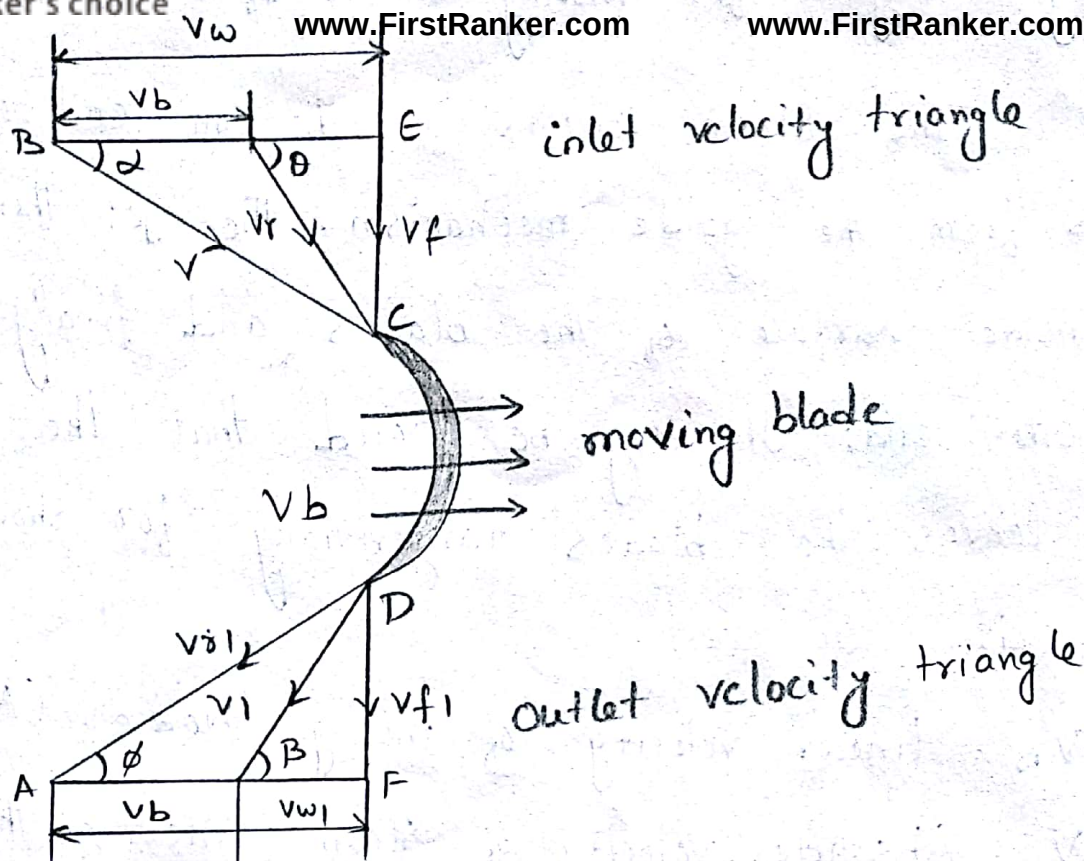
V_f = Velocity of flow at entrance (EC). Vertical component of V .

V_w = Whirl velocity at entrance (BE). Horizontal component of V .

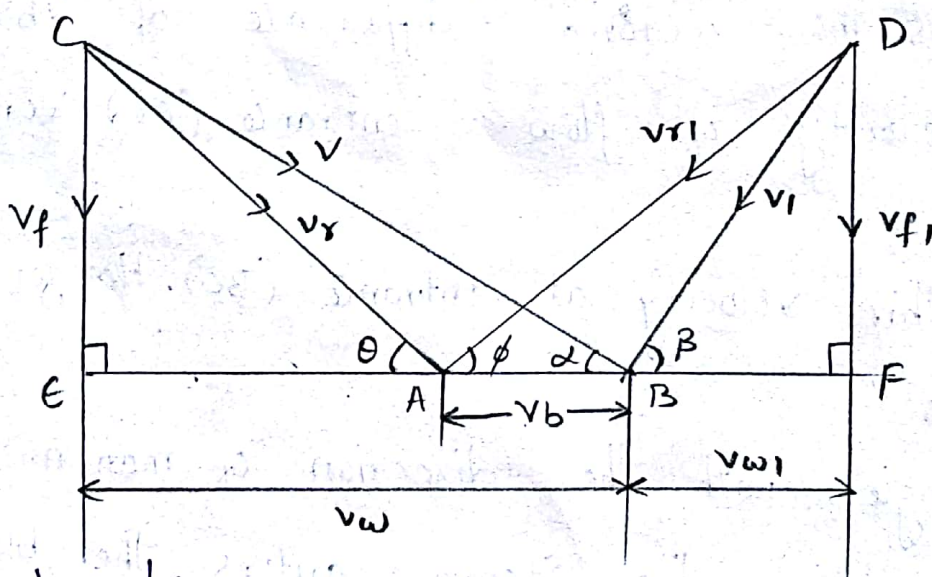
α = Angle with the direction of motion of the blade at which the steam enters the blade.

θ = Angle which the relative velocity of jet (V_r) makes with the direction of motion of blade.

$v, v_r, v_f, v_w, \beta, \phi$ = corresponding values of exit of the moving blade



Combined velocity triangle).



Power produced:

m = mass of the steam flowing through the turbine.

$(V_w + V_{w1})$ = change in the velocity of whirl in m/sec

According to Newton's second law of motion,

$$F_x = m (V_w + V_{w1}) \text{ Newtons}$$

Work done = Power = $m(v_w + v_{w1}) v_b$ watts (4)

$$P = m(v_w + v_{w1}) v_b \text{ watts}$$

$$\text{Work done per kg of steam} = v_b (2v \cos \alpha - v_b)$$

(i) Blade efficiency:

$$\eta_b = \frac{2(v_w + v_{w1}) v_b}{v^2}$$

or

Diagram efficiency

$$\eta_b = \frac{v^2 - v_1^2}{v^2}$$

(ii) Gross or Stage efficiency:-

$$\eta_s = \frac{(v_w + v_{w1}) v_b}{1000 (h_1 - h_2)}$$

(iii) Nozzle efficiency:

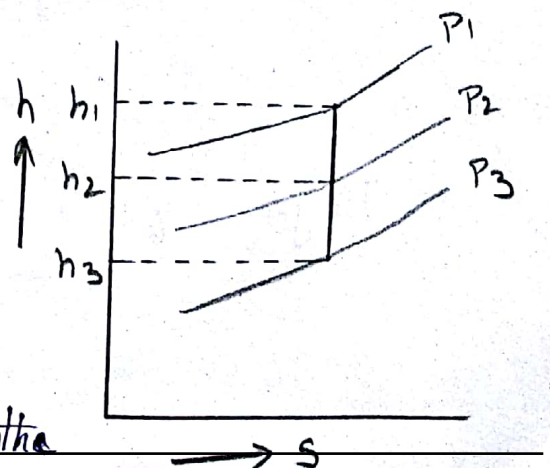
$$\eta_s = \eta_b \times \eta_n$$

$$\eta_n = \frac{v^2}{2000 (h_1 - h_2)}$$

Degree of Reaction

The pressure drop takes place in both the fixed and moving blades. In other words,

there is an enthalpy drop in both



fixed and moving blades. The ratio of enthalpy or heat drop in the moving blades to the total enthalpy or heat drop in the stage is known as degree of reaction.

$$\text{Degree of reaction} = \frac{\text{Enthalpy or heat drop in moving blades}}{\text{Total enthalpy or heat drop in stage.}}$$

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

The enthalpy drop in the fixed blades per kg of steam is

$$h_1 - h_2 = \frac{v^2 - v_1^2}{2000} \text{ kJ/kg.}$$

in moving blades, $h_2 - h_3 = \frac{v_{r1}^2 - v_r^2}{2000} \text{ kJ/kg.}$

Total enthalpy drop in the stage.

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

$$h_1 - h_3 = \frac{v^2 - v_1^2}{2000} + \frac{v_{r1}^2 - v_r^2}{2000}$$

$$= 2(h_2 - h_3) \text{ kJ/kg.}$$

[∵ for parson's turbine $v = v_{r1}$ & $v_1 = v_r$]

$$\text{Degree of reaction} = \frac{h_2 - h_3}{h_1 - h_3}$$

$$= \frac{h_2 - h_3}{2(h_2 - h_3)}$$

parson's reaction turbine.

Height of Blades of a Reaction turbine!

In a reaction turbine, the steam enters the moving blades over the whole circumference. As a result of this, the area through which the steam flows is always full of steam. Now consider a reaction turbine whose end view of the blade ring

d = diameter of rotor drum,

h = height of blades, and

v_{f1} = Velocity of flow at exit.

Total area available for steam flow,

$$A = \pi (d + h) h$$

$$\text{volume of steam flowing} = \pi (d + h) h v_{f1}$$

We know that volume of 1 kg of steam at the given pressure is $x v_g$ (from steam tables)

$$m = \frac{\pi(d+h)h\nu f_1}{x \nu g} \quad \text{kg/sec}$$

$$m = \frac{\pi \cdot (d+h)h\nu f}{x \nu g}$$

$$[\because \nu_f = \nu_{f_1}]$$

UNIT-IV

REACTION

TURBINES AND

STEAM

CONDENSERS

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These guide blades are also called fixed blades. The guide blades are properly designed in order to:

- (a) allow the steam to enter the runner without shock. This is done by keeping the relative velocity at inlet of the runner tangentially to the blade angle.
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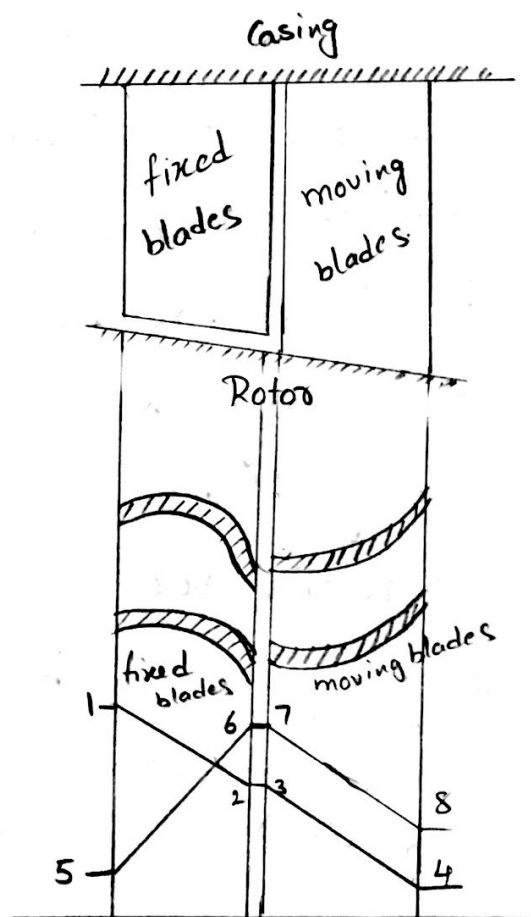
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Reaction turbine

1. The Steam flows first through guide mechanism and then through moving blades.
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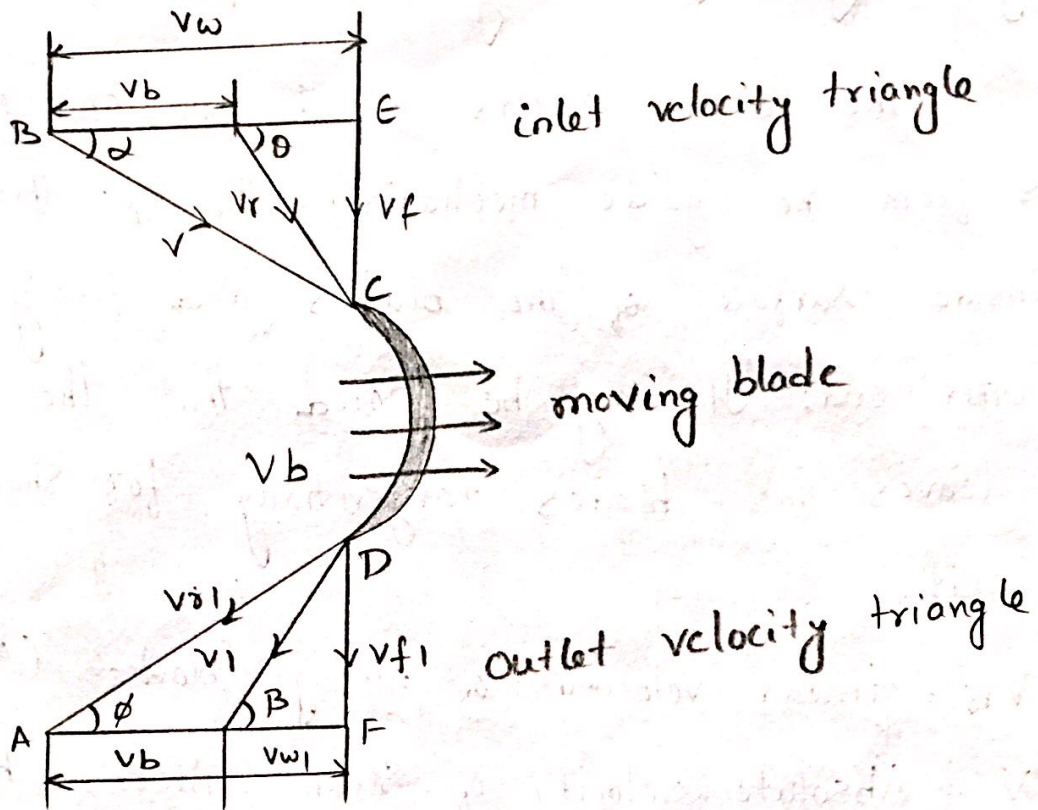
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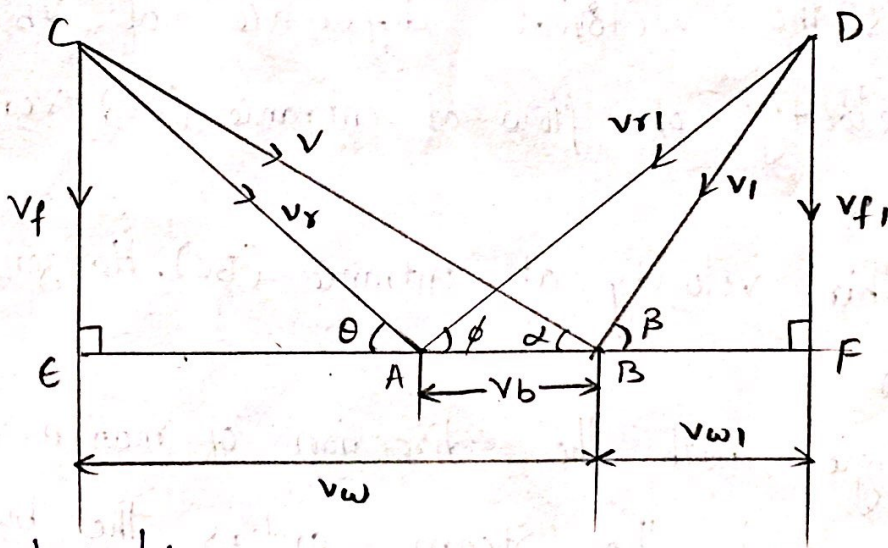
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or

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$$\eta_s = \frac{(v_w + v_{w1}) v_b}{1000 (h_1 - h_2)}$$

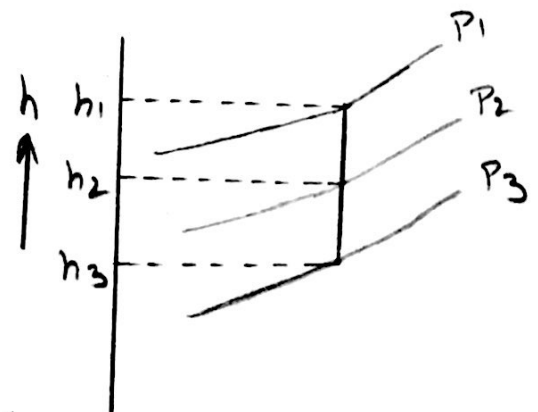
(iii) Nozzle efficiency.

$$\eta_s = \eta_b \times \eta_n$$

$$\eta_n = \frac{v^2}{2000 (h_1 - h_2)}$$

Degree of Reaction

The pressure drop takes place in both the fixed and moving blades. In other words,



fixed and moving blades - The ratio of enthalpy or heat drop in the moving blades to the total enthalpy or heat drop in the stage is known as degree of reaction.

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in moving blades, $h_2 - h_3 = \frac{v_{r1}^2 - v_r^2}{2000} \text{ kJ/kg.}$

Total enthalpy drop in the stage.

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

$$h_1 - h_3 = \frac{v^2 - v_1^2}{2000} + \frac{v_{r1}^2 - v_r^2}{2000}$$

$$= 2(h_2 - h_3) \text{ kJ/kg.}$$

[∵ for parson's turbine $v = v_{r1}$
 $v_r = v_r$]

$$\text{Degree of reaction} = \frac{h_2 - h_3}{h_1 - h_3}$$

$$= \frac{h_2 - h_3}{2(h_2 - h_3)}$$

parson's reaction turbine.

Height of Blades of a Reaction turbine!

In a reaction turbine, the steam enters the moving blades over the whole circumference. As a result of this, the area through which the steam flows is always full of steam. Now consider a reaction turbine whose end view of the blade ring

d = diameter of rotor drum,

h = height of blades, and

v_{f1} = Velocity of flow at exit.

Total area available for steam flow,

$$A = \pi (d + h) h$$

$$\text{volume of steam flowing} = \pi (d + h) h v_{f1}$$

We know that volume of 1 kg of steam at the given pressure is x_{vg} (from steam tables)

$$m = \frac{\pi (d+h) h v_f}{x v_g}$$

kg/sec

$$m = \frac{\pi \cdot (d+h) h v_f}{x v_g}$$

[$\therefore v_f = v_{fi}$]

A Steam Condenser has the following two objects:-

1. The primary object is to maintain a low pressure (below atmospheric pressure) so as to obtain the maximum possible energy from steam and thus to secure a high efficiency.
2. The secondary object is to supply pure feed water to the hot well, from where it is pumped back to the boiler.

Note: The low pressure is accompanied by low temperature and thus all condensers maintain a vacuum under normal conditions.

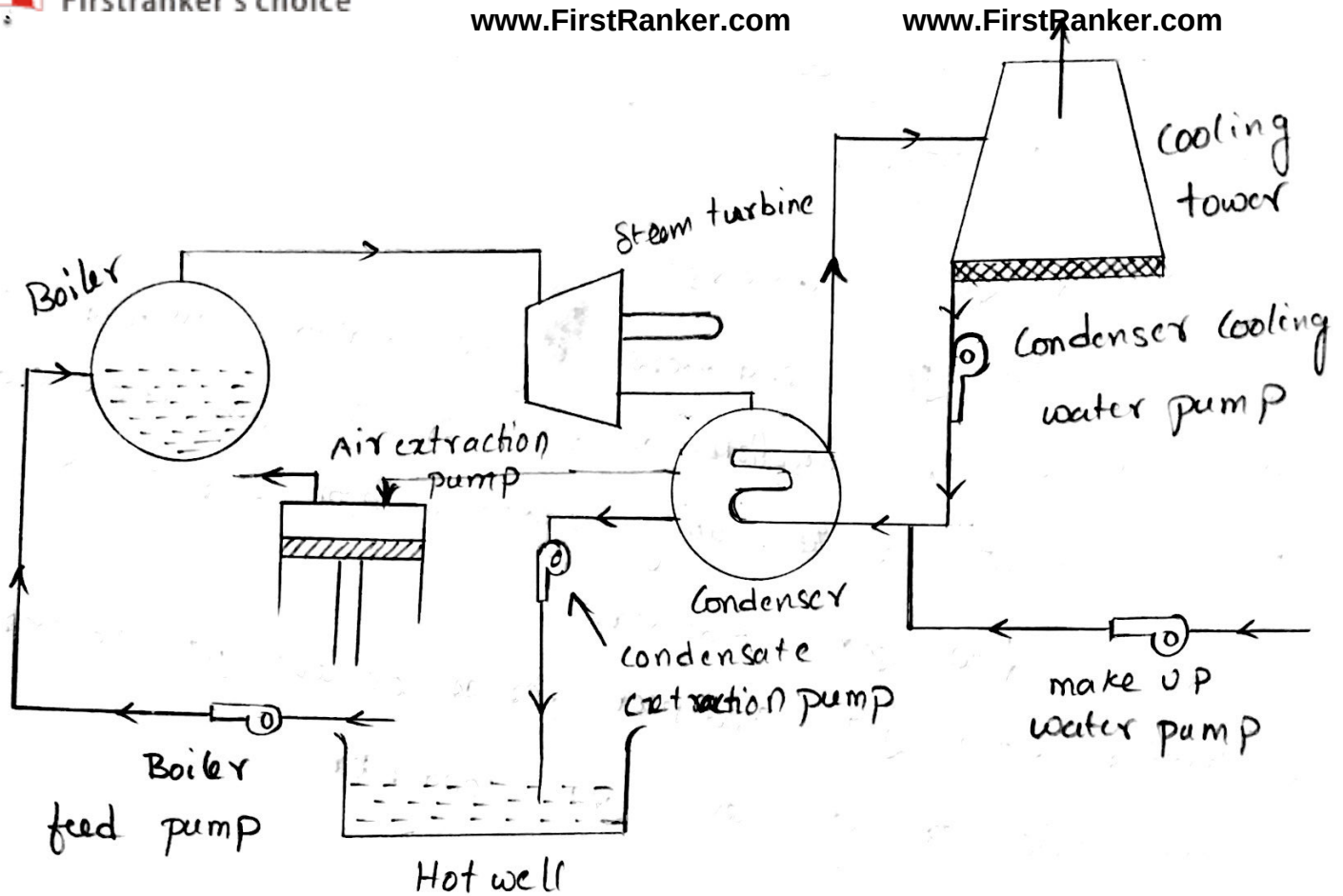
Advantages of Condenser in steam power plant:-

1. It increases the expansion ratio of steam, and thus increases efficiency of the plant.
2. It reduces the back pressure of steam, and thus more work can be obtained.
3. It reduces temperature of exhaust steam.
4. The reuse of condensate as feed water for boilers reduces the cost of power generation.

that of fresh water. so the amount of heat supplied per kg of steam is reduced.

Requirements of a Steam Condensing plant!

1. Condenser: It is a closed vessel in which steam is condensed. The steam gives up heat energy to coolant during the process of condensation.
2. Condensate pump: It is a pump, which removes condensate from the condenser to the hot well.
3. Hot Well: It is a sump between the condenser and boiler, which receives condensate pumped by condensate pump.
4. Boiler feed pump: It is a pump, which pumps the condensate from the hotwell to the boiler. This is done by increasing the pressure of condensate above the boiler pressure.
5. Air extraction pump: A pump which extracts air from the condenser.
6. Cooling tower: A tower used for cooling the water which is discharged from the condenser.
7. Cooling water pump: A pump, which circulates the cooling water through the condenser.



Classification of Condensers:

Depending up on the way in which the steam is condensed.

1. Jet or mixing type Condensers
2. Surface or non-mixing type Condensers.

Jet Condensers:

The jet Condensers are seldom used because there is some loss of condensate during the process of condensation and high power requirements for the pump used. Moreover, the condensate cannot be used as feed water to the boiler as it is not free from

However, jet condensers may be used at places where water of good quality is easily available in sufficient quantity.

Types of Jet Condensers!

The jet condensers may be further classified, on the basis of the direction of flow of the condensate and the arrangement of the tubing system, into four types:

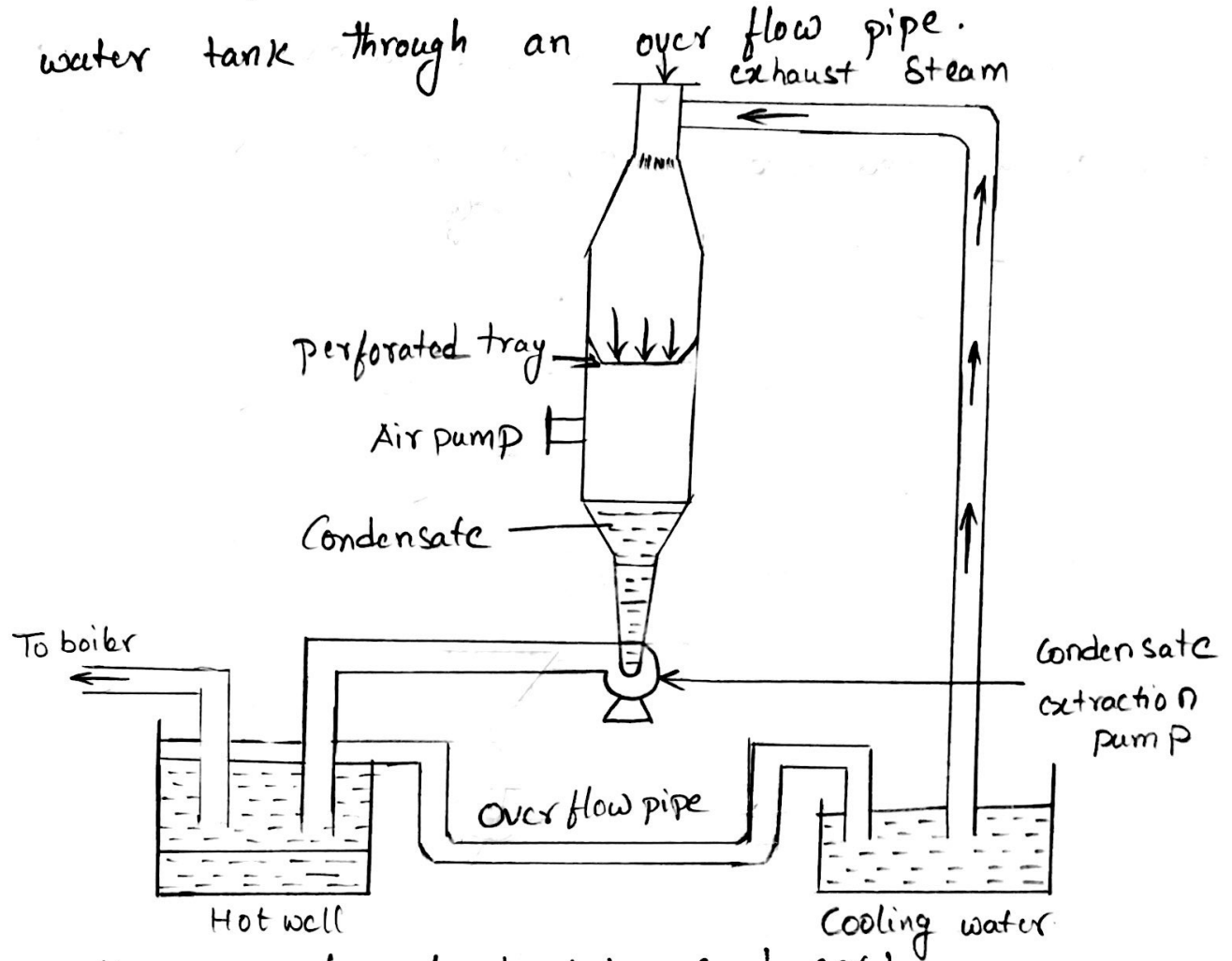
1. Parallel flow jet condenser.
2. Counter flow jet condenser for or low level jet condenser
3. Barometric or high level jet condenser.
4. Ejector Condenser.

1. Parallel flow jet condenser:

In parallel flow jet condensers, both the steam and water enter at the top, and the mixture is removed from the bottom.

The exhaust steam is condensed when it mixes up with water. The condensate, cooling water and air flow downwards & are removed by two separate pumps known as air pump and condensate pump. Some times, a single pump known as wet air pump, is also used to remove both air and condensate. But the former gives a

The condensate pump delivers the condensate to the hot well, from where surplus water flows to the cooling water tank through an overflow pipe. (3)

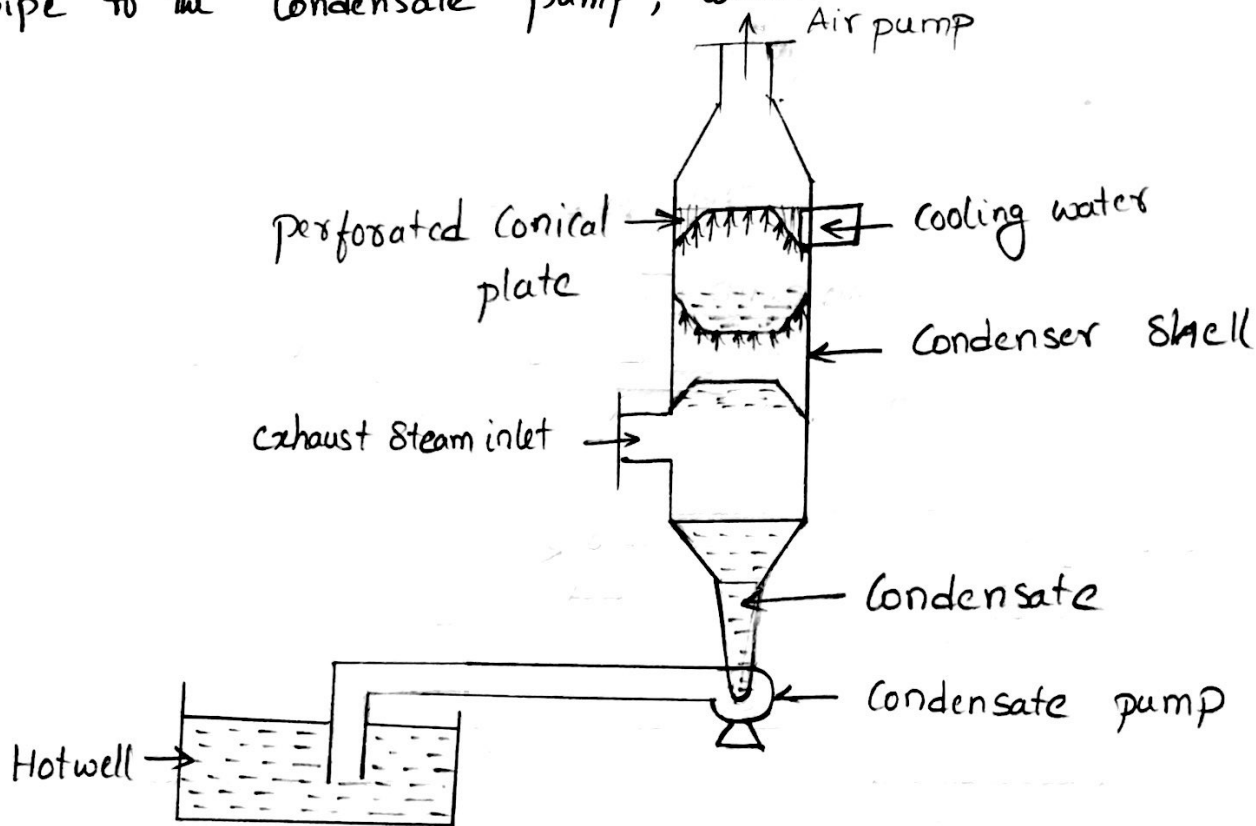


Counter flow or low level jet Condensers!

In Counter flow or low level jet Condensers, the exhaust steam enters at the bottom, flows upwards and meets the down coming cooling water.

The vacuum is created by the air pump, placed at the top of the Condenser shell. This draws the supply of cooling water, which falls in a large number of jets, through perforated conical plate. The falling water is caught in the trays, from which it escapes in

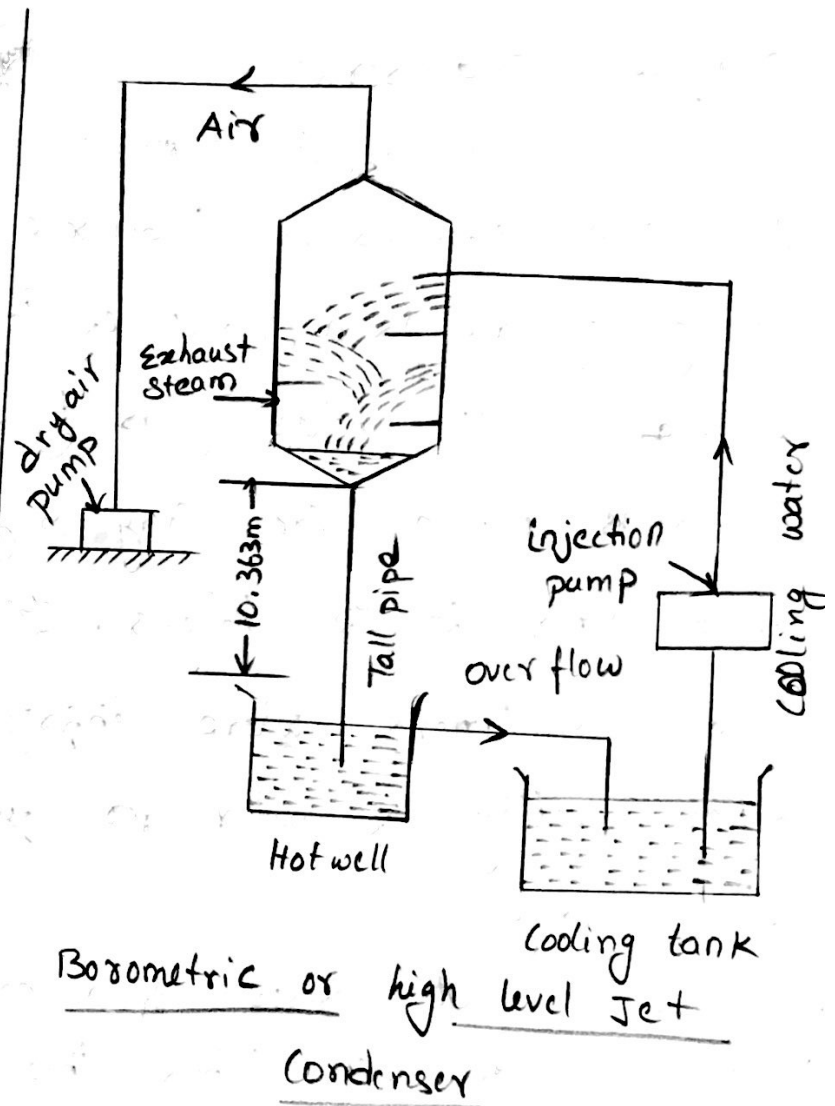
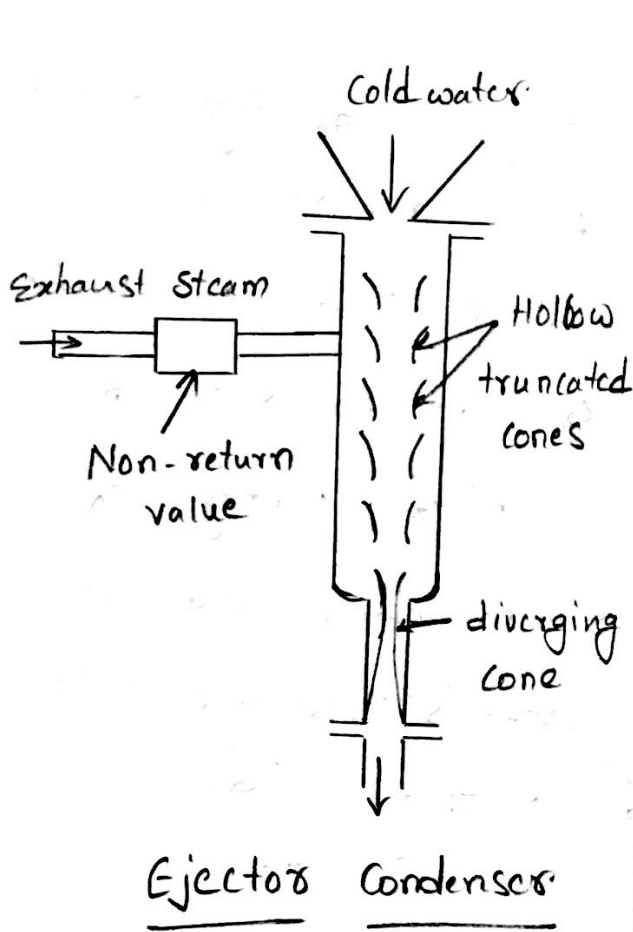
second Series of jets and meets the exhaust steam entering at the bottom. The rapid Condensation occurs and the Condensate and cooling water descends through a vertical pipe to the Condensate pump, which delivers it to the hot well.



Barometric or high level jet Condenser:

These Condensers are provided at a high level with a long vertical discharge pipe. In high level jet Condensers, exhaust steam enters at the bottom, flows upwards and meets the downcoming cooling water in the same way as that of low level jet Condenser. The vacuum is created by the air pump, placed at the top of the Condenser shell. The Condensate and cooling water descends through

The surplus water from the hotwell flows to the cooling water tank through an overflow pipe.



Ejector Condenser)

In ejector Condensers, the steam and water mix up while passing through a series of metal cones. water enters at the top through a number of guide cones. The exhaust steam enters the Condenser through the non-return valve arrangement. The steam and air then passes through the hollow truncated cones. After that it

is partly transformed to pressure energy. The Condensate and cooling water is then discharged to the hot well

Surface Condensers:

A surface Condenser has a great advantage over the jet Condensers, as the Condensate does not mix up with the cooling water. As a result of this, whole Condensate can be reused in the boiler. This type of Condenser is essential in ships which can carry only a limited quantity of fresh water for the boilers. It is also widely used in land installations, where inferior water is available or the better quality of water for feed is to be used economically.

It consists of a horizontal cast iron cylindrical vessel packed with tubes, through which the cooling water flows. The ends of the Condenser are cut off by vertical perforated type plates into which water tubes are fixed. This is done in such a manner that the leakage of water into the center Condensing space is prevented. The water tubes pass horizontally through the main Condensing space for the steam.

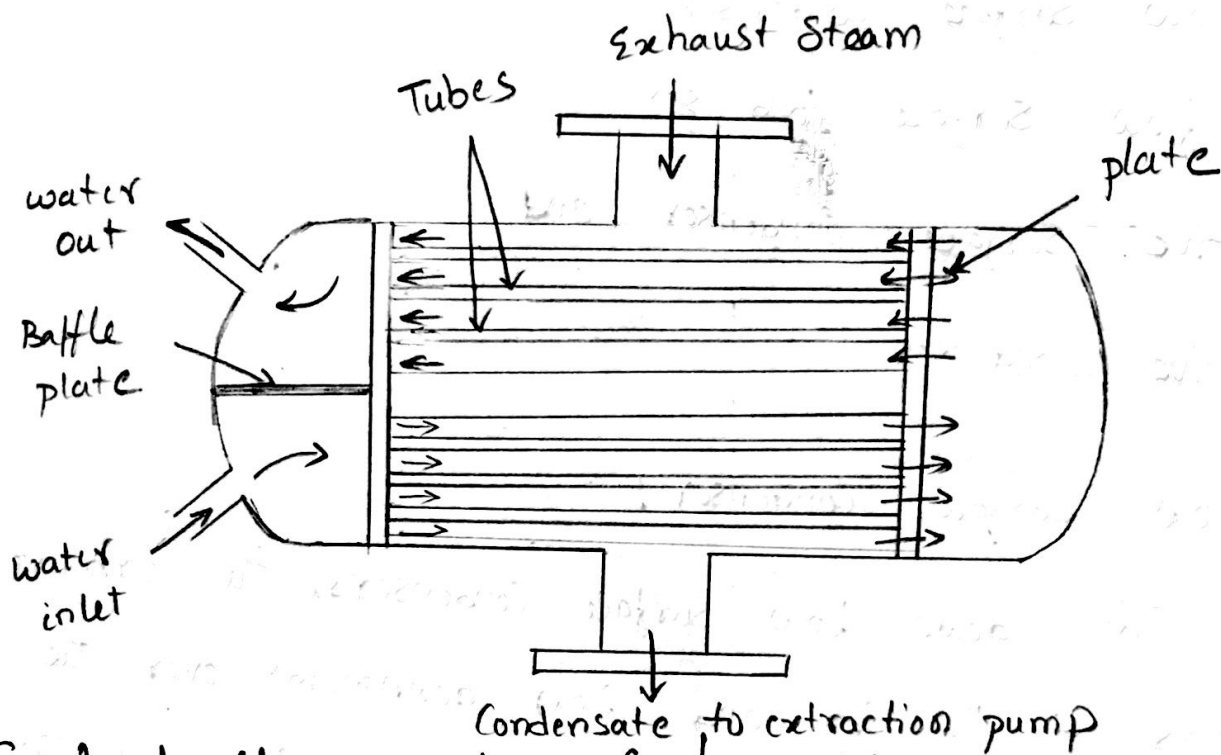
Basing on the direction of flow of the Condensate,

1. Down flow Surface Condenser
2. Central flow Surface Condenser
3. Regenerative Surface Condenser and.
4. Evaporative Condenser

1. Down flow Surface Condenser:

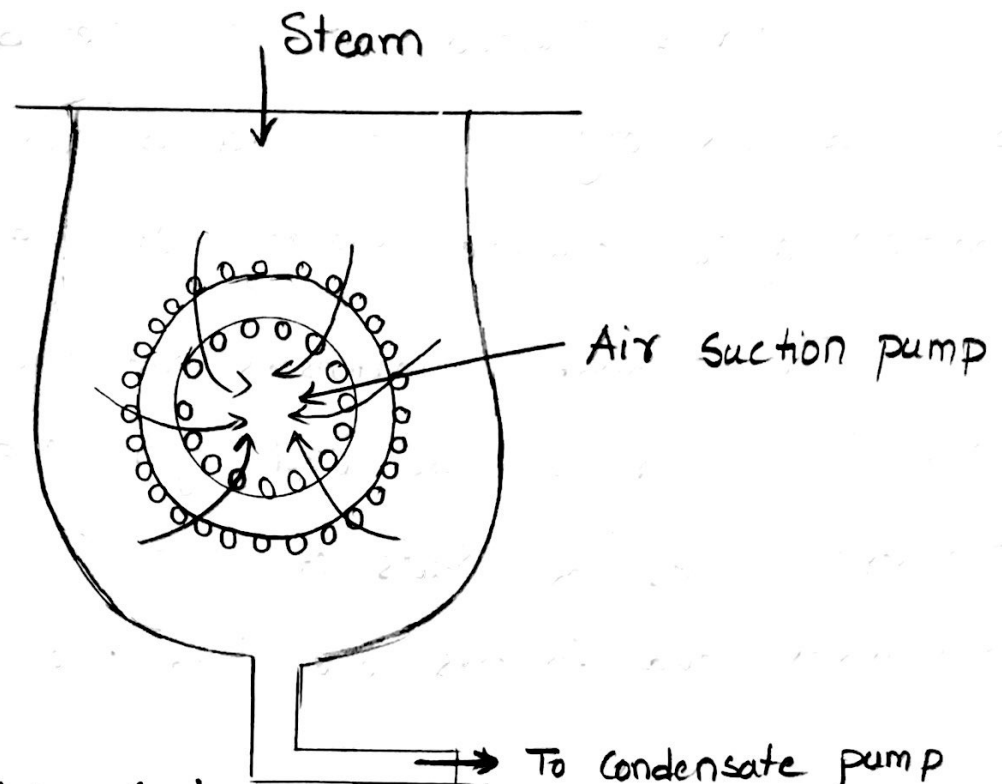
In down flow surface condensers, the exhaust Steam enters at the top and flow downwards over the tubes due to force of gravity as well as suction of the extraction pump fitted at the bottom. The Condensate is collected at the bottom and then pumped by the extraction pump. The dry air pump suction pipe, which is provided near the bottom, is covered by a baffle so as to prevent the entry of Condensed Steam into it.

As the steam flows perpendicular to the direction of flow of cooling water (inside the tubes), this is also called a cross surface condenser.



Central flow Surface Condensers:

In central flow surface condensers, the exhaust steam enters at the top and flows downwards. The suction pipe of the air extraction pump is placed in the center of the tube nest. This causes the steam to flow radially inwards over the tubes towards the suction pipe. The condensate is collected at the bottom and then pumped by the extraction pump.



Regenerative Surface Condensers!

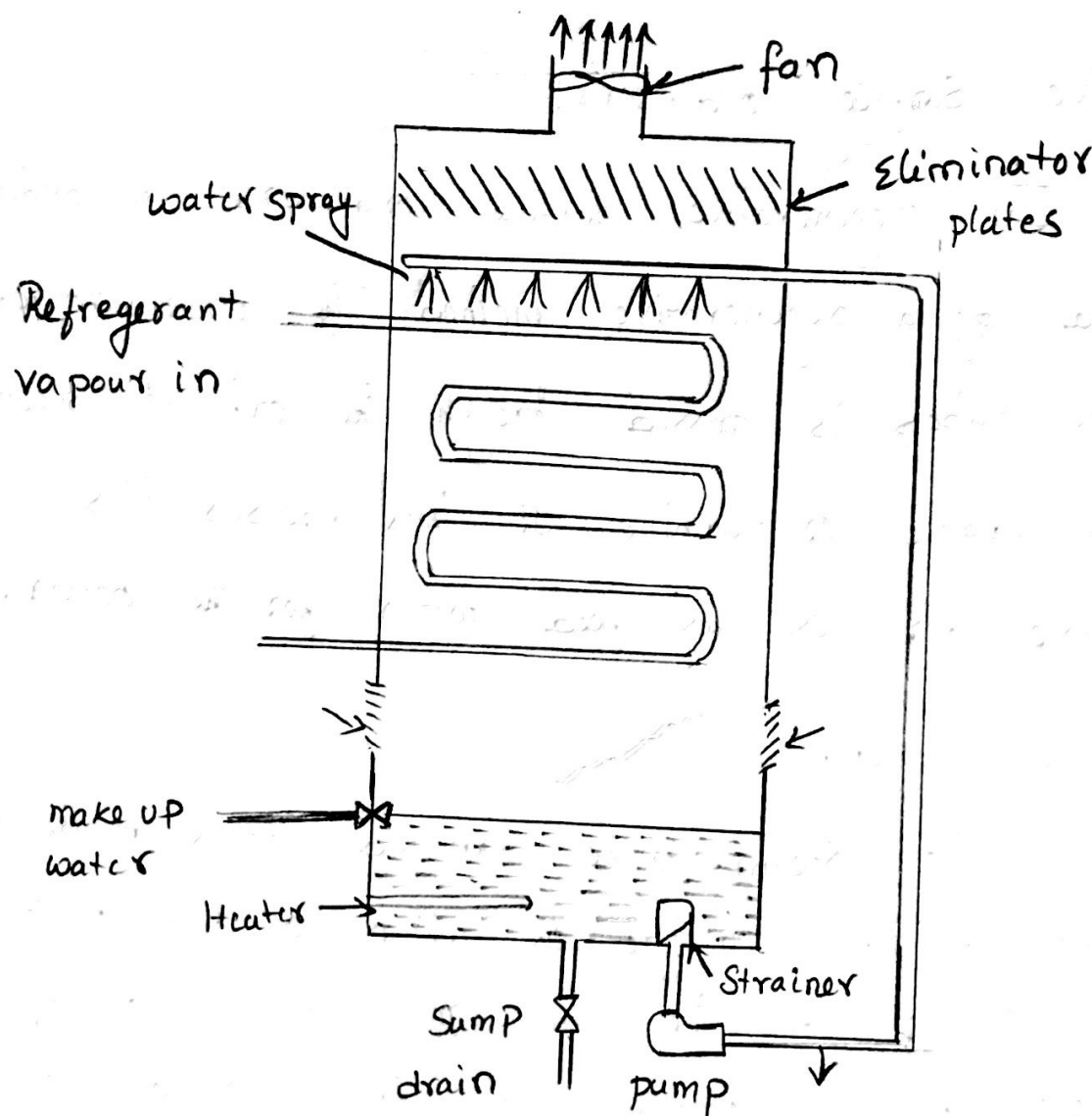
In regenerative surface condensers, the condensate is heated by a regenerative method. The condensate after leaving the tubes is passed through the exhaust steam from the engine or turbine. It thus, raises its temperature for use as feed water for the boiler.

Evaporative Condensers:

The steam to be condensed enters at the top of a series of pipes outside of which a film of cold water is falling. At the same time, a current of air circulates over the water film, causing rapid evaporation of some of the cooling water. As a result of this, the

circulating inside the pipe is condensed. The remaining cooling water is collected at an increased temperature and is reused. Its original temperature is restored by the addition of the requisite quantity of cold water

The evaporative Condensers are provided when the circulating water is to be used again and again. These Condensers Consists of Sheets of gilled piping, which is bent back wards and forwards and placed in a vertical plane.



of Cooling water required for Condensation of Steam:

m_w = mass of cooling water.

m_s = mass of Steam Condensed (Condensate)

h = Total heat of Steam entering the Condenser

h_{f1} = Total heat in Condensate

t_i = Inlet water temperature

t_o = Outlet water temperature

C_w = Specific heat of water.

Heat lost by Steam = Heat gained by cooling water.

$$m_s(h - h_{f1}) = m_w C_w (t_o - t_i)$$

$$m_w = \frac{m_s (h - h_{f1})}{C_w (t_o - t_i)}$$

Dalton's law of partial pressure:

"The pressure of the mixture of the air and Steam is equal to the sum of the pressures, which each constituent would exert, if it occupied the same space by itself."

$$P_c = P_a + P_s$$

P_a = partial pressure of air

P_s = partial pressure of steam.

Comparison:

Jet Condensers

1. Cooling water and Steam are mixed up.
2. Less Suitable for high Capacity plants
3. Condensate is wasted
4. It requires less quantity of circulating water
5. The Condensing plant is economical and simple
6. Its maintenance cost is low
7. More power is required for air pump
8. High power is required for water pumping

Surface Condensers

1. Cooling water and Steam are not mixed up.
2. More Suitable for high Capacity plants
3. Condensate is reused.
4. It requires a large quantity of circulating water.
5. The Condensing plant is costly and complicated
6. Its maintenance cost is high
7. Less power is required for air pump.
8. Less power is required for water pumping.

Vacuum efficiency:

The minimum absolute pressure (ideal pressure) at the Steam inlet of a Condenser is the pressure corresponding to the temperature of the Condensed Steam. The corresponding vacuum (ideal vacuum) is the maximum vacuum that can be obtained in a corresponding plant, with no air present at that temperature. The pressure in actual Condenser is greater than the ideal pressure by an amount equal to the pressure of air present in the Condenser.

"The ratio of the actual vacuum to the ideal vacuum is known as vacuum efficiency."

$$\eta_v = \frac{\text{Actual vacuum}}{\text{Ideal vacuum}}$$

Actual vacuum = Barometric pressure - Actual pressure

Ideal vacuum = Barometric pressure - Ideal pressure

Condenser efficiency:

The definition was proposed by M/s C.A parsons & Co, Today this definition is widely used.

The ratio of temperature raise of cooling water to the difference of vacuum temperature and inlet cooling water temperature.

$$\eta_c = \frac{t_o - t_i}{t_v - t_i}$$

t_o = out let temperature of cooling water

t_i = inlet temperature of cooling water

t_v = vacuum temperature.

Air pump:

The main function of an air pump is to maintain the vacuum in the condenser as nearly as possible, corresponding to exhaust steam temperature. This is done by removing the uncondensable air from the condenser.

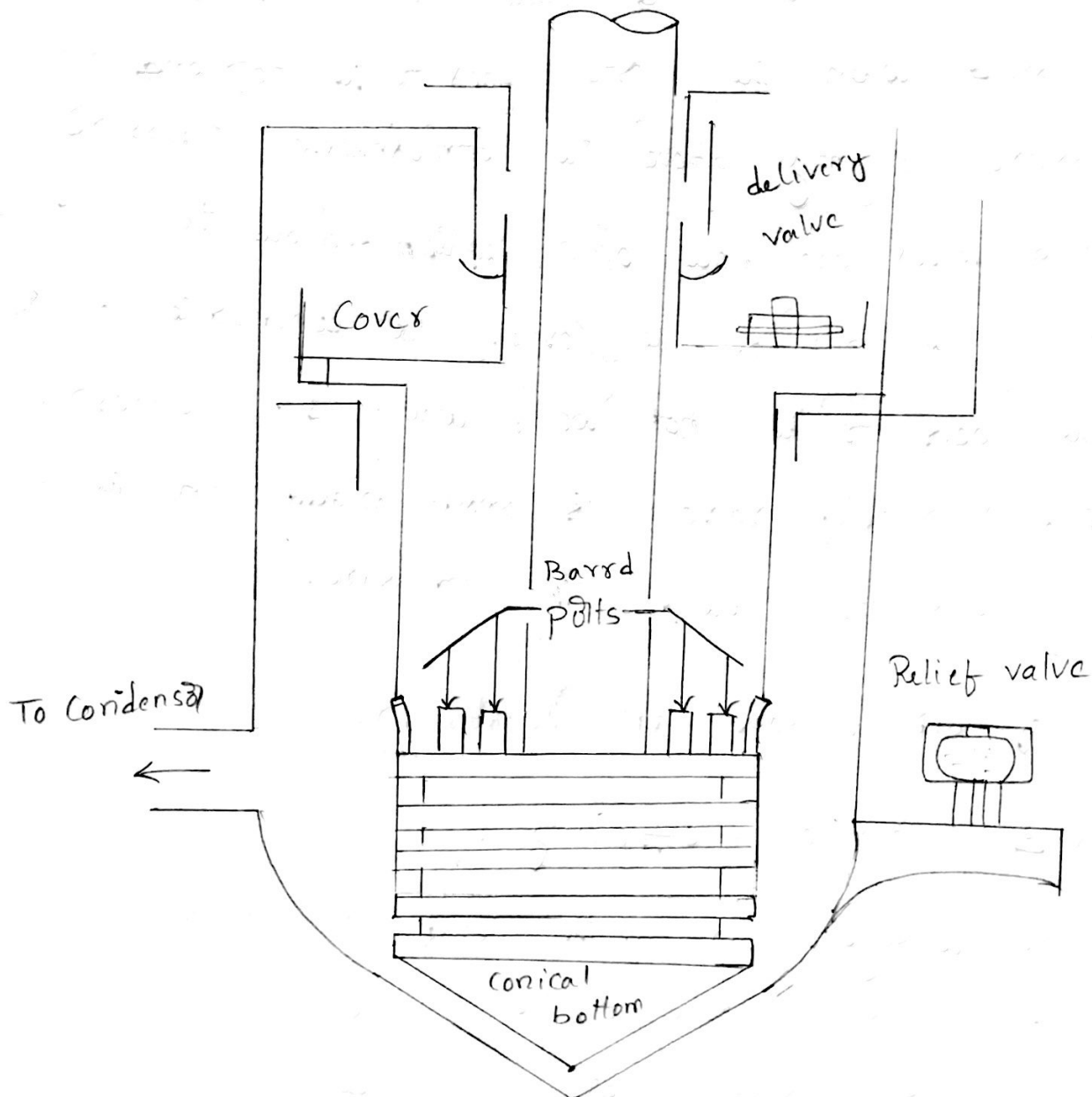
The air pump, which extracts both the condensate and air is called a wet air pump. But a pump which extracts only moist air is known as dry air pump. The air pumps may be of reciprocating or rotary type.

Edward's Air pump:

It is a wet air pump of reciprocating type. The special features of Edward's air pump is the absence of suction & bucket valve, which are necessary in the ordinary reciprocating type air pumps.

The Edward's air pump consists of delivery or

valves. The valves are placed in the cover which is on the top of the pump barrel lever. The reciprocating piston of the pump is flat on its upper surface and conical at the bottom. The pump lever has a ring of ports around its lower end for the whole circumference. This communicates with the Condenser.



When the piston is at the top of the barrel the Condensate and air are collected in the conical portion of the lower part of the barrel, through the ports. On the downward stroke of reciprocating piston, the vacuum is produced above it, since the head valves are closed and sealed by water. The piston uncovers the ports. When it moves downwards, the mixture of Condensate, vapour and air rushes into the space above the piston. This mixture is compressed, when the piston goes to the top and raises the pressure slightly above the atmospheric pressure. The head valves are now open, which allow the mixture to pass on the top of the cover. The Condensate flows over the weir to the hot well, which is at atmospheric pressure. A relief valve is open, placed in the base of the cylinder to release the pressure.

Effects of air leakage in Condensers:

1. Lowered thermal efficiency :

The leakage air in the Condenser results in increased back pressure on the prime mover which means there is loss of heat drop and consequently thermal efficiency of Steam power plant reduced.

The leaked air in the Condenser lowers the partial pressure of the Steam which means a lowered saturation temperature of Steam. As the saturation of temperature of Steam, lowers its latent heat increases so it will require increased amount of cooling water for increased latent heat.

3. Reduced heat transfer:

Air has poor thermal conductivity. Hence leaked air reduces the rate of heat transfer from the vapour and consequently surface of tubes of a surface condenser to be increased for a given condenser capacity.

4. Corrosion:

The presence of air in the Condenser increase the corrosive action.

Cooling towers:

The cooling towers are used in many engineering application the main applications are power plants and refrigerant plant in function is to cool the hot water from the Condenser by exposing it to the atmospheric air so that cold water may

following are some factors effect the cooling water in a cooling water tower.

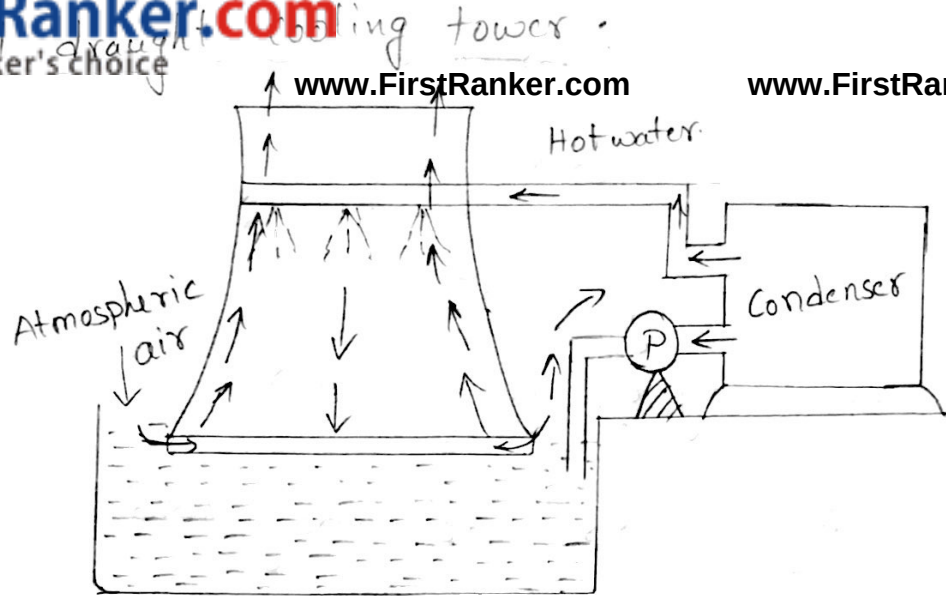
1. Size and height of cooling tower
2. Arrangement of plates in cooling tower
3. Velocity of air entering the cooling tower
4. Temperature of air
5. Humidity of air
6. Accessibility of air to all parts of cooling tower

Types of cooling towers:

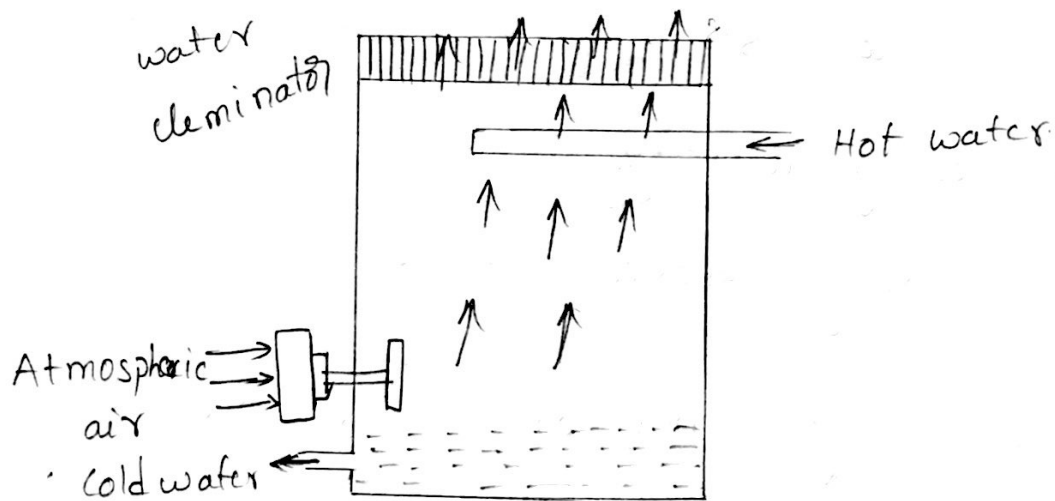
1. According to the type of draught

The cooling tower are classified.

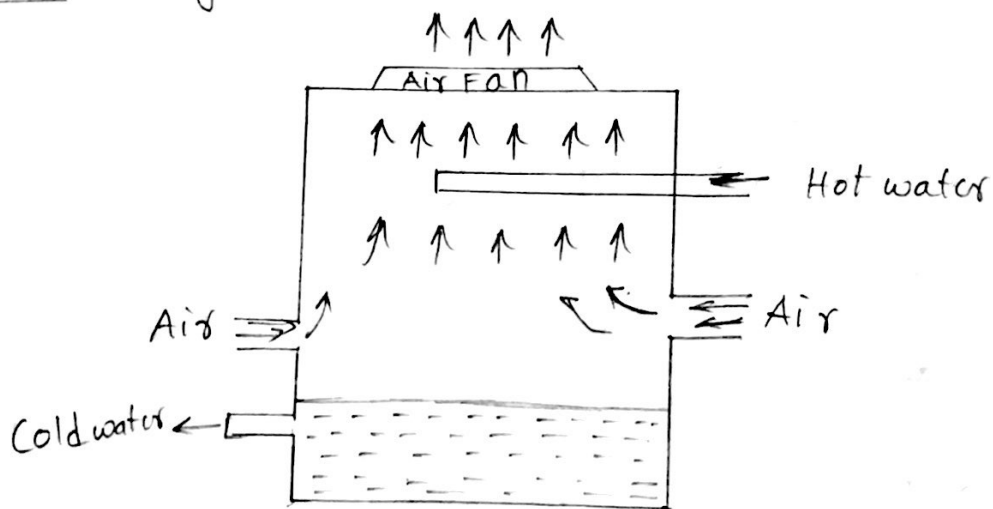
1. Natural draught cooling tower
2. forced draught cooling tower
3. Induced draught cooling tower



2. forced draught:



3. Induced draught :



1. Timber cooling tower
2. Concrete cooling tower
3. Steel duct type cooling tower.

1. Timber cooling towers are rarely used because of following disadvantages.

1. Short life
2. high maintenance cost
3. limited cooling capacity
4. design generally does not facility

2. The Concrete cooling tower are mostly used because of following advantage.

1. large capacity
2. Improved draught and air circulation
3. low maintenance.
4. Increased stability under pressure.

3. The duct type cooling towers are rarely used in case of nuclear power plant due to their small capacity.

UNIT-V

GAS TURBINES

* Comparison between gas turbine & Steam turbine.

Gas turbine	Steam turbine
1. The important components are Compressor, Combustion chamber	1. The important components are boiler and its accessories.
2. The mass of gas turbine per kw developed is less	2. The mass of steam turbine per kw developed is more
3. It requires less space for installation.	3. It requires more space for installation.
4. The starting of gas turbine is very easy	4. The starting of steam turbine is very difficult takes long time
5. The installation and running cost is less	5. The installation and running cost is higher
6. It controls with changing in load condition is easy	6. Its controls with changing load conditions is difficult.
7. A gas turbine does not depend on water supply	7. A steam turbine depends on water supply
8. The efficiency is less gas turbine	8. The efficiency is more in steam turbine.

Gas turbine

1. The mass of gas turbine per kW developed is less
2. Its having high efficiency for gas turbine.
3. The balancing of gas turbine is perfect
4. The torque produced is uniform so no requirement of flywheel
5. The lubrication and ignition system is simple
6. It can be driven at high speeds
7. The pressures used are very low (about 5 bar)
8. The exhaust of gas turbine is free from smoke and less polluting
9. It is very suitable for air crafts.
10. The Starting of gas turbine is not simple

I.C engine.

1. The mass of I.C engine per kW developed is more.
2. Its efficiency is more for I.C engine.
3. The balancing of I.C engine is not perfect.
4. The torque produced is not uniform so it requires flywheel
5. The lubrication and ignition system is difficult.
6. It cannot be driven at high speed.
7. The pressures used are very high (above 60 bar)
8. The exhaust of I.C engine is more polluting.
9. It is less suitable for air crafts.
10. The Starting of I.C engine is simple.

Classification of gas turbines!

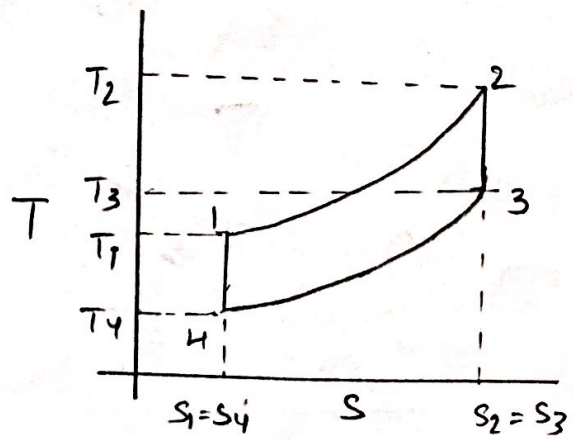
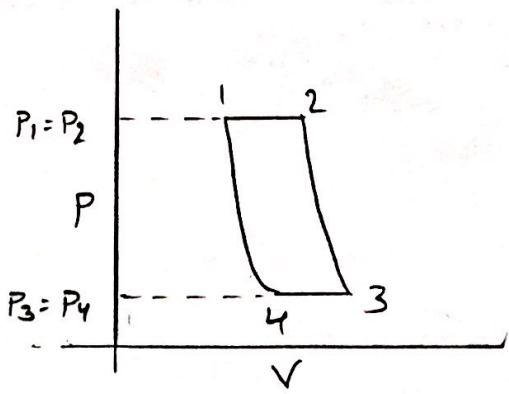
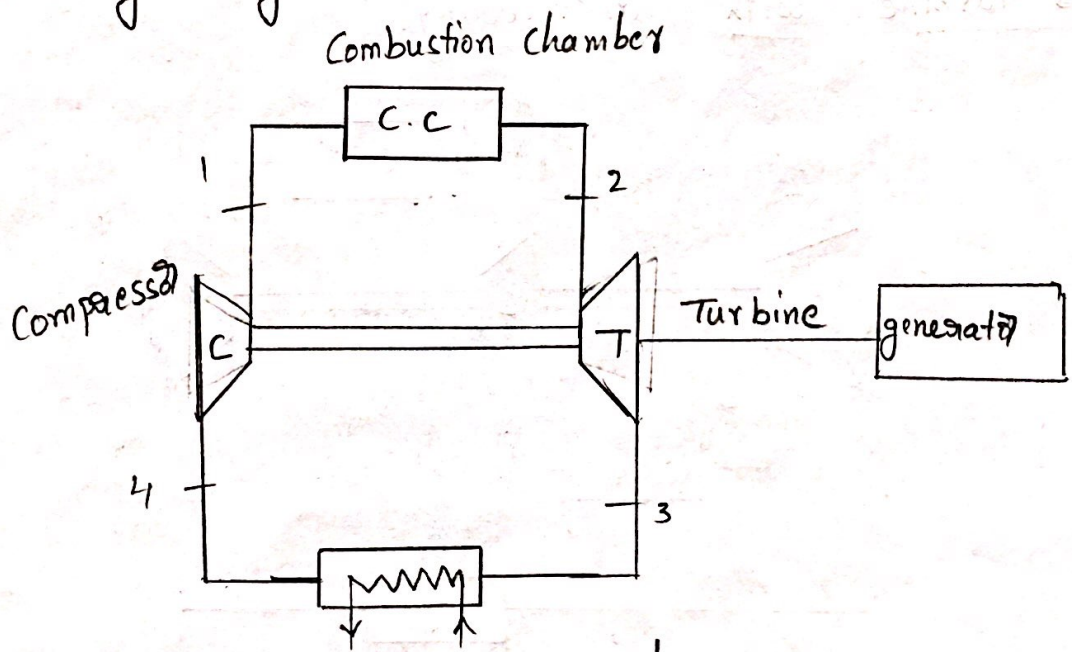
1. According to path of the working substance.

- a. open cycle gas turbine
- b. closed cycle gas turbine
- c. Semi-closed cycle gas turbine

2. According to process of heat absorption.

- a. Constant pressure gas turbine
- b. Constant volume gas turbine.

* closed cycle gas turbine.



2-3 process Isentropic expansion of air in turbine

3-4 process Constant pressure heat rejection.

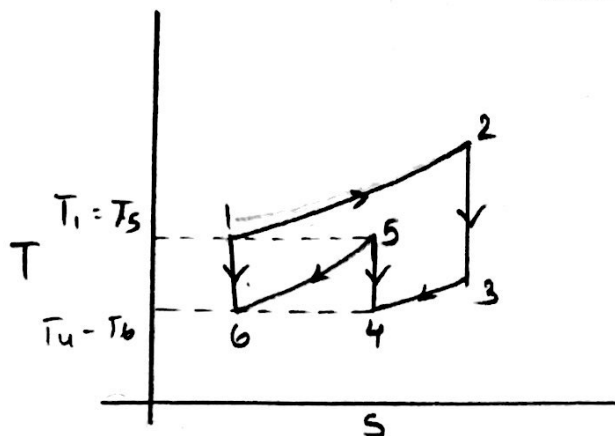
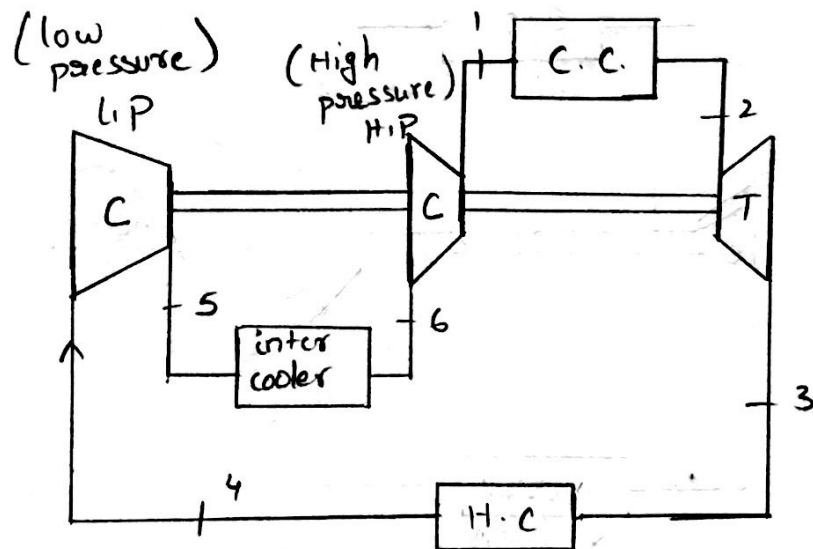
4-1 process Isentropic compression of air in compressor.

Work done by the system $w_T = c_p (T_2 - T_3)$

Work done on the system $w_c = c_p (T_1 - T_4)$

Net work done $w_{net} = w_T - w_c$

* Gas turbine with inter cooling!



$W_{net} = W_T$ www.FirstRanker.com

$$W_T = C_P (T_2 - T_3)$$

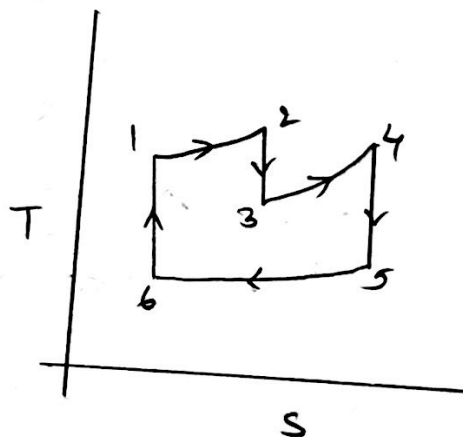
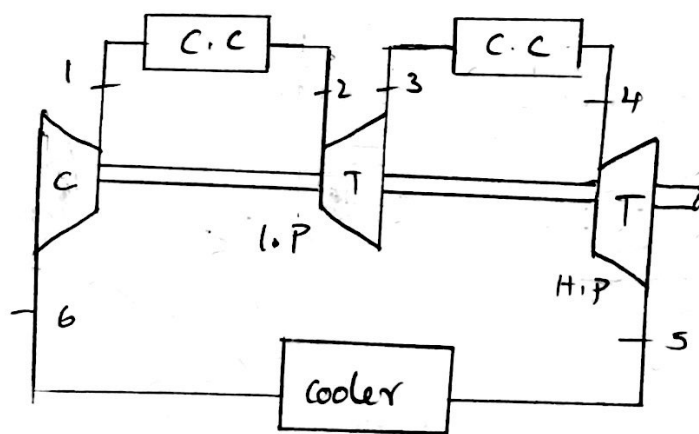
$$w_c = c_p (T_5 - T_4) + (T_1 - T_6)$$

for the perfect intercooling $T_4 = T_6$

$$T_5 = T_1, \quad P_6 = P_5$$

$$P_6 = P_5 = \sqrt{P_1 \times P_4} \times \sqrt{P_2 \times P_3}$$

* Gas turbine with reheat:

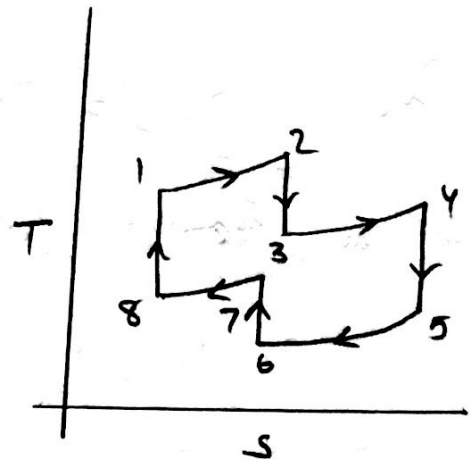
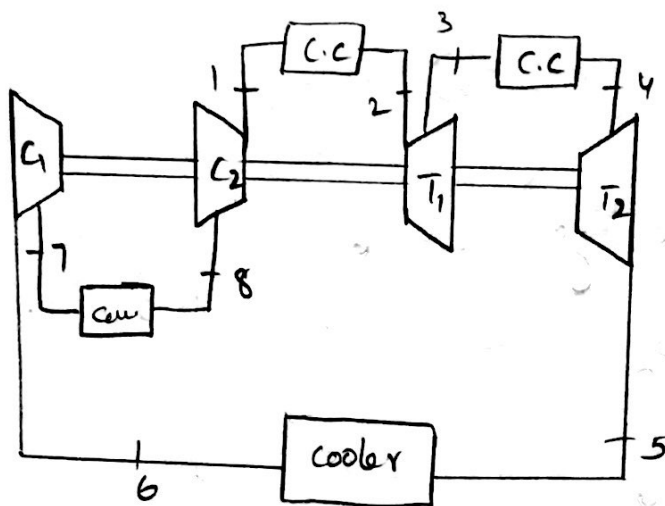


$$W_{net} = W_T - W_C$$

$$W_T = C_p (T_2 - T_3) + C_p (T_4 - T_5)$$

$$w_c = Cp (T_1 - T_b)$$

$$P_3 = P_4 = \sqrt{P_2 \times P_5} = \sqrt{P_1 \times P_6}$$



$$W_{net} = W_T - W_C$$

$$W_T = C_p (T_2 - T_3) + C_p (T_4 - T_5)$$

$$W_C = C_p (T_7 - T_6) + C_p (T_1 - T_8)$$

* Thermal efficiency of ideal gas turbine!

$$\eta_{th} = \frac{\text{Net work done}}{\text{Heat supply}}$$

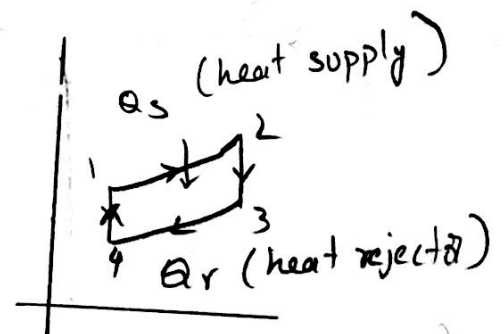
$$W_{net} = W_T - W_C$$

$$= C_p (T_2 - T_3) - C_p (T_1 - T_4)$$

$$\text{Heat supplied} = C_p (T_2 - T_1)$$

$$\eta_{th} = \frac{(T_2 - T_3) - (T_1 - T_4)}{(T_2 - T_1)}$$

$$= 1 - \frac{(T_3 - T_4)}{(T_2 - T_1)}$$



$$r_p = \frac{P_1}{P_4} = \frac{P_2}{P_3}$$

from 1-4 isentropic process

$$\frac{T_4}{T_1} = \left(\frac{P_4}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$$

$$T_1 = T_4 \left(\frac{P_1}{P_4} \right)^{\frac{\gamma-1}{\gamma}}$$

$$T_1 = T_4 (r_p)^{\frac{\gamma-1}{\gamma}}$$

from 2-3 isentropic process.

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2} \right)^{\frac{\gamma-1}{\gamma}}$$

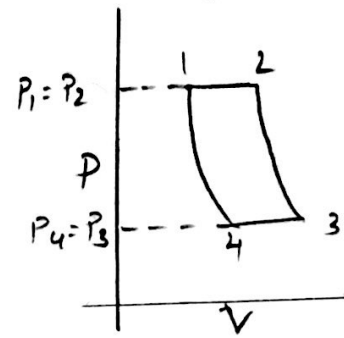
$$T_2 = T_3 (r_p)^{\frac{\gamma-1}{\gamma}}$$

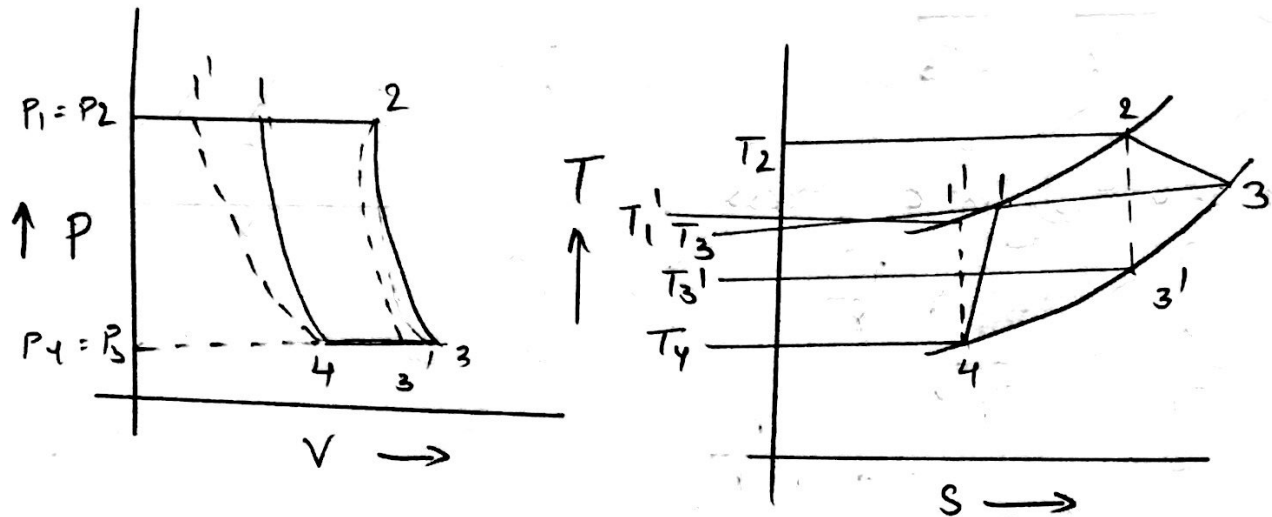
$$\eta_{th} = 1 - \frac{(T_3 - T_4)}{(T_2 - T_1)}$$

$$= 1 - \frac{(T_3 - T_4)}{T_3 (r_p)^{\frac{\gamma-1}{\gamma}} - T_4 (r_p)^{\frac{\gamma-1}{\gamma}}}$$

$$= 1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}$$

$$= 1 - \left(\frac{1}{r_p} \right)^{\frac{\gamma-1}{\gamma}}$$





Ideal $\rightarrow 1' - 2 - 3' - 4$

Actual $\rightarrow 1 - 2 - 3 - 4$

$$W_T = CP(T_2 - T_3)$$

$$W_C = CP(T_1 - T_4)$$

$$W_{net} = W_T - W_C$$

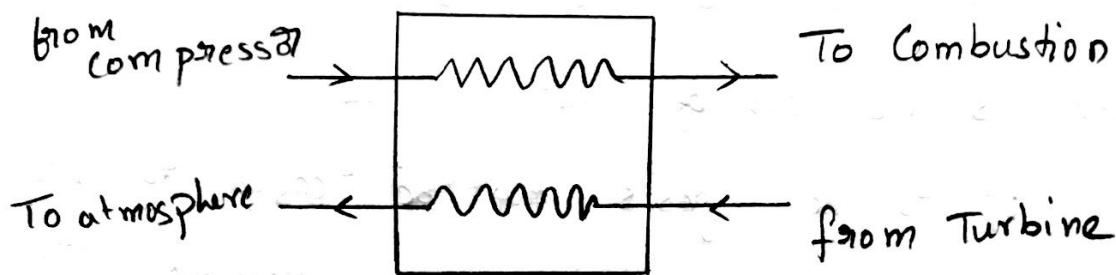
$$\eta_{\text{compressor}} = \frac{T_1' - T_4}{T_1 - T_4}$$

$$\eta_{\text{turbine}} = \frac{T_2 - T_3}{T_2 - T_3'}$$

* Heat exchanger!

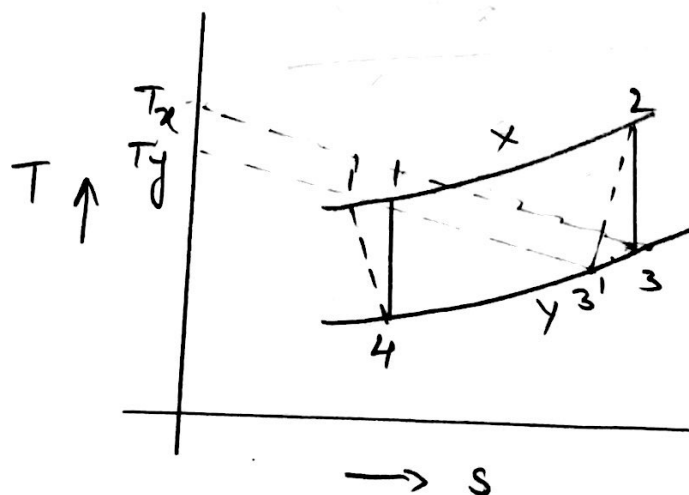
As a matter of a fact exhaust gases leaving in the turbine at the end of expansion having very high Temperatures if this gases are

to pass in to atmosphere then it amounts to the loss of available heat energy in order to achieved fuel economy some of available heat energy is recovered by passing the gases from turbine through a heat exchanger simply have a two passage as shown in figure.



In heat exchanger hot gases from the turbine gets cooled where as air from the compressor gets heated before entering the combustion chamber.

* Efficiency of heat exchanger:-



Let T_x be the temperature of compressed air and T_y is the hot gases temperatures after passing

In an ideal heat exchanger the compressed air would be heated from T_1 to T_2 (T_3) similarly hot gases will be cooled from T_3 to T_4 (T_1) but in actual practice it is not possible. In this case a finite temperature difference is required i.e. $(T_3 - T_2)$ or $(T_4 - T_1)$

If there is no loss of heat in heat exchanger then heat given up to the gases must be equal to heat taken by the air but it is rarely possible. Then the heat exchange efficiency or heat exchanger effectiveness.

$$\eta_c = \frac{\text{Actual heat Transfer}}{\text{max. possible heat transfer}}$$

$$\eta_c = \frac{C_p \times (T_2 - T_1)}{C_p (T_3 - T_1)}$$

UNIT-VI

JET PROPULSION

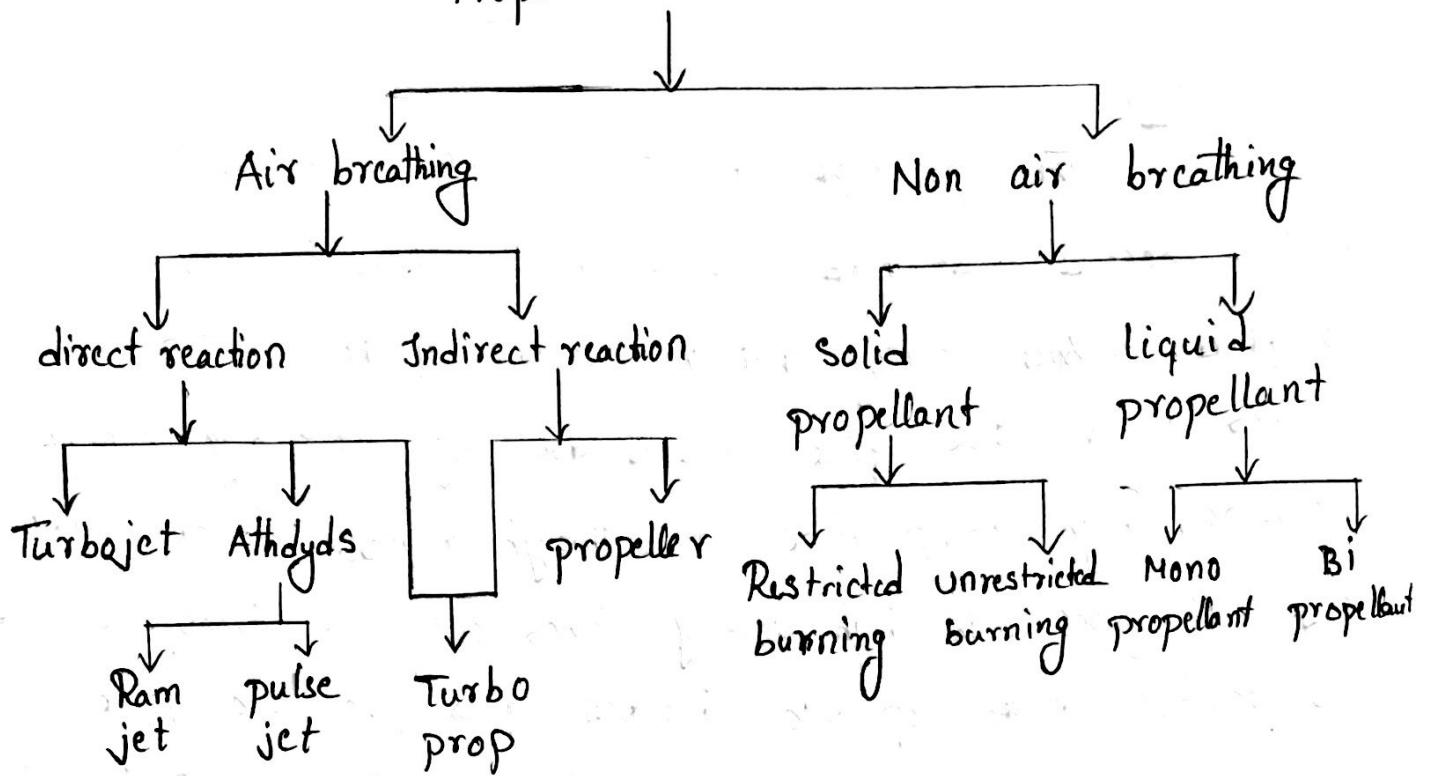
Introduction:

The principle of jet propulsion is based on the Newton's second and third laws of motion. Momentum is imparted to a fluid in such a way that the reaction of the imparted momentum provides a propulsive force. This is done by expanding a high pressure, high temperature gas through a nozzle due to which a jet of gases with high velocity comes out into atmosphere and its reaction in the opposite direction gives propulsive force. (force necessary to move a vehicle forward). Jet propulsion has got its name because the driving force to move a vehicle comes from the reaction of a high velocity jet of gases. For jet propulsion systems, an open cycle gas turbine is a most suitable choice.

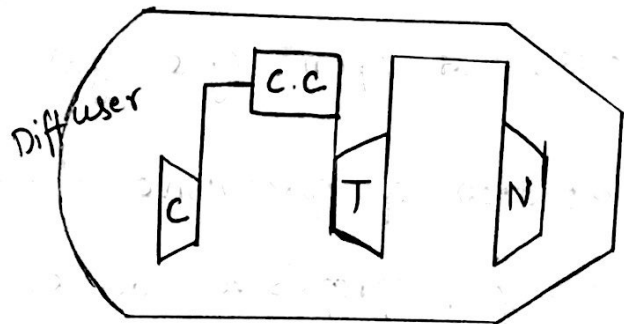
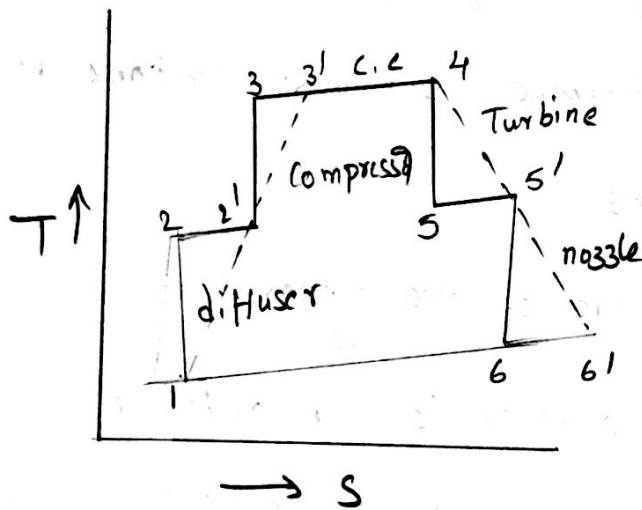
Classification of propulsive devices:

Basically, propulsive devices are of two types:

1. Devices which make use of atmospheric air as the main propulsive fluid. These are called as atmospheric jet engines or air breathing engines.
2. Devices which carry their own propulsive fluid. These are known as - Rockets or Non air breathing engines.



* Turbo jet engines:-



process 1-2 the entering air from the atmosphere is diffuser (that means the air velocity is slows down and this velocity is converted to pressure energy) Isentropically from c_1 to 0. (i.e $c_2 = 0$) it indicates diffuser having 100%.

1-2' is actual process.

process 2-3 isentropic compression of air

2'-3' is actual process.

process 3-4 isentropic compression ideal addition of heat at constant pressure.

3'-4' is actual heat addition at constant process.

process 4-5 isentropic expansion of gas in the turbine.

4-5' is actual expansion in turbine

process 5-6 isentropic expansion of gas in nozzle

5'-6' actual expansion.

Consider one kg of working fluid to the system.

Diffuser:- Between states one and two write an energy equation.

$$\frac{v_1^2}{2} + h_1 + Q_{1-2} = \frac{v_2^2}{2} + h_2 + W_{1-2}$$

v_1 = Velocity of entering air

v_2 = velocity of after diffusing = 0

Q_{1-2} = heat addition = 0

$W_{1-2} = 0$

$$h_2 = h_1 + \frac{v_1^2}{2}$$

In temperature $T_2 = T_1 + \frac{v_1^2}{2c_p} \quad (h = c_p T)$

$\therefore$ diffuser efficiency $= \frac{h_2 - h_1}{h_2' - h_1}$

Temperature $\eta_d = \frac{T_2 - T_1}{T_2' - T_1}$

$h_2' = h_1 + \frac{v_1^2}{2\eta_d} \quad (a) \quad T_2' = T_1 + \frac{v_1^2}{2c_p \eta_d}$

Compressor:

Energy equation between 2-3

$$h_2 + \frac{v_2^2}{2} + e_{2-3} + w_c = h_3 + \frac{v_3^2}{2}$$

Assuming, changes in potential & kinetic energies are zero.

The ideal expansion of work compression.

$$w_c = h_3 - h_2 = c_p (T_3 - T_2)$$

The actual work.

$$w_{act} = h_3' - h_2$$

$$= \frac{h_3 - h_2}{\eta_c} = \frac{c_p (T_3 - T_2)}{\eta_c}$$

Ideal heat supplied $Q_{3-4} = h_4 - h_3$
 $= c_p (T_4 - T_3)$

Actual heat supplied $Q = \left(1 + \frac{m_f}{m_a}\right) (h_4 - h_{3'})$
 $= c_{p_g} \left(1 + \frac{m_f}{m_a}\right) T_4 - c_{p_a} T_{3'}$

Turbine: Between states 4-5

Energy equation for turbine.

$$h_4 + \frac{v_4^2}{2} + Q_{4-5} = h_5 + \frac{v_5^2}{2} + W_{4-5}$$

$$Q_{4-5} = 0$$

ideal
 Turbine work $W_T = h_4 - h_5 + \left(\frac{v_4^2 - v_5^2}{2}\right)$

If we neglect the kinetic energy

$$W_T = h_4 - h_5 = c_p (T_4 - T_5)$$

Actual work. $W_T = h_4 - h_{5'}$
 $= c_p (T_4 - T_{5'})$
 $= c_p (T_4 - T_5) \eta_t$

Jet nozzle: Between states 5-6

ideal $h_5 + \frac{v_5^2}{2} = h_6 + \frac{v_6^2}{2}$

v_5 is very small compared to v_6

$$h_5' = h_6' + \frac{v_6'^2}{2}$$

$$\frac{v_6'^2}{2} = h_5' - h_6'$$

$$v_6' = \sqrt{2 (h_5' - h_6')}$$

Velocity of jet

$$v_j \text{ (or) } v_6' = \sqrt{2 \eta_n (h_5' - h_6')}$$

$$\text{Thermal efficiency} = \frac{\text{work done}}{\text{heat supplied}}$$

$$\eta_{th} = \frac{(h_4 - h_6') - (h_3' - h_1)}{(h_4 - h_3')}$$

$$= \frac{(T_4 - T_6') - (T_3' - T_1)}{(T_4 - T_3')}$$

Advantages of turbo jet engines:

1. Simplicity - The construction is simpler compared to reciprocating engines and there are no unbalanced forces of reciprocating parts.
2. Low Specific weight - Compared to reciprocating engines, the specific weight is much less.

power output - much higher power than a reciprocating engine can be developed. It can operate on a larger range of mixture strength

4. Much higher speeds can be obtained.
5. No lubrication is needed.
6. Small frontal area.
7. Compared to reciprocating engines, weight to power ratio is higher.
8. Because of no reciprocating parts, it is vibration free and greater reliability is thus achieved.
9. At high speeds and at high altitudes, the efficiency is much higher than a propeller.
10. Combustion and power output are continuous and there are no fluctuations of pressure.

Disadvantages:

A Turbojet engine suffers from the following disadvantages.

1. At low altitudes and low speeds, the fuel consumption is more than that of a reciprocating engine.
2. Life of unit is relatively shorter
3. Materials are costlier and noise is more
4. During take off, the thrust is low,

1. Thrust T :

The jet engines are compared on the basis of engine thrust. Thrust is the force produced due to change of momentum of working fluid.

Let V_a = velocity of air craft through the air. It is also called as velocity of approach of air - m/sec

V_j = velocity of jet relative to air craft - m/sec

m_a = Mass flow of air - kgs

m_f = Mass of fuel - kgs.

$\therefore \left(1 + \frac{m_f}{m_a}\right)$ = mass of products leaving the nozzle for 1 kg of air

$\therefore$ Thrust of jet engine $T = \left(1 + \frac{m_f}{m_a}\right) \cdot (V_j - V_a) \text{ N} \cdot \text{kg of air/sec}$

mass of fuel is very less and hence can be neglected.

Assuming expansion upto atmospheric pressure (There is no pressure thrust and the vehicle is moving in still air), thrust of turbojet

$$T = m_a \cdot (V_j - V_a) \text{ N/sec.}$$

2. Thrust power : T.P : It is defined as the rate at which work must be developed by the engine if the vehicle is to be kept moving at a constant velocity V_a against friction

Thrust power T.P = Thrust $\times$ Velocity of vehicle.

Neglecting mass of fuel

$$T.P = m_a (v_j - v_a) \cdot v_a \text{ - watts.}$$

$$= (v_j - v_a) \cdot v_a \text{ - watts / kg of air}$$

3. Propulsive power : P.P

It represents the energy required to change the momentum of mass flow of air and is expressed as the difference between rate of kinetic energies of entering air & exhaust gases.

Neglecting mass of fuel

$$\therefore P.P = \frac{(v_j^2 - v_a^2)}{2} \cdot m_a \text{ watts.}$$

Also, $P.P = \text{Thrust power} + \text{kinetic energy loss.}$

4. Propulsive efficiency: It is defined as the ratio of thrust power to propulsive power.

Neglecting mass of fuel,

$$\eta_p = \frac{[(v_j - v_a) \cdot v_a]}{\left(\frac{v_j^2 - v_a^2}{2}\right)} = \frac{2v_a}{(v_a + v_j)} = \frac{2}{\left(1 + \frac{v_j}{v_a}\right)}$$

The propulsive efficiency increases with an increase in aircraft velocity but the thrust decreases. The propulsive

Efficiency becomes 100% when v_a approaches v_j . Then the thrust reduces to zero. So, a lower value of propulsive efficiency is used to obtain reasonable thrust.

$$\eta_p = \frac{(v_j - v_a) \cdot v_a}{v_j^2}$$

$$\eta_p = \frac{T \cdot P}{P \cdot P} = \frac{T \cdot P}{T \cdot P + \text{kinetic energy loss}}$$

The kinetic energy loss is the kinetic energy of jet dissipated as the stream of jet velocity comes to rest relative to the surroundings. There must be a loss wherever the effective jet velocity is not equal in magnitude to the speed of the flight through the surroundings.

5. Thermal efficiency : η_{th} :

It is defined as the ratio of propulsive power to heat energy supplied.

$$\begin{aligned} \eta_{th} &= \frac{\text{Propulsive work}}{\text{Heat energy supplied.}} \\ &= \frac{\text{change in kinetic energy of gases}}{\left(\frac{m_f}{m_a} \times \text{calorific value of fuel} \right)} \end{aligned}$$

Neglecting mass of fuel.

$$\eta_{th} = \frac{(v_j^2 - v_a^2)}{2 \left(\frac{m_f}{m_a} \right) \cdot \text{C.V.}}$$

$$\eta_{ov} = \eta_{th} \times \eta_p = \text{Thermal efficiency} \times \text{propulsive efficiency.}$$

Also, $\eta_{ov} = \text{propulsive efficiency} \times \text{Turbine efficiency} \times \text{nozzle efficiency.}$

$$= \frac{v_a (v_j - v_a)}{\left(\frac{m_f}{m_a}\right) \cdot \text{calorific value.}}$$

7. Jet efficiency : η_j : It is defined as.

$$\eta_j = \frac{\text{final kinetic energy in the jet}}{\text{Isentropic heat drop in the jet pipe + carry over from steam turbine}}$$

Thrust Augmentation:

One of the drawbacks of a turbojet engine is that relatively small power will be available at the time of take off and climb compared to reciprocating engine. So, temporary thrust augmentation is necessary for take off and climb. It is also necessary for combat and emergency power requirements of military air crafts.

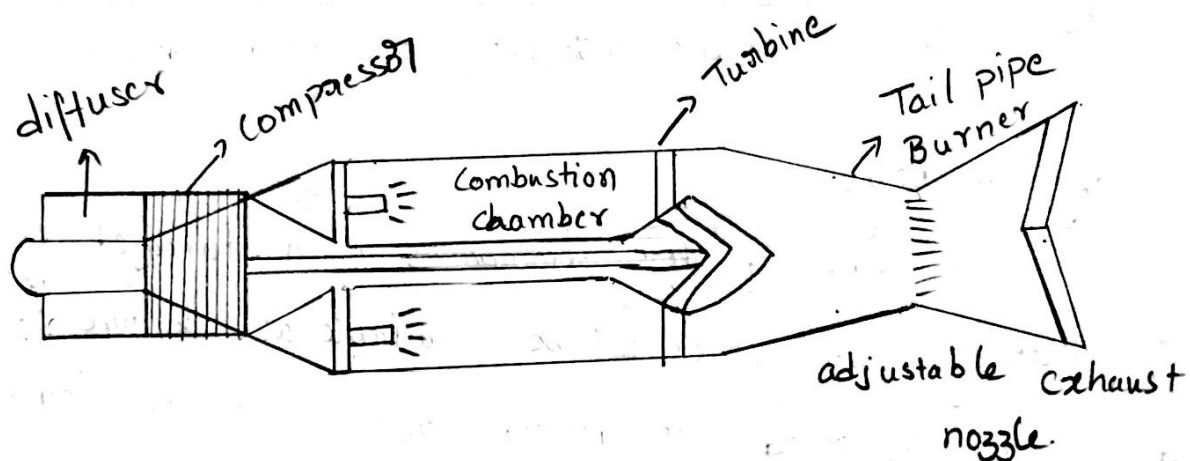
The thrust may be increased by increasing the mass flow rate of air or by increasing the jet exit velocity or by increasing both. Two principal methods of thrust augmentation are.

2. Water - methanol injection.

Turbojet with after burner!

After burning is the most effective means of thrust augmentation but uneconomical and so it is used for short durations only whenever necessary rather than continuously.

The figure shows a turbojet engine equipped for after burning or tail pipe burning



After burning consists of introducing and burning the fuel between the turbine and nozzle exit and has the same effect as a reheater. Its function is to increase the exit temperature, which results in an increased jet velocity thus increasing the thrust.

A turbojet operates with 4-5 times as much air as is required for the combustion of fuel to limit the gas

①
has enough air to support further combustion. For a turbojet engine with after burner, the inlet velocities must be sufficiently low to support stable combustion and to avoid excessive pressure loss, a diffuser is provided b/w turbine outlet and tail pipe burner inlet.

The burning of fuel increases volume of gas and hence causes the stream to be ejected from the jet pump pipe nozzle at an increased velocity so increasing the thrust produced. The amount of fuel injection is limited by the temperature the tail pipe or reheat pipe can withstand.

In jet engines, there is an optimum nozzle area for particular conditions. With after burner, a larger exit area is required for burning gases. This is incorporated by providing a variable area nozzle.

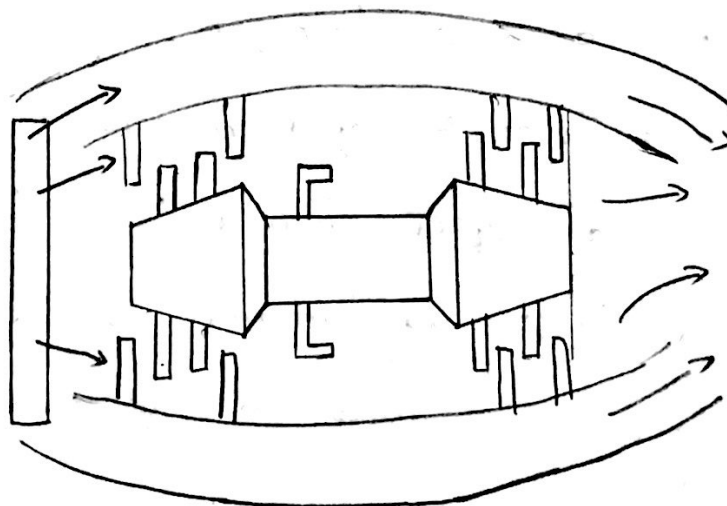
The after burner may be considered as a ram jet engine attached to the end of a turbojet engine. The turbojet engine "rams" the air into the after burner. So, the combination of turbojet engine and after burner is called - "Turbo ramjet". Besides a thrust augmentation device, the turbo-ramjet engine may be considered as special type of engine for flight at super sonic speed.

It consists of spraying a mixture of water and methanol into the inlet compressor. This increases the thrust by causing and increase in mass flow due to the inlet air temperature being reduced plus the addition of mass of water-methanol itself.

The combustion of methanol produces high enough heat to offset the cooling effect of water otherwise the flow of fuel would have to be increased abnormally. This method may increase the thrust by 25%. The disadvantage of this method is that besides fuel, another liquid is required to be carried.

By pass Turbojet engine!

This increases the thrust without adversely affecting the propulsive efficiency and fuel economy



The figure shows a by pass turbojet engine.

A fan is located in the front portion and it is driven by the main shaft. part of the air drawn by the fan is sent over the combustion chamber via suitable ducting to the exhaust unit thus by passing the engine and hence the name - "By pass"

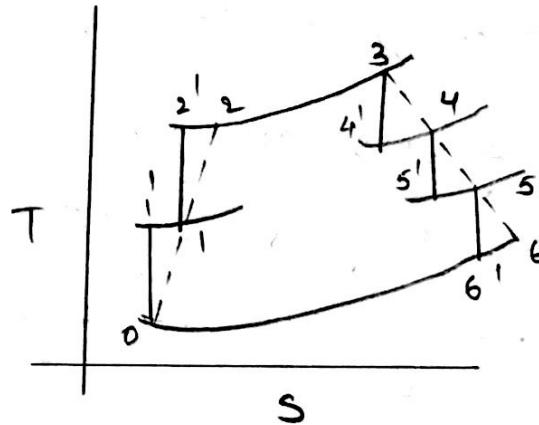
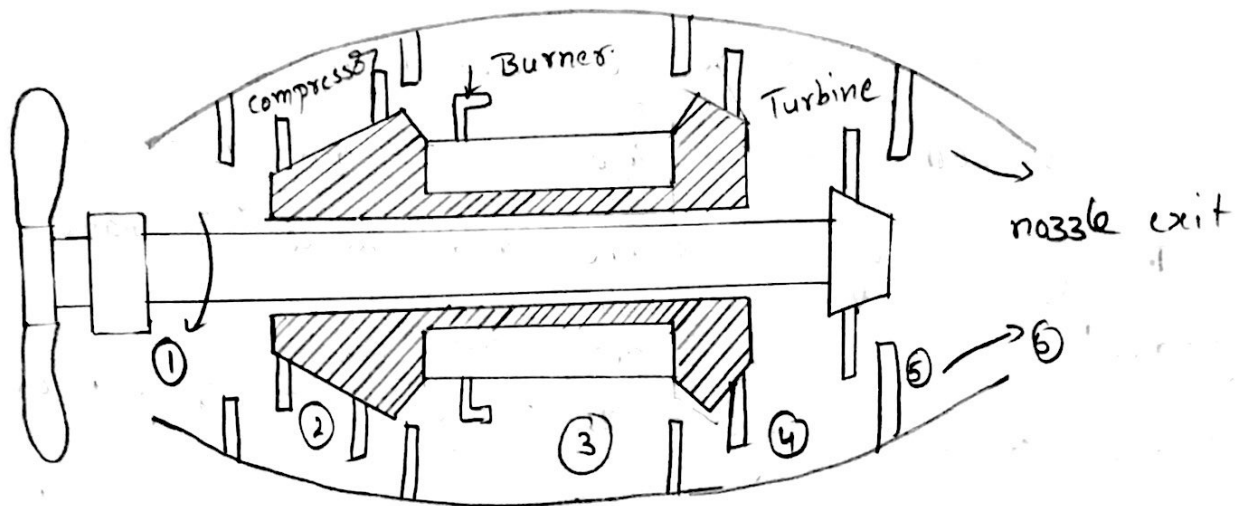
A portion of air is sent to the engine compressor with an added advantage of creating a super charging effect. The by pass ratio is selected according to the requirement.

The advantage of by pass arrangement is that the lower velocity of jet efflux gives a better propulsive efficiency and better fuel economy than a straight jet for a given thrust as less kinetic energy is wasted to atmosphere. This applies particularly at air craft speed below sonic and for long range air craft

Turbo prop engine:

When a gas turbine is used to drive a propeller the engine is known as - Turbo propeller engine.

The figure shows a turbo prop consisting of two independent turbines.



The turbo prop consists of a geared propeller attached to the turbojet engine. The power developed by the turbine is consumed in driving the compressor and the propeller. To add more power to the propeller shaft the turbine is modified by adding additional stages.

About 80-90% of the power developed is used to drive the shaft and the remaining is used to obtain thrust from the jet. The control of the engine is governed

of fuel burned.

In the turboprop engine shown, one turbine drives the compressor while the other drives the propeller through a reduction gear.

The cycle of turboprop is same as that of turbojet engine cycle except the turbine expansion process is greater. Regenerators, inter coolers and reheaters may be incorporated to improve its power and efficiency.

Athodyds (Ram jets and pulse jets):

At high aircraft speed, the turbojet is designed to take the advantage of ram compression. At mach No. 2, the ideal ram compression ratio is about 8. At such high ram compression, there is no need of a compressor. In a turbojet, the turbine is only to drive the compressor. So when compressor is eliminated, turbine also gets eliminated. Ramjet and pulse jet engine work on this principle. The work 'Athodyd' is derived from - Aero-thermodynam duct.

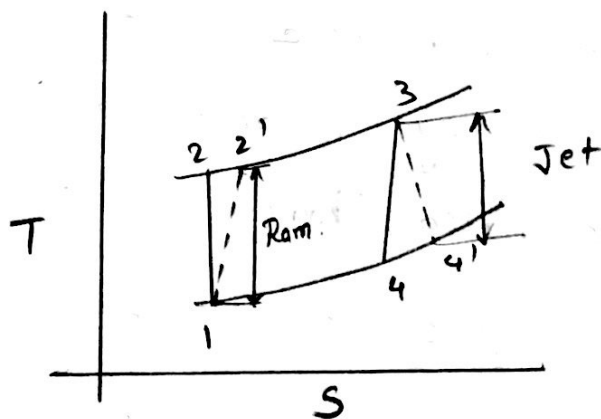
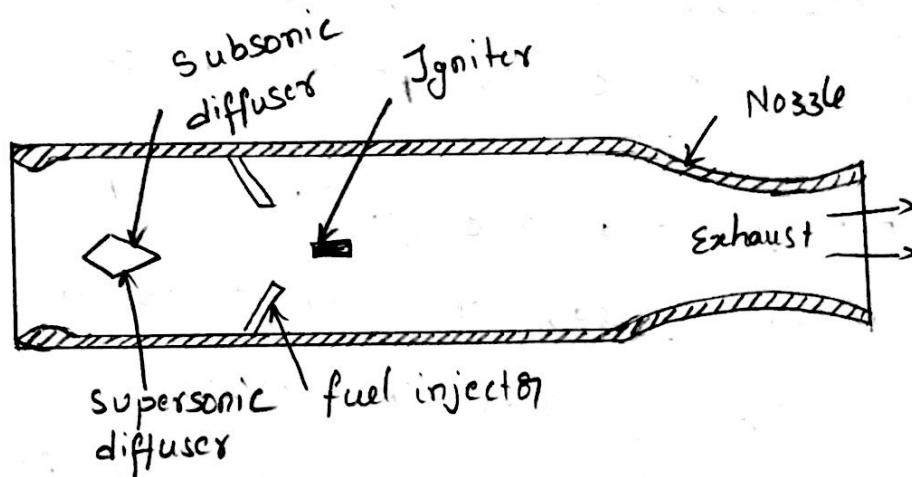
Ram jet!

It is also called as - Lamin tube or flying stovepipe.

Ramjet engines have the capability to fly at super sonic

The ramjet consists of an inlet diffuser, combustion chamber and exit nozzle or a tail pipe. It is a steady combustion or continuous flow engine and has simplest construction of any propulsion engine.

The figure shows the ramjet and its corresponding working cycle on T-s diagram.



The air enters the plant with super sonic speed and it is slowed down to sonic velocity in the super sonic diffuser. The air is compressed due to compression shock waves as the velocity changes. Further compression and hence pressure rise takes place in the subsonic

the velocity of air passing through the diffuser decreases and hence the pressure increases. This is called - Ram Compression. A 'pressure barrier' is created after the end of diffuser.

Advantages:

1. It is simple in construction.
2. It has no moving parts and so free from unbalancing and vibrations.
3. Except rocket, thrust developed per unit engine weight is more than any other propulsion unit.
4. Wide range of fuels can be used.

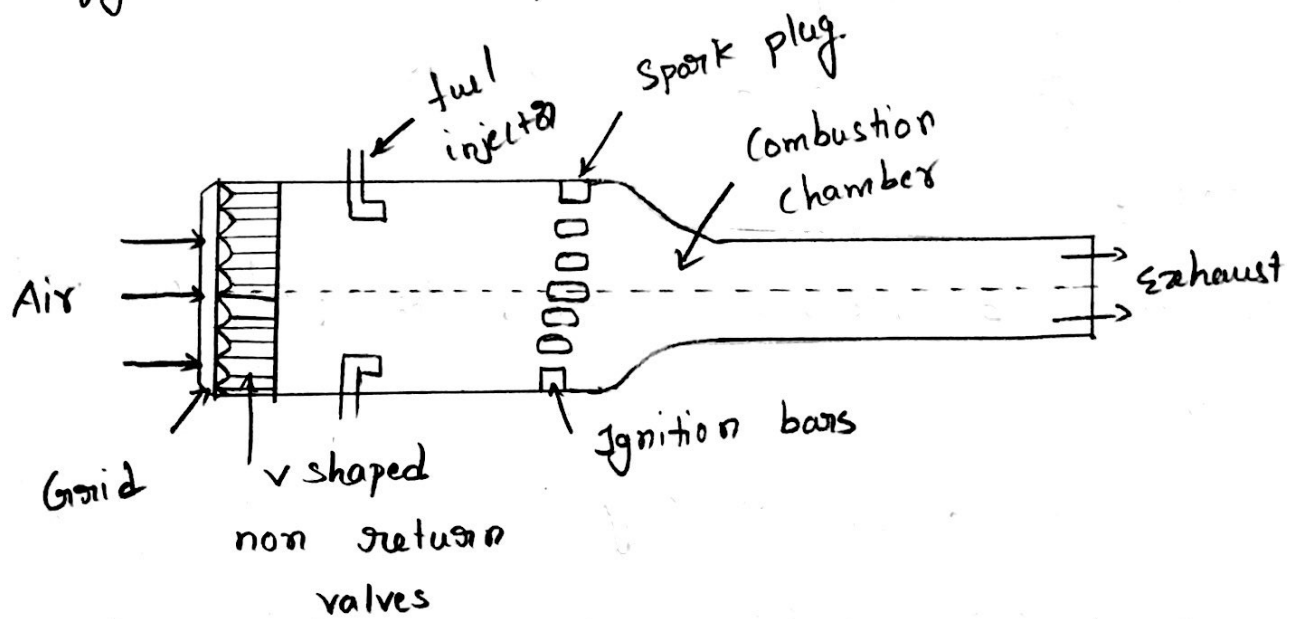
Limitations:

1. At low and moderate speeds, the fuel consumption is high.
2. It will not operate statically (when not moving), since it needs velocity of air incoming for compression. So, it needs a turbojet or rocket to boost it upto a speed of 400 km/hr or more before it produces any thrust and propels itself.
3. To obtain steady combustion and flame stabilization, devices like flame holders are required.

Like ram jet engine, this also develops power or thrust by a high velocity jet of exhaust gases without the need of a compressor or turbine.

A pulse jet engine is an intermittent combustion engine and operates on a cycle similar to a reciprocating engine whereas turbojet and ramjet are continuous in operation and are based on brayton cycle.

The figure shows a pulse jet engine.



The compression of incoming air is done by ram effect in the diffuser. The grid passages are opened and closed by v-shaped non return valves.

The fuel is injected into the combustion chamber by fuel injectors and the combustion is initiated by a spark

Once the combustion starts, sparks is turned off and the residual flame in the combustion chamber is used for subsequent combustion.

After the passage of hot gases to atmosphere, the pressure in the chamber falls and the high pressure air in the diffuser forces the valves to open and fresh air enters the combustion chamber and the cycle repeats.

As the airflow is not continuous; this is an intermittent combustion engine.

Advantages:

1. This is very inexpensive compared to a turbojet engine.
2. It is capable of producing static thrust and produces thrust in excess of drag at much lower speeds than a ram jet.

Limitations:

1. Noise level is high
2. High rate of fuel consumption.
3. Thermodynamic efficiency is low
4. Serious limitations to mechanical valve arrangement
5. Vibrations are severe.
6. The operating altitude is limited by air density consideration.

Introduction!

The principle of rocket has been adopted for propulsion of air crafts, missiles and space crafts.

Unlike jet engines, the rocket engine carries its own oxygen and so not dependents on atmosphere for its working. Similar to jet propulsion, the thrust required for rocket propulsion is produced by high velocity jet of gases passing through the nozzle.

Classification of rockets:

The rockets may be mainly classified as:

1. According to type of propellants.

(a) Solid propellant rocket.

(b) liquid propellant rocket.

2. According to number of motors.

(a) single stage rocket (one motor only)

(b) Multi stage rocket (more than one motor)

Applications of rockets:

The following are the important applications of rockets.

1. Missiles.

3. Signalling and fire work display.
4. Space ships
5. Research
6. long range artillery.
7. Air crafts.

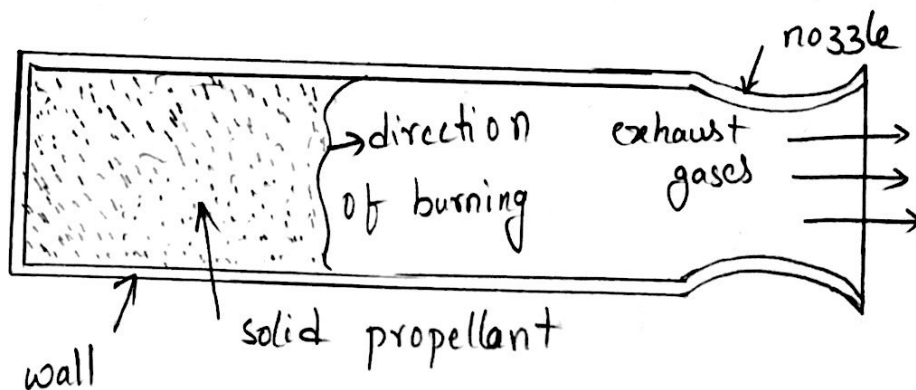
Requirements of an ideal rocket propellant:

A good rocket propellant should have the following characteristics

1. High calorific value
2. High density so that it occupies less space
3. Stability and ease of handling.
4. Reliable smooth ignition.
5. low toxicity and corrosiveness.

Solid propellant rocket:

figure shows the schematic diagram of a solid propellant rocket.



It consists of a seamless tube usually made of steel closed at one end. The tube is filled with solid propellant which contains both fuel and oxidiser. The propellant is ignited electrically and burns continuously. There is no method to stop the burning of propellant. The open end contains a convergent-divergent nozzle through which gases are ejected out at supersonic speed. The reaction to ejection of high velocity gases produces the thrust of the rocket.

The configuration of the solid propellant varies according to the required thrust-time programme for the engine. The rate of burning is controlled by the configuration of the propellant.

There are 2 important types of solid propellants.

1. Composite or heterogeneous propellant.
2. Homogeneous double base propellant.

The composite solid propellant consists of an inorganic oxidiser such as potassium perchlorate or sodium nitrate dispersed in a fuel matrix. The double base propellant consists of colloid of Nitroglycerin - Nitrocellulose.

The main advantages of solid propellant rocket is its simplicity as it has no moving parts, and main disadvantage is this is short range application only.

and as boosters for aircrafts and space crafts.

Liquid propellant rockets!

The liquid propellants are of 2 types

1. Mono propellant

2. Bi propellant.

A mono propellant is a liquid that requires no oxidiser for releasing the energy. Nitromethane, propyl nitrate and hydrogen peroxide are the general monopropellants.

In liquid propellant rockets, separate tanks are provided for fuel and oxidiser. Both these mix in a Combustion chamber where combustion takes place. In case of solid propellant rockets, the self tube in which propellant is filled forms the combustion chamber.

Some propellants are ignited with an electrical igniter

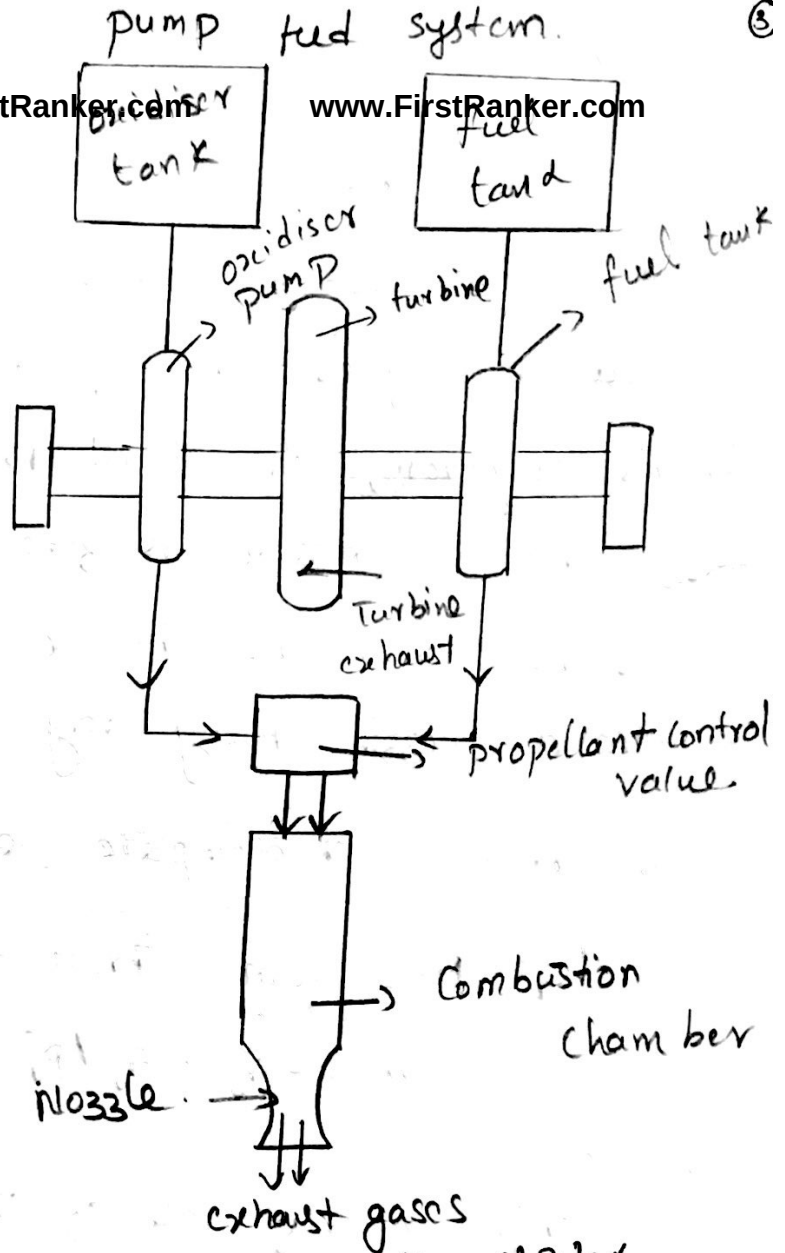
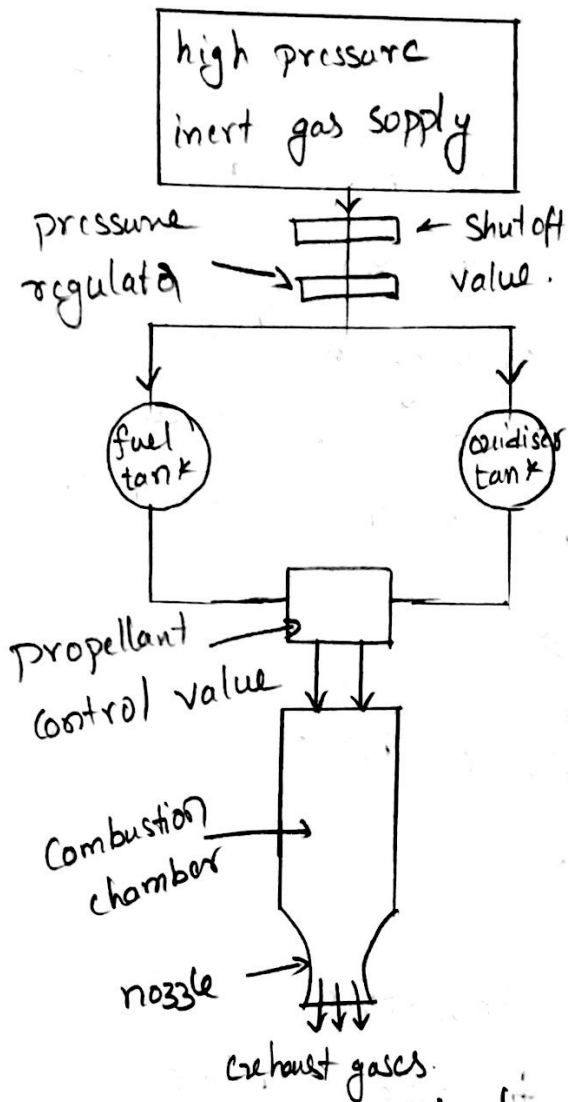
Some propellants ignite upon contact with each other

These self igniting propellants are called - Hypergolic propellants.

Liquid propellant rockets operate on 2 systems

1. Pressure feed system

pressure feed system



The pressure feed system is suitable for shorter duration and pump feed system is suitable for rockets of high power and longer duration.

The use of additional thrust by rocket motor at take off is termed as - jet assistance take off (JATO) or Rocket assistance take off (RATO). pressure feed system has been used for RATO.

The thrust is equal to rate of change of momentum of the working medium. The maximum velocity from nozzle is obtained when gases are expanded upto ambient pressure. In this situation, the thrust is only due to velocity and the thrust due to pressure is zero. When operating at high altitudes this is not practicable because complete expansion would require a nozzle having very large exit to throat area ratio.

The thrust with incomplete expansion.

$$T = \text{Momentum thrust} + \text{pressure thrust}$$

$$= m_p \cdot v_j + A_j (P_j - P_a)$$

Where

m_p = mass of rate of propellant consumption - kgs/sec.

v_j = jet exit velocity relative to nozzle - m/sec

P_j = Exit Static pressure - bar

P_a = Ambient pressure - bar, A_j = Exit area - m^2

Effective jet exit velocity v_{je} :

This is a term used in rocket motor testing.

$$\text{Thrust } T = m \cdot v_{je}$$

$$= m_p \cdot v_j + A_j (P_j - P_a)$$

$$\therefore v_{je} = v_j + \frac{A_j}{m_p} (P_j - P_a)$$

It is the Thrust multiplied by the flight velocity

$$T_p = T \cdot v_a$$

$$= m_p \cdot v_{je} \cdot v_a$$

v_a = velocity of air relative to the engine.

Propulsive efficiency of a rocket η_p :

propulsive efficiency.

$$\eta_p = \frac{\text{Thrust power}}{\text{Thrust power} + \text{K.E loss.}}$$

$$= \frac{m_p \cdot v_{je} \cdot v_a}{(m_p \cdot v_{je} \cdot v_a) + (m_p \cdot (v_{je} - v_a)^2 / 2)}$$

Specific impulse!

It is another term used in the performance of a rocket. It is defined as the ratio of thrust force to rate of propellant expenditure.

$$I_s = \frac{T}{m_p} \text{ kg thrust / kg propellant / sec.}$$

$$= \frac{m_p \cdot v_{je}}{m_p}$$

$$= v_{je} \text{ seconds.}$$

1. A rocket is a device which works on the principle of jet propulsion, carries its own oxygen for combustion of fuel and so it can work at high altitudes and in vacuum also.
2. Rockets can be mainly classified based on the type of propellant and number of stages.
3. fuel along with oxidiser
4. The unit of specific impulse is - seconds.
5. for given nozzle and reactant, thrust of rocket at any altitude is a function of combustion pressure.
6. The specific thrust increases with increasing value of combustion temperature and low molecular weight of gases
7. With liquid propellants, rate of combustion can be controlled better.
8. Propulsive efficiency of a rocket is less than propeller and turbojet.