Reaction turbines

The reaction turbines which are used these days are really impulse - reaction turbine. pure reaction turbines are not in general use. The expansion of steam and heat drop occur both fixed and moving blades. Mech - A

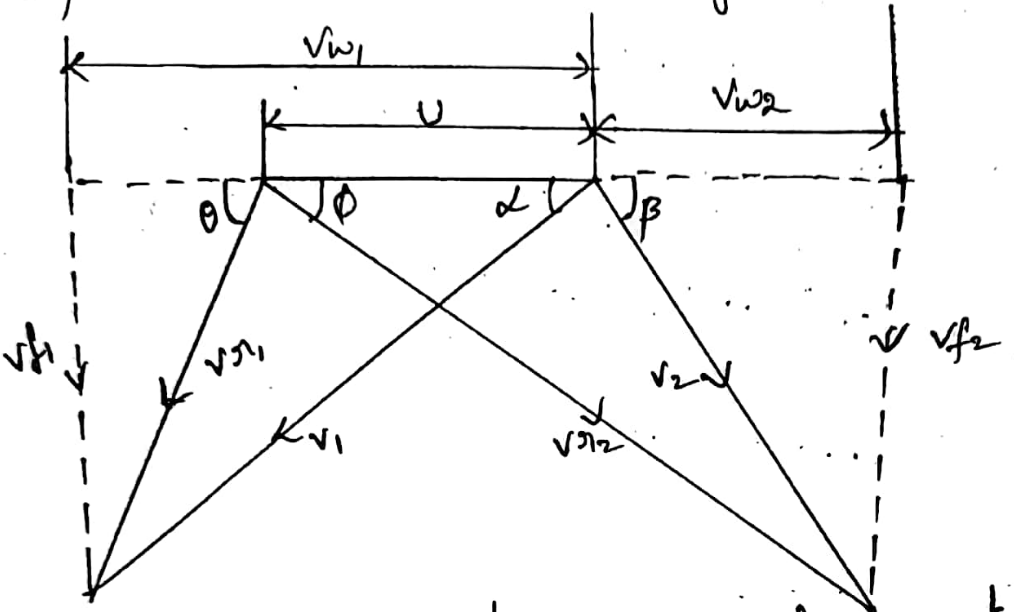
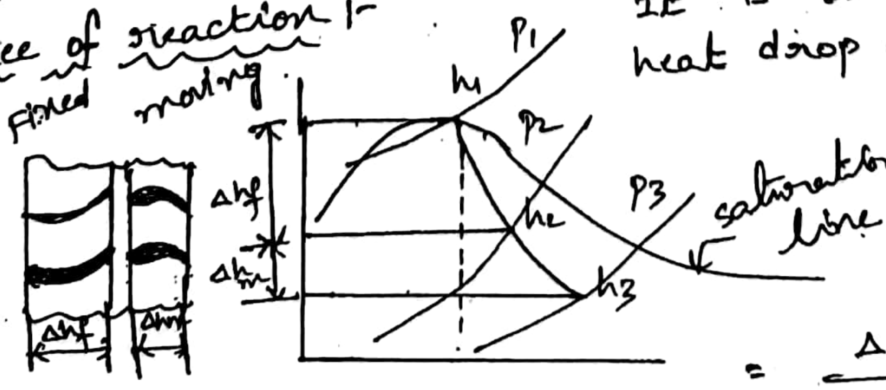


Fig. shows the velocity diagram for reaction turbine blade Incase of an impulse turbine blade the relative velocity of steam either remains constant. As the steam glides over the blades or is reduced slightly due to friction. In reaction turbine blades, the steam continuously expands as it flows over the blades. The effect of the continuous expansion of steam during the flow over the blade is to increase the relative velocity velocity of steam. for reaction turbines.

$V_{r_2} > V_{r_1}$ for reaction turbines.

Degree of reaction :- It is the ratio of ~~reaction~~ heat drop over moving blades to the total heat drop in the stage.



$$= \frac{\Delta h_m}{\Delta h_f + \Delta h_m}$$

The total heat drop in the stage is equal to the workdone by steam in the stage.

$$\Delta h_f + \Delta h_m = u(V_{w_1} + V_{w_2})$$

$$\Delta h_m = \frac{V_{r_2}^2 - V_{r_1}^2}{2}$$

$$(R_d) = \frac{V_{r_2}^2 - V_{r_1}^2}{2u(V_{w_1} + V_{w_2})}$$

So

$V_{r_2} = V_{f_2} \operatorname{cosec}\phi$

$V_{r_1} = V_{f_1} \operatorname{cosec}\theta$

$V_{w_1} + V_{w_2} = V_{f_1}\cot\theta + V_{f_2}\cot\phi$

$V_{f_1} = V_{f_2} = V_f$

$$(R_d) = \frac{V_f^2(\operatorname{cosec}^2\phi - \operatorname{cosec}^2\theta)}{2uV_f(\cot\theta + \cot\phi)}$$

$$= \frac{V_f}{2u}\left[\frac{(\cot^2\phi + 1) - (\cot^2\theta + 1)}{\cot\theta + \cot\phi}\right]$$

$$= \frac{V_f}{2u}\left[\frac{\cot^2\phi - \cot^2\theta}{\cot\phi + \cot\theta}\right]$$

$$= \frac{V_f}{2u}\left[\cot\phi - \cot\theta\right]$$

If turbine is 50% reaction turbine $\Delta h_f = \Delta h_m$

$$\frac{1}{2} = \frac{V_f}{2u}\left[\cot\phi - \cot\theta\right]$$

$$u = V_f\left[\cot\phi - \cot\theta\right]$$

$$u = V_f\left[\cot\phi - \cot\beta\right]$$

$$u = V_f\left[\cot\alpha - \cot\theta\right]$$

when comparing the above equations

$$\theta = \beta, \quad \phi = \alpha$$

which means that moving blade and fixed blade must have the same shape if the degree of reaction is 50%. This condition gives symmetrical velocity diagrams this type of turbine is known as parson's reaction turbine.

The blades are symmetrical means exit angle of the fixed blade equal to ~~and~~ the ~~inlet~~ exit angle of moving blade the inlet angle of moving blade is equal to the inlet angle of fixed blade. since the blades are symmetrical the velocity diagram also symmetrical In such a case the degree of reaction is 50%. Applying the steady flow energy equation to the fixed blades and assuming that the velocity of steam leaving the previous moving row

$\Delta h_f = \frac{V_1^2 - V_2^2}{2}$, $\Delta h_m = \frac{V_{r_2}^2 - V_{r_1}^2}{2}$, $V_1 = V_{r_2}$, $V_2 = V_{r_1}$, $\Delta h_f = \Delta h_m$

$$\text{Degree of reaction} = \frac{\Delta h_m}{\Delta h_f + \Delta h_m} = \frac{1}{2}$$

Condition for maximum efficiency :- The following assumptions.

1. Degree of reaction is 50%.
2. The moving blades and fixed blades are symmetrical.

workdone / kg of steam

$W = u(V_{w_1} + V_{w_2}) = u\left[V_1 \cos\alpha + (V_{r_2}\cos\phi - u)\right]$

$\phi = \alpha$, $V_{r_2} = V_{r_1}$ as per the assumptions

$$W = u\left[2V_1\cos\alpha - u\right]$$

$$\rho = \frac{u}{V_1}$$

$$W = V_1^2\left[\frac{2uV_1\cos\alpha}{V_1^2} - \frac{u^2}{V_1^2}\right]$$

$$= V_1^2\left[2\rho\cos\alpha - \rho^2\right]$$

K.E supplied to fixed blade $= \frac{V_1^2}{2g}$

" " " moving blade $= \frac{V_{r_2}^2 - V_{r_1}^2}{2}$

Total energy supplied to stage $= \Delta h_f + \Delta h_m$

$$= \frac{V_1^2}{2} + \frac{V_{r_2}^2 - V_{r_1}^2}{2}$$

$V_{r_2} = V_1 \Rightarrow \Delta h = \frac{V_1^2}{2} + \frac{V_{r_2}^2 - V_{r_1}^2}{2}$

$$= V_1^2 - \frac{V_{r_1}^2}{2}$$

But $V_{r_1}^2 = V_1^2 + u^2 - 2V_1 \cdot u\cos\alpha$ [from fig of velocity diagram]

substitute the value of $V_{r_1}^2$ value in above equation

Total energy supplied to the stage

$$\Delta h = v_1^2 - (v_1^2 + u^2 - 2v_1 u \cos\alpha)/2$$

$$= (v_1^2 + 2v_1 u \cos\alpha - u^2)/2$$

$$= \frac{v_1^2}{2}\left[1 + \frac{2u}{v_1}\cos\alpha - \left(\frac{u}{v_1}\right)^2\right]$$

$$= \frac{v_1^2}{2}\left[1 + 2\rho\cos\alpha - \rho^2\right]$$

Blade efficiency of reaction turbine is given by

$$\eta_{bl} = \frac{W}{\Delta h}$$

substitute W and Δh values in above equation.

$$\eta_{bl} = \frac{v_1^2[2\rho\cos\alpha - \rho^2]}{\frac{v_1^2}{2}(1 + 2\rho\cos\alpha - \rho^2]}$$

$$= \frac{2(2\rho\cos\alpha - \rho^2)}{(1 + 2\rho\cos\alpha - \rho^2)} = \frac{2\rho(2\cos\alpha - \rho)}{(1 + 2\rho\cos\alpha - \rho^2)}$$

$$= \frac{2(1 + 2\rho\cos\alpha - \rho^2) - 2}{(1 + 2\rho\cos\alpha - \rho^2)} = 2 - \frac{2}{1 + 2\rho\cos\alpha - \rho^2}$$

when $1 + 2\rho\cos\alpha - \rho^2$ becomes maximum the efficiency will maximum

The required equation is

$$\frac{d}{d\rho}(1 + 2\rho\cos\alpha - \rho^2) = 0$$

$$2\cos\alpha - 2\rho = 0$$

$$\rho = \cos\alpha$$

substitute ρ value in blade efficiancioncy formula

$$\eta_b = 2 - \frac{2}{1 + 2\cos^2\alpha - \cos^2\alpha}$$

$$= 2\left[1 - \frac{1}{1 + \cos^2\alpha}\right)$$

$$= \frac{2\cos^2\alpha}{1 + \cos^2\alpha}$$

$$\boxed{(\eta)_{max} = \frac{2\cos^2\alpha}{1 + \cos^2\alpha}}$$

Blade & diagram efficiency :- It is the ratio of workdone on the blade/sec to the energy entering the blade/second.

Stage efficiency :- $\dfrac{\text{Net workdone on shaft / stage / kg of steam}}{\text{Adiabatic heat drop / stage.}}$

Internal efficiency :- $\dfrac{\text{Heat converted into useful work}}{\text{Total adiabatic heat drop}}$

Overall efficiency :- $\dfrac{\text{work delivered at the turbine coupling}}{\text{Total } \overset{\text{adiabatic}}{\text{heat}} \text{ drop.}}$

Net efficiency :- $\dfrac{\text{Heat converted into useful work}}{\text{Total adiabatic heat drop.}}$

Adiabatic power :- It is the power based on the total internal steam flow and adiabatic heat drop.

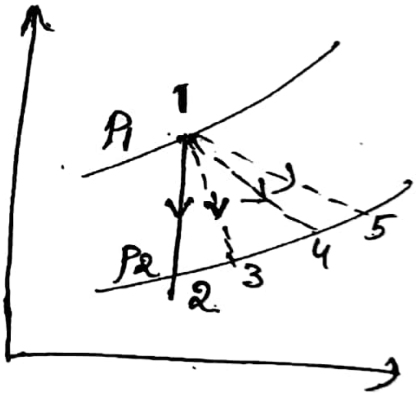
Shaft power :- It is the actual power transmitted by the turbine.

$m_s(h_1 - h_5)$

Rim power :- It is the power developed at the rim. It is also called blade power.

$m_s(h_1 - h_4)$

$A.P = m_s(h_1 - h_2)$



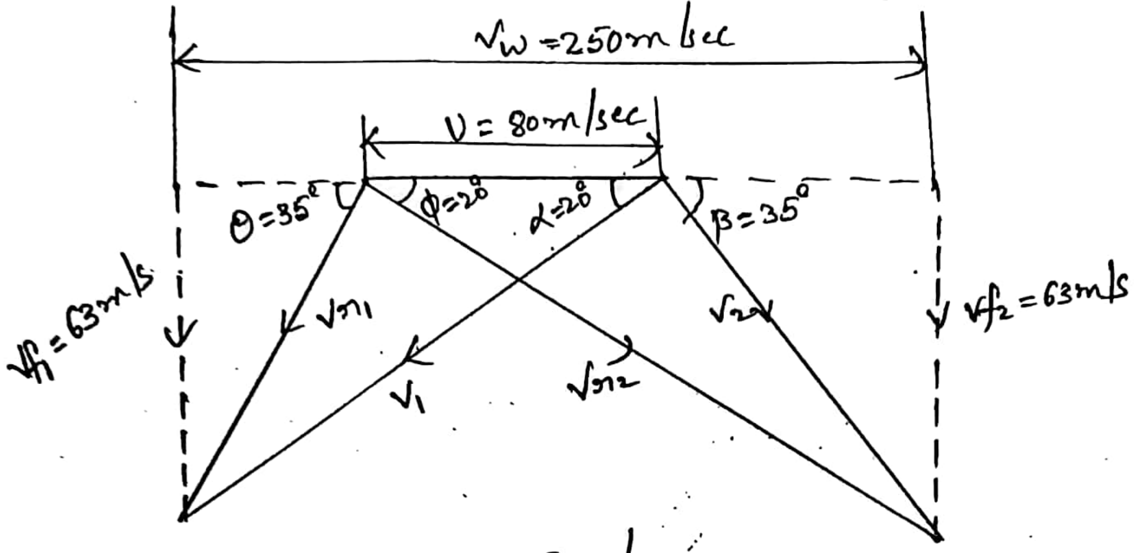
In one stage of reaction steam turbine both the fixed and moving blades have inlet and outlet blade tip angles of 35° and 20° respectively. The mean blade speed is 80m/s and the steam consumption is 22500 kg/hr. Determine power developed and stage efficiency if the isentropic heat drops in both fixed and moving rows is 23.5 kJ/kg in the pair.

Given :- Inlet blade angle $\theta = 35^\circ = \beta$
outlet " " $\phi = 20^\circ = \alpha$

Blade speed $(u) = 80\,m/s$

mass of steam consumption $(m_s) = \frac{22,500}{3600}$

$= 6.25$ kg/sec



From the diagram $V_w = 250$ m/sec

power $(P) = \frac{m(V_w)u}{1000}$

$= \frac{6.25(250)80}{1000} = 125$ kW

stage efficiency $(\eta_{stage}) = \frac{(V_w)u}{1000 \times \Delta h} = \frac{250 \times 80}{1000 \times 23.5}$

$= 85.1\%$

Height of Blades of a reaction turbine:-

h = height of blades

In reaction turbines, the steam enters the moving blades over the whole circumference so the area of steam flow is full of steam

D = Diameter of rotor drum

$V_{f1} = V_f = V_{f2}$ = velocity of flow

Area of steam flow $= \pi(D+h)h$

D+h = mean diameter of blade

$m = \frac{\text{Area of steam flow} \times \text{velocity of flow}}{\text{specific volume of steam}}$

$= \frac{(\pi(D+h)h)V_f}{v}$

$v = v_g$ = Dry steam

$v = x v_g$ = wet "

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unit-6

UNIT – 6

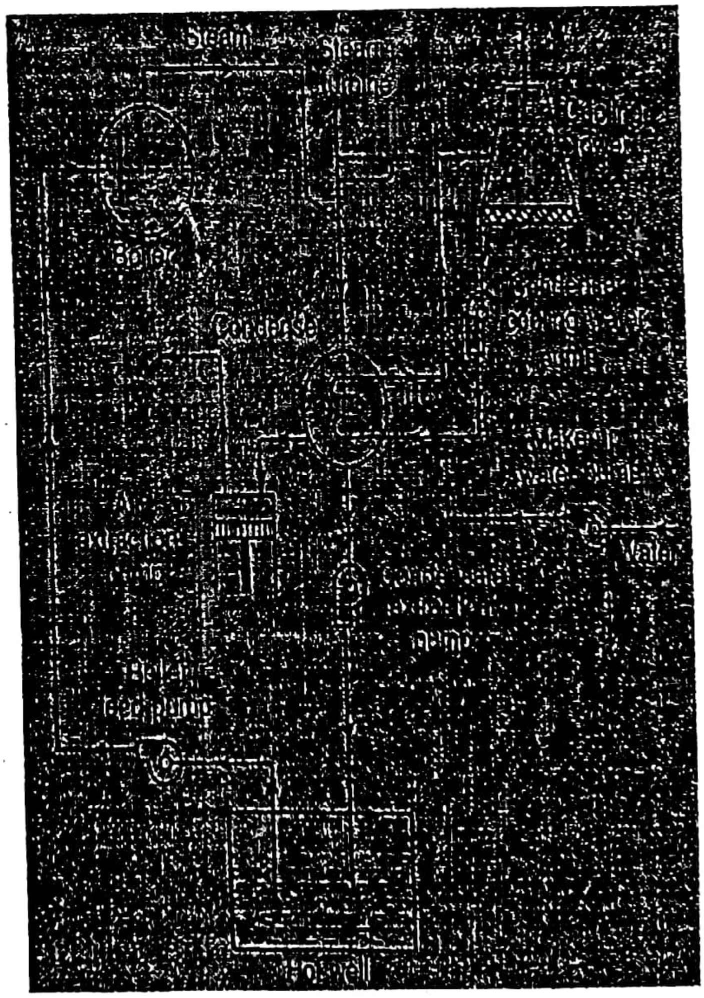
Steam Condensers

Elements of a condensing plant, Types of condensers, Comparison of jet and surface condensers, Condenser vacuum, Sources of air leakage & its disadvantages, Vacuum efficiency, Condenser efficiency

- **Steam Condenser:** It is a device or an appliance in which steam condenses and heat released by steam is absorbed by water.

- **Elements of a steam condensing plant:**

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

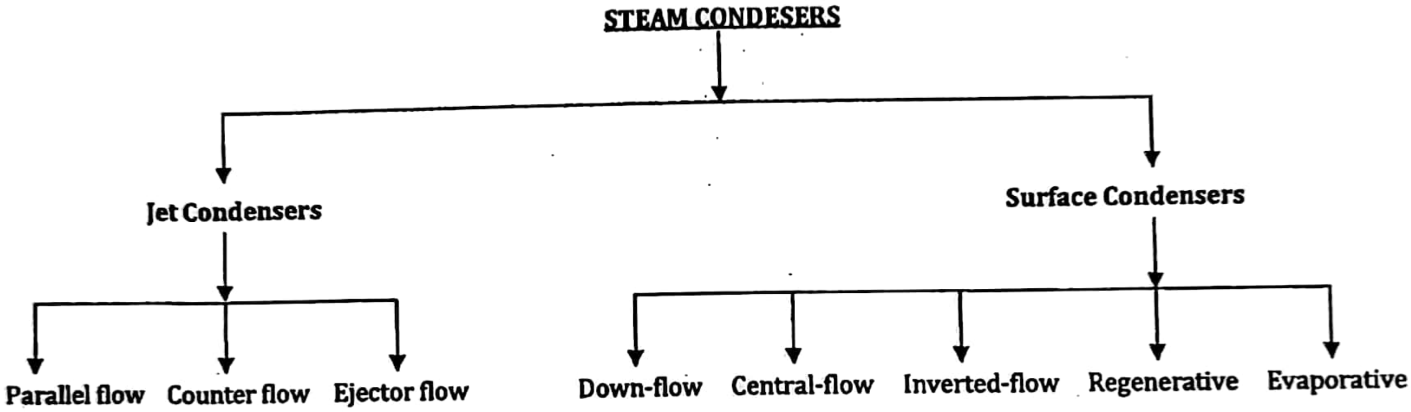


➢ Classification of Condensers

- Jet condensers
- Surface condenser

✓ **Jet Condensers**: The exhaust steam and water come in direct contact with each other and temperature of the condensate is the same as that of cooling water leaving the condenser. The cooling water is usually sprayed into the exhaust steam to cause, rapid condensation.

✓ **Surface Condensers**: The exhaust steam and water do not come into direct contact. The steam passes over the outer surface of tubes through which a supply of cooling water is maintained.



1. **Parallel- Flow Type of Jet Condenser:** The exhaust steam and cooling water find their entry at the top of the condenser and then flow downwards and condensate and water are finally collected at the bottom.

2. **Counter- Flow Type jet Condenser:** The steam and cooling water enter the condenser from opposite directions. Generally, the exhaust steam travels in upward direction and meets the cooling water which flows downwards.

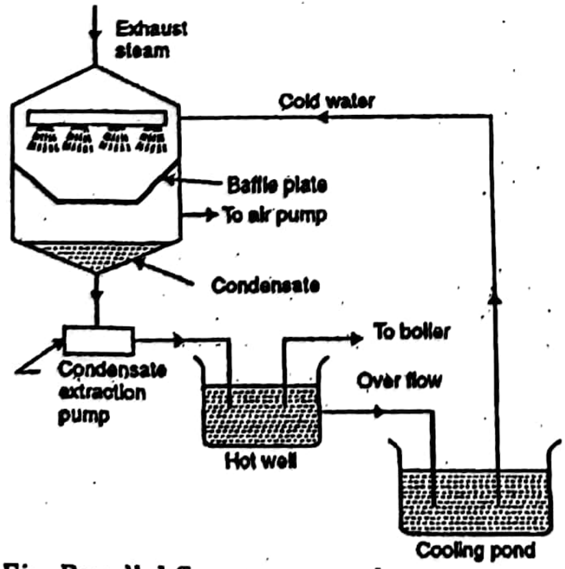


Fig. Parallel flow type condenser

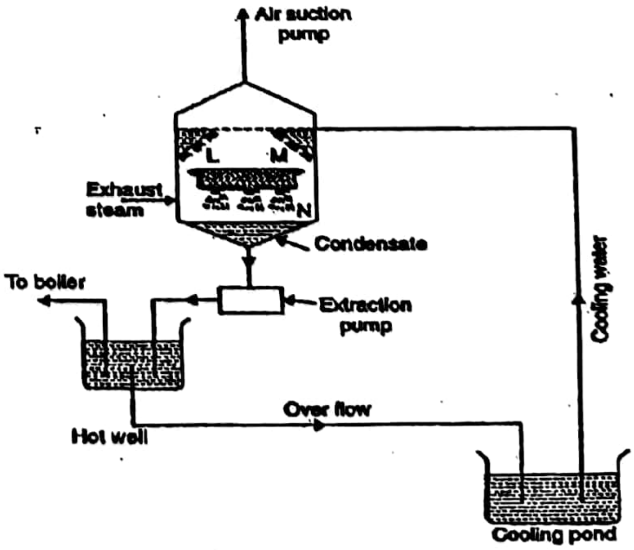


Fig. Low level counter flow type condenser

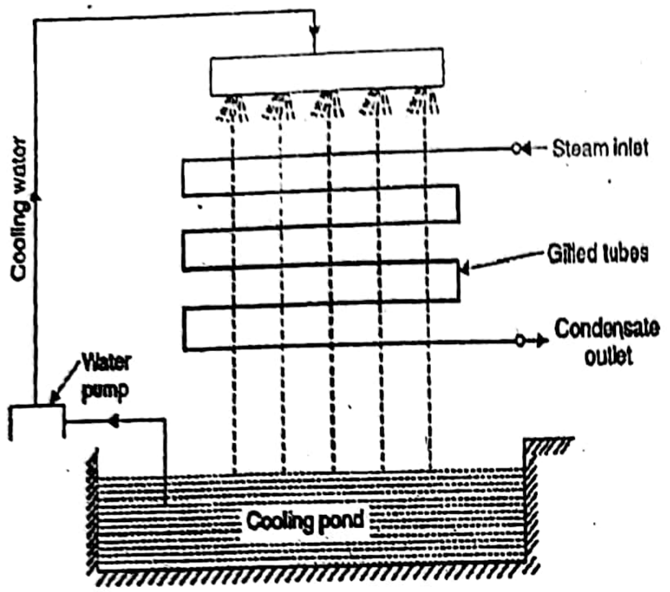


Fig. Evaporative Type

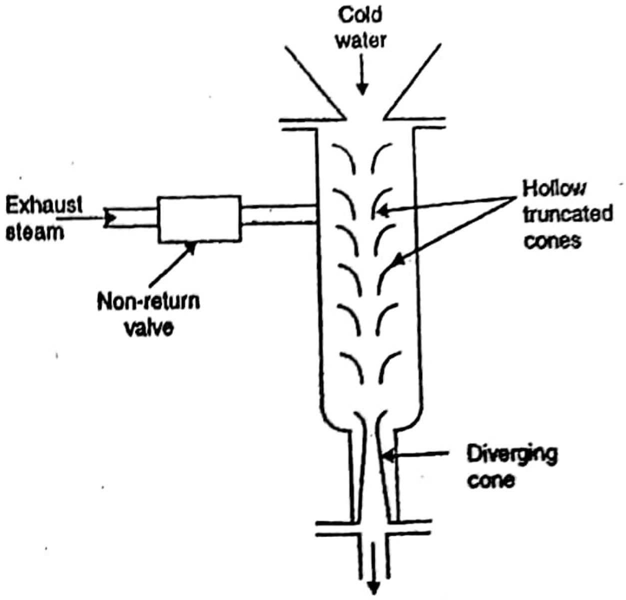


Fig. Ejector flow type condenser

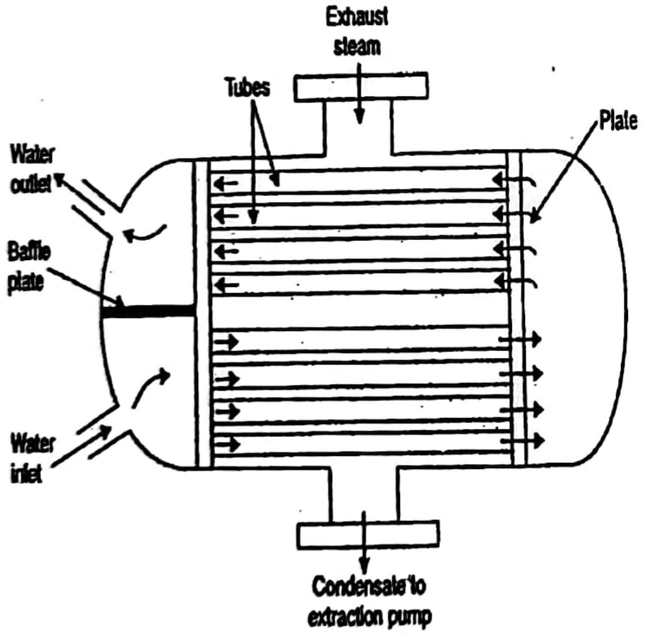


Fig. Down-Flow Type

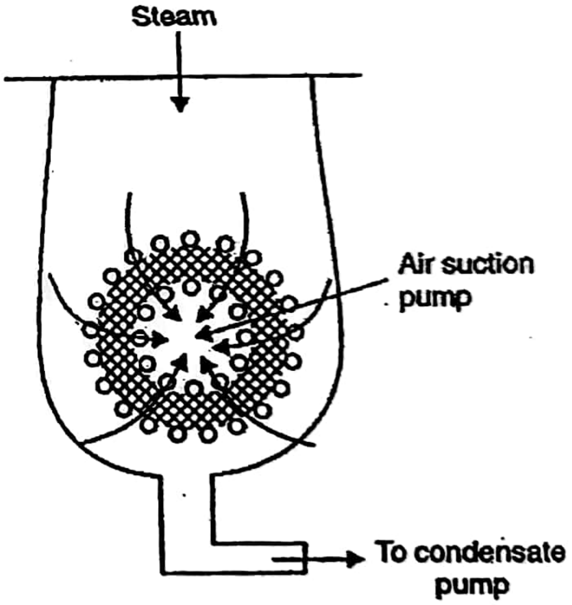


Fig. Central Flow Type

7. **Inverted Flow Type:** This type of condenser has the air suction at the top; the steam after entering at the bottom rises up and then again flows down to the bottom of the condenser, by following a path near the outer surface of the condenser. The condensate extraction pump is at the bottom.

8. **Regenerative Type:** This type is applied to condensers adopting a regenerative method of heating of the condensate. After leaving the tube nest, the condensate is passed through the entering exhaust steam from the steam engine or turbine thus raising the temperature of the condensate, for use as feed water for the boiler.

- **Low Level Jet Condenser (Counter-Flow Type Jet Condenser):** Figure Shows, L, M and N are the perforated trays which break up water into jets. The steam moving upwards comes in contact with water and gets condensed.

  The condensate and water mixture is sent to the hot well by means of an extraction pump and the air is removed by an air suction pump provided at the top of the condenser.

- **High Level Jet Condenser (Counter-Flow Type Jet Condenser):** It is also called barometric condenser. In this type the shell is placed at a height about 10.363 meters above hot well and thus the necessity of providing an extraction pump can be obviated. However provision of own injection pump has to be made if water under pressure is not available.

3. **Ejector Condenser Flow Type Jet Condenser:** Here the exhaust steam and cooling water mix in hollow truncated cones. Due to this decreased pressure exhaust steam along with associated air is drawn through the truncated cones and finally lead to diverging cone.

   In the diverging cone, a portion of kinetic energy gets converted into pressure energy which is more than the atmospheric so that condensate consisting of condensed steam, cooling water and air is discharged into the hot well. The exhaust steam inlet is provided with a non-return valve which does not allow the water from hot well to rush back to the engine in case a failure of cooling water supply to condenser.

4. **Down-Flow Type:** The cooling water enters the shell at the lower half section and after traveling through the upper half section comes out through the outlet. The exhaust steam entering shell from the top flows down over the tubes and gets condensed and is finally removed by an extraction pump. Due to the fact that steam flows in a direction right angle to the direction of flow of water, it is also called cross-surface condenser.

5. **Central Flow Type:** In this type of condenser, the suction pipe of the air extraction pump is located in the centre of the tubes which results in radial flow of the steam. The better contact between the outer surface of the tubes and steam is ensured; due to large passages the pressure drop of steam is reduced.

6. **Evaporative Type:** The principle of this condenser is that when a limited quantity of water is available, its quantity needed to condense the steam can be reduced by causing the circulating water to evaporate under a small partial pressure.

   The exhaust steam enters at the top through gilled pipes. The water pump sprays water on the pipes and descending water condenses the steam. The water which is not evaporated falls into the open tank (cooling pond) under the condenser from which it can be drawn by circulating water pump and used over again.

   The evaporative condenser is placed in open air and finds its application in small size plants.

- **Vacuum Efficiency:** The minimum absolute pressure (also called ideal pressure) at the steam inlet of a condenser is the pressure corresponding to the temperature of the condensed steam. The corresponding vacuum (called ideal vacuum) is the maximum vacuum that can be obtained in a condensing plant, with no air present at that temperature. The pressure in the 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. Mathematically, vacuum efficiency

$$\eta = \text{Actual Vacuum} / \text{Ideal Vacuum}$$

Where, η = Vacuum efficiency
Actual vacuum = Barometric pressure - Actual pressure
And Ideal vacuum = Barometric pressure - Ideal pressure

- **Condenser Efficiency**

It is defined as the ratio of the difference between the outlet and inlet temperatures of cooling water to the difference between the temperature corresponding to the vacuum in the condenser and inlet temperature of cooling water, i.e.,

$$\text{Condenser efficiency} = \frac{\text{Rise in temperature of cooling water}}{\begin{bmatrix}\text{Temp. corresponding to vacuum}\\ \text{in the condenser}\end{bmatrix} - \begin{bmatrix}\text{Inlet temp. of}\\ \text{cooling water}\end{bmatrix}}$$

$$= \frac{\text{Rise in temperature of cooling water}}{\begin{bmatrix}\text{Temp. corresponding to the absolute}\\ \text{pressure in the condenser}\end{bmatrix} - \begin{bmatrix}\text{Inlet temp. of}\\ \text{cooling water}\end{bmatrix}}$$

- **Sources of air into the condensers:**

1. The dissolved air in the feed water enters into the boiler, which in turn enters into the condenser with the exhaust steam.
2. The air leaks into the condenser, through various joints, due to high vacuum pressure in the condenser.
3. In case of jet condensers, dissolved air with the injection water enters into the condenser.

- **Effects of Air Leakage:**

1. It reduces the vacuum pressure in the condenser.
2. Since air is a poor heat conductor, particularly at low densities, it reduces the rate of heat transmission.
3. It requires a larger air pump. Moreover, an increased power is required to drive the pump.

➢ Comparison Between Jet And Surface Condensers

	Jet Condenser	Surface Condenser
1.	Cooling water and steam are mixed up.	Cooling water and steam are not mixed up.
2.	Low manufacturing cost.	High manufacturing cost.
3.	Lower up keep.	Higher upkeep.
4.	Requires small floor space.	Requires large floor space.
5.	The condensate cannot be used as feed water in the boilers unless the cooling water is free from impurities.	Condensate can be reused as feed water as it does not mix with the cooling water.
6.	More power is required for air pump.	Less power is needed for air pump.
7.	Less power is required for water pumping.	More power is required for water pumping.
8.	It requires less quantity of cooling water.	It requires large quantity of cooling water.
9.	The condensing plant is simple.	The condensing plant is complicated.
10.	Less suitable for high capacity plants due to low vacuum efficiency.	More suitable for high capacity plants as vacuum efficiency is high.

➢ Mixture of Air and Steam (Dalton's Law of Partial Pressures):

It states "The pressure of the mixture of air and steam is equal to the sum of the pressures, which each constituent would exert, if it occupied the same space by itself" Mathematically, pressure in the condenser containing mixture of air and steam,

$$P_c = P_a + P_s$$

Where, P_c = Pressure in condenser
P_a = Partial pressure of air and,
P_s = Partial pressure of steam

➢ Measurement of Vacuum in a Condenser:

- **Vacuum**: The difference between the atmospheric pressure and the absolute pressure.

In the study of condensers, the vacuum is generally converted to correspond with a standard atmospheric pressure, which is taken as the barometric pressure of 760 mm of mercury (Hg). Mathematically, vacuum gauge reading corrected to standard barometer or in other words:

Corrected vacuum in the condenser = 760 - (Barometer reading - Vacuum gauge reading)

Note: We know that; Atmospheric pressure = 760 mm of Hg = 1.013 bar

$\therefore$ 1 mm of Hg = 1.013/760 = 0.00133 bar = 133 N/m^2 ($\because$ 1 bar = 10^5 N/m^2)

Cooling Towers

In a cooling tower water is made to trickle down drop by drop so that it comes in contact with the air moving in the opposite direction. As a result of this some water is evaporated and is taken away with air. In evaporation, the heat is taken away from the bulk of water, which is thus cooled.

Types of Cooling Tower

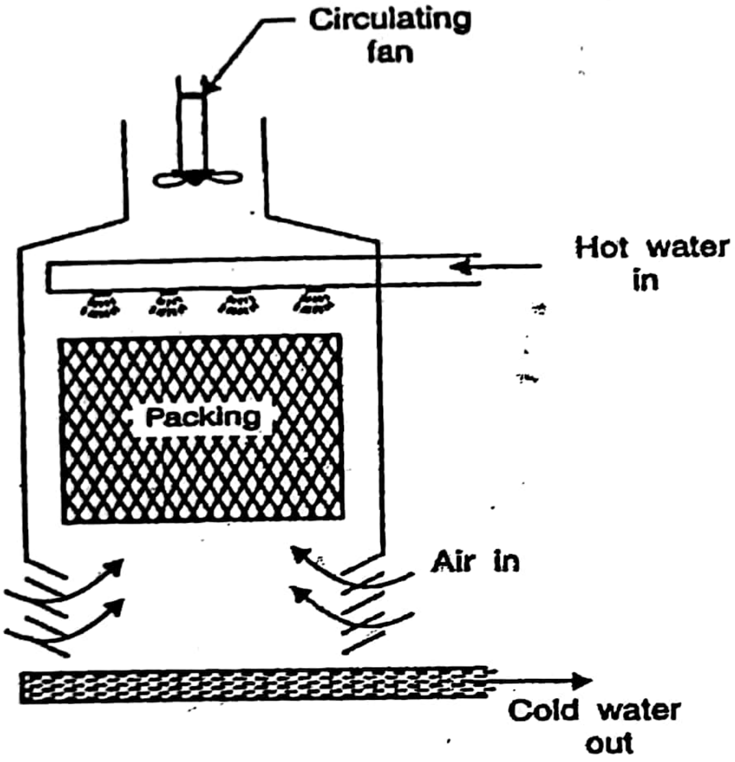


Fig. Natural draught cooling tower

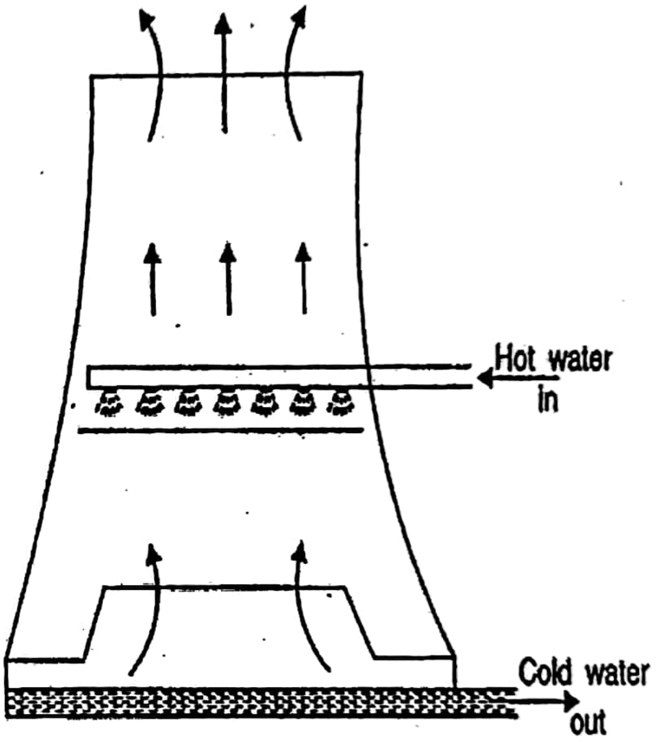


Fig. Forced draught cooling tower

Student Notes:

The following observations were recorded during a test on a steam condenser

Barometer reading = 765 mm of Hg

condenser vaccum = 710 mm of Hg

mean condenser temperature = 35°c

condensate temperature = 28°c

condensate collected/ hour = 2 tonnes

Quantity of cooling water/ hour = 60 tonnes

Temperature of cooling water at inlet = 10°c

" " " outlet = 25°c

Find vaccum corrected to the standard barometer reading, vaccum efficiency, undercooling of the condensate, condenser efficiency, Quality of steam entering in the condenser volume, mass of air/kg of mass of air/m³ of condenser volume, mass of air/kg of uncondensed steam.

Barometer reading = 765 mm of Hg, $T = 35°c \Rightarrow 308 K$

condenser vaccum = 710 mm of Hg, $t_c = 28°c$, $m_s = 2000 kg/h$

$m_w = 60{,}000 kg/h$, $t_i = 10°c$, $t_o = 25°c$

Absolute pressure in the condenser

= 765 − 710 = 55 mm of Hg

standard barometer reading vaccum corrected = 760 mm of Hg

= 760 − 55 = 705 mm of Hg

From the steam table corresponding mean temperature of 35°,

$$P_s = 0.0562 \text{ bar} = \frac{0.0562}{0.00133} = 42.2 \text{ mm of Hg}$$

$$\text{Ideal vaccum} = \underset{765}{(B.P)} - \underset{42.2}{(I.P)} = 722.8 \text{ mm of Hg}$$

$$\eta_v = \frac{\text{Actual vaccum}}{\text{Ideal vaccum}} = \frac{710}{722.8} = 98.2\%$$

undercooling the condensate = Mean condenser temp − condensate temp

= 35 − 28 = 7°c

pressure in the condenser = (P_c) = 765 − 710 = 55 mm of Hg

= 55 × 0.00133

= 0.073 bar

from steam tables at 0.073 bar $(t_v) = 39.83°c$

$$\eta_c = \frac{\text{Temp. rise of cooling water}}{\text{vaccum temp} - \text{Inlet cooling temp}}$$

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

$$= \frac{25-10}{39.83-10} = 50.3\%$$

at 0.073 bar
$h_f = 166.7$ KJ/kg, $h_{fg} = 2407.4$ KJ/kg

$$h = h_{f_1} + x h_{fg}$$
$$h = 166.7 + x(2407.4) \text{ KJ/kg}$$

mass of cooling water

$$60{,}000 = \frac{m_s(h - h_{f_1})}{C_w(t_o - t_i)} = \frac{2000(166.7 + x \times 2407.4 - 117.3)}{4.2(25-10)}$$

$$x = 0.76$$

From Dalton's law

$$P_a = P_c - P_s = 0.073 - 0.0562$$
$$= 0.0168 \text{ bar}$$
$$= 1680 \text{ N/m}^2$$

$$m_a = \frac{P_a V}{RT} = \frac{1680 \times 1}{287 \times 308} = 0.019 \text{ kg}$$

at mean temperature 35°c, $v_g = 25.245$ m³/kg

$$m_g = \frac{P_a v_g}{RT} = \frac{1680 \times 25.245}{287 \times 308}$$
$$= 0.48 \text{ kg}$$

The air leakage into a surface condenser operating with a steam turbine is estimated as 84 kg/h. The vaccum near the inlet of air pump is 70mm of Hg when barometer reads 760mm of Hg. The temperature at inlet of vaccum pump 20°c calculate. The minimum capacity of the air pump m3/h, The dimensions of the recipro cating air pump to remove air if it runs at 200 rpm Take L/D ratio = 1.5 and volumetric efficiency 100%, The mass of vapour extracted/min.

pressure in condenser = (P_c) = Barometer reading − condenser vaccum

$= 760 - 700 = 60$ mm of Hg

$= 60 \times 0.00133$

$= 0.0798$ bar

at mean temperature 20°c, the pressure of steam

$P_s = 0.0234$ bar

pressure of air = (P_a) = $P_c - P_s = 0.0798 - 0.0234$

$= 0.0564$ bar

$= 5640\ N/m^2$

minimum capacity of the air pump

$$V_a = \frac{m_a R T}{P_a} = \frac{84 \times 287 \times 293}{5640}$$

$= 1252.4\ m^3/h$

dimensions of reciprocating pump:- Length of stroke

$= 1.5D$

$\eta_{vol} = 100\% = 1$

N = Speed of rpm = 200 rpm

minimum capacity of air (Va)

$$\frac{1252.4}{60} = \frac{\pi}{4} \times D^2 \times L \times N = \frac{\pi}{4} \times D^2 \times 1.5D \times 200 = 235.6D^3$$

$D^3 = 0.0886 \Rightarrow D = 0.446m$

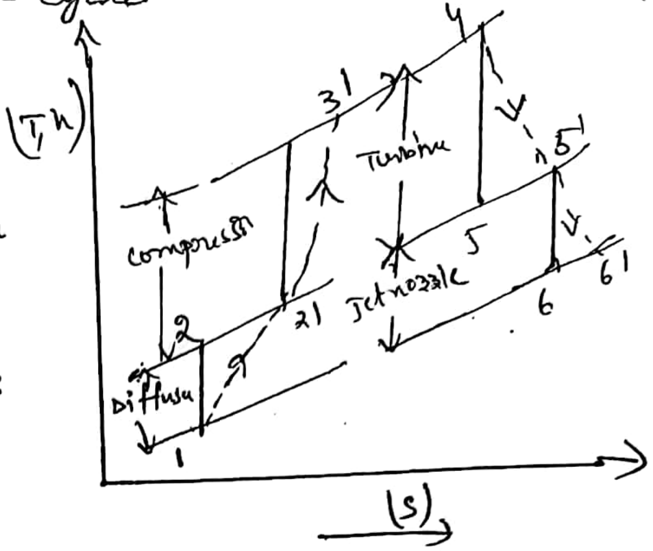
$L = 1.5D \Rightarrow 1.5 \times 0.446 = 0.669m$

mass of vapour extracted/min = $\frac{V_a}{V_g}$

at Tmean 20°C, $V_g = 57.84\ m^3/kg$

$$= \frac{1252.4}{60 \times 57.84} = 0.361\ kg/min$$

Turbo-jet engine :- The basic cycle for turbo jet engine is the joule or Brayton cycle



Process 1-2 :- The air entering from atmosphere is diffused isentropically from velocity C_1 This indicates that the diffuser has an efficiency of 100%. This is termed as ram compression.

process 2-3 :- 2'-3' process shows the actual compression of air

process 3-4 :- 3'-4 shows the actual addition of heat at constant process $P_3 = P_4$

process 4-5 :- 4'-5' shows actual expansion in the turbine

process 5-6 :- 5'-6' shows actual expansion of gas in the nozzle.

Diffuser :- $\frac{C_a^2}{2} + h_1 + Q_{1-2} = \frac{C_2^2}{2} + h_2 + W_{1-2}$

In an ideal diffuser $C_2 = Q_{1-2} = W_{1-2} = 0$

$\boxed{h = C_p T}$

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

$$T_2 - T_1 + \frac{C_a^2}{2C_p}$$

$$\eta_d = \frac{h_2 - h_1}{h_2' - h_1} \Rightarrow \frac{T_2 - T_1}{T_2' - T_1}$$

$$T_2' = T_1 + \frac{C_a^2}{2 \times C_p \times \eta_d}$$

Compressor :- Energy equation between states 2 and 3 gives

$$h_2 + \frac{C_2^2}{2} + Q_{2-3} + W_C = h_3 + \frac{C_3^2}{2}$$

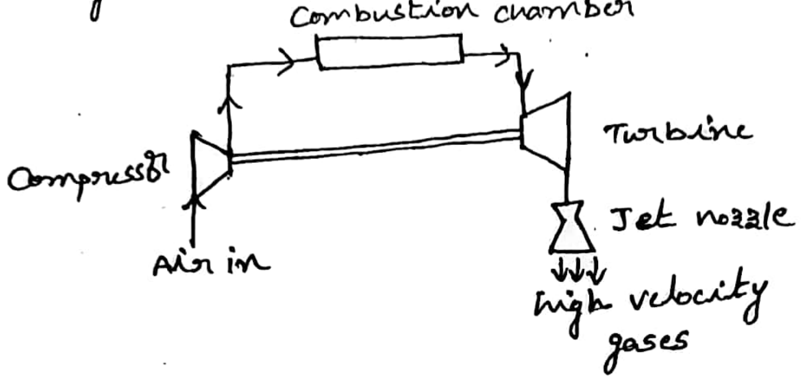
change in P.E and K.E negligable

$$W_C = h_3 - h_2 = C_p (T_3 - T_2)$$

actual work $= h_3' - h_2 = \frac{h_3 - h_2}{\eta_c} = \frac{C_p (T_3 - T_2)}{\eta_c}$

Jet propulsion

The working of Jet engines is based on Newtons laws of motion. In these units the energy of fuel is converted into kinetic energy of a jet of gases. The propulsive forces is obtained from the reaction of the jet of gases which are discharged with a very high velocity from the rear side of the unit.

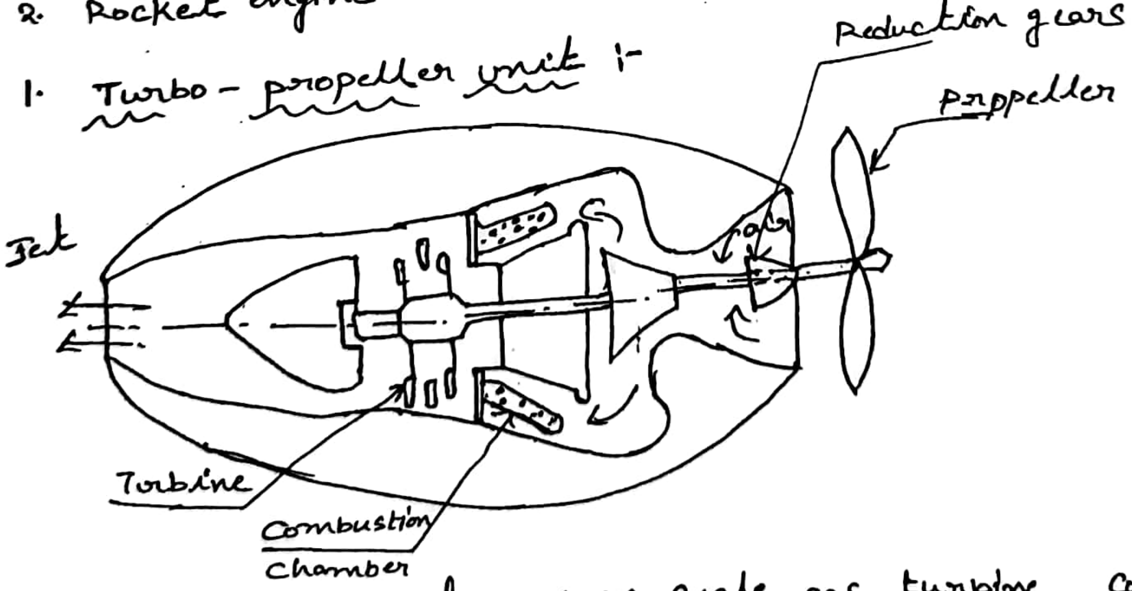


Types of Jet propulsion units :-

According to the method of operation all the jet engines.

1. Atmospheric jet engines
   a) Turbo - propeller units (engine)
   b) Turbo - Jet unit (engine)
   c) Ram jet engine
2. Rocket engine

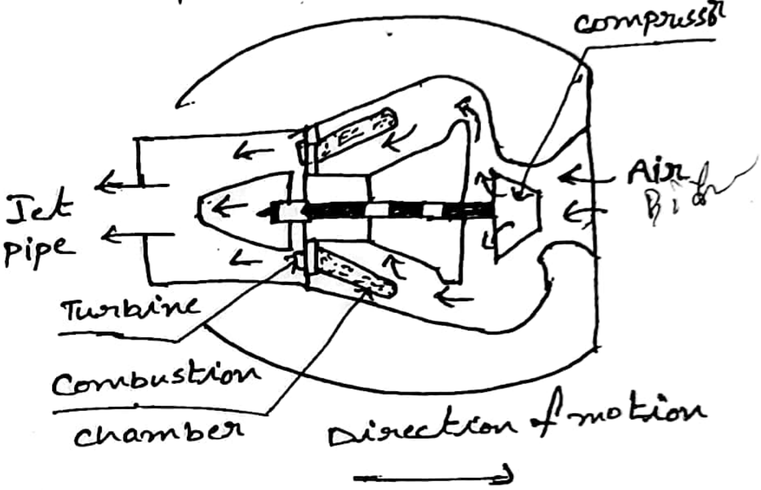
1. Turbo - propeller unit :-



It consists of an open cycle gas turbine, compressor, combustion chamber, turbine and a propeller added to the engine.

Air enters into compressor where it is compressed to a high pressure. The compressed air is then entered into combustion chamber in which the combustion of fuel take place. The products of combustion are forced into the gas turbine The power produced in the turbine is used to drive the compressor and propeller. A set of reduction gears is used to reduce the speed of rotation of the propeller. The Jet of exhaust gases leave the unit from its rear end. Approximately 80 to 90% of the thrust of the turboprop engine is produced by propeller and about 10 to 12% of the thrust is produced by the reaction of the jet at exit.

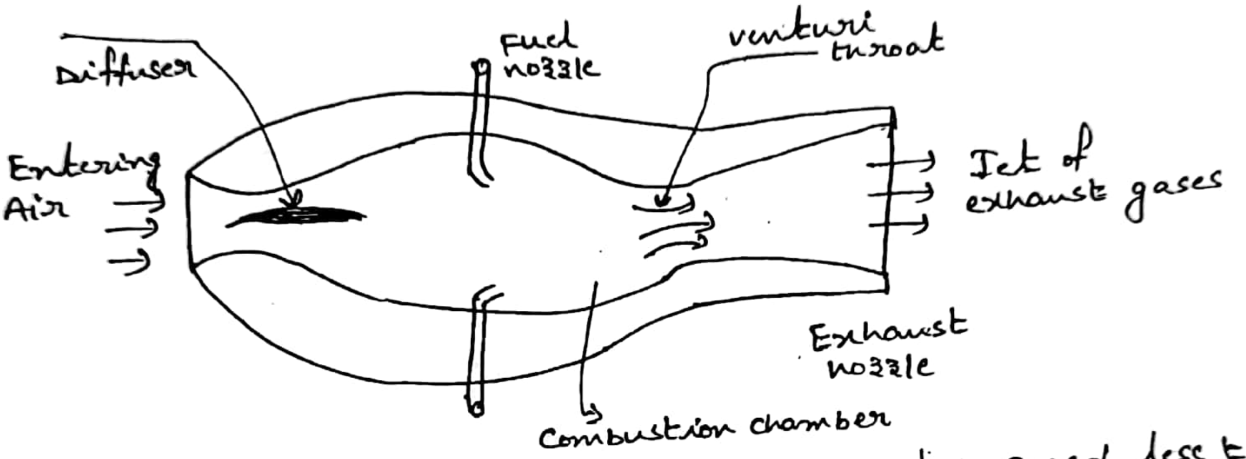
Turbo - Jet unit :- It consists of a open cycle gas turbine with a diffuser in front of the compressor and an exit nozzle added to the turbine end.



Air enters into compressor through a diffuser where it is compressed. Small pressure rise in the entering air is caused in the diffuser, but the major part of pressure rise is accomplished in the compressor which is driven by turbine. Compressed air passed into the combustion chamber in which fuel is injected at high pressure. Combustion of fuel takes place at constant pressure. Due to combustion temperature and volume of products of combustion increases considerable High air fuel ratio limits the temperature of hot gases. The hot gases is then expanded through exit nozzle in which the thermal energy of the hot gases in converted into kinetic energy. The jet of gases is discharged out through the rear end of the unit. The reaction of the jet provides the thrust to move the unit in the direction opposite to that of the jet.

Ram Jet engine :- It consists of an inlet diffuser, a combustion chamber and an exit nozzle. It has no compressor and turbine.

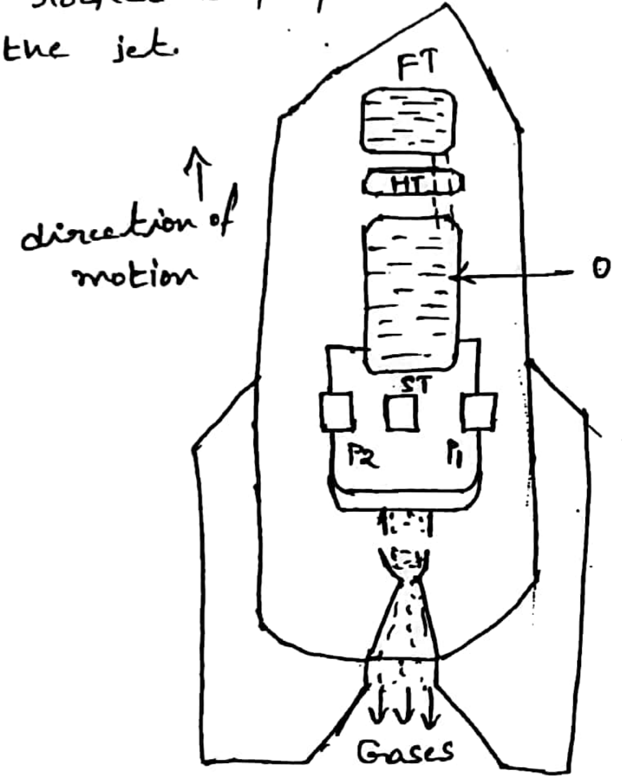
The velocity of air entering the diffuser is decreased and is acompained by an increase in pressure. This pressure rise due to decrease in velocity of incoming air is known as ram effect. The air at high pressure is passed into combustion chamber by fuel nozzle. The mixture is ignited by a spark plug. The temperature of combustion products is not limited as in the case of turbo jet engine. Air-fuel ratio of around 15 to 1 used. This produces exhaust gas temperatures in the range of 1950° to 2200°C. High pressure and temperature gases pass through the nozzle where the pressure energy is converted into kinetic energy. The high velocity jet leaving a nozzle exert a thrust to the ram jet engine



In ram jet engines, travelling at a speed less than Super sonic Speed the air enters through grid. Grid valves (shutter valves) are operated automatically by the pressure difference on either side of grid. If the pressure in combustion chamber is more, the valves are closed. The pressure in the combustion chamber decreases due to expansion of gases then the valves are automatically opened air flows into the diffuser.

Rocket engines:- It carries both the fuel and oxidising agent. As a result this type of engine is independent of the atmosphere. From this point of view rocket engines are most attractive and can be operated in the vaccum. however the propellant (oxidiser and fuel) consumption is very high.

Rocket consists two tanks one containing fuel (alcohol) and other oxidiser (liquid oxygen) two pumps (P_1 and a steam turbine (ST) and a combustion chamber. The fuel and oxidiser are supplied to the combustion chamber by the pumps The pumps are driven by steam turbine. The steam required for turbine is produced by mixing a very concentrated hydrogen peroxide with calcium permanganate. The oxidiser and fuel burn in the combustion chamber producing high pressure gases. The high pressure gases are passed through the nozzle where pressure is converted into kinetic energy. The gas jet is ejected to the atmosphere at supersonic speed through a nozzle. The jet produce the thrust on the rocket engine and rocket is propelled into sky in the direction opposite to the jet.



FT = Fuel tank
HT = Hydrogen peroxide tank
O = oxidiser tank
ST = steam turbine
P1, P2 = pumps
C.C = combustion chamber
HG = Hot gases
N = Nozzle

Fuels used in jet propulsion:-

1. petrol
2. avitation Kerosine
3. Gasoline
4. paraffin
5. Alcohol
6. Natural gas

Combustion chamber :- Ideal heat supplied / kg $= h_4 - h_3$

$= C_p (T_4 - T_3)$

Actual heat supplied $= \left(1 + \frac{m_f}{m_a}\right) h_4 - h_3'$

$= C_{pg}\left(1 + \frac{m_f}{m_a}\right) T_4 - C_{pa} T_3'$

Turbine :- The energy equation

$$h_4 + \frac{C_4^2}{2} + Q_{4-5} = h_5 + \frac{C_5^2}{2} + W_t$$

$$Q_{4-5} = 0 \qquad W_t = (h_4 - h_5) + \frac{C_4^2 - C_5^2}{2}$$

change in K.E is neglected

$$W_t = (h_4 - h_5) \Rightarrow C_p (T_4 - T_5)$$

Actual work $= C_p (T_4 - T_5') \eta_t$

$$C_p (T_4 - T_5') = C_p (T_4 - T_5) \eta_t$$

Nozzle :- $h_5' + \frac{C_5'^2}{2} = h_6' + \frac{C_6'^2}{2}$

$$h_5' = h_6' + \frac{C_6'^2}{2}$$

$$C_6' = \sqrt{2 \times \eta_n C_p (T_5' - T_6)}$$

Thermal efficiency :- $\frac{(h_4 - h_6') - (h_3' - h_1)}{(h_4 - h_3')}$

Thrust :- The atmospheric air to be still the velocity of air relative to aircraft at entry to the air craft will be Ca. It is called velocity of approach of air.

Cj = velocity of jet relative to the exit nozzle

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

change of momentum $= \left(1 + \frac{m_f}{m_a}\right)(C_j - C_a)$ N/kg of air/sec

neglecting the mass of fuel

$$T = (C_j - C_a)$$

Thrust power :- The rate at which work must be developed by the engine if the aircraft is to be kept moving at a constant velocity Ca against friction force

$T.P$ = forward thrust × speed of aircraft

$= \left[\left(1 + \frac{m_f}{m_a}\right)(C_j - C_a)\right] C_a$ W/kg of air mass of fuel is neglected

$$= \frac{(c_j - c_a)\, c_a}{1000} \text{ kW/kg of air}$$

propulsive power:- The energy recquired to change the momentum of the mass flow of gas represents the propulsive power. It is expressed as the difference between the rate of kinetic energies of the entering air and exit gases.

$$p.p = \Delta K.E = \frac{\left(1+\frac{m_f}{m_a}\right) c_j^2}{2} - \frac{c_a^2}{2} \text{ w/kg}$$

$$= \frac{c_j^2 - c_a^2}{2} \text{ w/kg}$$

propulsive efficiency:- The ratio of thrust power to propulsive power is called the propulsive efficiency.

$$= \frac{\left[\left(1+\frac{m_f}{m_a}\right)(c_j - c_a)\right] c_a}{\left[\frac{\left(1+\frac{m_f}{m_a}\right) c_j^2}{2} - \frac{c_a^2}{2}\right]}$$

$$= \frac{2\left[\left(1+\frac{m_f}{m_a}\right)(c_j - c_a)\right] c_a}{\left[\left(1+\frac{m_f}{m_a}\right) c_j^2 - c_a^2\right]}$$

Neglecting mass of fuel.

$$\eta_{prop} = \frac{2(c_j - c_a)\, c_a}{c_j^2 - c_a^2} = \frac{2(c_j - c_a)\, c_a}{(c_j + c_a)(c_j - c_a)}$$

$$\eta_{prop} = \frac{2c_a}{c_j + c_a}$$

Thermal efficiency :- $\dfrac{\text{propulsive work}}{\text{Heat released by the combustion of fuel}}$

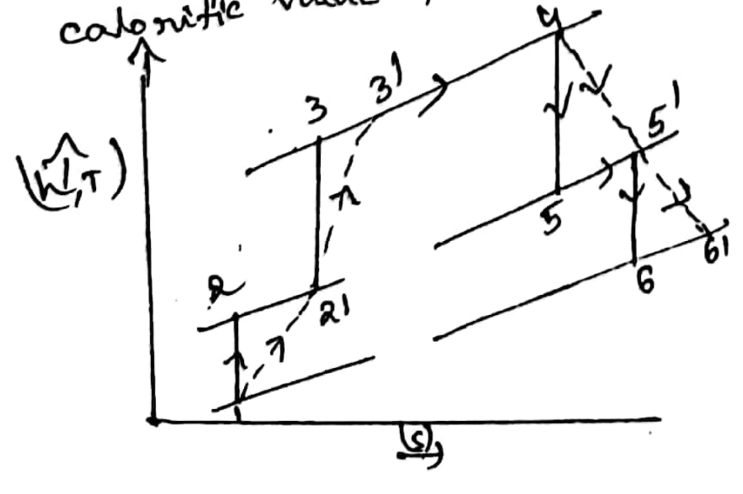
$$= \frac{\left(1+\frac{mf}{ma}\right) c_j^2 - ca^2}{2\left(\frac{mf}{ma}\right) cv}$$

$$= \frac{c_j^2 - ca^2}{2\left(\frac{mf}{ma}\right) cv}$$

Overall efficiency :- $\eta_{th} \times \eta_{prop} = \dfrac{c_j^2 - ca^2}{2\left(\frac{mf}{ma}\right) cv} \times \dfrac{2ca}{c_j + ca}$

$$= \frac{(c_j - ca)\, ca}{\left(\frac{mf}{ma}\right) cv}$$

A turbo jet engine travels at 216 m/s in air at 0.78 bar and $-7.2°C$. Air first enters diffuser in which it is brought to rest relative to the unit and it is then compressed in a compressor through a pressure ratio 5.8 and fed to a turbine at 1110c. The gases expand through the turbine and then through the nozzle to atmospheric pressure. The effeciencies of diffuser, nozzle and compressor are each 90%. The effeciency of turbine 80%. pressure drop in the combustion chamber is 0.168 bar. Determine 1) Air-fuel ratio 2) Specific thrust of the unit 3) Total thrust, if the inlet c/s of diffuser is $0.12 m^2$ assume calorific value of fuel as 44150 kJ/kg of fuel



Speed of air craft $(Ca) = 216 m/s$

Intake air temp (T_1)

$= -7.2 + 273$

$= 265.8 K.$

Intake air pressure $(P_1) = 0.78$ bar

pressure ratio in the compressor = 5.8

Temperature of gases entering the gas turbine

$T_4 = 1110+273 = 1383K$

pressure drop in the combustion chamber

$= 0.168$ bar

$\eta_d = \eta_n = \eta_c = 90\%;\ \eta_t = 80\%$

1. Diffuser:-

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

$$\boxed{h_2 - h_1 = \frac{Ca^2}{2}}$$

$$\boxed{T_2 - T_1 = \frac{Ca^2}{2c_p}}$$

$$= 265.8 + \frac{(216)^2}{2 \times 1.005 \times 1000}$$

$$\boxed{T_2 = 289K}$$

$$T_2' = T_1 + \frac{Ca^2}{2c_p\eta_d}$$

$$= 265.8 + \frac{216^2}{2 \times 1.005 \times 1000 \times 0.9}$$

$$\boxed{T_2' = 291.6K.}$$

$$\Rightarrow \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$p_2 = (p_1)^{\frac{\gamma}{\gamma-1}} \times \left(\frac{T_2}{T_1}\right)$$

$$\boxed{p_2 = 1.044\text{ bar}}$$

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

$$T_3 = 291.6 \times 1.652 = 4817K.$$

$$\eta_c = \frac{T_3 - T_2'}{T_3' - T_2'} =$$

$$\boxed{T_3' = 5028K}$$

Heat Supplied:-

$$(m_f \times CV) = (m_a + m_f)c_p T_4 - m_a c_p T_3'$$

$$m_a c_p (T_4 - T_3') = m_f (CV - c_p T_4)$$

$$\frac{m_a}{m_f} = \frac{CV - c_p T_4}{c_p (T_4 - T_3')}$$

$$\boxed{\frac{m_a}{m_f} = 48.34}$$

⇒ Specific thrust of the unit

$$p_4 = p_3 - 0.168 =$$

$$= 5.8 \times 1.044 - 0.168$$

$$\boxed{p_4 = 5.88\text{ bar}}$$

Assume turbine drives compressor only.

$$c_p(T_3' - T_2') = c_p(T_4 - T_5')$$

$$(T_3' - T_2') = T_4 - T_5'$$

$$T_5' = T_4 - (T_3' - T_2')$$

$$\boxed{T_5' = 1171.8K.}$$

$$\eta_t = \frac{T_4 - T_5'}{T_4 - T_5}$$

$$T_5 = T_4 - \frac{T_4 - T_5'}{\eta_t}$$

$$\boxed{T_5 = 1119K.}$$

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\boxed{p_5 = 2.8\text{ bar.}}$$

$\frac{T5'}{T6} = \left(\frac{P5}{P6}\right)^{\frac{\gamma-1}{\gamma}}$ $\boxed{P6=P1}$

$T6 = 813.75K$

$\eta_n = \frac{T5' - T6'}{T5' - T6}$

$T6' = 849.5K$

Velocity at the exit of nozzle

$C_j = 44.72\sqrt{h5' - h6'}$

$= 44.72\sqrt{cp\,(T5' - T6')}$

$= 804.8\,m/s$

Special thrust $= (1 + mf)\,C_j$

$= \left(1 + \frac{1}{48.34}\right) 804.8$

$= 821.45$ N/kg of air/sec

Total thrust:-

volume of flowing air

$(V_1) = 0.12 \times 216$

$= 25.92\,m^3/s$

$ma = \frac{P_1V_1}{RT_1}$

$= \frac{0.78 \times 10^5 \times 25.92}{(0.287 \times 1000)\,265.8}$

$= 26.5$ kg/s

Total thrust

$= 26.5 \times 821.45$

$= 21768.4N$

A turbo-jet engine consumes air at the rate of 60.2 kg/s when flying at a speed of 1000km/h calculate exit velocity of jet when the inthalaphy change for the nozzle is 230 kJ/kg and velocity co-effecient is 0.96. Fuel flow rate in kg/s when air fuel ratio is 70:1, thrust specific fuel consumption, thermal efficiency of the plant when the combustion efficiency is 92% and the calorific value of fuel is used is 42000 kJ/kg. propulsive power, propulsive efficiency, overall efficiency.

Rate of air consumption

$(ma) = 60.2$ kg/s

Enthalaphy change for nozzle

$\Delta h = 230$ kJ/kg

velocity coeffocient $(\eta) = 0.96$

Air-fuel ratio $= 70:1$

$\eta_{combustion} = 92\%$

Calorific value (cv) = 42000 kJ/kg

Aircraft velocity (ca)

$= \frac{1000 \times 1000}{3600}$

$= 277.8$ m/sec

Exit velocity of jet

$C_j = 44.72$

$C_j = \eta\sqrt{2 \times \Delta h \times 1000}$

$= 0.96\sqrt{2 \times 1000 \times 230}$

$= 651$ m/s

Fuel flow rate

$mf = \frac{\text{Air consumption}}{\text{Air-fuel ratio}}$

$= \frac{60.2}{70}$

$= 0.86$ kg/sec

Thrust specific fuel consumption

$$= \frac{\text{fuel consumption}}{\text{Thrust}}$$

$$= \frac{0.86}{\text{Thrust}}$$

Thrust $= m_a (C_j - C_a)$

$= 60.2 (651 - 277.8)$

$= 22466.6\,N$

$$= \frac{0.86}{22466.6}$$

$= 3.828 \times 10^{-5}$ kg/N

$$\eta_{overall} = \frac{\text{Thrust work}}{\text{Heat supplied by fuel}}$$

$$= \frac{(C_j - C_a) C_a}{\left(\frac{m_f}{m_a}\right) cv \times \eta_{com}}$$

$$= \frac{(651 - 277.8)\, 277.8}{\frac{1}{70} \times 42000 \times 0.92 \times 100}$$

$= 18.78\%$

$$\eta_{thermal} = \frac{\text{work output}}{\text{Heat supplied}}$$

$$= \frac{C_j^2 - C_a^2}{\left(\frac{m_f}{m_a}\right) cv \times \eta_{com} \times 1000}$$

$$= \frac{(651)^2 - (277.8)^2}{2 \times \frac{1}{70} \times 42000 \times 0.92 \times 1000}$$

$= 31.39\%$

propulsive power:-

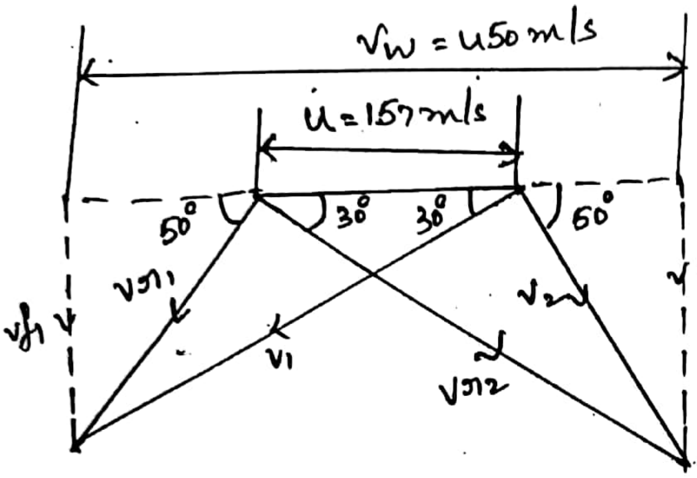
$$= \frac{\text{Thrust power}}{\text{propulsive power}}$$

$$= \frac{2C_a}{C_j + C_a} = \frac{2 \times 277.8}{651 + 277.8}$$

$= 59.8\%$

A 50% reaction turbine stage running at 3000 rpm the exit angles are 60° and the inlet angles are 50°. The mean diameter is 1m. The steam flowrate is 10,000 kg/min stage efficiency is 85%, find the power developed and enthalaphy drop in a stage.

$$u = \frac{\pi DN}{60}$$
$$= \frac{\pi \times 1 \times 3000}{60}$$
$$= 157 \text{ m/s}$$



$$m = \frac{10,000}{60}$$
$$= 166.67 \text{ kg/s}$$
$$\eta_{stage} = 0.85$$

$V_w = 450$ m/sec

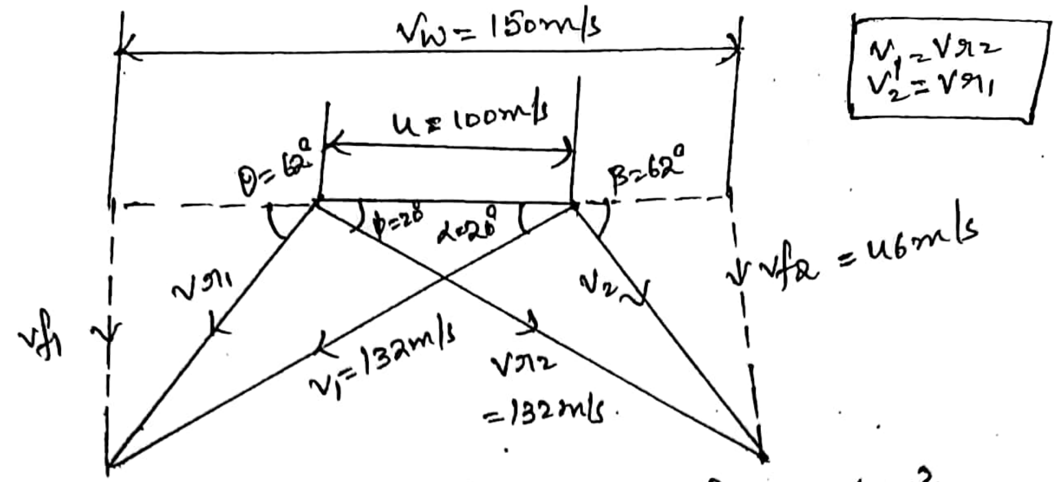
$$P = \frac{m(V_w)u}{1000}$$
$$= \frac{166.67 \times 450 \times 157}{1000}$$
$$= 11,775 \text{ kW}$$

$$\eta_{stage} = \frac{(V_w)u}{\Delta h \times 1000}$$
$$\Delta h = 83.12 \text{ kJ/kg}$$

The total tangential force on one ring of parsion's turbine is 1200N when the blade speed is 100 m/s. The mass flow rate is 8 kg/s the blade outlet angle is 20° Determine the steam velocity at outlet from the blades. If the friction loss which occurs with pure impulse are 30% of the kinetic energy and if the expansion losses are 15% of the heat drop in the blades, determine the heat drop / stage and stage efficiency.

Tangential force = 1200N
Blade Speed (u) = 100 m/s
$m = 8$ kg/s, $\phi = 20°$

$$F = \frac{m(V_w)u}{\;}$$
$$V_w = \frac{F}{m} \rightarrow \frac{1200}{8} = 150 \text{ m/s}$$



~~Δa~~ $\Delta h_f = \Delta h_m = \frac{V_1^2 - 0.7V_2^2}{2\times1000} \Rightarrow \frac{132^2 - 0.7(52)^2}{2\times1000\times0.85}$

$= 9.14\ kJ/kg$

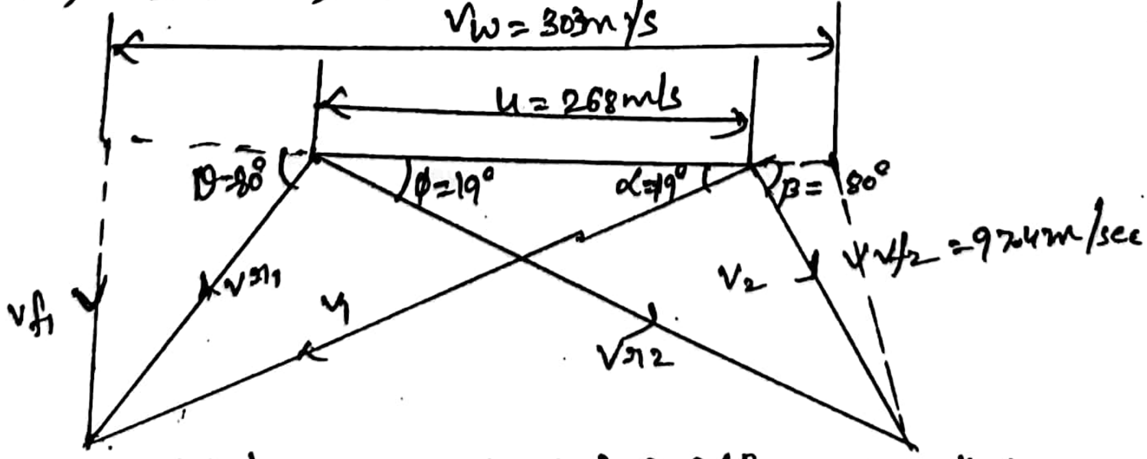
Total heat drop $= \Delta h_f + \Delta h_m = 18.28\ kJ/kg$.

$\eta_{stage} = \frac{(V_w)u}{1000\times\Delta h} = 82.1\%$.

In a stage of impulse reaction turbine operating with 50% Degree of reaction the blades are identical in shape. The outlet ~~angle~~ of moving blades is 19° and the absolute discharge velocity of steam is 100m/s in direction at 100° to the motion of blades. If the rate of flow of steam through the turbine is 15000 kg/hr. Calculate power developed by turbine.

$m = \frac{15000}{3600} = 4.167\ kg/s$

$\phi = 19°$, $V_2 = 100m/s$, $\beta = 180 - 100 = 80°$,

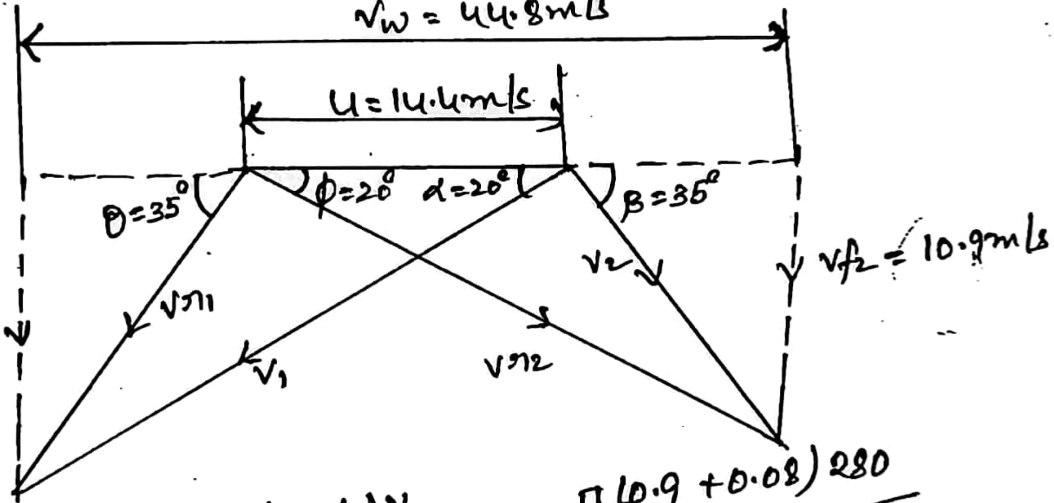


$P = \frac{m(V_w)u}{1000} = \frac{4.167\times303\times268}{1000} = 338.4\ kW$

In a reaction turbine, the blade tip angles at inlet and exit are 35° and 20° respectively at a certain place in the turbine, the drawn diameter is 0.9m and the blades are 0.08m high At this place steam has a pressure of 1.7 bar and dryness fraction 0.935. If the speed of turbine is 280 rpm and the steam passess through the blades without shock find the mass of steam flow and the power developed in the ring of moving blades.

$\theta = \beta = 35^\circ$, $\phi = \alpha = 20^\circ$, $D = 0.9m$, $h = 0.08m$, $p = 1.7\,bar$

$x = 0.935$, $N = 280\,rpm$.



$$\text{Blade Speed } (u) = \frac{\pi(D+h)N}{60} = \frac{\pi(0.9+0.08)280}{60}$$

$$= 14.4 m/s$$

at pressure 1.7 bar, $v_g = 1.031\, m^3/kg$

sp. volume $v_g = x v_g \Rightarrow 0.935 \times 1.031 = 0.964\, m^3/kg$

$$\dot{m} = \frac{[\pi(D+h)h]V_{f2}}{V_g}$$

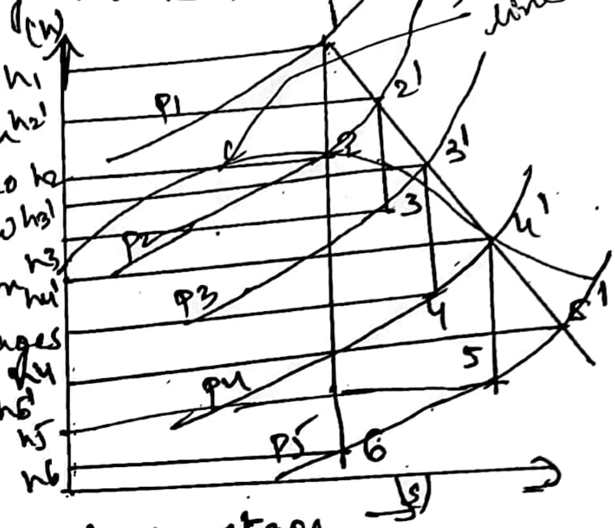
$$= \frac{[\pi(0.9+0.08)0.08]\,10.9}{0.964} = 2.78\, kg/s$$

$$\text{power } (P) = \frac{\dot{m}(V_w)u}{1000}$$

$$= \frac{2.78(44.8)14.4}{1000} = 1.8\, kW$$

State point locus and reheat factor:- In multistage turbine steam leaving from the first moving blade is made to flow through fixed ring and again it is made to strike on second moving blade now it is completed 2 stages.

After leaving second moving blade it is again made to flow through fixed ring. and again it is made to strike on third moving blade. now it completes 3 stages. If the steam passes through many number of stages then the turbine is known as multistage turbine



Let

P_1 = Inlet pressure of steam entering first stage.

" " " leaving ~~Second~~ first "

P_2 = Exit " " " " ~~Third~~ Second "

P_3 = " " " " " ~~Fo~~third "

P_4 = " " " " Fourth "

P_5 = " " " " "

The locus passing through 1, 2', 3', 4' and 5' is known as state point locus

If the friction is neglected then (h_1-h_6) will represent the isentropic heat drop the sum of $(h_1-h_2) + (h_2'-h_3) + (h_3'-h_4) + (h_4'-h_5)$ is known as cumulative heat drop. The ratio of cumulative heat drop to the isentropic heat drop is known as reheat factor.

$$\text{Reheat factor :-} \frac{\text{Cumulative heat drop}}{\text{Isentropic heat drop}}$$

$$= \frac{(h_1-h_2) + (h_2'-h_3) + (h_3'-h_4) + (h_4'-h_5)}{(h_1-h_6)}$$