UNIT - 1

Rankine Cycle

(i) Simple rankine cycle.

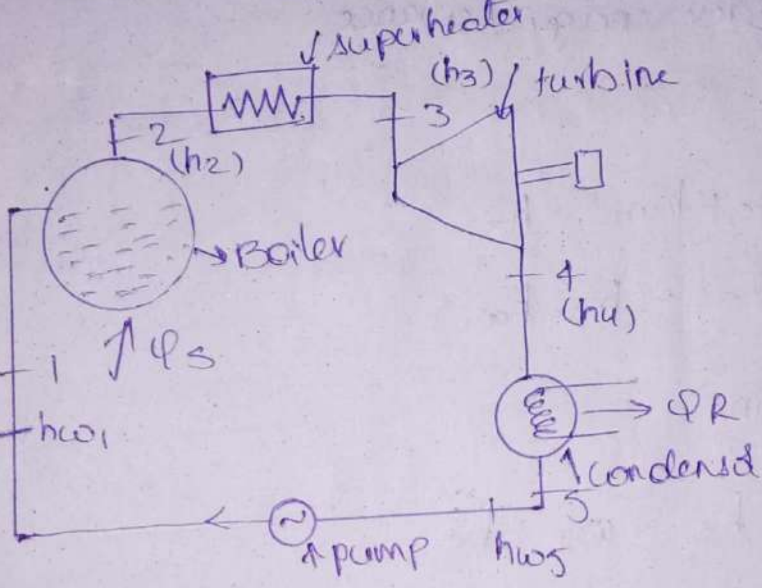
(ii) Reheat Rankine cycle

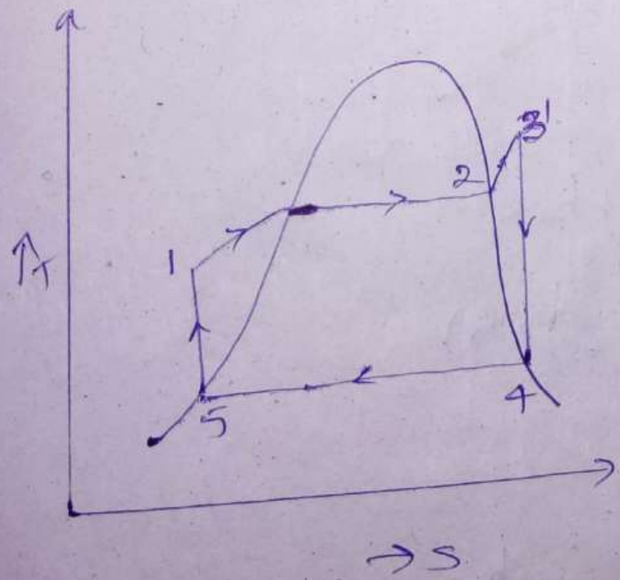
(iii) Regenerative Rankine cycle

(iv) combined Reheat & regenerative Rankine cycle

(v) modified Rankine cycle

1. Simple Rankine cycle :





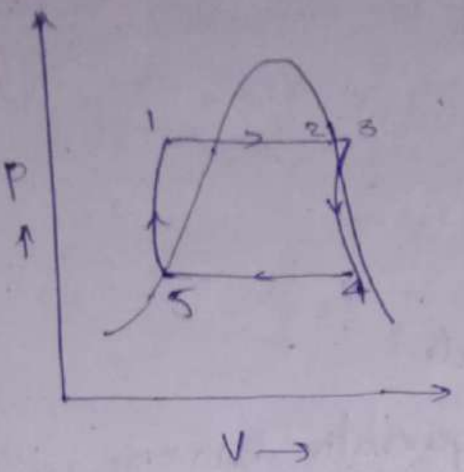
1 – 2 : heat addition to boiler

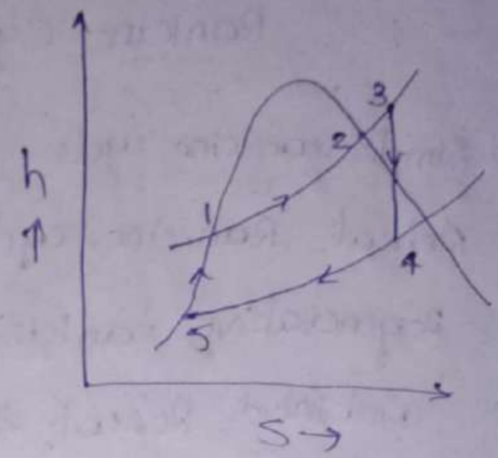
2 - 3 : super heating

3 – 4 : turbine expansion

4 - 5 : const press. heat rejection

5 – 1 : Isentropic compl.





* Thermal η of rankine cycle

consider energy balance

(i) boiler

$$Q_s + h_{w_1} = h_3$$

$$Q_s = (h_3 - h_{w_1})$$

(ii) Turbine

$$h_3 = W_T + h_4$$

$$W_T = (h_3 - h_4)$$

(iii) condensa

$$h_4 = Q_R + h_{w_5}$$

$$Q_R = (h_4 - h_{w_5})$$

(iv) pump

$$h_{w_5} + W_P = h_{w_1}$$

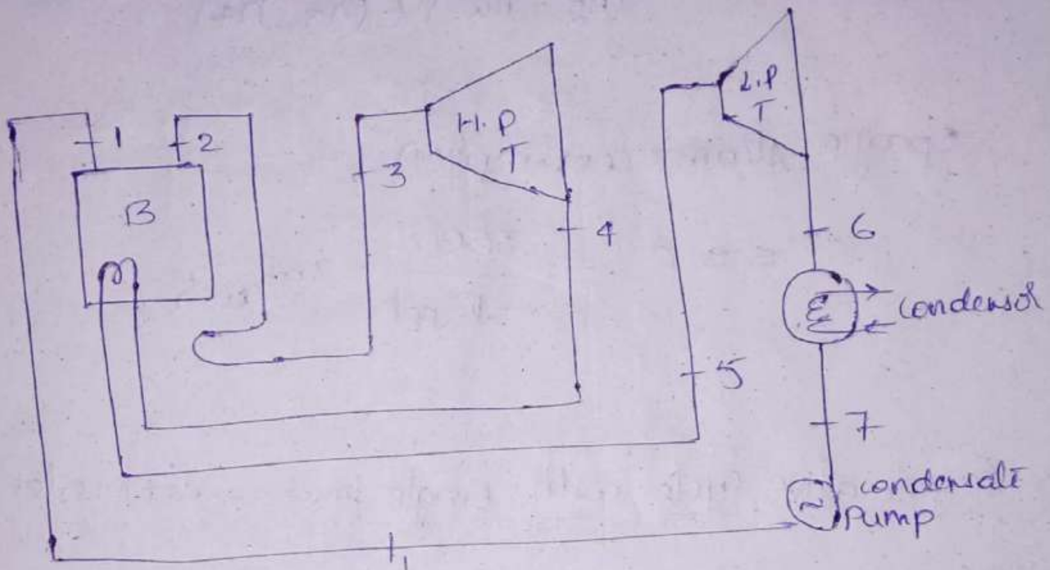
$$W_P = (h_{w_1} - h_{w_5})$$

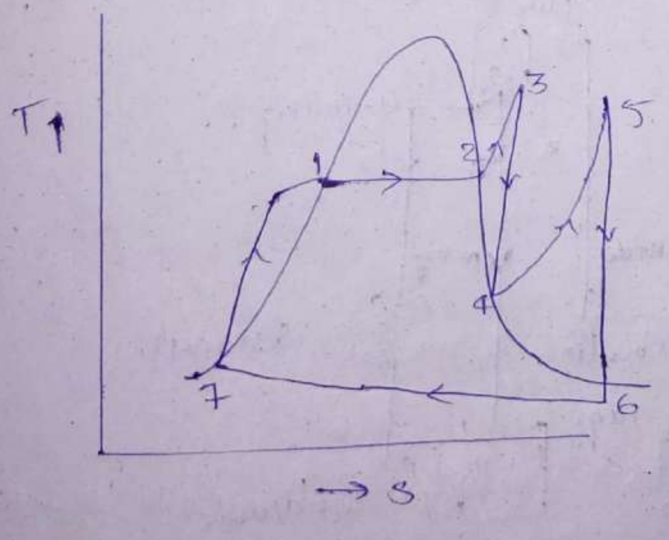
$$\eta_{th} = \frac{W_{net}}{Q_s}$$

$$\eta_{th} = \frac{W_T - W_P}{Q_s} \qquad (\because W_P = 0)$$

$$\boxed{\eta_{th} = \frac{h_3 - h_4}{h_3 - h_{w_1}}}$$

2. Reheat Rankine cycle :-





$$\eta_{th} = \frac{W_{net}}{Q_s} \times 100$$

$$= \frac{(W_{H.P.T} + W_{L.P.T}) - W_P}{Q_B + Q_R} \times 100$$

$$w_{HPT} = (h_3 - h_4)$$

$$w_{LPT} = (h_5 - h_6)$$

$$w_P = (h_1 - h_7) = v_7 (P_1 - P_7)$$

$$Q_B = (h_2 - h_{w1})$$

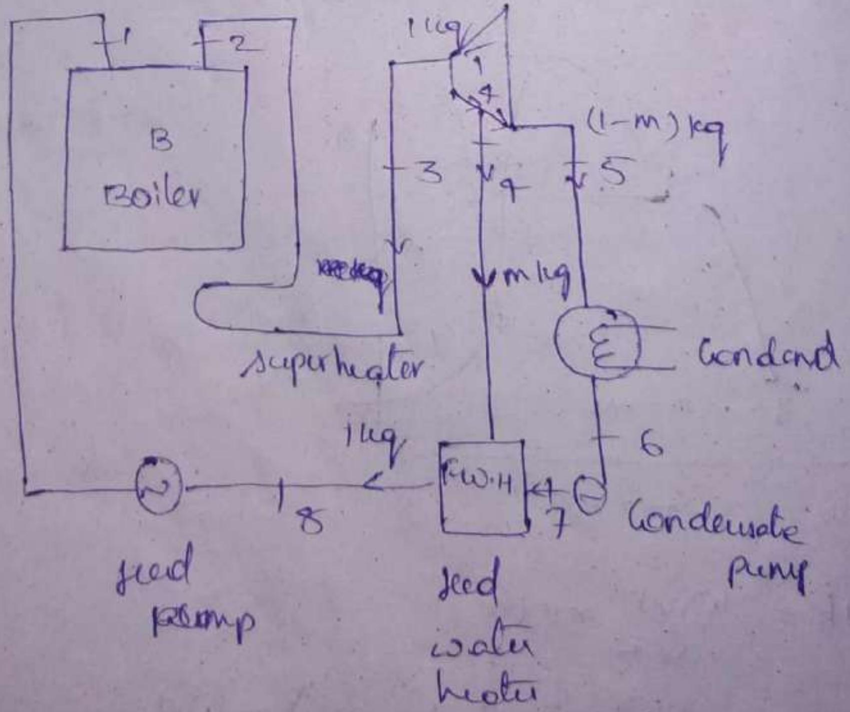
$$Q_R = (h_5 - h_4)$$

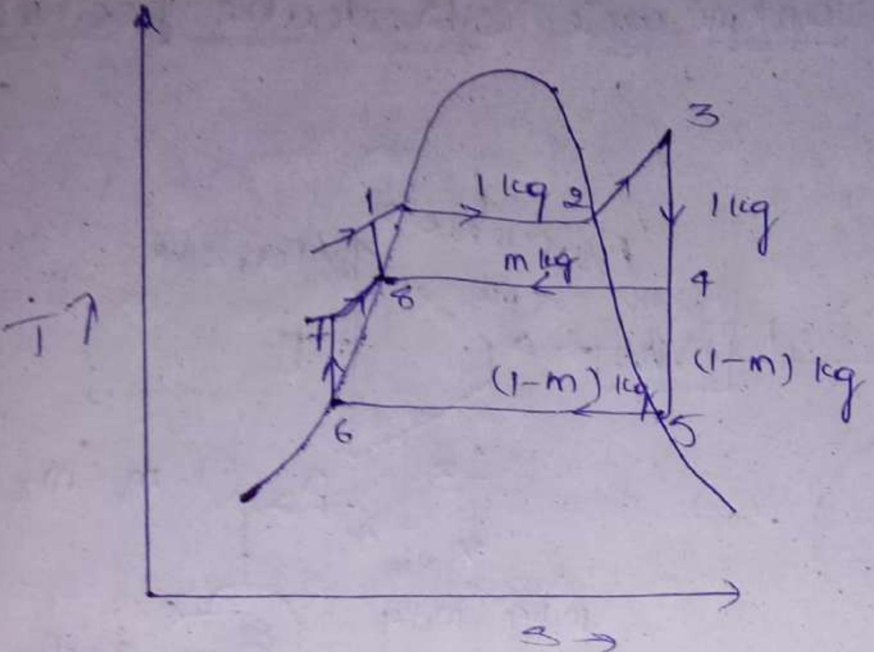
$$\eta_{th} = \frac{[(h_3 - h_4) + (h_5 - h_6)] - (h_1 - h_7)}{(h_2 - h_{w1}) + (h_5 - h_4)}$$

specific steam consumption

$$S.S.C = \frac{3600}{W_{net}} \text{ kg/kW.h}$$

3. Regenerative cycle with single feed water heater :-





$$\eta_{th} = \frac{W_{net}}{Q_s} \times 100$$

$$= \frac{W_T - (W_{CPt} + W_{FP})}{(h_3 - h_{w1})} \times 100$$

$$W_T = 1(h_3 - h_4) + (1-m)(h_4 - h_5)$$

$$W_{CP} = (h_7 - h_6) = v_6 (P_7 - P_6)$$

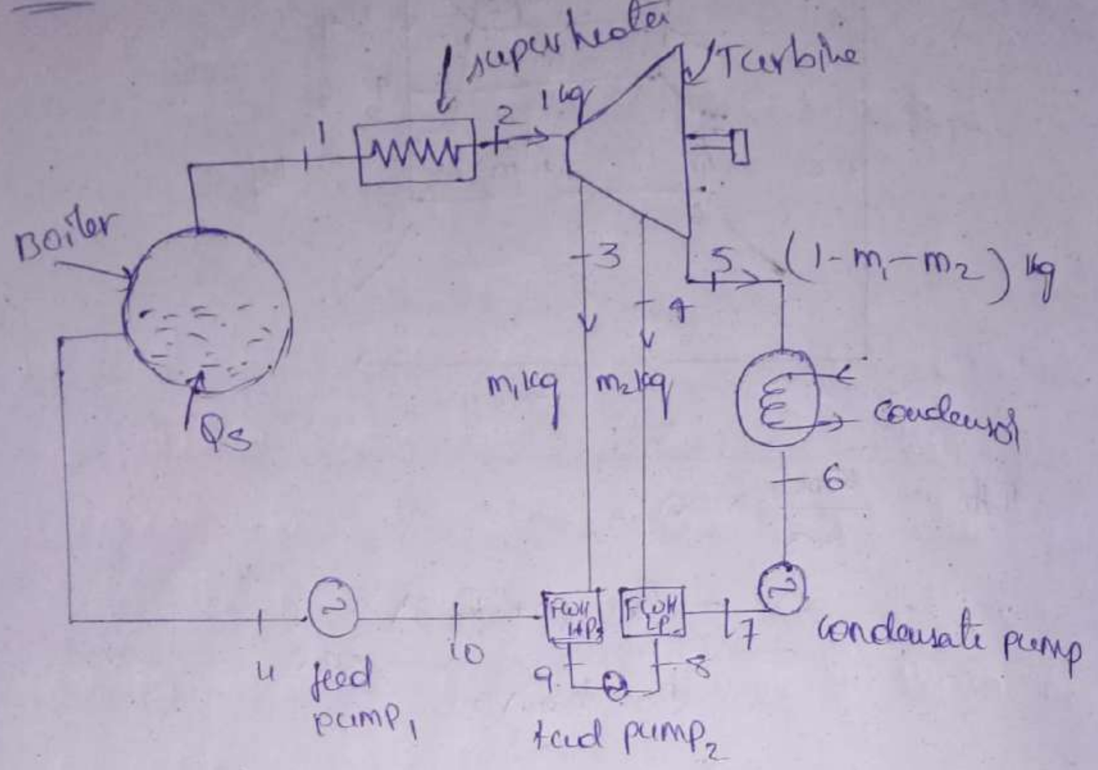
$$W_{F.P} = (h_1 - h_8) = v_8 (p_1 - p_8)$$

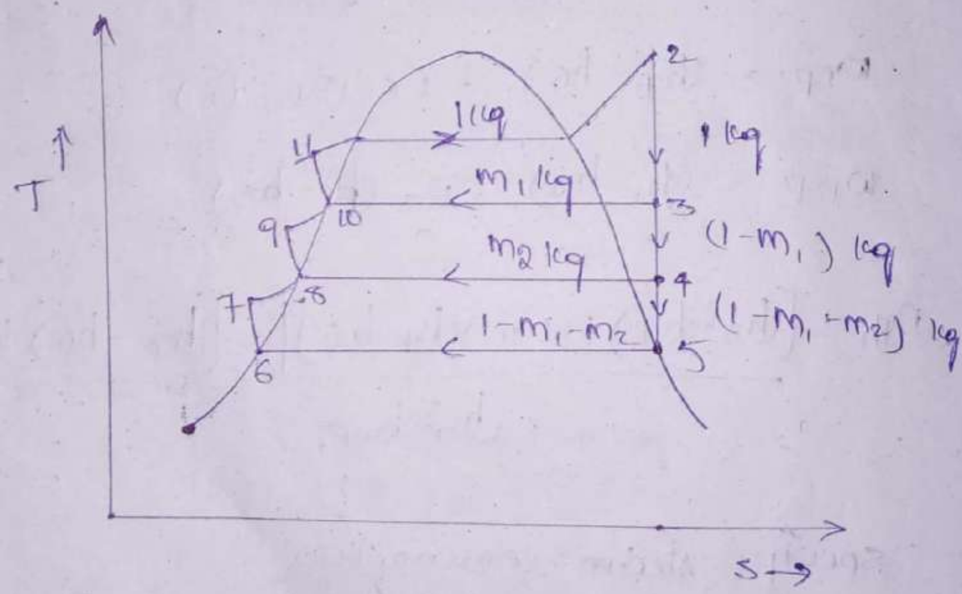
$$\eta_{th} = \frac{\left[(h_3 - h_4) + (1-m)(h_4 - h_5)\right] - \left[(h_7 - h_6) + (h_1 - h_8)\right]}{(h_3 - h_{w1})}$$

specific steam consumption

$$S.S.C = \frac{3600}{W_{net}} \text{ kg/kWh}$$

Regenerative rankine cycle with double feed water heater :-





$$\eta_{th} = \frac{W_{net}}{Q_S} \times 100 = \frac{W_T - W_P}{Q_S} \times 100$$

$$W_T = 1(h_2 - h_3) + (1-m_1)(h_3 - h_4) + (1 - m_1 - m_2)(h_4 - h_5)$$

$$W_P = W_{CP} + W_{FP_1} + W_{FP_2}$$

$$= (h_7 - h_6) + (h_9 - h_8) + (h_{11} - h_{10})$$

heat supplied $Q_s = (h_2 - h_{11})$

$$\eta_{th} = \frac{\left[1(h_2-h_3)+(1-m_1)(h_3-h_4)+(1-m_1-m_2)(h_4-h_5)\right] - \left((h_7-h_6)+(h_9-h_8)+(h_{11}-h_{10})\right)}{h_2-h_{11}}$$

specific steam consumption

$$S.S.C = \frac{3600}{W_{net}} \ kg/kW.h$$

→ mass of the steam exerted for H.P feed water heater (m_1) :-

consider energy balance for HP FWH

$$m_1 h_3 + (1-m_1) h_{w9} = 1 \times h_{w10}$$

$$m_1 h_3 + h_{w9} - m_1 h_{w9} = h_{w10}$$

$$m_1 (h_3 - h_{w9}) = h_{w10} - h_{w9}$$

$$\boxed{m_1 = \frac{h_{w10} - h_{w9}}{h_3 - h_{w9}}}$$

→ mass of the steam extracted for LP feed water (m_2).

consider energy balanced for LP FWH.

$$m_2 h_4 + (1-m_1-m_2) h_{w7} = (1-m_1) h_{w8}$$

$$m_2 h_4 + h_{w7} - m_1 h_{w7} - m_2 h_{w7} = (1-m_1) h_{w8}$$

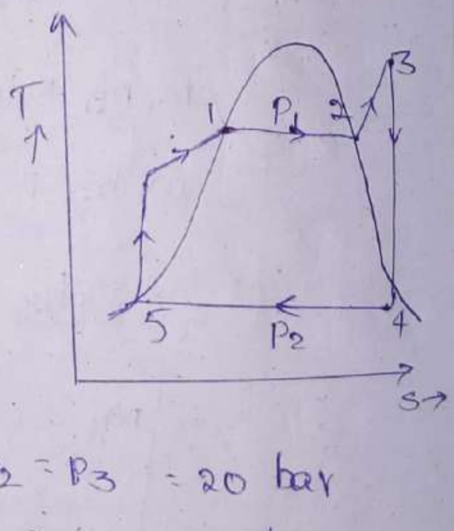
$$m_2 h_4 + h_{w7} - m_1 h_{w7} - m_2 h_{w7} = h_{w8} - m_1 h_{w8}$$

$$m_2 (h_4 - h_{w7}) + h_{w7} - m_1 h_{w7} = h_{w8} - m_1 h_{w8}$$

$$m_2 = \frac{h_{w8} - m_1 h_{w8} - h_{w7} + m_1 h_{w7}}{h_4 - h_{w7}}$$

1. In a steam turbine steam at 20 bar, 360°C is expanded to 0.08 bar. It is then enters into condenser where it is condensate to saturated liquid water the pump feed back to water into the boiler. Assume ideal process. find per kg of steam the net work & cycle η.

sol Given data



$P_1 = 20$ bar

$P_2 = 0.08$ bar

$T_1 = 360°C$

$t_s \rightarrow 212.4°C$

find $W_{net} = ?$

$\eta_{cycle} = ?$

$P_1 = P_2 = P_3 = 20$ bar

$P_4 = P_5 = 0.08$ bar.

enthalpy of super heated steam

$$h_3 = h_{sup_3} = h_{s_3} + c_p (t_{sup} - t_s)$$

$$= 2792.2 + 2.1 (360 - 212.4)$$

$$= 3107.1 \text{ kJ/kg}$$

$\phi_3 = \phi_4$

$\phi_{sup_3} = \phi_{wet\,4}$

$$\phi_{s3} + c_p \ln\left[\frac{T_{sup_3}}{T_{s3}}\right] = \phi_{w4} + x_4\,\phi_{e4}$$

$$6.337 + 2.1 \ln\left[\frac{360+273}{212.4+273}\right] = 0.593 + x_4 \times 7.637$$

$x_4 = 0.82.$

enthalpy of wet exhaust steam

$h_4 = h_{wet_4} = h_{w4} + x_4 L_4$

$= 173.9 + 0.82 \times 2403.2$

$= 2144.52$ kJ/kg.

$W_{net} = W_T - W_P$

$W_T = (h_3 - h_4)$

$= 3107.1 - 2144.52$

$= 962.5$ kJ/kg

$W_P = (h_{w1} - h_{w5}) = v_5 (P_1 - P_5)$

$= 0.001008 (20 - 0.08) \times 100$

$= 2$ kJ/kg

$W_{net} = W_T - W_P$

$= 962.5 - 2.00$

$= 960.5$ kJ/kg

$w_p = h_{w01} - h_{w05} = 2$

$h_{w01} = 2 + 173.9$

$h_{w01} = 175.9 \text{ kJ/kg}$

$Q_s = (h_3 - h_{w1})$

$= 3107.1 - 175.9$

$= 2931.2 \text{ kJ/kg}$

$\eta_{cycle} = \frac{W_{net}}{Q_s} \times 100$

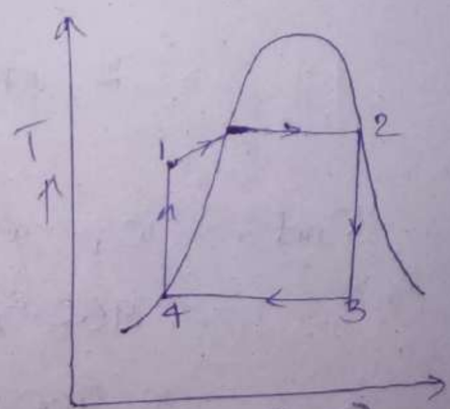
$= \frac{960.5}{2931.2} \times 100$

$= 32.76\%$

2. In a rankine cycle, the steam at inlet to the turbine is saturated at a pressure of 35 bar at exhaust pressure is 0.2 bar. Determine pump work, turbine work, η rankine, condenser heat flow, dryness of the end of the expansion. Assume flow rate is 9.5 kg/sec

sol $P_1 = P_2 = 35 \text{ bar}$

$P_3 = P_4 = 0.2 \text{ bar}$



$x_2 = 1$

$x_3 = ?$

$h_2 = h_{s2} = 2802$ kJ/kg

$\phi_2 = \phi_3$

$\phi_{s2} = \phi_{wet\,3}$

$6.123 = \phi_{w3} + x_3 \phi_{e3}$

$6.123 = 0.832 + x_3 (7.077)$

$x_3 = 0.74 < 1.$

enthalpy of exhaust steam

$h_3 = h_{wet\,3} = h_{w3} + x_3 l_3$

$= 251.5 + 0.74 \times 2358.4$

$= 1996.71$ kJ/kg

$h_4 = h_{w4} = 251.5$ kJ/kg

→ Pump work $w_p = v_4 (P_1 - P_4) \times 100$

$= 0.001017 \; (35 - 0.2) \times 100$

$= 3.5$ kJ/kg

$w_p = (h_{w_1} - h_{w4}) = 3.5$

$h_{w_1} = 3.5 + 251.5$

$= 255$ kJ/kg

→ turbine work $w_T = (h_2 - h_3)$

$= \dot{m} (h_2 - h_3)$

$= 9.5 \; (2802 - 1996.71)$

$= 7652$ kW

BOILER MOUNTINGS

INTODUCTION TO BOILER

Definition:

- ✓ A boiler is a closed vessel in which water is converted in to steam by burning of fuel in presence of air at desired temperature, pressure and at desired mass flow rate.
- ✓ According to the Indian Boiler Act 1923, a boiler is a closed pressure vessel with capacity more than 23 liters and used for generating steam under pressure and includes all the mountings fitted to a closed vessel.
- ✓ According to American society of Mechanical Engineers (A.S.M.E.), a steam generator or a boiler is defined as "a combination of apparatus for producing, finishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized.

PRINCIPAL OF WORKING

In case of boiler, any type of fuel burn in presence of air and form flue gases which are at very high temperature (hot fluid). The feed water at atmospheric pressure and temperature enters the system from other side (cold fluid). Because of exchanges of heat between hot and cold fluid (water) temperature raises and it form steam. The flue gases (hot fluid) temperature decreases and at lower temperature hot fluid is thrown in to the atmosphere via stack/chimney.

FUNCTION OF A BOILER

The steam generated is employed for the following purposes:

- ➤ Used in steam turbines to develop electrical energy.
- ➤ Used to run steam engines.
- ➤ In the textile industries, sugar mills or in chemical industries as a cogeneration plant.
- ➤ Heating the buildings in cold weather.
- ➤ Producing hot water for hot water supply.

IBR AND NON-IBR BOILERS

- ✓ Boiler generating steam at working pressure below 10 bar and having water storage capacity less than 22.75 liters are called non-IBR boilers. (INDIAN BOILER REGULATION).
- ✓ Boilers outside these limits are covered by the IBR and have to observe certain specified conditions before being operated.

CLASSIFICATION OF BOILERS

The different ways to classify the boilers are as follows

1. According to location of boiler shell axis

- Horizontal (Lancashire boiler, Locomotive boiler, Babcock and Wilcox etc.)
- Vertical (Cochran boiler, vertical boiler etc.)
- Inclined boilers

When the axis of the boiler shell is horizontal the boiler is called horizontal boiler. If the axis is vertical, the boiler is called vertical boiler and if the axis of the boiler is inclined it is known as inclined boiler.

2. According to the flow medium inside the tubes

- Fire tube (Lancashire, Locomotive, Cochran and Cornish boiler.)
- Water tube boilers (Simple vertical boiler, Babcock and Wilcox boiler.)

The boiler in which hot flue gases are inside the tubes and water is surrounding the tubes is called fire tube boiler. When water is inside the tubes and the hot gases are outside the boiler is called water tube boiler.

3. According to boiler pressure

According to pressure of the steam raised the boilers are classified as follows

- Low pressure (Below 80 bar) [Cochran and Cornish boiler, Lancashire and locomotive boiler]
- High pressure boilers (> 80 bar) [Babcock and Wilcox boiler]

4. According to the draft used:

- Natural draft (Simple vertical boiler, Lancashire boiler.)
- Artificial draft boilers (Babcock and Wilcox boiler, Locomotive boiler.)

Boilers need supply of air for combustion of fuel. If the circulation of air is provided with the help of a chimney, the boiler is known as natural draft boiler. When either a forced draft fan or an induced draft fan or both are used to provide the flow of air in the boiler is called artificial draft boiler.

5. According to method of water circulation:

- Natural circulation (Babcock and Wilcox boiler, Lancashire boiler.)
- Forced circulation (Velox boiler, Lamont boiler, Loffler boiler.)

If the circulation of water takes place due to difference in density caused by temperature of water, the boiler is called natural circulation boiler. When the circulation is done with the help of a pump the boiler is known as forced circulation boiler.

6. According to furnace position:

- Internally fired (Simple vertical boiler Lancashire boiler, Cochran boiler.)
- Externally fired boilers (Babcock and Wilcox boiler.)

When the furnace of the boiler is inside its drum or shell, the boiler is called internally fired boiler. If the furnace is outside the drum the boiler is called externally fire boiler.

7. According to Fuel Used.

- Solid
- Liquid
- Gaseous
- Electrical
- Nuclear energy fuel boilers

The boiler in which heat energy is obtained by the combustion of solid fuel like coal or lignite is known as solid fuel boiler. A boiler using liquid or gaseous fuel for burning is known as liquid or gaseous fuel boiler. Boilers in which electrical or nuclear energy is used for generation of heat are respectively called as electrical energy headed boilers and nuclear energy heated boiler.

8. According to number of tubes

- Single tube (Cornish boiler, Vertical boiler.)
- Multi-tube boiler (Lancashire boiler, Locomotive boiler, Babcock and Wilcox.)

A boiler having only one fire tube or water tube is called a single, tube boiler. The boiler having two or more, fire or water tubes is called multi-tube boiler.

9. According to boiler mobility

- Stationary (Lancashire, Babcock and Wilcox boiler, Vertical boiler.)
- Portable (Locomotive boiler, Marine boiler)
- Marine boilers

When the boiler is fixed at one location and cannot be transported easily it is known as stationary boiler. If the boiler can be moved from one location to another it is known as portable boiler. The boiler which work on surface of water are called marine boilers.

FACTORS AFFECTING THE SELECTION OF A BOILER

One has to send the technical details to the manufacturer to purchase a boiler. The technical details that are used to give information about a particular boiler include the following things:

- Size of drum (Diameter and Length)
- Rate of steam generation (kg/hr)
- Heating surface (Square meters)
- Working pressure(Bar)
- Number of tubes /drum
- Type of boiler
- Manufacture of boiler
- Initial cost
- Quality of steam
- Repair and inspection facility

BOILER MOUNTINGS

The boiler mountings are the different fittings and devices which are mounted on a boiler shell for proper functioning and safety.

(A) Mountings for safety

1. **Safety valve (02 Nos.)**
2. **High pressure and low water safety valve on Lancashire and Cornish boiler (01 each)**
3. **Water level indicator (02 Nos.)**
4. **Fusible plug (01 No.)**

(B) Mountings for controls

1. **Pressure gauge (01 No.)**
2. **Steam stop valve (01 No.)**
3. **Feed check valve (01 No.)**
4. **Blow off cock (01 No.)**
5. **Man hole (01 No.)**
6. **Mud box (01 No.)**

SAFETY VALVE

Safety valve is located on the top of the boiler. They guard the boiler against the excessive high pressure of steam inside the drum. If pressure exceeds the working pressure then the safety valve allows to blow off a certain quantity of steam to the atmosphere, and the pressure falls in the drum.

There are four types of safety valves.

1. Dead-weight safety valves

Figure 01 shows the schematic of a dead weight safety valve. It is similar to dead weight (whistle) loaded on a pressure cooker and functions in a similar way. A gunmetal valve rests on gunmetal seat. The gunmetal seat is mounted on a steel steam pipe. The valve is fastened to a weight carrier. The dead weight is in the form of cylindrical discs are placed on the carrier so it acts downward. When the force due to steam pressure exceeds the total dead weight acting downward, the valve lifts up from the seat and some quantity of steam left the atmosphere, thus reducing the steam pressure in the boiler shell, and the valve is again closed. The dead weight safety valve is used on stationary boilers.

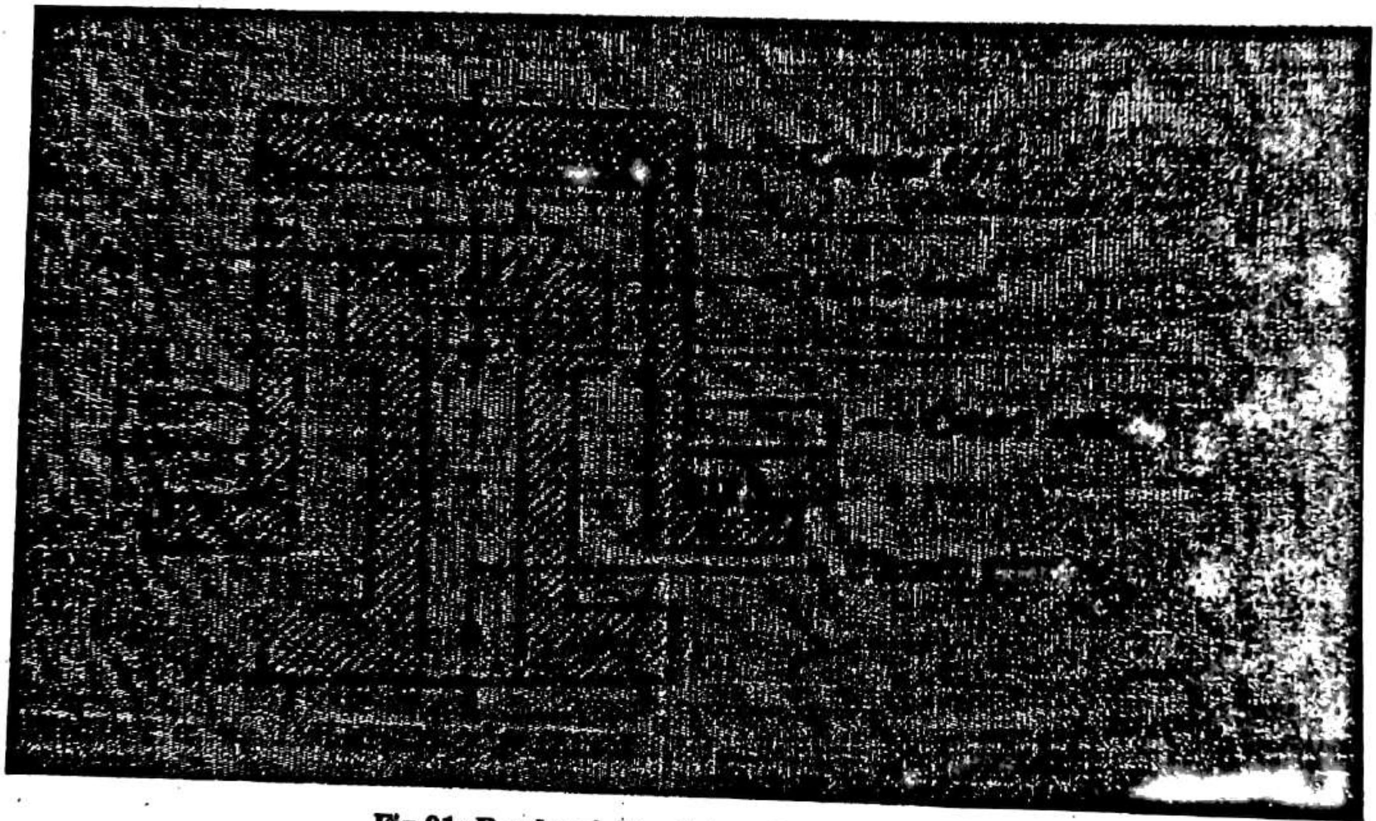


Fig.01: Dead weight safety valve

2. Spring- loaded safety valve

The dead weight safety valve cannot be used on locomotive and marine boilers. The spring loaded safety valve is used on locomotive marines and on high –pressure valve. Fig shows the valve close the steam passages under the action of a central helical spring. When the upward force of steam exceeds the down ward spring tension, the valves open and some steam escape to the atmosphere. Thus lower the steam pressure in the boiler and the valves are closed again under the spring force.

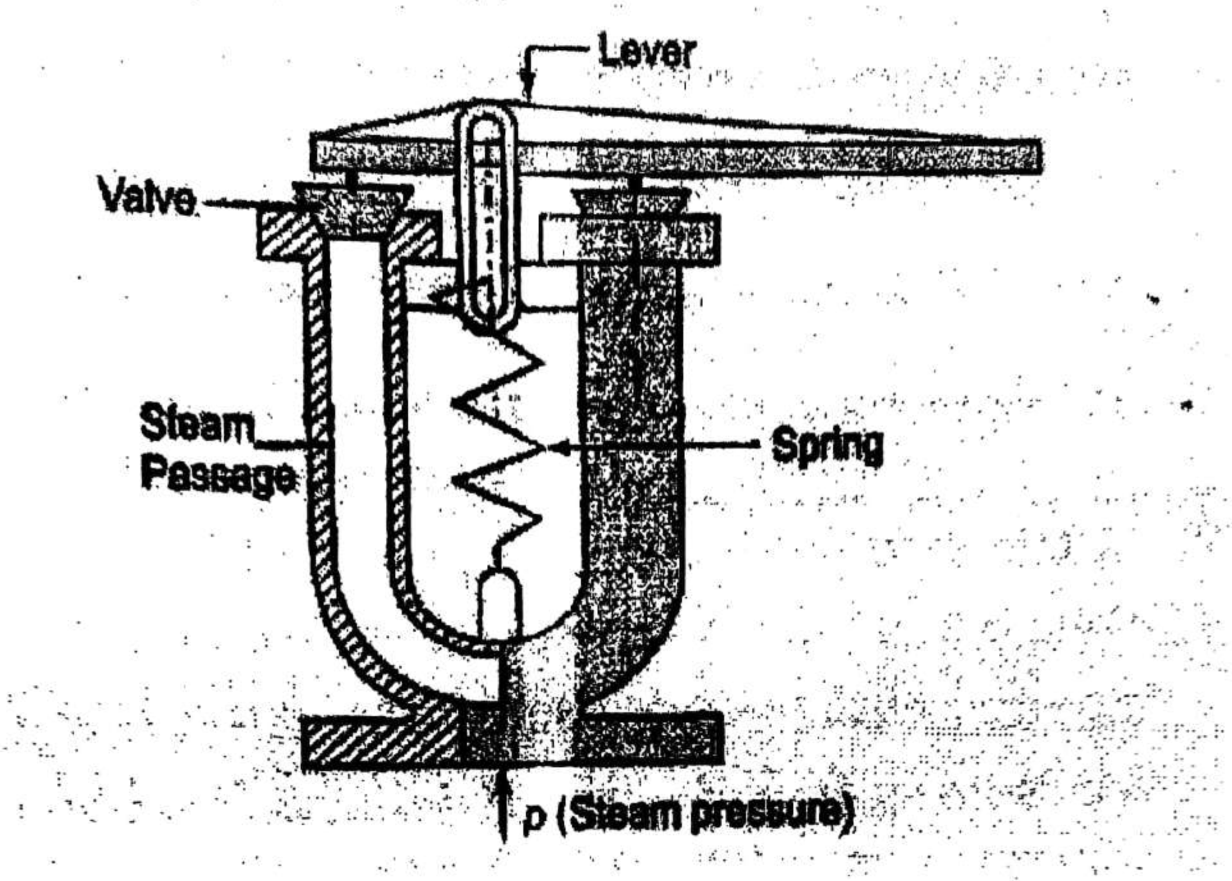


Fig.02: Spring –loaded safety valve

3. **Lever-loaded safety valve**

   The fig. shows the lever- loaded spring safety valve, the body of valve is fastened on the top of the boiler shell. A gunmetal valve is placed on the steam passage formed in the casing. A cast iron lever attached to a fulcrum on one end and loaded by weight on the other end keeps the valve on the seat in a closed position.

   When the upward force due to steam pressure exceeds the load on the valve, the valve opens, and allows some quantity of steam to escape. The pressure of steam in the boiler falls and the valve again rests on the seat.

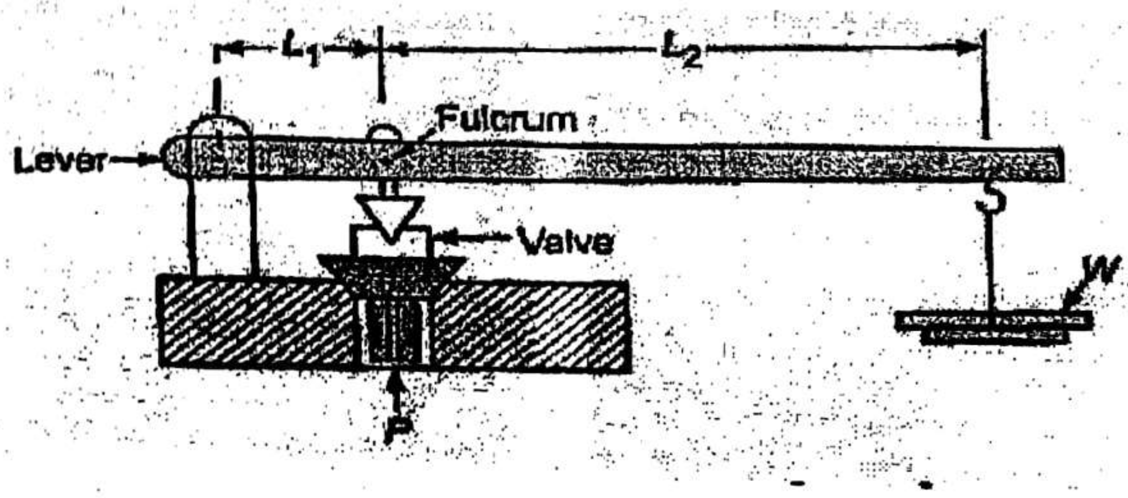


Fig.03: Lever-loaded safety valve

4. **High steam and low water safety valve**

This valve is combination of two valves as shown in fig 4. It is used in Cornish and Lancashire boilers. One of the valves is lever loaded and is operated when steam pressure in the boiler exceeds the working pressure. The second valve operates and blows off steam with a louder noise, when water level in the boiler falls below the normal level.

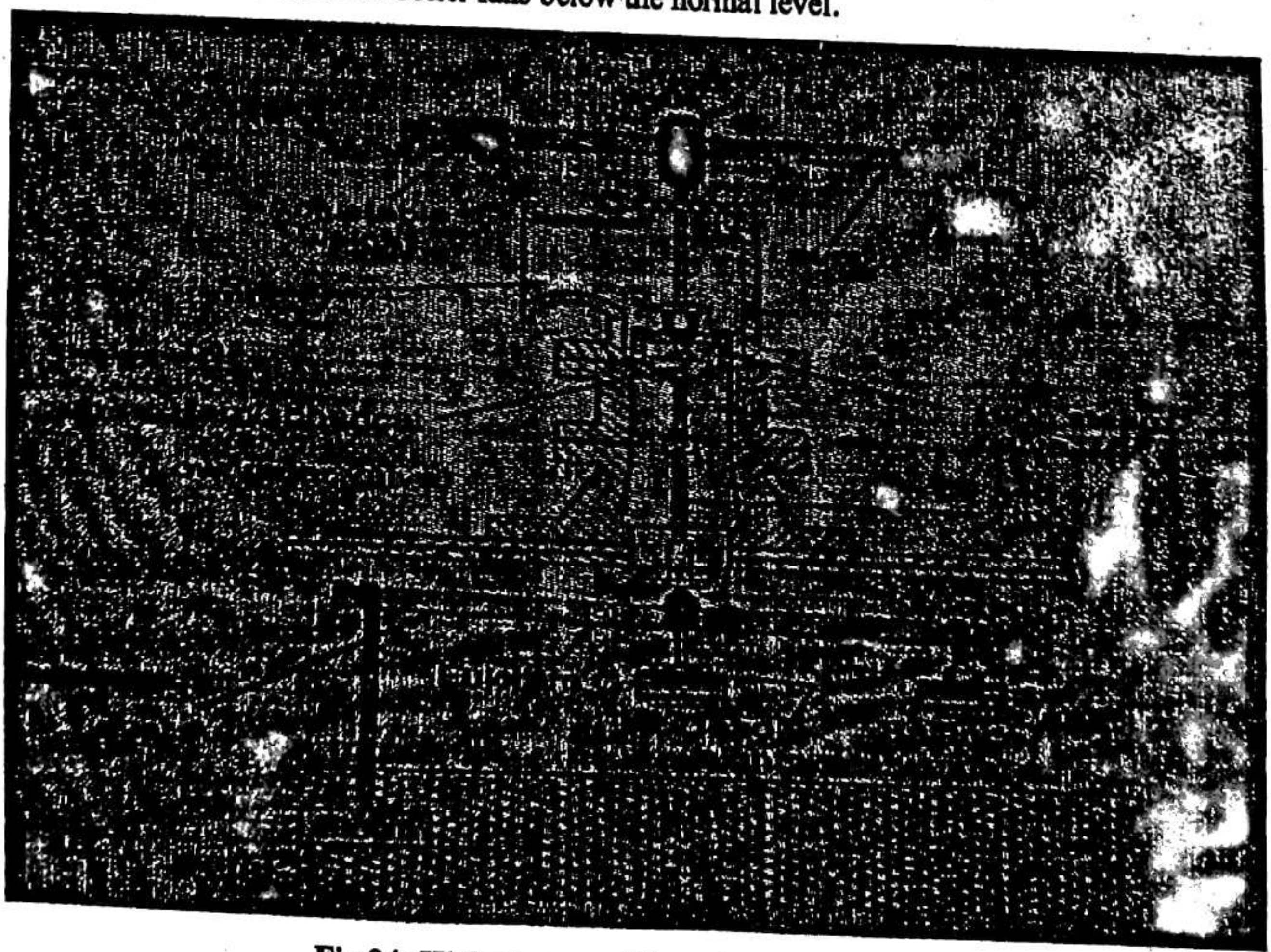


Fig.04: High steam and low steam safety valve

WATER LEVEL INDICATOR

The water level indicator is located in front of the boiler in such a position that the level of water can easily be seen by the attendant. Two water level indicators are used on all boilers. A water level indicator consists of a metal tube and a strong glass tube with markings. The upper and lower ends are connected to two gunmetal hollow pipes. The drain cock is to ensure the water and steam cock are clear. During operation steam cock and water cock remains open while the drain cock remains close. During the normal operation, the two balls provided inside the gunmetal pipe remains in position as shown in figure , hence the water can reach the glass gauge and its level can be seen.

In case the glass gauge breaks accidently, the water and steam simultaneously rush out through the gunmetal pipes. The force is exerted on two balls and they are carried away by water and steam and the passage are closed. The water and the steam cocks are then closed and the glass gauge is replaced.

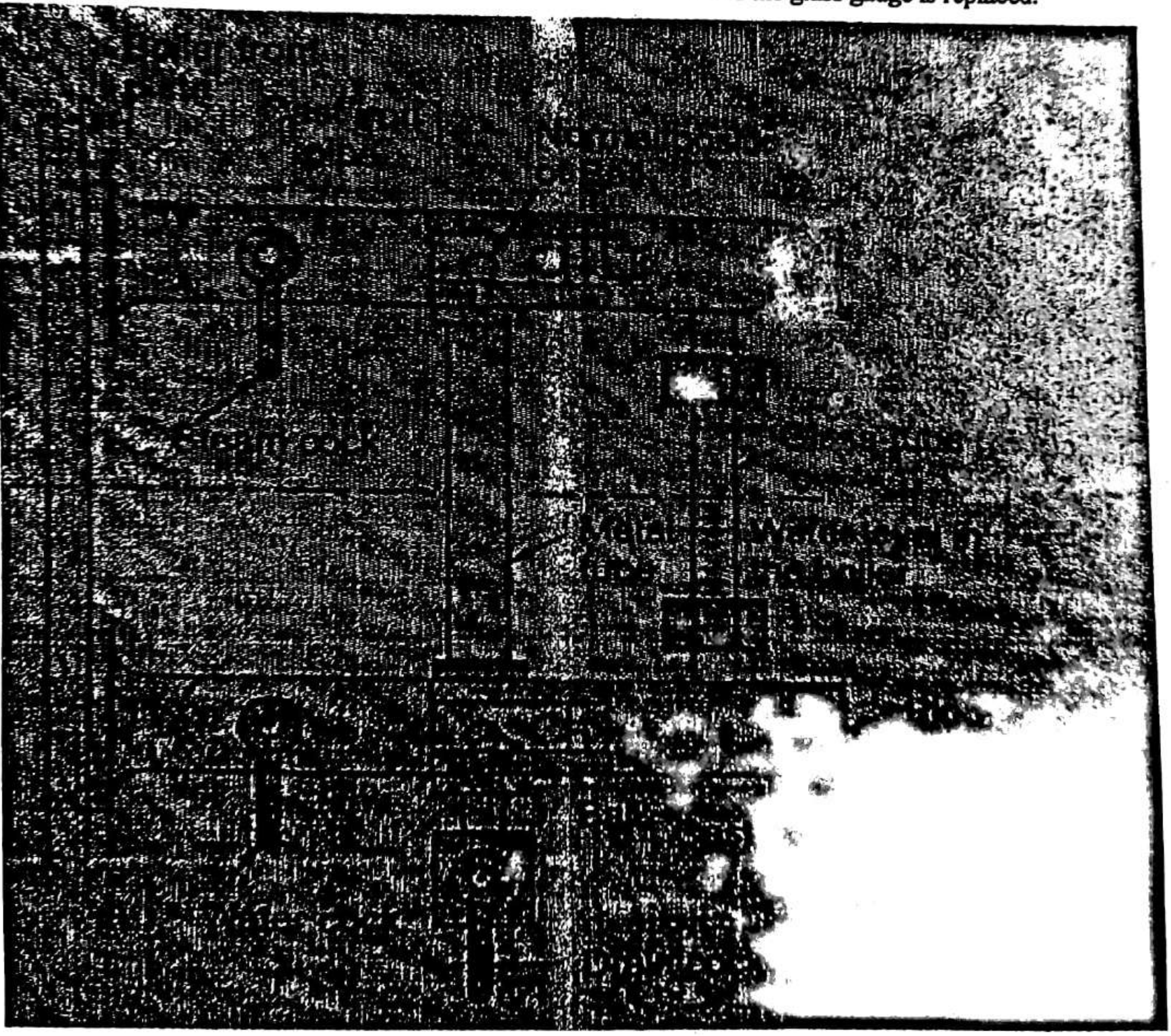


Fig.05: Water level indicator.

PRESSURE GAUGE

A pressure gauge is fitted in front of the boiler in such a position that the operator can conveniently read it. It read the pressure of steam in the boiler and is connected to the steam space by a siphon tube.

The most commonly used gauge is the bourdon pressure gauge. Fig 6. Illustrates the bourdon pressure gauge. It consists of an elliptical spring bourdon tube. One end of the tube is connected to the siphon tube and other end is connected by levers and gears to pointer.

When fluid pressure acts on the bourdon tube, it tries to make its cross section change from elliptical to circular. In this process, the lever end of the tube moves out as indicated by an arrow. The tube movement is magnified by the mechanism and given to pointer to move over a circular scale indicating the pressure.

The siphon tube is shown in Fig.07. It connects the steam space of the boiler to the bourdon gauge is filled with water in order to avoid the effect of high temperature steam on the gauge components. The steam pressure is transferred by water to the bourdon gauge.

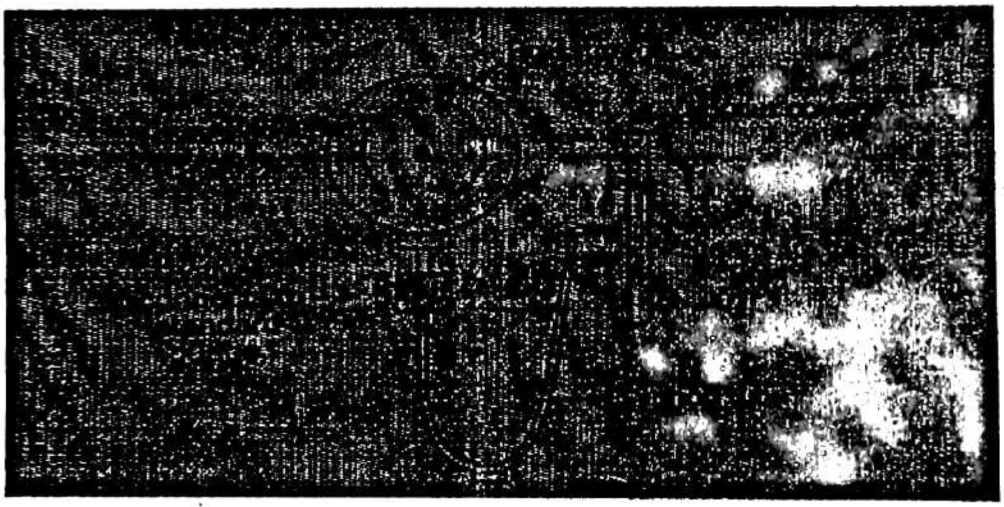


Fig.06: Bourdon pressure gauge

Fig.07: pressure gauge with siphon tube.

UNIT - III

Steam Nozzle (a)

→ Steam nozzle is a device of varing cross-section used to convert the enthalpy & heat energy into kinetic energy

→ functions :-

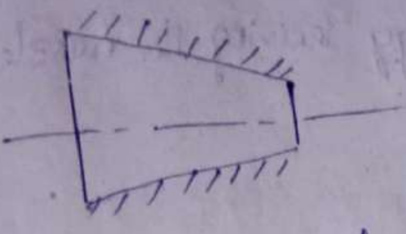
1. It is used to convert pressure energy of steam into kinetic energy
2. In impulse turbine, nozzle is used to directs the high velocity steam on to a rotating rotor.
3. In reaction turbine, the nozzles are due to rotate the blade

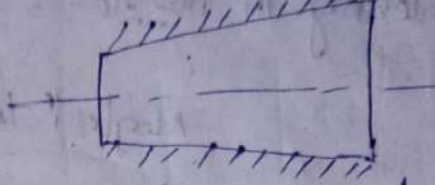
→ Applications :-

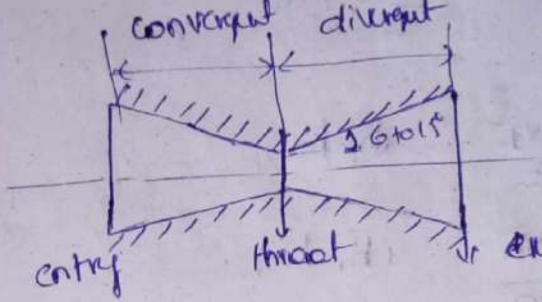
1. It is used in the steam turbines & gas turbines (for converting the) to obtain high velocity stream of working fluid
2. for metring the flow of fluid in a pipe line
3. used in the ejectors for the removal of the air from the condensor
4. It is used in the steam injector for pumping feed water to the boiler

→ Types of nozzles :-

1. convergent Nozzle
2. Divergent nozzle
3. Convergent - Divergent Nozzle

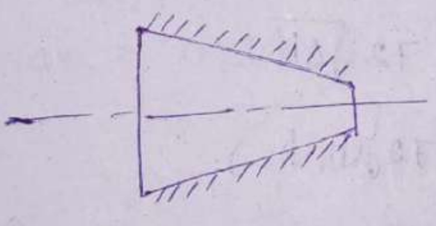






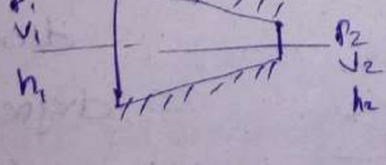
convertgent - divergent nozzle

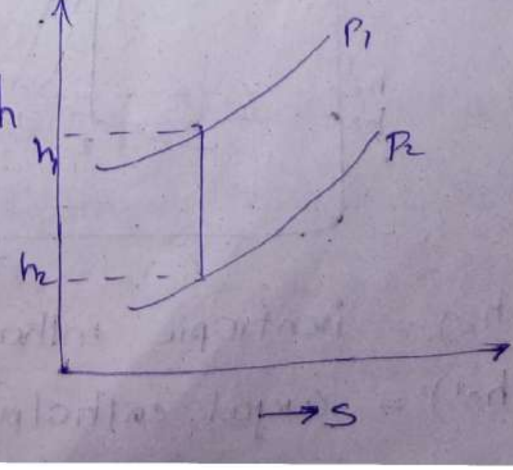
→ flow of steam through a nozzle :-



1. adiabatic expansion of steam (friction is consider)
2. Isentropic expansion of steam (friction less adiabatic process)

→ Isentropic expansion of steam through nozzle :-





consider nozzle as open system

energy entering the nozzle = energy leaving the nozzle + losses

neglect losses

$m = 1\,kg$

$$h_1 + \frac{V_1^2}{2} = \frac{V_2^2}{2} + h_2$$

$$\frac{V_2^2 - V_1^2}{2} = (h_1 - h_2)$$

$$\frac{V_2^2 - V_1^2}{2000} = (h_1 - h_2)$$

$$V_2^2 - V_1^2 = 2000\,(h_1 - h_2)$$

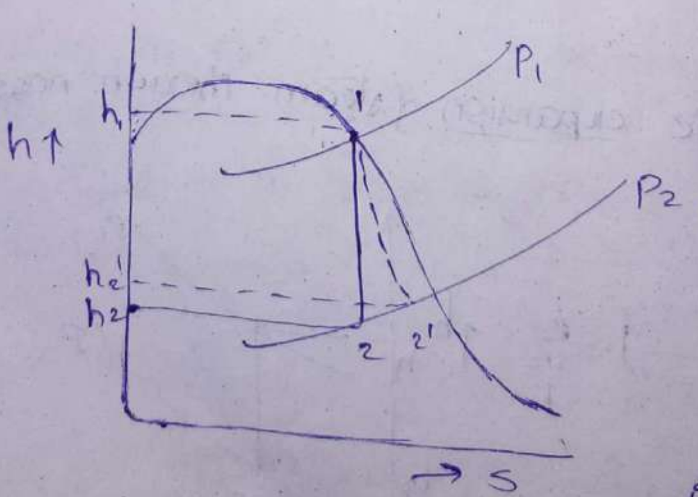
$$V_2^2 - V_1^2 = 2000\,(\Delta h)$$

$$V_2 = \sqrt{2000\,(\Delta h) + V_1^2} \qquad (\because V_1 = 0)$$

$$V_2 = 44.72\sqrt{\Delta h}$$

$$V_2 = 44.72\sqrt{(h_1 - h_2)}$$

→ Adiabatic expansion of steam through nozzle :-



Effects due to Friction

① enthalpy drop

② exit velocity decreases

③ dryness fraction of steam at exit increases

$(h_1 - h_2)$ = isentropic enthalpy drop

$(h_1 - h_2')$ = actual enthalpy drop

Nozzle efficiency (or) Nozzle coefficient (or) friction factor (k)

$$\eta_N \text{ (or) } K = \frac{\text{useful heat drop}}{\text{isentropic heat drop}}$$

$$K = \frac{h_1 - h_2'}{h_1 - h_2}$$

$$V_2 = 44.72\sqrt{(h_1 - h_2')}$$

$$\boxed{V_2 = 44.72\sqrt{K(h_1 - h_2)}}$$

→ Velocity co-efficient :-

It is the ratio of actual exit velocity to the exist velocity when the flow is isentropic b/w two pressures. It is also defined as square of nozzle η

$$C_V = \frac{\text{Actual exit velocity}}{\text{Isentropic exist velocity}} = \frac{V_2'}{V_2}$$

$$C_V = \sqrt{\text{Nozzle efficiency}}$$

$$C_V = \sqrt{\frac{\text{useful enthalpy drop}}{\text{isentropic enthalpy drop}}}$$

→ Critical pressure ratio

It is the ratio of throat pressure to the inlet pressure of the steam entering into the nozzle for maximum discharge. The pressure of the throat of the nozzle is called as critical pressure.

If the expansions of the steam in the nozzle is greater than the throat pressure then we have to use divergent portion of the nozzle.

* Discharge flowing through a pipe (or) Nozzle per second is given by

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

m is a function of $\left[(P_2/P_1)^{2/n} - (P_2/P_1)^{\frac{n+1}{n}}\right]$

derive right hand side term w.r.to (P_2/P_1) and equate to zero '0'

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

$$\frac{2}{n}(P_2/P_1)^{\frac{2}{n}-1} - \frac{n+1}{n}(P_2/P_1)^{\frac{n+1}{n}-1} = 0$$

$$\frac{2}{n}(P_2/P_1)^{\frac{2-n}{n}} - \frac{n+1}{n}(P_2/P_1)^{\frac{n+1-n}{n}} = 0$$

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

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

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

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

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

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

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

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

→ values of critical pressure ratio :-

* for steam intially superheated $(n = 1.3)$

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

$$(P_2/P_1) = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}}$$

$$(P_2/P_1) = 0.545$$

* when steam is intially dry & saturated $(n = 1.135)$

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

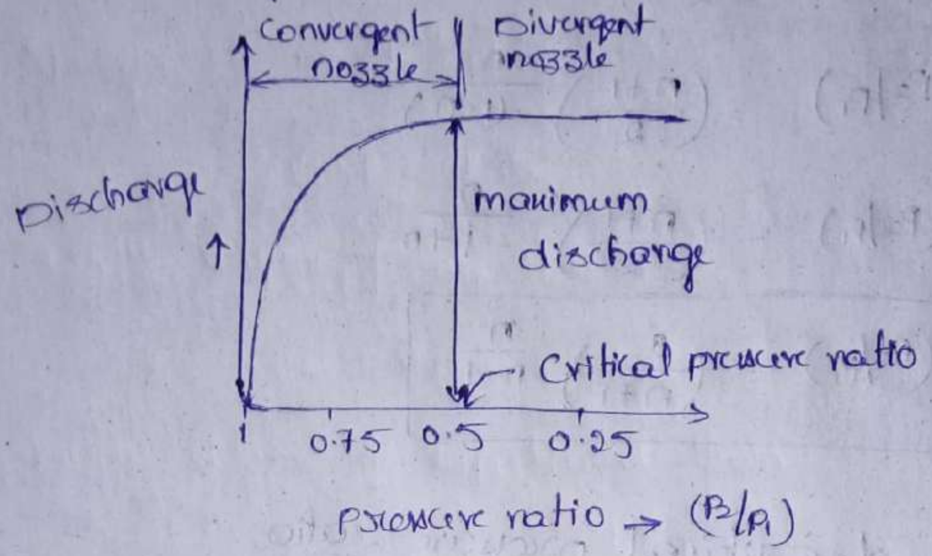
$$(P_2/P_1) = 0.577$$

* when steam is intially wet $(n = 1.035 + 0.1x)$
* when gas is expanded in nozzle $(n = 1.4)$

$$(P_2/P_1) = \left(\frac{2}{1.4+1}\right)^{\frac{1.4}{1.4-1}}$$

$$(P_2/P_1) = 0.528$$

→ **Significance of critical pressure ratio :-**



→ **Condition for max discharge through a nozzle :-**

Discharge through a nozzle per sec is given by

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

substitute critical pressure ratio (P_2/P_1) for max discharge

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

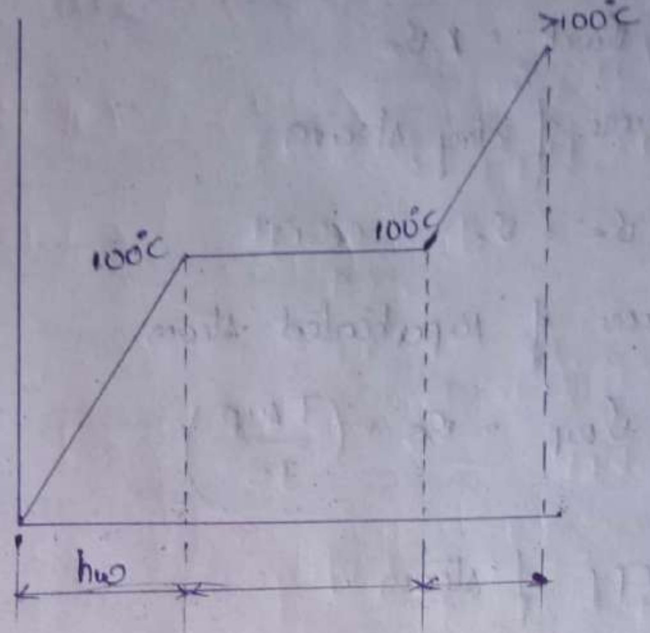
$$m_{max} = A\sqrt{\frac{2n}{n-1} \times \frac{P_1}{v_1}\left[\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}} - \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}\right]}$$

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

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

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

→ continuity equation :-



enthalpy of steam :-

(i) enthalpy of wet steam

$$H_{wet} = h_w + xL$$

h_w = (sensible heat KJ/kg)

x - dryness fraction

L = latent heat (KJ/kg)

(ii) specific enthalpy of dry steam

$$H_s = h_w + L \quad (x = 1)$$

(iii) specific enthalpy of superheated steam

$$H_{sup} = h_s + c_p (t_{sup} - t_s)$$

$$= h_w + L + c_p (t_{sup} - t_s)$$

c_p = sp. heat of superheated steam = 2.1 KJ/kg.K

t_{sup} = super heated temp °C

t_s = saturated temp in °C

* Specific volume of steam :-

(i) Specific volume of wet steam

$$v_{wet} = x \cdot v_s$$

(ii) Specific volume of dry steam

$$v_s = v_s \quad (x = 1)$$

(iii) Specific volume of superheated steam

$$v_{sup} = v_s \times \left(\frac{T_{sup}}{T_s} \right)$$

* Specific entropy of steam :-

(i) Specific entropy of wet steam

$$\phi_{wet} = \phi_\omega + x\,\phi_e$$

ϕ = entropy of water (KJ/kg.K)

ϕ_e = entropy of evapration (KJ/kg.K)

(ii) Specific entropy of dry steam

$$\phi_s = \phi_\omega + \phi_e$$

(iii) sp: entropy of super heated steam

$$\phi_{sup} = \phi_s + c_p \ln \left(\frac{T_{sup}}{T_s} \right)$$

• Estimate the mass flow rate of the steam in a nozzle with the following data, inlet pressure & temp is 10 bar & 220°C, back pressure is 0.5 bar, throat dia is 12 mm

sol Given data

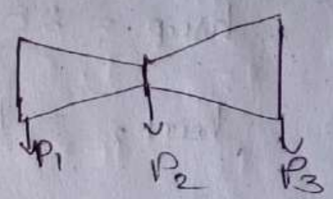
inlet pressure $P_1 = 10$ bar

temp $t_1 = 200°C$

back pressure $P_3 = 0.5$ bar

throat dia $d_2 = 12$ mm $= 0.012$ m

mass flow rate = ?



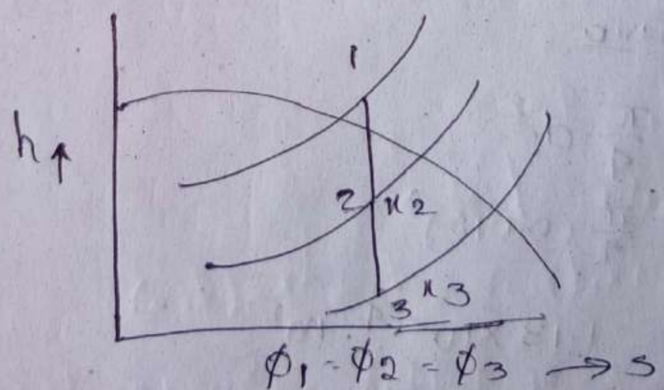
Critical pressure ratio

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

$$= \left(\frac{2}{1.3+1}\right)^{1.3/0.3}$$

$$= 0.545$$

$$P_2 = 0.545 \times 10 = 5.45 \text{ bar}$$



$\phi_1 = \phi_2$

$\phi_{sup} = \phi_{wet\,2}$

$6.692 = 1.892 + x_2(4.899)$

$$x_2 = \frac{6.692 - 1.892}{4.898} = 0.92$$

$\phi_1 = \phi_3$

$\phi_{sup} = \phi_{wet\,3}$

$6.692 = 1.091 + x_3 (6.509)$

$$x_3 = \frac{6.692 - 1.091}{6.504}$$

$x_3 = 0.86$

from steam tables

$h_1 = h_{sup} = 2826.8$ KJ/kg

$h_2 = h_{wet_2} = 1653.8 + 0.92 * 2897.4$

$= 2688.27$ KJ/kg

throat velocity

$V_2 = 44.72 \sqrt{h_1 - h_2}$

$= 44.72 \sqrt{(2826.8) - (2688.72)}$

$= 526.3$ m/s

throat area

$A_2 = \frac{\pi}{4} d_2^2$

$= \frac{\pi}{4} (0.012)^2$

$= 1.13 \times 10^{-4}$ m^2

S.P of wet steam

$v_{wet} = x . v_s$

$= 0.92 \times 0.348 = 0.33$ m^3/kg

mass $m_2 = \frac{A_2 V_2}{v_{wet}}$

$= \frac{1.130 \times 10^{-4} \times 526.3}{0.33}$

$= \underline{0.13}$ kg/s.

1. Steam at a pressure of 10 bar and 0.9 dry discharge at through a nozzle having throat area of 450 mm² If the back pres/. is 1 bar find final velocity of the steam cross section area of a nozzle at exit where max discharge.

sol Given data

steam pressure $P_1 = 10$ bar

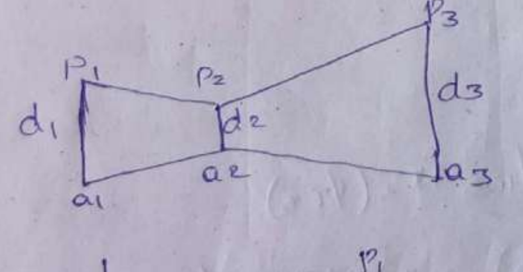
dryness fraction $x = 0.9$

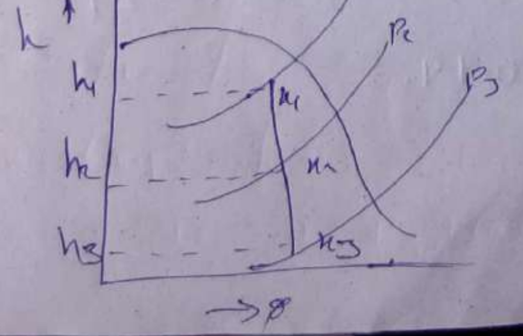
throat area $a_2 = 450$ mm²

back pres/. $P_3 = 1$ bar

final velocity $V_3 = ?$

cross section area of exit $a_3 = ?$





Critical pressure ratio

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

$n = 1.035 + 0.1x$

$= 1.035 + 0.1\,(0.9)$

$= 1.125$

$$P_2/P_1 = \left(2/1.125+1\right)^{\frac{1.125}{1.125-1}}$$

$P_2/P_1 = 0.579$

$P_2 = P_1 \times 0.579$

$P_2 = 10 \times 0.579 = 5.8$ bar

$\phi_1 = \phi_2$

$\phi_{wet_1} = \phi_{wet_2}$

$\phi_{w_1} + x_1\phi_{e_1} = \phi_{w_2} + x_2\phi_{e_2}$

$2.138 + 0.9(4.445) = 1.931 + x_2\,(4.851)$

$x_2 = 0.86$

$\phi_1 = \phi_3$

$\phi_{wet_1} = \phi_{wet_3}$

$\phi_{w_1} + x_1(\phi_{e_1}) = \phi_{w_3} + x_3(\phi_{e_3})$

$2.138 + 0.9\,(4.445) = 1.303 + x_3\,(6.057)$

$x_3 = 0.79.$

2. A reheat cycle has steam generated as 50 bar, 500°C for being sends to high pressure turbine and expanded upto 5 bar before supplied to low pressure turbine steam enters at 5 bar, 400°C into low pressure turbine after being reheated in the boiler. steam finally enters condensor at 0.05 bar and subsequently feed water send to the boiler. Determine cycle efficiency & specific heat consumption

3. A boiler is to provided 7000 kg/hr of steam which superheated by 40°C at a pressure of 20 bar. The temp of the feed water is 60°C. If the thermal η of the boiler is 75%, how much fuel oil will be consumed in 1 hr? The calorific value of the oil is 45000 KJ/kg. Take specific heat of the superheated steam as 2.093 KJ/kg·K. & also calculate the equivalent evaporation from and at 100°C

4. steam at 15 bar, 300°C expands in a nozzle till it pressure falls to 1 bar. If 12% of the isentropic heat drop is lost in friction. Find out the mass of the steam passing through a nozzle of exit diameter is 1.5cm. neglect the intial velocity of the steam

5. A chimney of 24 m height is used to produce a natural draught at flue gas temp is 300°C and ambient temp is 25°C. The air supplied

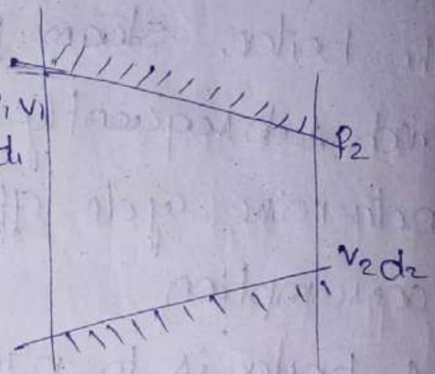
is 20 kg/kg of fuel burnt. Find the

(i) critical theoretical draught produced in mm of water

(ii) velocity of hot gases passing through the chimney if 50% of the theoretical draught is lost in friction.

4 sol

Given data



$P_1 = 15$ bar

$T_1 = 300°C$

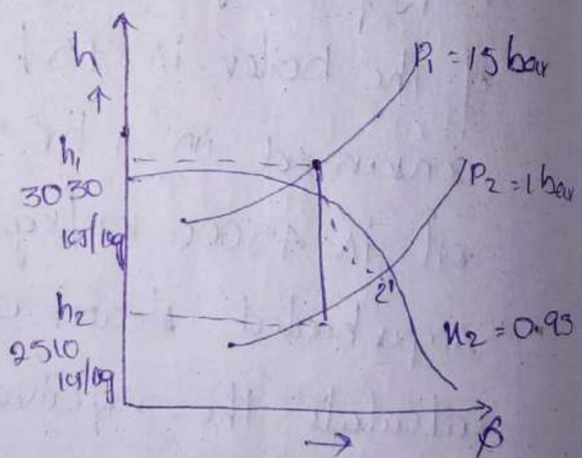
$P_2 = 1$ bar

$\eta_{NO} = 100\% - 12\% = 88\% = 0.88$

$m_2 = ?$

$d_2 = 1.5$ cm

$V_1 = 0.$



$$\eta_N = \frac{h_1 - h_2'}{h_1 - h_2}$$

$$h_1 - h_2' = \eta_N (h_1 - h_2)$$

$$V_2 = 44.72 \sqrt{h_1 - h_2'}$$

$$V_2 = 44.72 \sqrt{\eta_N (h_1 - h_2)}$$

$$V_2 = 44.72 \sqrt{0.88 (3030 - 2510)}$$

$$V_2 = 960 \text{ m/s}$$

exit area

$$A_2 = \pi/4 \, d_2^2$$

$$= \frac{\pi}{4}(0.015)^2$$

$$= 1.767 \times 10^{-4} \ m^2$$

from

$$h_1 - h_2' = \eta_N (h_1 - h_2)$$

$$3030 - h_{wet_2}' = 0.88 \, (3030 - 2510)$$

$$3030 - (h_{f2} + x_2 h_{fg2}) = 0.88 \, (3030 - 2510)$$

$$3030 - (417.5 + x_2'(2257.9)) = 0.88 \, (3030 - 2510)$$

$$\boxed{x_2' = 0.95}$$

$$m = \frac{A_2 V_2}{v_2}$$

$$m = \frac{A_2 V_2}{v_{wet_2}} \Rightarrow \frac{A_2 V_2}{x_2' v_{s2}}$$

$$= \frac{1.767 \times 10^{-4} \times 960}{0.95 \times 1.693.8}$$

$$\boxed{m = 0.1054 \ kg}$$

3 sd

→ η thermal of the boiler :-

It is the ratio of heat ultilized to form steam by heat released by the fuel.

$$\eta_{ther} = \frac{m_s (h_2 - h_w)}{m_f \times CV} \times 100$$

$m = m_s/m_f$ (kg/kg)

m_s = mass of steam generated kg/hr

m_f = mass of fuel kg/hr

$$\eta_{ther} = \frac{m(h_2 - h_{w1})}{CV} \times 100$$

→ equivalent evaporation :-

$$m_e = \frac{m_s(h_2 - h_{w1})}{2256.9} \text{ kg/hr}$$

m_s = mass of steam generated/hr (kg/hr)

h_2 = enthalpy of steam kJ/kg

h_{w1} = feed water enthalpy (kJ/kg)

$$m_e = \frac{m(h_2 - h_{w1})}{2256.9} \text{ kg/kg of fuel}$$

Given data

m_s = 7000 kg/hr of steam

$C_p(t_{sup} - t_s)$ = 40°C

P_1 = 20 bar

t_w = 60°C

η_{th} = 75% ⇒ 0.75

m_f = ? in 1hr

CV = 45000 kJ/kg

m_e = 100°C at = ?

C_p = 2.093 kJ/kg·K

Scanned by CamScanner

at $P_1 = 20$ bar $\rightarrow t_s = 212.4^\circ C$

$\rightarrow \quad \eta_{th} = \dfrac{m_s (h_2 - h_{w1})}{m_f \times C.V} \times 100$

$c_p \times (t_{sup} - t_s) = 40^\circ C$

$2.093 \, (t_{sup} - 212.4) = 40$

$t_{sup} = 231.5^\circ C$

$h_2 = h_{sup_2} = h_{s2} + c_p (t_{sup} - t_s)$

$h_2 = 2797.2 + 40$

$h_2 = 2837.2$ kJ/kg

$\rightarrow \quad 0.75 = \dfrac{7000 \, (2837.2 - 253.1)}{m_f \times 45000}$

$m_f = 536.18$ kg/hr

at $t_w = 60^\circ \rightarrow h_{w1} = 251.1$ kJ/kg

at kg/kg

$\rightarrow \quad m = m_s / m_f = 7000 / 536.18 = 13.05$ kg/kg

$\rightarrow \quad m_e = \dfrac{m_s \, (h_2 - h_{w1})}{2256.9}$

$m_e = \dfrac{7000 \, (2837.2 - 251.1)}{2256.9} = \underline{8021.04}$ kg/hr

$m_e = \dfrac{m \, (h_2 - h_{w1})}{2256.9}$

$= \dfrac{13.05 \, (2837.2 - 251.1)}{2256.9} = \underline{14.95}$ kg/kg

Sol given data

height $H = 24\,m$

flue gas temp $t_2 = 300^\circ C$

ambient temp $t_1 = 25^\circ C$

$m = 20$ kg/kg of fuel burnt

50% of theoretical draught is losses

(i) $$h = 353 H\left[\frac{1}{T_1} - \frac{m_a+1}{m_a T_2}\right]$$

$$h = 353(24)\left[\frac{1}{298} - \frac{20+1}{20(573)}\right]$$

$h = 12.90$ mm of water

(ii) velocity of flue gases

Equivalent gas head

$$H_1 = H\left[\frac{m_a}{m_a+1} \times \frac{T_2}{T_1} - 1\right]$$

$$= 24\left[\frac{20}{20+1} \times \frac{573}{298} - 1\right]$$

$= 21.09$ m

available head

$0.5 \times 21.09 = 10.5\,m$

velocity of flue gases

$$= \sqrt{2gH_1}$$

$$= \sqrt{2 \times 9.81 \times 10.5}$$

$= 14.38$ m/s

Sol Given data

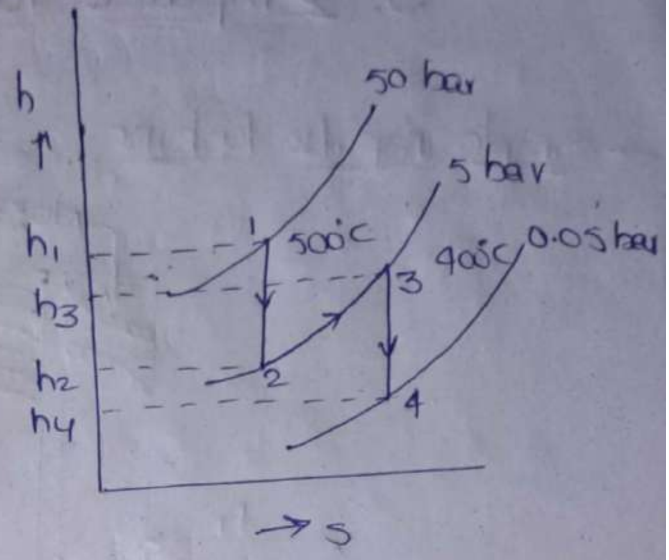
$P_1 = 50$ bar

$T_1 = 500°C$

$P_3 = 5$ bar

$T_3 = 400°C$

$P_4 = 0.05$ bar



$h_1 = 3440$ KJ/kg

$h_2 = 2820$ KJ/kg

$h_3 = 3260$ KJ/kg

$h_4 = 2390$ KJ/kg

$h_4 = h_{f4}$ from steam tables

$h_{f4} = 137.8$ KJ/kg

(i) Rankine cycle (η) $= \dfrac{(h_1-h_2)+(h_3-h_4)}{(h_3-h_2)+(h_1-h_{f4})}$

$= \dfrac{(3440-2820)+(3260-2390)}{(3260-2820)+(3440-137.8)}$

$= 0.398$ (or) 39.8%

(ii) Specific steam consumption

1 kwh = 3600 KJ

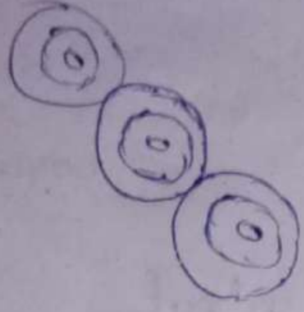
KJ/s × s

$sfc = \dfrac{1 \cdot kwh}{(h_1-h_2)+(h_3-h_4)}$

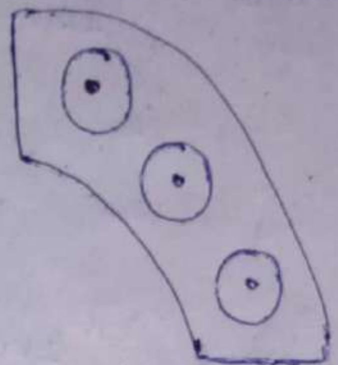
$= \dfrac{3600}{(3440-2820)+(3260-2390)}$

$= 2.416$ kg/kw.hr

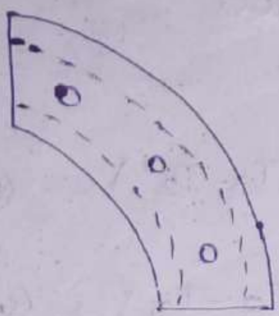
1. cam type



2. cannular type



3. annular type



1. In an air standard regenerative gas turbine cycle the pressure ratio is 5. Air enters the compressor at 1 bar, 300 K and leaves at 490 K. The max temp in the cycle is 1000 K. calculate cycle efficiency, given that efficiency of regenerator & the turbine are 80%. Assume ratio of specific heat as 1.4

sol Given data.

$P_2/P_1 = 5$

$P_1 = 1$ bar

$T_1 = 300K$

$T_2' = 490K$

$$\eta_{turbine} = \frac{\text{Actual work output}}{\text{Isentropic work output}} \times 100$$

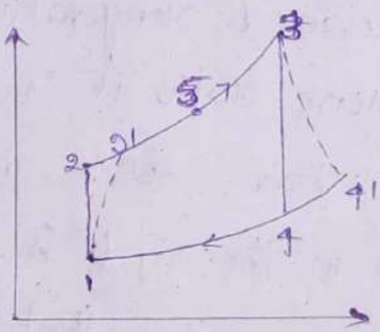
$$= \frac{T_3 - T_4'}{T_3 - T_4} \times 100$$

$$\eta_{comp} = \frac{\text{Isentropic work output}}{\text{Actual work output}} \times 100$$

$$= \frac{T_2 - T_1}{T_2' - T_1} \times 100$$

heat supplied $Q = mc_p (T_3 - T_2')$ (without regenerator)

$Q = mc_p (T_3 - T_5)$ (with regenerator)



$$\eta_{th} = \frac{\text{Net work}}{\text{heat supplied}} \times 100$$

$$\eta_{th} = \frac{\text{Turbine work} - \text{comp work}}{\text{heat supplied}} \times 100$$

$$\eta_{th} = \frac{W_T - W_C}{Q_S} \times 100$$

$\eta_{th} \uparrow$, $Q_S \downarrow$

Contin

$T_3 = 1000\ K$

$\eta_{turb} = 80\% = 0.80$

$\eta_{regenerator} = 80\% = 0.80$

$\gamma = 1.4$

Cycle efficiency = ?

$C_p = 1.005\ kJ/kgK$

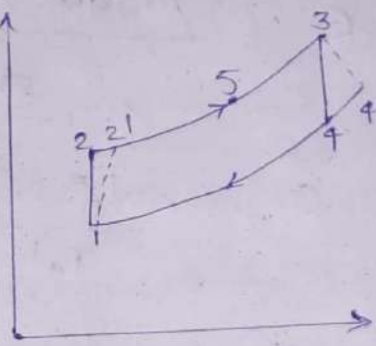
$C_v = 0.718\ kJ/kgK$

$\gamma = 1.4$

$R = 0.287\ kJ/kgK$

$P_1 = P_4$ } 1 bar

$P_2 = P_3$ } 5 bar



1-2 : Isentropic compression

$$\left(\frac{T_2}{T_1}\right)^{1/\gamma-1} = (P_2/P_1)^{1/\gamma}$$

$$\left(\frac{T_2}{T_1}\right) = (P_2/P_1)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = (5)^{1.4-1/1.4} \times 300$$

$$T_2 = 475\ K$$

3-4 : Isentropic expansion

$$(T_3/T_4)^{1/\gamma-1} = (P_3/P_4)^{1/\gamma}$$

$$\frac{1000}{T_4} = (5)^{1.4-1/1.4}$$

$$T_4 = \frac{1000}{(5)^{0.4/1.4}}$$

$$T_4 = 631.48\ K$$

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$$\eta_{turb} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.8 = \frac{1000 - T_4'}{1000 - 631.48}$$

$$T_4' = 704.8 \text{ K}$$

$$\epsilon = \frac{\text{Actual heat exchanger di transfered}}{\text{available heat}}$$

$$\epsilon = \frac{T_5 - T_2'}{T_4' - T_2'}$$

$$0.8 = \frac{T_5 - 490}{704.8 - 490}$$

$$T_5 = 661 \text{ K}$$

Turbine work

$$W_T = mC_p (T_3 - T_4')$$

$$= 1 \times 1.005 (1000 - 704.8)$$

$$= 296.6 \text{ KJ/kg}$$

compressor work

$$W_C = mc_p (T_2' - T_1)$$

$$= 1 \times 1.005 (490 - 300)$$

$$= 190.95 \text{ KJ/kg}$$

Scanned by CamScanner

heat supplied $Q = mc_p(T_3 - T_5)$

$= 1 \times 1.005 \, (1000 - 661.2)$

$= 340.49$ kJ/kg

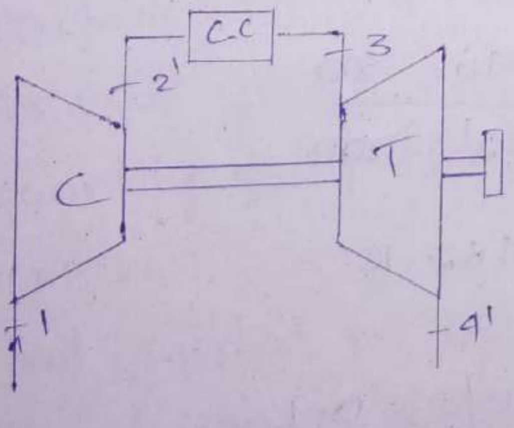
$$\eta_{cycle} = \frac{W_T - W_C}{Q_S} \times 100$$

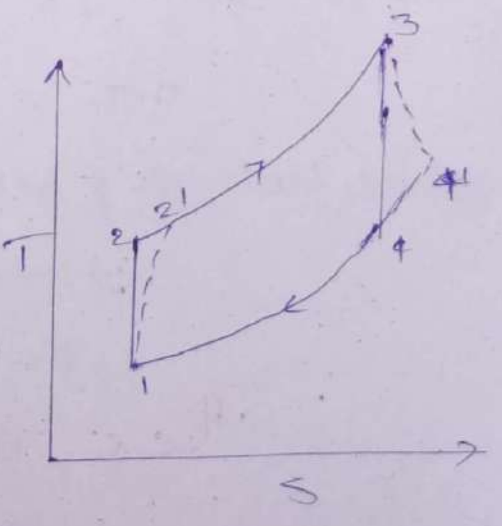
$$= \frac{296.6 - 190.95}{340.49} \times 100$$

$= 31.02\%$

2 Find the required air-fuel ratio in a gas turbine where turbine & compressor efficiencies are 85% & 80%. max cycle temp is 875°C the working fluid taken as air which enters the compressor at 1 bar & 27°C. The pressure ratio is 4. calorific value of the fuel is 42000 kJ/kg. There is a loss of 10% of calorific value in the combustion chamber.

Sol





$\eta_{turb} = 0.85$

$\eta_{com} = 0.8$

$T_3 = 875^\circ C + 273 = 1148 K$

$P_1 = 1 bar$

$T_1 = 27^\circ C + 273 = 300 K$

$P_2/P_1 = 4$

$CV = 42000 \ kJ/kg$

10% loss in combustion chamber

$$\left(\frac{T_2}{T_1}\right)^{1/\gamma - 1} = (P_2/P_1)^{1/\gamma}$$

$$T_2 = (4)^{0.4/1.4} \times 300$$

$$T_2 = 446 \ K$$

$$\eta_{com} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{446 - 300}{T_2' - 300}$$

$$T_2' = 482 . K$$

$$\eta_{c.c} = 90\% = 0.9$$

$$\eta_{cc} = \frac{(m_a + m_f) \times C_P (T_3 - T_2')}{m_f \times C.V}$$

$$\eta_{cc} \times CV \times m_f = (m_a + m_f) \times c_p (T_3 - T_2')$$

$$\eta_{cc} \times CV = \left(\frac{m_a + m_f}{m_f}\right) \times c_p (T_3 - T_2')$$

$$CV = \left(\frac{m_a}{m_f} + 1\right) \times \frac{c_p (T_3 - T_2')}{\eta_{cc}}$$

$$42000 = \left(\frac{m_a}{m_f} + 1\right) \times \frac{1.005 (1148 - 482)}{0.9}$$

$$\frac{m_a}{m_f} + 1 = 56.474$$

$$\frac{m_a}{m_f} = 55.474$$

3. In a constant pressure open cycle gas turbine air enters at 1 bar & 20°C and leaves the compressor at 5 bar. use the following data.
Temperatures of gases entering the turbine is 680°C, pressure loss in the combustion chamber is 0.1 bar, efficiency of the compressor is 85%, turbine η is 80%. $\eta_{comp. cha}$ is 85%. $\gamma = 1.4$, $c_p = 1.024$ KJ/kg.K for air & gas, find

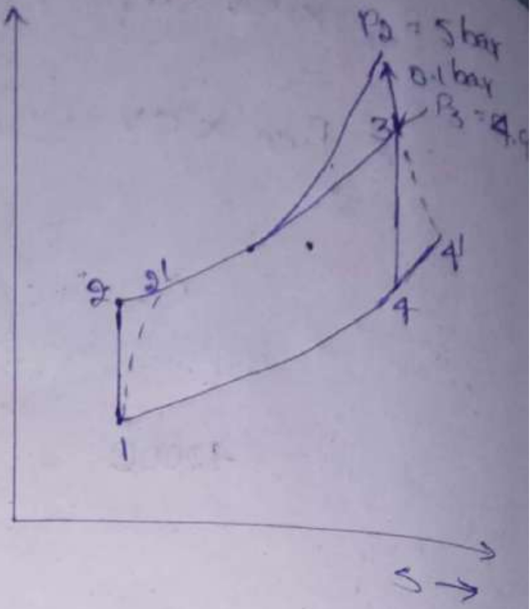
(i) quantity of air circulations if the plant develop 1065 kW

(ii) heat supplied per kg of air

(iii) thermal efficiency of the cycle

mass of the fuel is neglected.

Sol Given data



$P_1 = 1$ bar

$T_1 = 20+273 = 293$ K

$P_2 = 5$ bar

$T_3 = 680+273 = 953$ K

$P_3 = 5 - 0.1 = 4.9$ bar

$\eta_{comp} = 85\% = 0.85$

$\eta_{turb} = 80\% = 0.80$

$\eta_{c.c} = 85\% = 0.85$

$\gamma = 1.4$

$C_P = 1.024$ kJ/kg.K

$P = 1065$ kW

heat supplied = Q_s/kg of air = ?

$\eta_{th} = ?$

$m_a = ?$

$$(T_2/T_1)^{1/\gamma - 1} = (P_2/P_1)^{1/\gamma}$$

$$T_2 = (5)^{1.4-1/1.4} \times 293$$

$$T_2 = 464.05 \text{ K}$$

$$(T_3/T_4)^{1/\gamma - 1} = (P_3/P_4)^{1/\gamma}$$

$$\left(\frac{953}{T_4}\right)^{1/1.4-1} = (4.9/1)^{1/1.4}$$

$$T_4 = \frac{953}{1.574}$$

$$T_4 = 605.193 \text{ K.}$$

$$\eta_{comp} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{464.05 - 293}{T_2' - 293}$$

$$T_2' = 494.23 \text{ K}$$

$$\eta_{turb} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.8 = \frac{953 - T_4'}{953 - 605.193}$$

$$T_4' = 674.75 \text{ K}$$

turbine work $W_T = m\, c_p (T_3 - T_4')$

$= 1 \times 1.024 (953 - 674.75)$

$= 284.92$ KJ/kg

compressor work $W_C = m c_p (T_2' - T_1)$

$= 1 \times 1.024 \; (494.23 - 293)$

$= 206.05$ KJ/kg

→ (i) $P = m_a \times W_{net}$

$m_a = P / W_{net}$

$$m_a = \frac{P}{W_T - W_C}$$

$$m_a = \frac{1065}{284.92 - 206.05}$$

$$m_a = 13.504 \text{ kg/s}$$

→ 2. $\eta_{cc} = \frac{m c_p (T_3 - T_2')}{m_f \times C.V}$

$$H.S = m_f \times C.V$$

(heat supplied) $H.S = \frac{m c_p (T_3 - T_2')}{\eta_{cc}}$

$$= \frac{1 \times 1.024 (953 - 494.23)}{0.85}$$

$$= 552.68 \text{ kJ/kg}$$

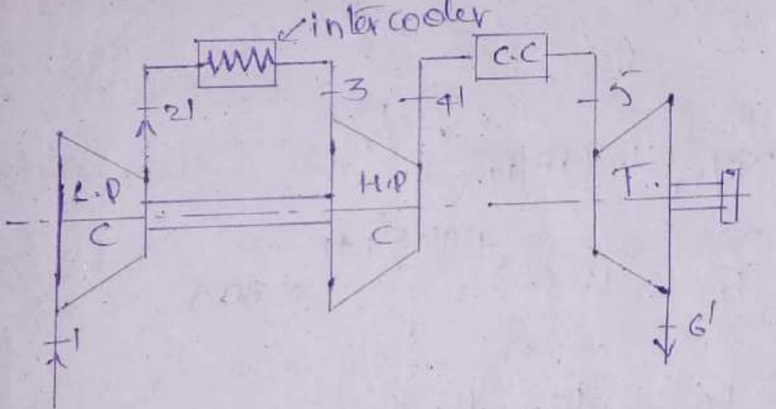
→ (c) $\eta_{th} = \frac{W_{net}}{H.S} \times 100$

$$= \frac{78.87}{552.68} \times 100$$

$$= 14.27 \%$$

4. The pressure ratio of an open cycle gas turbine power plant 5.6. Air is taken as 30°C & 1 bar The compression is carried out in two stages with perfect intercooling b/w them. The max temp of the cycle 700°C. Assume isentropic efficiency of the each compression stage is 85% and turbine is 90%.. Determine power developed & η of the power plant, if the air flow rate is 1.2 kg/s. mass of the fuel is neglected. Take $C_p = 1.02$ kJ/kg.K., $\gamma = 1.41$.

sol



Given data

$P_4/P_1 = 5.6$

$T_1 = 30+273 = 303K$ T_1

$P_1 = 1$ bar

$T_5 = 700+273 = 973K$

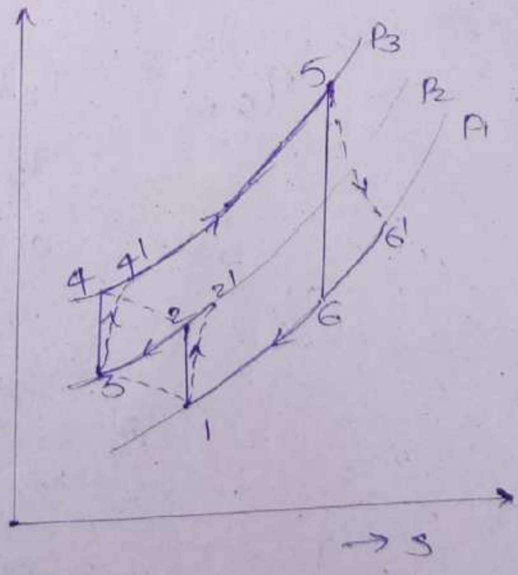
$\eta_{com} = 85\% = 0.85$

$\eta_{tur} = 0.9$

$m = 1.2$ kg/s

$C_p = 1.02$ kJ/kg.K

$\gamma = 1.41$.



$T_1 = T_3$;

$T_2 = T_4$;

$W_{cp1} = W_{cp2}$ } same

$\eta_{com} = \eta_{comp}$ (both are

$$\frac{P_4}{P_1} = \frac{P_4}{P_3} \times \frac{P_2}{P_1} \qquad \therefore (P_2 = P_3)$$

$$= \frac{P_4}{P_2} \times P_2/P_1 \qquad (\because P_4/P_3 = P_2/P_1)$$

$$P_4/P_1 = (P_2/P_1)^2$$

$$P_2/P_1 = \sqrt{(P_4/P_1)}$$

$$P_2/P_1 = \sqrt{5.6}$$

$$P_2/P_1 = 2.66$$

(1-2) process :-

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (2.66)^{1.41-1/1.41} \times 303$$

$$T_2 = 402.70 \text{ K}$$

$$\eta_{com} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{402.70 - 303}{T_2' - 303}$$

$$T_2' = 420.30 \text{ K}$$

$$T_1 = T_3 = 303 \text{ K}$$

$$T_2 = T_4 = 402.70 \text{ K}$$

$$T_2' = T_4' = 420.30 \text{ K}$$

(5-6) process :- (at const pressure line) ($P_4/P_1 = P_5/P_6$)

$T_5/T_6 = (P_5/P_6)^{\gamma-1/\gamma}$

$973/T_6 = (5.6)^{1.41-1/1.41}$

$T_6 = 589.59$ K

$\eta_{turb} = \dfrac{T_5 - T_6'}{T_5 - T_6}$

$0.9 = \dfrac{973 - T_6'}{973 - 589.59}$

$T_6' = 627.936$ K.

turbine work $W_T = mcp(T_5 - T_6')$

$= 1.2 \times 1.02 (973 - 627.30)$

$= 423.94$ kW.

compressor work $W_C = [mcp(T_2' - T_1)] \times 2$

$= [1.2 \times 1.02 (420.30 - 303)] \times 2$

$= 287.15$ kW.

$W_{net} = W_T - W_C$

$= 427.13 - 287.15$

$= 135.98$ kW

Heat supplied $Q_s = mcp(T_5 - T_4')$

$= 1.2 \times 1.02 (973 - 420.30)$

$\doteq 676.50$ kW

$$\eta_{th} = \frac{W_{net}}{Q_s} \times 100$$

$$= \frac{135.98}{676.50} \times 100$$

$$= 20.10\ \%$$

5. A simple gas turbine cycle works with a pressure ratio of 8. The compressor & turbine inlet temp are 300 K & 800 K. If the volume flow rate of the air is 250 m³/s, calculate power output & thermal efficiency.

Sol Given data :

pressure ratio $P_2/P_1 = 8$

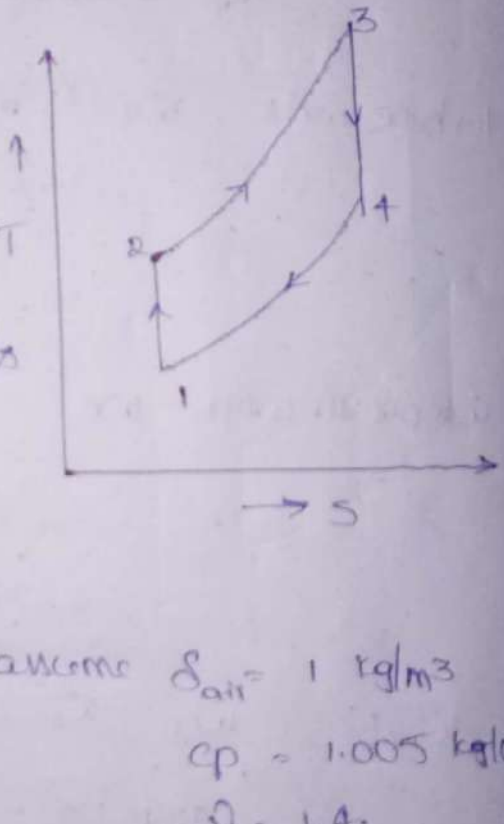
$T_1 = 300K$

$T_3 = 800K$

volume flow rate $V = 250\ m^3/s$

$P = ?$

$\eta_{th} = ?$



→ $\rho = m/v$

assume $\rho_{air} = 1\ kg/m^3$

$c_p = 1.005\ kJ/kgK$

$\gamma = 1.4$

$\dot{m} = \rho \times v$

$= 1 \times 250$

$= 250\ kg/s$

→ (1-2) process :-

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (8)^{1.4-1/1.4} \times 300$$

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$T_2 = 543.43\ K$

→ (3-4) process :

$(P_3/P_1 = P_3/P_4)$

$$T_3/T_4 = (P_3/P_4)^{\gamma-1/\gamma}$$

$$\frac{T_3}{T_4} = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_4 = \frac{800}{(8)^{1.4-1/1.4}}$$

$$T_4 = 441.63\ K$$

→ power $P = W_{net} \cdot \dot{m}$

$$P = \dot{m}\ (W_T - W_C)$$

$$W_T = mc_p (T_3 - T_4)$$

$$= 1 \times 1.005\ (800 - 441.63)$$

$$= 360.15\ kJ/kg$$

$$W_C = mc_p (T_2 - T_1)$$

$$= 1 \times 1.005\ (543.43 - 300)$$

$$= 244.64\ kJ/kg$$

$$P = 250 \times (360.15 - 244.64)$$

$$= 28877.5\ kW$$

heat supplied $Q_s = mc_p (T_3 - T_2)$

$$= 1 \times 1.005\ (800 - 543.43)$$

$Q_s = 257.85$ kJ/kg

$$\eta_{th} = \frac{W_{net}}{Q_s} \times 100$$

$$= \frac{115.51}{257.85} \times 100$$

$$= 44.79\ \%$$

6. A constant pressure open cycle gas turbine plant works b/w the range of temp is 15°c & 700°c and pressure ratio of 6. find the mass of air circulating in the installation, if it develop 1100 KW. Also find the heat supplied in the heating chamber.

sol

Given data

$T_1 = 15 + 273 = 288K$

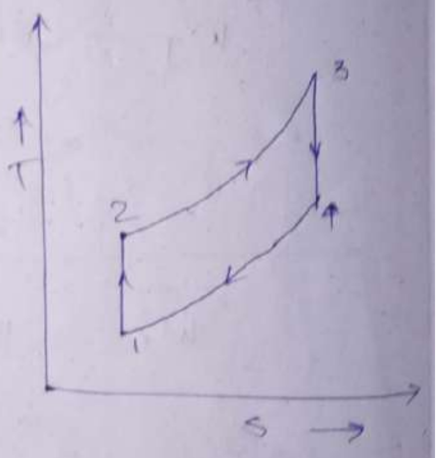
$T_3 = 700 + 273 = 973K$

pressure ratio $P_2/P_1 = 6$

power $P = 1100$ KW

$Q_s = ?$

$m_{air} = ?$



→ (1-2) process

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (6)^{1.4-1/1.4} \times 288$$

$$T_2 = 480.53\ k$$

→ (3-4) process :

$$T_3/T_4 = (P_3/P_4)^{\gamma-1/\gamma} \qquad (P_2/P_1 = P_3/P_4)$$

$$T_4 = \frac{973}{(6)^{1.4-1/1.4}}$$

$$T_4 = 583.15 \text{ K}$$

→ heat supplied $Q_s = mcp(T_3 - T_2)$

$= 1 \times 1.005 (973 - 480.53)$

$= 494.93$ KJ/kg

→ $W_C = mcp(T_2 - T_1)$

$= 1 \times 1.005 (480.53 - 288)$

$= 193.49$ KJ/kg

→ $W_T = m \cdot cp (T_3 - T_4)$

$= 1 \times 1.005 (973 - 583.15)$

$= 391.79$ KJ/kg

→ power $P = m_a W_{net}$

$1100 = m_a (W_T - W_C)$

$1100 = m_a (391.79 - 193.49)$

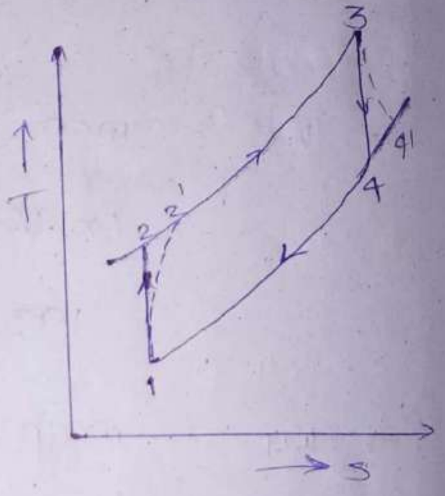
$m_a = 5.546$ kg/s.

[illegible]

7. A gas turbine unit recieve the air at 100 kpa & 300 K is compressed adiabatically to 620 kpa with efficiency of compressor of 88%. The heating value of the fuel is 44180 KJ/kg & fuel air ratio is 0.017 kg of fuel/kg of air. The turbine internal efficiency is 90% calculate compressor work, turbine work & thermal η.

Sol

Given data :



$P_1 = 100$ kpa

$T_1 = 300$ K

$P_2 = 620$ kpa

$\eta_{com} = 88\% = 0.88$

C.V = 44180 KJ/kg

$\frac{m_f}{m_a} = 0.017$ kg/kg

$\eta_{turb} = 90\% = 0.90$

→ (1-2) process :

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (620/100)^{1.4-1/1.4} \times 300$$

$$T_2 = 505.26 \text{ K}$$

$\rightarrow \eta_{com} = \frac{T_2 - T_1}{T_2' - T_1}$

$0.88 = \frac{505.26 - 300}{T_2' - 300}$

$T_2' = 533.25$ K.

$\rightarrow \eta_{c.c} = \frac{(m_a + m_f)\, c_p\, (T_3 - T_2')}{m_f \times C_V}$ (if 100% η_{cc})

$m_f \times C_V = (m_a + m_f)\, c_p\, (T_3 - T_2')$

divided by m_a

$\frac{m_f \times C_V}{m_a} = \frac{(m_a + m_f)\, c_p\, (T_3 - T_2')}{m_a}$

$\frac{m_f}{m_a} \times C_V = \left(1 + \frac{m_f}{m_a}\right) c_p\, (T_3 - T_2')$

$0.017 \times 44180 = (1 + 0.017) \times 1.005 \times (T_3 - 533.25)$

$T_3 = 1268.081$ K

$\rightarrow$ (3-4) process

$T_3/T_4 = (P_3/P_4)^{\gamma - 1/\gamma}$

$T_3/T_4 = (620/100)^{1.4-1/1.4}$

$T_4 = \frac{1268.081}{1.6842}$

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$T_4 = 752.92\ K$

→ compressor work

$$W_c = mc_p(T_2' - T_1)$$

$$= 1 \times 1.005\ (533.25 - 300)$$

$$= 234.41\ kJ/kg$$

→ turbine work

$$W_T = mc_p(T_3 - T_4')$$

$$= 1 \times 1.005\ (1268.081 - 806)$$

$$= 465.64\ kJ/kg$$

→ $$\eta_{turb} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.9 = \frac{1268.081 - T_4'}{1268.081 - 752.92}$$

$$T_4' = 804.43\ K$$

→ heat supplied $Q_s = mc_p(T_3 - T_2')$

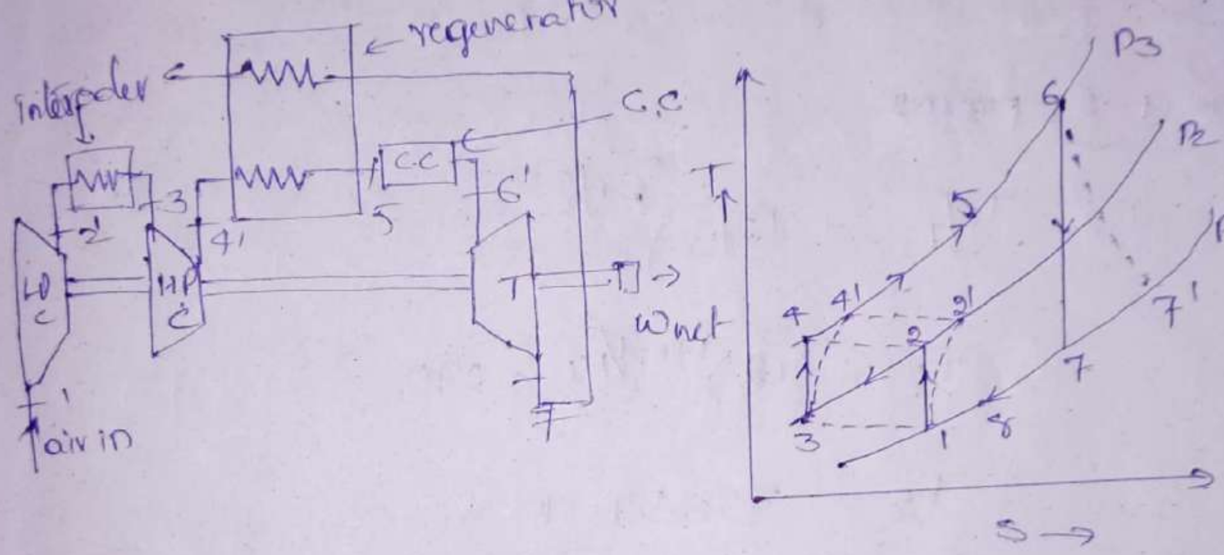
$$= 1 \times 1.005\ (1268.081 - 533.25)$$

$$= 738.505\ kJ/kg$$

→ $$\eta_{th} = W_{net}/Q_s$$

$$= \frac{231.55}{738.505} \times 100 = 31.35\ \%$$

6. Determine the efficiency of a gas turbine plant fitted with a heat exchanger of 75% effectiveness. The pressure ratio is 4:1 & compressor is carried out in two stages and in equal pressure ratio with intercooling back to initial temp of 290 K. The max temp is 925 K. Turbine isentropic η is 88%. and each compressor η is 85%. for air $\gamma = 1.4$, $C_p = 1.005$ KJ/kg.K



sol $\epsilon = 75\% = 0.75 = \frac{T_5 - T_{4'}}{T_{7'} - T_{4'}}$

$P_4/P_1 = 4$

$P_4/P_3 = P_2/P_1$

$P_4/P_1 = P_4/P_3 \times P_2/P_1$

$P_4/P_1 = (P_2/P_1)^2$

$P_2/P_1 = \sqrt{P_4/P_1}$

$= \sqrt{4} = 2.$

$T_1 = T_3 = 290\ K$

$T_6 = 925\ K$

$\eta_T = 88\% = 0.88$

$\eta_{C_1} = \eta_{C_2} = 85\% = 0.85$

$\gamma = 1.4$

$C_P = 1.005\ KJ/Kg.K$

→ (1-2) process

$$T_2/T_1 = (P_2/P_1)^{\gamma-1/\gamma}$$

$$T_2 = (2)^{1.4-1/1.4} \times 290$$

$$T_2 = 353.51\ K$$

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{353.51 - 290}{T_2' - 290}$$

$$T_2' = 364.722\ K$$

→ (3-4) = (1-2) process

$T_2 = T_4$

$T_2' = T_4'$

→ (6-7) process

$$T_6/T_7 = (P_6/P_7)^{\gamma-1/\gamma}$$

$$T_6/T_7 = (4)^{1.4-1/1.4}$$

$$T_7 = \frac{925}{1.485}$$

$$T_7 = 622.47 \text{ K}$$

→ $$\eta_{tur} = \frac{T_6 - T_7'}{T_6 - T_7}$$

$$0.88 = \frac{925 - T_7'}{925 - 622.47}$$

$$T_7' = 658.77 \text{ K}$$

→ $$\epsilon = \frac{T_5 - T_4'}{T_7' - T_4'}$$

$$0.75 = \frac{T_5 - 364.722}{658.77 - 364.722}$$

$$T_5 = 585.27 \text{ K}$$

→ compressor work

$$W_C = (mc_p(T_2' - T_1))\,2$$

$$= 1 \times 1.005\,(364.722 - 290)\,2$$

$$= 150.19 \text{ kJ/kg}$$

→ turbine work

$$W_T = mc_p(T_6 - T_7')$$

$$= 1 \times 1.005\,(925 - 658.77)$$

$$= 267.56 \text{ kJ/kg}$$

→ $\eta_{th} = W_{net}/Q_s$

→ heat supplied $Q_s = mc_p(T_6 - T_5)$

$$= 1 \times 1.005\,(925 - 585.27)$$

$$= 341.42 \text{ kJ/kg}$$

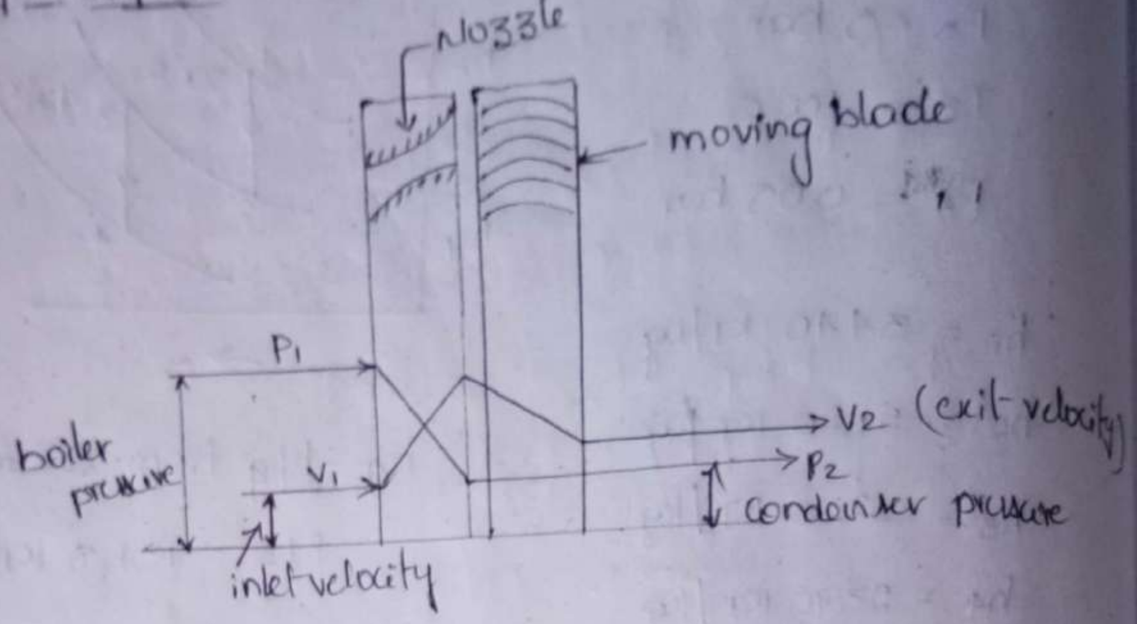
→ $$\eta_{th} = \frac{W_T - W_C}{Q_s} \times 100$$

$$= \frac{267.56 - 150.19}{341.42} \times 100$$

$$= 34.37\,\%$$

3. Impulse turbine

→ Simple impulse turbine.



→ Compounding :- Reduce the speed of the rotor by adding external parts to it

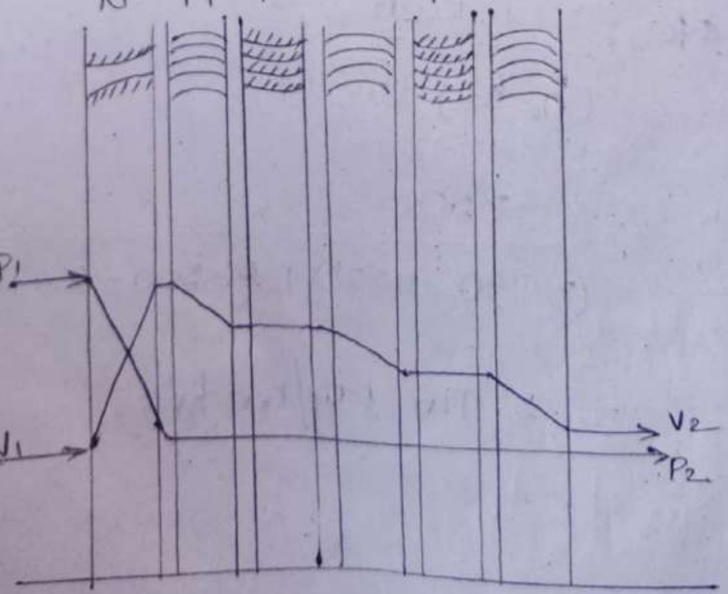
* Methods of compounding

(i) velocity compounding

(ii) pressure compounding

(iii) velocity - pressure compounding

(i) velocity compounding :-

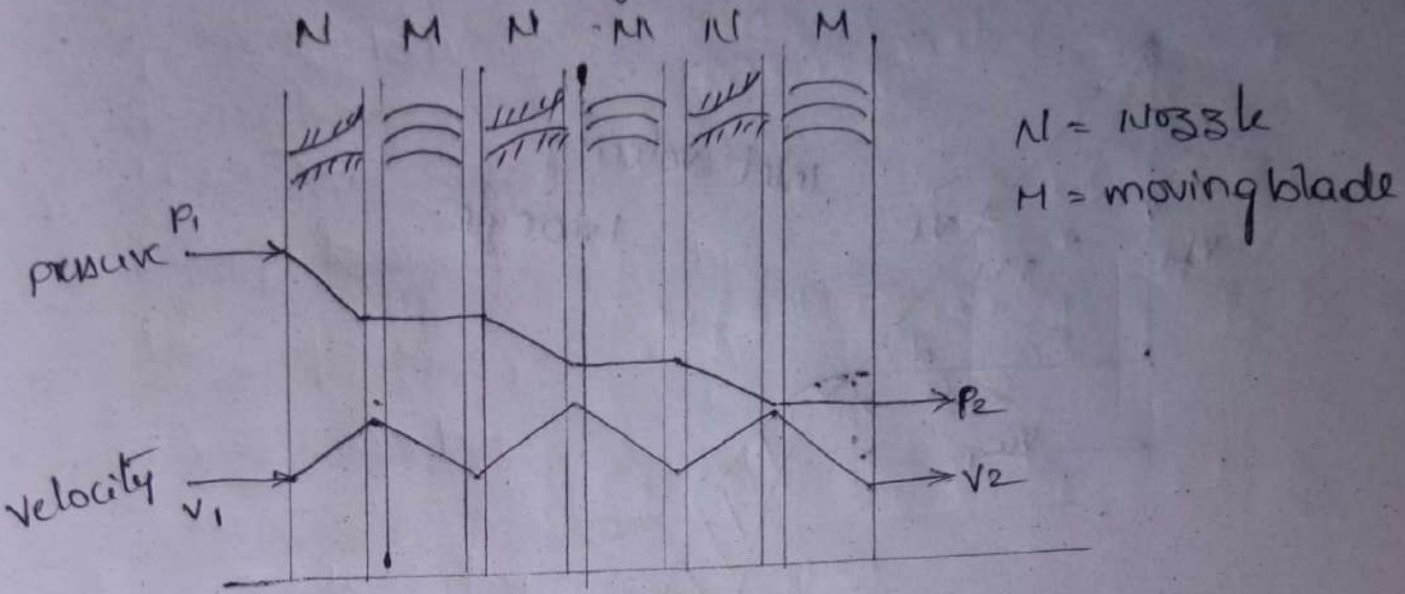


N = Nozzle

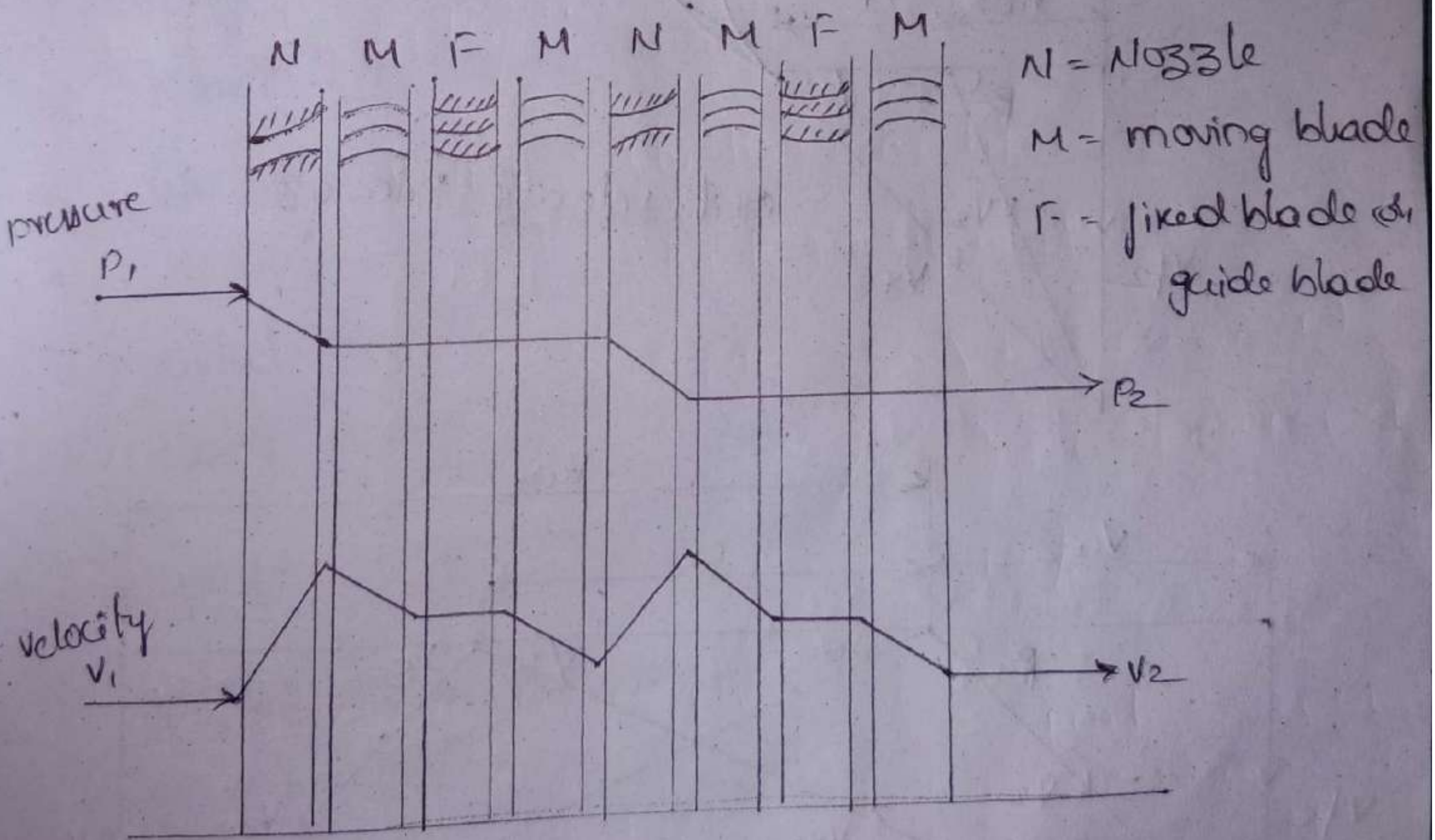
M = moving blades

F = fixed blade (or) Guide blade

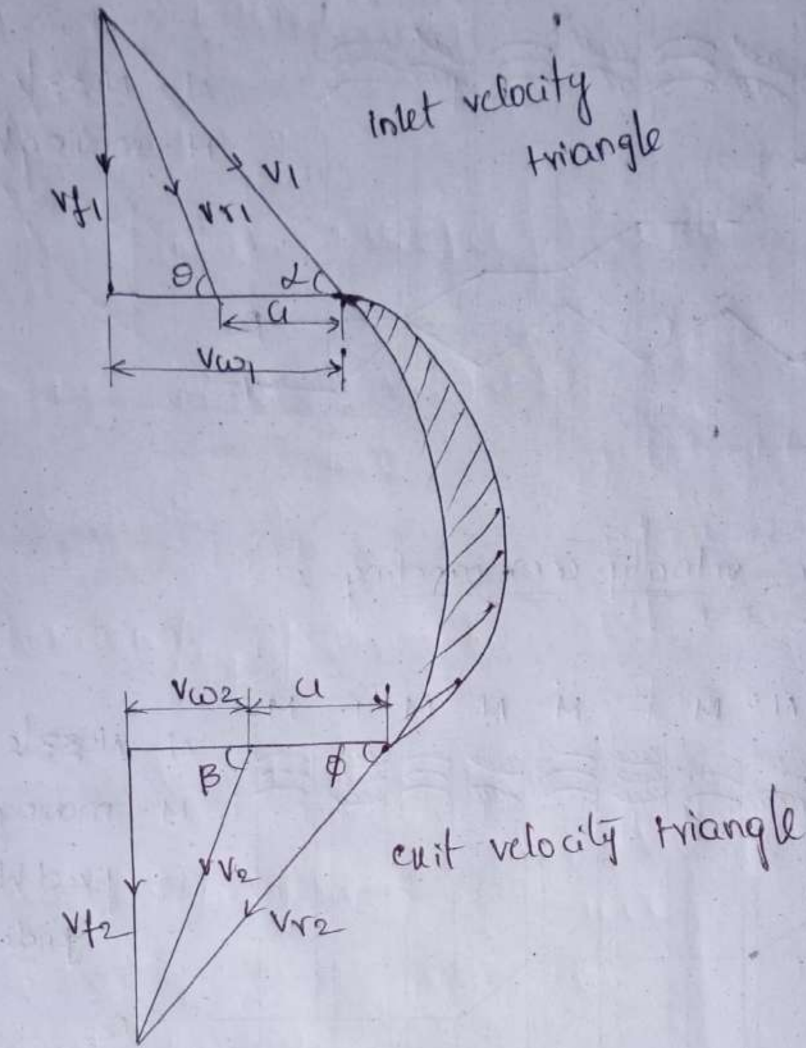
(ii) pressure compounding :-

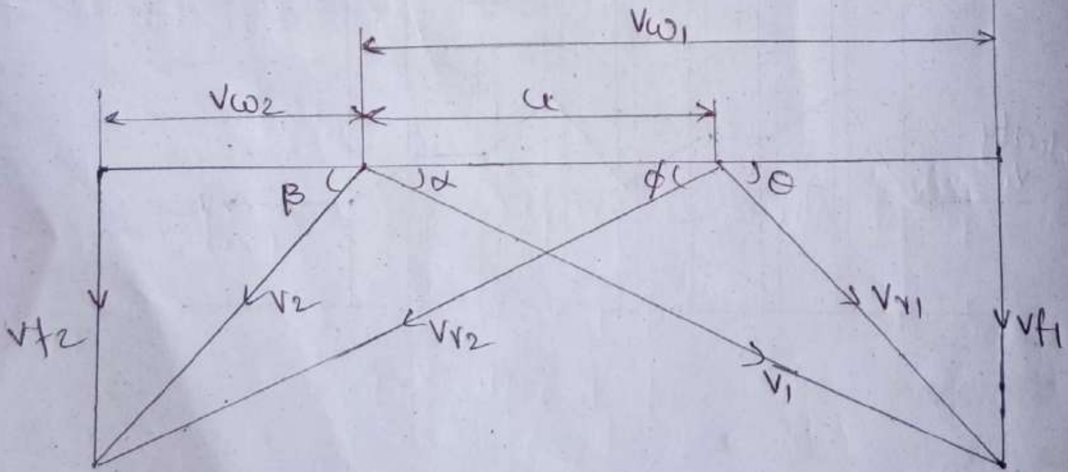


(iii) pressure - velocity compounding :-



→ * Combined velocity diagram for impulse turbine:





u → blade velocity m/s

V_1 → inlet steam velocity at blade inlet m/s

V_{f_1} → flow velocity at inlet m/s

V_{ω_1} → whril velocity at inlet m/s

V_{ω_2} → whril velocity at exit m/s

V_{f_2} → flow velocity at exit m/s

$\alpha \rightarrow$ Nozzle angle

$\theta \rightarrow$ moving blade inlet angle

$\beta \rightarrow$ discharge angle

$\phi \rightarrow$ moving blade outlet angle

Important Terms :-

a. tangential force (F_T)

b. power developed

c. work done / kg of steam

d. Nozzle efficiency

e. Blade / diagram efficiency

f. stage efficiency

g. Blade velocity co-efficient

h. loss due to friction

i. driving force on wheel

J. axial thrust

k. blade speed ratio

→ Tangential force (F_T) :-

$$F_T = m \times a$$

$$\boxed{F_T = \dot{m} \times [V_{w1} \pm V_{w2}]}$$

$$F_T = kg/s \times m/s = \frac{kg\text{-}m}{s^2} = N.$$

+ve sign → when V_{w1} & V_{w2} are in

- ve sign → when V_{w1} & V_{w2} are in

→ Power developed :-

P = workdone / second

$P = F_T \times u$

$$P = \dot{m}(V_{w1} \pm V_{w2})u \quad \text{watts}$$

$$\Rightarrow P = \frac{\dot{m}(V_{w1} \pm V_{w2})u}{1000} \quad \text{kW}$$

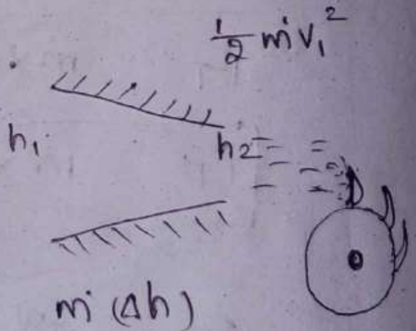
→ workdone / kg of steam :-

if $m = 1$ kg/s

$$\Rightarrow \text{workdone/kg of steam} = \frac{(V_{w1} \pm V_{w2})u}{1000} \quad \text{kW}$$

→ Nozzle efficiency :-

$$\Rightarrow P = \frac{\dot{m}(V_{w1} \pm V_{w2})u}{1000} \quad \text{kW}$$



$$\eta_N = \frac{\text{K.E of steam at exit of nozzle}}{\text{enthalpy drop in nozzle}}$$

$$\eta_N = \frac{\frac{1}{2}\dot{m}V_1^2}{\dot{m}(\Delta h)} \times 100$$

$$\Rightarrow \eta_N = \frac{V_1^2}{2(\Delta h)} \times 100$$

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→ Blade (or) diagram efficiency :-

$$\eta_d = \frac{\text{work done on blade}}{\text{K.E of steam at inlet to turbine}}$$

$$= \frac{\dot{m}(V_{w1} \pm V_{w2})\,u}{\frac{1}{2}\dot{m}V_1^2}$$

$$\Rightarrow \eta_{bl} = \frac{2u(V_{w1} \pm V_{w2})}{V_1^2} \times 100$$

→ stage efficiency :-

$$\eta_s = \frac{\text{work done on blade}}{\text{enthalpy drop in nozzle}}$$

$$= \frac{\dot{m}(V_{w1} \pm V_{w2})\,u}{\dot{m}(\Delta h)} \times 100$$

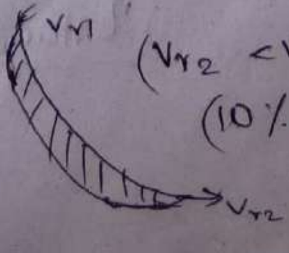
$$\Rightarrow \eta_s = \frac{(V_{w1} \pm V_{w2})\,u}{(\Delta h)} \times 100 \quad \text{(or)}$$

$$\Rightarrow \eta_{stage} = \eta_{nozzle} \times \eta_{blade}$$

→ Blade velocity co-efficiency / coefficient of velocity / friction factor (K)

$$K = \frac{\text{relative velocity of steam at exit}}{\text{relative velocity of steam at entry}}$$

$$\Rightarrow K = \frac{V_{r2}}{V_{r1}}$$



$(V_{r2} < V_{r1})$
(10% - 15%)

→ loss due to friction :-

$$\Rightarrow \frac{V_{r_1}^2 - V_{r_2}^2}{2000} \text{ KJ}$$

→ driving force on wheel :-

$$\Rightarrow F_T = \dot{m}\,(V_{w_1} \pm V_{w_2}) \text{ N.}$$

→ axial thrust :-

$$F_a = \dot{m} \times \text{axial acceleration}$$

$$\Rightarrow F_a = \dot{m}\,(V_{f_1} - V_{f_2}) \text{ N.}$$

if $V_{f_1} = V_{f_2}$

$$\Rightarrow F_a = \dot{m}\,(0) = 0$$

→ blade speed ratio :-

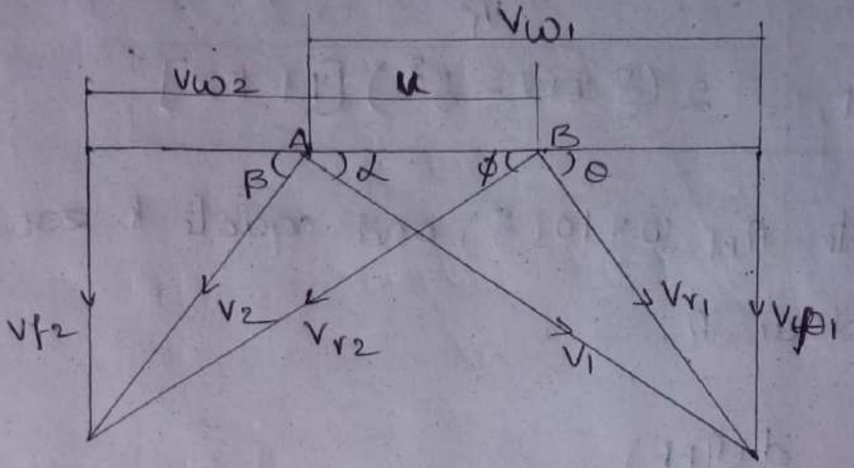
$$\delta = \frac{\text{Blade speed}}{\text{steam speed}}$$

$$\Rightarrow \delta = \frac{u}{V_1}$$

Note :- if friction losses are neglected then

$$\boxed{\eta_{stage} = \eta_{blade}}$$

** Expression for optimum value of blade speed to the steam speed (for max η condition) for single stage impulse turbine :-



$$V_w = V_{r_1}\cos\theta + V_{r_2}\cos\phi$$

$$V_w = V_{r_1}\cos\theta\left[1 + \frac{V_{r_2}\cos\phi}{V_{r_1}\cos\theta}\right]$$

Note : Assume no friction force in moving blade.

$$K = (V_{r_1} = V_{r_2})$$

$$K = 1$$

for impulse turbine, assume blade is symmetrical

$$Z = \frac{\cos\phi}{\cos\theta} \quad (\theta = \phi)$$

$$Z = 1.$$

$$V_w = V_{r_1}\cos\theta\,(1 + KZ)$$

$$V_w = (V_1\cos\alpha - u)(1 + KZ)$$

from blade η

$$\eta_{bl} = \frac{2u\,(V_w)}{V_1^2}$$

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$$\eta_{bl} = \frac{2u(V_1 \cos\alpha - u)(1+KZ)}{V_1^2}$$

$$\eta_{bl} = \frac{2(uV_1 \cos\alpha - u^2)(1+KZ)}{V_1^2}$$

$$\boxed{\eta_{bl} = 2(\delta \cos\alpha - \delta^2)[1+KZ]}$$

differentiate η_{bl} w.r.to (δ) and equate to zero for max blade η.

$$\frac{d(\eta_{bl})}{d\delta} = 0$$

$$\Rightarrow 2(\cos\alpha - 2\delta)[1+KZ] = 0$$

$$\Rightarrow \cos\alpha - 2\delta = 0$$

$$\Rightarrow \cos\alpha = 2\delta$$

$$\boxed{\delta = \frac{\cos\alpha}{2}} \rightarrow \text{for optimum}$$

$$\eta_{bl} = 2\delta(\cos\alpha - \delta)(1+KZ)$$

$$= 2 \times \frac{\cos\alpha}{2}\left(\cos\alpha - \frac{\cos\alpha}{2}\right)[1+KZ]$$

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

$$= \cos\alpha\left(\frac{\cos\alpha}{2}\right)(1+KZ) \qquad \{K=1 \text{ \& } Z=1\}$$

$$= \cos\alpha\left(\frac{\cos\alpha}{2}\right)(1+1)$$

$$= \cos\alpha\left(\frac{\cos\alpha}{2}\right)2$$

$$\boxed{\eta_{bl} = \cos^2\alpha} \rightarrow \text{for max blade } \eta.$$

Assume $\alpha = 20°$ for impulse turbine

$$\eta_{bl} = \cos^2(20°)$$

$$= 0.883 \times 100$$

$$= 88.3\% \rightarrow \text{in theoretical}$$

$$\eta_{bl} = 55\% \rightarrow \text{for actual.}$$

Work done/kg of steam is given by :

$$W = F_T \times u$$

$$W = \dot{m}\,(V_{w1} \pm V_{w2}) \times u$$

$$\therefore [\dot{m} = 1\ kg/s \;\; \& \;\; V_w = V_{w1} \pm V_{w2}]$$

$$W = V_w \times u$$

$$W = (V_1 \cos\alpha - u)[1 + KZ] \times u \qquad \begin{Bmatrix} K = 1 \\ Z = 1 \end{Bmatrix}$$

$$W = (V_1 \cos\alpha - u)\, 2u$$

$$W = (V_1\, 2\delta - u)\, 2u \qquad \left\{ \begin{array}{l} \delta_{opt} = \frac{\cos\alpha}{2} \\ \cos\alpha = \delta_{opt} \times 2 \\ \delta = \frac{u}{V_1} \end{array} \right.$$

$$W = \left(V_1 \times 2 \times \frac{u}{V_1} - u\right) 2u$$

$$W = 2u\,(2u - u)$$

$$W = 2u\,(u)$$

$$\boxed{W_{max} = 2u^2}$$

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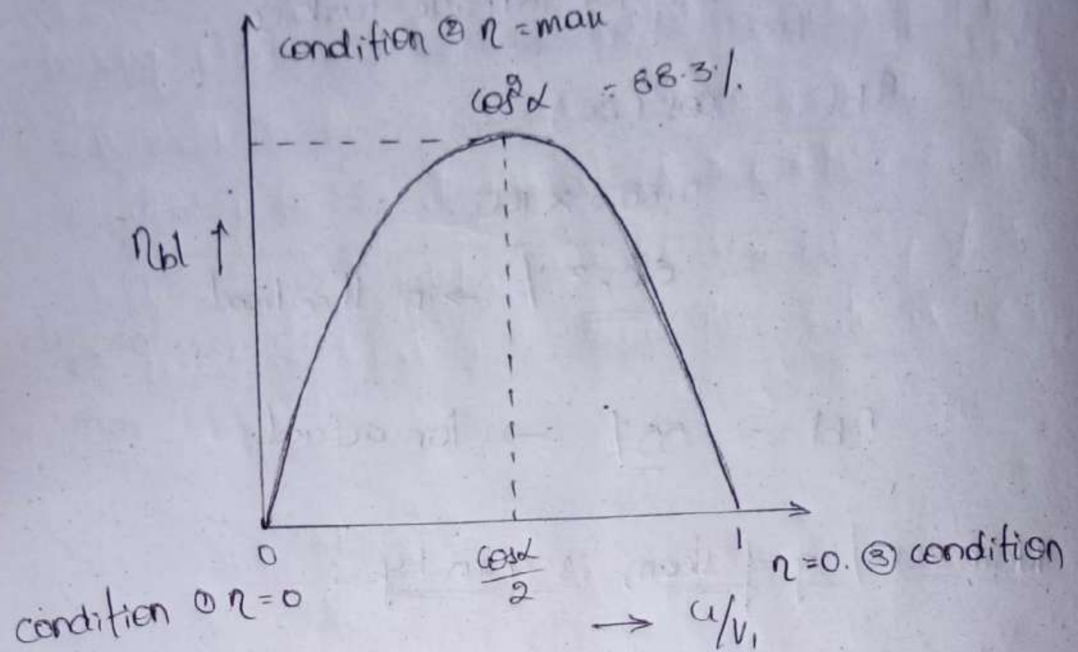
** Variation of blade efficiency with blade steam ratio



$\delta = u/V_1$

$(\alpha = 20°)$

$\frac{\cos\alpha}{2} = u/V_1$

$\frac{\cos 20°}{2} = u/V_1$

$u/V_1 = \frac{1}{2} \Rightarrow \boxed{u = \frac{1}{2} V_1}$

① In a single stage impulse turbine the blade angles are equal & nozzle angle is 20°. The velocity coefficient for the blade is 0.83. Find the max blade efficiency possible. If the actual blade efficiency is 90% of max blade efficiency (η_{bl}). Find the possible ratio of blade speed to the steam blade speed.

Sol Given data

$\alpha = 20°$

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velocity coefficient of blade $k = 0.83$

blade angle $\theta = \phi$

actual $\eta_{blade} = 90\% = 0.90$ max η_{blade}

$\frac{u}{V_1} = \delta = ?$

$$[\eta_{blade}]_{max} = \left(\frac{\cos^2\alpha}{2}\right)[1 + kZ]$$

$$= \left(\frac{\cos^2 20^\circ}{2}\right)[1 + 0.83(1)]$$

$$= 80.7\%$$

$$[\eta_{blade}]_{actual} = (0.90 \times 0.80) \times 100$$

$$= 72\%$$

$$(\eta_{blade})_{actual} = 2[\delta \cos\alpha - \delta^2](1 + kZ)$$

$$0.727 = 2(\delta \cos 20 - \delta^2)[1 + 0.83(1)]$$

$$0.727 = 2[\delta\, 0.939 - \delta^2][1.83]$$

$$0.727 = (0.939\delta - \delta^2)\, 3.66$$

$$\delta^2 - 0.939\delta + 0.1986 = 0$$

$$\boxed{\delta = 0.6172}$$

1. steam enters a impulse wheel having a nozzle angle of 20° at a velocity of 450 m/s. The exit angle of the moving blade is 20° and relative velocity of the steam assumed to be remains constant over the moving blade. If the blade speed is 180 m/s. calculate blade angle at inlet. B). work done per kg of steam c). power developed if the steam flow rate is 1.6 kg/sec

sol Given data

$V_1 = 450$ m/s

$\alpha = 20°$

$\phi = 20°$

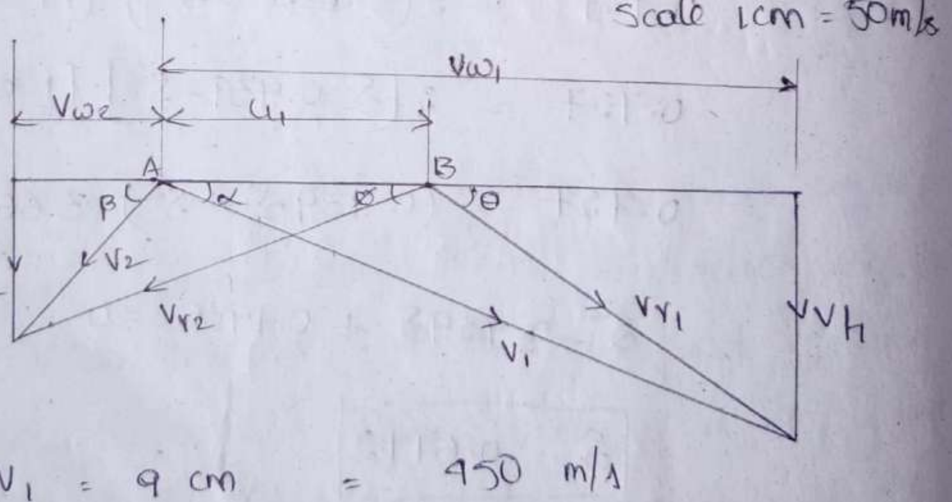
$u = 180$ m/s

$V_{r1} = V_{r2}$; $K = 1$

$\theta = ?$; $w/p = ?$; $P = ?$

$m = 1.6$ kg/sec

Scale 1cm = 50m/s



$V_1 = 9$ cm $= 450$ m/s

$V_{r1} = 5.8$ cm $= 290$ m/s

$V_{r2} = 5.8$ cm $= 290$ m/s

$V_2 = 2.8$ cm $= 140$ m/s

$\theta = 32°$

$\alpha = 20°$

$\phi = 20°$

$\beta = 47°$

$u_1 = 3.6$ cm $= 180$ m/s

$V_{w_1} = 8.3$ cm $= 425$ m/s

$V_{w_2} = 1.9$ cm $= 95$ m/s

(i) blade angle at inlet

$\theta = 32°$

(ii) work done per kg of steam

$$W.D/kg = \frac{\dot{m}(V_{w_1} + V_{w_2})u}{1000}$$

$V_{w_1} = 8.3 \times 50 = 425$ m/s

$V_{w_2} = 1.9 \times 50 = 95$ m/s

$$W.D/kg = \frac{1(425 + 95)180}{1000}$$

$= 93.6$ KJ/kg

(iii) power $$P = \frac{\dot{m}(V_{w_1} + V_{w_2})u}{1000}$$

$$P = \frac{1.6(425 + 95)180}{1000}$$

$P = 149.76$ KW

2. In a single stage impulse turbine, the steam jet leaves the nozzle at 20° to the plane of wheel at a speed of 670 m/s and it enters the moving blades at an angle of 35° to the drum axis. The moving blades are symmetrical in shape. Determine the blade velocity & diagram efficiency.

Sol. Given data

$V_1 = 670$ m/s

$\alpha = 20°$

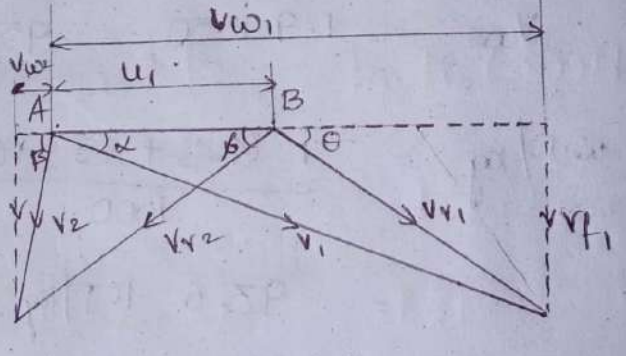
$\theta = 35°$

$\theta = \phi$

$u = ?$

$\eta_{diag} = ?$

scale 1cm = 100 m/s



$u_1 = 2.9$ cm $= 290$ m/s

$V_1 = 6.7$ cm $= 670$ m/s

$V_{r1} = 4.1$ cm $= 410$ m/s

$V_{r2} = 4.1$ cm $= 410$ m/s

$V_2 = 2.4$ cm $= 240$ m/s

$V_{w1} = 6.3$ cm $= 630$ m/s

$V_{w2} = 0.5$ cm $= 50$ m/s

(i) blade velocity

$u = 2.9\,cm \times 100$

$\therefore u = \underline{290\ m/s}$

(ii) diagram efficiency

$$\eta_{bl} = \frac{2u\,(V_{w_1} + V_{w_2})}{V_1^2} \times 100$$

$$= \frac{2 \times 290\,(630 + 50)}{670^2} \times 100$$

$$= \frac{394400}{448900} \times 100$$

$$= \underline{87.8\ \%}$$

3. steam leaves the nozzle of a single stage impulse turbine at 840 m/s. The nozzle angle is 18°. and the blade angles are 29° at the inlet and outlet. The friction coefficient is 0.9. calculate (i) blade velocity
(ii) steam mass flow rate in kg/hr to develop 300 kW power

sol

Given data

$V_1 = 840\ m/s$

$\alpha = 18°$

$\theta = 29°$

$\phi = 29°$

$K = 0.9$

$V_{r_1} = K\,V_{r_2}$

$P = 300\ kW$

$= 300 \times 10^3\ W$

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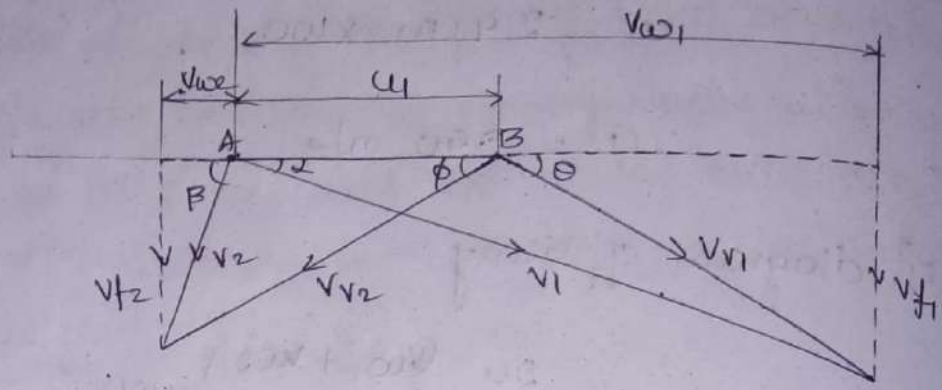
scale 1cm = 100 m/s



$V_1 = 8.4 \text{ cm} = 840 \text{ m/s}$

$V_2 = 2.5 \text{ cm} = 250 \text{ m/s}$

$V_{r1} = 5.3 \text{ cm} = 530 \text{ m/s}$

$V_{r2} = 4.8 \text{ cm} = 480 \text{ m/s}$

$\alpha = 18°$

$\theta = 29°$ & $\phi = 29°$

(i) blade velocity

$u_1 = 3.3 \times 100$

$u_1 = 330 \text{ m/s}$

(ii) steam mass flow in kg/hr

$$P = \frac{\dot{m}(V_{\omega_1} + V_{\omega_2})}{1000} \times u$$

$$300 \times 10^3 = \frac{\dot{m}(800 + 90)}{1000} \times 330$$

$\dot{m} = 1.021145$ kg/sec

$\dot{m} = 3677.22$ kg/hr

4 A single row impulse turbine develops 132.4 kW at a blade speed of 175 m/sec using 2 kg of steam /sec steam leaves the nozzle at 400 m/sec. velocity coefficient of the blades is 0.9. steam leaves the turbine blades axially. Determine nozzle angle, blade angles at entry and exit. Assume no shock

sol Given data

$P = 132.4$ kW

$u = 175$ m/sec $= 3.5$ m/s

$V = 400$ m/s $= 8$ m/s

$\dot{m} = 2$ kg

$K = 0.9$

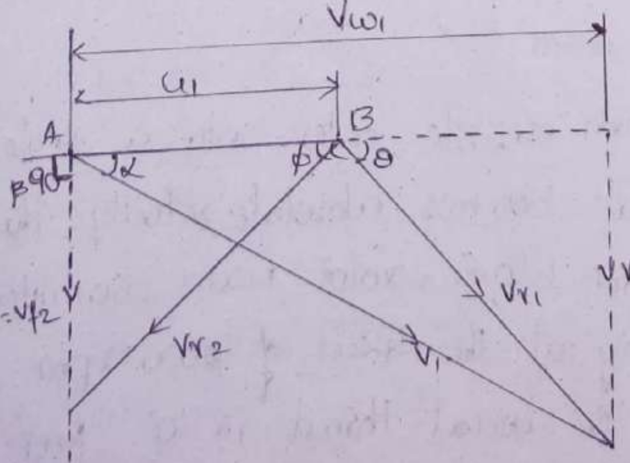
$\theta, \phi, \beta, \alpha = ?$

$\delta = u/V$

$= 175/400 = 0.437$

$\delta = \frac{\cos\alpha}{2} \Rightarrow \alpha = \frac{2\delta}{\cos} = \alpha = 28.95°$

scale 1cm = 50m/s



$\theta = 48°$

$\phi = 42°$

$\alpha = 28.95$

$\beta = 90°$

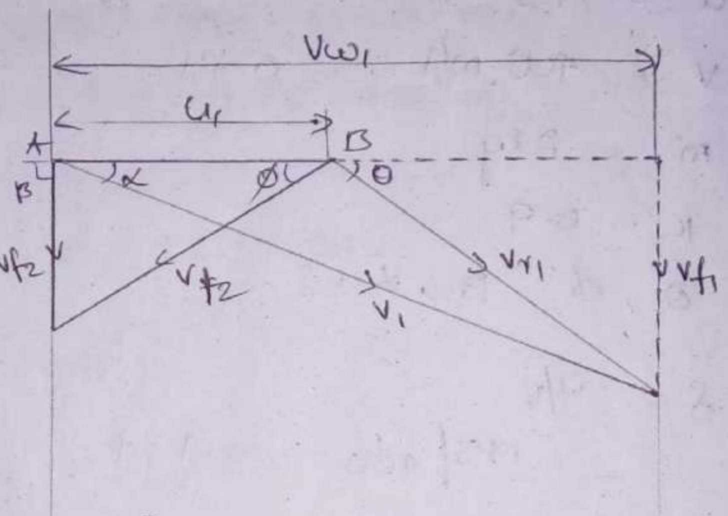
83

$$P = \frac{\dot{m}\,(V_{w01} + V_{w02})\,u}{1000}$$

$$132.4 = \frac{2\,(V_{w01} + 0)\,u}{1000}$$

$V_{w01} = 378.4$ m/s.

$V_{w01} = 7.5$ cm   scale 1cm = 50 m/s



$\alpha = 20.5°$

$\theta = 36°$

$\phi = 31°$

$\beta = 90°$

(5) steam from nozzle enters into a single stage impulse turbine at 300 m/s absolute velocity the nozzle angle is 25° and blade rotor mean diameter is 100 cm is rotating at the speed of 2000 rpm find the blade angles if the axial thrust is 0. find the power developed when the steam flow rate is 600 kg/min. Take blade velocity coefficient 0.9.

Sol Given data

$\alpha = 25^\circ$

$V_1 = 300$ m/s

$d = 100$ cm

$N = 2000$ rpm

θ & ϕ = ?

axial thrust = 0. ($V_{f1} = V_{f2}$)

$\dot{m} = 600$ kg/min $= 600/60 = 10$ kg/sec

$K = 0.9.$

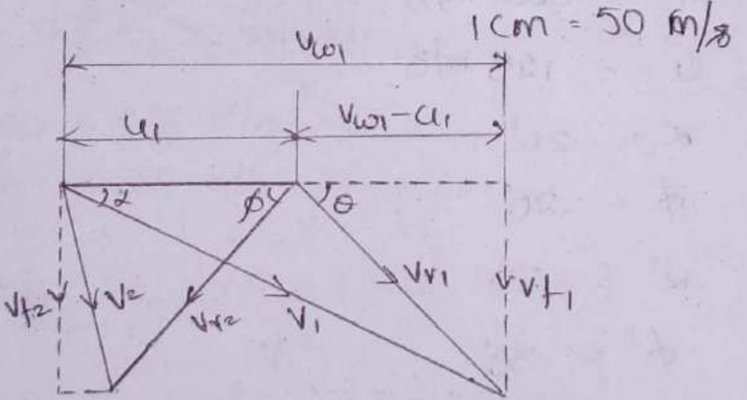
$V_{r2} = 0.9 \times V_{r1}$

$u_1 = d\pi N/60$

$= \frac{100}{100} \pi \times 2000/60$

$= 1 \times \pi \times 2000/60$ $V_{f2} = 3.24$

$= 104.71$ m/s



$\theta = 45^\circ$

$\phi = 49^\circ$

$V_{w1} = 5.4 \times 50 = 270$ m/s

$V_{w2} = 0$

$$P = \frac{\dot{m}(V_{w1} - V_{w2})\, u}{1000}$$

$$= \frac{10(260 - 0) \times 145}{1000} = 391.5 \text{ kw}$$

* Problems on compound impulse turbine :-

1. The following data relate to a compound impulse tur having two rows of moving blades and one row of fixed blade in b/w them.

a. velocity of the leaving the nozzle = 600 m/s
b. blade speed = 125 m/s
c. Nozzle angle $\alpha = 20^\circ$
d. first moving blade discharge angle = 20°
e. first fixed blade discharge angle = 25°
f. second moving blade discharge angle = 30°.
g. friction loss in each ring = 10% of relative velo

find diagram η & power developed for a steam flow of 6 kg/sec.

sol

Given data

$V_1 = 600$ m/s

$u = 125$ m/s

$\alpha = 20^\circ$

$\phi = 20^\circ$

$\alpha' = 25^\circ$

$\phi' = 30^\circ$

$K = 0.9$

$\dot{m} = 6$ kg/s

$\eta_{blade} = ?$

$P = ?$

$\alpha \quad \theta \quad \phi \qquad \alpha' \quad \theta' \quad \phi'$

N M1 F M2

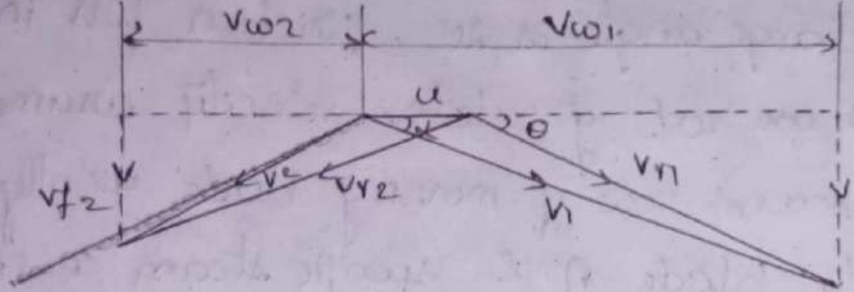
$V_1 \quad V_2 \quad V_1' \quad V_2'$

$K = \frac{V_{r2}}{V_{r1}} = 0.9$

$K = \frac{V_{r2}'}{V_{r1}'} = 0.9$

Scale 1cm = 100 m/s

$K = \frac{V_1'}{V_2} = 0.9$

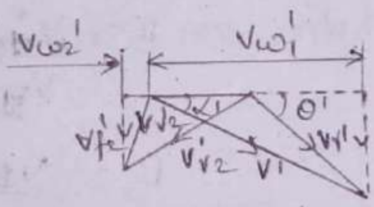


$V_{r1} = 4.9 \times 100 = 490$ (m/s) first row of moving blade

$V_{r2} = 4.41 \times 100 = 441$ (m/s)

$V_{w1} = 5.7 \times 100 = 570$ (m/s)

$V_{w2} = 2.8 \times 100 = 280$ (m/s)



$\frac{V_1'}{V_2} = 0.9$

$V_1 =$ — ✓

$V_{w1} = 2.6 \times 100 = 260$ m/s

$V_{w2} = 0.3 \times 100 = 30$ m/s

→ $\eta_{blade} = \frac{2u\,(V_{w1} + V_{w2} + V_{w1}' + V_{w2}')}{V_1^2}$

$= \frac{2 \times 125\,(570 + 280 + 260 + 30)}{(600)^2} = 79.16\%$

→ power $P = \frac{\dot{m}\,(V_{w1} + V_{w2} + V_{w1}' + V_{w2}')\,u}{1000}$

$= \frac{6\,(570 + 280 + 260 + 30)\,125}{1000}$

$= 855$ kW

2. The following data relate to a compound impulse turbine having 2 rows of moving blades and one row of fixed blade in b/w them. Steam velocity coming out of the nozzle 450 m/s, nozzle angle 15°, moving blade tip discharge angles are 30°, fixed blade discharge angle is 20°, friction loss in each blade rows are 10% of relative velocity assume steam leaves the second row of moving blade axially. Find blade velocity, blade η & specific steam consumption of the turbine.

$\alpha\ \theta\ \phi \quad \alpha'\ \theta'\ \phi'$

[N] [M1] [F] [M2]

$V_1 \quad V_2 \quad V_1' \quad V_2'$

Sol: Given data

$V_1 = 450\ m/s$

$\alpha = 15°$

$\phi = \phi' = 30°$

$\alpha' = 20°$

$\beta' = 90°$

$K = 0.9$

$K = V_{r2}/V_{r1} = 0.9$

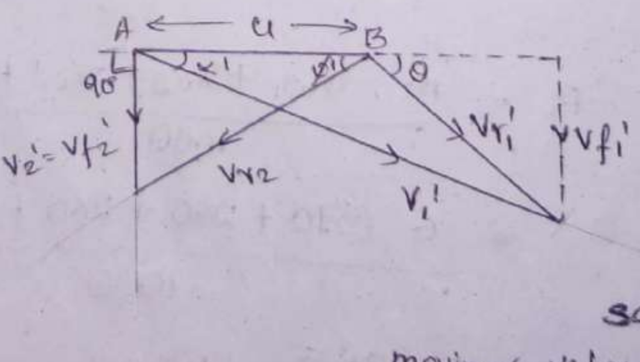
$K = \frac{V_{r2}'}{V_{r1}'} = 0.9$

$K = \frac{V_1'}{V_2'} = 0.9$

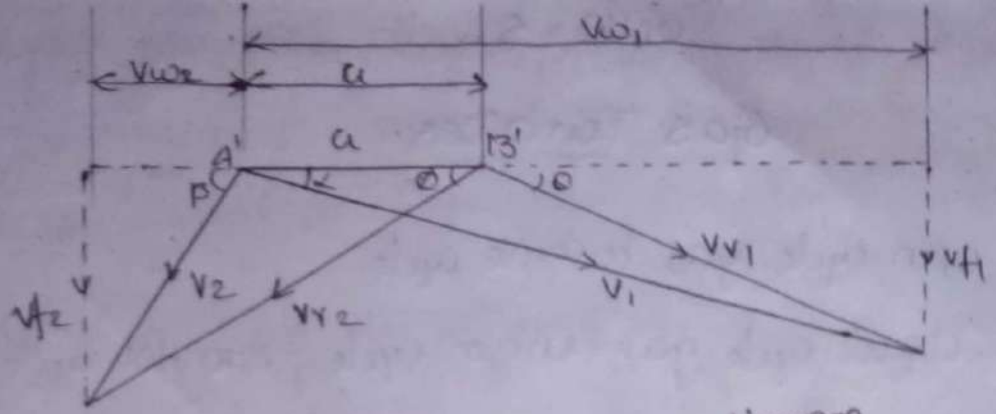
take u = 3cm

Scale

1 cm = 50 m/s



second row of moving velocity diagram



first row of moving diagram

$V_{r2}/V_{r1} = 0.9$

$V_{r2} = V_{r1} \times 0.9$

$V_{r2} =$

$$\eta_{blade} = \frac{2u(V_{w1} + V_{w2} + V_{w1}' + V_{w2}')}{V_1^2} \times 100$$

$$= \frac{2 \times 108 (313.2 + 68.4 + 190.8 + 0)}{324^2} \times 100$$

$= 0.97 = 97\%$

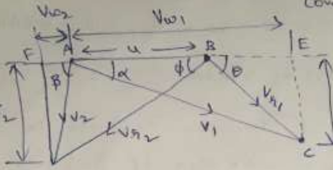
Specific steam consumption (m_s)

$$m_s = \frac{3600}{(V_{w1} + V_{w2} + V_{w}')\,u}$$

$$= \frac{3600}{(435 + 95 + 265)\,150}$$

$= 0.03101$ kg/wh

(1)



Combined velocity diagram of Impulse turbine

u = Velocity of blade in m/s

V_1 = Absolute velocity of steam entering the blade, m/s

V_{r_1} = relative velocity of steam at inlet, m/s

V_{w_1} = whirl velocity at inlet

V_{f_1} = velocity of flow at inlet

V_2 = Absolute velocity of steam at exit

V_{r_2} = relative velocity of steam at exit

V_{w_2} = whirl velocity at exit

V_{f_2} = velocity of flow at exit

α = Nozzle angle

θ = inlet angle of moving blade

ϕ = exit or outlet angle of moving blade

β = Angle of dischage at exit.

If Axial thrust is zero

$V_{f_1} = V_{f_2}$

(a) work done on blade

From Newton's second law of motion

Tangential force = mass × acceleration

= mass/sec × change in whirl velocity

$= m\,(V_{w_1} \pm V_{w_2})$ N

$\frac{kg-m}{s^2} = 1N$

w.d/s = F × Dist. moved/sec

$\Rightarrow m\,(V_{w_1} \pm V_{w_2})\,u \quad \frac{Nm}{s}$ (or) $\frac{J}{s}$

Power developed, $P = m(V_{w_1} \pm V_{w_2}) \cdot u$ watts

m = mass of steam flowing / sec over blades

Note: use +ve sign, if V_{w_1} and V_{w_2} are in opposite direction, and -ve sign if V_{w_1} and V_{w_2} are in same direction.

(b) Blade or diagram efficiency

It is the ratio of work done on blade to the energy supplied to blade.

$$\text{Blade or diagram efficiency} = \frac{\text{work done on blade}}{\text{energy supplied to blade}}$$

$$= \frac{m(V_{w_1} \pm V_{w_2})u}{\frac{1}{2} m V_1^2}$$

$$\eta_b = \frac{(V_{w_1} \pm V_{w_2}) 2u}{V_1^2}$$

(b) Nozzle efficiency

It is the ratio of kinetic energy of steam at exit of the nozzle to the enthalpy drop in nozzle.

$$\text{Nozzle efficiency} = \frac{\frac{1}{2} m V_1^2}{m \Delta h} = \frac{V_1^2}{2 \Delta h}$$

V_1 = abs. velocity of steam, m/s

Δh = enthalpy drop in nozzle, Joules.

(c) Stage efficiency

It is ratio of workdone on blade to enthalpy drop in nozzle.

(2)

$$\text{Stage efficiency} = \frac{m(V_{w_1} \pm V_{w_2})u}{m(\Delta h)}$$

$$\Rightarrow \frac{(V_{w_1} \pm V_{w_2})2u}{V_1^2} \times \frac{V_1^2}{2\Delta h}$$

∴ Stage efficiency = Blade efficiency × Nozzle efficiency

Note: If losses in nozzle are neglected,

then, Stage η = blade η.

(d) Axial thrust:

Axial thrust on the wheel occurs when velocity of flow at inlet is not equal at outlet.

Axial Force = mass × axial acceleration

$$= m(V_{f_1} - V_{f_2})\ N$$

Axial thrust acts along the shaft and is absorbed by bearings.

(e) Driving force on the wheel:

$$F_x = m(V_{w_1} \pm V_{w_2})\ N$$

(f) Loss of energy due to friction

$$\Rightarrow \frac{V_{r_1}^2 - V_{r_2}^2}{2000}\ \text{KJ}$$

(g) Effect of blade friction

In practice, some resistance is always offered by blade surface to gliding steam jet, whose effect is to reduce relative velocity of jet. i.e to make V_{r_2} less than V_{r_1}.

The ratio of $\frac{V_{R_2}}{V_{R_1}}$ is known as blade velocity coefficient (or) coefficient of velocity (or) friction factor (k)

Blade velocity coefficient,

$$k = \frac{V_{R_2}}{V_{R_1}}$$

(h) Blade speed ratio:

It is ratio of blade velocity to absolute velocity of steam jet at entry to the blade.

Blade speed ratio, $\rho = \frac{u}{V_1}$

Maximum efficiency of Impulse (De Laval) Turbine:

Blades of impulse turbine are made symmetrical i.e $\theta = \phi$

Energy supplied / kg of steam $= \frac{1}{2} V_1^2$

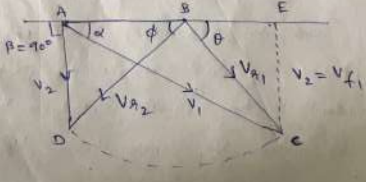
Energy rejected / kg of steam $= \frac{1}{2} V_2^2$

work done per kg of steam $= \frac{V_1^2 - V_2^2}{2}$

work done is maximum, where V_2 is minimum i.e when the angle, $\beta = 90°$.

Neglecting friction, $V_{R_2} = V_{R_1}$

$\theta = \phi$ for De-laval turbine



(3)

$$\angle BAD = \angle BEC = 90^\circ$$

$$AB = BE = \frac{1}{2} AE = \frac{1}{2} \cdot AC \cos\alpha$$

$$u = \frac{1}{2} \cdot V_{w_1} = \frac{1}{2} \cdot V_1 \cos\alpha$$

optimum blade speed, $\rho = \frac{u}{V_1}$

$$\rho = \frac{V_1 \cos\alpha}{2 V_1}$$

$$\rho = \frac{\cos\alpha}{2}$$

$$V_2 = EC = V_1 \sin\alpha$$

$$\text{efficeincy} = \frac{\text{w.d /kg of steam}}{\text{K.E supplied /kg of steam}}$$

$$\rightarrow \frac{\frac{V_1^2 - V_2^2}{2}}{\frac{V_1^2}{2}} \Rightarrow \frac{V_1^2 - V_2^2}{V_1^2}$$

$$\text{Maximum efficeincy}, = \frac{V_1^2 - V_1^2 \sin^2\alpha}{V_1^2}$$

$$= 1 - \sin^2\alpha$$

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

For De laval turbine, Nozzle angle

$$\alpha = 20^\circ$$

$$\eta_{max} = \cos^2 20^\circ = 0.883 = 88.3\%$$

The Above value is only under ideal conditions. In actual practice, the maximum efficeincy of De-laval turbine is about 55%.

Further, when $\beta = 90^\circ$, $V_{w_2} = 0$

w.D / kg of steam $= (V_{w_1}) \cdot u$

For max. efficiency, $V_{w_1} = 2u$

Maximum w.D (or) power $= 2u^2$ J/s (or) watts

efficiency is maximum for small nozzle angle $(16^\circ - 22^\circ)$

$\rho_{opt} =$

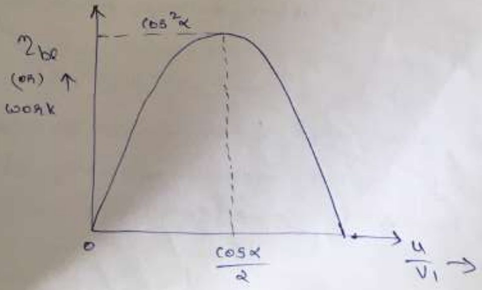
optimum value of ratio of blade speed to steam speed is

$$\rho_{opt} = \frac{\cos\alpha}{2}$$

$$\frac{u}{V_1} = \frac{\cos\alpha}{2}$$

blade velocity should be approximately half of absolute velocity of steam jet coming out from nozzle (fixed blade) for maximum work developed per kg of steam (or) for maximum efficiency.

Variation of η_{bl} (or) work developed per kg of steam with $\frac{u}{V_1}$. fig shows that

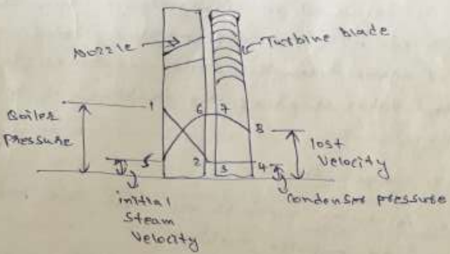


(4) (a) when $\frac{u}{V_1} = 0$, the work done becomes zero

(b) maximum efficiency is $\cos^2\alpha$ and maximum work done / kg of steam is $2u^2$, when $\frac{u}{V_1} = \frac{\cos\alpha}{2}$

(c) when $\frac{u}{V_1} = 1$, work done is zero

Simple Impulse turbine



The pressure of steam jet is reduced in the nozzle and remains constant while passing through moving blade. The velocity of steam is increased in nozzle, and is reduced while passing through moving blades. In this turbine, the 'exit velocity' or leaving velocity or lost velocity may amount to 3.3% of nozzle outlet velocity. Since all the kinetic energy is to be absorbed by one ring of moving blades only, the velocity of wheel is too high (varying from 25000 to 30,000 Rpm). Thus wheel or rotor speed can be reduced by different compounding methods.

Compounding (or) Methods of Reducing Rotor Speed

If the steam is expanded from high boiler pressure to condenser pressure, the steam velocity is extremely high and turbine speed will be very high. Such speeds are not practicable for power generation. Further there will be 10 to 12% loss in kinetic energy with single stage. To overcome these limitations, the steam is expanded in many stages, each stage comprises a set of fixed and moving blades. expansion of steam through a series of stages to reduce the rotor speed of the turbine is called compounding.

Methods of compounding

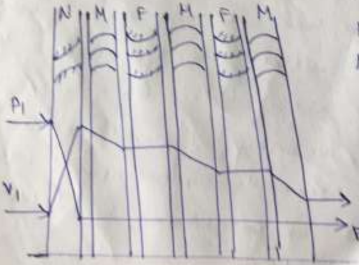
The following methods are used for reducing the speed of an impulse turbine.

(a) Velocity compounding

(b) pressure Compounding

(c) Velocity - pressure compounding

(a) Velocity Compounding



N - Nozzle

M - Moving blade

F = Fixed (or) guide blade.

(5) Fig shows rings of fixed nozzles incorporated between the rings of moving blades. The steam at boiler pressure enters the first set of nozzles and expands partially. The kinetic energy of steam thus obtained is absorbed by the moving blades (stage 1). The steam then expands partially in second set of nozzles where its pressure again falls and velocity increases; the kinetic energy so obtained is absorbed by the second ring of moving blades (stage 2). This is repeated in stage 3 and steam finally leaves the turbine at low velocity and pressure. The number of stages, depends on number of rows of nozzles through which steam must pass.

This method of compounding is used in Rateau and Zoelly turbine. This is most efficient turbine, since speed ratio remains constant but it is expensive owing to a large number of stages.

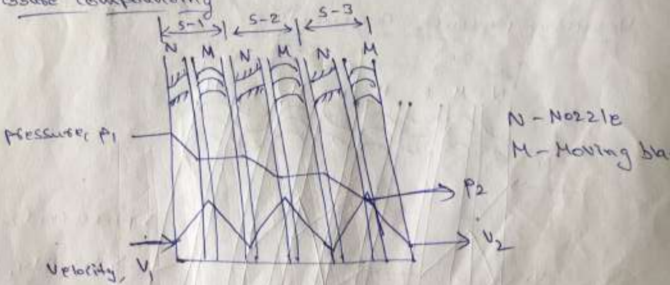
Velocity - pressure Compounding

(7)

(6) Steam is expanded through a stationary nozzle from boiler pressure to condenser pressure. So the pressure drops in nozzle, the kinetic energy of steam increases. A portion of this available energy is absorbed by a row of moving blades. The steam (whose velocity has decreased while moving over moving blades) 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 and steam leaves the turbine with a low velocity. Above fig despits changes in pressure and velocity as steam passes through nozzle, fixed and moving blades.

Though this method has advantage that the initial cost is low due to lesser number of stages, but its efficeincy is low.

Pressure Compounding



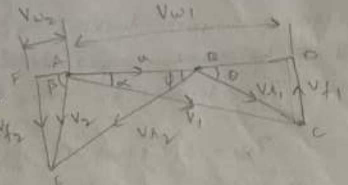
⑦

Experience

⑥ The speed of turbine may be reduced by splitting up the available energy by arranging two or more simply velocity-compounded turbines in series on the same shaft. The total drop in steam pressure is divided into stages ~~and~~ (i.e two or more stages). and 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 each stage. In this method, less stages are required for given pressure drop. But due to low efficiency, it is not widely used in power generation.

(7)

Expression for optimum value of Ratio of blade speed to steam speed (for max efficiency) for single stage Impulse turbine.



$$V_w = V_{r_1}\cos\theta + V_{r_2}\cos\phi$$

$$\Rightarrow V_{r_1}\cos\theta\left[1 + \frac{V_{r_2}\cos\phi}{V_{r_1}\cos\theta}\right]$$

$$\Rightarrow V_{r_1}\cos\theta\,(1 + kz)$$

For impulse turbine, $\quad z = \frac{\cos\phi}{\cos\theta}$

$$\theta = \phi \qquad z = 1$$

$$V_{r_1}\cos\theta = V_1\cos\alpha - u$$

$$V_w = (V_1\cos\alpha - u)(1 + kz)$$

w.k.T $= \eta_b = \dfrac{(V_{w_1} \pm V_{w_2})\,2u}{V_1^2}$

$$\Rightarrow \frac{V_w \cdot 2u}{V_1^2}$$

$$\Rightarrow \frac{2u\,(V_1\cos\alpha - u)(1 + kz)}{V_1^2}$$

$$\Rightarrow \frac{2(V_1 u\cos\alpha - u^2)(1 + kz)}{V_1^2}$$

$$\Rightarrow 2(s\cos\alpha - s^2)(1 + kz)$$

$$\Rightarrow 2s(\cos\alpha - s)(1 + kz)$$

Blade speed ratio, $s = \dfrac{u}{V_1} = \dfrac{\text{Blade speed}}{\text{steam speed}}$

$s = 0.6192$ (or) 0.3208

(8)

For particular impulse turbine α, K and Z may assumed to be constant and from equation it is seen that η_{bl} depends on value of ρ only.

$$\eta_{bl} = 2(\rho\cos\alpha - \rho^2)(1+KZ) \quad -(i)$$

Hence differentiating w.r.t ρ & equate to zero for maximum value.

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

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

$$\cos\alpha = 2\rho$$

$$\rho = \frac{\cos\alpha}{2}$$

optimum value of ratio of blade speed to steam speed is

$$\boxed{\rho_{opt} = \frac{\cos\alpha}{2}} \quad -(ii)$$

Substituting eq (ii) in eq (i)

$$\eta_{bl} = 2\rho(\cos\alpha - \rho)(1+KZ)$$

$$(\eta_{bl})_{max} = 2 \times \frac{\cos\alpha}{2}\left(\cos\alpha - \frac{\cos\alpha}{2}\right)(1+KZ)$$

$$\Rightarrow \cos\alpha \cdot \frac{\cos\alpha}{2}(1+KZ)$$

$$\boxed{\eta_{bl_{max}} \rightarrow \frac{\cos^2\alpha}{2}(1+KZ)}$$

(8) Assume symmetrical blades ($\theta = \phi$) and no friction in fluid passage

$$z = 1, \quad k = 1$$

$$(\eta_{bl})_{max} = \cos^2\alpha$$

From eq (ii) it is obvious that blade velocity should be approximately half of absolute velocity of steam jet coming out from the nozzle for maximum work developed per kg of steam or for maximum efficiency. For other values of blade speed the absolute velocity at outlet from the blade will increase, hence more energy will be carried away by steam and efficiency will decrease.

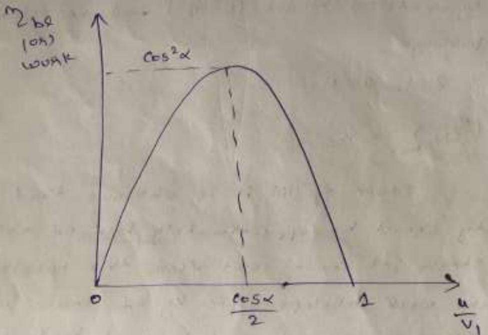
The variations of η_{bl} or work developed per kg of steam with $\frac{u}{V_1}$. This fig shows that

(a) when $\frac{u}{V_1} = 0$, the work done becomes zero as the distance travelled by the blade (u) is zero.

(b) Maximum efficiency is $\cos^2\alpha$ and maximum work done per kg of steam is $2u^2$, when

$$\frac{u}{V_1} = \frac{\cos\alpha}{2}$$

(c) when $\frac{u}{V_1} = 1$, the work done is zero as the torque acting on the blade becomes zero.



workdone per kg of steam is given by

$$W = m(V_{w_1} + V_{w_2})u$$

$$V_w = V_{w_1} + V_{w_2}$$

$$W = V_w \cdot u = (V_1\cos\alpha - u)(1 + kz) \cdot u$$

$\Rightarrow$ when $k = 1$, $z = 1$

$$\Rightarrow 2u(V_1\cos\alpha - u)$$

$$\rho = \frac{\cos\alpha}{2}$$

~~$W_{max} = 2u(V_1$~~

$$\cos\alpha = 2\rho$$

$$\cos\alpha = 2 \cdot \frac{u}{V_1}$$

$$W_{max} = 2u\left(V_1\, 2 \cdot \frac{u}{V_1} - u\right)$$

$$\Rightarrow 2u(2u - u)$$

$$\Rightarrow 2u(u)$$

$$\Rightarrow 2u^2(2-1)$$

$$\boxed{W_{max} \Rightarrow 2u^2}$$

15A] (9)

$\theta = \phi$

$\alpha = 20^\circ$

$$k = \frac{V_{R_2}}{V_{R_1}} = 0.83$$

Actual blade efficiency = 90% of maximum blade efficiency.

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

Maximum blade efficiency

$$(\eta_{bl})_{max} = \frac{\cos^2\alpha}{2}(1+kz)$$

$$\Rightarrow \frac{\cos^2\alpha}{2}(1+k) \qquad z = \frac{\cos\phi}{\cos\theta} = 1$$

$k = 0.83$

$$(\eta_{bl})_{max} = \frac{\cos^2 20^\circ}{2}(1+0.83) \times 100$$

$$= 80.79\%$$

Actual efficiency of turbine

$$\eta_{bl} = 0.9 \times 80.79 = 72.71\%$$

Blade efficiency of a single stage impulse turbine is given by relation

$$\eta_{bl} = 2(\rho\cos\alpha - \rho^2)(1+k)$$

$$0.727 = 2(\rho \times \cos 20^\circ - \rho^2)(1+0.83)$$

$$0.727 = 2 \times 1.83(0.94\rho - \rho^2)$$

$$0.19863 = 0.94\rho - \rho^2$$

$$\rho^2 - 0.94\rho + 0.19863 = 0$$

$$\rho = \frac{0.94 \pm \sqrt{(0.94)^2 - 4 \times 0.19863}}{2}$$

$$\rho \Rightarrow \frac{0.94 \pm 0.2984}{2}$$

$\Rightarrow$ Hence possible ratio is $\rho = 0.6192$ (or) 0.3208

16A]

$V_1 = 300\ m/s$ Scale: 1 cm = 50 m/s

$\alpha = 25°$

$D = 100\ cm = 1\ m$

$N = 2000\ rpm$

Axial thrust, $F_a = m(V_{f_1} - V_{f_2}) = 0$

$(V_{f_1} = V_{f_2})$

To find:

$\theta = ?$

$\phi = ?$

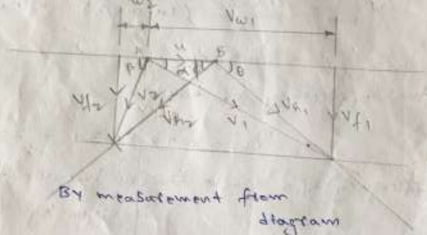
$P = ?$

$m = 600\ \frac{kg}{min}$

$k = 0.9 = \frac{V_{R_2}}{V_{R_1}}$

Blade speed, $u = \frac{\pi D N}{60} = \frac{\pi \times 1 \times 2000}{60}$

$\Rightarrow 104.71\ m/s$



$V_{R_1} = 215\ m/s$

$V_{R_2} = 193.5\ m/s$

By measurement from diagram

$\theta = 37°$

$\phi = 43°$

Power developed, $P = \frac{m(V_{w_1} + V_{w_2})u}{1000}\ kW$

$= \frac{600 \times 310 \times 104.71}{60 \times 1000}\ kW$

$\Rightarrow 324.601\ kW$

9A] (10)

$V_1 = 840$ m/s

$\alpha = 18°$

$\theta = \phi = 29°$

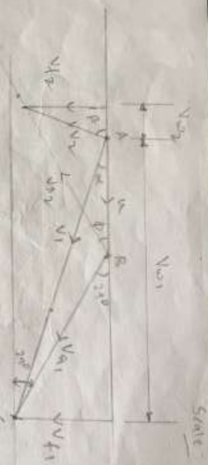
$K = 0.9 = \frac{V_{R_2}}{V_{R_1}}$

$P = 300$ kW

To find: (a) $u = ?$

(b) $m = ?$ (kg/hr)

Scale: 1 cm = 100 m/s



$V_{R_1} = 540$ m/s

$V_{R_2} = 486$ m/s

(a) $u = 340$ m/s

(b) $P = \frac{m(V_{w_1} + V_{w_2})u}{1000}$ kW

$300 = \frac{m(880) \times 340}{1000}$

$m = 1$ kg/sec $= 3600$ kg/hr

12 A]

$P = 132.4$ kW

$u = 175$ m/s

$m = 2$ kg/sec

$V_1 = 400$ m/s

$k = \frac{V_{R2}}{V_{R1}} = 0.9$

Scale: 1 cm = 50 m/s

[Discharge is axial $\beta = 90^\circ$, $V_{w2} = 0$]

To find:

$\alpha = ?$

$\theta = ?$

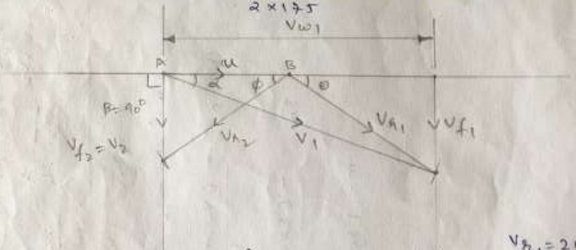
$\phi = ?$

Power developed

$$P = \frac{m(V_{w1} + V_{w2})u}{1000} \text{ kW}$$

$$132.4 = \frac{2(V_{w1} + V_{w2})175}{1000}$$

$$V_{w1} + V_{w2} = \frac{132.4 \times 1000}{2 \times 175} \Rightarrow 378.28 \text{ m/s}$$



From diagram, (by measurement)

$V_{R1} = 240$ m/s

$V_{R2} = 216$ m/s

$\alpha = 21^\circ$

$\theta = 36^\circ$

$\phi = 32^\circ$

7A) (ii)

$\alpha = 20^\circ$

$V_1 = 670$ m/s

$\theta = 35^\circ$

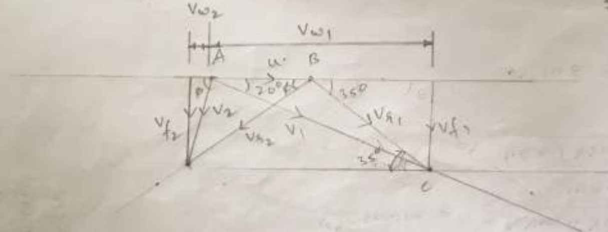
$\theta = \phi = 35^\circ$

To find:

$u = ?$

$\eta_b = ?$

Scale, 1cm = 100 m/s



(a) $u = 280$ m/s

(b) Diagram efficiency

$$\eta_b = \left[\frac{(V_{w_1} + V_{w_2}) \cdot 2u}{V_1^2}\right] \times 100$$

$$\Rightarrow \left[\frac{680 \times 2 \times 280}{(670)^2}\right] \times 100$$

$\Rightarrow 84.8\%$

14A

1. 2A)

$\alpha = 20°$

$V_1 = 450$ m/s

$\phi = 20°$

$V_{r_2} = V_{r_1}$

$u = 180$ m/s

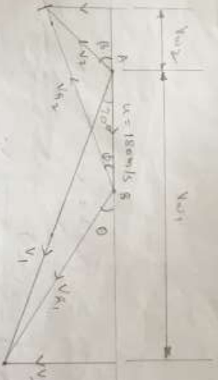
$m = 1.6$ kg/s

To find:

(a) θ

(b) w.D/kg

(c) power



(a) $\theta = 32°$

(b) $\text{W.D/kg} = \dfrac{m(V_{w_1} + V_{w_2})u}{1000}$ kJ/kg

$\Rightarrow \dfrac{1 \times (420 + 95) \times 180}{1000}$ kJ/kg

$\Rightarrow 92.7$ kJ/kg

(c) $\text{Power} = \dfrac{m(V_{w_1} + V_{w_2})u}{1000}$ kW

$\Rightarrow \dfrac{1.6 \times (420 + 95) \times 180}{1000}$

$\Rightarrow 148.32$ kW

1. Steam with a velocity of 600 m/s enters the row of blade (12) of an impulse turbine. The blade angle at entry is 25°. The mean blade speed is 250 m/s. The exit angle of blade is 30°. There is 10% loss in relative velocity due to friction in the blades. Determine.

(a) Nozzle angle (b) work done per kg of steam

(c) Diagram efficiency (d) Axial thrust per kg of steam.

Ans:

$V_1 = 600$ m/s

$\theta = 25^\circ$

$u = 250$ m/s

$\phi = 30^\circ$

$k = \frac{V_{R_2}}{V_{R_1}} = 0.9$

Scale : 1 cm = 100 m/s

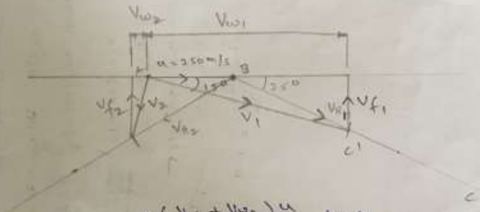
$\alpha = 15^0$

$V_{r_1} = 3.7 cm \times 100$

$\Rightarrow 370$ m/s

$V_{r_2} = 0.9 \times 370$

$\Rightarrow 333$ m/s



(a) w.d /kg = $\dfrac{m(V_{w_1} + V_{w_2})u}{1000}$ kJ/kg

$\Rightarrow \dfrac{1 \times (570 + 50) \times 250}{1000} = 155$ kJ/kg

(b) Diagram efficiency $= (\eta_b) = \dfrac{(V_{w_1} + V_{w_2})2u}{V_1^2}$

$\Rightarrow \left[\dfrac{620 \times 2 \times 250}{600^2}\right] \times 100 = 86\%$

(c) Axial thrust per kg of steam

$F_a = m(V_{f_2} - V_{f_1}) = 1 \times (20) = 20$ N

14A] (13)

$V_1 = 450$ m/s

$\alpha = 15°$

$\phi = 30°$

$\phi' = 30°$

$\alpha' = 20°$

$K = 0.9 = \frac{V_{r_2}}{V_{r_1}}$

$\frac{V_1'}{V_2} = 0.9$,

$\frac{V_{r_2}'}{V_{r_1}'} = 0.9$

$\alpha_1 \quad \theta_1 \quad \phi_2 \quad \alpha_1' \quad \theta_1' \quad \phi_2'$

Nozzle $\rightarrow$ M.B $\rightarrow$ F.B $\rightarrow$ M.B $\rightarrow$

V_1 V_2 10% V_1' 10% 10% V_2'

To find

a) $u = ?$

b) $\eta_{be} = ?$

c) $m_s = ?$

Measure V_1 from inlet velocity triangle

$V_1 = 13.5$ cm $= 450$ m/s

Scale is now calculated as

Scale, 1 cm $= \frac{450}{13.5} = 33.3$ m/s

(a) Blade velocity (u)

$u = 3 \times 33.3 = 100$ m/s

(b) Blade efficiency (η_{be})

$$\eta_{be} = \frac{\text{Rotor output}}{\text{K.E supplied to blade}} \times 100$$

$$\Rightarrow \frac{\dot{m}(V_{w_1} \pm V_{w_2})u}{\frac{1}{2}\dot{m}V_1^2} = \frac{2u(V_{w_1} + V_{w_2})}{V_1^2}$$

$$\eta_{be} = \frac{2u(V_{w_1} + V_{w_2} + V_w')}{V_1^2} \times 100$$

$$\Rightarrow \frac{2 \times 100\left((12.9 \times 33.3) + (5.3 \times 33.3) + (6 \times 33.3)\right)}{(450)^2} \times 100$$

$\Rightarrow 79.6\%$

(c) Specific steam consumption, m_s

$$m_s = \frac{3600}{(V_w + V_w')u} \text{ kg/wh}$$

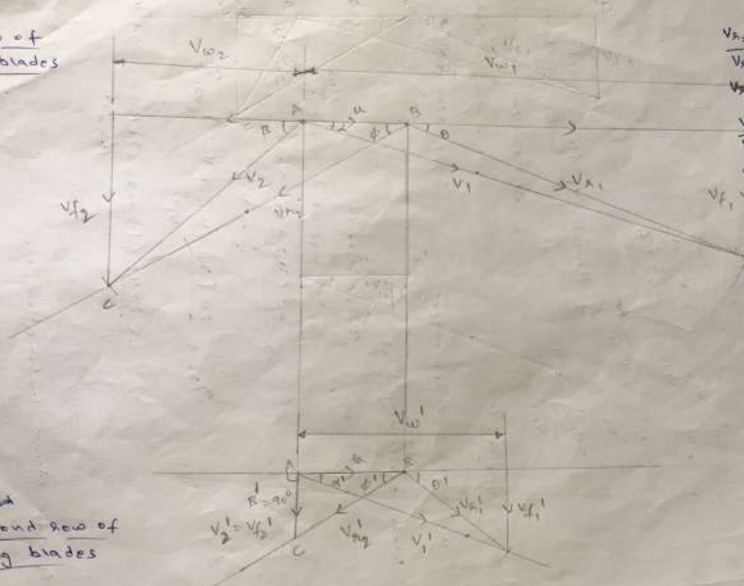
$V_w = V_{w_1} + V_{w_2}$

$$\Rightarrow \frac{3600 \times 1000}{(V_w + V_w')u} = \_\_\_\_ \text{ kg/kwh}$$

Assume, $u = 3\ cm$

$1\ cm = 50\ m/s$

First Row of moving blades



Second Row of moving blades

$$\frac{V_{r_2}}{V_{r_1}} = 0.9$$

$$V_{r_2} = 5.5\ cm$$

$$\frac{V_1'}{V_2} = 0.9$$

$$V_1' = 0.9 \times 3.2 = 2.88\ cm$$

$$\frac{V_{r_2}'}{V_{r_1}'} = 0.9$$

$$V_{r_1}' = \frac{3.5}{0.9} \Rightarrow 3.88\ cm$$

$$V_2 = \frac{6.4}{0.9} \Rightarrow 7.11\ cm$$

$$V_{r_1} = \frac{9.6}{0.9} \Rightarrow 10.66\ cm$$

Unit - IV   M

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

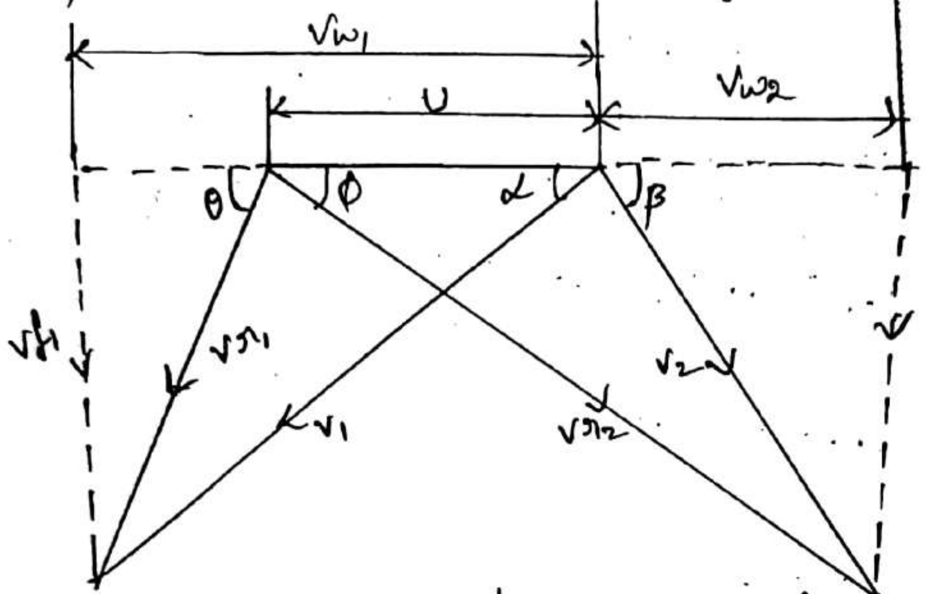
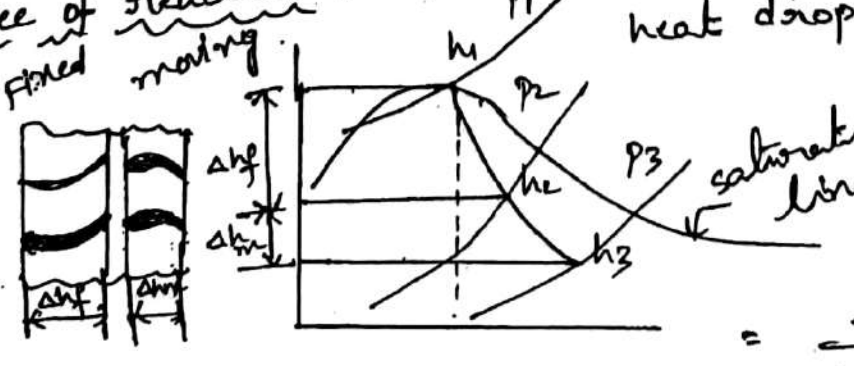


Fig. shows the velocity diagram for reaction turbine blade Incase of an impulse turbine blade the relative velocity of steam either remains constant. As the steam glides over the blades or is reduced slightly due to friction. In reaction turbine blades, the steam continuously expands as it flows over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

$V_{r2} > V_{r1}$ 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.

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

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

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

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

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

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

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

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

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

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

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

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 the 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

$$\Delta h_f = \frac{V_1^2 - V_2^2}{2}, \quad \Delta h_m = \frac{V_{r2}^2 - V_{r1}^2}{2}, \quad V_1 = V_{r2}, \quad V_2 = V_{r1}, \quad \Delta h_f = \Delta h_m$$

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

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

$$W = u(V_{w1} + V_{w2}) = u\left[V_1 \cos\alpha + (V_{r2}\cos\phi - u)\right]$$

$\phi = \alpha$, $V_{r2} = V_{r1}$ as per the assumptions

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

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

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

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

" " " moving blade $= \frac{V_{r2}^2 - V_{r1}^2}{2}$

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

$$= \frac{V_1^2}{2} + \frac{V_{r2}^2 - V_{r1}^2}{2}$$

$$V_{r2} = V_1 \Rightarrow \Delta h = \frac{V_1^2}{2} + \frac{V_{r2}^2 - V_{r1}^2}{2}$$

$$= V_1^2 - \frac{V_{r1}^2}{2}$$

But $V_{r1}^2 = V_1^2 + u^2 - 2V_1 \cdot u\cos\alpha$ [from fig of velocity diagram]

substitute the value of V_{r1}^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 efficiency formula

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

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

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

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

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

Stage efficiency :- $\frac{\text{Network done on shaft / stage / kg of steam}}{\text{Adiabatic heat drop / stage}}$

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

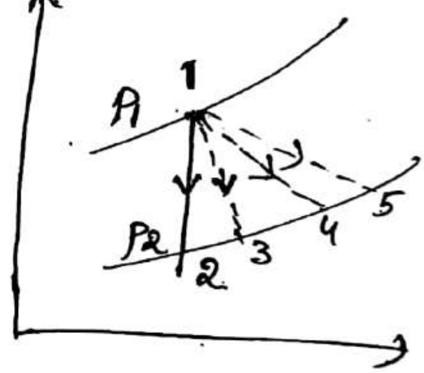
Overall efficiency :- $\frac{\text{work delivered at the turbine coupling}}{\text{Total adiabatic heat drop}}$

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

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.

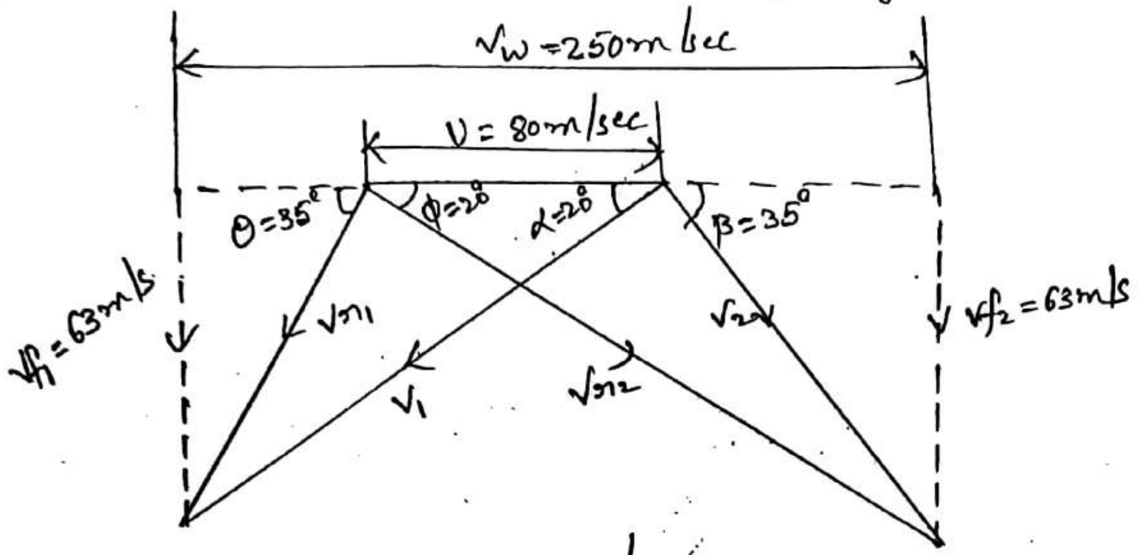
Given :- Inlet blade angle $\theta = 35° = \beta$

outlet " " $\phi = 20° = \alpha$

Blade Speed $(u) = 80 m/s$

mass of steam consumption (m_s) = $\frac{22500}{3600}$

= 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 (η_{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 "

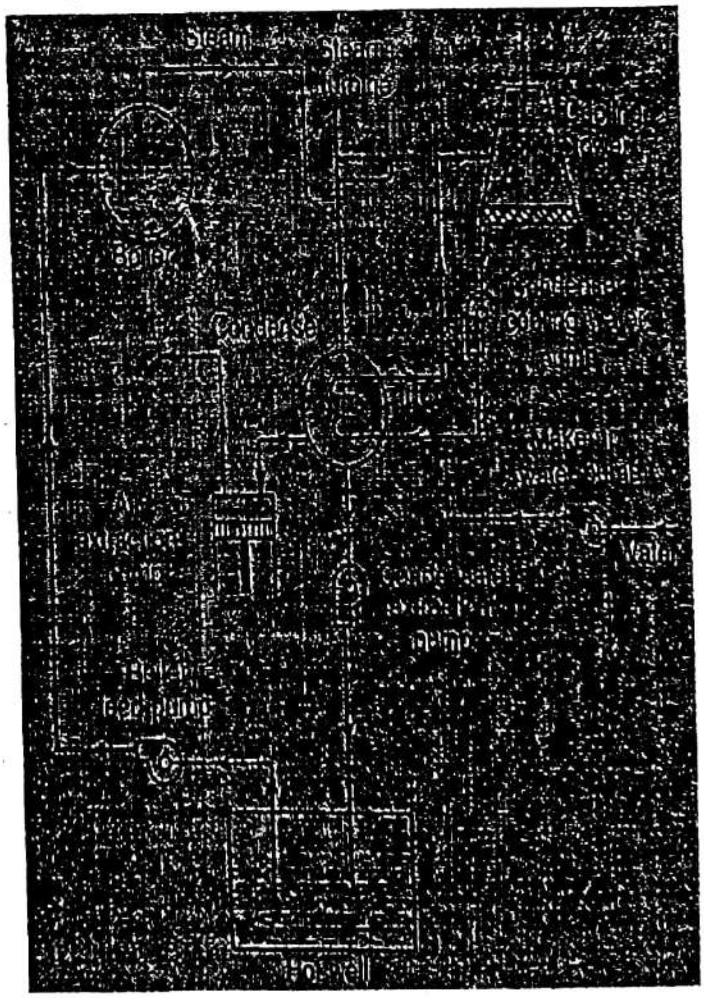
UNIT – 6 *Steam Condensers*

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.



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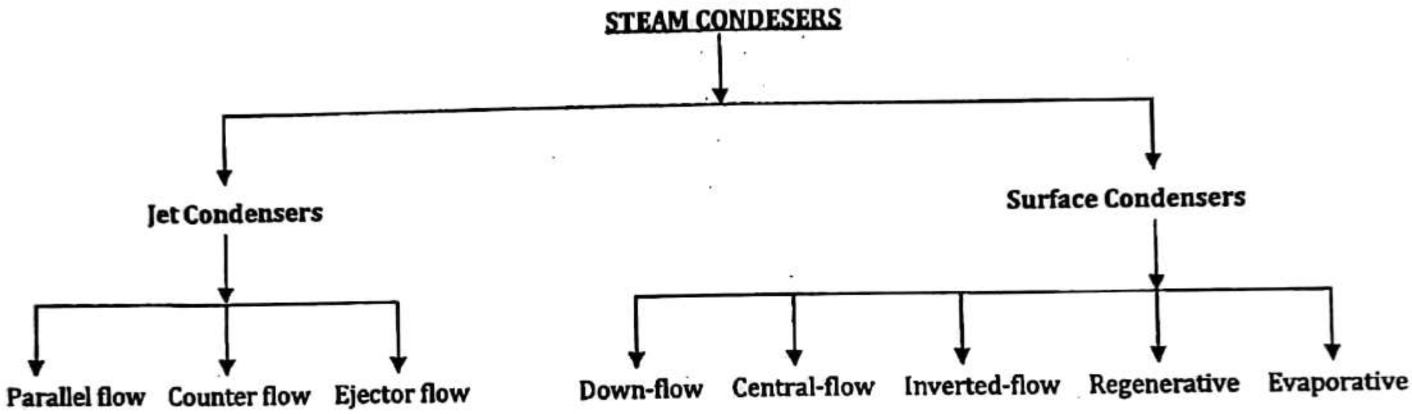
➢ Classification of Condensers

- 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.

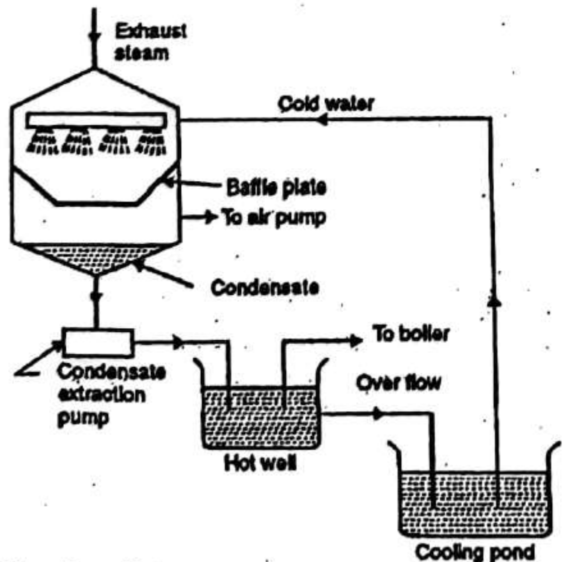


Fig. Parallel flow type condenser

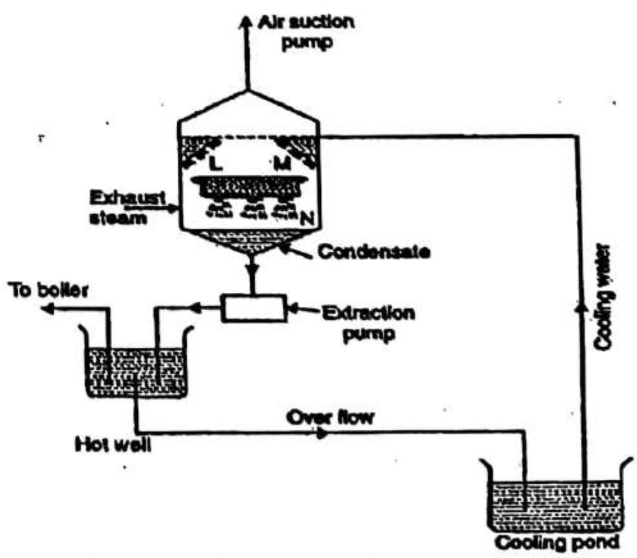


Fig. Low level counter flow type condenser

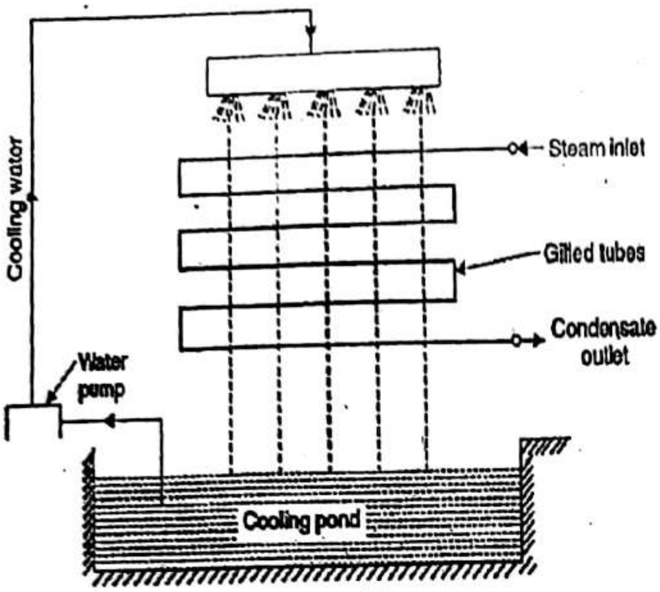


Fig. Evaporative Type

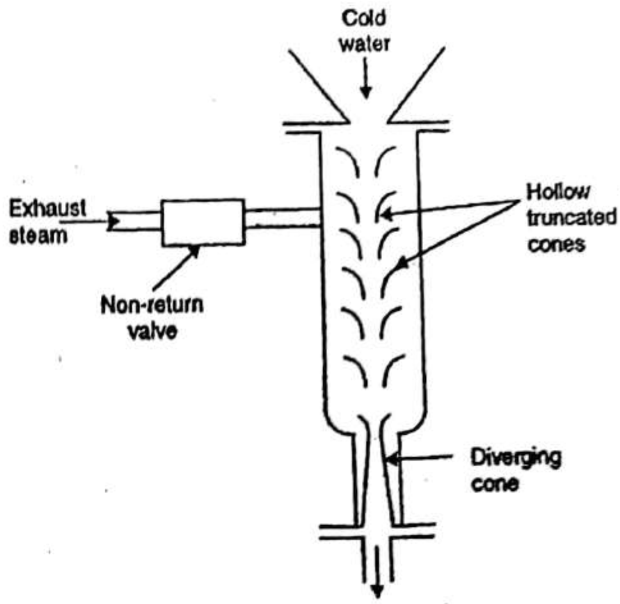


Fig. Ejector flow type condenser

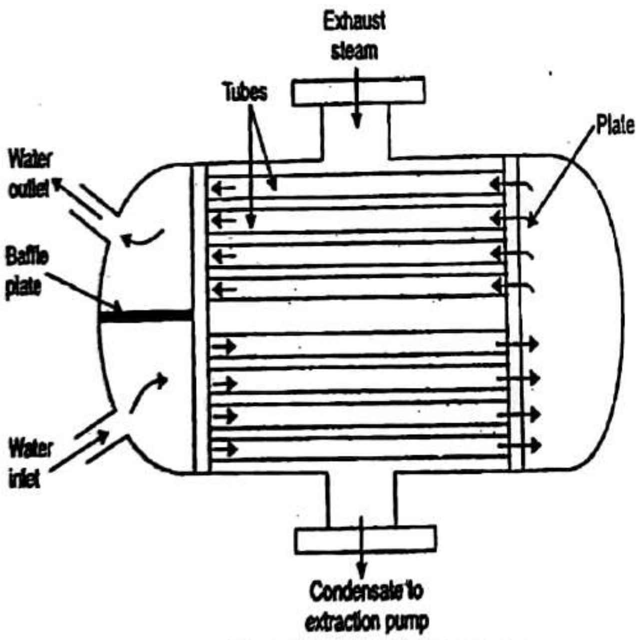


Fig. Down-Flow Type

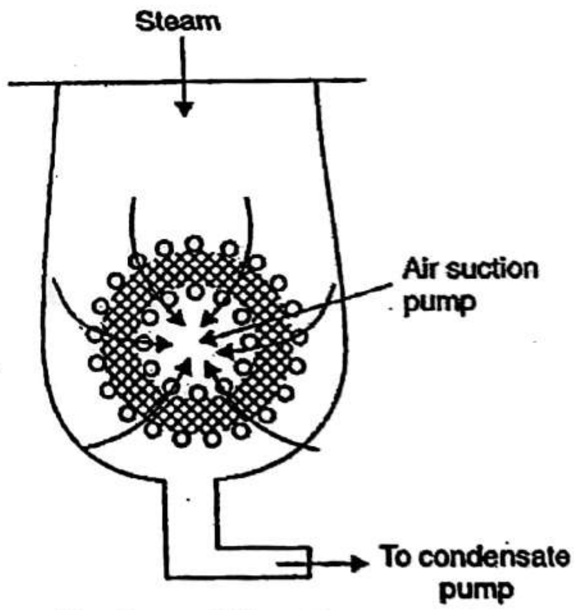


Fig. Central Flow Type

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.

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- **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 $\quad$ ($\because$ 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

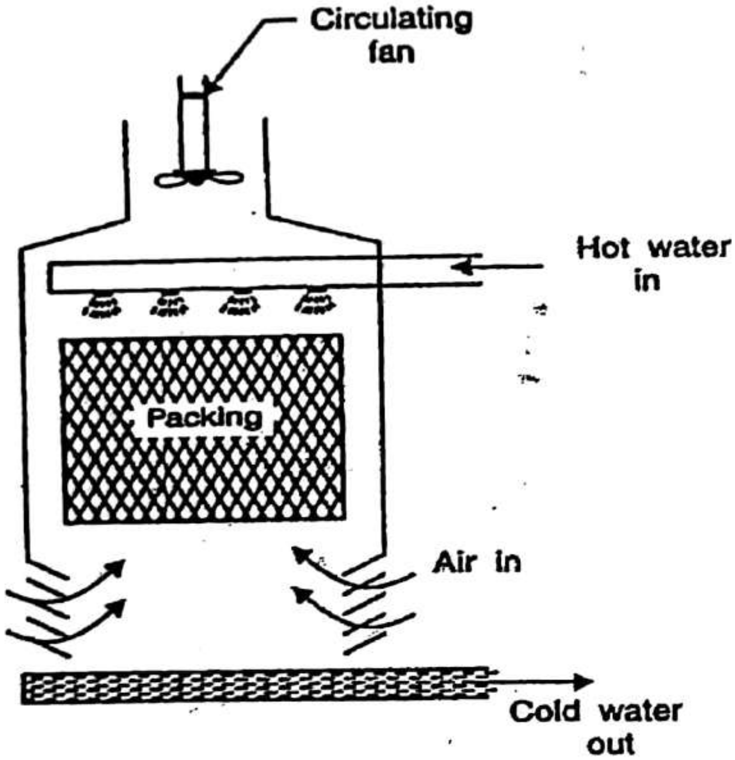


Fig. Natural draught cooling tower

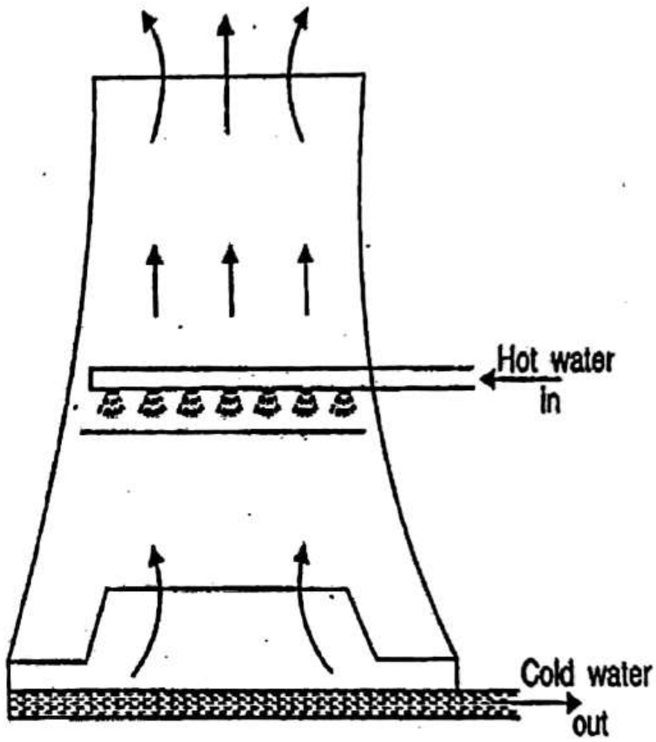


Fig. Forced draught cooling tower

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 = $35^{\circ}C$
condensate temperature = $28^{\circ}C$
condensate collected/hour = 2 tonnes
Quantity of cooling water/hour = 60 tonnes
Temperature of cooling water at inlet = $10^{\circ}C$
" " " outlet = $25^{\circ}C$

Find vaccum corrected to the standard barometer reading, vaccum efficiency, undercooling of the condensate condenser efficiency, Quality of steam entering in the condensor, 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, $T = 35^{\circ}C \Rightarrow 308K$
condenser vaccum = 710 mm of Hg, $t_c = 28^{\circ}C$, $m_s = 2000 kg/h$
$t_i = 10^{\circ}C$, $t_o = 25^{\circ}C$
$m_w = 60,000 kg/h$,

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°,

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

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

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

undercooling the condensate = Mean condenser temp − condensate temp
$= 35 - 28 = 7^{\circ}C$

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

$h = h_{f_1} + x h_{fg}$
$h = 166.7 + x(2407.4)$ 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 70 mm of Hg when barometer reads 760 mm 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)

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

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

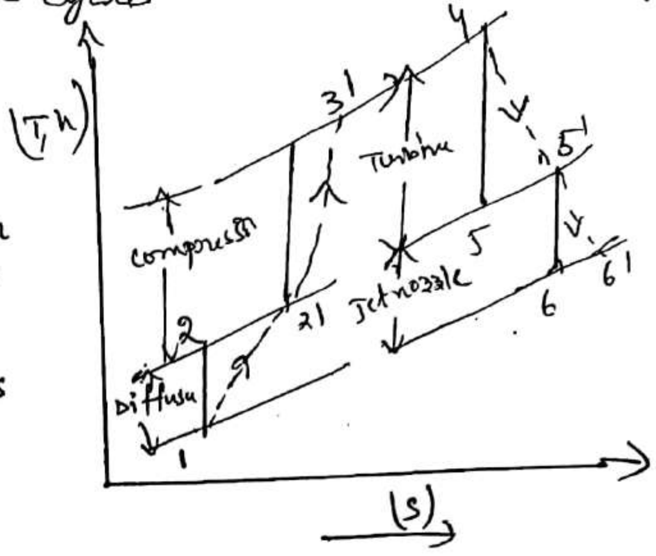
$L = 1.5D \Rightarrow 1.5 \times 0.446 = 0.669m$

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 :- $6'$-$6'$ 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 $C_2 = Q_{1-2} = W_{1-2} = 0$

$h = C_pT$

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

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

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

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

Compressor :- Energy equation between states 2 and 3 gives

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

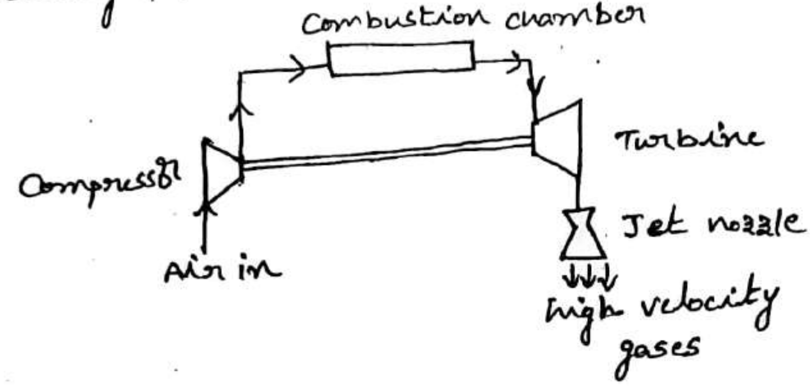
change in P.E and K.E negligable

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

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.

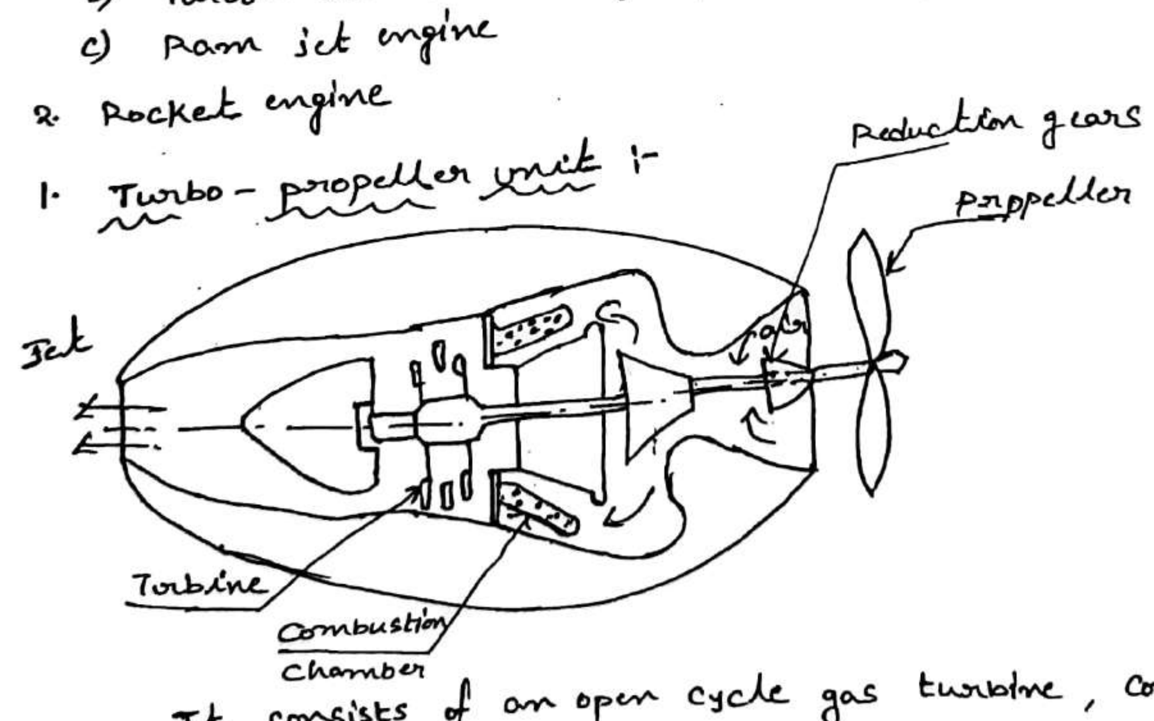


Types of Jet propulsion units :-

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

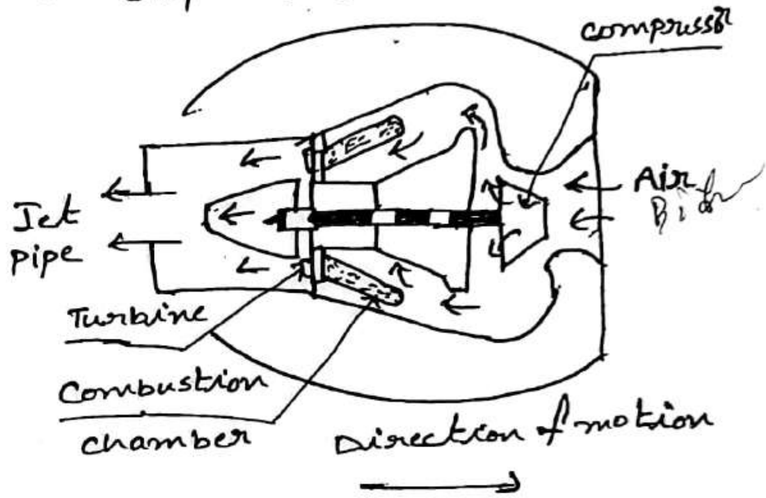
1. Turbo - propeller unit :-



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.

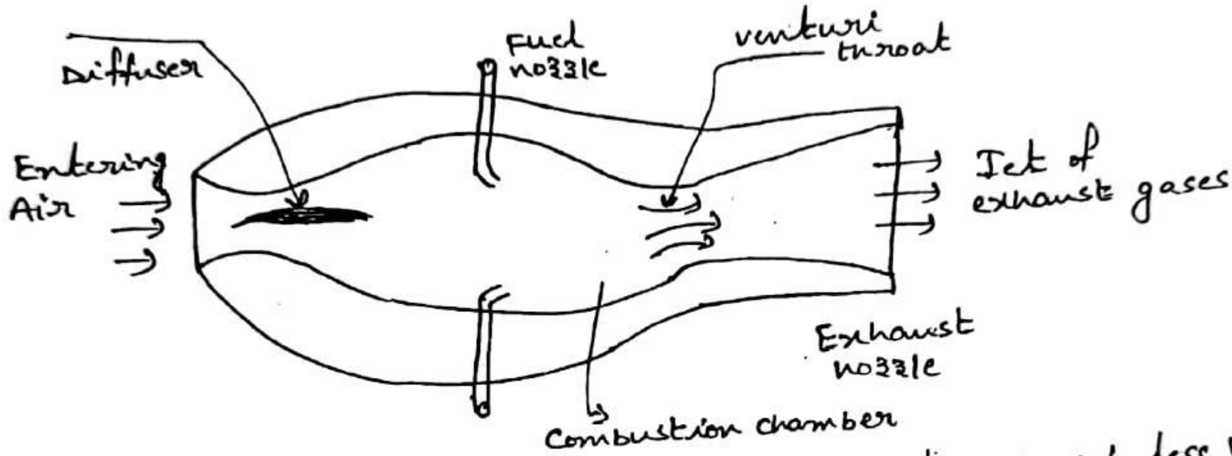
Turbo - Jet unit :- It consists of a open cycle gas turbine with a diffuser infront of the compressor and an exit nozzle added to the turbine end.



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.

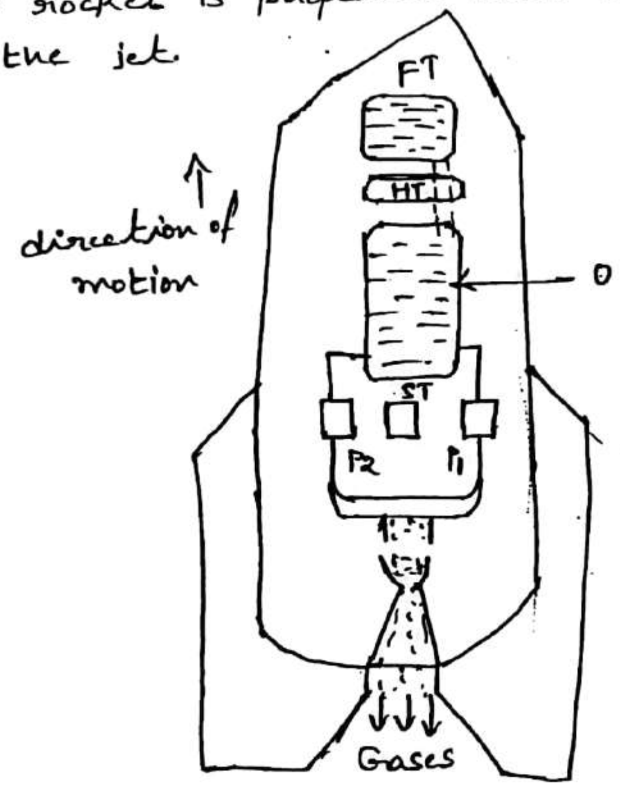
The velocity of air entering the diffuser is decreased and is acompained by an increase in pressure. This pressure rise due to decrease in velocity of incoming air is known as ram effect. The air at high pressure is passed into combustion chamber by fuel nozzle. The mixture is ignited by a spark plug. 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.

<u>Rocket engines</u> :- 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 P_2) 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
P_1, P_2 = 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

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

$$\text{Actual work} = C_p (T_4 - T_5')$$

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

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 C_a. It is called velocity of approach of air.

C_j = 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/1kg 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 C_a 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/1kg of air mass of fuel is neglected

$$= \frac{(C_j - C_a) C_a}{1000} \text{ kW/kg of air}$$

propulsive power:- The energy required 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 :- $\dfrac{\text{propulsive work}}{\text{Heat released by the combustion of fuel}}$

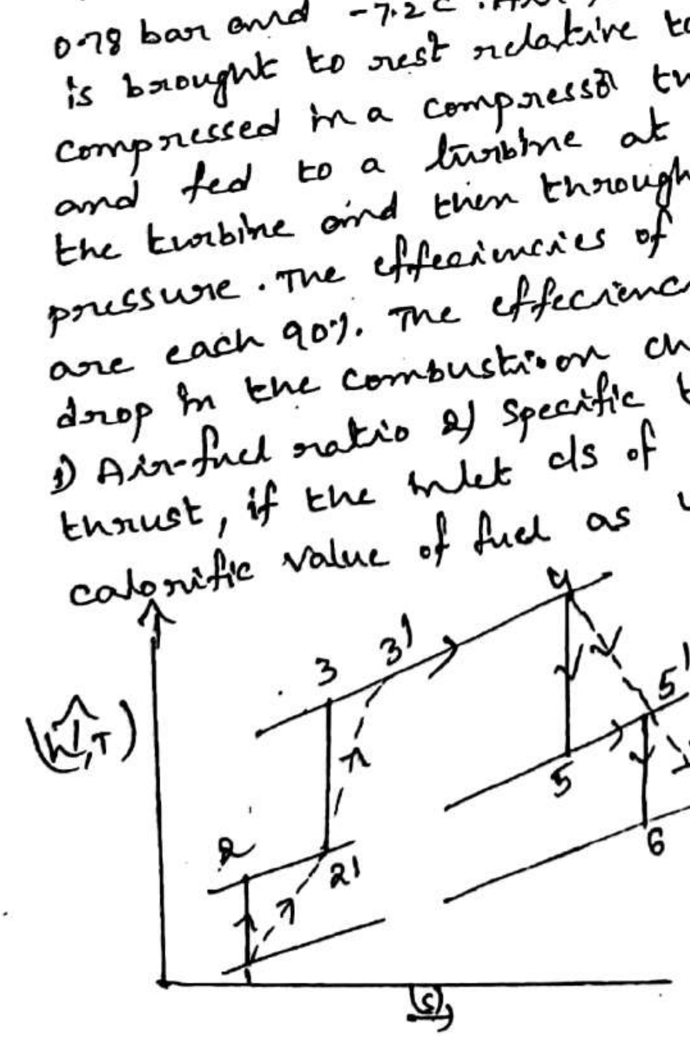
$$= \frac{\left(1+\frac{m_f}{m_a}\right) c_j^2 - c_a^2}{2\left(\frac{m_f}{m_a}\right) CV}$$

$$= \frac{c_j^2 - c_a^2}{2\left(\frac{m_f}{m_a}\right) CV}$$

Overall efficiency :- $\eta_{th} \times \eta_{prop} = \dfrac{c_j^2 - c_a^2}{2\left(\frac{m_f}{m_a}\right) CV} \times \dfrac{2c_a}{c_j + c_a}$

$$= \frac{(c_j - c_a)\, c_a}{\left(\frac{m_f}{m_a}\right) CV}$$

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 1110°C. 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 0.12m² assume calorific value of fuel as 44150 kJ/kg of fuel



Speed of air craft $(c_a) = 216$ 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:-

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

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

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

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

$T_2 = 289K$

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

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

$T_2' = 291.6K$

$\Rightarrow \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

$P_2 = (P_1) \times \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$

$P_2 = 1.044$ bar

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

$T_3 = 291.6 \times 1.662 = 484.7K$

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

$T_3' = 502.8K$

Heat supplied:-

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

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

$\frac{m_a}{m_f} = \frac{CV - CpT_4}{Cp(T_4 - T_3')}$

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

$\Rightarrow$ Specific thrust of the unit

$P_4 = P_3 - 0.168 =$

$= 5.8 \times 1.044 - 0.168$

$P_4 = 5.88$ bar

Assume turbine drives compressor only.

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

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

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

$T_5' = 1171.8K$

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

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

$T_5 = 1119K$

$\frac{T_4}{T_5} = \left(\frac{P_4}{P_5}\right)^{\frac{\gamma-1}{\gamma}}$

$P_5 = 2.8$ bar

$$\frac{T_5'}{T_6} = \left(\frac{P_5}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \boxed{P_6 = P_1}$$

$T_6 = 813.75K$

$$\eta_n = \frac{T_5' - T_6'}{T_5' - T_6}$$

$T_6' = 849.5K$

Velocity at the exit of nozzle

$$C_j = 44.72\sqrt{h_5' - h_6'}$$

$$= 44.72\sqrt{c_p(T_5' - T_6')}$$

$= 804.8 m/s$

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

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

$= 821.45$ N/kg of air/sec

Total thrust:-

volume of flowing air

$(V_1) = 0.12 \times 216$

$= 25.92 m^3/s$

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

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

$= 26.5$ kg/s

Total thrust

$= 26.5 \times 821.45$

$= 21768.4 N$

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 enthalaphy 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

$(m_a) = 60.2$ kg/s

Enthalaphy change for nozzle

$\Delta h = 230$ kJ/kg

velocity coefficient $= 0.96$

Air-fuel ratio $= 70:1$

$\eta_{combustion} = 92\%$

Calorific value (CV) $= 42000$ kJ/kg

Aircraft velocity (C_a)

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

$= 277.8 m/sec$

Exit velocity of jet

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

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

$= 651 m/s$

Fuel flow rate

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

$$= \frac{60.2}{70}$$

$= 0.86$ kg/sec

Thrust specific fuel consumption

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

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

Thrust $= m_a(C_j - C_a)$

$= 60.2(651 - 277.8)$

$= 22466.6\,N$

$= \frac{0.86}{22466.6}$

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

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

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

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

$= 18.78\%$

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

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

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

$= 31.39\%$

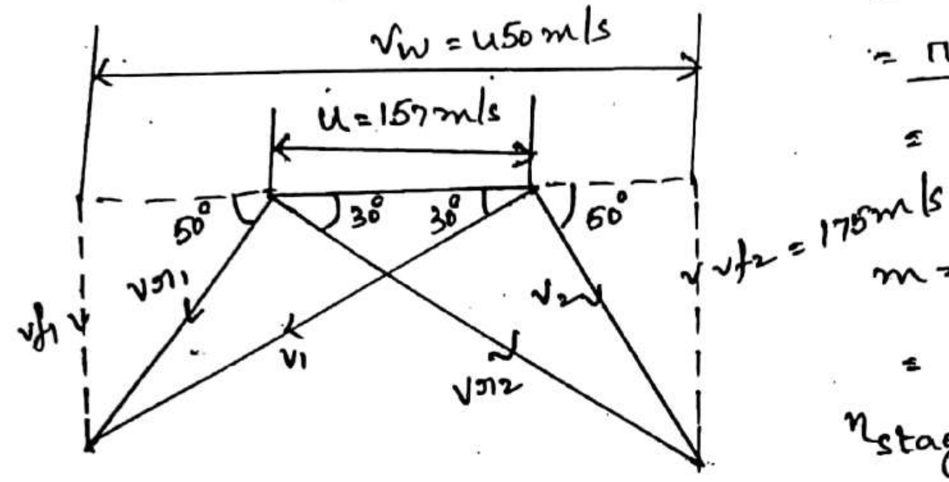
propulsive power:-

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

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

$= 59.8\%$

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 enthalphy drop in a stage.



$u = \frac{\pi D N}{60}$

$= \frac{\pi \times 1 \times 3000}{60}$

$= 157 \text{ m/s}$

$m = \frac{10,000}{60}$

$= 166.67 \text{ kg/s}$

$\eta_{stage} = 0.85$

$V_w = 450 \text{ m/sec}$

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

$= \frac{166.67 \times 450 \times 157}{1000}$

$= 11,775 \text{ kW}$

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

$\Delta h = 83.12 \text{ kJ/kg}$

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.

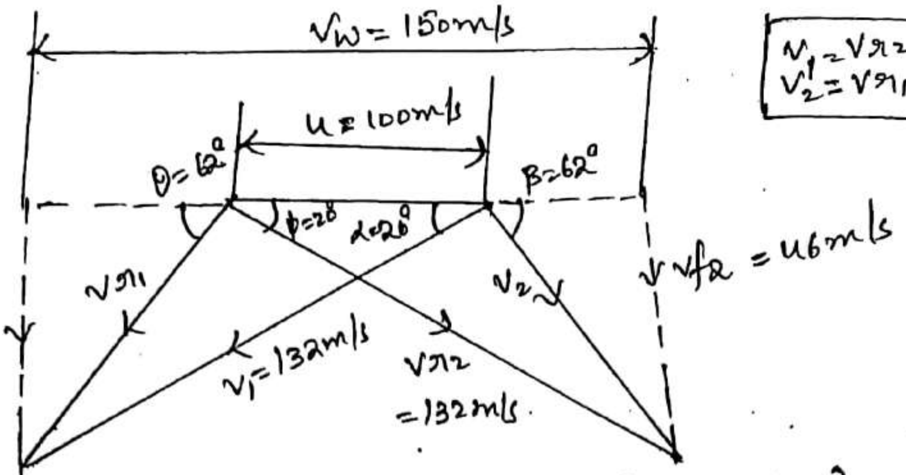
Tangential force = 1200N

Blade speed (u) = 100 m/s

$m = 8 \text{ kg/s}, \quad \phi = 20°$

$F = \frac{m (V_w) u}{u}$

$V_w = \frac{F}{m} \Rightarrow \frac{1200}{8} = 150 \text{ m/s}$



$V_1 = V_{r2}$
$V_2' = V_{r1}$

$$\Delta h_f = \Delta h_m = \frac{V_1^2 - 0.7V_2^2}{2\times 1000} \Rightarrow \frac{132^2 - 0.7(52)^2}{2\times 1000 \times 0.85}$$

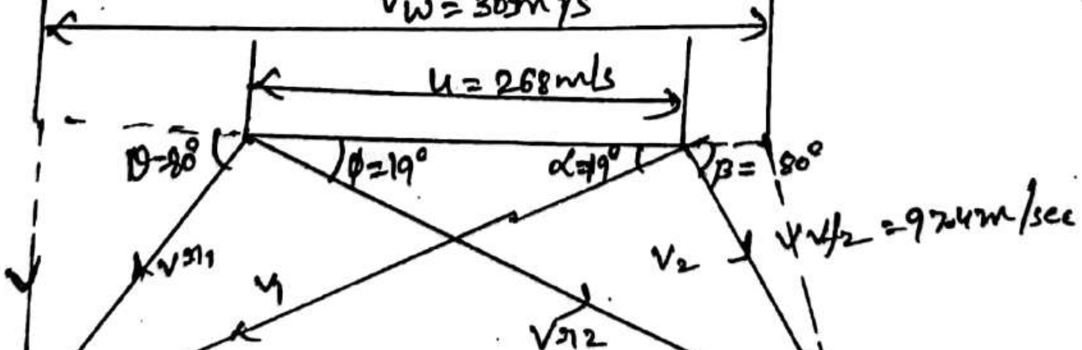
$$= 9.14 \text{ kJ/kg}$$

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.

$\phi = 19°$, $V_2 = 100$ m/s, $\beta = 180 - 100 = 80°$, $m = \frac{15000}{3600} = 4.167$ kg/s

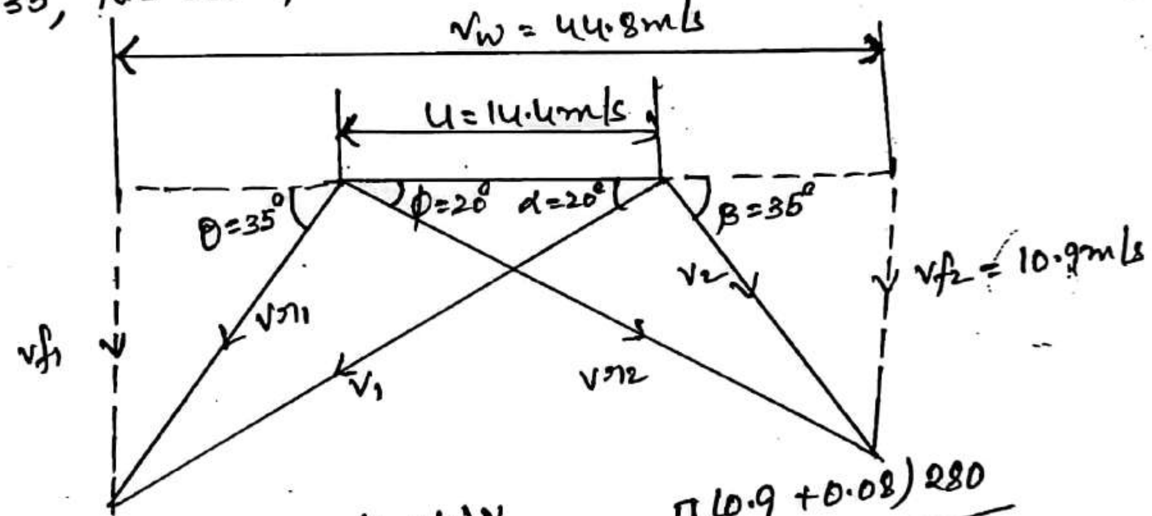


$$P = \frac{m(V_w)u}{1000} = \frac{4.167 \times 303 \times 268}{1000} = 338.4 \text{ kW}$$

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.

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

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



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 $v_g = x v_g \Rightarrow 0.935 \times 1.031$

$= 0.964 \, m^3/kg$

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

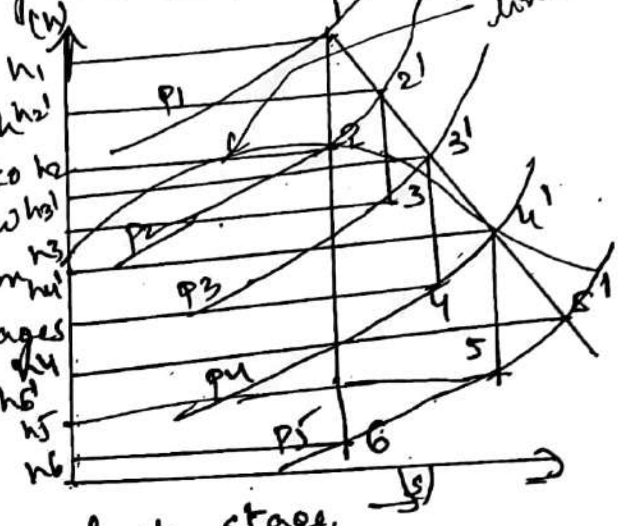
$= \frac{[\pi (0.9+0.08) 0.08] 10.9}{0.964} = 2.78 \, kg/s$

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 multi stage 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.

P_2 = Exit " " " leaving first "

P_3 = " " " " " second "

P_4 = " " " " " third "

P_5 = " " " " " Fourth "

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.

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

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

Gas turbines

Gas turbine is a rotary type of I.C engine. The cyclic events of gas turbine are similar to reciprocating type I.C engine. But each event in gas turbine is carried out in different devices. The simple gas turbine consists of rotary compressor, combustion chamber and turbine unit.

The air is first compressed in a rotary compressor before passing to a combustion chamber where the fuel is injected and ignited. The hot burnt gases expand through the blades of a turbine where the kinetic energy of burnt gases is utilised to produce power. Finally the gases are exhausted from the turbine unit.

Advantages :-

1. Comparatively small weight and size
2. The mechanical efficiency is higher.
3. Torque produced is uniform
4. poor quality of fuels can be used
5. small working pressures are involved.

Limitations :-

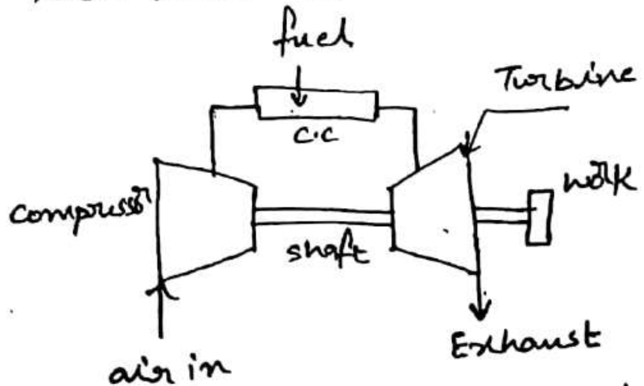
1. part of power produced is utilised for driving the compressor.
2. Not a self-starting unit
3. Relatively low overall efficiency
4. Requires costly reducing gears for normal industrial aplications.

classification of gas turbines:-

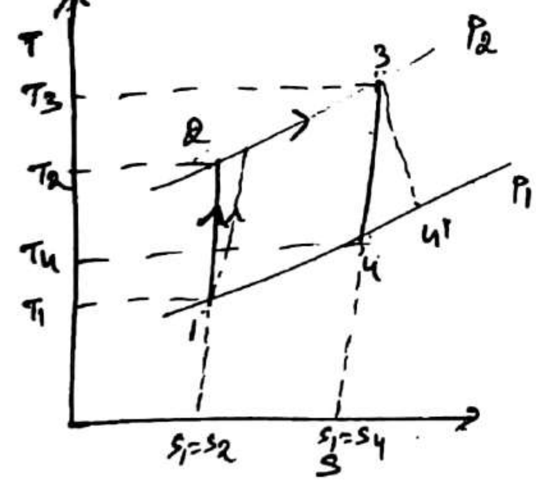
1. According to the path of working fluid
   a) open cycle gas turbine
   b) closed cycle gas turbine
   c) Semi closed cycle gas turbine
2. According to the basis of combustion process
   a) Constant pressure

b) Constant volume

Open cycle gas turbine :- The open cycle gas turbine in which a rotary compressor and a turbine are mounted on a common shaft. Air is drawn into the compressor and after compression passes a combustion chamber. Energy is supplied in the combustion



chamber by spraying fuel into the air stream and resulting hot gases expand through the turbine to the atmosphere. In order to achieve network output from the unit, the turbine must develop more gross work output than is required to drive the compressor and to overcome mechanical losses in drive. The products of combustion coming out from the turbine are exhausted to the atmosphere.



1-2' = Adiabatic compression
2'-3 = constant pressure heat supply
3-4' = Adiabatic expansion
1-2 = Ideal Isentropic Compression
3-4 = Ideal Isentropic expansion.

work input (compressor) $= c_p(T_2' - T_1)$
Heat supplied $= c_p(T_3 - T_2')$
work output (turbine) $= c_p(T_3 - T_4')$

Net work output = work output - work input
$= c_p(T_3 - T_4') - c_p(T_2' - T_1)$

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

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

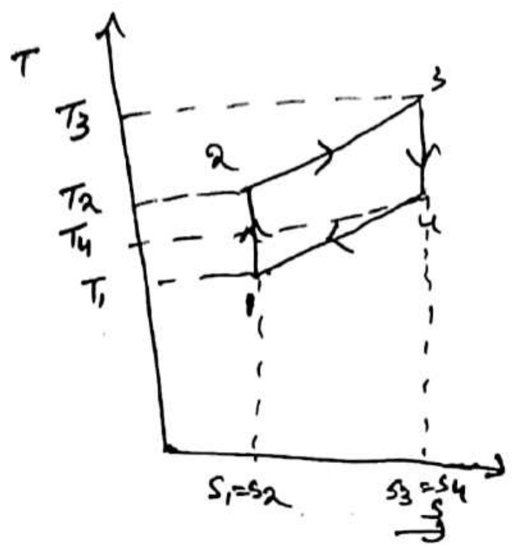
$$\eta_{compressor} = \frac{\text{work input required in Isentropic compression}}{\text{Actual work required.}}$$

$$= \frac{c_p(T_2 - T_1)}{c_p(T_2' - T_1)} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$\eta_{Turbine} = \frac{\text{Actual work output}}{\text{Isentropic work output}}$$

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

1. The simple gas [illegible] has the pressure ratio 6 and the maximum and minimum temperatures of the cycle are 1000K and 288K respectively. Assuming an ideal cycle, calculate the efficiency and specific workout of the plant.



pressure ratio $\frac{P_2}{P_1} = \frac{P_3}{P_4} = 6$

Minimum temperature $(T_1) = 288K$

Maximum temperature $(T_3) = 1000K$

$\gamma = 1.4 \quad C_p = 1.005\ kJ/kg\ K$

$$\eta = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \frac{1}{6^{\frac{1.4-1}{1.4}}} = 0.401$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 6^{\frac{0.4}{1.4}} = 6^{0.2857}$$

$T_2 = (288)(6^{0.2857}) = 480.53K$

Also $\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$, $T_4 = 1000 \times 0.599 = 599K$

Turbine work $= C_p(T_3 - T_4) = 1.005(1000 - 599) = 403\ kJ/kg$

Compressor work $= (W_C) = C_p(T_2 - T_1) = 1.005(480.53 - 288) = 193.49\ kJ/kg$

Specific workoutput $= W_T - W_C = 403 - 193.49 = 209.51\ kJ/kg$

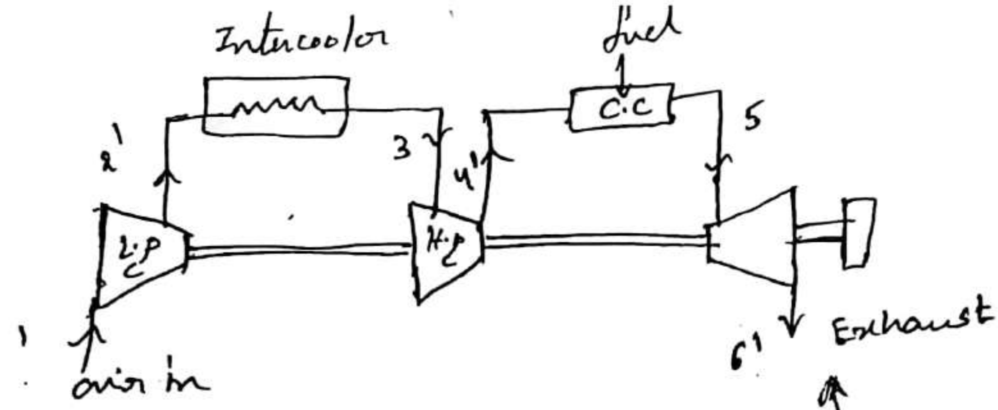
$$\eta = \frac{W}{Q_{sup}} = \frac{209.51}{1.005(1000 - 480.53)} = 0.401 = 40.1\%$$

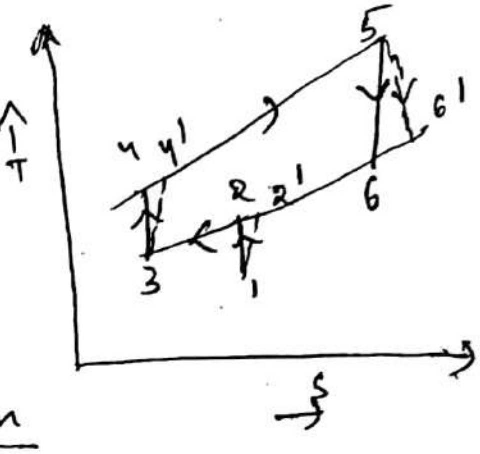
Methods for improvement of thermal efficiency of open cycle gas turbine plant :-

The following methods are employed to increase the specific output and thermal efficiency of plant.

1. **Intercooling** :- A compressor in a gas turbine cycle utilises the major percentage of power developed by the gas turbine. The work required by the compressor can be reduced by compressing the air in two stages and incorporating an intercooler between the two. The actual processes take place as follows.

1-2' = L.P compression, 3-4' = H.P compression, 5-6' = Turbine expansion,
2'-3 = Intercooling, 4'-5 = A.C heating,





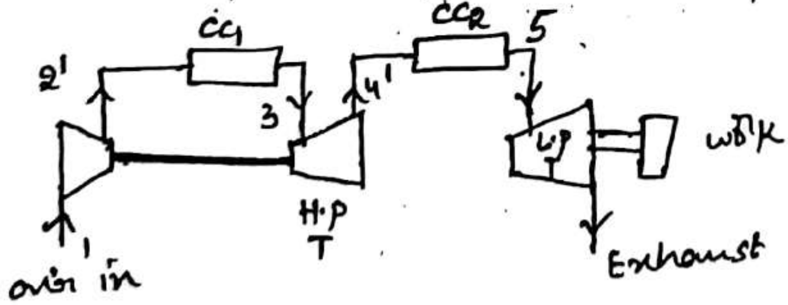
The ideal cycle for this arrangement is 1-2-3-4-5-6

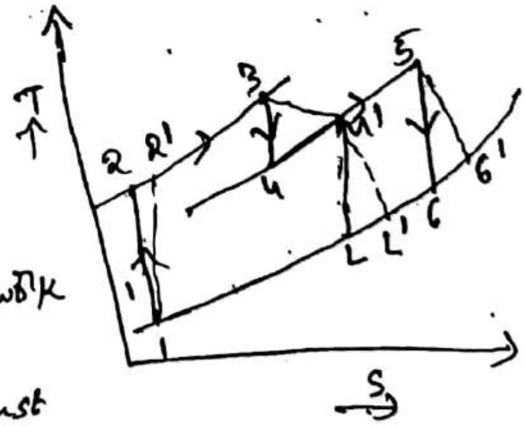
~~now the workoutput (with intercooling)~~

work ratio = $\frac{\text{Net work output}}{\text{Gross work output}}$

$= \frac{\text{work of expansion} - \text{work of compression}}{\text{work of expansion}}$

2. Reheating :- The workoutput of a gas turbine can be amply improved by expanding the gases in two stages with a reheater between the two as shown in fig. The Hp turbine drives the compressor and L.p turbine provides the useful power output





Neglecting mechanical losses the workoutput of the H.p turbine must be exactly equal to the work input required for the compressor.

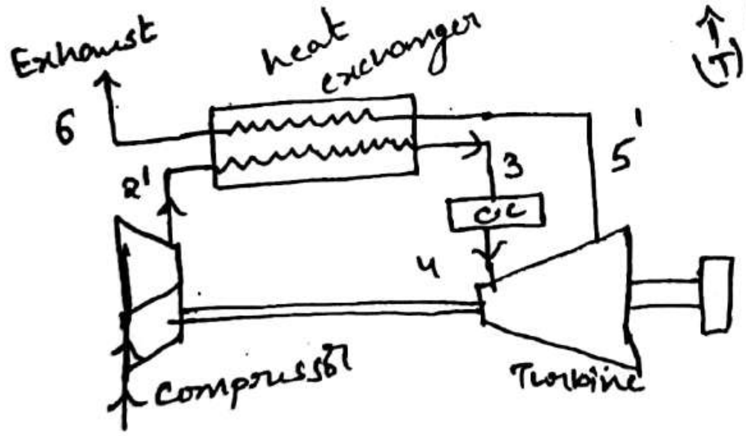
$$c_{pa}(T_2' - T_1) = c_{pg}(T_3 - T_4')$$

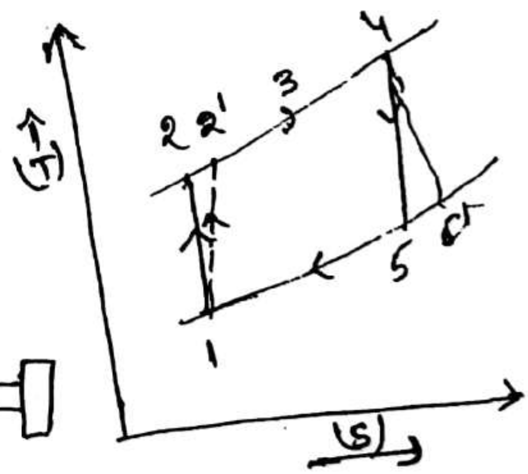
Net workoutput (with reheating) $= c_{pg}(T_5 - T_6')$

" " (without ") $= c_{pg}(T_4' - T_L)$

From the T-s diagram temperature difference $(T_5 - T_6')$ is always greaterthan $(T_4' - T_L)$ so that <u>reheating increases the workoutput.</u> 4.

3. <u>Regeneration</u> :- The exhaust gases from a gas turbine carry a large quantity of heat with them since their temperature is far above the ambient temperature. They can be used to heat the air coming from the compressor thereby reducing the mass of fuel supplied in the combustion chamber. In a figure 2'-3 represents the heat flow into the compressed air during its passage through the heat exchanger and 3-4 represents the heat taken from the combustion of fuel point 6 represents the temperature of exhaust gases at discharge from the heat exchanger. The maximum temperature to which the air could be heated in the heat exchanger is ideally that of exhaust gases.



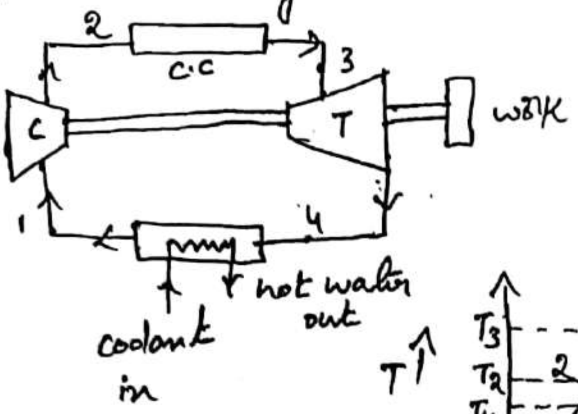


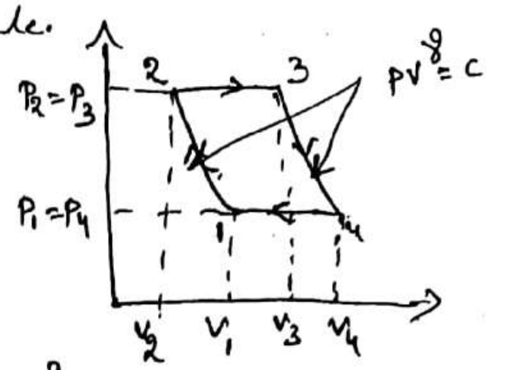
The effectiveness of heat exchanger is given by

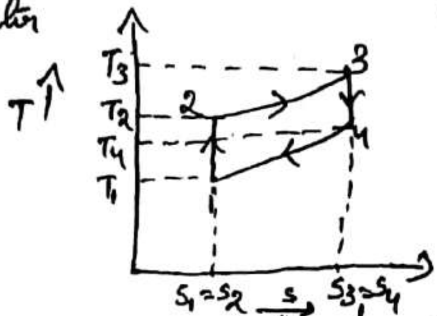
$$= \frac{\text{Increase in enthalpy / kg of air}}{\text{Available increase in enthalpy / kg of air}}$$

$$= \frac{T_3 - T_2'}{T_5' - T_2'}$$

Closed cycle gas turbine :- This cycle operates on a constant pressure cycle in which the closed system consists of air behaving as an ideal cycle.







1-2 :- The air is compressed isentropically from the lower pressure P_1 to upper pressure P_2, the temperature raising from T_1 to T_2. No heat flow occurs.

2-3 :- Heat flow into the system increasing volume from V_2 to V_3 and temperature from T_2 to T_3. whilst the pressure remains constant at P_2. Heat received $= mc_p(T_3 - T_2)$

3-4 :- The air is expanded isentropically from P_2 to P_3. The temperature falling from T_3 to T_4. No heat flow occurs.

4-1 :- Heat is rejected from system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at P_1. Heat rejected $= mc_p(T_4 - T_1)$

$$\eta_{\text{air-standard}} = \frac{\text{work done}}{\text{Heat received}}$$

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

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

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

5.

From 1-2 process:-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \times T_1$$

$P_2 = P_3 = r_p$
$P_1 = P_4 = r_p$

3-4 process:-

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \quad T_3 = T_4\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

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

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

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

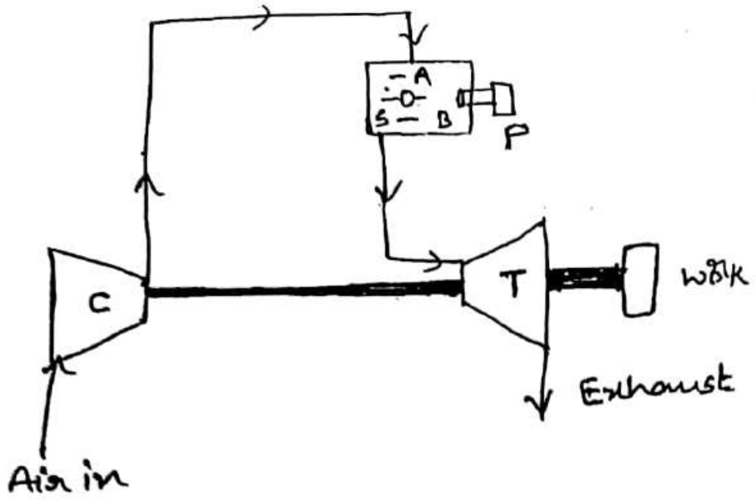
Merits of closed cycle:-

1. Higher thermal efficiency
2. Reduced size
3. No contamination
4. Improved part load efficiency
5. Greater output
6. Inexpensive fuel.

Demerits of closed cycle:-

1. Complexity
2. Dependent system
3. Requires the use of a very large air heater.

Constant volume combustion turbines:- The compressed air from an air compressor C is admitted into the C.C D through the valve A. When valve A is closed, the fuel is admitted into the chamber by means of a fuel pump P. Then the mixture is ignited by means of a spark plug S. The combustion take place at constant volume with increase of pressure. The valve B opens and the hot gases flow to the turbine T and finally they are discharged into atmosphere. The energy of hot gases is thereby converted into mechanical energy. For continuous running of the turbine these operations are repeated.



1. A gas turbine unit received air at 1 bar and 300K and compressess it adiabatically to 6.2 bar. The compressor efficiency is 88%. The fuel has a heating value of 44186 KJ/kg and the fuel air ratio is 0.017 KJ/kg of air. The turbine internal efficiency is 90%. Calculate the work of turbine and compressor / kg of air compressed and thermal efficiency For products of combustion $C_p = 1.147$ KJ/kgK $\gamma = 1.4$

$P_1 = P_4 = 1$ bar, $T_1 = 300$ K $P_2 = P_3 = 6.2$ bar, $\eta_{compressor} = 88\%$
$c = 44186$ KJ/kg, Fuel air ratio $= 0.017$ KJ/kg, $\eta_{turbine} = 90\%$
$C_p = 1.147$ KJ/kgK $\gamma = 1.4$

1-2 process :-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$= 300\left(\frac{6.2}{1}\right)^{\frac{1.4-1}{1.4}}$$

$$= 505.2 \text{ K}$$

$$\eta_{com} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow 0.88 = \frac{505.2 - 300}{T_2' - 300}$$

$$T_2' = 533.2 \text{ K.}$$

$$\text{Heat supplied} = m\left(1 + \frac{m_f}{m_a}\right) c_p \,(T_3 - T_2') = \frac{m_f}{m_a} \times c$$

$$(1 + 0.017)\, 1.005\, (T_3 - 533.2) = 0.017 \times 44186.$$

$$T_3 = 1268 \text{ K.}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = \frac{T_3}{\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}} \Rightarrow 1268 \times 0.634 = 803.9 \text{ K.}$$

$$\eta_{Turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$

6.

$$T_4' = 1268 - 0.9\,(1268 - 803.9) = 850.3\,K.$$

$$w_{compressor} = C_p\,(T_2' - T_1) = 1.005\,(533.2 - 300) = 234.4\ KJ/kg$$

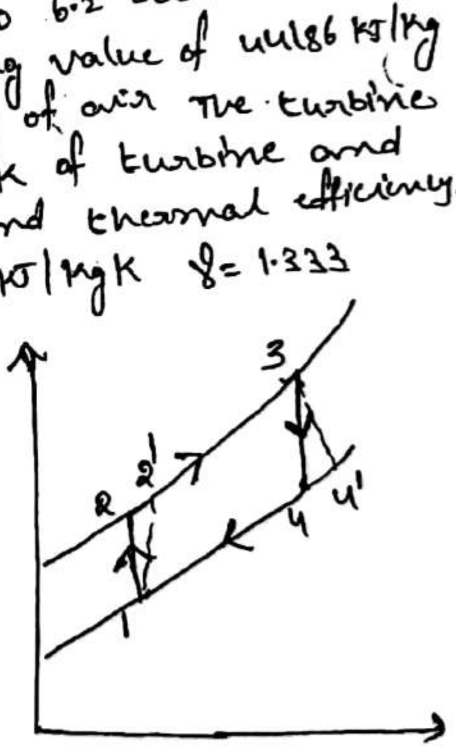
$$w_{turbine} = C_{pg}\,(T_3 - T_4') = 1.147\,(1268 - 850.3) = 479.1\ KJ/kg$$

$$Network = w_{turbine} - w_{compressor} = 244.7\ KJ/kg$$

$$\text{Heat supplied / kg of air} = 0.017 \times 44186 = 751.2\ KJ/kg$$

$$\eta_{thermal} = \frac{Network}{Heat\ supplied} = \frac{244.7}{751.2} = 32.57\%$$

A Gas turbine unit receives air at 1 bar and 300K and compresses it adiabatically to 6.2 bar. The compressor efficiency is 88%. The fuel has heating value of 44186 KJ/kg and the air fuel ratio is 0.017 KJ/kg of air. The turbine efficiency is 90%. Calculate the work of turbine and compressor / kg of air compressed and thermal efficiency. for products of combustion $C_p = 1.147\ KJ/kgK$ $\gamma = 1.333$



Given :-

$P_1 = P_4 = 1$ bar, $T_1 = 300K$

$P_2 = P_3 = 6.2$ bar

$C = 44186\ KJ/kg$

Fuel air ratio $= 0.017\ KJ/kg$

$\eta_{turbine} = 90\%$

$C_p = 1.147\ KJ/kg\,K$

$\gamma = 1.333$

$\gamma = 1.4$

From 1-2 process :-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \left(\frac{6.2}{1}\right)^{\frac{1.4-1}{1.4}} \Rightarrow$$

$$T_2 = 300 \times 1.684 = 505.2K.$$

$\gamma = 1.333$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.88 = \frac{505.2 - 300}{T_2' - 300}$$

$$T_2' = 533.2\,K.$$

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = 1268 \times 0.634 = 803.9\,K.$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$T_4' = 850.3\,K.$$

Heat supplied :-

$$(m_a + m_f)\, C_p\, (T_3 - T_2') = m_f \times C$$

$$\left(1 + \frac{m_f}{m_a}\right) C_p\, (T_3 - T_2') = \left(\frac{m_f}{m_a}\right) C$$

$$(1 + 0.017)\, 1.005\, (T_3 - 533.2) = 0.017 \times 44186$$

$$T_3 = 1268\,K.$$

$$W_{compressor} = C_p\,(T_2' - T_1) = 1.005\,(533.2 - 300) = 234.4\ KJ/kg$$

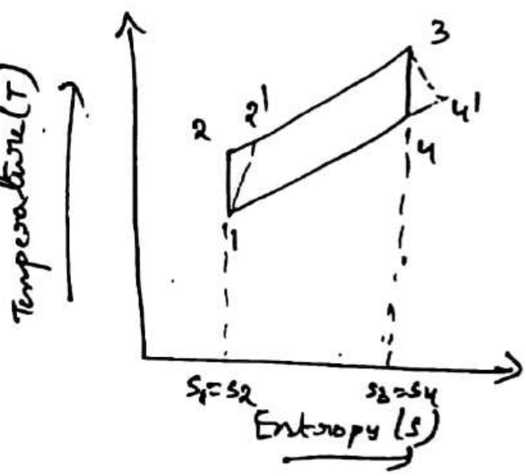
$$W_{Turbine} = C_{pg}\,(T_3 - T_4') = 1.147\,(1268 - 850.3) = 479.1\ KJ/kg$$

$$\text{net work output} = W_{Turbine} - W_{compressor} = 479.1 - 234.4 = 244.7\ KJ/kg$$

$$\text{Heat supplied / kg of air} = \left(\frac{m_f}{m_a}\right) CV = 0.017 \times 44186 = 751.2\ KJ/kg$$

$$\text{Thermal efficiency} = \frac{\text{Network}}{\text{heat supplied}} = \frac{244.7}{751.2} = 32.57\%$$

1. A gas turbine employs a heat exchanger with a thermal ratio of 72%. The turbine operates between the pressure of 1.01 bar and 0.04 bar and ambient temperature is 20°c. Isentropic efficiencies of compressor and turbine are 80%. and 85% respectively. The pressure drop on each side of the heat exchanger is 0.03 bar and in the combustion chamber 0.14 bar. Assume combustion efficiency to be unity and calorific value of the fuel to be 41800 kJ/kg. Calculate the increase in efficiency due to heat exchanger over that for simple cycle. $c_p = 1.024$ kJ/kgK. and assume $\gamma = 1.4$, air-fuel ratio = 90:1 and for the heat exchanger cycle the turbine entry temperature is the same as for a simple cycle.



1-2 process :-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.40}{1.01}\right)^{\frac{1.4-1}{1.4}}$$

$$T_2 = (293)(1.486) = 435.4 \text{ K.}$$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{435.4 - 293}{T_2' - 293}$$

$$T_2' = 471 \text{ K}$$

$$(m_a + m_f) c_p (T_3 - T_2') = m_f \times C$$

$$T_3 = \frac{m_f \times C}{c_p (m_a + m_f)} + T_2' \Rightarrow \frac{1 \times 41800}{1.024\,(90+1)} + 471 = 919.5 \text{ K}$$

3-4 process :-

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = (T_3)\left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow 919.5\left(\frac{1.01}{3.9}\right)^{\frac{1.4-1}{1.4}}$$

$$T_4 = 625 \text{ K}$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4} \Rightarrow T_4' = 919.5 - 0.85(919.5 - 625) = 669 \text{ K}$$

$$\eta_{thermal} = \frac{(T_3 - T_4') - (T_2' - T_1)}{(T_3 - T_2')} = \frac{(919.5 - 669) - (471 - 293)}{(919.5 - 471)} = 16.16\%$$

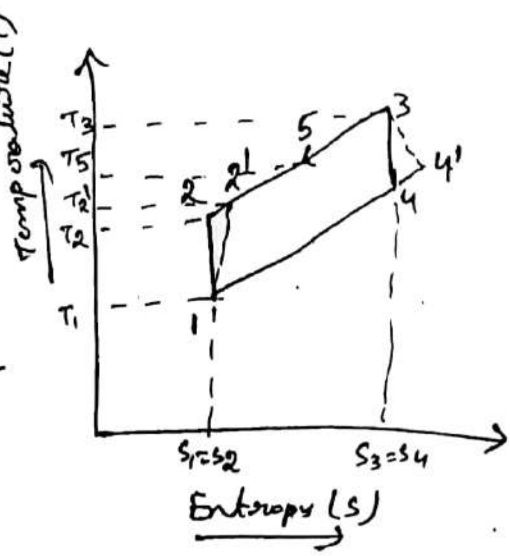
Heat exchanger cycle :-

$P_3 = 4.04 - 0.14 - 0.05 = 3.85$ bar

$P_4 = 1.01 + 0.05 = 1.06$ bar

$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \left(\frac{1.06}{3.85}\right)^{\frac{1.4-1}{1.4}} = 0.69$

$T_4 = 919.5 \times 0.69 = 634 K.$



$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4} \Rightarrow 0.85 = \frac{919.5 - T_4'}{919.5 - 634}$

$T_4' = 677 K$

Thermal ratio (Effectiveness)

$\epsilon = \frac{T_5 - T_2'}{T_4' - T_2'} \Rightarrow 0.72 = \frac{T_5 - 471}{677 - 471}$

$T_5 = 619 K$

$\eta_{thermal} = \frac{(T_3 - T_4') - (T_2' - T_1)}{(T_3 - T_5)}$

$= \frac{(919.5 - 677) - (471 - 293)}{(919.5 - 619)}$

$= \frac{64.5}{300.5} = 21.46\%.$

Increase in thermal efficiency = 21.46 - 16.16 = 5.3%.

2. Air is drawn in a gas turbine unit at 15°c and 1.01 bar and pressure ratio is 7:1. The compressor is driven by the H.P turbine and L.P turbine drives a seperate power shaft. The Isentropic efficiencies of compressor, and the H.p and L.p turbines are 0.82, 0.85 and 0.85 respectively. If the maximum cycle temperature is 610°c calculate

1. The pressure and temperature of gases entering the power turbine
2. The net power developed by the unit / Kg mass flow.
3. work ratio
4. Thermal efficiency of the unit. Neglect the mass of fuel and assume the following for compression process

$C_{pa} = 1.005$ KJ/kg K, $\gamma = 1.4$ $C_{pg} = 1.15$ KJ/Kg and $\gamma = 1.333$

Given :-

8.

$T_1 = 15 + 273 = 288K$, $\eta_{compressor} = 0.85$, $\eta_{turbine\,(H.P)} = 0.85$

$P_1 = 1.01$ bar $\frac{P_2}{P_1} = 7$, $\eta_{turbine\,(LP)} = 0.85$, Maximum temperature $(T_3) = 610 + 273 = 883K$

1. 1-2 process :-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (7)^{\frac{1.4-1}{1.4}} = 1.745$$

$$T_2 = 1.745 \times 288 = 502.5K$$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow T_2' = 549.6K$$

work of compressor $= C_{pa}(T_2' - T_1) = 1.005\,(549.6 - 288) = 262.9$ kJ/kg

work output of H.p turbine = work input to compressor.

$$C_{pg}\,(T_3 - T_4') = 262.9 \Rightarrow T_4' = 654.4K$$
$$1.15\,(883 - T_4') = 262.2$$

$$\eta_{turbine} = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.85 = \frac{883 - 654.4}{883 - T_4} \Rightarrow T_4 = 614K.$$

2. 3-4 process :- (Isentropic expansion)

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$P_4 = \frac{P_3}{4.32} = 1.636 \text{ bar}$$

pressure of gases entering the L.p or power turbine = 1.636 bar

3) Net power developed / kg/s mass flow =

$P_2 = P_3$
$P_1 = P_5$

pressure ratio $\frac{P_4}{P_5} \Rightarrow \frac{P_4}{P_3} \times \frac{P_3}{P_5}$

$$= \frac{P_4}{P_3} \times \frac{P_2}{P_5} = \frac{7}{4.32} = 1.62$$

Then

$$\frac{T_4'}{T_5} = \left(\frac{P_4}{P_5}\right)^{\frac{\gamma-1}{\gamma}} = (1.62)^{\frac{0.33}{1.33}} = 1.127$$

$$T_5 = \frac{T_4'}{1.127} = 580.6K$$

Efficiency of turbine (L.p turbine) $= \frac{T_4' - T_5'}{T_4' - T_5}$

$$0.85 = \frac{654.4 - T_5'}{654.4 - 580.6}$$

$T_5' = 654.4 - 0.85\,(654.4 - 580.6) = 591.7\,K$

work of L.P turbine $= C_{pg}\,(T_4' - T_5') = 1.15\,(654.4 - 591.7)$
$= 72.1$ KJ/kg

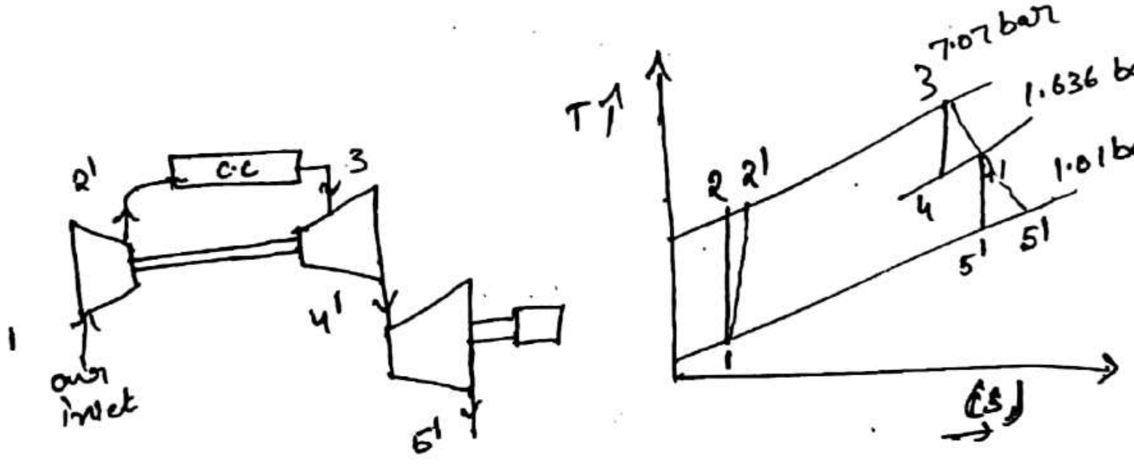
hence net power output = 72.1 KW

3) work ratio :- $\dfrac{\text{Net work output}}{\text{Gross work output}} = \dfrac{72.1}{72.1 + 262.9} = 0.215$

4) Thermal efficiency of the unit ($\eta_{thermal}$) :-

Heat supplied $= C_{pg}\,(T_3 - T_2') = 1.15\,(883 - 549.6)$
$= 383.4$ KJ/kg

$$\eta_{thermal} = \frac{\text{Network output}}{\text{Heat supplied}} = \frac{72.1}{383.4} = 18.8\%$$



3. The pressure ratio of an open-cycle gas turbine power plant is 5.6. Air is taken at 30°c and 1 bar The compression is carried out in two stages with perfect intercooling in between. The maximum temperature of the cycle is limited to 700°c. Assuming isentropic efficiency of each compressor stage as 85%. and that of turbine as 90%. Determine the power developed and the efficiency of power plant, if the air flow is 1.2 kg/s and the mass of fuel may be neglected, and it may be assumed that $c_p = 1.02$ KJ/kgK and $\gamma = 1.41$

The pressure ratio of the open-cycle gas turbine = 5.6

Temperature of intake air $(T_1) = 30°c = 30 + 273 = 303K$

pressure of intake air $(P_1) = 1$ bar

Maximum temperature of cycle $= (T_3) = 700 + 273 = 973K$

Isentropic efficiency of each compressor $(\eta_{comp}) = 85\%$

Isentropic efficiency of turbine $(\eta_{turbine}) = 90\%$

mass rate of flow (ma) = 1.2 kg/s, c_p = 1.02 kJ/kg γ = 1.4.

power developed and efficiency of the power plant 9.

assume pressure ratio in each stage is same we have

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \sqrt{\frac{P_4}{P_1}} = \sqrt{5.6} = 2.366.$$

$\eta_{comp_1} = \eta_{comp_2}$ and $\frac{P_2}{P_1} = \frac{P_4}{P_3}$ so that work required for each compressor is same since both the compressors have the same inlet temperature $T_1 = T_3$, $T_2' = T_4'$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (2.366)^{\frac{1.4-1}{1.4}} = T_2 = (303)(1.2846) = 389.23\,K.$$

$$\eta_{comp} = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow T_2' = \frac{389.23 - 303}{0.85} + 303 = 404.44\,K.$$

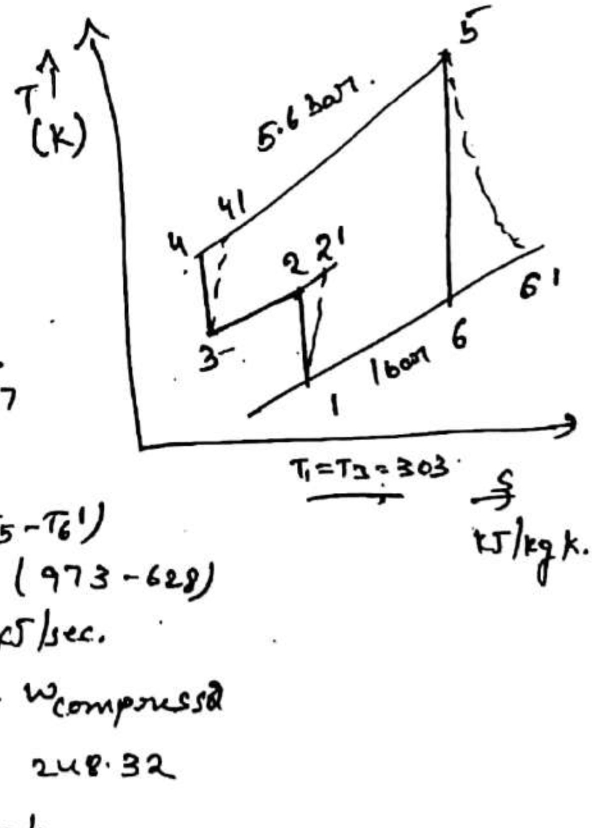
2-stage compressor = $2 \times m \times c_p (T_2' - T_1)$ = $2 \times 1.2 \times 1.02 (404.44 - 303)$ = 248.32 kJ/s

For turbine we have

$$\frac{T_5}{T_6} = \left(\frac{P_5}{P_6}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_6 = \frac{973}{1.65} = 589.7\,K.$$

$$\eta_{turbine} = \frac{T_5 - T_6'}{T_5 - T_6} = 0.9 = \frac{973 - T_6'}{973 - 589.7}$$



$T_6' = 628$ K.

work output of turbine = $mc_p (T_5 - T_6')$
= $1.2 \times 1.02 (973 - 628)$
= 422.28 kJ/sec.

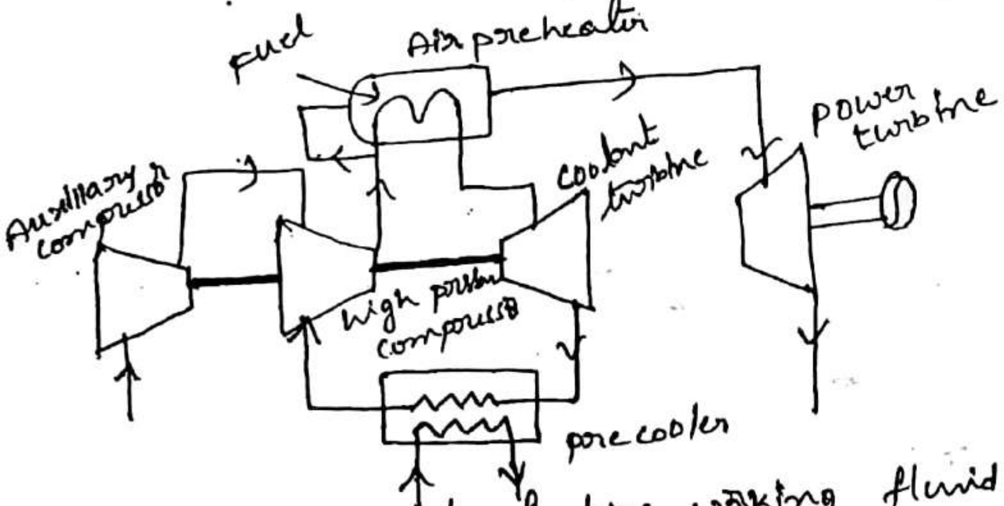
net work output = $W_{turbine} - W_{compressor}$
= 422.28 − 248.32
= 173.96 kJ/sec.

hence power developed = 173.9 kW

heat supplied (Q_s) = $mc_p (T_5 - T_4')$
= $1.2 \times 1.02 (973 - 404.44)$
= 695.92 kJ/sec.

$$\eta_{efficiency} = \frac{W_{net}}{Q_s} = 0.25 = 25\%.$$

Semi closed cycle gas turbine :-



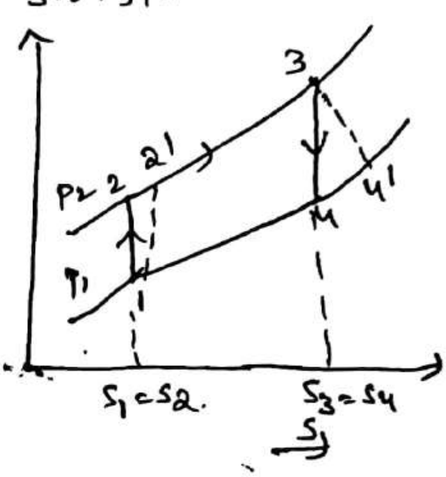
when some part of the working fluid is confined to the plant and another part flows into and from the atmosphere it is called semi cycle. It is basically a high pressure system and the component parts are smaller than an open cycle for the same power output.

The basic working medium is air. compressed air from auxillary compressor and exhaust air of turbine passing through the precooler enters the high pressure compressor and is compressed. The high pressure air before entering the air heater is in two parts one part serving the power turbine is used to intial combustion in the air heater and another ~~plant~~ part which does not mix with the fuel is heated by the heat of external combustion so that all the time this part of air may be circulated in a closed system. The exhaust of power turbine goes to atmosphere.

The air enters the compressor of an open cycle plant pressure of 1 bar and temperature 20°C The pression of air after compression is 4 bar. The isentropic efficiency of compressor and turbine are 80% and 85% respectively. The air fuel ratio used as 90:1. If the flow rate of air is 3.0 kg/s Find power developed, Thermal efficiency of cycle $C_p = 1.0$ KJ/kgK, $\gamma = 1.4$ for air and gases CV of fuel = 41800 KJ/kg

$P_1 = 1$ bar, $P_2 = 4$ bar, $\eta_{compressor} = 0.8$, $\eta_t = 0.85$

$T_1 = 20+273 = 293K$, $A/F = 90/1$, $m_a = 3.0$ kg/sec.



1-2 process:-

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = (20+273)(1.486) = 435.4\ K.$$

$$\eta_{compressor} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$T_2' = \frac{435.4-293}{0.8} + 293 = 471\ K$$

3-4 process:- $T_3/T_4 = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

$T_4 = 1268 \times 0.634 = 803.9K$

Heat supplied by fuel = Heat taken by burning gases

$$m_f \times cv = (m_a + m_f)\ C_p (T_3 - T_2')$$

$$cv = \left(\frac{m_a}{m_f} + 1\right) C_p (T_3 - T_2')$$

$$41800 = (90+1)\ 1.0\ (T_3 - 471)$$

$$T_3 = 930\ K$$

$$T_4 = 624.9\ K$$

$$\eta_T = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$T_4' = 930 - 0.85(930 - 624.9) = 670.6K.$$

workdone by turbine $= (m_f + m_a)\ C_p (T_3 - T_4')$

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

$$= 1\left(\frac{1}{90} + 1\right) 1.0\ (930 - 670.6)$$

$= 262.28$ KJ/kg of air

$W_{compressor} = m_a C_p (T_2' - T_1)$
$= 1 \times 1.0 (471 - 293) = 178$ KJ/kg of air

$W_{net} = W_T - W_C$
$= 262.28 - 178 = 84.28$ KJ/kg of air

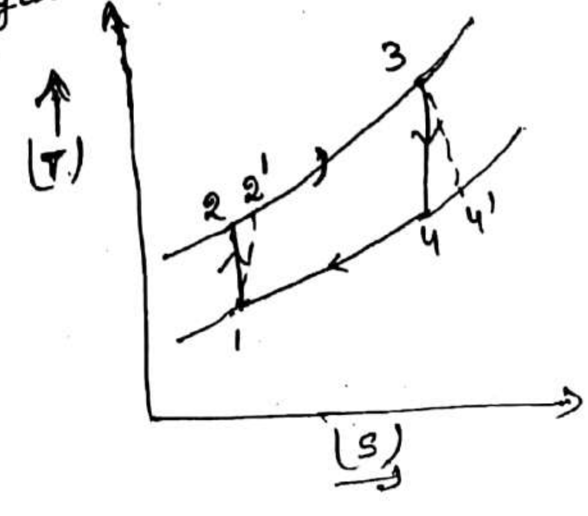
power = W_{net} × mass of air
$= 84.28 \times 3 = 252.84$ KW/kg of air

$$\eta_{thermal} = \frac{\text{workoutput}}{\text{Heat Supplied}}$$

$$\text{Heat supplied} = \left(\frac{m_f}{m_a}\right) CV$$
$$= \left(\frac{1}{90}\right) 41800 = 464.44 \text{ KJ/kg of m/s}$$

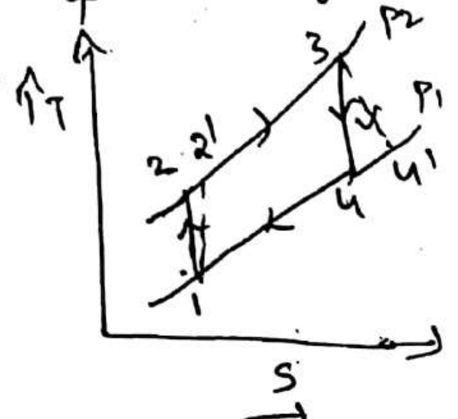
$$= \frac{84.28}{464.44}$$
$$= 0.1814 \%$$

In a constant pressure open cycle gas turbine air enters at 1 bar and 20°c and leaves the compressor at 5 bar - using the following data Temperature of gases entering the turbine 680°c, pressure loss in the combustion chamber 0.1 bar, $\eta_c = 85\%$, $\eta_t = 80\%$, $\eta_{cc} = 85\%$, $\gamma = 1.4$ $C_p = 1.024$ KJ/kgK for the air and gas. Find the quantity of air circulation if the plant develops 1065 KW, Heat supplied/kg of air circulation the thermal efficiency of cycle mass of fuel may be neglected.



Given :-
$P_1 = 1$ bar, $P_2 = 5$ bar
$P_3 = 5 - 0.1 = 4.9$ bar, $P_4 = 1$ bar
$T_1 = 20 + 273 = 293K$.
$T_3 = 680 + 273 = 953K$.
$\eta_c = 0.85$, $\eta_T = 0.8$, $\eta_{cc} = 0.85$
$P = 1065$ KW, $C_p = 1.024$ KJ/kgK
$\gamma = 1.4$

A gas turbine unit has a pressure ratio of 6:1 and maximum cycle temperature of 610°C. The isentropic efficiencies of compressor and turbine are 0.8 and 0.82. Calculate power output when the air enters the compressor at 15°C at the rate of 16 kg/sec. Take $C_p = 1.005$ kJ/kgK, $\gamma = 1.4$ for compression, $C_p = 1.11$ kJ/kgK and $\gamma = 1.333$ for expansion process.



$T_1 = 15 + 273 = 288\,K$ $\frac{P_2}{P_1} = \frac{6}{1}$

$T_3 = 610 + 273 = 883\,K$

$\eta_c = 0.8$, $\eta_T = 0.82$

Air flow rate 16 kg/sec.

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = 481\,K$

$\eta_c = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow T_2' = 529\,K$

$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_4 = 564\,K$

$\eta_T = \frac{T_3 - T_4'}{T_3 - T_4} = 621.4\,K$

Compressor work input
$= C_p (T_2' - T_1)$
$= 1.005 (529 - 288) = 242.2$ kJ/kg

Turbine work output
$= C_p (T_3 - T_4')$
$= 1.11 (883 - 621.4)$
$= 290.4$ kJ/kg

Network output $= W_T - W_C$
$= 290.4 - 242.2 = 48.2$ kJ/kg

power in kW $= 48.2 \times 16$ (mass) $= 771.2$ kW

$\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{T_2}{T_1}\right)$

$\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$

UNIT 5

JET PROPULSION & ROCKETS

Course Objective:

Applications and the principles of thermodynamics to components and systems.

Course Outcome:

Develop problem solving skills through the application of thermodynamics.

5
JET PROPULSION ENGINES

5.1 Introduction

Jet propulsion, similar to all means of propulsion, is based on Newton's Second and Third laws of motion.

The jet propulsion engine is used for the propulsion of aircraft, missile and submarine (for vehicles operating entirely in a fluid) by the reaction of jet of gases which are discharged rearward (behind) with a high velocity. As applied to vehicles operating entirely in a fluid, a momentum is imparted to a mass of fluid in such a manner that the reaction of the imparted momentum furnishes a propulsive force. The magnitude of this propulsive force is termed as thrust.

For efficient production of large power, fuel is burnt in an atmosphere of compressed air (combustion chamber), the products of combustion expanding first in a gas turbine which drives the air compressor and then in a nozzle from which the thrust is derived. Paraffin is usually adopted as the fuel because of its ease of atomisation and its low freezing point.

Jet propulsion was utilized in the flying Bomb, the initial compression of the air being due to a divergent inlet duct in which a small increase in pressure energy was obtained at the expense of kinetic energy of the air. Because of this very limited compression, the thermal efficiency of the unit was low, although huge power was obtained. In the normal type of jet propulsion unit a considerable improvement in efficiency is obtained by fitting a turbo–compressor which will give a compression ratio of at least 4 : 1.

5.2 Classification

Jet propulsion engines are classified basically as to their method of operation as shown in fig. 5–1. The two main catagories of jet propulsion systems are the *atmospheric*

- Jet Propulsion Engines
  - Atmospheric Jet Engines (Use atmospheric air)
    - Turboprop or Propjet
    - Turbojet
    - Turbojet with after burner
    - Ramjet
    - Pulsejet
  - Rockets (Use own oxidizer)
    - Liquid Propellant
    - Solid Propellant

Fig. 5 – 1. Jet propulsion engines.

jet engine and *rocket*. Atmospheric jet engines require oxygen from the atmosperic air for combustion of fuel, *i.e.* they are dependent on atmospheric air for combustion.

The rocket engine carries its own oxidizer for combustion of fuel and is, therefore, independent of the atmospheric air. Rocket engines are discussed in art. 5·6.

The turboprop, turbojet and turbojet with after burner are modified simple open cycle gas turbine engines. In turboprop thrust is not completely due to jet. Approximately 80 to 90 percent of the thrust in turboprop is produced by acceleration of the air outside the engine by the propeller (as in conventional aeroengines) and about 10 to 20 percent of the thrust is produced by the jet of the exhaust gases. In turbojet engine, the thrust is completely due to jet of exhaust gases. The turbojet with after burner is a turbojet engine with a reheater added to the engine so that the extended tail pipe acts as a combustion chamber.

The ramjet and pulsejet are aero–thermo–dynamic–ducts, i.e. a straight duct type of jet engine without compressor and turbine. The ramjet has the simplest construction of any propulsion engine, consisting essentially of an inlet diffuser, a combustion chamber and an exit nozzle of tail pipe. Since the ramjet has no compressor, it is dependent entirely upon ram compression.

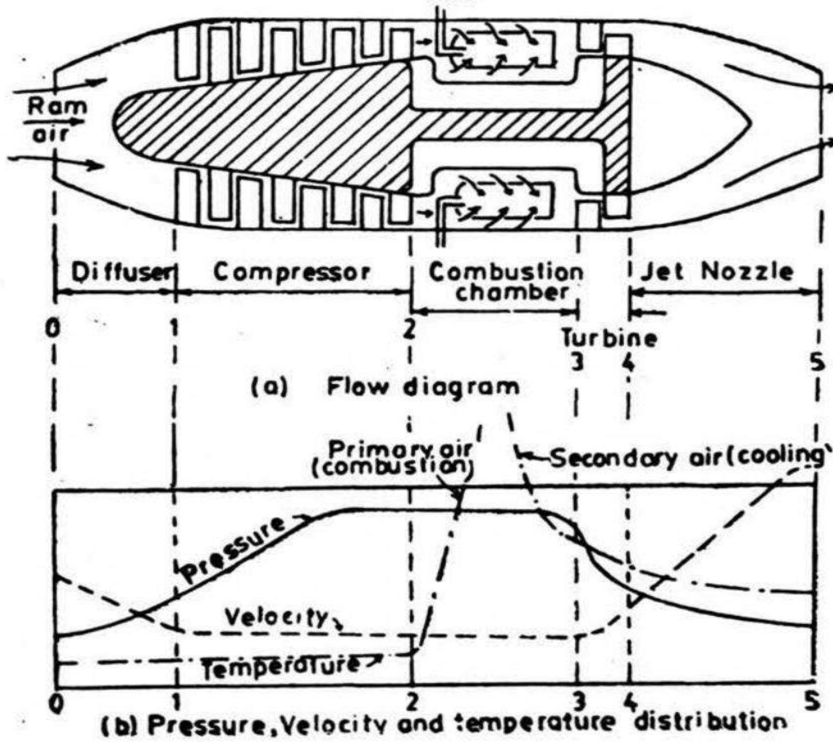


Fig. 5-2 Turbojet engine.

The pulsejet is an intermittent combustion jet engine and it operates on a cycle similar to a reciprocating engine and may be better compared with an ideal Otto cycle rather than the Joule or Bryton cycle. From construction point of view, it is some what similar to a ramjet engine. The difference lies in provision of a mechanical valve arrangement to prevent the hot gases of combustion from going out through the diffuser.

5.3 Turbojet Engine

The turboject engine (fig. .5–2) is similar to the simple open cycle constant pressure gas turbine plant (fig. 4–2) except that the exhaust gases are first partially expanded in the turbine to produce just sufficient power to drive the compressor. The exhaust gases leaving the turbine are then expanded to atmospheric pressure in a propelling (discharge) nozzle. The remaining energy of gases after leaving the turbine is used as a high speed jet from which the thrust is obtained for forward movement of the aircraft.

Thus, the essential *components* of a turbojet engine are :

- An entrance air diffuser (diverging duct) in front of the compressor, which causes rise in pressure in the entering air by slowing it down. This is known as *ram*. The pressure at entrance to the compressor is about 1·25 times the ambient pressure.
- A rotary compressor, which raises the pressure of air further to required value and delivers to the combustion chamber. The compressor is the radial or axial type and is driven by the turbine.
- The combustion chamber, in which paraffin (kerosene) is sprayed, as a result of this combustion takes place at constant pressure and the temperature of air is raised.
- The gas turbine into which products of combustion pass on leaving the combustion chamber. The products of combustion are partially expanded in the turbine to provide necessary power to drive the compressor.
- The discharge nozzle in which expansion of gases is completed, thus developing the forward thrust.

A Rolls–Royce Derwent jet engine employs a centrifugal compressor and turbine of the impulse–reaction type. The unit has 550 kg mass. The speed attained is 960 km/hour.

5.3.1 Working Cycle : Air from surrounding atmosphere is drawn in through the diffuser, in which air is compressed partially by ram effect. Then air enters the rotary compressor and major part of the pressure rise is accomplished here. The air is compressed to a pressure of about 4 atmospheres. From the compressor the air passes into the annular combustion chamber. The fuel is forced by the oil pump through the fuel nozzle into the combustion chamber. Here the fuel is burnt at constant pressure. This raises the temperature and volume of the mixture of air and products of combustion. The mass of air supplied is about 60 times the mass of the fuel burnt. This excess air produces sufficient mass for the propulsion jet, and at the same time prevents gas temperature from reaching values which are too high for the metal of the rotor blades.

The hot gases from the combustion chamber then pass through the turbine nozzle ring. The hot gases which partially expand in the turbine are then exhausted through the discharge (propelling nozzle) by which the remaining enthalpy is converted into kinetic energy. Thus, a high velocity propulsion jet is produced.

The oil pump ad compressor are mounted on the same shaft as the turbine rotor. The power developed by the turbine is spent in driving the compressor and the oil pump.

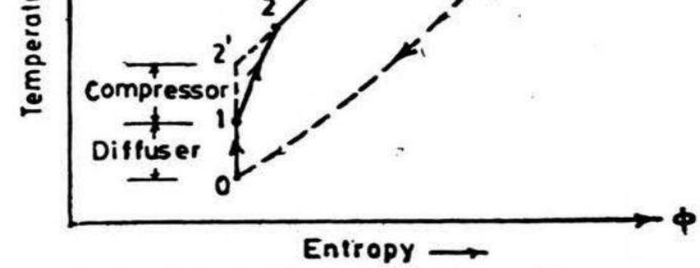


Fig. 5-3. A typical turbojet engine cycle on T – ϕ diagram.

Some starting devicé such as compressed air motor or electric motor, must be provided in the turbojet plant. Flight speeds upto 800 km per hour are obtained from this type of unit.

The basic thermodynamic cycle for the turbojet engine is the Joule or Brayton cycle as shown in $T - \Phi$ diagram of fig. 5–3. While drawing this cycle, following simplifying assumptions are made :

- There are no pressure losses in combustion chamber.
- Specific heat of working medium is constant.
- Diffuser has ram efficiency of 100 percent *i.e.*, the entering atmospheric air is diffused isentropically from velocity V_o to zero (V_o is the vehicle velocity through the air).
- Hot gases leaving the turbine are expanded isentropically in the exit nozzle *i.e.*, the efficiency of the exit nozzle is 100 percent.

5.3.2 Thrust Power and Propulsive Efficiency : The jet aircraft draws in air and expels it to the rear at a markedly increased velocity. The action of accelerating the mass of fluid in a given direction creates a reaction in the opposite direction in the form of a propulsive force. The magnitude of this propulsive force is defined as thrust. It is dependent upon the rate of change of momentum of the working medium i.e. air, as it passes through the engine.

The basis for comparison of jet engines is the thrust. The thrust, T of a turbojet engine can be expressed as,

$$T = m(V_i - V_o) \qquad \ldots (5.1)$$

where, m = mass flow rate of gases, kg/sec.,

V_j = exit jet velocity, m/sec., and,

V_o = vehicle velocity, m/sec.

The above equation is based upon the assumption that the mass of fuel is neglected. Since the atmospheric air is assumed to be at rest, the velocity of the air entering relative to the engine, is the velocity of the vehicle, V_O. The thrust can be increased by increasing the mass flow rate of gas or increasing the velocity of the exhaust jet for given V_o.

Thrust power is the time rate of development of the useful work achieved by the engine and it is obtained by the product of the thrust and the flight velocity of the vehicle. Thus, thrust power TP is given by

$$TP = T\,V_o = m(V_j - V_o)\,V_o\,\frac{\text{N·m}}{\text{sec.}} \qquad \ldots (5.2)$$

The kinetic energy imparted to the fluid or the energy required to change the momentum of the mass flow of air, is the difference between the rate of kinetic energy of entering air and the rate of kinetic energy of the exist gases and is called propulsive power. The propulsive power PP is given by

$$PP = \frac{m(V_j^2 - V_0^2)}{2}\ \text{N.m/sec.} \qquad \ldots (5.3)$$

Propulsive efficiency is defined as the ratio of thrust power (TP) and propulsive power (PP) and is the measure of the effectiveness with which the kinetic energy imparted to the fluid is transformed or converted into useful work. Thus, propulsive efficiency η_p is given by

$$\eta_p = \frac{TP}{PP} = \frac{m(V_j - V_0)\ V_0}{1} \times \frac{2}{m(V_j^2 - V_0^2)}$$

$$\therefore \eta_p = \frac{2(V_j - V_o)V_o}{V_j^2 - V_o^2} = \frac{2V_o}{V_j + V_o} = \frac{2}{1 + \left(\frac{V_j}{V_o}\right)} \quad \ldots (5.4)$$

From the expression of n_p it may be seen that the propulsion system approaches maximum efficiency as the velocity of the vehicle approaches the velocity of the exhaust gases. But as this occurs, the thrust and the thrust power approach zero. Thus, the ratio of velocities for maximum propulsive efficiency and for maximum power are not the same. Alternatively, the propulsive efficiency can be expressed as

$$\eta_p = \frac{TP}{PP} = \frac{TP}{TP + K.E.\ \text{losses}} \quad \ldots (5.5)$$

Thermal efficiency of a propulsion is an indication of the degree of utilization of energy in fuel (heat supplied) in accelerating the fluid flow and is defined as the increase in the kinetic energy of the fluid (propulsive power) and the heat supplied. Thus,

$$\text{Thermal efficiency, } \eta_T = \frac{\text{Propulsive power}}{\text{Heat supplied}}$$

$$= \frac{\text{Propulsive power}}{\text{Fuel flow rate} \times \text{C.V. of fuel}} \quad \ldots (5.6)$$

The overall efficiency is the ratio of the thrust power and the heat supplied. Thus, overall efficiency is the product of propulsive efficiency and thermal efficiency. The propulsive and overall efficiencies of the turboject engine are comparable to the mechanical efficiency and brake thermal efficiency respectively, of the reciprocating engine.

Problem – 1 : *A jet propulsion unit, with turbojet engine, having a forward speed of 1,100 km/hr produces 14 kN of thrust and uses 40 kg of air per second. Find: (a) the relative exist jet velocity, (b) the thrust power, (c) the propulsive power, and (d) the propulsive efficiency.*

(a) Forward speed, $V_o = \frac{1,100 \times 1,000}{3,600} = 305{\cdot}55$ m/sec.

Using eqn. (5.1), thrust, $T = m(V_j - V_o)$

$$i.e.,\ 14,000 = 40(V_j - 305{\cdot}55)$$

$$\therefore V_j = \frac{14,000}{40} + 305{\cdot}55 = 350 + 305{\cdot}55 = 655{\cdot}55 \text{ m/sec.}$$

Thus relative exist jet velocity, V_j = **655·55 m/sec.**

(b) Using eqn. (5.2)

Thrust power, $TP = T \times V_o$

$= 14,000 \times 305{\cdot}55 = 42,77,700$ N.m/sec. or = **4,277.7 kN.m/sec.**

(c) Using eqn. (5.3),

$$\text{Propulsive power, } PP = \frac{m(V_2^2 - V_0^2)}{2}$$

$$= \frac{40\{(655{\cdot}55)^2 - (305{\cdot}55)^2\}}{2}$$

$= 6,727 \times 10^3$ N.m/sec = 6,727 KN.m/sec or **6,727 kW**

(d) Using eqn. (5.4),

is not effective and that there are pulsations created in the combustion chamber which affect the air flow in front of the diffuser.

Since the ram jet engine has no turbine, the temperature of the gases of combustion is not limited to a relatively low figure as in the turbojet engine. Air fuel ratios of around 15·1 are used. This produces exhaust temperatures in the range of 2000°C to 2200°C. Extensive research is being conducted on the development of hydrocarbon fuels that will give 30 percent more energy per unit volume than current aviation gasolines. Investigations are carried out to determine the possibility of using solid fuels in the ram jet and in the after burner of the turbojet engine. If powdered aluminium could be utilized as an aircraft fuel, it would deliver over 2·5 times as much heat per unit volume as aviation gasoline, while some other could deliver almost four times as much heat.

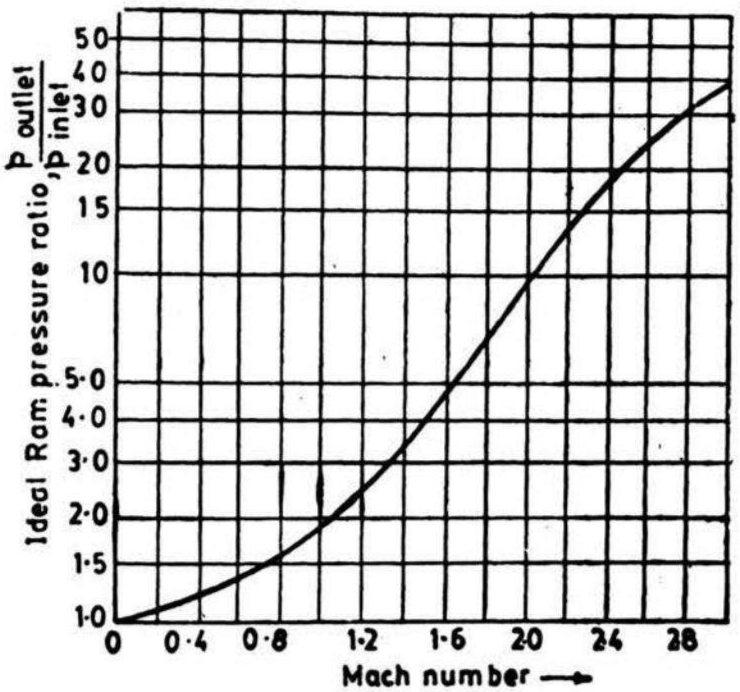


Fig. 5–5. Ram pressure ratio versus Mach number of vehicle for sea level condition.

The temperature, pressure and velocity of the air during its passage through a ram jet engine at supersonic flight are shown in fig. 5–4.

The cycle for an ideal ram jet, which has an isentropic entrance diffuser and exit nozzle, is the Joule cycle as shown by the dotted lines in fig. 5–6. The difference between the actual and ideal jet is due principally to losses actually encountered in the flow system. The sources of these losses are :

- Wall friction and flow separation in the subsonic diffuser and shock in the supersonic diffuser.
- Obstruction of the air stream by the burners which introduces eddy currents and turbulence in the air stream.
- Turbulence and eddy currents introduced in the flow during burning.
- Wall friction in the exit nozzle.

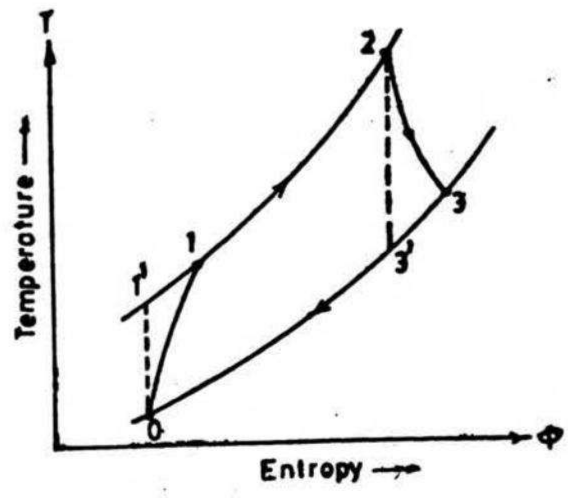


Fig. 5–6. T – ϕ diagram of Ram jet engine.

By far, the most critical component of the ram jet is the diffuser. Due to the peculiarities of steamline flow, a diffuser which is extremely

Because of the simplicity of the engine, the ram jet develops greater thrust per unit engine weight than any other propulsion engine at supersonic speed with the exception of the rocket engine. The thrust per unit frontal area increases both with the efficiency and the air flow through the engine; therefore much greater thrust per unit area is obtainable at high supersonic speeds. General performance of a ram jet engine in the subsonic range would have a specific fuel consumption between 0.6 to 0·8 kg fuel per N thrust – hr and a specific weight between 0·01 to 0·02 kg per N thrust. The supersonic ram jet engine has a specific fuel consumption between 0·25 to 0·04 and a specific weight between 0·01 to 0·04. Thus, the best performance of the ram jet engine is obtained at flights speeds of 1500 to 3500 km/hr.

5.5 Pulse Jet Engine

The pulse jet engine is somewhat similar to a ram jet engine. The difference is that a mechanical valve arrangement is used to prevent the hot gases of combustion from flowing out through the diffuser in the pulse jet engine.

Paul Schmidt patented principles of the pulse jet engine in 1930. It was developed by Germany during World–War–II, and was used as the power plant for "buzz bomb".

The turbojet and ram jet engines are continuous in operation and are based on the constant pressure heat addition (Bryton) cycle. The pulse jet is an intermittent combustion engine and it operates on a cycle similar to a reciprocating engine and may be better compared with an ideal Otto cycle rather than the Joule or Bryton cycle.

The compression of incoming air is accomplished in a diffuser. The air passes through the spring valves and is mixed with fuel from a fuel spray located behind the valves. A spark plug is used to initiate combustion but once the engine is operating normally, the spark is turned off and residual flame in the combustion chamber is used for ignition. The engine walls also may get hot enough to initiate combustion.

The mechanical valves which were forced open by the entering air, are forced shut when the combustion process raises the pressure within the engine above the pressure in the diffuser. As the combustion products cannot expand forward, they move to the rear at high velocity. The combustion products cannot expand forward, they move to the rear at high velocity. When the combustion products leave, the pressure in the combustion chamber drops and the high pressure air in the diffuser forces the valves open and fresh air enters the engine.

Since the products of combustion leave at a high velocity there is certain scavenging of the engine caused by the decrease in pressure occasioned by the exit gases. There is a stable cycle set up in which alternate waves of high and low pressure travel down the engine. The alternating cycles of combustion, exhaust, induction, combustion, etc. are related to the acoustical velocity at the temperature prevailing in the engine. Since the temperature varies continually, the actual process is complicated, but a workable assumption is that the tube is acting similar to a quarter wave length organ pipe. The series of pressure and rarefaction waves move down it at the speed of sound for an assumed average temperatures.

The frequency of the combustion cycle may be calculated from the following expression:

$$f = \frac{a}{4L} \text{ cycles/sec.} \quad \ldots (5.7)$$

where, $a = \sqrt{\gamma RT}$ = sound velocity in the medium at temperature, T, and

L = length of engine (from valves to exit).

efficient at a given speed may be quite inadequate at another velocity.

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The frequency of the combustion cycle may be calculated from the following expression:

^ = 4 l cvc*es/sec-

where, a = VfTTT = sound velocity in the medium at temperature, *T*, and

L = length of engine (from valves to exit).

A serious limitation placed upon pulse jet engine is the mechanical valve arrangement. Unfortunately, the valves used have resonant frequencies of their own, and under certain conditions, the valve will be forced into resonant vibration and will be operating when they should be shutting. This limitation of valves also limits the engine because the gas goes out of the diffuser when it should go out of the tail pipe.

Despite the apparent noise and the valve limitation, pulse jet engines have several *advantages* when compared to other thermal jet engines.

. . The pluse jet is very inexpensive when compared to a turbojet.

. . The pulse jet produces static thrust and produces thrust in excess of drag at much lower speed than a ram jet.

. . The potential of the pulse jet is quite considerable and its development and research may well bring about a wide range of application.

5.6 Rocket Motors

The jet propulsion action of the rocket has been recognised for long. Since the early beginning, the use of rockets has been in war time as a weapon and in peace time as a signaling or pyrotechnic displays. Although, the rocket was employed only to an insignificant extent in World War–I, marked advances were made by the research that was undertaken at that time. In World War–II, the rocket became a major offensive weapon employed by all warring powers. Rockets and rocket powered weapons have advanced to a point where they are used effectively in military operations.

Rocket type engine differs from the atmospheric jet engine in that the entire mass of the jet is generated from the propellant carried within the engine i.e. the rocket motor carries both the fuel and the oxidizing agent. As a result, this type of engine is independent of the atmospheric air that other thermal jet engines must rely upon. From this point of view rocket motors are most attractive. There are, however, other operational features that make rocket less useful. Here, the fundamentals of rocket motor theory and its applications are discussed.

Rocket engines are classified as to the type of propellant used in them. Accordingly, there are two major groups:

One type belonging to the group that utilizes liquid type propellants and other group that uses solid type propellants.

The basic theory governing the operation of rocket motor is applied, equally to both the liquid and the solid propellant rocket.

Rocket propulsion, at this time, would not be regarded as a competitor of existing means for propelling airplanes, but as a source of power for reaching objectives unattainable by other methods. The rocket motors are under active development programmes for an increasing number of applications. Some of these *applications* are :

– Artillery barrage rockets,
– Anti–tank rockets,
– All types of guided missiles,
– Aircraft launched rockets,
– Jets assisted take–off for airplanes,
– Engines for long range, high speed guided missiles and pilotless aircrafts, and
– Main and auxiliary propulsion engines on transonic airplanes.

It will be repeated again that the rocket engine differs from the other jet propulsion engines in that the entire mass of the gases in the jet is generated from the propellants carried within the engine. Therefore, it is not dependent on the atmospheric air to furnish the oxygen for combustion. However, since the rocket carries its own oxidiser, the propellant consumption is very high.

The particular advantages of the rocket are :

. . Its thrust is practically independent of its environments.

. . It requires no atmospheric oxygen for its operation.

. . It can function even in a vacuum.

. . It appear to be the simplest means for converting the themochemical energy of a propellant combination (fuel plus oxidizer) into kinetic energy associated with a jet flow gases.

Despite its apparent simplicity, the development of a reliable rocket system must be light in weight and the rocket motor must be capable of sustained operation in contact with gases at temperature above 2800° C and at appreciable pressures.The problem of materials in consequently a major one. Furthermore, owing to the enormous energy releases involved, problem of ignition, smooth start up, thrust control, cooling etc. arise.

A major problem of development of rocket is selection of suitable propellant to give maximum energy per premium total weight (propellant plus containing vessels) and convenience factors such as a safety in handling, dependability, corrosive tendencies, cost, availability and storage problems. In general, it can be stated that there is a wide variety of fuels that are satisfactory for rocket purpose, but choice of oxidizers is at present distinctly limited.

5.6.1 Basic Theory : Figure 5–7 shows a schematic diagram of a liquid bi–propellant rocket engine. It consists of an injection system, a combustion chamber, and an exit nozzle. The oxidizer and fuel burnt, in the combustion chamber produces a high pressure. The pressure produced is governed by

– Mass rate of flow of the propellants,

– Chemicals characteristics of the propellants, and

– Cross–section area of the nozzle throat.

The gases are ejected to the atmosphere at supersonic speeds through the nozzle. The enthalpy of high pressure gases is converted into kinetic energy. The reaction to the ejection of the high velocity, produces the thrust on the rocket engine.

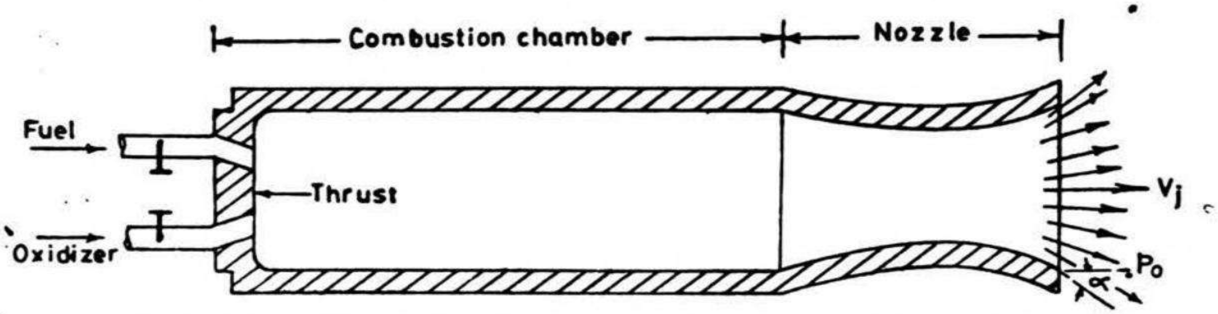

Fig. 5-7. Schematic diagram of a liquid bi-propellant uncooled rocket motor.

The *thrust* developed is a resultant of the pressure forces acting upon the inner and the outer surface of the rocket engine. The resultant internal force acting on the engine is given by

Resultant force = $m_p \ V_j + p_j \ A_j \ N$

where, m_p = Mass rate of propellant consumption, kg/sec,

V_j = Jet velocity relative to nozzle, m/sec,

V_{xj} = Average value of the x–component of the velocity of gases crossing, A_j,

p_j = Exist static pressure, N/m^2, and

A_j = Exit area of nozzle, m^2.

The resultant external forces acting on the rocket engine are $p_o A_o$, where p_o is the atmospheric pressure in N/m^2. The thrust which is a resultant of the total pressure forces becomes

$$T = m_p V_{xj} + A_j (p_j - p_o) \ N \qquad \ldots (5.8)$$

Let V_j = the exit velocity of the rocket gases, assumed constant and

let $V_{xj} = \lambda V_j$. Then, eqn. (5.8) becomes

$$T = \lambda m_p V_j + A_j (p_j - p_o) \ N \qquad \ldots (5.9)$$

The coefficient λ is the correction factor for the divergence angle *a* of the exit conical section of the nozzle. λ is given by

$$\lambda = \frac{1 - \cos 2\alpha}{4(1 - \cos \alpha)} = \frac{1}{2}(1 + \cos \alpha) \qquad \ldots (5.10)$$

Equation (5.8) shows that thrust of a rocket engine increases as the atmospheric pressure decreases. Therefore, maximum thrust will be obtained when P_o= 0, *i.e., rocket engine produces maximum thrust when operating in a vacuum.*

In testing a rocket engine, thrust and propellant consumption for a given time are readily measured. It is convenient then, to express the thrust in terms of the mass rate of flow of propellant and an effective jet velocity, V_{ej}

i.e., Thrust, $T = m_p \times V_{ej}$ . . . (5.11)

The *effective jet exit velocity* is a hypothetical velocity and for convenience in test work it is defined from eqns. (5.9) and (5.11) as under :

$$V_{ej} = \lambda V_j + \frac{A_j}{m_p}(p_j - p_o) \ \text{m/sec.} \qquad \ldots (5.12)$$

The effective jet exit velocity has become an important parameter in rocket motor performance.

The *thrust power, TP* developed by a rocket motor is defined as the thrust multiplied by the flight velocity, V_o.

$$TP = T V_o = m_p \cdot V_{ej} \cdot V_o \ \text{N.m/sec.} \qquad \ldots (5.13)$$

The *propulsive efficiency,* η_p is the ratio of the thrust power to propulsive power supplied. The propulsive power is the thrust power plus the kinetic energy lost in the exhaust,

i.e., K.E. Loss $= \frac{1}{2} m_p (V_{ej} - V_o)^2$ N.m/sec.

Therefore, the propulsive efficiency may be expressed as

$$\eta_p = \frac{TP}{TP + \text{K.E. Loss}} = \frac{m_p V_{ej} V_o}{m_p V_{ej} V_o + \frac{1}{2} m_p (V_{ej} - V_o)^2}$$

$$\therefore \eta_p = \frac{2 (V_o/V_{ej})}{1 + (V_o/V_{ej})^2} \quad \ldots (5.14)$$

Specific Impulse, I_{sp} has become an important parameter in rocket motor performance and is defined as the thrust produced per unit mass rate of propellant consumption.

$$I_{sp} = \frac{T}{m_p} = \frac{m_p \cdot V_{ej}}{m_p} = V_{ej} \quad \ldots (5.15)$$

Specific impulse, with the units, Newtons of thrust produced per kg of propellant burned per second, gives a direct comparison as to the effectiveness among propellants. It is desirable to use propellants with the greatest possible specific impulse, since, this allows a greater useful load to be carried for a given overall rocket weight.

5.6.2. Types of Rocket Motors : The propellant employed in a rocket motor may be a solid, two liquids (fuel plus oxidizer), or materials containing an adequate supply of available oxygen in their chemical composition (monopropellant). Solid propellants are used for rockets which are to operate for relatively short periods, upto possibly 45 seconds. Their main application is to projectiles, guided missiles, and the assisted take-off aircraft.

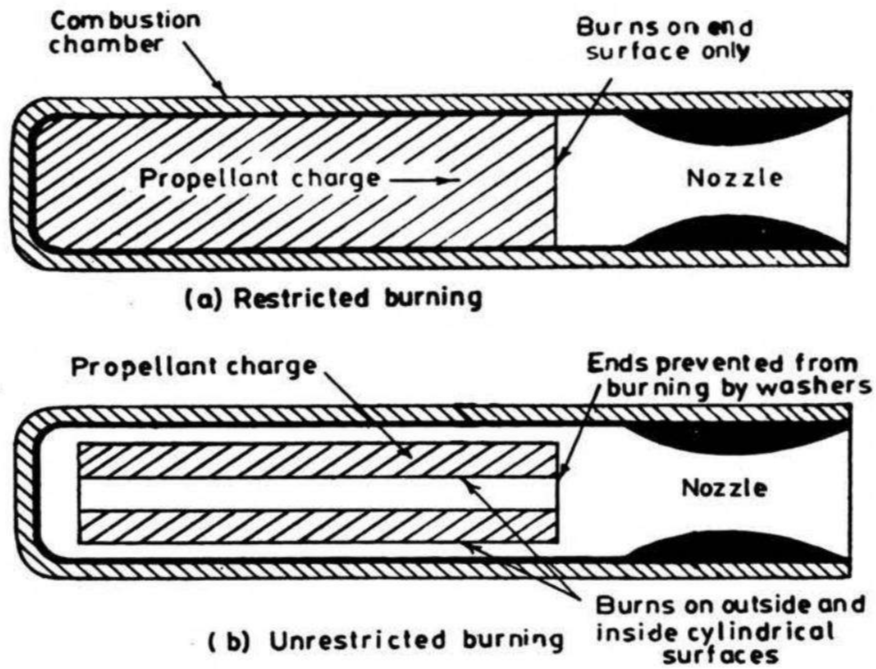

Fig. 5-8 Schematic diagram of a solid propellant rocket.

Solid propellant rockets (fig. 5–8) have been of two basic types :

. . Unrestricted burning types for projectiles and launching rockets; and

. . Restricted burning types for assisted take–off of aircraft and for propelling missiles.

In the unrestricted burning rocket [fig. 5–8(a)] all surfaces of the propellant grain except the ends are ignited; in restricted burning rockets [fig. 5–8(b)] only one surface of the propellant is permitted to burn. Liquid propellant rockets utilizes liquid propellants which are stored in the containers outside the combustion chamber. The basic theory of operation of this type of rocket is same as that for solid propellant rocket. Liquid propellant rockets were developed in order to overcome some of the undesirable features of the

which ar

solid propellant rockets such as short duration of thrust, and no provisions for adequate cooling or control of the burning after combustion starts. Here, the propellant in the liquid

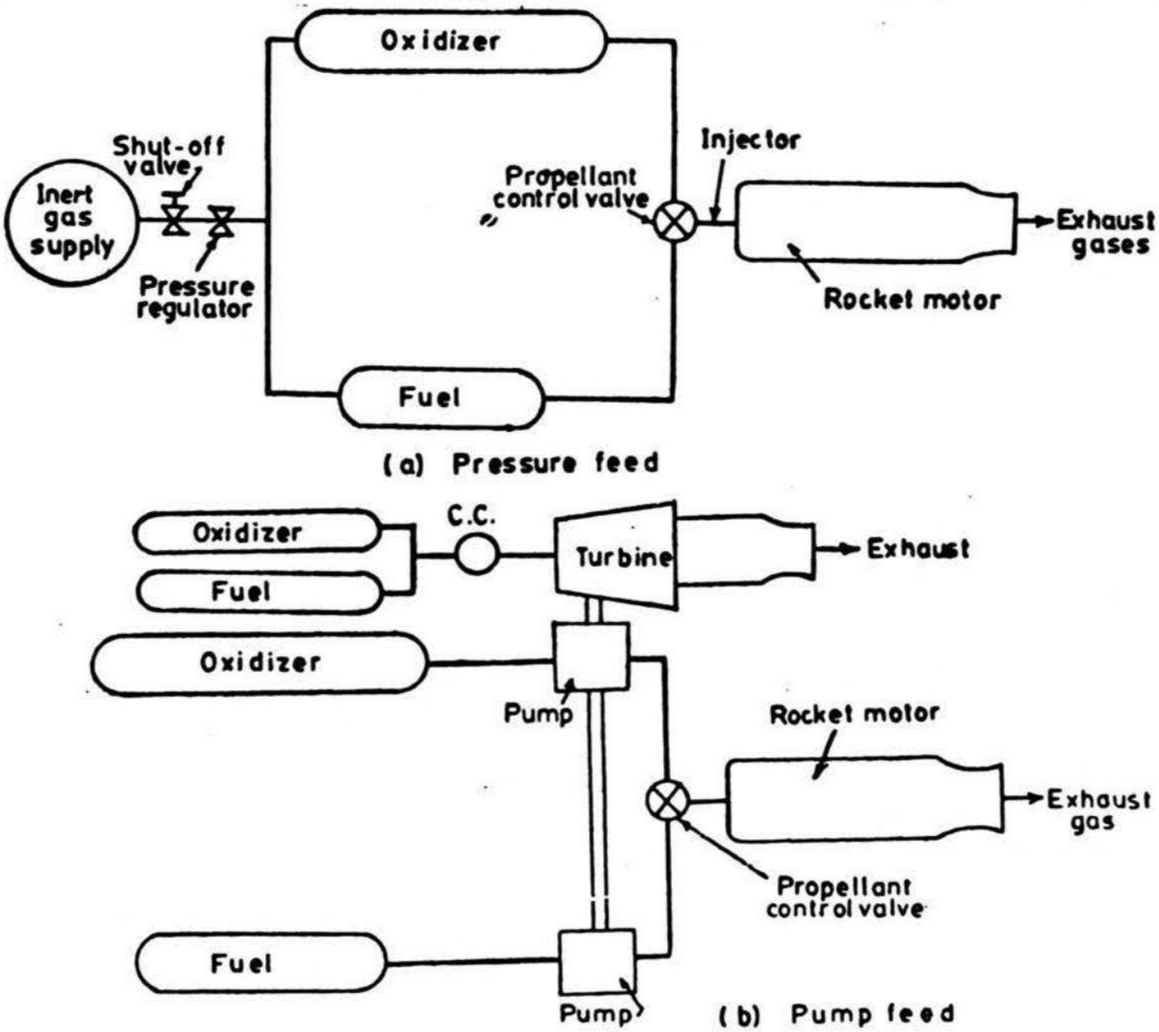

Fig. 5-9. Schematic diagrams of bi-propellant rocket system.

state is injected into a combustion chamber, burned and exhausted at a high velocity through the nozzle. The liquid propellant is also used to cool the rocket motor by circulation of fuels around the walls of the combustion chamber and around the nozzle. Certain liquid fuel, however, such as hydrogen peroxide, burn at such temperatures that no cooling is necessary. Figure 5–9 shows schematic diagrams of pressure feed and pump feed liquid bipropellant rocket systems.

Problem–2 : *The effective exit jet velocity of a rocket is 3000 m/sec, the forward flight velocity is 1500 m/sec and the propellant consumption is 70 kg per sec. Calculate : (a) Thrust, (b) Thrust power, (c) Specific impulse, (d) Specific propellant consumption, and (e) Propulsive efficiency of the rocket.*

(a) Using eqn. (5.11),

Thrust, $T = m_p \times V_{ej} = 70 \times 3{,}000 = 2{,}10{,}000$ N or **210 kN**

(b) Using eqn. (5.13),

Thrust power, $TP = T\ V_o = 2{,}10{,}000 \times 1{,}500 = \mathbf{315 \times 10^6}$ **N.m/s**

(c) Using eqn. (5.14),

$$\text{Specific impluse, } I_{sp} = \frac{T}{m_p} = \frac{m_p \cdot V_{ej}}{m_p} = V_{ej} = \mathbf{3{,}000 \ N.s/kg}$$

(d) Specific propellant consumption $= \frac{m_p}{T} = \frac{m_p}{m_p \, V_{ej}} = \frac{1}{V_{ej}} = \frac{1}{3{,}000}$

$$= \mathbf{3{\cdot}3 \times 10^{-4} \ kg/N.s}$$

(e) Using eqn. (5.14),

$$\text{Propulsive efficiency, } \eta_p = \frac{2\,(V_o/V_{ej})}{1 + (V_o/V_{ej})^2}$$

$$= \frac{2(1500/3000)}{1 + (1500/3000)^2} = 0{\cdot}8 \text{ i.e., } \mathbf{80\%}$$

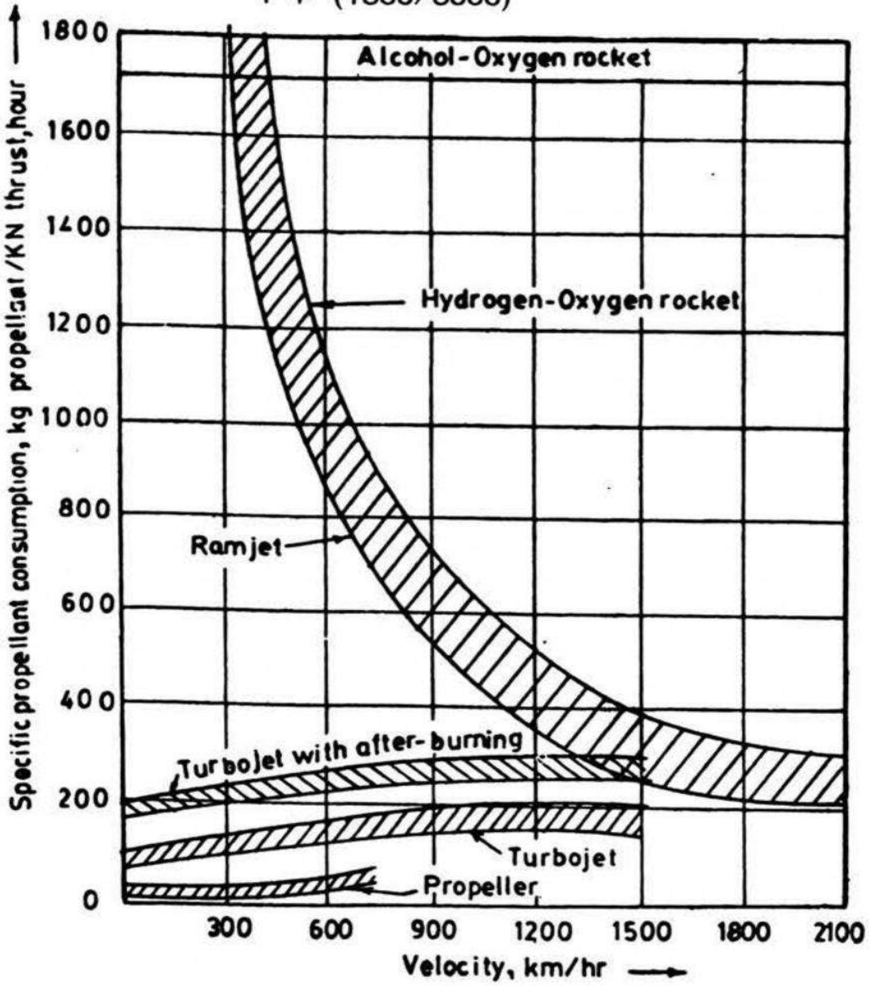

Fig. 5-10. Propellant or fuel consumption versus flight speed for different propulsion systems.

5.7 Comparison of the Various Propulsion Systems

Figure 5–10 shows the specific propellant consumption in kg per kN thrust versus speed for different engines. The curves in this figure indicate that the use of rocket engines to power air planes, as we know them today, is not feasible because of their high fuel consumption. Also, the use of ram jet engines is not economical at lower than 1500 km/hr vehicle speeds.

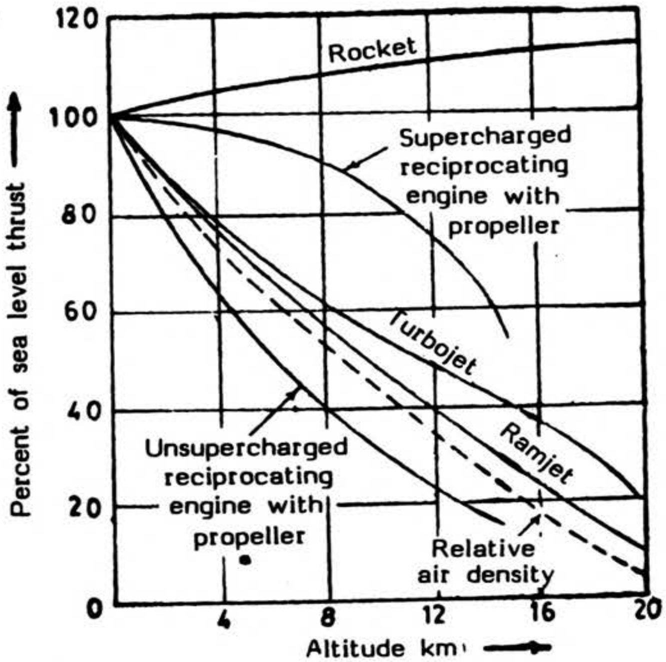

Fig. 5–11 Variation of thrust with altitude for different propulsion systems.

Figure 5–11 shows variation of thrust with altitude for different propulsion systems. It may be noted that the thrust of rocket motor increases with altitude while the thrust of other types of vehicles decreases with altitude.

Figure 5–12 gives relative picture of the probable operating envelope of the various propulsion systems.

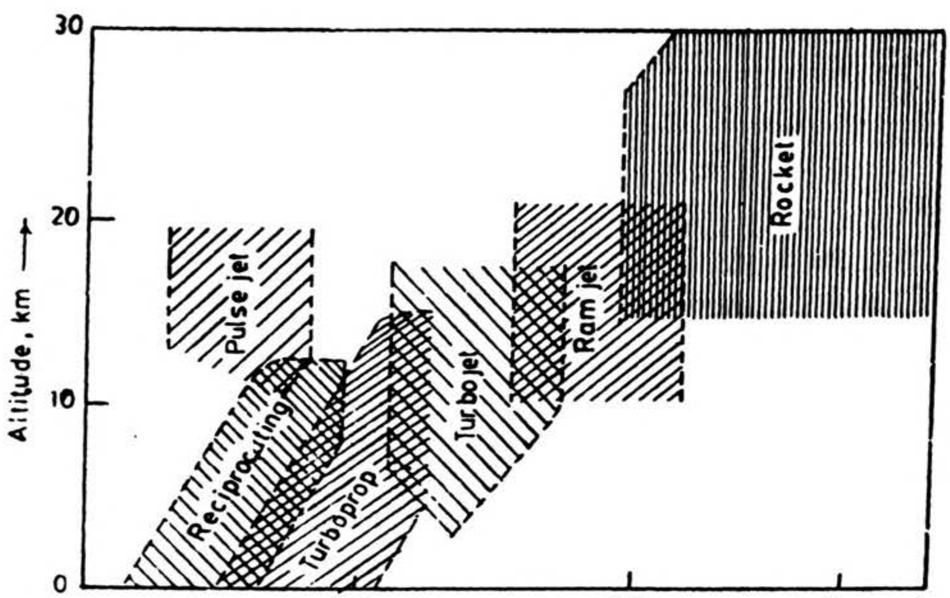

Fig. 5-12 Comparison of probable best performance for various propulsion engines.

INDUSTRIAL APPLICATIONS

INDUSTRIAL APPLICATIONS

- IN AIRCRAFT- Fighter plane, Missiles, Rocket, Airplane.
- Jet propulsion, land and sea transport, racing car.
- The first use of the jet engine was to power military aircraft.
- The General electric company used a "turboprop" jet engine to run an electric generator.
- The jet engine is not only used on aircraft but on boats, where water jets are used to propel the boat forward.
- Normal type of jet engine is used for domestic purpose i.e. Traveling, carrying goods etc.

An aircraft using this type of jet engine could dramatically reduce the time which it takes to travel from one place to another, potentially putting any place on Earth within a 90-minute flight.

Scramjet vehicle has been proposed for a single stage to tether vehicle, where a Mach 12 spinning orbital tether would pick up a payload from a vehicle at around 100 km and carry it to orbit

Rocket applications

1. Satellites in space serve air communication
2. Spacecraft
3. Missiles
4. Jet assisted air planes
5. Pilotless aircraft

TUTORIAL QUESTIONS

Theory Questions:

1. What are the different rocket propulsion systems? Brief the working differences between the propeller-jet, turbojet and turbo-prop.
2. With a neat diagram explain the working of rocket engine
3. Describe briefly about thrust augmentation method used in propulsion.
4. With a neat sketch, explain the working of turbo jet engine.
5. Differentiate between solid propellant and liquid propellant rocket engines.
6. What are the applications of pulse jet engines
7. Give the difference between ramjet and pulse jet engines
8. What are composite and homogeneous solid propellants? How do they work? State their merits and demerits.
9. What is the essential difference between rocket propulsion and turbo-jet propulsion?
10. Write a detailed classification of rockets. Explain liquid propellant rocket with a neat sketch Define and explain the terms:
    i. Thrust
    ii. Thrust power,
    iii. Effective jet exit velocity,
    iv. Propulsive efficiency related to turbojet engines.
11. What are the various applications of rockets?
12. Explain the advantages and disadvantages of bipropellants used in rocket engines over monopropellants.
2. Derive expressions for the thrust and propulsion efficiency of rockets and compare with those of turbojet

Numerical Problems:

1. A jet propulsion system has to create a thrust of 100 tones to move the system at a velocity of 700 km/hr. If the gas flow rate through the system is restricted to a maximum of 30 kg/s. find the exit gas velocity and propulsive efficiency.

2. In a jet propulsion unit, initial pressure and temperature to the compressor are 1.0 bar and 100C. The speed of the unit is 200m/s. The pressure and temperature of the gases before entering the turbine are 7500 C and 3 bar. Isentropic efficiencies of compressor and turbine are 85% and 80%. The static back pressure of the nozzle is 0.5 bar and efficiency of the nozzle is 90%. Determine (a) Power consumed by compressor per kg of air. (b)Air-fuel ratio if calorific value of fuel is 35,000 kJ/kg. Cp of gases=1.12 kJ/kg K, _ =1.32 for gases.
3. A turbo-jet engine flying at a speed of 960 km/h consumes air at the rate of 54.5 kg/s. calculate i). Exit velocity of the jet when the enthalpy change for the nozzle is 200 KJ/kg and velocity coefficient is 0.97. ii).fuel flow rate in kg/s when air fuel ratio is 75:1 iii). Thrust specific fuel consumption iv). Propulsive power v). Propulsive efficiency.
4. A simple turbine jet unit was tested when stationary and the ambient conditions were 1bar and 150C. The pressure ratio for the compressor was 4:1. A fuel consumption of 0.37kg/s was obtained for an air flow of 23kg/s. Calculate the thrust produced if the exhaust gases from the turbine were expanded to atmospheric pressure in a convergent nozzle. Assume the following data:

   Isentropic efficiency of compressor-80% Isentropic efficiency of turbine-85%

   Efficiency of nozzle-93% Transmission efficiency-98%

   Calorific value of fuel-42000kJ/kg Assuming working fluid to be air throughout.

5. In a turbojet, air is compressed in an axial compressor at inlet conditions of 1 bar and 1000C

   3.5 bar. The final temperature is 1.25 times that for isentropic compression. The temperature of gases at inlet to turbine is 4800C. The exhaust gases from turbine are expanded in a velocity of approach is negligible and expansion may be taken to be isentropic in both turbine and nozzle. Value of gas constant R and index r are same for air and flue gases.

   Determine

   i) Power required to drive the compressor per kg of air/sec

   ii) Air-fuel ratio if the calorific value of fuel is 42,000 kJ/kg

   iii) Thrust developed / kg of air / sec.

ASSIGNMENT QUESTIONS

ASSIGNMENT QUESTIONS

1. Why is thrust augmentation necessary? What are the methods for thrust augmentation in a turbojet engine?
2. A turbo-jet engine flying at a speed of 960 km/h consumes air at the rate of 54.5 kg/s. calculate i). Exit velocity of the jet when the enthalpy change for the nozzle is 200 KJ/kg and velocity coefficient is 0.97. ii).fuel flow rate in kg/s when air fuel ratio is 75:1 iii). Thrust specific fuel consumption iv). Propulsive power v). Propulsive efficiency.
3. With a neat diagram explain the working of rocket engine
4. What is turbine and classify them?