1. THERMAL POWER PLANT

1.1 Introduction

- The steam power plants, Diesel power plants, Gas Turbine power plants and Nuclear Power plant are known as Thermal power Plant. However, generally steam power plant is called as thermal power plant. The Steam power plant can perform two purposes .**1)** To generate electricity only **2)** To generate electricity along with production of steam for process heating.

1.2 Working of a Steam Power Plant

- Steam power plant basically works on the Rankine cycle in which steam and water is working fluid. In the boiler steam is generated from water by using heat of flue gases which is produced by means of burning of coal. The Steam which is expanded in a turbine, which produces mechanical power. The output power of turbine is utilized to run the generator. The steam after expansion in turbine is usually condensed in a condenser. The condensed steam (Water) is again feed to the boiler and cycle is repeated.
- The Schematic diagram of Rankine Cycle is shown in Fig 1.1. A Rankine cycle is represented on p-v, T-s and h-s diagram in Fig 1.2.
- The Main Components of cycle are: 1) Boiler 2) Turbine 3) Condenser 4) Feed Pump

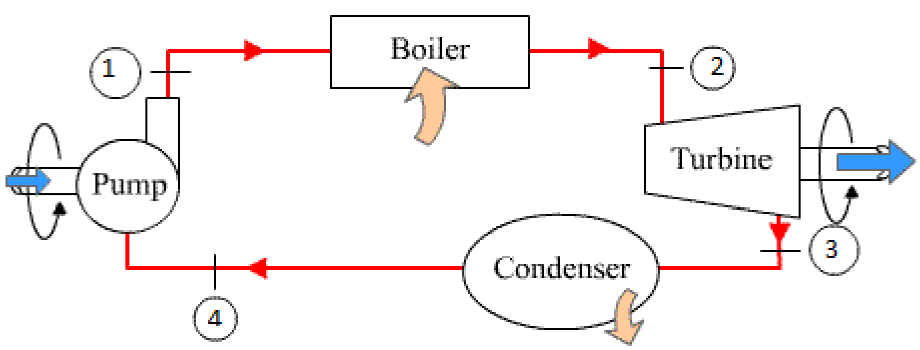


Fig 1.1 Schemtaic diagram of Rankine cycle

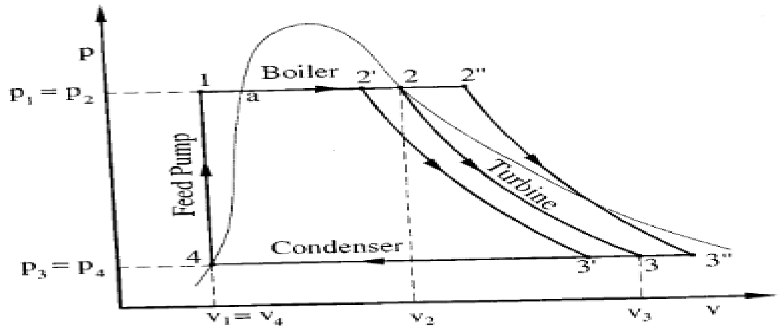


Fig. 1.2(a) p-v diagram of Rankine cycle

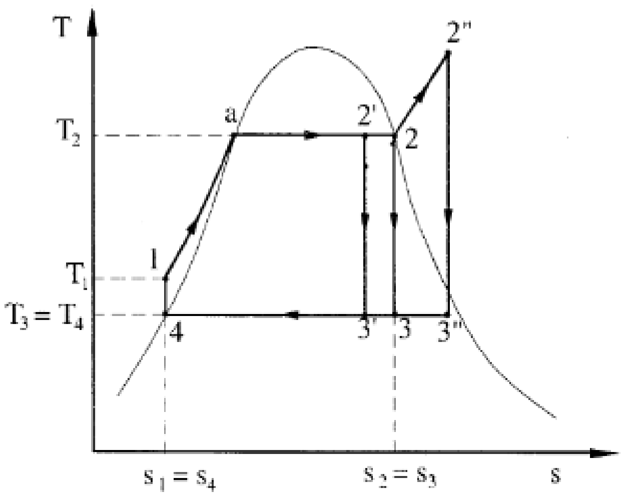


Fig. 1.2 (b) T-s diagram of Rankine cycle

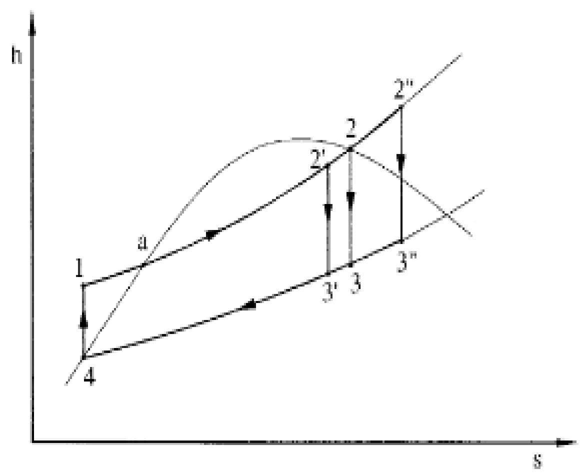


Fig. 1.2 (c) h-s diagram of Rankine cycle

- Consider 1 kg of saturated water at pressure p_1 and temperature T_1. The cycle is completed by the following four processes.

1) Process 1-2: The water at constant pressure P_1 is heated in the boiler until the saturated temperature is reached (Process 1-a). Saturated water may be converted into dry saturated steam (Process a-2), wet steam (a-2') or superheated steam (a-2") at constant pressure P_1. **(Constant pressure transfer of heat in the Boiler)**

2) Process 2-3: Steam expand reversibly and adiabatically in the turbine from state 2 to state 3.during this process pressure and temperature falls from p_2 to p_3 and T_2 to T_3 respectively.
(Reversible adiabatic expansion in the Turbine)

3) Process 3-4: The steam coming from turbine at state 3 is now isothermally condensed in a condenser and the heat is rejected at constant temperature T_3 and pressure P_3 until the whole steam is condensed into water.
(Constant pressure transfer of heat in condenser)

4) Process 4-1: The condensate water coming from condenser at state 4 is pumped to boiler pressure at state 1 reversibly and adiabatically with help of feed pump.
(Reversible adiabatic pumping process in feed pump)

1.3 Efficiency of a Rankine Cycle

- Heat Supplied in the boiler $q_S = h_2 - h_1$
- Work produced by the Turbine $W_T = h_2 - h_3$
- Heat rejected to cooling water in condenser $q_R = h_3 - h_4$
- Work input to feed pump $W_P = h_1 - h_4$

Now, Net Output $W_{net} = W_T - W_p = (h_2 - h_3) - (h1 - h_4)$

$$Rankine \text{ cycle efficiency} = \frac{Net \text{ work output}}{Heat \text{ supplied}} = \frac{W_{net}}{q_S}$$

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

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

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

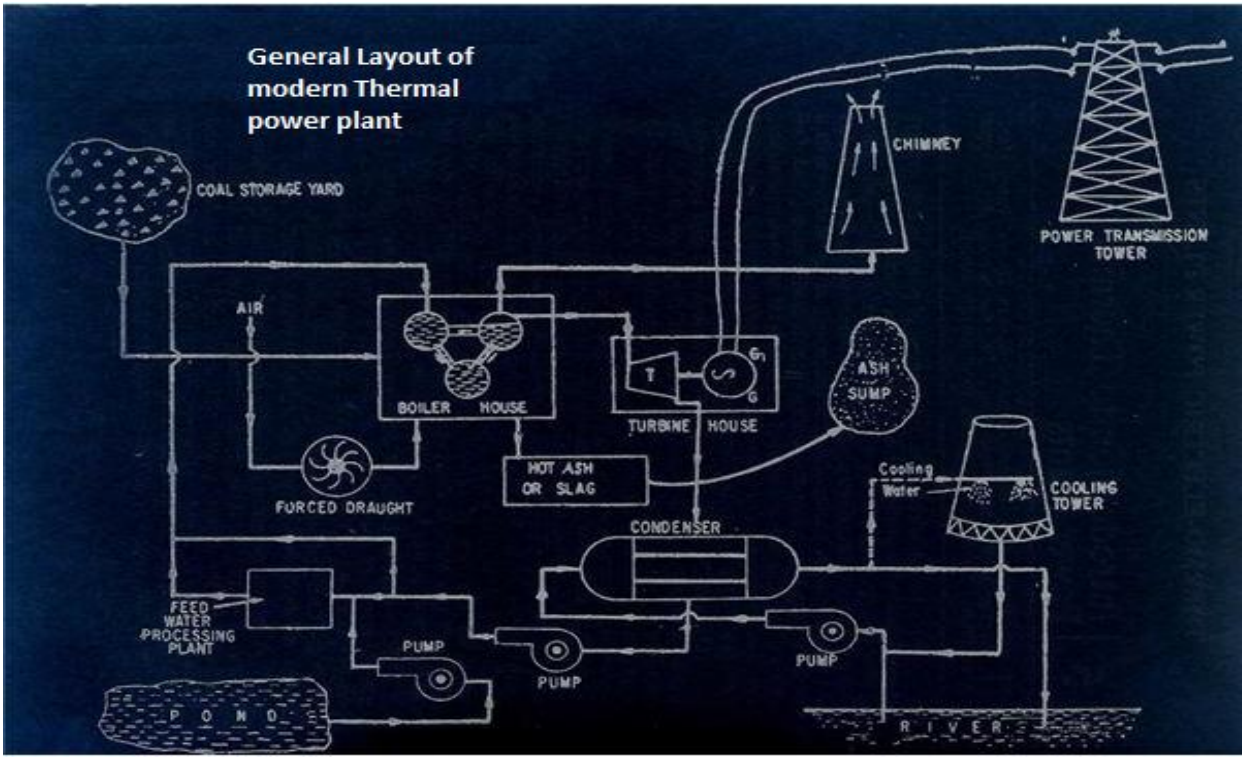
Usually pump work is very small, hence it may be neglected.

$$Rankine \text{ cycle efficiency} = \frac{h_2 - h_3}{h_2 - h_1}$$

1.4 General Layout of Modern Thermal Power Plant

- The general layout of the thermal power plant consists of mainly 4 circuits as shown in Fig.
- **The four main circuits are:**

1) **<u>Coal and ash handling circuit</u>:**
    - In this circuit ,the coal from the storage is fed to the boiler through coal handling equipment for the generation of steam. Ash produced due to combustion of coal is removed to ash storage through ash handling system.
2) **<u>Air and gas circuit</u>:**
    - Air is supplied to the combustion chamber of the boiler either through F.D. or I.D. fan or by using both. The dust from the air is removed before supplying through combustion chamber. The exhaust gases carrying sufficient quantity of heat and ash are passed through the air heater where exhaust heat of gases is given to the air and then it is passed through the dust collectors where most of the dust is removed before exhausting the gases to the atmosphere through chimney.
3) **<u>Feed water and steam circuit</u>:**
    - The steam generated in the boiler is fed to the steam prime mover to develop the power. The steam coming out of prime mover is condensed in the condenser and then fed to the boiler with the help of the pump. The condensate is heated in the feed heaters using the steam tapped from different points of the turbine.
    - Some of the steam ad water is lost passing through different components of the system, therefore feed water is supplied from external source to compensate this loss.
    - The feed water supplied from external source is passed through the purifying plant to reduce the dissolved salts to an acceptable level to avoid the scaling of the boiler tubes.
4) **<u>Cooling water circuit</u>:**
    - The quantity of cooling water required to condense the steam is considerably large and it is taken either from lake, river or sea. The cooling water is taken from the upper side of the river, it is passed through the condenser and heated water is discharge through the lower side of the river. such system of cooling water is possible if adequate cooling water available throughout the year. This system is known as **open system.**
    - When adequate water is not available, then the water coming out from the condenser is cooled either in cooing tower or cooling pond**.** The cooling is effected by partly evaporating the water. When the cooling water coming out from the condenser is cooled again supplied to the condenser then the system is known as **closed system.**



1.5 Site selection of Thermal Power plant

- Following important factors to be considered for the selection of site for thermal power plants are as follows:

1) **<u>Availability of coal</u>**:
    - The major source of energy which is available in India for thermal power plants is coal. Therefore, it is necessary to concentrate for the best use of coal for power generation.
    - The huge quantity of coal is required for large thermal power stations. A thermal power plant of 400 MW capacity requires 5000 to 6000 tons of coal per day. Therefore, it is necessary to install the power station near the coal mines. In this case, the power generation must be transported to the long distances therefore, it is necessary to find the location which will give the lowest cost considering the coal transport and power transmission charge.
2) **<u>Ash Disposal Facilities:</u>**
    - The ash removal problem has become more serious particularly in India because the coal used for power generation contains large percentages of ash(20 to 40%). The quantity of ash to be handled is as large as 1500 to 2000 tons per day.
    - The ash handling problem is more serious than coal handling because it comes out in hot condition and it is highly corrosive. Its effect on atmospheric pollution is more serious as the human health is concerned. Therefore there must be sufficient

space dispose of large quantity of ash. A 400 MW power station requires nearly 10 hectares area per year if the ash is dumped to a height of 6.5 meters.

- The ash can be easily disposed off to river ,sea or lake economically if such facilities are available at plant site. Presently the ash from the power plants is used for many industrial processes, therefore, the question of its disposal to sea or river does not arise.

3) **Space Requirement:**
   - The average land requirement is 3 to 5 acres per MW capacity which includes the space required for coal storage, ash disposal, staff colony, market facilities and the space required for whole machinery.
   - Generally the space occupied in 10% of the buildings, 33% for coal storage,27% for cooling towers,7% for switch yard and 235 for other purposes. The cost of land adds in the final cost of the plant therefore it should be available at cheap rates.
4) **Nature of Land**:
   - The selected site for the power plant should have good bearing capacity as it has to withstand the dead load of the plant and forces transmitted to the foundation due to machine operations. The minimum bearing capacity of the land should be 10 bar.
5) **Availability of water**:
   - Large quantities of water are required for condenser, for disposal of ash and as feed water to the boiler and drinking water to the working staff.
   - The quantity of cooling water required in the condenser condensing the steam coming out from the turbines of 60 MW capacity plant is of the order of 20 to 30 thousand tons per hour if it discharged to the lower side of the river. If the cooling towers are used, then the makeup water required is also 500 to 600 tons per hour. It is therefore, necessary to locate the power plant near the water source which will able to supply the required quantity of water throughout the year.
6) **Transport Facilities**:
   - It is always necessary to have a railway line available near the power station for bringing in heavy machinery for installation and for bringing the coal.
   - It is always thought that the site of thermal power plant near the coal pit-head is more economical than selecting the site near the load centre.
7) **Availability of labour**:
   - Cheap labour should be available at the proposed site as enough labour is required during construction of the plant.

8) **Public Problems**:
    - The proposed site should be far away from the towns to avoid the nuisance from smoke, fly ash and heat discharge from the power plant.
9) **Size of the Plant**:
    - In small capacity plants, the cost of getting fuel into the plant and ease of water supply are relatively insignificant factors and the problem of the plant location reduces almost entirely to an electric transmission problem. Other things being equal, the plant must be located at such a point that the investment in electric cables for transmitting the power together with annual operating costs should be minimum.

1.6.1 Advantages of Thermal Power plant

1) Thermal power plant can be located near the load centre if water source available near the site.
2) They can respond quickly against change of load without difficulty.
3) The power plant does not depend on natural sites available and hydrological cycle in that country as hydro power plant.
4) Thermal power plant is more flexible to use any types of boilers and fuels.The FBC boiler can be used with any types of low grade fuel including municipal wastes and therefore it is a cheaper method of power generation.
5) A portion of steam generated can be used a process steam in different industries.
6) The steam turbine can be work under 25% of overload continuously.
7) Thermal power plant requires less investment cost compared to hydro electric power plants.
8) Less space is required compare to hydro electric power plants.
9) Thermal efficiency of thermal power plant can be increased when it works conjuction with gas turbine power plant.
10) Thermal power plant requires less time for installation compared to hydro electric power plant.
11) The application of thermal power plant is most economical if sited near coal mines and by the side of river or canal.

1.6.2 Disadvantages of Thermal Power plant

1) Thermal power plant requires large quantity of water for boiler and condenser.
2) The fuel transportation cost is high especially when the power plants are away from coal mines and has no railway siding.
3) It has a very high operating cost compared to hydro and nuclear power plants.
4) The thermal power plant pollutes the atmosphere by fumes, and residues of pulverized fuels.

5) The thermal power plant requires large number of equipments compared to other power plants, hence plant becomes very complex.
6) In thermal power plant, there is great difficulty experienced in coal handling.
7) The thermal power plant is less efficient below 75% of load.
8) The thermal power plant requires long times for erection and putting into action.

1.7.1 Present status of power Generation in India

- Economic growth in India depends on the power sector. The electric energy demands in the last two decades have increased at enormous space. In 1947, the total power generation was only 1360 MW.

- India is still short of 20% of power generation in India. Due to depleting natural resources of fuel, India is also developing non-conventional energy sources like wind, tide, biomass, geothermal and solar energy based power plants.

Type of power plant	**1991**	**8th plan (1997)**	**9th plan (2002)**	**10th plan (2007)**	**Total**
Thermal(including gas based plants)	45000	28000	32000	58000	163000
Hydro	18443	8680	26000	23000	76123
Nuclear	1500	1320	2880	-	5700
Additional	-	38000	60880	81000	-
Total	64943	102943	163823	244823	244823

1.7.2 Role of NTPC in development of power in India

- NTPC Limited was established in 1975 which is a premier Public Sector Enterprise. It is a world class integrated power major and its role is to develop power for India's growth with increasing global presence.

- NTPC has an installed capacity of 27904 MW through 26 power stations. It includes the power stations under joint venture with states and private sector.

- It has power stations producing power which are coal, oil and gas based. Also it has its presence in hydro power, coal mining, oil and gas exploration power distribution and trading also has plans to develop nuclear power plants.

- NTPC has planned to develops 50000 MW power by 2012 and 75000 MW by 2017.It has about 21% share of total installed capacity of the nation.
- The company has equity stake of about 45% for manufacturing of transformers in the Transformers & Electricals Kerala Ltd (TELK). The company has also plans o set up and operate thermal power plants overseas. In this regard, they have already signed a MOU with Nigeria and Srilanka.
- At present, it has hydropower development of 1920 MW capacity. It's subsidiary company NTPC Hydro Ltd has planned to set up 4791 MW of small hydro projects in various places in the country.

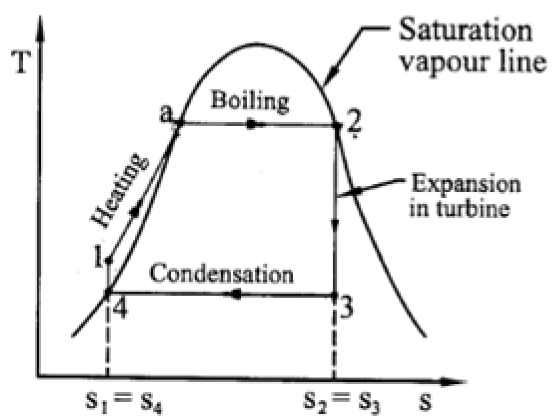
1.8 Exercise of Rankine cycle

Ex-1.

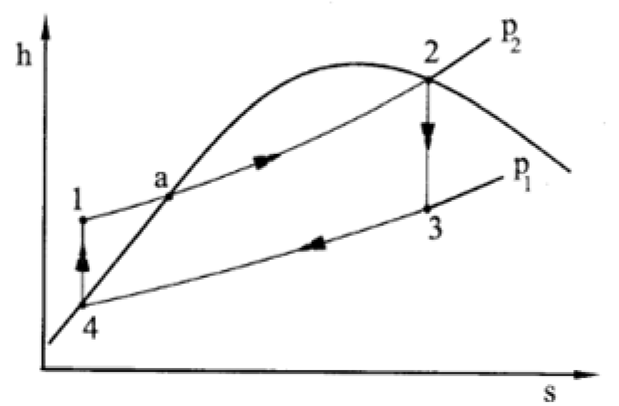
A steam power plant working on Rankine cycle has range of operation from 40 bar dry saturated at 0.05 bar. Determine: 1) Cycle efficiency 2) work ratio 3) specific steam consumption

Sol^n: Given Data: P_1=P_2=40 bar, P_3=P_4=0.05 bar, η_r =? , WR=? $\dot{m}_s$=?

The steam at the inlet of turbine is dry saturated. Hence point 2 is on saturated vapour line as shown in Fig.



T-s diagram of Rankine cycle



h-s diagram of Rankine cycle

- At state point **2**, P_2=40 bar, dry saturated steam. Hence from steam table

  h_{g2}= 2800.3 KJ/Kg , Sg_2= 6.0685 KJ/Kg k

- At state point **3**, P_3=0.05 bar hence from steam table

h_{f3}=137.8 KJ/Kg , h_{fg3}= 2423.7 KJ/Kg

S_{f3}=0.476 KJ/Kg k , S_{fg3}= 7.919 KJ/Kg k

V_{f3}=0.001005 m^3/kg (Specific volume of water)

- **For isentropic expansion process 2-3 (constant entropy process) $S_2=S_3$**

But for dry steam $S_2=S_{g2}$ and for wet steam $S_3=S_{g3}+ x_3 S_{fg3}$

$S_{g2}= S_{g3}+ x_3 S_{fg3}$

6.0685=0.476 + x_3 (7.919)

x_3=0.706 (dryness fraction of steam at outlet of turbine)

- Now, Enthalpy at point 2, $h_2= h_{g2}$= 2800.3 KJ/Kg

  Enthalpy at point 3, $h_3= h_{g3}+ x_3 h_{fg3}$=137.8 + 0.706 x 2423.7= 1848.93 KJ/Kg

- Work produced by steam turbine $W_T=h_2-h_3$=2800.3-1848.93=951.37 KJ/Kg

- Work consumed by pump Wp= V_4 x (P_1-P_4)

But $V_4= V_{f3}$, $P_1=P_2$, $P_4=P_3$

$\therefore$ W_p= 0.001005(40 x 10^5 - 0.05 x $10^{5)}$ (here 1 bar = 10^5 N/m^2 taken)

$\therefore$ W_p=4014.97 J/kg=4.0149 KJ/kg

- Net Work Produced $W_{net}= W_T$- Wp=951-4.0149=947.35 KJ/kg.

But $W_p=h_1-h_4$

$h_1= W_p+ h_4$=4.0149 + 137.8 = 141.81 KJ/kg

- Now, heat supplied to the boiler

  $q_s= h_2-h_1$= 2800.3-141.81=2658.49 KJ/kg

1) Cycle efficiency $\eta_R = \frac{Wnet}{qs} = \frac{947.35}{2658.49} x100$ **= 35.63 %**

2) Work ratio WR = $\frac{Wnet}{Wt} = \frac{947.35}{951.37} = 0.99$

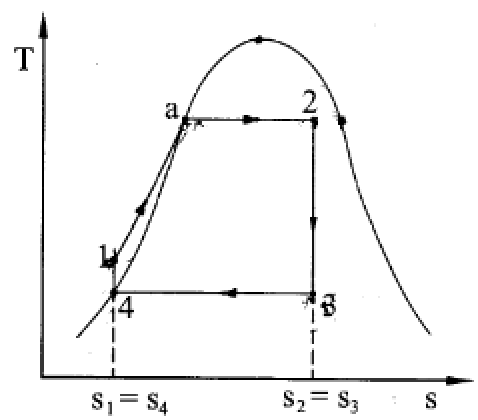
3) Specific steam consumption = Amount of steam in kg per KW hr.

$$= \frac{3600}{h_2 - h_3} = \frac{3600}{W_T} = \frac{3600}{951.37} = \mathbf{3.78\ kg/kW\ hr}$$

Ex-2.

Determine the Rankine efficiency for a cycle working between pressure limits of 20 bar and 0.05 bar, when steam is a) wet and dryness fraction 0.78 b) dry and saturated c) superheated and temperature of superheated steam being 300˚C.

Sol^n: **a) The steam is wet (x_2=0.78) at inlet of the turbine**, hence state point 2 is left side of saturated vapour line as shown in Fig.



- **From Steam table at 20 bar**

  h_{f2}=908.6 KJ/Kg , h_{fg2}= 1888.6 KJ/Kg , h_{g2}= 2797.2 KJ/Kg ,

  S_{f2}=2.4469 KJ/Kg k , S_{fg2}= 3.8898 KJ/Kg k , Sg_2= 6.3366 KJ/Kg k

- Enthalpy of steam at state point 2

  $h_2 = h_{f2} + x_2 h_{fg2}$ **(wet steam)**

  h_2= 908.6 + 0.78 x (1888.6) = 2381.71 KJ/Kg

- Entropy of steam at state point 2

  $S_2 = S_{f2} + x_2 S_{fg2}$ **(wet steam)**

  S_2= 2.4469 + 0.78 x (3.8898) = 5.4809 KJ/Kg k

- **From Steam table at 0.05 bar**

  h_{f3} = 137.8 KJ/kg , h_{fg3}= 2423.7 KJ/kg

S_{f3} = 137.8 KJ/kg k , S_{fg3}= 2423.7 KJ/kgk , V_{f3}= 0.001005 m^3/kg

Now, let us find out the dryness fraction of steam (x_3) at exit of steam turbine.

- For isentropic expansion process 2-3, $\mathbf{S_2=S_3}$

$S_2= S_{f3}+ x_3 S_{fg3}$

$\therefore 5.4809 = 0.476 + x_3 \text{ x } (7.919)$

$\therefore x_3 = 0.632$

Now, Enthalpy of steam at state point 3

$h_3= h_{f3}+ x_3 h_{fg3}$

h_3= 137.8 + 0632 x (2423.7) = 1669.5 KJ/kg

- Work produced by turbine

$W_T= h_2 – h_3$= 2381.71 – 1669.5 = 712.13 KJ/kg

- Work consumed by pump

$W_P = V_4 \text{ x } (P_1\text{-}P_4)$

W_P = 0.001005(20 x 10^5 - 0.05 x $10^{5)}$ (here 1 bar = 10^5 N/m^2 taken and V_4=V_{f3})

W_P = 2.005 KJ/kg

But $Wp=h_1\text{-}h_4$

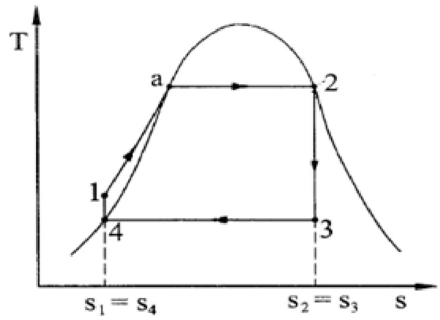
$h_1= W_p+ h_{f3}$=2.005+ 137.8 = 139.8 KJ/kg

- Now, heat supplied to the boiler

$q_s= h_2\text{-}h_1$= 2381.71-139.8=2241.9 KJ/kg

- Rankine Cycle efficiency $\eta_R = \dfrac{Wnet}{qs} = \dfrac{W_T - W_p}{qs} = \dfrac{712.13 - 2.005}{2241.9}$ **= 31.67 %**

b) The steam is dry and saturated at inlet of the turbine, hence state point 2 is on saturated vapour line as shown in Fig.



$h_2 = h_{g2}$ and $S_2 = S_{g2}$ (for dry and saturated steam)

h_2= 2797.2 KJ/kg and S_2= 6.3366 KJ/kg k

But for isentropic process 2-3, $\mathbf{S_2 = S_3}$

$S_2 = S_{f3} + x_3 S_{fg3}$

$\therefore 6.3366 = 0.476 + x_3 \times (7.919)$

$\therefore \mathbf{x_3 = 0.74}$

Now, $h_3 = h_{f3} + x_3 h_{fg3} = 137.8 + 0.74 \times (2423.7) = 1931.5$ KJ/Kg

$W_T = h_2 - h_3 = 2797.2 - 1931.5 = 865.69$ KJ/Kg

$W_p = V_{f3} \times (P4 - P_{3)}) = 2.005$ KJ/Kg and

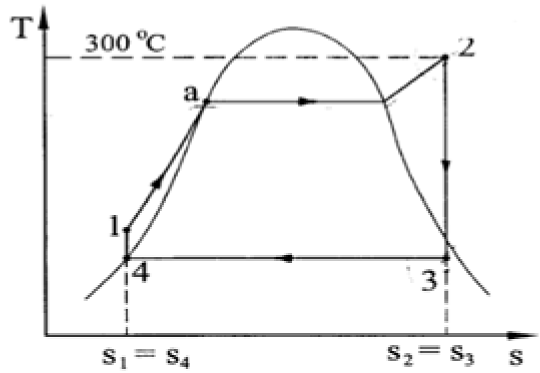
$h_1 = W_p + h_{f3} = 139.8$ KJ/Kg (same as previous case)

- heat supplied to the boiler

  $q_s = h_2 - h_1 = 2797.2 - 139.8 = 2657.4$ KJ/kg

- Rankine Cycle efficiency $\eta_R = \dfrac{Wnet}{qs} = \dfrac{W_T - W_p}{qs} = \dfrac{865.69 - 2.005}{2657.4}$ = **32.50 %**

c) The steam is superheated at inlet of the turbine and superheated temperature 300˚C; hence state point 2 is right side of saturated vapour line as shown in Fig.



- h_2= enthalpy of superheated steam at pressure 20 bar and temperature 300˚C.

  From superheated steam table at 20 bar and T_{sup}= 300˚C.

  h_2= 3025.0 KJ/Kg , S_2= 6.770 KJ/Kg k

  But for isentropic process, $\mathbf{S_2=S_3}$

  $S_2 = S_{f3} + x_3 \times (7.919)$

  $\therefore 6.770 = 0.476 + x_3 \times (7.919)$

  $\therefore \mathbf{x_3 = 0.794}$

  Now, Enthalpy of steam at state point 3

  $h_3 = h_{f3} + x_3 h_{fg3}$

  $\therefore h_3 = 137.8 + 0.794 \times (2423.7) = 2064.15$ KJ/kg

- $W_T = h_2 - h_3 = 3025.0 - 2064.15 = 960.85$ KJ/kg
- W_p= 2.005 KJ/kg and h_1= 139.8 KJ/kg (Same as previous case)
- $q_s = h_2 - h_1 = 3025.0 - 139.8 = 2885.2$ KJ/kg
- Rankine Cycle efficiency $\eta_R = \frac{Wnet}{qs} = \frac{W_T - W_p}{qs} = \frac{960.85 - 2.005}{2885.2}$ = **33.23 %**

Ex-3.

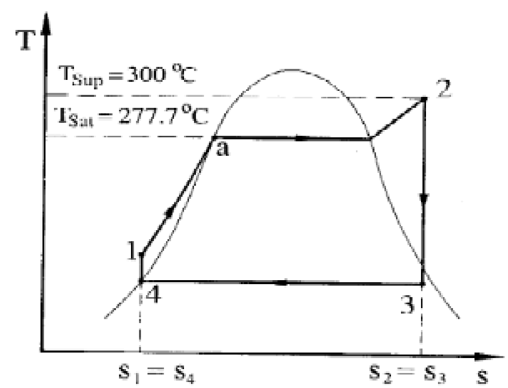
A simple Rankine cycle steam turbine power plant works between pressure 62 bar and 0.07 bar. The temperature of steam at inlet of turbine is 300˚C. calculate the steam consumption when plant developing 40 MW power. Neglect pump work.

Sol^n: Given Data: P_2=P_1= 62 bar, P_4=P_3=0.07 bar, T_2= 300˚C , m_s= ? , P= 40 MW.

- **From steam table at 62 bar**

  T_{s2}= 277.7 ˚C , h_{g2}= 2782.9 KJ/kg , S_g= 2.8283 KJ/Kg k

- At 62 bar pressure saturation temperature is 277.7˚C(from steam table), but temperature of steam is 300˚C. Hence, steam is superheated at inlet of turbine as shown in Fig



- So we need to find out the enthalpy of steam at 62 bar and 300˚C from **superheated steam table.** Since in steam table 62 bar pressure raw is not given. Therefore, the enthalpy of steam at 62 bar and 300˚C can be found by interpolation as follows:

- At 60 bar and 300˚C, from superheated steam table

  $h_{2(60)}$= 2885 KJ/Kg , $S_{2(60)}$= 6.069 KJ/Kg k

- At 70 bar and 300˚C, from superheated steam table

  $h_{2(70)}$= 2839 KJ/Kg , $S_{2(70)}$= 5.933 KJ/Kg k

As equation of interpolation $\frac{h_A - h_B}{P_A - P_B} = \frac{h_A - h_C}{P_A - P_C}$

$$\therefore \frac{h_{2(70)} - h_{2(60)}}{70 - 60} = \frac{h_{2(70)} - h_{2(62)}}{70 - 62}$$

$$\therefore \frac{2839-2885}{70-60}=\frac{2839-h_{2(62)}}{70-62}$$

$\therefore$ **h_2** at 62 bar **= 2875.8 KJ/Kg K.**

Similarly, by interpolation S_2= 6.0962 KJ/Kg k

- From steam table at 0.07 bar

  h_{f3} = 163.4 KJ/kg , h_{fg3}= 2408.1KJ/kg

  S_{f3} = 0.559 KJ/kg k , S_{fg3}= 7.717 KJ/kg k

- For isentropic process 2-3, $S_2=S_3$

  $S_2= S_{f3} + x_3 S_{fg3}$

  $\therefore$ 6.0962=0.559 + x_3 x (7.717)

  $\therefore$ **x_3= 0.717**

Now , $h_3= h_{f3} + x_3 h_{fg3}$= 163.4 + 0.717 x (2409.1) = 1892.9 KJ/Kg

- Net work developed by plant $W_{net}= W_T-W_p$

  = (h_2-h_3)-0=2875.8-1892.0=983.79 KJ/kg

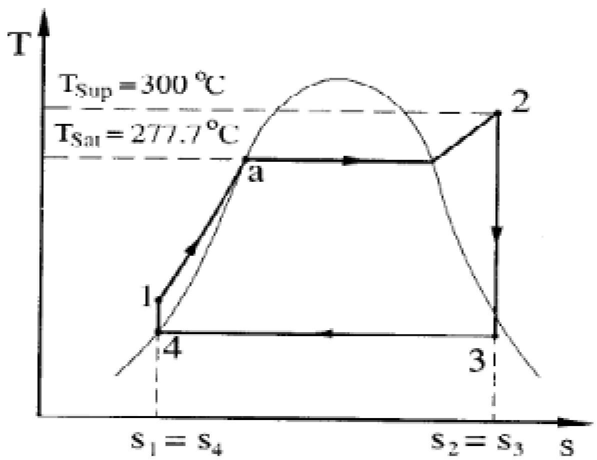
- Net power developed kW = W_{net} x m_s

  $\therefore$ 40 x 10^3 = 983.79 x $\dot{m}_s$

  $\therefore$ **$\dot{m}_s$ =** 40.66 kg/s = 40.66 x 3600 = 146.37 x 10^3 kg/hr

Ex-4. A steam power plant operates on simple Rankine cycle, develops 200 MW power. The boiler and condenser pressures are 60 bar and 0.1 bar respectively. The temperature of steam at inlet of turbine is 400˚C. Determine 1) the quality of steam at the turbine exit, 2) mass flow rate of steam and 3) thermal efficiency of the cycle.

Sol^n: Given Data: P=200MW, P_2=P_1= 60 bar, P_4=P_3=0.1 bar, x_3=? , m_s=? , η_R =?



- From steam table at 60 bar pressure

  T_s=275.5 ˚C (saturation temperature of steam)

Since, Tsup= 400˚C is greater than T_s=275.5 ˚C. Hence at inlet of turbine the steam is superheated.

- From superheated steam table at 60 bar and 400˚C.

  h_2= 3180.1 KJ/kg, S_2= 6.546 KJ/Kg k.

- From steam table at 0.1 bar pressure

  h_{f3}= 191.8 KJ/kg, h_{fg3}= 2392.8 KJ/kg

  $\mathbf{S}_{f3}$ = 0.649 KJ/kgk , S_{fg3}= 7.501 KJ/kg k , V_{f3}= 0.001010 m^3/kg

1) The quality of steam at exit of turbine

For isentropic expansion process 2-3, S_2=$\mathbf{S_3}$

S_2= S_{f3}+ x_3 S_{fg3}

$\therefore 6.546 = 0.649 + x_3 \text{ x } (7.501)$

$\therefore$ **x_3 = 0.786** (dryness fraction at outlet of turbine)

Now, Enthalpy of steam at exit of turbine

$h_3 = h_{f3} + x_3\, h_{fg3}$

$h_3 = 191.8 + 0.786\text{x } (2392.8) = 2072.93\text{KJ/kg}$

- $W_T = h_2 - h_3 = 3180.1 - 2072.93 = 1107.17$ KJ/kg
- $W_p = V_4 (P_1 - P_4) = 0.001010 (60-0.1) \text{ x } 10^5 = 6.0499$ KJ/kg (here $V_4 = V_{f3}$ taken)
- Net work produced $W_{net} = W_T - W_P = 1107.17 - 6.0499 = 1101.12$ KJ/kg

2) Mass flow rate of steam ($\dot{m}_s$)

- Power developed by plant P = $m_{s\ x}\, W_{net}$

$200 \text{ x } 10^3 = m_{s\ x}\, 1101.12$

$\dot{m}_s$ = 181.63 kg/s

- The pump work also given by $W_p = h_1 - h_4$

$6.0489 = h_1 - 191.8$ (here $h_4 = h_{f3}$ taken)

$h_1 = 197.85$ KJ/kg

- Now, heat supplied $q_s = h_2 - h_1 = 3180.1 - 197.85 = 2982.25$ KJ/kg

3) Thermal efficiency of the cycle

$$\eta_R = \frac{W_{net}}{q_s} = \frac{1101.12}{2982.25} x 100 = \mathbf{36.92\ \%}$$

Ex-5. A steam power plant working between boiler pressure 50 bar and condenser pressure 0.1 bar. At inlet of the turbine steam is dry saturated. Mass flow rate of steam is 10000 kg/hr. calculate 1) power output of turbine 2) heat supplied to the boiler 3) heat rejected to the condenser 4) Mass flow rate of cooling water circulating in the condenser. Assume inlet and outlet cooling water temperature are 20˚C and 31˚C respectively.

Sol^n: Given Data: P_1=P_2= 50 bar, P_3=P_4=0.1 bar, x_3=? , m_s= 10000 kg/hr = 2.778 kg/s ,

t_{cwi}= 20˚C, t_{cwo}= 31˚C , P=? , q_s=? , q_R=? , m_{cw} =?

- From steam tables, at 50 bar pressure (for dry saturated steam)

  h_{g2}= 2794.2 KJ/kg, Sg_2= 5.9735 KJ/kg k

- At pressure 0.1 bar

  h_{f3}= 191.8 KJ/kg, h_{fg3}= 2392.8 KJ/kg

  S_{f3} = 0.649 KJ/kgk, S_{fg3}= 7.501 KJ/kg k , V_{f3}= 0.001010 m^3/kg

- For isentropic process 2-3, S2=**S_3**

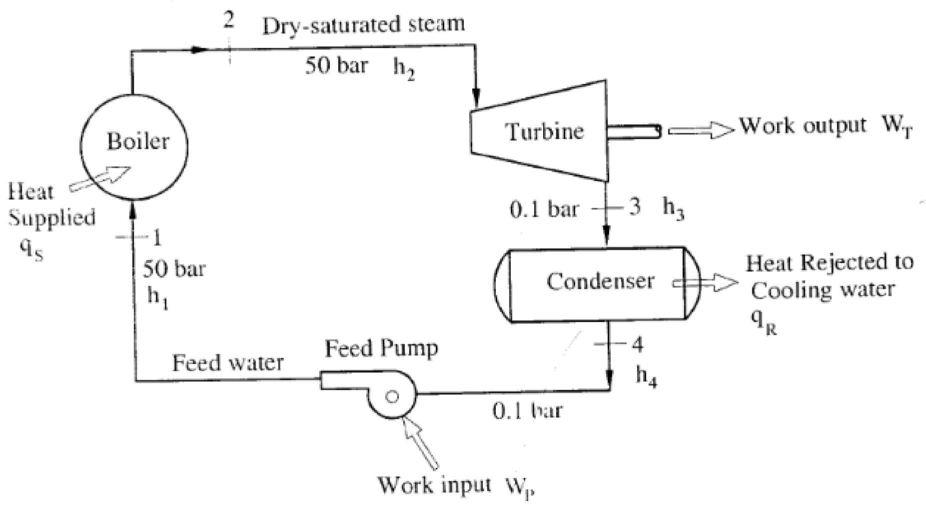
  S_{g2}= S_{g3}+ x_3 S_{fg3}

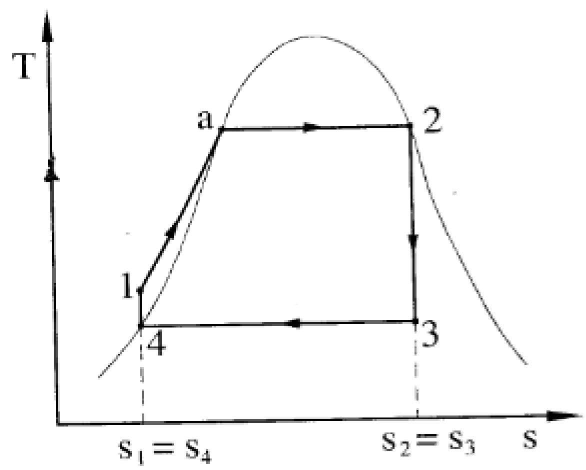
  $\therefore$ 5.9735 = 0.649 + x_3 x (7.501)

  $\therefore$ **x_3 = 0.709** (dryness fraction at outlet of turbine)

  h_3= h_{f3}+ x_3 h_{fg3}

  h_3= 191.8 + 0.709x (2392.8) = 1890.3 KJ/kg





1) **Power developed by plant**

$W_T = h_2 - h_3 = 2794.2 - 1890.3 = 903.89$ KJ/kg

$W_p = V_{f4} \times (P_1 - P_4) = 0.001010 \times (50 - 0.1) \times 10^5 = 5.0399$ KJ/kg

$W_{net} = W_T - W_p = 903.89 - 5.0399 = 898.86$ KJ/kg

Power developed P = $m_s \times W_{net}$

$= 2.778 \times 898.86 =$ **2497 KW**

Also $W_p = h_1 - h_4$ but $h4 = h_{f3}$

$h_1 = W_p + h_4 = 5.0349 + 191.8 = 196.84$ KJ/kg

2) **Heat supplied to the boiler**

$q_s = h2 – h_1 = 2794.2 – 196.84 = 2597.36$ KJ/kg

$Q_s = m_s (h_2 – h_1) = 2.778 \times 2597.36 =$ **7215.46 KJ/s**

3) Heat rejected to the condenser

$q_R = h_3 – h_4 = 1890.3 – 191.8 = 1698.5$ KJ/kg

$Q_R = m_s (h_3 – h_4) = 2.778 \times 1698.5 =$ **4718.43 KJ/s**

4) Mass flow rate of cooling water

Heat rejected by steam to condenser = heat gain by cooling water

$Q_R = m_{cw} (t_{cwo} – t_{cwi})$

$\therefore 4718.5 = m_{cw} (31-20)$ $\therefore m_{cw} = 428.94$ kg/s = **15.44×10^5 kg/hr**

2. STEAM POWER PLANT

2.1 Introduction

- Steam turbine is one of the most important prime mover for generating electricity. This falls under the category of power producing turbo machines. In the turbine, the energy level of the working fluid goes on decreasing along the flow stream

2.2 Principle of Operation of Steam Turbine

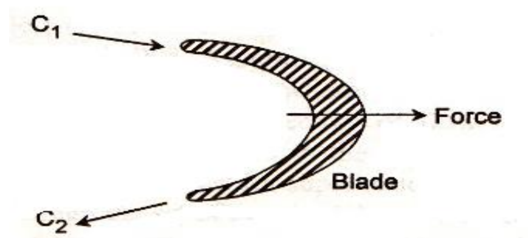


Fig.. 2.1(a). Principle of Working of Turbine.

- The principle of the operation of steam turbine is entirely different from the steam engine. In reciprocating steam engine, the pressure energy of steam is used to overcome external resistance and the dynamic action of steam is negligibly small. But the steam turbine depends completely upon the dynamic action of the steam. According to Newton’s Second law of Motion, the force is proportional to the rate of change of momentum (mass X velocity). If the rate of change of momentum is caused in the steam by allowing a high velocity jet of steam to pass over curved blade, the steam will impart a force to the blade. If the blade is free, it will move off (rotate) in the direction of force [Fig.2.1 (a)].
- In other words, the motion power in a steam turbine is obtained by the rate of change in moment of momentum of a high velocity jet of steam impinging on a curved blade which is free to rotate. The steam from the boiler is expanded in a passage or nozzle where due to fall in pressure of steam, thermal energy of steam is converted into kinetic energy of steam, resulting in the emission of a high velocity jet of steam which impinges on the moving vanes or blades attached on a rotor which is mounted on a shaft supported on bearings, and here steam undergoes a change in direction of motion due to curvature of blade which gives rise to a change in momentum and therefore a force. This constitutes the driving force of the turbine. This arrangement is shown in Fig 2.1 (b). It should be realized that static pressure of the steam or from any impact of the jet, because the blade

in designed such that the steam jet will glide on and off the blade without any tendency to strike it.

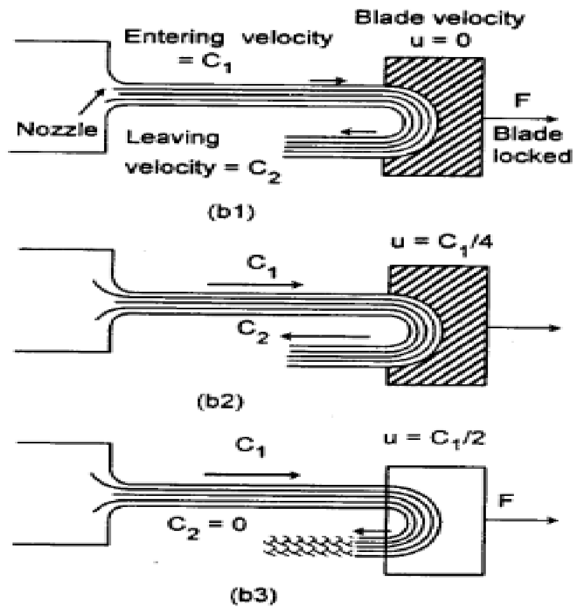


Fig. 2.1(b). Effect of Blade Velocity

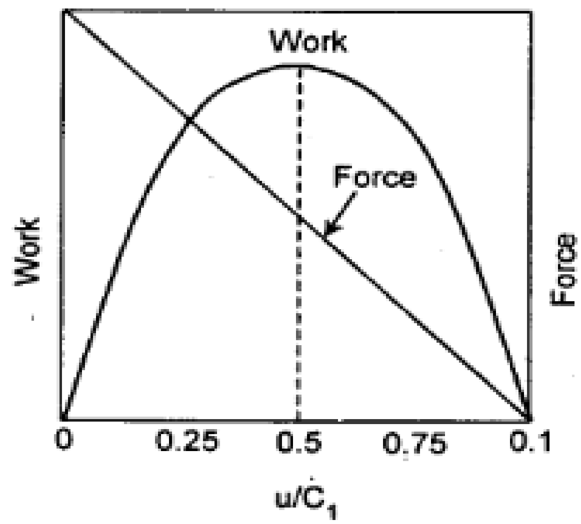


Fig 2.2 work, Force & blade velocity

- From the above discussion, it follows that a steam turbine should have a row of nozzles, a row of moving blade fixed to the rotor, and the casing (cylinder). A row of nozzles and a row of moving blades constitutes a stage of turbine.

2.3Classification of Steam Turbine

(A)On the basis of the principle Operation:-

(i) Impulse turbine

(a)Simple, (b) Velocity stage,(c)Pressure stage, (d) combination of (b) and (c)

(ii)Impulse-reaction turbine

(a)50% (Parson’s) reaction, (b)Combination of impulse and reaction.

(i) **Impulse Turbine :** If the flow of steam through the nozzles and moving blade of a turbine takes place in such a manner that the *steam is expanded only in nozzles and pressure at the outlet sides of the blades is equal to that at inlet side*”

(ii) **Impulse-Reaction Turbine:** In the turbine, the *drop in pressure of steam takes place in fixed (nozzles) as well as moving blades*

(B)On the basis of "Direction of flow":

(i) Axial flow turbine, (ii) radial flow turbine, (iii) Tangential flow turbine.

(i) **Axial Flow Turbine: -** In axial flow turbine, the steam flows along the axis of the shaft.
(ii) **Radial Flow Turbine:** In this turbine, the steam flows in the radial direction.
(iii) **Tangential Flow Turbine:** In this type, the steam flows in the tangential direction.

(C)On the basis of Means of Heat Supply:

(i) Single Pressure turbine, (ii) Mixed or dual pressure turbine
(ii) Reheated turbine, (a) Single (b) Double

(i) Single Pressure turbine: In this type of turbine, there is single source of steam supply
(ii) Mixed or Dual Pressure turbine: This type of turbine, use two source of steam at different pressure. The dual pressure turbine is found in nuclear power stations where it uses both sources continuously.
(iii)Reheated turbine: During its passage through the turbine steam may be taken out to be reheated in a reheater incorporated in the boiler and returned at higher temperature to be expanded.

(D) On the basis of Means of Heat Rejection:

(i)Pass-out or extraction turbine, (ii) Regeneration turbine, (iii) Condensing turbine, (iv) Non-condensing turbine, (v) Back pressure or topping turbine.

(i) Pass-out Turbine: In this turbine, a considerable proportion of the steam is extracted from some suitable point in the turbine where the pressure is sufficient for use in process heating; the remainder continuing through the turbine.
(ii) Regenerative Turbine: This turbine incorporates a number of extraction branches, through which small proportions of the steam are continuously extracted for the purpose of heating the boiler feed water in a feed heater in order to increase the thermal efficiency of the plant
(iii) Condensing Turbine: In this turbine, the exhaust steam is condensed in a condenser and the condensate is used as feed water in the boiler.
(iv) Non-Condensing Turbine: When the exhaust steam coming out from the turbine is not condensed but exhausted in the atmosphere is called non-condensing turbine.

(v) Back Pressure or Topping Turbine: This type of turbine rejects the steam after expansion to the lowest suitable possible pressure at which it is used for heating purpose. Thus back pressure turbine supplies power as well as heat energy.

(E) On the basis of Number of Cylinder:

(i)Single Cylinder and (ii) Multi-cylinder

(i) Single Cylinder: - When all stages of turbine are housed in one casing,
(ii) Multi-Cylinder: - In large output turbine, the number of the stages needed becomes so high that additional bearing are required to support the shaft.

(F) On the basis of Arrangement of Cylinder Based on General Flow of Steam.

(i)Single flow, (ii) Double flow and (iii) Reversed flow

(i) Single Flow. In a single flow turbines, the steam enters at one end, flows once through the bladings in a direction approximately parallel to this axis,
(ii) Double Flow. In this type of turbines, the steam enters at the centre and divides, the two portions passing axially away from other through separate sets of blading on the same rotor.

(G) On the Basis of Number of Shaft

(i) Tandem Compound. Most multi-cylinder turbines drive a single shaft and single generator.
(ii) Cross Compound. In this type, two shafts are used driving separate generator. The reason may be one of turbine house arrangement, limited generator size, or a desire to run the hp. Shafting at half speed.

(H) On the basis of Rotational Speed

(i) Constant Speed turbines (a) for 60 cycle/s generators, (b) For 50 cycles/s generator, (c) For 25 cycles/s generator, (ii) Variable Speed turbines
(i) Constant Speed Turbines. Requirements of rotational speed are extremely rigid in turbine which is directly connected to electric generators as these must be a-c.

2.4 The Simple Impulse Turbine

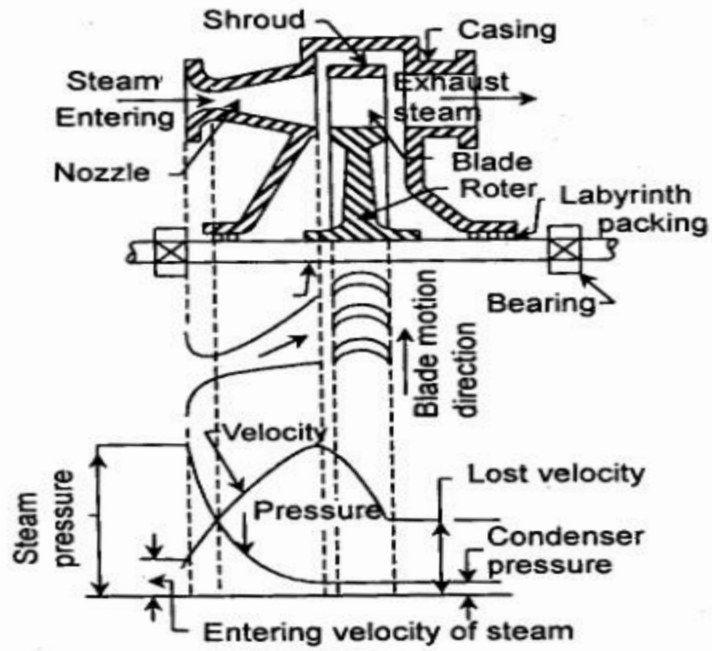


Fig. 2.3 Diagrammatic Arrangement of a Simple (de- Lavel) Turbine.

- This type of turbine works on principle of impulse and is shown diagrammatically in Fig 2.3.It mainly consists of a nozzle or a set of nozzles, a rotor mounted on a shaft, one set of moving blades attached to the rotor and a casing. The uppermost portion of the of the diagram shows a longitudinal section through the upper half of the turbine, the middle portion shows the development of nozzles and blading i.e. the actual shape of nozzle and blading, and the bottom portion shows the variation of absolute velocity and absolute pressure during flow of steam through passage of nozzles and blades. The example of this type of turbine is de-laval turbine.
- It is obvious from the figure that the complete expansion of steam from the steam chest pressure to the exhaust pressure or condenser pressure takes place only in one set of nozzles. i.e. the pressure drop takes place only in nozzles. It is assumed that pressure in the recess between nozzles and blades remains the same. The steam at condenser pressure or exhaust pressure enters the blade and comes out from at the same pressure i.e. the pressure of steam in the blade passages remains approximately constant and equal to condenser pressure.
- Generally, converging – diverging nozzles are used. Due to the relatively large ratio of expansion of steam in the nozzles, the steam leaves the nozzle at a very high velocity

(supersonic) , of about 1100 m/s. The steam at such a high velocity enters the blades and reduces the along the passage of blades and comes out with an appreciable amount of velocity.

2.4 Compounding of Impulse Turbine

- Compounding is the method for reducing the rotational speed of the impulse turbine to practical limits. As we have seen, if the high velocity steam is allowed to flow through one row moving blades, it produces a rotor speed of about 30000 r.p.m. which is too high for practical use. Not only is this leaving loss also very high. It is therefore essential to incorporate some improvements in Impulse turbine for practical use and also to achieve high performance. This is possible by making use of more than one set of nozzles, blades, rotors in a series, keyed to common shaft, so that either the steam pressure or the jet of velocity is absorbed by the turbine in stages .The leaving loss also will then be less. This process is called compounding of steam turbines. There are three main types.
  - (a) Pressure-compounded impulse turbine
  - (b) Velocity-compounded impulse turbine
  - (c) Pressure and velocity compounded impulse turbine

2.5 Pressure compounded Impulse Turbine

- In this type of turbine, the compounding is done for pressure of steam only i.e. to reduce high rotational speed of turbine the whole expansion of steam is arranged in a number of steps by employing a number of simple impulse turbine in a series keyed on the same shaft as shown in fig 2.4. Each of these simple impulse turbines consisting of one set of nozzles and one row of moving blades is known as a stage of turbine and thus this turbine consists of several stages. The exhaust from each row of moving blades enters the succeeding set of nozzles. Thus we can say that this arrangement is nothing but splitting up the whole pressure drop from steam chest pressure to the condenser pressure into a series of smaller pressure drop across several stages of impulse turbine hence this turbine is called pressure compound impulse turbine.
- The pressure and velocity variation are also shown in fig. he nozzles are fitted into a diaphragm which is locked in the casing. This diaphragm separates one wheel chamber from another. All rotors are mounted on the same shaft and the blades are attached on the rotor. The rotor (i.e. disc) may be keyed to the shaft or it may be integral part of the shaft.

2.6 Velocity compounded Impulse Turbine

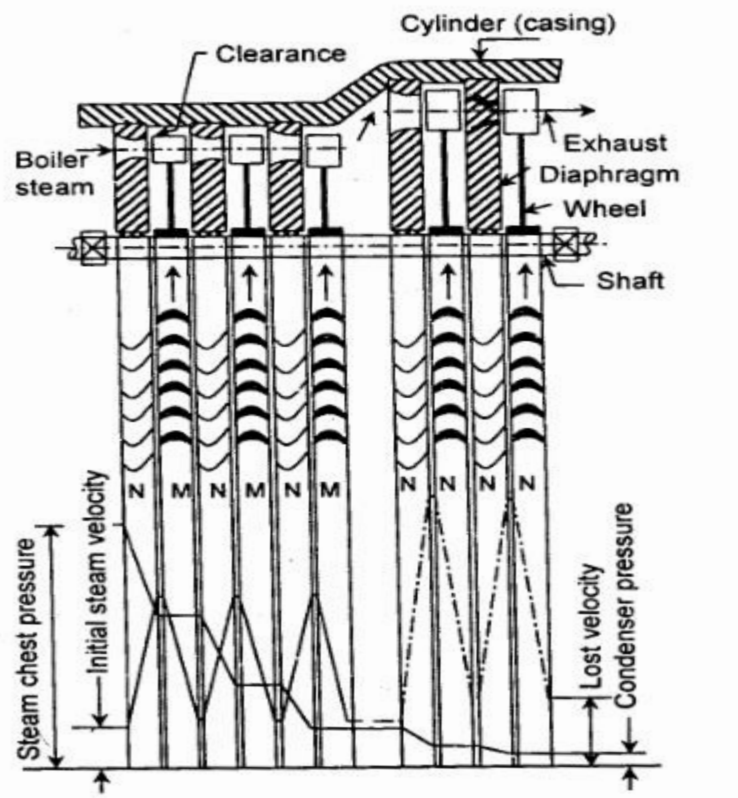


Fig 2.4 Diagrammatic Arrangement of Pressure Compounded Impulse Turbine.

- In this type of turbine, the compounding is done for velocity of steam only i.e. drop in velocity is arranged in many small drops through many moving rows of blades instead of a single row of moving blades. It consists of a nozzle or set of nozzles and rows of moving blades attached to the rotor or wheel and rows of fixed blades attached to casing.
- The fixed blades are guide blades which guide the steam to succeeding rows of moving blades, suitably arranged between the moving blades and set in a reversed manner. In this turbine, three rows of rings of moving blades are fixed on a single wheel or rotor and this type of wheel is termed as the three row wheel. There are two rows of guide blades or fixed blades placed between the first and the second and the second and the third rows of moving blades respectively.
- The whole expansion of steam from the steam chest pressure down to the exhaust pressure takes place in the nozzles only. There is no drop of pressure take place either in the moving blades or the fixed blades i.e. the pressure remains the constant in the blades

as in the simple impulse turbine. The steam velocity from the exit of the nozzle is very high as in the simple impulse turbine. Steam with high velocity enters the first row of moving blades and on passing through these blades, the velocity slightly reduces i.e. the steam gives up a part of its kinetic energy and reissues from this row of blades with a fairly high velocity. It then enters the first row of guide blades which directs the steam to the second row of moving blades. On passing through the second row of moving blades, some drop in velocity again occurs i.e. steam gives up another portion of its kinetic energy to the rotor. After this, it is redirected again by the second row of guide blades to the third row of moving blades where again some drop in velocity occurs and finally the steam leaves the wheel with a certain velocity in a more or less axial direction.

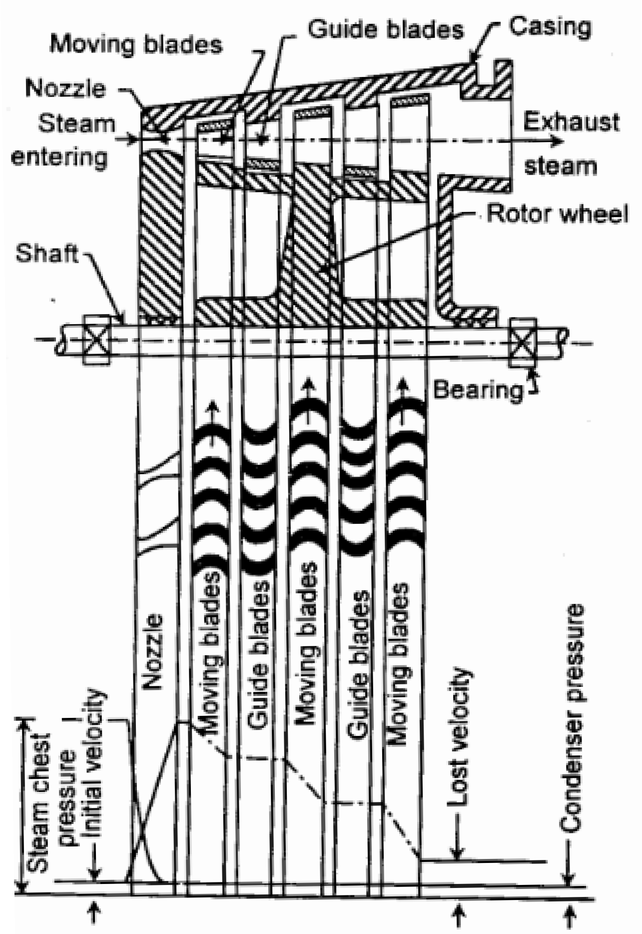


Fig. 2.5 Diagrammatic Arrangement of Velocity Compounded Impulse Turbine.

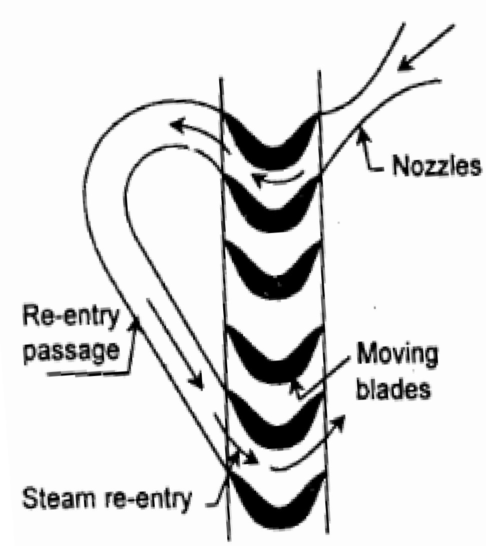


Fig. 2.6 Re-entry Velocity Compounding.

- So we can say that this arrangement is nothing but splitting up the velocity gained from the exit of the nozzles into many drops through several rows of moving blades and hence the name velocity compounded. This type of turbine is also termed as Curtis turbine .The two row wheel is more efficient than the three row wheel.

2.6 Pressure Velocity compounded Impulse Turbine

- This type of turbine is a combination of pressure and velocity compounding and is shown diagrammatically in Fig. the arrangement shown here is only for two rotors. There are two wheels or rotors and on each, only two rows of moving blades are attached because two row wheels are more efficient than three row wheel. In each wheel or rotor, velocity drops i.e. drop in velocity is achieved by many rows of moving blades hence it is velocity compounded. There are two set of nozzles in which whole pressure drop takes place i.e. whole pressure drop has been divided in small drops, hence it is pressure compounded.
- In the first set of nozzles, there is some decrease in pressure which gives some kinetic energy to the steam and there is no drop in pressure in the two rows of moving blades of the first wheel and in the first row of fixed blades. Only there is a velocity drop in moving blades through there is also a slight drop in velocity due to friction in the fixed blades. In second set of nozzles, the remaining pressure drop takes place but the velocity here increases and the drop in velocity takes place in the moving blades of the second wheel or rotor.
- Compared to the pressure-compounded impulse turbine this arrangement was more popular due to its simple construction. It is, how it’s simple construction. It is, however , very rarely used now due to its low efficiency.

2.7 Impulse Reaction Turbine

- As the name implies this type of turbine utilizes the principle of impulse and reaction both. Such a type of turbine is diagrammatically shown in fig.2.8 there are number of rows of moving blades attached to the rotor and an equal number of fixed blades attached to the casing. In this type of turbine, the fixed blades which are set in a reversed manner compared to moving blades, corresponds to nozzles mentioned in connection with the impulse turbine. Due to row of fixed blade at the entrance, instead of the nozzles, steam is admitted for the whole circumference and hence there is all round or complete admission. In passing through the first row of fixed blades, the steam undergoes a small drop in pressure and hence its velocity somewhat increases. After this it then enters the first row of moving blades and just as in the impulse turbine, it suffers a change in direction and therefore in momentum. This momentum gives rise to an impulse on the blades.

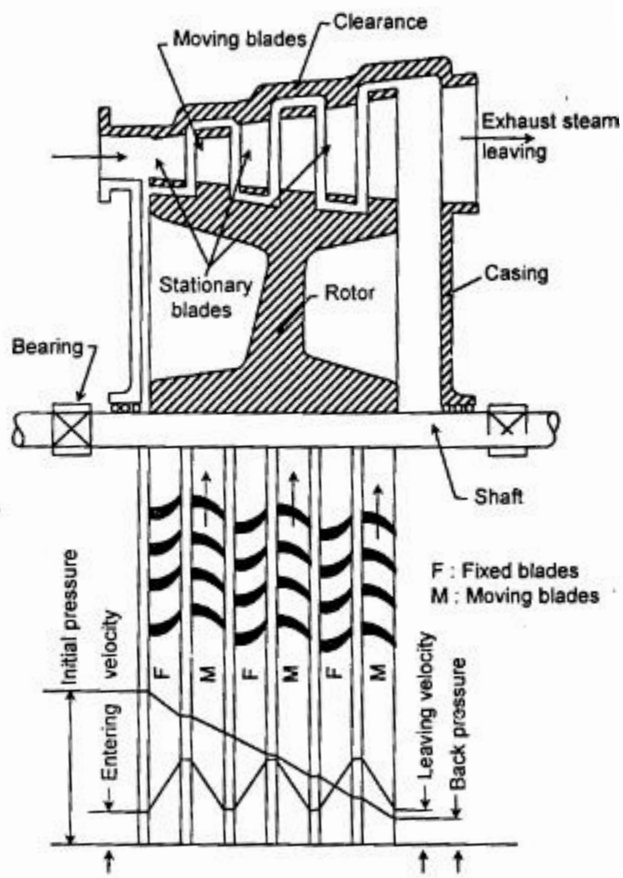


Fig. 2.8 Diagrammatic Arrangement of Impulse-Reaction Turbine.

- But in this type of turbine, the passage of the moving blades is so designed (converging) that there is a small drop in pressure of steam in the moving blades which result in a increase in kinetic energy of steam. This kinetic energy gives rise to reaction in the direction opposite to that of added velocity. Thus, the gross propelling force or driving force is the vector sum of impulse and reaction forces. Commonly this type of turbine is called Reaction turbine. The pressure and velocity variations are as shown in Fig.2.8 It is obvious from the figure that there is a gradual drop in pressure in both moving blades and fixed blades.
- As the pressure falls, the specific volume increases and hence in practice, the height of blades is increased in steps i.e. Say up to 4 stages it remains constant, and then it increases and remains constant for the next two stages.
- In this type of turbine, the steam velocities are comparatively moderate and its maximum value is about equal to blade velocity.

2.8 Difference between Impulse and Reaction Turbines

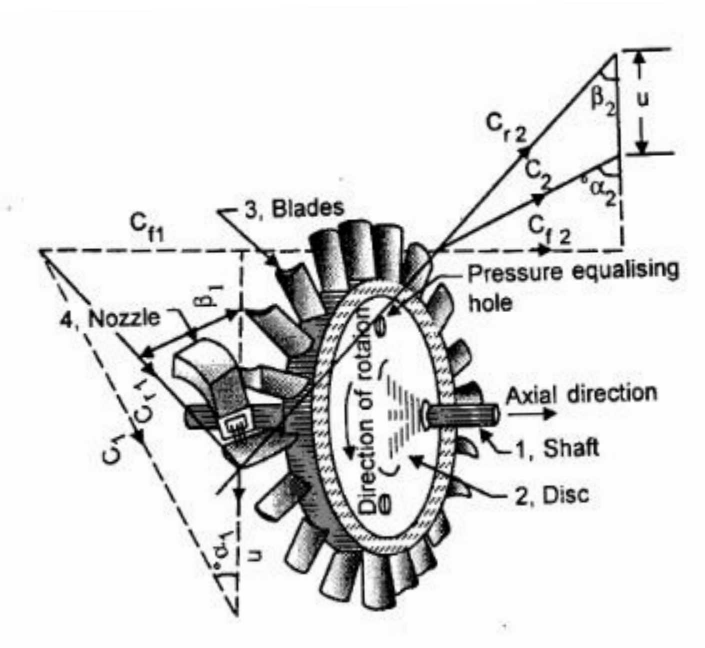
Impulse Turbine	Reaction Turbine
Pressure drops only in nozzles and not in moving blade channels.	Pressure drops in fixed blades (nozzles) as well as moving blade channels.
Constant blade channels area.	Varying blade channels area(converging types)
Profile type blades.	Aerofoil type blades.
Not all round or complete admission of steam.	All round or complete admission.
Diaphragm contains the nozzles.	Fixed blades similar to moving blades attached to casing serve nozzles and guide the steam.
Not much power can be developed.	Much power can be developed.
Occupies less space for same power.	Occupies more space for same power
Lesser blading efficiency.	Higher blading efficiency.
Suitable for small power requirements.	Suitable for medium and higher power requirements.
Blade manufacturing is not difficult an thus not costly.	Blade manufacturing process is difficult compared to impulse and hence costly.
Velocity of steam is slightly higher.	Reduced velocity of steam.

2.9 Velocity Diagrams for Impulse Turbines

- It is an established fact that velocity is a vector quantity. It has (a) magnitude (b) direction and (c) sense of direction. Thus, we can represent velocity by a straight line and indicate (a) its magnitude by the length of that straight line to a suitable scale (b) its direction by the direction of said straight line with reference to some fixed direction and (c) its sense of direction by an arrow placed on a straight line.
- Suffixes 1 and 2 refer to inlet and outlet condition of moving blades as shown in fig.

- C_1 = absolute velocity of steam at inlet to the moving blade
- α_1 = angle of the nozzle or angle made by entering steam having velocity C_1 with tangent of the wheel
- C_{r1} = Relative velocity of steam with respect to the tip of the blade at inlet
- β_1 = angle of the blade at inlet
- C_{w1} = tangential component of velocity C_1 known as velocity of whirl or the component of velocity responsible for the whirling or rotating of the turbine rotor.
- C_{f1} = axial component of C_1, called the velocity of flow.
- C_2 = absolute velocity of steam at outlet from the blade
- C_{r2} = relative velocity with respect to the tip of the blade outlet.
- α_2 = angle to the tangent of wheel at which the absolute velocity of steam C_2 leaves the blades.
- β_2 = outlet angle of the blade

- C_{f2} = outlet axial velocity or the axial component of C_2 or the velocity flow at outlet.
- C_{w2} = tangential component of the velocity C_2, known as the velocity of whirl at outlet.
- u = peripheral velocity of blade (mean value)
- K = blade velocity coefficient = $Cr_2/C_{r1.}$
- $Cr_1 = Cr_2$ for the case of without friction.
- $KCr_1 = Cr_2$ for the case of with friction.
- $\dot{m}$ = mass flow rate, kg/s.
- All the velocities are in meters per second.



Rotor and Approaching Flow

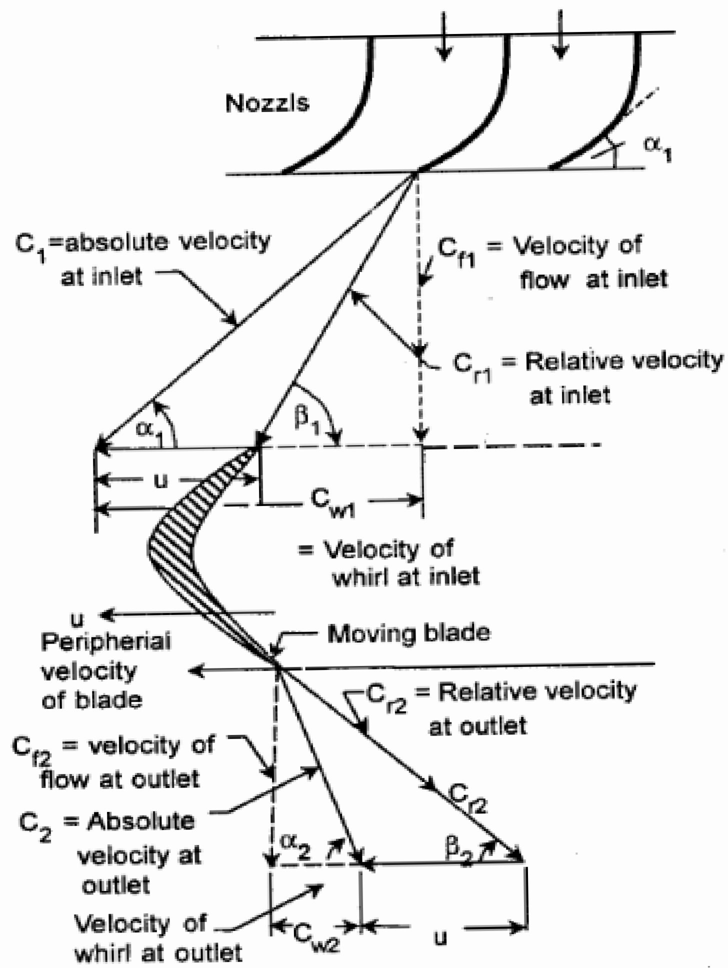


Fig.B Velocity Diagram for Impulse Turbine.

2.10 Combination of vector diagram.

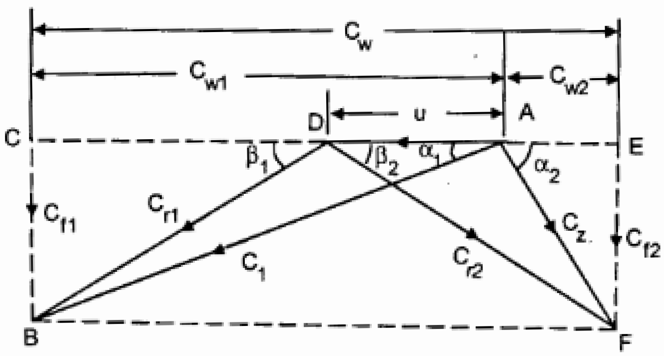


Fig. C Combined Velocity Diagram

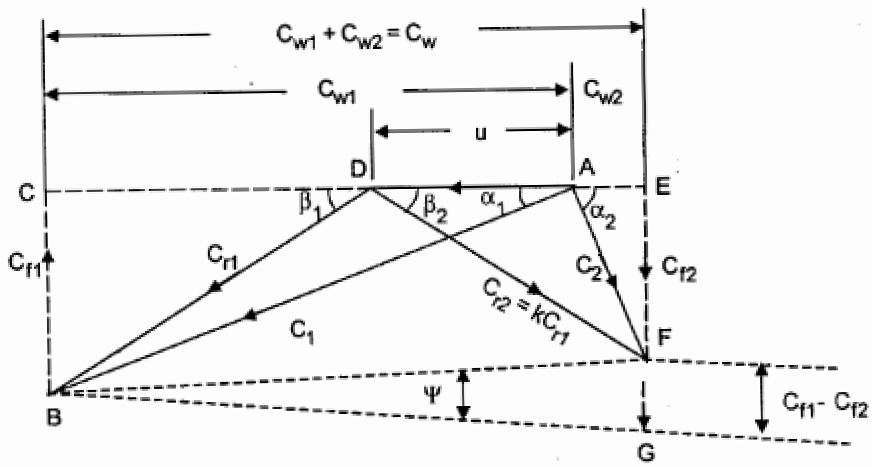


Fig. D Velocity Diagram Showing Effect of Friction.

- The industrial method of constructing velocity diagrams is to combine both velocity diagrams at inlet as well as at outlet of the blade into a single diagram as shown In Fig. In this, both velocity diagrams are drawn on a common base representing the blade velocity, u.when there is no friction ($Cr_1=C_{r2}$) and $\beta_1 = \beta 2$, then $C_{f1} = C_{f2}$.
- In actual practice, there is frictional resistance to the flow of steam jet over the blade, the effect of which is to cause a slowing down of the relative velocity,C_{r2} which is I the range of 85 to 90 percent of C_{r1}.Thus due to frictional resistance from Fig.D.

  $$C_{r2} = k\, C_{r1}$$

  Where k is called the blade velocity coefficient which takes into account the blade losses due to friction.
- The resultant force parallel to BF is inclined at an angle ψ to the plane in which the wheel rotates. The resultant force may be resolved into two components as shown in Fig.

1) A useful thrust or tangential force acting in the direction of blade motion, F_t.
2) An idle thrust or axial force; perpendicular to the wheel plane i.e. parallel to the turbine axis, F_a.

2.11 Forces on the blades and work done by Blades

- **Force:** From Newton's second low of Motion, tangential force on the blade

F_t = Mass x acceleration in the tangential direction

F_t = Mass per second x change in velocity in the tangential direction

$F_t = m (Cw_1 - C_{w2})$

It is obvious from the velocity diagram that C_{w2} is opposite in direction to the blade motion. By giving the same direction of C_{w2}, The force becomes

$F_t = m (Cw_1 + C_{w2})$; N

$F_t = m\, C_w$ (where m=mass flow rate of steam in kg per sec, $C_w = (Cw_1 + C_{w2})$)

In general $F_t = m (Cw_1 \mp C_{w2})$

- **Work and Power:** work done by blade per second is given by

W = Tangential force x Distance moved in unit time in the direction of force

W = Tangential force x Blade velocity in the direction of force

$W = F_t\, u = m (Cw_1 + C_{w2})\, u$; w

Power developed is given by

$$\text{Power} = P = \frac{m(Cw1+Cw2)u}{1000} = \frac{m\ Cw\ u}{1000} \text{ ; KW} \qquad \text{eq. E}$$

It is to be noted that power developed given by equation E is by one stage. If n be the number of identical stages then the power developed is given by

$$P = \frac{n\ m\ Cw\ u}{1000} \text{ ; KW} \quad \text{,where n = No. of stages}$$

2.12.1Blade or Diagram Efficiency.

- Blade or diagram efficiency is defined as the ratio of the work done by blade per second to the energy entering the blade per second.
- Energy of the steam entering the blade per sec.= $\frac{m\,C_1^2}{2}$,w

Therefore, the blade efficiency $\eta_b = \frac{m\,u\,C_w}{m\,C_1^2/2} = \frac{2\,u\,C_w}{C_1^2}$

2.12.2 Axial Thrust or End Thrust on the rotor.

- Axial force = F_a = mass x acceleration in axial direction

  Or F_a = mass per second x change in velocity in axial direction

  ∴ Axial force = F_a = m ($C_{f1} - C_{f2}$) ; N

- Due to the reduced axial velocity C_{f2} at the outlet from blade of an impulse turbine the force producing acceleration of the steam does not act wholly in the plain of the wheel, hence the force component (m) ($C_{f1} - C_{f2}$) tends to push the shaft axially. The axial thrust on the wheel must be taken by a thrust bearing. When there is no blade friction i.e., $Cr_1 = C_{r2}$ and if $\beta_1 = \beta_2$, then $C_{f1} = C_{f2}$, hence axial thrust is zero. It should be noted that this axial thrust is also augmented by the steam pressure acting on each side of the wheel or disc.

2.12.3 Gross Stage Efficiency.

- Gross stage efficiency (η_{gs}) is defined as the ratio of the work done by the blades per kg of steam flowing through the stage (i.e. nozzles and moving blades or a set of fixed and moving blades constitutes a stage) to the isentropic enthalpy drop per kg of steam in that stage.Ths,

$$\eta_{gs} = \frac{\textit{workdone per kg}\ \text{in}\ \textit{the stage}}{\textit{Isentropic enthalpy drop in the stage}}$$

- Δh_{isen} = isentropic enthalpy drop per kg in nozzle only in the impulse turbines.

  Now, work done on the blades per kg of steam flow is $u \cdot C_w$, J

$$\therefore \ \eta_{gs} = \frac{u \cdot C_w}{\Delta h_{isen}} = \frac{2\,u \cdot C_w}{C_1^2}\,\frac{C_1^2}{2\,\Delta h_{isen}} \qquad \text{eq. A}$$

Or $\eta_{gs} = \eta_b \times \eta_n$

Thus, the gross stage efficiency is the product of blade efficiency and the nozzle efficiency.

2.13 Influence of Ratio of blade velocity to steam velocity on Blade Efficiency in a single stage Impulse Turbine.

- Let us consider the case of single stage impulse turbine. Here the effect of friction in the blade channel is taken into account and accordingly the velocity diagram is shown in fig. 2.9 Due to friction C_{r2} is less than C_{r1} and $C_{r2}/C_{r1} = k$ where k is blade velocity co-efficient, which is always less than unity .Generally, in practice $\beta_1 = \beta_2$, in some cases β_2 is somewhat smaller than β_1 but in pure impulse turbine the difference between the angles is always small.

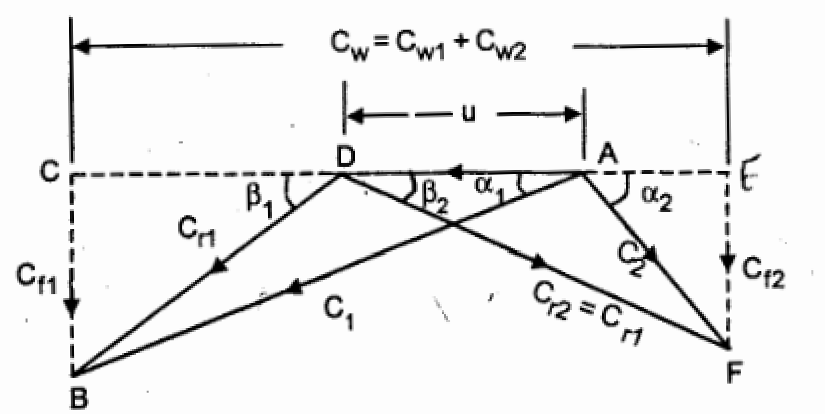


Fig. 2.9 Velocity Diagram for Single Stage Impulse Turbine.

- We know the blade efficiency is

$$\eta_b = \frac{m\,u\,C_w}{m\,C_1^2/2} = \frac{2\,u\,C_w}{C_1^2}$$

- From the velocity diagram find the value of $u\,C_w$

$$C_w = CD + DE = C_{r1}\cos\beta_1 + C_{r2}\cos\beta_2 = C_{r1}\cos\beta_1\left(1 + \frac{C_{r2}\cos\beta_2}{C_{r1}\cos\beta_1}\right)$$

$= C_{r1} \cos \beta_1 (1 + KB)$

Where $B = \cos \beta_2 / \cos \beta_1$

- Since β_1 and β_2 are usually almost equal, so for this analysis we assume that B is a constant. We have

  $Cr_1 \cos \beta_1 = C_1 \cos \alpha_1 - u$ so $Cw = (C_1 \cos \alpha 1 - u)(1 + KB)$

  Therefore, $2 u Cw = 2u (C_1 \cos \alpha_1 - u)(1 + KB)$

- The blade velocity ratio = $\rho = u/C_1$ is a very important factor in the design of steam turbines. The efficiency of the turbine depends upon this factor.

  Now $u = \rho C1$ and $2 u Cw = 2 \rho C_1 (C_1 \cos \alpha_1 - \rho C_1)(1 + KB)$

  $\therefore 2u. Cw = 2 C^2{}_1 (\rho \cos \alpha_1 - \rho^2)(1 + KB)$

- Putting the velocity of 2 u Cw in equation A we have,

$$\eta_b = \frac{2 u . Cw}{C^2_1} = 2(1 + KB)\left(\rho \cos \alpha_1 - \rho^2\right)$$

- Equation is the equation of the parabola which is shown in Fig.2.10

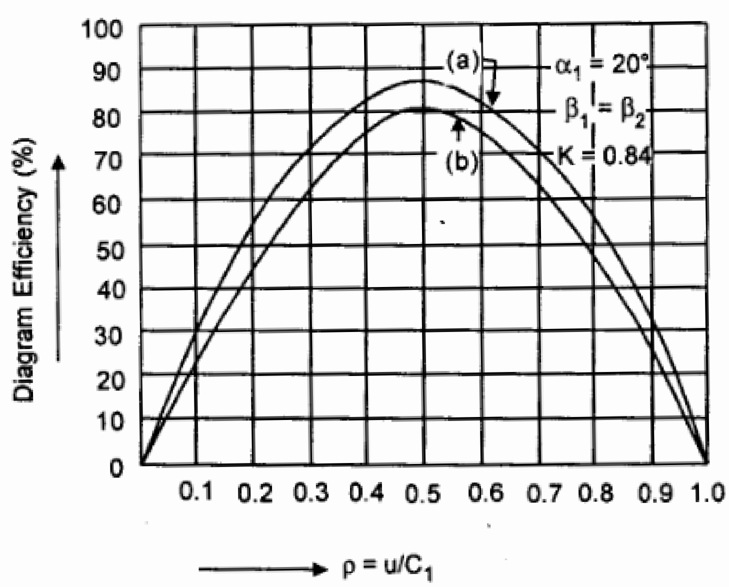


Fig. 2.10(*a*) Diagram Efficiency without Losses. (*b*) Diagram Efficiency with Losses.

- From the graph is obvious that the blade efficiency increases as ρ is increased until ρ reaches the value a value which is approximately one-half, after which blade efficiency decreases.
- If α_1 , K and B are assumed to be constant; then the blade efficiency depends on the value of ρ. For maximum blade efficiency the first differential with respect to ρ should be zero and the second differential with respect to ρ should be negative. In the first differential

$$\frac{d\eta_b}{d\rho} = 0 = 2(1+KB)(\cos\,\alpha_1 - 2\rho)$$

- And in the second differential $\frac{d^2\eta_b}{d\rho} = -4(1+KB) = -ve,$

So for the maximum blade efficiency, $2(1+KB)\left(\rho\cos\,\alpha_1 - 2\rho\right) = 0$

Or $(\cos\,\alpha_1 - 2\rho) = 0$

Therefore, optimum value of ρ is $\rho_{opt} = (u/C_1)_{opt} = = \frac{\cos\,\alpha_1}{2}$

eq. B

- The maximum value of the blade efficiency will be given by putting the value of ρ_{opt} for ρ in the equation, thus we have

$$(\eta_b)_{max} = 2(1+KB)\ \left(\frac{\cos\,\alpha_1\cos\,\alpha_1}{2} - \frac{\cos^2\alpha_1}{4}\right) = (1+KB)\frac{\cos^2\alpha_1}{2}$$

If k=1 and B=1,

$(\eta_b)_{max} = \cos^2\alpha_1$

- From equation B we see that for maximum blade efficiency the blade efficiency the blade velocity should be half of the steam velocity multiplied by $\cos\,\alpha_1$.
- The maximum power output per kg of steam from a single stage impulse turbine having equiangular blades and for without friction is given by

$(Power)_{max} = (u\,C_w)\ max = [\,u\,(C_1\cos\,\alpha_1 - u)\,(1 + KB)\,]_{max}$

Substituting the value of (u/C_1) opt we have

$(Power)_{max} = 2\,u^2$ for K=1 and B=1.

2.14 **Impulse –Reaction Turbine Velocity Diagram and work done**

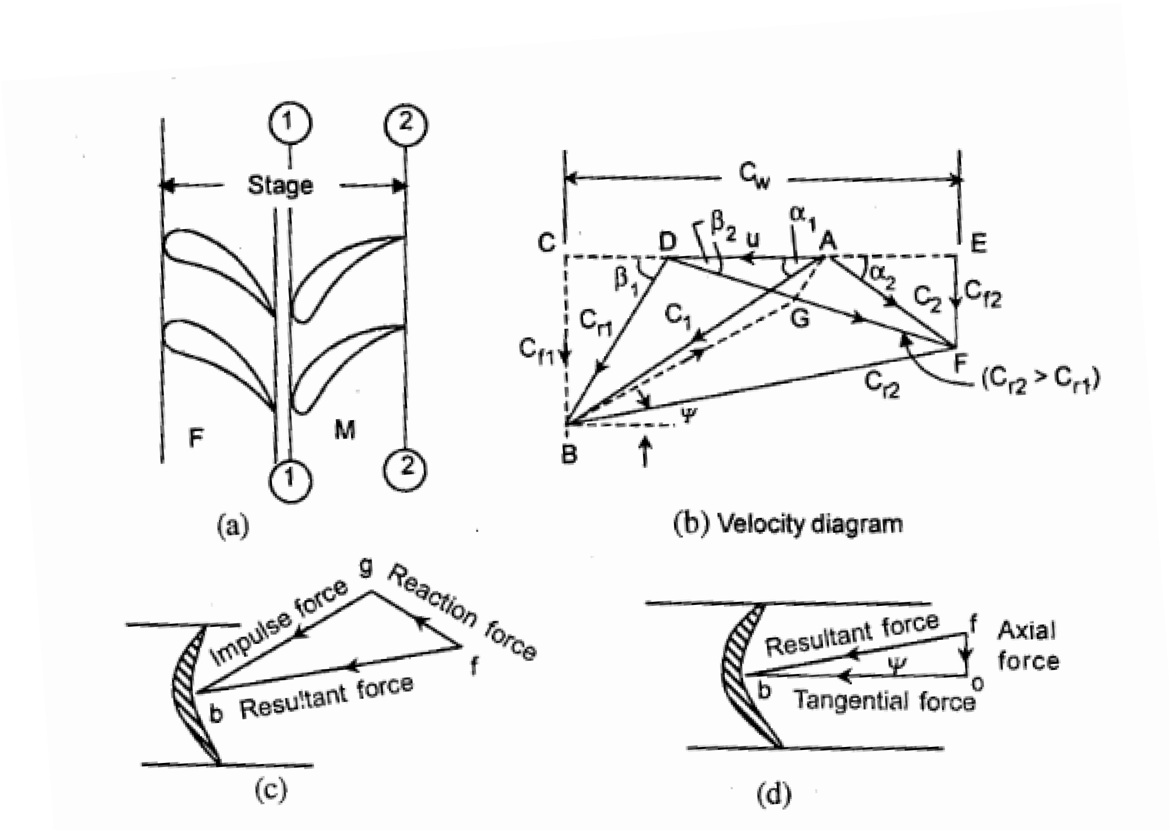


Fig. 2.11. Stage, Velocity and Force Diagram.

- Here, like the Impulse turbine, the tangential force is $F_t = m\ C_w$, where C_w is whirl velocity

Work done = $m\ u\ C_w$

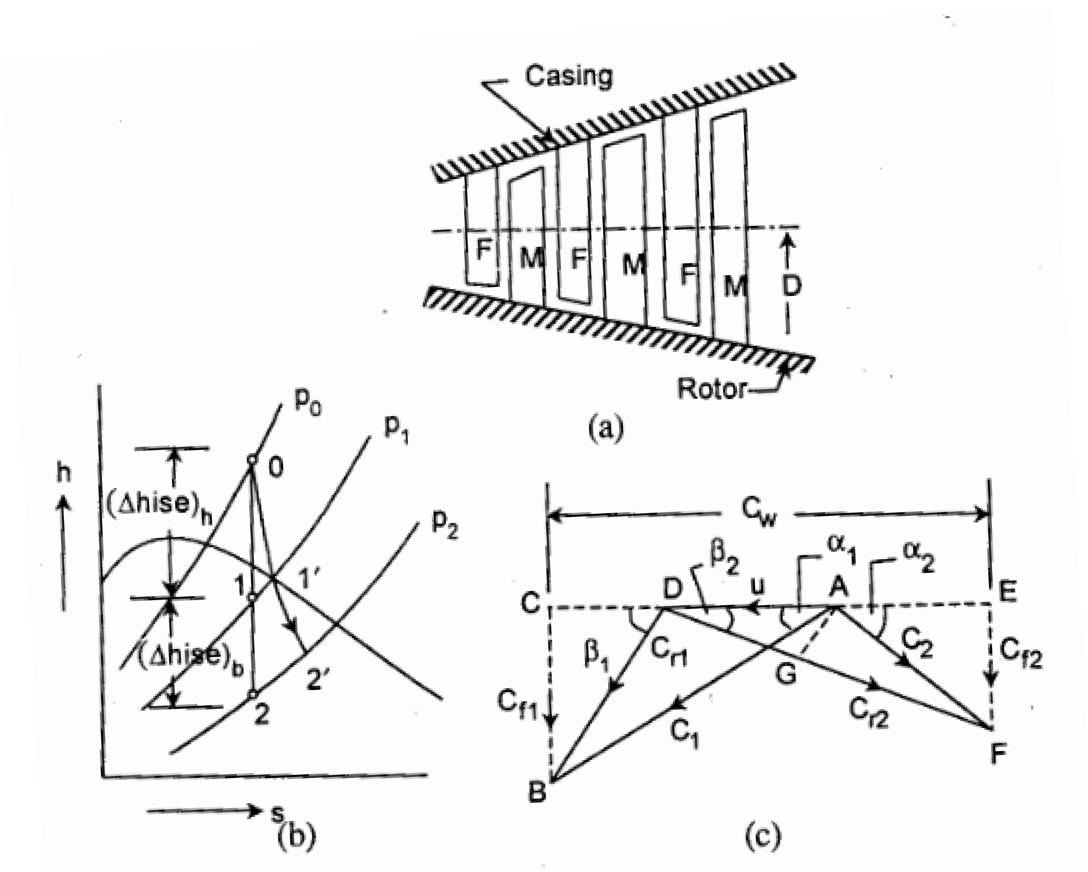
Power developed = $\frac{m\ u\ Cw}{1000}$; KW

2.15 Degree of Reaction

- The degree of reaction, R is defined as the ratio of isentropic heat drop in the moving blades to the sum of the isentropic heat drops in the fixed and the moving blades i.e. in a stage. Mathematically, the degree of reaction is

$$R = \frac{(\Delta h_{isen})_b}{(\Delta h_{isen})_n + (\Delta h_{isen})_b}$$

- Where $(\Delta h_{isen})_b$ and $(\Delta h_{isen})_n$ are the isentropic heat drop in moving blades and fixed blades respectively. In pure impulse turbine, degree of reaction is zero, In pure reaction turbine , R=1.



Impulse-reaction Turbine

2.16 Impulse reaction Turbine with similar Blade section and Half degree Reaction (Parson's Turbine)

Consider a particular case of reaction turbine i.e. Parson's reaction turbine in which the degree of reaction is half and the section of blades is the same in both fixed and moving rows of blades as shown in Fig. below.

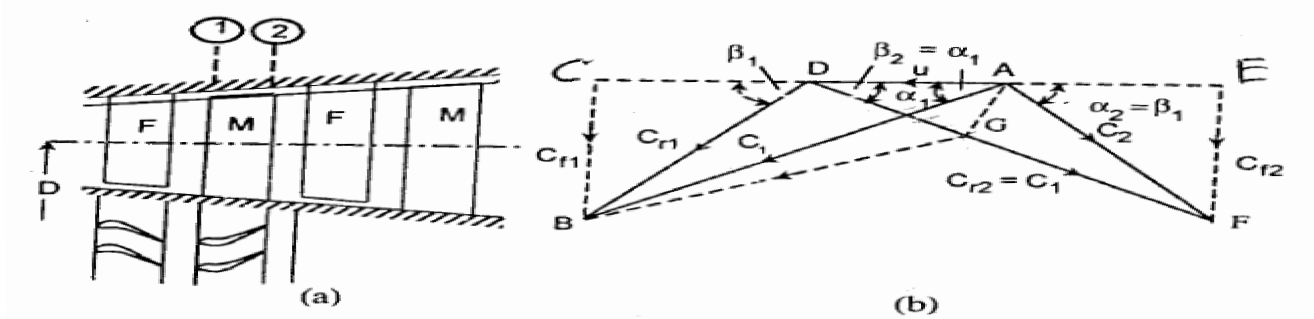


Fig. Parson's Reaction Turbine

- In the parson's reaction turbine, it is assumed that the blade section and the mean diameter of fixed a well as the moving blades are the same and the blade height is progressively so increased such that the velocity of steam at exit from each row of blades is uniform throughout the stage thus, the velocity triangle at the inlet and outlet of moving blade will be similar.
- The angle $\alpha_1 = \beta_2$, $\alpha_2 = \beta_1$ and velocity $C_{r2} = C_1$ from Fig above.

2.17 Degree of Reaction

- For parson's turbine we can prove that the degree of reaction is half. For the pure impulse working condition DG represents the velocity of steam from the moving blades which is equal to K C_{r1} Due to the expansion of steam in the moving blades, the relative velocity is increased to the value of $C_{r2}=C_1$, represented by DF. Gain in the kinetic energy in the moving blades is

$$\frac{C^2_{r2} - K^2C^2_{r1}}{2} = \frac{C^2_1 - \phi C^2_{r1}}{2}$$ Where $\phi = K^2$ = carry-over coefficient

- If η_n be the efficiency of the moving blades as well as fixed blades, then the isentropic heat drop in each row of moving blades is

$$(\Delta h_{isen})_b = \frac{C^2_1 - \phi C^2_{r1}}{2\eta_n} \text{ KJ/kg}$$

- From the velocity triangle. We know, $C^2_{r1} = C_1^2 + u^2 - 2u\,C_1 \cos\alpha_1$

  Since $\rho = u/C_1$, then $C^2_{r1} = C_1^2 (1+ \rho^2 - 2\rho \cos\alpha_1)$

- By putting the value of C^2_{r1} in equation the isentropic heat drop in each row of moving blades becomes

$$(\Delta h_{isen})_b = \frac{C^2_1}{2\,\eta_n}\{1-\phi(1+\rho^2-2\rho\cos\alpha_1)\}$$

- Except for the first set of fixed blades, the gain in kinetic energy in each row of fixed blade is given by

$$\frac{C_1^2 - \phi C_2^2}{2} = \frac{C_1^2 - \phi C_{r1}^2}{2}$$

- So the isentropic heat drop in fixed blades = $(\Delta h_{isen})_n = \dfrac{C_1^2 - \phi C_{r1}^2}{2\eta_n}$ KJ/kg

- Thus the isentropic heat drop in the fixed and the moving blades is the same i.e.

  $(\Delta h_{isen})_n = (\Delta h_{isen})_b$ hence **R=0.5**

2.18 Gross stage Efficiency and optimum value of ρ

- The isentropic heat drop in a stage i.e. in a pair of blades consisting of fixed and moving is

$$(\Delta h_{isen})_n = (\Delta h_{isen})_b = \frac{C_1^2}{\eta_n}\{1-\phi(1+\rho^2-2\rho\cos\alpha_1)\}$$

- Gross stage efficiency = $\eta_{gs} = \dfrac{\text{work done per kg}}{\text{Isentropic heat drop in a stage per kg}}$

- Work done per kg of steam = u C_w; KJ/kg

$$C_w = C_1 \text{Cos}\alpha_1 - u + C_{r2}\text{Cos}\beta_2 = C_1 \text{Cos}\alpha_1 - u + C_1\text{Cos}\alpha_1$$

- So work done per kg of steam = u C_w = u (C_1 Cosα_1 – u + C_1Cosα_1)

$$= C_1^2\ (2\rho\cos\alpha_1 - \rho^2)$$

$$\eta_{gs} = \frac{C_1^2\ (2\rho\cos\alpha_1-\rho^2)}{\frac{C_1^2}{\eta_n}\{1-\phi(1+\rho^2-2\rho\cos\alpha_1)\}} = \frac{\eta_n(2\rho\cos\alpha_1-\rho^2)}{1-\phi(1+\rho^2-2\rho\cos\alpha_1)}$$

eq. **C**

- It may be put in another form also, $\eta_{gs} = \dfrac{\eta_n}{\{(1-\phi)/(2\rho\cos\alpha_1-\rho^2)\}+\phi}$

- The above equation shows that the gross stage efficiency is maximum when $2\rho\cos\alpha_1-\rho^2$ is maximum where η_n and ϕ are constant. For maximum value of gross stage efficiency

$$\frac{d(\eta_{gs})}{d\rho} = 0 \text{ , which gives}$$

$$\frac{d(\eta_{gs})}{d\rho} = 0 = 2\cos\alpha - 2\rho$$

` or $\rho = \rho_{opt} = \cos\alpha_1$

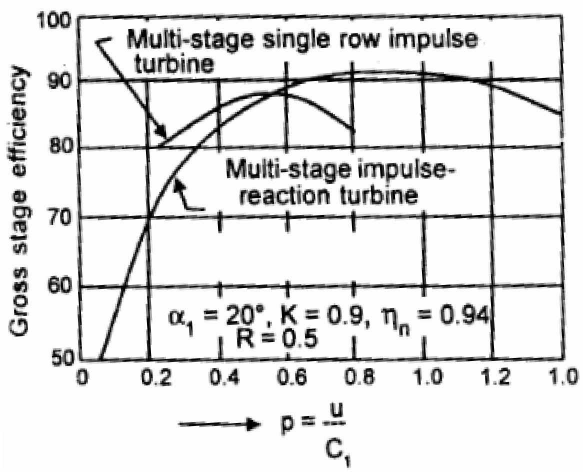


Fig. 2.12 Gross Stage Efficiency vs. ρ.

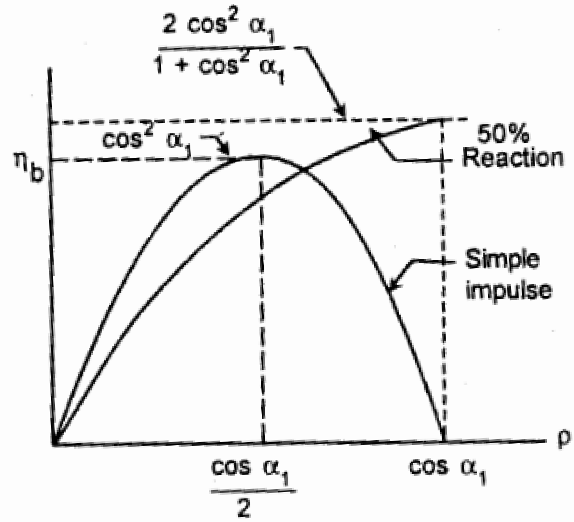


Fig. 2.13 Blade Efficiency vs. ρ.

- So we see that for maximum gross stage efficiency ρ_{opt} is equal to $\cos\alpha_1$ which is greater than ρ_{opt} of multi stage impulse turbine.

Putting the Value $\rho = \cos\alpha_1$, in equation C we get

$$\eta_{gs(\max)} = \frac{\eta_n \cos^2\alpha_1}{1-\phi(1-\cos^2\alpha_1)}$$

- Fig 2.12 shows the variation of η_{gs} with ρ .The curve is flat and the optimum value of ρ is 0.9 for α_1 =20 degree.

2.19Blade Efficiency

- The diagram or Blade efficiency = $\eta_b = \dfrac{work\ done\ per \sec}{Energy\ input\ per \sec}$
- Work done per kg = u $C_w = C^2{}_1\ (2\rho\cos\alpha_1 - \rho^2)$ and Energy input to the fixed blades= $C^2{}_1/2$
- Energy input to the moving blades = $\dfrac{C^2{}_{r2} - C^2{}_{r1}}{2}$
- Total energy input = $\dfrac{C^2{}_1}{2} + \dfrac{C^2{}_{r2} - C^2{}_{r1}}{2} = \dfrac{C^2{}_1}{2} + \dfrac{C^2{}_1 - C^2{}_{r1}}{2}$ for parson's turbine

$$= C^2{}_1 - \frac{C^2{}_{r1}}{2} = C^2{}_1 - \frac{C^2{}_1}{2}(1+\rho^2 - 2\rho\cos\alpha_1) = \frac{C^2{}_1}{2}(1+\rho^2 - 2\rho\cos\alpha_1)$$

$$\eta_b = \frac{C^2{}_1(2\rho\cos\alpha_1 - \rho^2)}{C^2{}_1/2[1-\rho^2+2\rho\cos\alpha_1]} = \frac{2(2\rho\cos\alpha_1 - \rho^2)}{(1-\rho^2+2\rho\cos\alpha_1)}$$

- Since $\rho_{opt} = \cos\alpha_1$, hence

$$(\eta_b)_{max} = \frac{2\cos^2\alpha_1}{1+\cos^2\alpha_1}$$

2.20 Governing of steam turbines

- **Need of Governing**

- The power output increases first with speed ,reaches a maximum (Rated) value at rated speed and after this decreases. He turbine speed (i.e. electrical frequency) is a function of electrical load (i.e. consumer's demand) ; the lower the load, higher the speed due to accelerating torque .The load may not remain the same, e.g. sometimes full, sometimes half as per consumer's demand and under this condition the electrical frequency will vary with load. This is not at all desirable as all the electrical machines and appliances are designed for a nominal electrical frequency. Therefore the governor is arranged to control the turbine so as to give its characteristics of falling output power with rising shaft speed above nominal value.

- The purpose of governing is to maintain the speed of the turbine fairly constant irrespective of load. The change in speed from no load to full load , divided by the full load (or rated) speed is termed as regulation (K) or the droop of turbine.

- The turbine power output power is controlled by varying the steam flow (power output is a function of a steam floe rate) by means of valves interposed between the boiler and the turbine. Based on the methods of varying steam flow rate, the cheap methods of governing are:-

  (a) Throttle control governing

  (b) Nozzle control Governing

  (c) By-Pass governing

  (d) Combination of (a) and (b) or (a) and (c)

2.20.1 Throttle control Governing

- The object of throttle governing is to throttle the steam to a suitable pressure and reduce the steam flow (i.e. to allow required quantity of steam to flow) through the turbine bladings whenever there is a reduction of load compared to economic or design load for maintaining the speed of the turbine.

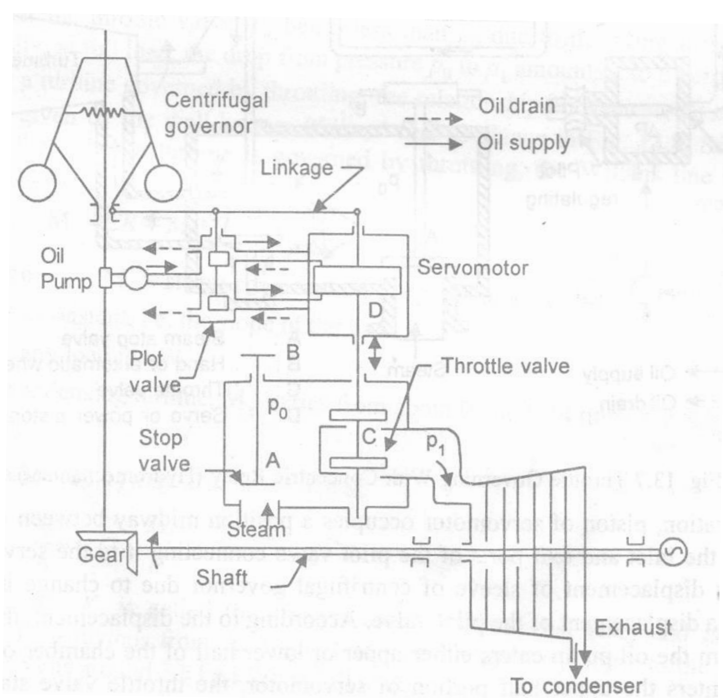


Figure.2.14 Throttle Governing

- The relay system shown in Fig. consists of a pilot valve and a servomotor. Under normal operation, piston of servomotor occupies a position midway between its travel in which both the inlet and exit ports of the pilot valve connecting it to the servomotor are closed. Any displacement of sleeve of centrifugal governor due to change in electrical load causes a displacement of the pilot valve. According to the displacement , the oil under pressure from the oil pump enters either upper or lower half of the chamber of servomotor. If oil enters the upper half portion of servomotor, the throttle valve starts closing reducing the quantity of steam flowing through the turbine thus reducing the power output of turbine till the speed is maintained fairly near nominal value. At the same time oil from bottom half of servomotor starts flowing out through the pilot valve port to drain. If oil under pressure enters the lower half chamber of servomotor, an exactly opposite process is affected opening the throttle valve till the speed is maintained.

- Throttling of incoming steam effects the work delivered to the shaft in two ways-a reduction of rate of flow and a decrease of energy conversion per kg of steam.

2.20.2 Nozzle control Governing

- In the nozzle control governing, the nozzles of the turbines are grouped in two, three or more groups, and each group of nozzles is fed with steam controlled by valves. various arrangement of valves and group of nozzles are employed. Whatever arrangement is employed , the nozzle control is necessarily restricted to the first stage of the turbine, the nozzle areas in the other stages remaining constant. If the condition of steam of the steam at inlet to the second stage is not materially affected by the changed condition in the first stage, the absolute pressure of steam in front of the second stage nozzles will be directly proportional to the rate of steam flow through the turbine.

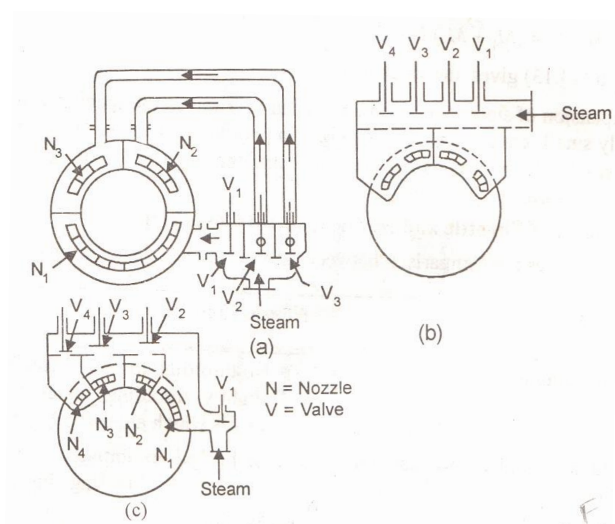


Figure.2.15 Nozzle Governing

- Fig. shows (a) an arrangement often employed in large steam turbines and turbines using high pressure steam. here, the nozzles are divided into three groups N_1 ,N_2 and N_3 under the control of three valves V_1 , V_2 and V_3 respectively. The number of nozzle groups may vary from three to five or more.

- Fig. shows (b) an another type of arrangement and it differs from Fig (a) in that nozzle control valves are arranged in a casting forming part of casing and containing passages leading to the individual nozzle groups. Here, four group of nozzles and four valves are shown. In this case, the nozzles are confined to the upper half of the casing and so the arc of admission is limited to $180^{\circ}C$ or less. The number of nozzles group may vary from 4 to 12.

- Fig. shows (c) In this arrangement four groups of nozzles N_1 is under the control of the valve V_1, through which all the steam entering the turbine passes and further admission of steam is through the valves V_2, V3, etc in turn.

Throttle control	Nozzle control
Severe throttling process	No throttling losses.(Actually there is slightly, throttling losses in nozzles valves which are partially open)
Employed in impulse and reaction turbine both	Employed in impulse and also in reaction(if initial stage impulse)
Lesser partial admission losses	Much partial admission losses
Lesser heat drop available	Larger heat drop available
Suitable for small, medium and large turbine	Suitable for medium and large steam turbines if initial stage is impulse

2.20.3 By Pass Governing

- The principle of by-pass governing is to by-pass some extra quantity of steam to the far down stream stages when the load is more than economic load. The modern high pressure impulse turbines consist of a number of stages or relatively small mean diameter in H.P. side and are designed to run at economic load at which the thermodynamic efficiency ratio of turbine is maximum. Owing to small heat drop in the first stage of the high pressure turbine, it is not advisable to employ nozzle control governing. Full admission of steam in the high pressure stages at the economic load is desirable to eliminate the partial admission losses. Further, in case of higher loads, the extra steam required cannot be admitted through additional nozzles in the first stage due to various reasons.

- By employing by-pass governing, these difficulties of regulation are overcome,

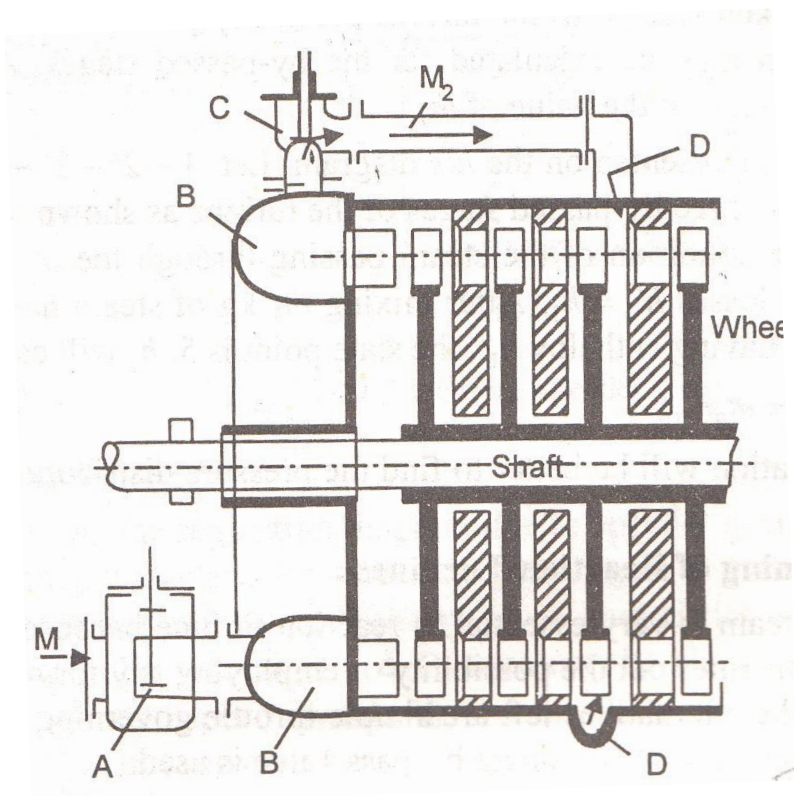


Figure.2.16 By-pass Governing

- An arrangement of by-pass governing is shown in Fig. The total amount of steam entering the turbine passes through the valve A which is under the control of speed governor. B is the nozzle box or steam chest. For all loads greater than economic load , a bypass valve C is opened , allowing steam to pass from the first stage nozzle box into the steam belt D and so into the nozzles of downstream stages say 4.The valve C is designed such that it is not opened until the lift of a valve A exceeds a certain value. The valve C closes first as the load diminishes. The by-pass valve C remains under the control of a speed governor for all loads within its range. More than one by-pass valve may be used.

Numerical Based On Steam Turbine

Ex-1

Steam issues from the nozzles of a de Laval turbine with a velocity of 1200 m/s. The nozzle angle is 20°, the mean blade velocity is 400 m/s, and the inlet and outlet angle of blade are equal. The mass of steam flowing through turbine per hour is 900 kg. Calculate: (a) The blade angles, (b) The relative velocity of steam entering the blades, (c) The tangential force on the blades, (d) The power developed, and (e) The blade efficiency. Assume that K = 0.8.

Solution:

Data given:

$C_1 = 1200$ m/s

$\alpha_1 = 20°$

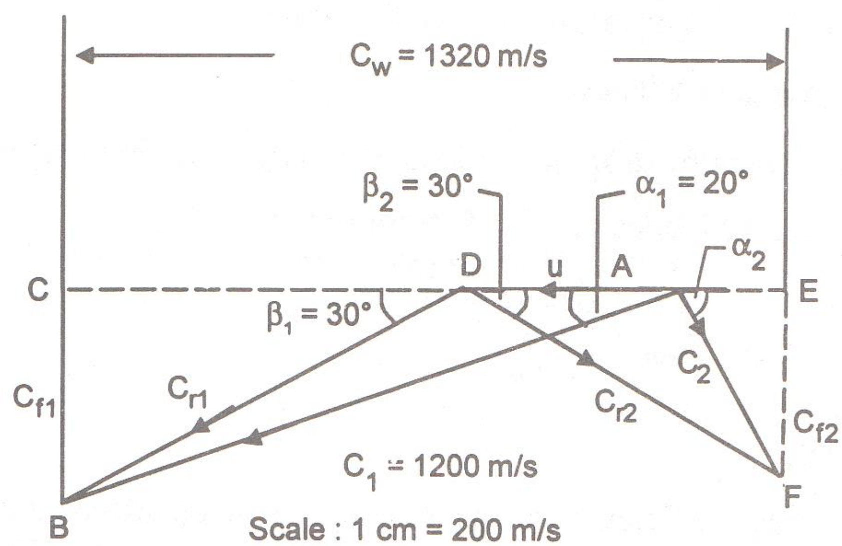
u = 400 m/s

$m = 900 \text{ kg/h} = \frac{900}{3600} \text{ kg/s}$

K = 0.8

$\beta_1 = \beta_2$

Find: β_1, β_2, C_{r1}, F_t, P, η_b



Refer the above figure.

The velocity diagram is shown in above figure. Scale used is 1 cm = 200 m/s.

With the help of C_1, α_1 and u, draw the inlet velocity triangle A B D.

Measure the blade angle at inlet (β_1). It is measured as 30°.

Since the blade angle are equal, $\beta_1 = \beta_2 = 30°$

Now measure B D. It is relative velocity at inlet. Hence, C_{r1} = 4.2(200) = 840 m/s.

The relative velocity at outlet, $C_{r2} = K (C_{r1})$ =0.8 (840) = 672 m/s.

Draw the outlet velocity triangle A D F using β_2 = 30° and C_{r2} = 672 m/s.

Measure C E = C_w = 1320 m/s

Tangential force on the inlet blades,

$$F_t = m\left(C_{w1} + C_{w2}\right) = m\left(C_w\right) = m(CE)$$

$$\therefore F_t = \frac{900}{3600} \times 1320 = 330N$$

Power developed,

$$P = \frac{m \cdot u \cdot C_w}{1000} = \frac{900 \times 400 \times 1320}{3600 \times 1000}$$

$$\therefore P = 132KW$$

Blade efficiency,

$$\eta_b = \frac{2 \cdot u \cdot C_w}{C_1^2} = \frac{2 \times 400 \times 1320}{(1200)^2} = 0.733$$

$$\eta_b = 73.3\%$$

EX-2

In a stage of an impulse turbine provided with a single row wheel, the mean diameter of the blade ring is 80 cm and the speed of rotation is 3000 rpm. The steam issues from the nozzles with a velocity of 300 m/s and the nozzle angle is 20°. The rotor blades are equiangular and due to friction in the blade channels the relative velocity of steam at outlet from the blades is 0.86 times the relative velocity of the steam entering the blades. What is the power developed in the blades when the axial thrust on the blades is 140 N?

Solution:

Data given:

D = 80 cm = $\frac{80}{100} m$

N = 3000 rpm

C_1 = 300 m/s

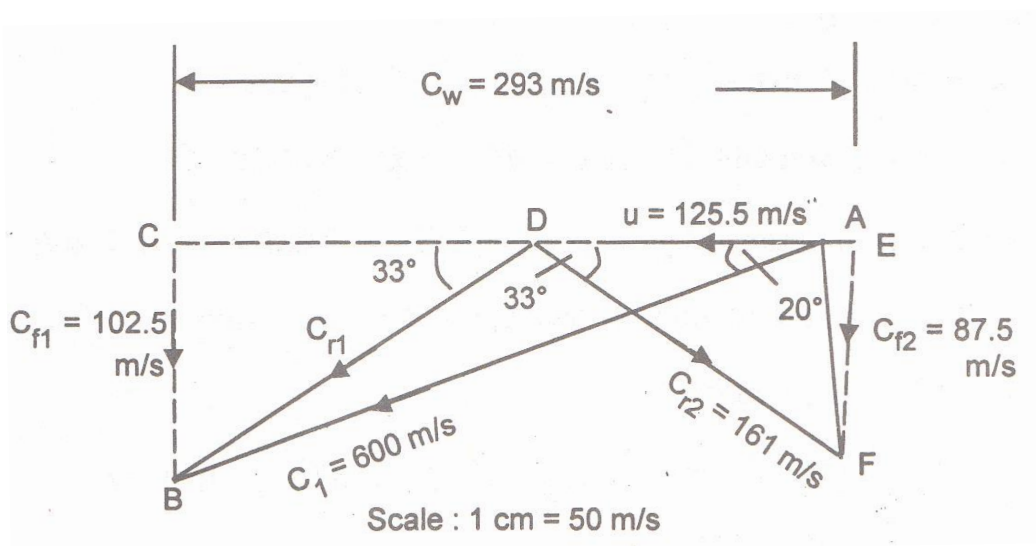
α_1 = 20°

K = 0.86

F_a = 140 N

$\beta_1 = \beta_2$

Find: P



Refer to above figure.

The velocity diagram is shown in above figure. Scale used is 1 cm = 50 m/s.

The peripheral velocity of blades,

$$u = \frac{\prod DN}{60} = \prod \frac{80}{100} \times \frac{3000}{60}$$

u = 125.66 m/s

With the help of C_1, α_1 and u, draw the inlet velocity triangle A B D.

Measure the blade angle at inlet (β_1). It is measured as 33°.

Since the blade angle are equal, $\beta_1 = \beta_2 = 33°$

Now measure B D. It is relative velocity at inlet. Hence, C_{r1} = 188 m/s.

The relative velocity at outlet, C_{r2} = K (C_{r1}) =0.8 (188) = 161 m/s.

Draw the outlet velocity triangle A D F using β_2 = 33° and C_{r2} = 161 m/s.

Measure C E = C_w = 293 m/s

Measure C B = C_{f1} = 102.5 m/s

Measure E F = C_{f2} = 87.5 m/s

Axial thrust,

$$F_a = m\left(C_{f1} - C_{f2}\right)$$

$$\therefore 140 = m(102.5 - 87.5)$$

$$\therefore m = 9.333 kg/s$$

Power developed,

$$P = \frac{m \cdot u \cdot C_w}{1000} = \frac{9.333 \times 293 \times 125.16}{1000}$$

$$\therefore P = 342.25 KW$$

EX-3

In a single stage impulse turbine, the steam velocity at nozzle mouth is 300 m/s. the nozzle angle is 18°, and the mean blade velocity is 144 m/s. Draw to a suitable scale the velocity diagram for the steam assuming that the outlet angle of blade is 3° less than inlet angle and that the relative velocity of the steam at outlet from the blade is 0.84 of the relative velocity at entrance. If the power developed is 1000 KW, calculate the mass of steam that must pass through the turbine per sec. Neglect the friction and leakage loss.

Solution:

Data given:

C_1 = 300 m/s

α_1 = 18°

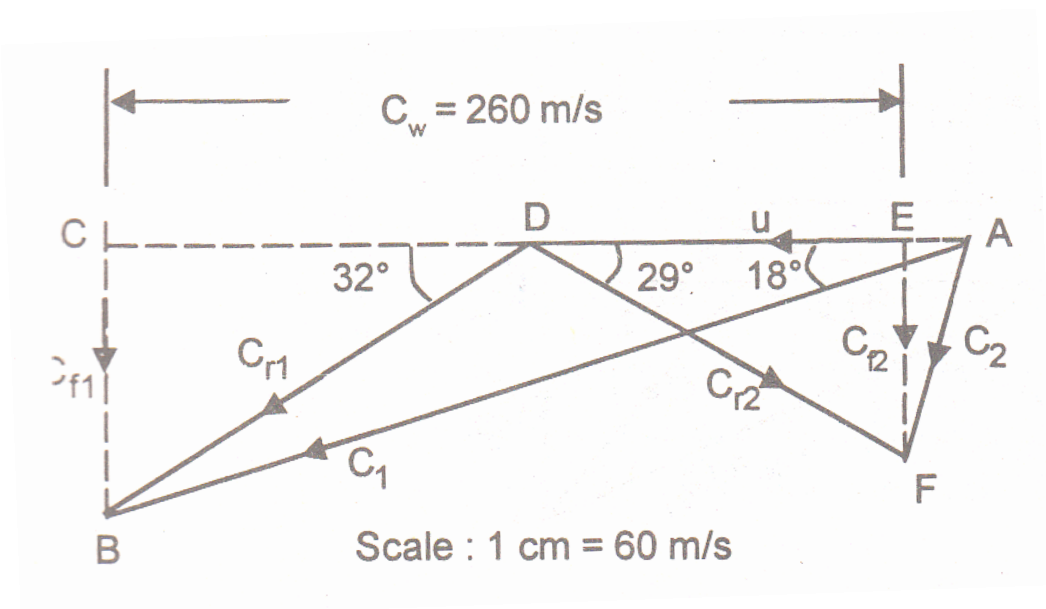
u = 144 m/s

K = 0.84

$\beta_2 = \beta_1 - 3°$

P=1000 KW

Find: m



Refer the above figure.

The velocity diagram is shown in above figure. Scale used is 1 cm = 60 m/s.

With the help of C_1, α_1 and u, draw the inlet velocity triangle A B D.

Measure the blade angle at inlet (β_1). It is measured as 32°.

Since the blade angle are equal, $\beta_2 = \beta_1 - 3° = 32 – 3 = 29°$.

Now measure B D = C_{r1}. It is relative velocity at inlet.

The relative velocity at outlet, $C_{r2} = K (C_{r1})$

Draw the outlet velocity triangle A D F using β_2 and C_{r2}.

Measure C E = C_w = 260 m/s

Power developed,

$$P = \frac{m \cdot u \cdot C_w}{1000}$$

$$1000 = \frac{m \times 144 \times 260}{1000}$$

$$\therefore m = 26.7 kg/s$$

EX-4

The following data refers to a stage of a Parson's steam turbine comprising one ring of fixed blades and one ring of moving blades: Mean diameter of blade ring = 70 cm, R.P.M. = 3000 rpm, Steam velocity at entrance of blades = 160 m/s, Blade outlet angle = 20°, Steam flow through blades = 7 kg/s.

Draw the velocity diagram and find the following: (a) Blade inlet angle, (b) Tangential force on the ring of moving blades, (c) Power developed in a stage.

Solution:

Data given:

D = 70 cm = $\frac{70}{100} m$

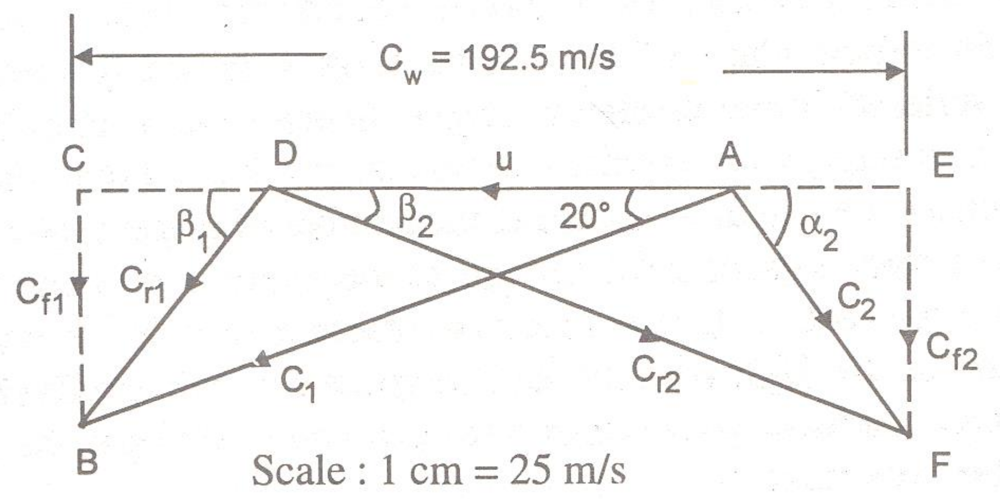
N = 3000 rpm

C_1 = 160 m/s

$\beta_2 = \alpha_1 = 20°$

m = 7 kg/s

Find: β_1, F_t, P



Refer the above figure.

The velocity diagram is shown in above figure. Scale used is 1 cm = 25 m/s.

The peripheral velocity of blades,

$$u = \frac{\prod DN}{60} = \prod \frac{70}{100} \times \frac{3000}{60}$$

u = 110 m/s

With the help of C_1, α_1 and u, draw the inlet velocity triangle A B D.

Measure the blade angle at inlet (β_1). It is measured as 52°.

In Parson's reaction turbine, $C_{r1} = C_2$, $C_{r2} = C_1$, $\beta_1 = \alpha_2$, $\beta_2 = \alpha_1$

Draw the outlet velocity triangle A D F.

Measure C E = C_w = 192.5 m/s

Tangential force on the inlet blades,

$$F_t = m(C_{w1} + C_{w2}) = m(C_w) = m(CE)$$

$$\therefore F_t = 7 \times 192.5 = 1347.5N$$

Power developed,

$$P = \frac{m \cdot u \cdot C_w}{1000} = \frac{7 \times 110 \times 192.5}{1000}$$

$$\therefore P = 148.22KW$$

References

Steam and gas turbine by – R Yadav

3. GAS TURBINE POWER PLANT

3.1 Introduction:

The gas turbine obtains its power by utilizing the energy of burnt gases and air which are at higher temperature and pressure by expanding through the several rings of fixed and moving blades.

A simple gas turbine cycle consists of

i. A compressor,

ii. A combustion chamber and

iii. A turbine

Since the compressor is coupled with the turbine shaft, it absorbs some of the power produced by the turbines (about 50 %) and hence lowers the efficiency.

The net work is therefore the difference between the turbine work and work required by the compressor to drive it.

Gas turbines have been constructed to work on the following: oil, natural gas, coal gas, producer gas, blast furnaces and pulverized coal.

3.2 Classification of Gas Turbines:

1. Constant pressure combustion chamber

   A. Open cycle constant pressure gas turbine

   B. Closed cycle constant pressure gas turbine

2. Constant volume combustion gas turbine

3.2.1 Simple open cycle gas turbine or air standard Brayton cycle:

The Brayton cycle is the most idealized cycle for the simple gas turbine power plant as shown in Figure 1.

Atmospheric air is compressed from p_1 a high pressure p_2 in the compressor and delivered to the combustion chamber where fuel is injected and burned.

The combustion process occurs nearly at constant pressure. Due to combustion heat is added to the working fluid in the combustor from T_2 to T_3.

The products of combustion from the combustion chamber expanded in the turbine from p_2 to atmospheric pressure p_1 and then discharged to the atmosphere.

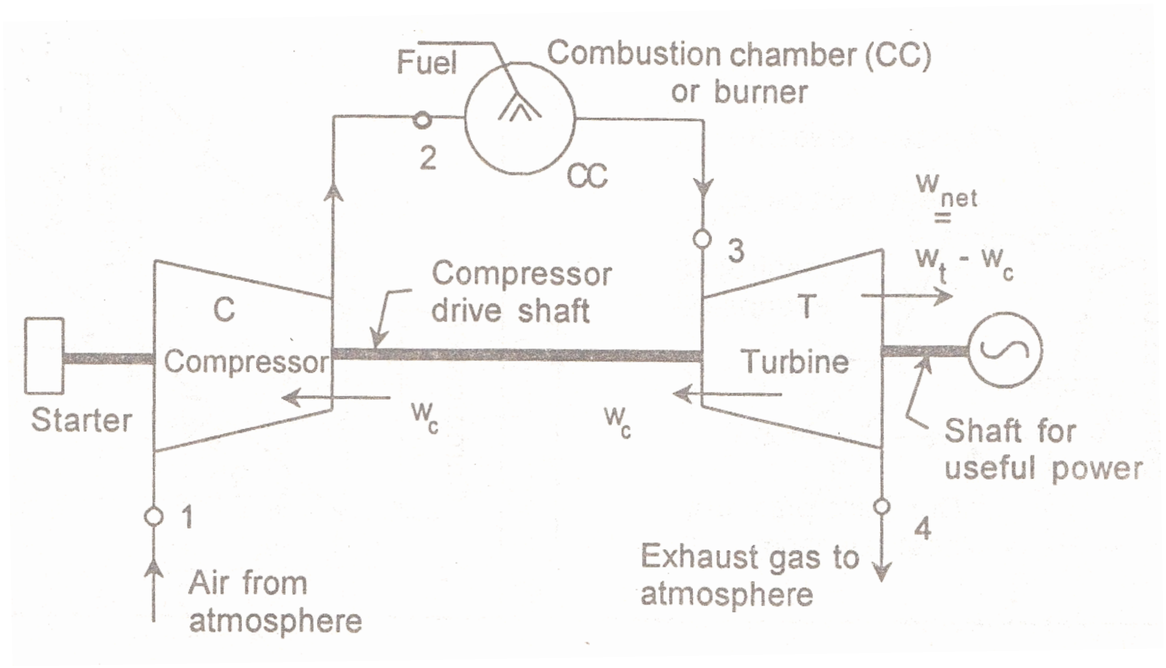


Fig. 1 Simple Open Cycle Gas Turbine

To first run the compressor, a starter is needed. When the turbine starts running, the starter is cut-off.

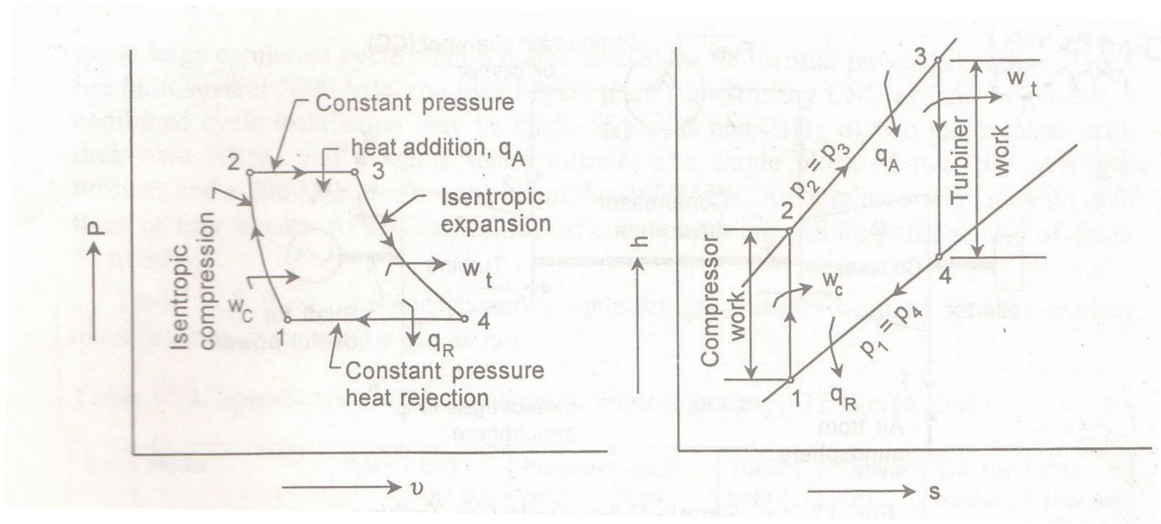


Fig. 2 Representation of Ideal Brayton Cycle on P-v and h-s Diagram

Representation of ideal Brayton cycle on p-v and h-s (or T-s) diagrams are shown in Figure 2.

Process **1-2** is the **isentropic compression in the compressor**

Process **2-3** is the **constant pressure heat addition in the combustion chamber**

Process **3-4** is the **isentropic expansion in the turbine**

Process **4-1** is the **constant pressure heat rejection**

Thermal efficiency on the basis of 1 kg of working fluid flow:

Heat supplied, $q_A = h_3 - h_2 = C_p (T_3 - T_2)$

Heat rejected, $q_R = h_4 - h_1 = C_p (T_4 - T_1)$

Net work = $q_A - q_R = C_p \{(T_3 - T_2) - (T_4 - T_1)\}$

The thermal efficiency is,

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

We know that, for any isentropic process

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \& \quad \frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore T_2 = T_1\left(r_p\right)^{\frac{\gamma-1}{\gamma}} \quad \& \quad T_3 = T_4\left(r_p\right)^{\frac{\gamma-1}{\gamma}}$$

But, $p_1 = p_4$ and $p_2 = p_3$

So, $\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(r_p\right)^{\frac{\gamma-1}{\gamma}}$ where, r_p = pressure ratio

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_4\left(r_p\right)^{\frac{\gamma-1}{\gamma}} - T_1\left(r_p\right)^{\frac{\gamma-1}{\gamma}}}$$

$$\eta_{th} = 1 - \frac{T_4 - T_1}{(T_4 - T_1)\left(r_p\right)^{\frac{\gamma-1}{\gamma}}}$$

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

3.2.2 Actual Brayton cycle

The actual Brayton cycle differs from the ideal Brayton cycle because of the following reasons

Due to frictional losses in compression and turbine, the compression and expansion processes are not frictionless and takes place with some increase in entropy (i.e. the processes are irreversible adiabatic).

A small pressure drop occurs in the combustion chamber.

Representation of actual Brayton cycle h-s (or T-s) diagrams are shown in Figure 3.

Process **1-2** is the **isentropic compression in the compressor**

Process **1-2’** is the **actual compression in the compressor**

Process **3-4** is the **isentropic expansion in the turbine**

Process 3-**4’** is the **actual expansion in the turbine**

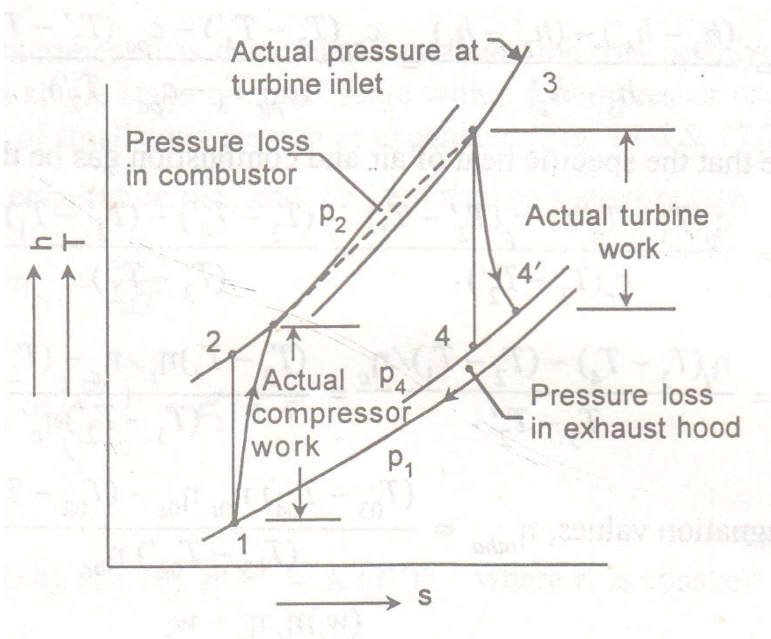


Figure 3 Actual Brayton Cycle on h-s diagram

Work input = $h_2' - h_1 = C_p (T_2' - T_1)$

Heat supplied = $h_3 - h_2' = C_p (T_3 - T_2')$

Work output = $h_3 - h_4' = C_p (T_3 - T_4')$

The thermal efficiency is,

$$\eta_{th} = \frac{\text{Net work output}}{\text{Heat supplied}} = \frac{C_p\left\{\left(T_3 - T_4'\right) - \left(T_2' - T_1\right)\right\}}{C_p\left(T_3 - T_2'\right)}$$

The isentropic compressor efficiency is,

$$\eta_c = \frac{\text{Isentropic Compressor work}}{\text{Actual Compressor work}} = \frac{h_2 - h_1}{h_2' - h_1} = \frac{C_p\left(T_2 - T_1\right)}{C_p\left(T_2' - T_1\right)} = \frac{T_2 - T_1}{T_2' - T_1}$$

The isentropic turbine efficiency is,

$$\eta_t = \frac{\text{Actual Turbine work}}{\text{Isentropic Turbine work}} = \frac{h_3 - h_4'}{h_3 - h_4} = \frac{C_p\left(T_3 - T_4'\right)}{C_p\left(T_3 - T_4\right)} = \frac{T_3 - T_4'}{T_3 - T_4}$$

3.3 Methods for improving the efficiency of gas turbine

The improvement in the gas turbine efficiency can be done by following methods:

1. Regeneration: This is done by preheating the air with the turbine exhaust, thus saving the fuel consumption.
2. Reheating: The whole expansion in the turbine is achieved in two or more stages and reheating is done after each stage.
3. Intercooling: The compressor work is reduced by intercooling the air between compressor stages.

3.3.1 Open Cycle Gas Turbine with Regeneration

In this method, it is done by preheating the air with the turbine exhaust, thus saving the fuel consumption.

The air delivered by the compressor passes through a heat exchanger (regenerator) utilizing the gases exhausted from the turbine.

The heated air then passes into the combustion chamber and part of it is employed to burn the fuel.

Since some heat is added to the air in the heat exchanger itself, so the same turbine gas inlet temperature is attained as that when no heat exchanger is employed; with lower fuel consumption, hence the thermal efficiency will accordingly be higher.

Only the heat required to be supplied in the combustion chamber is decreased which gives the gain in thermal efficiency.

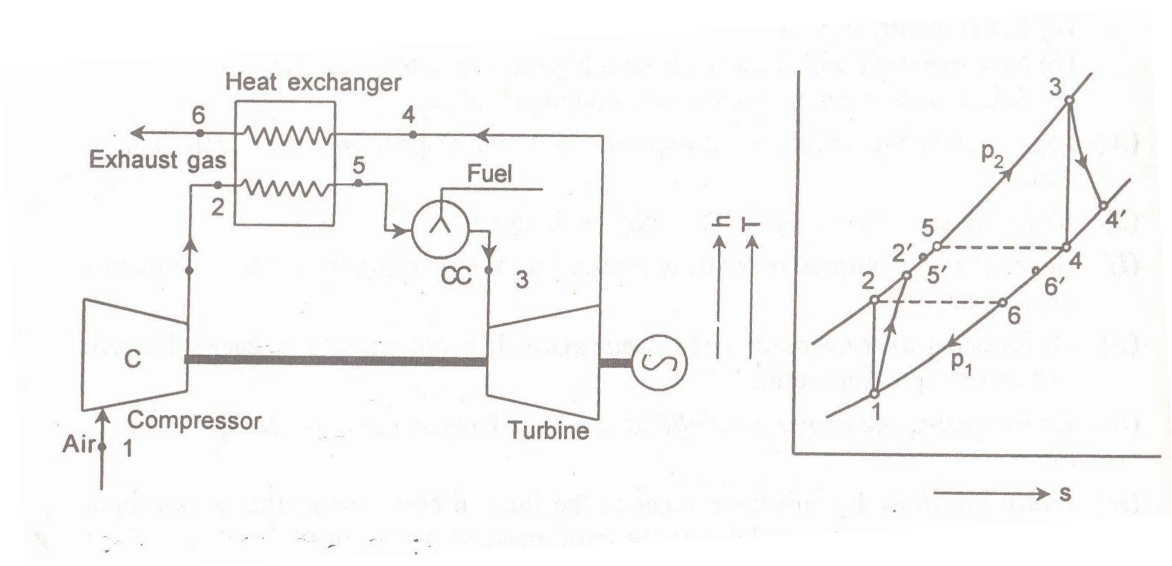


Fig 4 Open Cycle with Regeneration and its representation on h-s Diagram

Process 2' - 3 represents the heat flow into the compressed air during its passage through the heat exchanger.

Process 3 - 4 represents the heat taken in from the combustion of the fuel.

Net work,

$$W_{net} = W_t - W_c$$

$$W_{net} = C_p(T_4 - T_5') - C_p(T_2' - T_1)$$

Heat supplied,

$$q_A = h_4 - h_3 = C_p(T_4 - T_3)$$

$$\eta_{th} = \frac{W_{net}}{q_A} = \frac{C_p(T_4 - T_5') - C_p(T_2' - T_1)}{C_p(T_4 - T_3)}$$

$$\eta_{th} = \frac{(T_4 - T_5') - (T_2' - T_1)}{(T_4 - T_3)}$$

The effectiveness of the heat exchanger is given by,

$$\varepsilon = \frac{\text{Increase in enthalpy per kg of air}}{\text{Available increase in enthalpy per kg of air}} = \frac{T_3 - T_2'}{T_5' - T_2'}$$

3.3.2 Open Cycle Gas Turbine with Reheating

The whole expansion in the turbine is achieved in two or more stages and reheating is done after each stage.

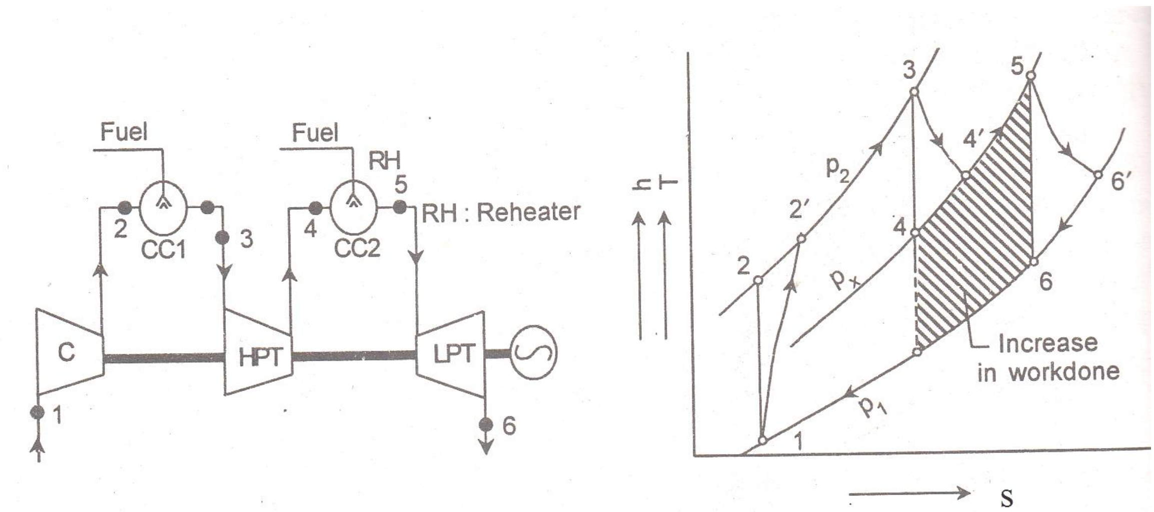


Fig. 5 Open Cycle with Reheating and its representation on h-s Diagram

By reheating or adding heat to the gases after they have passed through a part of the rows of the turbine blading (or a stage), a further increase in work done is obtained.

In reheating, the gas temperature, which has dropped due to expansion, is brought back to approximately the initial temperature for the expansion in the next stage.

Since the working fluid contains about 85% air, additional fuel can be burnt by injecting it into the gases without any additional air supply which gives the gain in thermal efficiency.

In this, the H. P. turbine drives the compressor and the L. P. turbine provides the useful work. Hence, the L. P. turbine is called power turbine. Net work,

$$W_{net} = W_t - W_c$$

$$W_{net} = C_p(T_3 - T_4') + C_p(T_5 - T_6') - C_p(T_2' - T_1)$$

Heat supplied,

$$q_A = C_p(T_3 - T_2') + C_p(T_5 - T_4')$$

$$\eta_{th} = \frac{W_{net}}{q_A} = \frac{C_p(T_3 - T_4') + C_p(T_5 - T_6') - C_p(T_2' - T_1)}{C_p(T_3 - T_2') + C_p(T_5 - T_4')}$$

$$\eta_{th} = \frac{(T_3 - T_4') + (T_5 - T_6') - (T_2' - T_1)}{(T_3 - T_2') + (T_5 - T_4')}$$

3.3.3 Open Cycle Gas Turbine with Intercooling

In this method, the compressor work is reduced by intercooling the air between compressor stages.

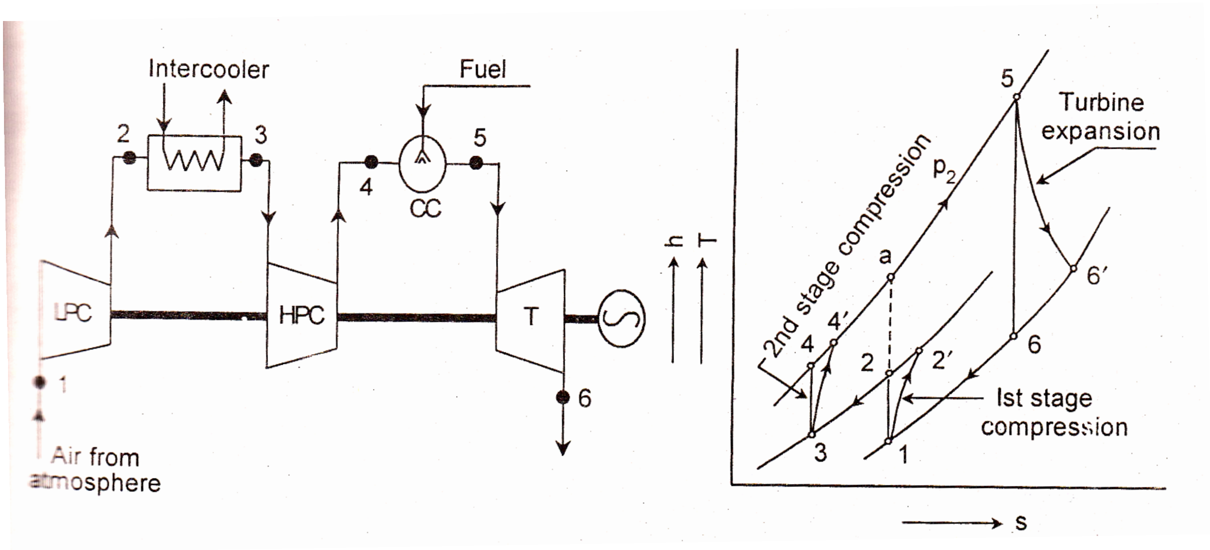


Fig. 6 Open Cycle with Intercooling and its representation on h-s Diagram

The net work of the gas turbine cycle may be increased by saving some compression work. This is done by using several stages of compression with Intercooling of air between stages.

The air from the low pressure stage compressor (LPC) is cooled in an intercooler approximately to initial temperature before entering to the high pressure stage compressor (HPC).

The effect of Intercooling is to increase the net work and decrease the efficiency as compared to the simple ideal cycle without Intercooling which gives the gain in thermal efficiency.

$$W_{net} = W_t - W_c$$

$$W_{net} = C_p (T_5 - T_6') - C_p (T_2' - T_1) - C_p (T_4' - T_3)$$

Heat supplied,

$$q_A = C_p (T_5 - T_4')$$

$$\eta_{th} = \frac{W_{net}}{q_A} = \frac{C_p (T_5 - T_6') - C_p (T_2' - T_1) - C_p (T_4' - T_3)}{C_p (T_5 - T_4')}$$

$$\eta_{th} = \frac{(T_5 - T_6') - (T_2' - T_1) - (T_4' - T_3)}{(T_5 - T_4')}$$

3.3.4 Closed Cycle Gas Turbine

As it has been seen that in the open cycle, the exhaust gas from the turbine is rejected into the atmosphere but in the case of closed cycle gas turbine, the same working fluid continuously circulates.

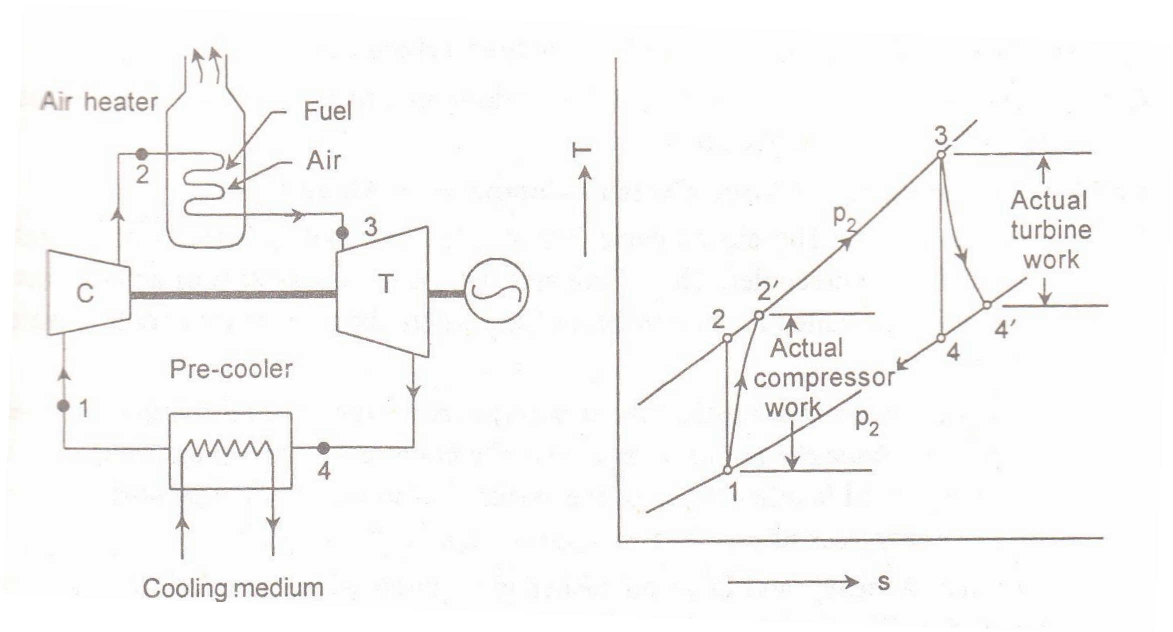


Fig. 7 Closed Cycle Gas Turbine Cycle and its representation on T-s Diagram

Since the closed cycle gas turbine continuously circulates the same working fluid, gases of higher density than air must be used as working fluid.

The heat added must be supplied through a heat exchanger (generally called air heater) from an external source and the heat rejected from the system must be through another heat exchanger with a cooling medium generally called precooler.

Figure shows a closed cycle gas turbine.

The gas is compressed from pressure p_1 to p_2 in the compressor.

The compressed gas is heated in an air heater where fuel and air are supplied from outside, and the temperature of the gas is increased from T_2 to T_3 at constant pressure.

After this, the compressed and heated gas expands in the turbine.

The exhaust gas from the turbine is cooled in a precooler from temperature T_4 to T_1 and is re-circulated to the compressor.

Note that all the modifications such as regeneration, Intercooling and reheating are possible, in closed cycle also.

3.3.5 Advantages and Disadvantages Of Closed Cycle Gas Turbine Over Open Cycle Gas Turbine

Following are some advantages of closed cycle gas turbine over open cycle gas turbine:

- Higher thermal efficiency
- Reduced size
- Improved part load efficiency
- Improved heat transmission
- Lesser fluid friction loss
- No contamination
- Greater output
- Inexpensive fuel
- No loss of working medium

Following are some disadvantages of closed cycle gas turbine over open cycle gas turbine:

- Dependent system
- Complexity
- Air heater

Numerical based on Gas Turbine Power Plant

Ex-1

A gas turbine power plant operates between temperatures 15° C and 1100° C. Calculate the following:
(i) The optimum pressure ratio for the cycle for maximum power output,
(ii) Compressor work, Turbine work, Shaft work and Work Ratio, and
(iii) Plant efficiency.
Take for air, C_p=1.005 KJ/kg K and γ = 1.4

Solution:

Data given:

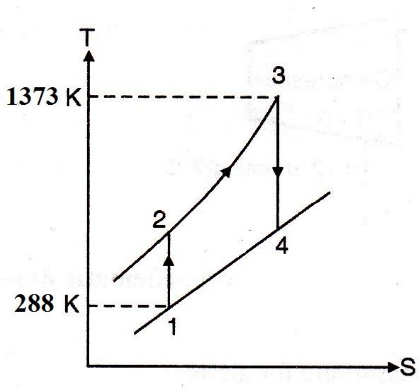
$T_{min} = T_1 = 15°\ C = 15+273 = 288\ K$

$T_{max} = T_3 = 1100°\ C = 1100+273 = 1373\ K$

C_p=1.005 KJ/kg K

$\gamma = 1.4$

Find: R_p, W_c, W_t, R_w, η_{th}



(i) The optimum pressure ratio for the cycle for maximum power output

$$R_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}} = \left(\frac{1373}{288}\right)^{\frac{1.4}{2(1.4-1)}} = 15.38$$

(ii) Compressor work:

$$\frac{T_2}{T_1} = \left(R_p\right)^{\frac{\gamma-1}{\gamma}} = \left(15.38\right)^{\frac{1.4-1}{1.4}}$$

$$\therefore T_2 = 288\left(15.38\right)^{\frac{1.4-1}{1.4}}$$

$\therefore T_2 = 628.81K$

$W_c = C_p\left(T_2 - T_1\right) = 1.005\left(628.81 - 288\right)$

$\therefore W_c = 342.52KJ/kg$

Turbine work:

$$\frac{T_3}{T_4} = \left(R_p\right)^{\frac{\gamma-1}{\gamma}} = \left(15.38\right)^{\frac{1.4-1}{1.4}}$$

$$\therefore T_4 = \frac{1373}{\left(15.38\right)^{\frac{1.4-1}{1.4}}}$$

$\therefore T_4 = 628.84K$

$W_t = C_p\left(T_3 - T_4\right) = 1.005\left(1373 - 628.84\right)$

$\therefore W_t = 747.88KJ/kg$

Shaft work:

$W_s = W_t - W_c$

$W_s = 747.88 - 342.52 = 405.36KJ/kg$

Work ratio:

$$R_w = \frac{W_s}{W_t} = \frac{405.36}{747.88} = 0.54$$

(iii) Plant efficiency:

Heat supplied

$q_A = C_p\left(T_3 - T_2\right) = 1.005(1373 - 628.81)$

$q_A = 747.91KJ/kg$

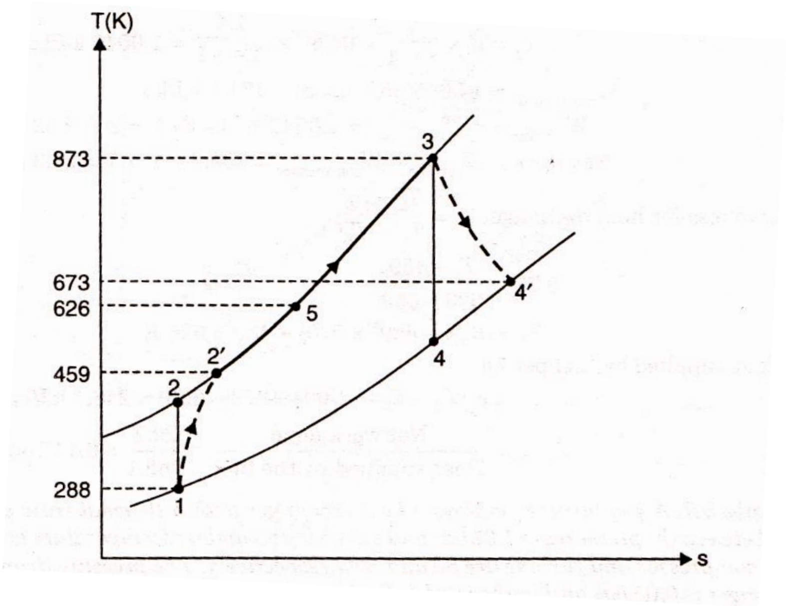
$$\eta_{th} = \frac{W_s}{q_A} = \frac{405.36}{747.91} = 0.542$$

$\eta_{th} = 54.2\%$

EX-2

In a gas turbine, the compressor takes in air at a temperature of 15° C and compresses it to four times the initial pressure with an isentropic efficiency of 82%. The air is then passed through a heat exchanger heated by the turbine exhaust before reaching the combustion chamber. In the heat exchanger, 78% of the available heat is given to the air. The maximum temperature after constant pressure combustion is 600° C and the efficiency of the turbine is 70%. Assuming the working fluid throughout the cycle to have the characteristic of air, find the efficiency of the cycle. Assume R=0.287 KJ/kg K and γ = 1.4 for air and constant specific heats throughout.

Solution:



Data given:

T_1 = 15° C = 15+273 = 288 K

$r_p = 4$

$\eta_{compressor}$ = 82%

Effectiveness of H.E. = ϵ = 0.78

T_3 = 1100° C = 1100+273 = 1373 K

$\eta_{turbine}$ = 70%

R=0.287 KJ/kg K

γ = 1.4

Find: η_{th}

$$\frac{T_2}{T_1} = \left(r_p\right)^{\frac{\gamma-1}{\gamma}} = \left(4\right)^{\frac{1.4-1}{1.4}}$$

$$\therefore \mathrm{T}_2 = 288(1.486)$$

$$\therefore \mathrm{T}_2 = 428K$$

$$\eta_{\text{compressor}} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.82 = \frac{428 - 288}{T_2' - 288}$$

$$\therefore \mathrm{T}_2' = 459K$$

$$\frac{\mathrm{T}_3}{\mathrm{T}_4} = (r_{\mathrm{p}})^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}}$$

$$\therefore \mathrm{T}_4 = \frac{873}{1.486}$$

$$\therefore \mathrm{T}_4 = 587.5K$$

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

$$0.70 = \frac{873 - T_4'}{873 - 587.5}$$

$$\therefore \mathrm{T}_4' = 673K$$

$$C_p = R\left(\frac{\gamma}{\gamma - 1}\right) = 0.287\left(\frac{1.4}{1.4 - 1}\right) = 1.0045KJ / kg.K$$

Compressor work:

$$\mathrm{W_c} = \mathrm{C_p}(\mathrm{T_2}' - \mathrm{T_1}) = 1.0045(459 - 288)$$

$$\therefore \mathrm{W_c} = 171.77KJ / kg$$

Turbine work:

$$\mathrm{W_t} = \mathrm{C_p}(\mathrm{T_3} - \mathrm{T_4}') = 1.0045(873 - 673)$$

$$\therefore \mathrm{W_t} = 200.9KJ / kg$$

Shaft work:

$$W_s = W_t - W_c$$

$$W_s = 200.9 - 171.77 = 29.13 KJ/kg$$

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

$$\therefore 0.78 = \frac{T_5 - 459}{673 - 459}$$

$$\therefore T_5 = 625.9K$$

Heat supplied

$$q_A = C_p\left(T_3 - T_5\right) = 1.0045(873 - 625.9)$$

$$q_A = 248.2 KJ/kg$$

Thermal efficiency

$$\eta_{th} = \frac{W_s}{q_A} = \frac{29.13}{248.2} = 0.117$$

$$\eta_{th} = 11.7\%$$

EX-3

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 separate 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:
(i) The pressure and temperature of the gases entering the power turbine,
(ii) The net power developed by the unit per kg/s mass flow,
(iii) The work ratio,
(iv) The thermal efficiency of the unit
For compression process, C_{pa} = 1.005 KJ/kg K and γ = 1.4
For combustion and expansion processes, C_{pg} = 1.15 KJ/kg K and γ = 1.333

Solution:

Data given:

T_1 = 15° C = 15+273 = 288 K

p_1=1.01 bar

r_p = 4

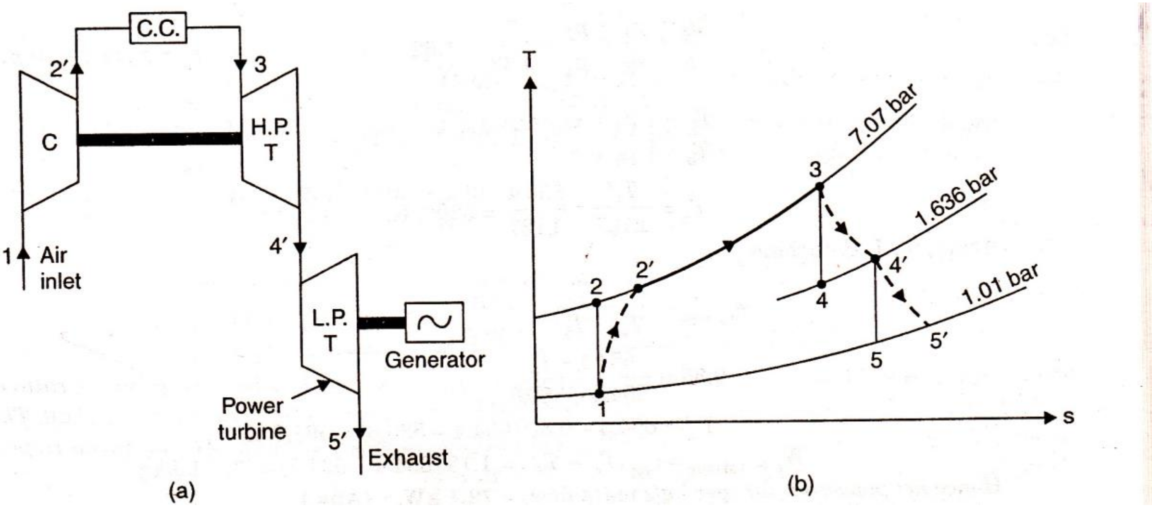
η compressor = 0.82

η turbine = 0.85

T_3 = 1100° C = 1100+273 = 1373 K

For compression process, C_{pa} = 1.005 KJ/kg K and γ = 1.4
For combustion and expansion processes, C_{pg} = 1.15 KJ/kg K and γ = 1.333

Find: p_4', T_4', P, r_w, η_{th}



$$\frac{T_2}{T_1} = \left(r_p\right)^{\frac{\gamma-1}{\gamma}} = \left(7\right)^{\frac{1.4-1}{1.4}}$$

$$\therefore T_2 = 288\left(1.745\right)$$

$$\therefore T_2 = 502K$$

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

$$0.82 = \frac{502 - 288}{T_2' - 288}$$

$$\therefore T_2' = 549.2K$$

Compressor work:

$$W_c = C_{pa}\left(T_2' - T_1\right) = 1.005\left(549.2 - 288\right)$$

$$\therefore W_c = 262.5 KJ/kg$$

Work output of H.P. turbine = Work input to compressor

$$C_{pg}\left(T_3 - T_4'\right) = 262.9$$

$$1.15\left(883 - T_4'\right) = 262.9$$

$$\therefore T_4' = 654.7K$$

For H. P. turbine,

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

$$0.85 = \frac{883 - 654.7}{873 - T_4}$$

$$\therefore T_4 = 614.5K$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{P_3}{P_4} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{883}{614.5}\right)^{\frac{1.33}{1.33-1}}$$

$$\frac{P_3}{P_4} = 4.31$$

$$P_4 = \frac{P_3}{4.31} = \frac{7.07}{4.31}$$

$$P_4 = 1.64bar$$

$$P_4' = 1.64bar\left(\because P_4 = P_4'\right)$$

$$\frac{T_4'}{T_5} = \left(\frac{P_4'}{P_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.64}{1.01}\right)^{\frac{1.33-1}{1.33}} = 1.62^{0.248} = 1.127$$

$$\therefore T_5 = \frac{T_4'}{1.127} = \frac{654.7}{1.127}$$

$$\therefore T_5 = 580.8K$$

For L. P. turbine,

$$\eta_{turbine} = \frac{T_4' - T_5'}{T_4' - T_5}$$

$$0.85 = \frac{654.7 - T_5'}{654.7 - 580.8}$$

$$\therefore T_5' = 591.9K$$

$$W_{\text{L.P. turbine}} = C_{pg}\left(T_4' - T_5'\right) = 1.15\left(654.7 - 591.9\right) = 72.2KJ/kg$$

Work ratio:

$$r_w = \frac{W_{L.P.turbine}}{W_{L.P.turbine} + W_c} = \frac{72.2}{72.2 + 262.5} = 0.215$$

Plant efficiency:

Heat supplied

$$q_A = C_{pg}\left(T_3 - T_2'\right) = 1.15(883 - 549.2)$$

$$q_A = 383.87KJ/kg$$

$$\eta_{th} = \frac{\text{Net work}}{q_A} = \frac{72.2}{383.87} = 0.188$$

$$\eta_{th} = 18.8\%$$

EX-4

In an open gas turbine plant, the pressure ratio through which air at 15° C is compressed is 14. The same air is then heated to a maximum permissible temperature of 1300° C first in a heat exchanger which is 75% efficient, and then in the combustion chamber. The same air at 1300° C is expanded in two stages such that the expansion work is maximum. The air is reheated to 1300° C after the high pressure stage. Determine the cycle thermal efficiency, the work ratio and the net shaft work per kg of air. The isentropic efficiencies may be assumed to be 85% and 86% for compressor and turbine respectively. Calculate the flow rate of air for an output of 240 MW. Assume Mechanical and Generator efficiency 99% each.

Solution:

Data given:

T_1 = 15° C = 15+273 = 288 K

r_p =14

T_4 = T_6 = 1300° C = 1300+273 = 1573 K

$\epsilon = 0.75$

$\eta_{compressor} = 85\%$

$\eta_{turbine} = 86\%$

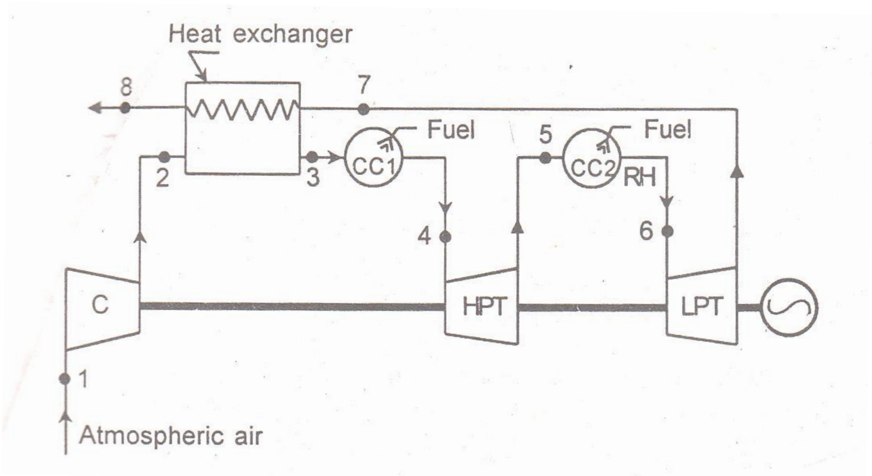
$\eta_{mech} = 99\%$

$\eta_{gen} = 99\%$

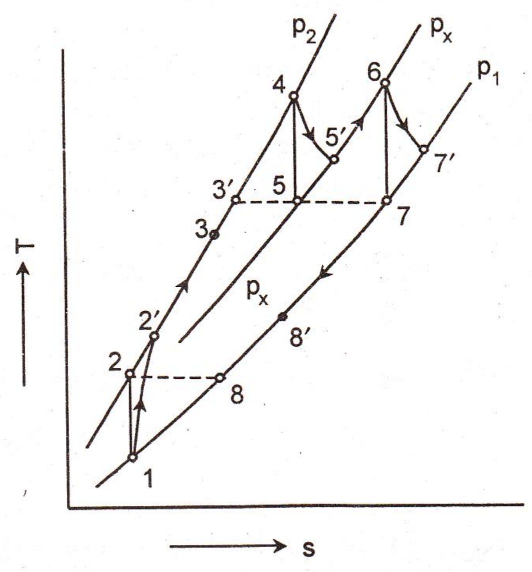
$P = 240$ MW $= 240 \times 10^3$ KW

Assume $C_p = 1.005$ KJ/kg K and $\gamma = 1.4$

Find: η_{th}, r_w, W_s, m_a



Gas turbine with Reheat and Regeneration



T – S diagram

$$\frac{T_2}{T_1} = \left(r_p\right)^{\frac{\gamma-1}{\gamma}} = (14)^{\frac{1.4-1}{1.4}}$$

$$\therefore T_2 = 612.15K$$

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

$$0.85 = \frac{612.25 - 288}{T_2' - 288}$$

$$\therefore T_2' = 669.35K$$

For maximum work output, the reheating should be done at intermediate pressure.

$$P_x = \sqrt{P_1.P_2}$$

$$P_x^2 = P_1.P_2 = P_1(14P_1) = 14P_1^2$$

$$\therefore P_x = \sqrt{14}P_1$$

$$P_x = \sqrt{P_1.P_2}$$

$$\therefore \frac{P_2}{P_x} = \frac{P_x}{P_1} = \frac{\sqrt{14}P_1}{P_1} = 3.74$$

$$\frac{T_4}{T_5} = \left(\frac{P_2}{P_x}\right)^{\frac{\gamma-1}{\gamma}} = (3.74)^{\frac{1.4-1}{1.4}}$$

$$T_5 = \frac{T_4}{(3.74)^{\frac{1.4-1}{1.4}}}$$

$$\therefore T_5 = 1079K$$

$$\eta_{turbine} = \frac{T_4 - T_5'}{T_4 - T_5}$$

$$0.86 = \frac{1573 - T_5'}{1573 - 1079}$$

$$\therefore T_5' = 1148.11K$$

$$\frac{T_6}{T_7} = \left(\frac{P_x}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (3.74)^{\frac{1.4-1}{1.4}}$$

$$T_7 = \frac{T_6}{(3.74)^{\frac{1.4-1}{1.4}}}$$

$$\therefore T_7 = 1079K$$

$$\eta_{turbine} = \frac{T_6 - T_7'}{T_6 - T_7}$$

$$0.86 = \frac{1573 - T_7'}{1573 - 1079}$$

$$\therefore T_7' = 1148.11K$$

$$\epsilon = \frac{T_3' - T_2'}{T_7' - T_2'}$$

$$\therefore 0.75 = \frac{T_3' - 669.35}{1148.11 - 669.35}$$

$$\therefore T_3' = 1028.42K$$

Compressor work:

$$W_{ca} = \frac{C_p (T_2' - T_1)}{\eta_{mech}} = \frac{1.005(669.35 - 288)}{0.99}$$

$$\therefore W_{ca} = 387.13KJ/kg$$

Turbine work:

$$W_{ta} = C_p [(T_4 - T_5') + (T_6 - T_7')]\eta_{mech}$$

$$W_{ta} = 1.005[(1573 - 1148.11) + (1573 - 1148.11)] \times 0.99$$

$$\therefore W_{ta} = 845.5KJ/kg$$

Shaft work:

$$W_{sa} = W_{ta} - W_{ca}$$

$$W_{sa} = (845.5 - 387.13) \times 0.99$$

$$W_{sa} = 457.78KJ/kg$$

Heat supplied:

$$q_{Aa} = C_p\left[\left(T_4 - T_3'\right)+\left(T_6 - T_5'\right)\right]$$

$$q_{Aa} = 1.005\left[\left(1573 - 1028.42\right)+\left(1573 - 1148.11\right)\right]$$

$$q_{Aa} = 974.32 KJ/kg$$

Thermal efficiency

$$\eta_{th} = \frac{W_{sa}}{q_{Aa}} = \frac{457.78}{974.32} = 0.4657$$

$$\eta_{th} = 46.57\%$$

Work ratio:

$$r_w = \frac{W_{sa}}{W_{ta}} = \frac{457.78}{845.5} = 0.5414$$

$$\text{Power output} = \text{mass flow rate of air} \times \text{shaft work}$$

$$\text{Power output} = m_a \times W_{sa}$$

$$240 \times 10^3 = m_a (457.78)$$

$$\therefore m_a = 524.27 kg/s$$

EX-5

The air enters the compressor of an open cycle constant pressure gas turbine at a pressure of 1 bar and temperature of 20˚C. The pressure of the air after compression is 4 Bar. The isentropic efficiency of compressor and turbine are 80 % and 85 % respectively. The air fuel ratio used is 90:1. If the flow rate of air is 3 kg per second, find
(i) Power developed
(ii) Thermal efficiency of the cycle
Assume, C_p = 1.0 KJ/kg K and γ = 1.4, for air & gases
And Calorific value of fuel = 41800 KJ/kg

Solution:

Data given:

T_1 = 20° C = 20+273 = 293 K

P_1 = 1 bar

P_2 = 4 bar

$\eta_{\text{compressor}}$ = 80%

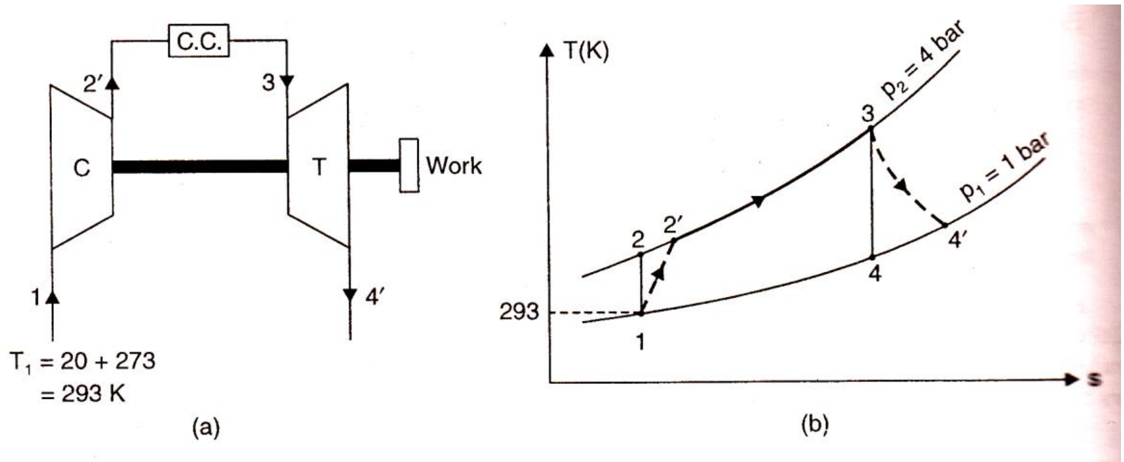
$\eta_{turbine}$ = 85%

Air fuel ratio, $\frac{m_a}{m_f} = 90$

m_a = 3 kg/s

C.V. = 41800 KJ/kg

C_p = 1.0 KJ/kg K and γ = 1.4
Find: P, η_{th}



$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}}$$

$$\therefore T_2 = 293(1.486)$$

$$\therefore T_2 = 435.4K$$

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

$$0.80 = \frac{435.4 - 293}{T_2' - 293}$$

$$\therefore T_2' = 471K$$

Heat supplied by fuel = Heat taken by burnt gases

$$m_f \times C.V. = (m_a + m_f)C_p(T_3 - T_2')$$

$$\therefore C.V. = \left(\frac{m_a + m_f}{m_f}\right)C_p(T_3 - T_2')$$

$$\therefore C.V. = \left(\frac{m_a}{m_f} + 1\right)C_p(T_3 - T_2')$$

$$\therefore 41800 = (90+1)1(T_3 - 471)$$

$$\therefore T_3 = 930K$$

$$\frac{T_3}{T_4} = (r_p)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}}$$

$$\therefore T_4 = \frac{930}{1.486}$$

$$\therefore T_4 = 625K$$

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

$$0.85 = \frac{930 - T_4'}{930 - 625}$$

$$\therefore T_4' = 671K$$

Mass of hot gases formed for 3 kg of air

$$m_g = 3\left(\frac{m_a + m_f}{m_a}\right) = 3\left(1 + \frac{m_f}{m_a}\right) = 3\left(1 + \frac{1}{90}\right) = 3.0333$$

Turbine work:

$$W_t = m_g \times C_p (T_3 - T_4') = 3.0333(1)(930 - 671)$$

$$\therefore W_t = 785.62KJ$$

Compressor work:

$$W_c = m_a \times C_p (T_2' - T_1) = 3(1)(471 - 293)$$

$$\therefore W_t = 534KJ$$

Shaft work:

$$W_s = W_t - W_c$$

$$W_s = (785.62 - 534)$$

$$W_s = 251.62KJ$$

Hence, Power developed:

P = 251.62 KW

Heat supplied:

$$q_A = \frac{m_f}{m_a}(C.V.) = \frac{1}{90}(41800)$$

$$q_A = 383.87 KJ/kg$$

$$\therefore q_A = 3(464.44) = 1393.33 KJ \text{ (Heat supplied for 3 kg of air)}$$

$$\eta_{th} = \frac{\text{Net work}}{q_A} = \frac{251.62}{1393.33} = 0.1806$$

$$\eta_{th} = 18.06\%$$

4.DIESEL POWER PLANT

4.1INTRODUCTION

- The oil engines and gas engines are called Internal Combustion Engines. In IC engines fuels burn inside the engine and the products of combustion form the working fluid that generates mechanical power. Whereas, in Gas Turbines the combustion occurs in another chamber and hot working fluid containing thermal energy is admitted in turbine.
- Reciprocating oil engines and gas engines are of the same family and have a strong resemblance in principle of operation and construction.
- The engines convert chemical energy in fuel in to mechanical energy.

- A typical oil engine has:
  1. Cylinder in which fuel and air are admitted and combustion occurs.
  2. Piston, which receives high pressure of expanding hot products of combustion and the piston, is forced to linear motion.
  3. Connecting rod, crankshaft linkage to convert reciprocating motion into rotary motion of shaft.
  4. Connected Load, mechanical drive or electrical generator.
  5. Suitable valves (ports) for control of flow of fuel, air, exhaust gases, fuel injection, and ignition systems.
  6. Lubricating system, cooling system

- In an engine-generator set, the generator shaft is coupled to the Engine shaft.
  The main differences between the gasoline engine and the diesel engine are:
- A gasoline engine intakes a mixture of gas and air, compresses it and ignites the mixture with a spark. A diesel engine takes in just air, compresses it and then injects fuel into the compressed air. The heat of the compressed air lights the fuel spontaneously.
- A gasoline engine compresses at a ratio of 8:1 to 12:1, while a diesel engine compresses at a ratio of 14:1 to as high as 25:1. The higher compression ratio of the diesel engine leads to better efficiency.
- Gasoline engines generally use either carburetion, in which the air and fuel is mixed long before the air enters the cylinder, or port fuel injection, in which the fuel is injected just prior to the intake stroke (outside the cylinder). Diesel engines use direct fuel injection to the diesel fuel is injected directly into the cylinder.
- The diesel engine has no spark plug, that it intakes air and compresses it, and that it then injects the fuel directly into the combustion chamber (direct injection). It is the heat of the compressed air that lights the fuel in a diesel engine.
- The injector on a diesel engine is its most complex component and has been the subject of a great deal of experimentation in any particular engine it may be located in a variety of places.

- The injector has to be able to withstand the temperature and pressure inside the cylinder and still deliver the fuel in a fine mist. Getting the mist circulated in the cylinder so that it is evenly distributed is also a problem, so some diesel engines employ special induction valves, pre-combustion chambers or other devices to swirl the air in the combustion chamber or otherwise improve the ignition and combustion process.
- One big difference between a diesel engine and a gas engine is in the injection process. Most car engines use port injection or a carburetor rather than direct injection. In a car engine, therefore, all of the fuel is loaded into the cylinder during the intake stroke and then compressed. The compression of the fuel/air mixture limits the compression ratio of the engine, if it compresses the air too much, the fuel/air mixture spontaneously ignites and causes knocking. A diesel compresses only air, so the compression ratio can be much higher. The higher the compression ratio, the more power is generated.
- Some diesel engines contain a glow plug of some sort. When a diesel engine is cold, the compression process may not raise the air to a high enough temperature to ignite the fuel. The glow plug is an electrically heated wire (think of the hot wires you see in a toaster) that helps ignite the fuel when the engine is cold so that the engine can start.
- Smaller engines and engines that do not have such advanced computer controls, use glow plugs to solve the cold-starting problem. We recommend diesels due to their:
    a) Longevity-think of an 18 wheeler capable of 1,000,000 miles of operation before major service)
    b) Lower fuel costs (lower fuel consumption per kilowatt (kW) produced)
    c) Lower maintenance costs-no spark system, more rugged and more reliable engine

- Today's modern diesels are quiet and normally require less maintenance than comparably sized gas (natural gas or propane) units. Fuel costs per kW produced with diesels are normally thirty to fifty percent less than gas units.
- 1800 rpm water-cooled diesel units operate on average 12–30,000 hours before major maintenance is required. 1800 rpm water-cooled gas units normally operate 6–10,000 hours because they are built on a lighter duty gasoline engine block.
- 3600 rpm air-cooled gas units are normally replaced not overhauled at 500 to 1500 hours.
- Because the gas units burn hotter (higher btu of the fuel) you will see significantly shorter lives than the diesel units.

- Diesel engine power plants are installed where
  1. Supply of coal and water is not available in desired quantity.
  2. Where power is to be generated in small quantity for emergency services.
  3. Standby sets are required for continuity of supply such as in hospital, telephone center.
- It is an excellent prime mover for electric generator capacities of from 100 hp to 5000 hp. The Diesel units used for electric generation are more reliable and long - lived piece of equipment compared with other types of plants.

4.2 Operating Principle

- All the gas engines and oil engines operate in the same general way. The working fluid undergoes repeated cycles. A thermodynamic cycle is composed of a series of sequential events in a closed loop on P-V or T-S diagram. A typical cycle has following distinct operations
  1. Cylinder is charged
  2. Cylinder contents are compressed
  3. Combustion (Burning) of charge, creation of high pressure pushing the piston and expansion of products of combustion.
  4. Exhaust of spent products of combustion to atmosphere.

  The route taken for these steps is illustrated conveniently on P-V diagram and T-S diagram for the cycle.

- Various types of Gas Engines and Oil Engines have been developed and are classified on the basis of their operating cycles. Cycles are generally named after their Inventors e.g. Carnot Cycle; Diesel Cycle; Otto Cycle; Sterling Cycle; Bryton Cycle; Dual Cycle, etc. New cycles are being developed for fuel saving and reduction of pollution.
- Two principal categories of IC Engines are:
  —Four Stroke Engines
  —Two Stroke Engines
- In a Four Stroke Engine Cycle, the piston strokes are used to obtain the four steps (intake, compression, expansion, exhaust) and one power stroke in two full revolutions of crankshaft. In a Two Stroke Engine Cycle, one power stroke is obtained during each full revolution of the crankshaft.

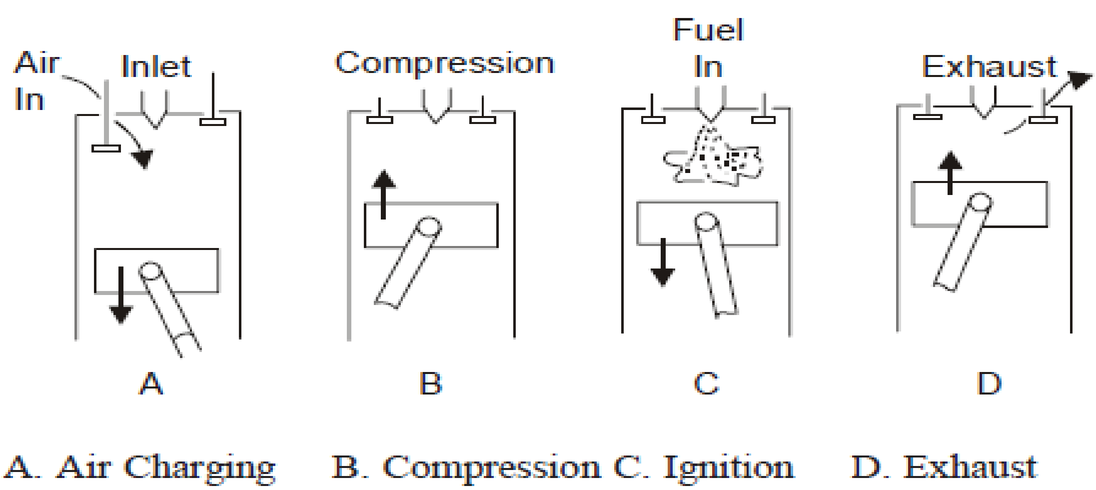


Fig 6.1 Operation In Ic Engine

- This is achieved by using air pressure slightly above atmospheric to blow out exhaust gases out of the cylinder and fill the fresh charge (scavenging). The methods of scavenging include: Crankcase scavenging; blower scavenging. Other methods include Super Charging; Turbo Charging.

4.3 Basic Types of Ic Engines

Although alike in main mechanical aspects, the oil engines differ from gas engines in fuels and fuel handling *i.e.*, when fuel and air are injected how much charge is compressed and how ignited. Many variants exist.

4.3.1 Two-Stroke, Spark Ignition Gas Engines/Petrol Engines

- The well-known automobile engine fueled with petrol (also called Gas) and Natural Gas Engine, Bio-gas Engine is of this category. The low compression gas engine (petrol engine/natural gas engine) mixes fuel and air, outside the cylinder, before compression. With the automobile engine, a carburetor is used for mixing the fuel and air and the mixture is injected in the cylinder. In a Natural Gas Engine, a mixing valve is used for the same purpose instead of the carburetor.
- In the mixture, the gas fuel and air proportion is almost perfect to produce complete combustion without excess air. This mixture flows into the cylinder and is then compressed. Near the end of the compression stroke, an electric spark ignites the inflammable mixture, which burns rapidly. The pressure in the cylinder rises rapidly and acts on the piston area and the piston is forced to move down on its power stroke.
- Since the compressed gas mixture rises in pressure during the compression stroke, the mixture may get pre-ignited before the sparking resulting in loss of power. Hence compression pressure must be limited in this type of engine. Compression Ratio is therefore an important parameter in establishing combustion without pre-ignition. The compression ratio is the ratio of cylinder volumes at the start and at the end of compression stroke.
- In general, higher the compression ratio, higher will be the maximum pressure reached during combustion and higher is the efficiency of the engine.
- Although it is desirable to have a high compression ratio, the nature of fuel imposes limits in engines where a nearly perfect mixture is compressed.
- With natural gas for example the compression ratio might be about 5:1 and compression pressure of about 8 bar, pre-ignition being the limiting factor.

4.3.2 Diesel Engines/Heavy Oil Engines

- In contrast to the engines in which the fuel and air mixes before compression, in diesel engines:
- air is compressed as the compression stroke begins and the fuel enters the cylinder at the end of compression stroke. Heat of compression is used for ignition of fuel.

- In a typical diesel engine, air is compressed to about 30 bars, which increases the temperature when finely atomized diesel fuel oil is sprayed into the heated air, it ignites and burns. High compression ratio is therefore essential for reliable combustion and high efficiency. Compression ratios above those needed to achieve ignition do not improve the efficiency.
- The pressure ratio depends on engine speed, cylinder size and design factors. Typical compression pressures in diesel engines range from 30 bar to 42 bar. Small high-speed engines have higher compression pressures.

4.3.3 Duel Fuel Engines

- In a duel fuel engine, a small quantity of pilot oil is injected near the end of the compression stroke. It is ignited by the compression and the mixture burns like standard diesel fuel. The pilot oil burning provides enough heat to the mixture of gas/air. Precise control of pilot oil injection and a separate set of fuel pumps and nozzles are added. Means are provided to reduce air quantity at partial loads.

4.3.4 High Compression Gas Engines

- With operation solely on gas, without duel mixtures and pilot oil, the high Compression Gas Engines of today use slightly richer mixtures of fuel and air, with lower compression ratios than duel fuel engines. The compression ratios are higher than conventional gas engines and lower than duel fuel engines. There is no need of pilot oil.

4.5 Advantage of Diesel Power Plant

The advantages of diesel power plants are listed below.

1. Very simple design also simple installation.
2. Limited cooling water requirement.
3. Standby losses are less as compared to other Power plants.
4. Low fuel cost.
5. Quickly started and put on load.
6. Smaller storage is needed for the fuel.
7. Layout of power plant is quite simple.
8. There is no problem of ash handling.
9. Less supervision required.
10. For small capacity, diesel power plant is more efficient as compared to steam power plant.
11. They can respond to varying loads without any difficulty.

4.6 Disadvantage of Diesel Power Plant

The disadvantages of diesel power plants are listed below.

1. High Maintenance and operating cost.

2. Fuel cost is more, since in India diesel is costly.
3. The plant cost per kW is comparatively more.
4. The life of diesel power plant is small due to high maintenance.
5. Noise is a serious problem in diesel power plant.
6. Diesel power plant cannot be constructed for large scale.

4.7 Application Of Diesel Power Plant

- Since there are many disadvantage of diesel power plant, although the plant find wide application in the following fields.

1. They are quite suitable for mobile power generation and are widely used in transportation systems consisting of railroads, ships, automobiles and aeroplanes.
2. They can be used for electrical power generation in capacities from 100 to 5000 H.P.
3. They can be used as standby power plants.
4. They can be used as peak load plants for some other types of power plants.
5. Industrial concerns where power requirement are small say of the order of 500 kW, diesel power plants become more economical due to their higher overall efficiency.

4.8 General Layout Of Diesel Power Plant

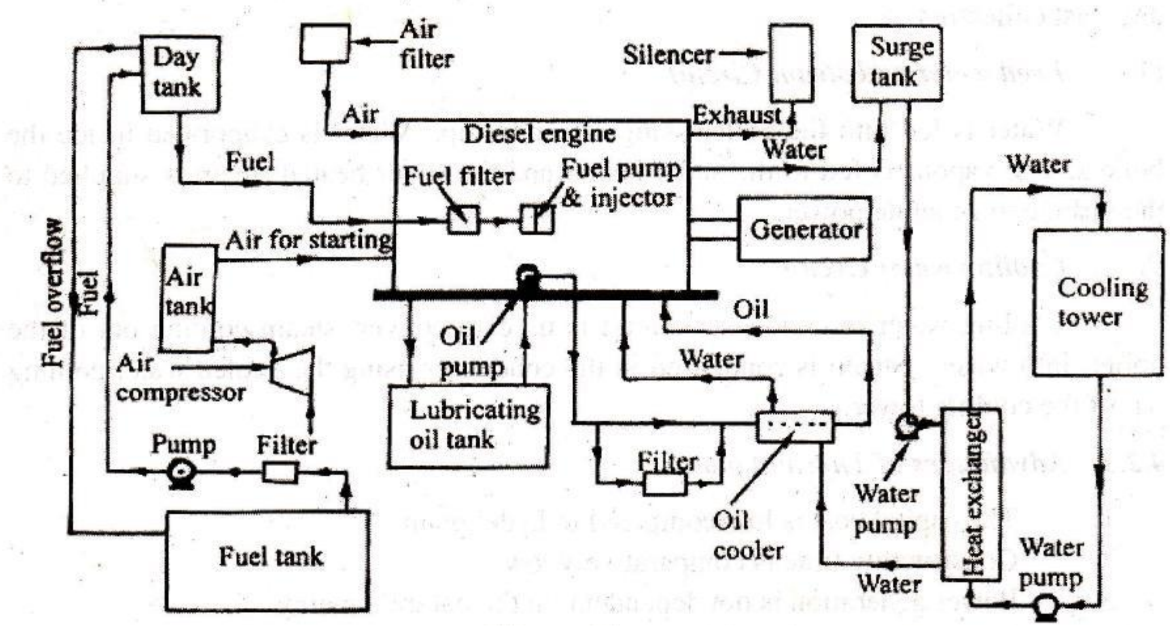


Fig. 6.2 General Layout of Diesel Power Plant

- ENGINE.
- FUEL SYSTEM.
- INTAKE SYSTEM.
- EXHAUST SYSTEM.
- COOLING SYSTEM.
- LUBRICATION SYSTEM.
- STARTING AND STOPING SYSTEM.
- GOVERNING SYSTEM .
- GENERATOR AND ALTERNATOR

4.8.1 Engine

- Engine is the main component of power plant the function of engine is generate mechanical power for generator.
- The diesel engine used for diesel power plants may be two stroke or four stroke engines.
- Two stroke engine is compact in construction simple in mechanical design, cheaper in cost, smaller flywheel required and develops more power for same speed and piston displacement.
- However a four stroke engine has lower specific fuel consumption and more effective lubrication ,more flexibility ,less noisy exhaust, simple and better cooling better scavenging and higher efficiency then two stroke engine.
- Generally two stroke diesel engines are favored only for diesel power plants due to high power out put, uniform turning moments, compactness and less capital cost.
- Due to high price of fuel(diesel) the 4 stroke engine used because it has low spc.
- The diesel engines are available in sizes from 75kw to 40MW.
- The size and number of engines depends upon plant capacity.

4.8.2 Fuel System

- It consists of fuel storage tank, daily consumption tank, fuel transfer pump, strainers fuel filters and fuel injection pump.
- The functions of fuel system are..,
- To supply fuel from storage tank to daily consumption tank.
- To filter the fuel.
- To measure and control the fuel supply.
- To inject the fuel in to engine as per the requirement quantity.

4.8.3 Intake system

- It consists of air supply pipe, air filters and super charger in case of supercharging engine.
- Its functions to clean the air, reduce noise of air intake.

4.8.4 Exhaust system

- It consists of piping from engine to a point where exhaust gases may be discharged with out any danger.

4.8.5 Cooling system

- The function of cooling system is to provide a proper amount of water circulation all around the engines to remove the part of heat from engine and maintain the requirement of cooling.
- It consists of water jacket, jacket water pump, surge tank, cooling tower, water pump and heat exchanger.

4.8.6 Lubricating system

- It consists of lubricating oil tank, pumps filters and lubricating oil cooler.
- It's functions to minimize the friction in between rubbing parts by providing the proper amount the oil.
- Oil cooler is used to maintain the temperature of oil because due to high temperature the properties of oil may change.

4.8.7 Starting and stopping system

- The starting system is used to rotate the engine initially while starting until firing starts and unit is runs in its own power.
- Small diesel engine plants are usually started manually by handles but for large capacity engine the compressed air or battery driven motors also used.
- The engine can be stopped by stopping fuel supply to the injection pump or stopping the action of injection pump.

4.8.8 Governing Systems

- This system controls the air fuel ratio in to the engine as per the increase or decrease the load on engine.
- The fuel supply stationary diesel engine is mostly controlled by centrifugal governor.

4.8.9 Electrical Generator

- The function of the generator is to convert mechanical energy in to the electrical enegy.
- The generator shaft is coupled with engine shaft and they are provided with automatic voltage regulators.
- The alternators used in diesel electric power plants are of rotating fields, salient pole construction, speed ranging from 214 to 1000 rpm (poles 28 to 6) and capacities ranging from 25 to 5000KVA at 0.8 power factor lagging.

4.9 Performance Of Diesel Engine

- The performance of the diesel engine means the power and efficiency. The engine develops as the various parameters of the engine, *e.g.* piston speed, air-fuel ratio, compression ratio, inlet air-pressure and temperature are varied.
  The two usual conditions under which I.C. engines are operated are:
  (1) constant speed with variable load, and
  (2) variable speed with variable load.
- The first situation is found in a.c. generator drives and the second one in automobiles, railway engines and tractors etc. A series of tests are carried out on the engine to determine its performance characteristics, such as: indicated power (I.P.), Brake power (B.P.), Frictional Power (F.P.), Mechanical efficiency (□*m*), thermal efficiency, fuel consumption and also specific fuel consumption etc. Below, we shall discussed how these quantities are measured

4.9.1 Indicated Mean Effective Pressure (Imep)

In order to determine the power developed by the engine, the indicator diagram of engine should be available. From the area of indicator diagram it is possible to find an average gas pressure that while acting on piston throughout one stroke would account for the network done. This pressure is called indicated mean effective pressure (I.M.E.P.).

4.9.2 Indicated Horse Power (Ihp)

The indicated horse power (I.H.P.) of the engine can be calculated as follows:

I.H.P. = (P· L· A· N · n) / (4500 · K)

Where
P = LM.E.P. in kg/cm^2
L = Length of stroke in metres
A = Piston areas in cm^2
N = Speed in R.P.M.
n = Number of cylinders
K = 1 for two stroke engine
= 2 for four stroke engine.

4.9.3 Brake Horse Power (B.H.P.)

Brake horse power is defined as the net power available at the crankshaft. It is found by measuring the output torque with a dynamometer.

$$\text{B.H.P.} = \frac{2\Pi NT}{4500}$$

where T = Torque in kg.m. N = Speed in R.P.NT.

4.9.4 Frictional Horse Power (F.H.P.)

The difference of I.H.P. and B.H.P. is called F.H.P. It is utilized in overcoming frictional resistance of rotating and sliding parts of the engine.
F.H.P. = I.H.P. – B.H.P.

4.9.5 Indicated Thermal Efficiency (□I)

It is defined as the ratio of indicated work to thermal input.

$$\eta_i = \frac{(\text{I.H.P.} \times 4500)}{(W \times C_v \times J)}$$

. .
where W = Weight of fuel supplied in kg per minute.
Cv = Calorific value of fuel oil in kcal/kg.
J = Joules equivalent = 427.

4.9.6 Brake Thermal Efficiency (Overall Efficiency)

It is defined as the ratio of brake output to thermal input.

$$\eta_b = \frac{(\text{B.H.P.} \times 4500)}{(W \times C_v \times J)}$$

4.9.7 Mechanical Efficiency (□M)

It is defined as the ratio of B.H.P. to L.H.P. Therefore,

$$\eta_m = \frac{\text{B.H.P.}}{\text{L.H.P.}}$$

4.10 Fuel System of Diesel Power Plant

- The fuel is delivered to the plant by railroad tank car, by truck or by barge and tanker and stored in the bulk storage situated outdoors for the sake of safety.
- From this main fuel tank, the fuel oil is transferred to the daily consumption tank by a transfer pump through a filter.
- The capacity of the daily consumption should be at least the 8-hour requirement of the plant.
- This tank is located either above the engine level so that the fuel flows by gravity to the injection pump or below the engine level and the fuel oil is delivered to the injection pump by a transfer pump driven from the engine shaft, Fig. 6.3. Fuel connection is normally used when tank-car siding or truck roadway is above tank level.
- If it is below tank level, then, an unloading pump is used to transfer fuel form tank car to the storage tank (dotted line).

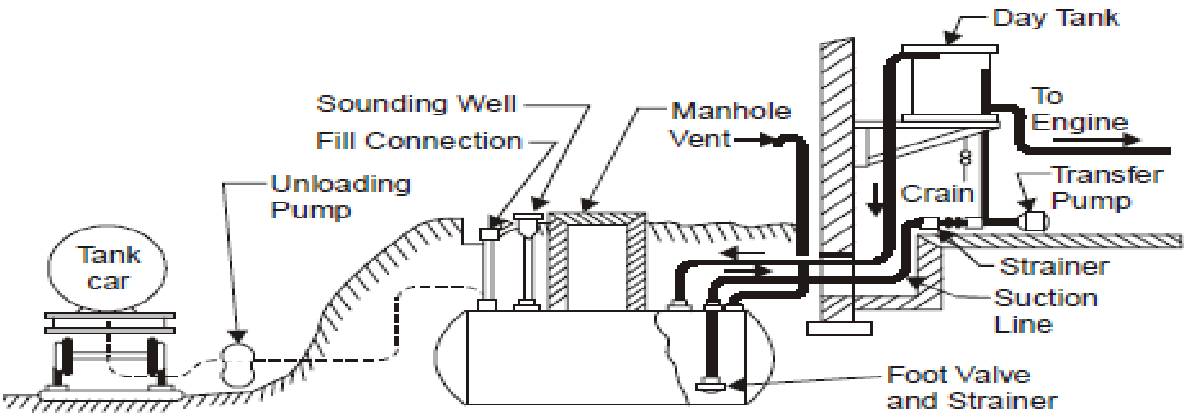
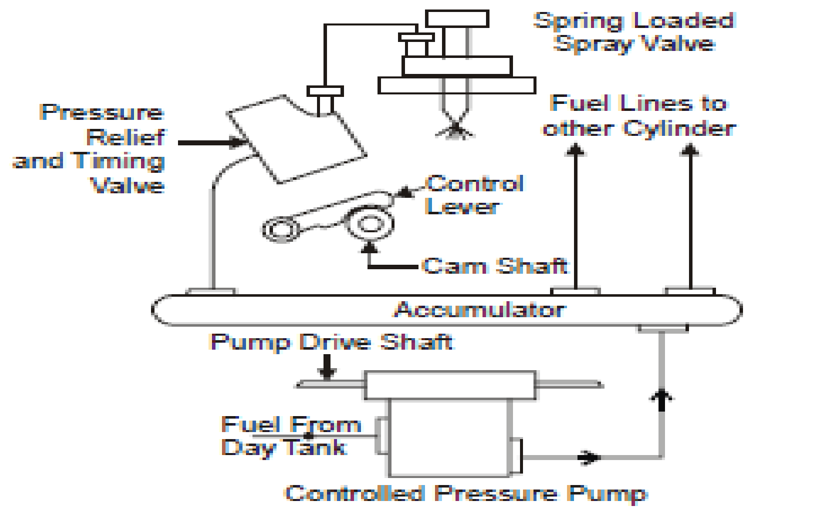


Fig.6.3 Fuel system

The five essential functions of a fuel injection system are
1. To deliver oil from the storage to the fuel injector.
2. To raise the fuel pressure to the level required for atomization.
3. To measure and control the amount of fuel admitted in each cycle.
4. To control time of injection.
5. To spray fuel into the cylinder in atomized form for thorough mixing and burning.

- The above functions can be achieved in a variety of ways. The following are the systems, which are usual on power station diesels:
  1. Common Rail.
  2. Individual Pump Injection.
  3. Distributor.



6.4 Common Rail System

- A typical common rail injection system is shown in Fig. 8.4. It incorporates a pump with built in pressure regulation, which adjusts pumping rate to maintain the desired injection pressure. The function of the pressure relief and timing valves is to regulate the injection time and amount. Spring-loaded spray valve acts merely as a check. When injection valve lifts to admit high-pressure fuel to spray valve, its needle rises against the spring. When the pressure is vented to the atmosphere, the spring shuts the valve.

4.11 Supercharging System of Diesel Power Plant

- The purpose of supercharging is to raise the volumetric efficiency above that value which can be obtained by normal aspiration. Since the I.H.P. produced by an I.C. engine is directly proportional to the air consumed by the engine. And greater quantities of fuel to be added by increasing the air consumption permit and result in greater power produced by the engine. So, it is, therefore, desirable that the engine should take in the greatest possible mass of air.
- The supply of air is pumped into the cylinder at a pressure greater than the atmospheric pressure and is called supercharging. When greater quantity of air is supplied to an I.C. engine it would be able to develop more power for the same size and conversely a small size engine fed with extra air would produce the same power as a larger engine supplied with its normal air feed. Supercharging is used to increase rated power output capacity of a given engine or to make the rating equal at high altitudes corresponding to the unsupercharged sea level rating.
- Installing a super charger between engine intakes does supercharging and air inlet through air cleaner super charger is merely a compressor that provides a denser charge to the engine thereby enabling the consumption of a greater mass of charge with the same total piston displacement.
- Power required to drive the super charger is taken from the engine and thereby removes from over all engine output some of the gain in power obtained through supercharging.

- Since the main object of supercharging is to increase the power output of these engine without increasing its rotational speed or the dimensions of the cylinder. This is achieved by increasing the charge of air, which results more burning of the fuel and a higher mean effective pressure. So there are three possible methods that increase the air consumption of an engine,
    a. To increasing the piston displacement, but this increases the size and weight of the engine, and introduces additional cooling problems.
    b. Running the engine at higher speeds, which results in increased fluid and mechanical friction losses, and imposes greater inertia stresses on engine parts.
    c. Increasing the density of the charge, such that a greater mass of charge is introduced into the same volume or same total piston displacement.

4.12 Cooling System of Diesel Power Plant

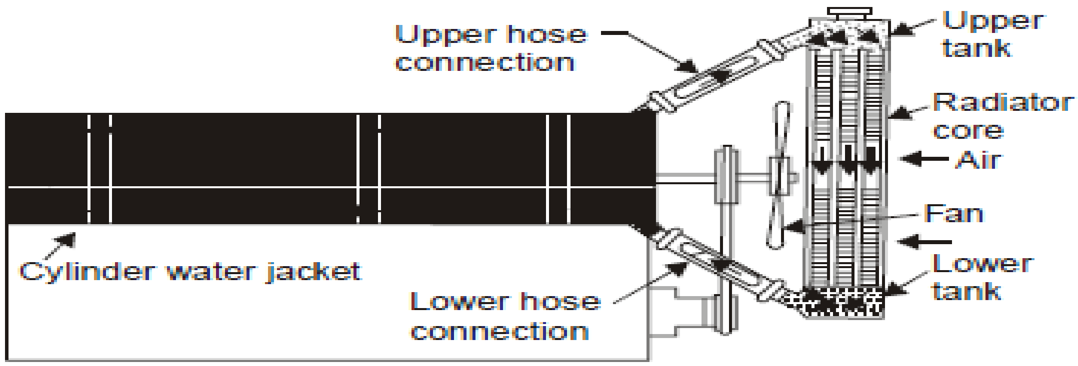
- Based on cooling medium two types of cooling systems is in general use. They are
  (*a*) Air as direct cooling system.
  (*b*) Liquid or indirect cooling system.
- Air-cooling is used in small engines and portable engines by providing fins on the cylinder. Big diesel engines are always liquid (water/special liquid) cooled.
- Liquid cooling system is further classified as
  (1) Open cooling system
  (2) Natural circulation (Thermo-system)
  (3) Forced circulation system
  (4) Evaporation cooling system

4.12.1 Open Cooling System

This system is applicable only where plenty of water is available. The water from the storage tank is directly supplied through an inlet valve to the engine cooling water jacket. The hot water coming out of the engine is not cooled for reuse but it is discharged.

4.12.2 Natural Circulation System

The system is closed one and designed so that the water may circulate naturally because of the difference in density of water at different temperatures. Fig. 8.14 shows a natural circulation cooling system. It consists of water jacket, radiator and a fan. When the water is heated, its density decreases and it tends to rise, while the colder molecules tend to sink. Circulation of water then is obtained as the water heated in the water jacket tends to rise and the water cooled in the radiator with the help of air passing over the radiator either by ram effect or by fan or jointly tends to sink. Arrows show the direction of natural circulation, which is slow.



6.5 Natural Circulation System

4.12.3 Force Circulation Cooling System

- Fig shows forced circulation cooling system that is closed one. The system consists of pump, water jacket in the cylinder, radiator, fan and a thermostat.
- The coolant (water or synthetic coolant) is circulated through the cylinder jacket with the help of a pump, which is usually a centrifugal type, and driven by the engine.

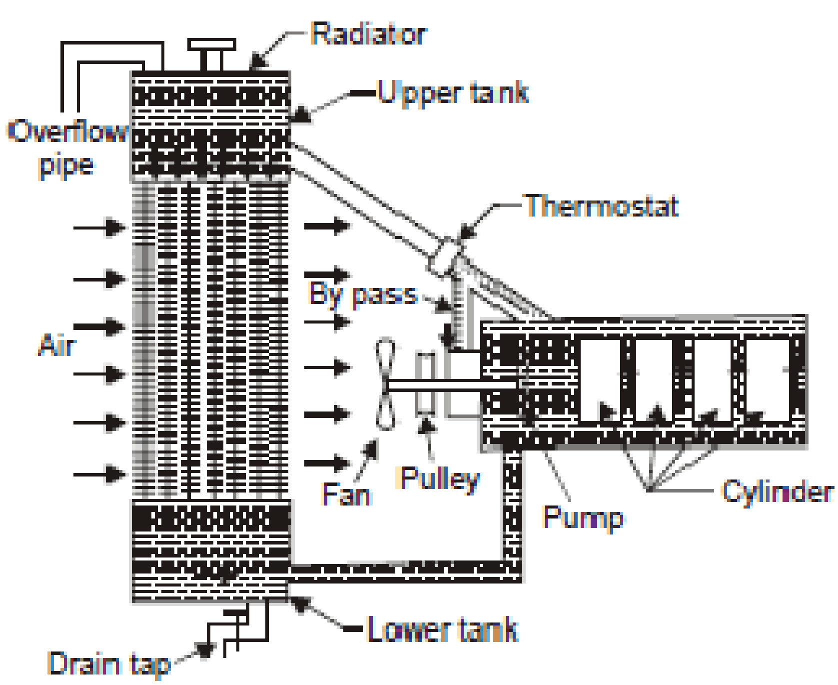


Fig.6.6 Natural Circulation System

- The function of thermostat, which is fitted in the upper house connection initially, prevents the circulation of water below a certain temperature (usually up to 85°C) through the radiation so that water gets heated up quickly.
- Standby diesel power plants up to 200 kVA use this type of cooling. In the case of bigger plant, he hot water is cooled in a cooling tower and recalculated again.
- There is a need of small quantity of cooling make-up water.

4.13 Lubrication System of Diesel Power Plant

- Since frictional forces causes wear and tear of rubbing parts of the engine and thereby the life of the engine is reduced. So the rubbing part requires that some substance should be introduced between the rubbing surfaces in order to decrease the frictional force between them. Such substance is called lubricant. The lubricant forms a thin film between the rubbing surfaces. And lubricant prevents metal to- metal contact. So we can say "Lubrication is the admission of oil between two surface having relative motion".

- The main function of lubricant is to,
  1. To reduce friction and wear between the parts having relative motion by minimizing the force of friction and ensures smooth running of parts.
  2. To seal a space adjoining the surfaces such as piston rings and cylinder liner.
  3. To clean the surface by carrying away the carbon and metal particles caused by wear.
  4. To absorb shock between bearings and other parts and consequently reduce noise.
  5. To cool the surfaces by carrying away heat generated due to friction.
  6. It helps the piston ring to seal the gases in the cylinder.
  7. It removes the heat generated due to friction and keeps the parts cool.

- The various parts of an engine requiring lubrication are;
  1. Cylinder walls and pistons.
  2. Main crankshaft bearings.
  3. Piston rings and cylinder walls.
  4. Big end bearing and crank pins.
  5. Small end bearing and gudgeon pin bearings.
  6. Main bearing cams and bearing valve tappet and guides
  7. Timing gears etc.
  8. Camshaft and cam shaft bearings.
  9. Valve mechanism and rocker arms.

- The various lubricants used in engines are of three types:
  1. Liquid Lubricants or Wet sump lubrication system.
  2. Solid Lubricants or Dry sump lubrication system.
  3. Semi-solid Lubricants or Mist lubrication system

4.11.1 Liquid Lubricants or Wet Sump Lubrication System

- These systems employ a large capacity oil sump at the base of crank chamber, from which the oil is drawn by a low-pressure oil pump and delivered to various parts. Oil then gradually returns back to the sump after serving the purpose.

Splash system.

- This system is used on some small four strokes, stationary engines. In this case the caps on the big ends bearings of connecting rods are provided with scoops which, when the connecting rod is in the lowest position, just dip into oil troughs and thus direct the oil through holes in the caps to the big end bearings. Due to splash of oil it reaches the lower portion of the cylinder walls, crankshaft and other parts requiring lubrication. Surplus oil eventually flows back to the oil sump. Oil level in the troughs is maintained by means of an oil pump which takes oil from sump, through a filter. Splash system is suitable for low and medium speed engines having moderate bearing load pressures. For high performance engines, which normally operate at high bearing pressures and rubbing speeds this system does not serve the purpose.

Semi-pressure system.

- This method is a combination of splash and pressure systems.

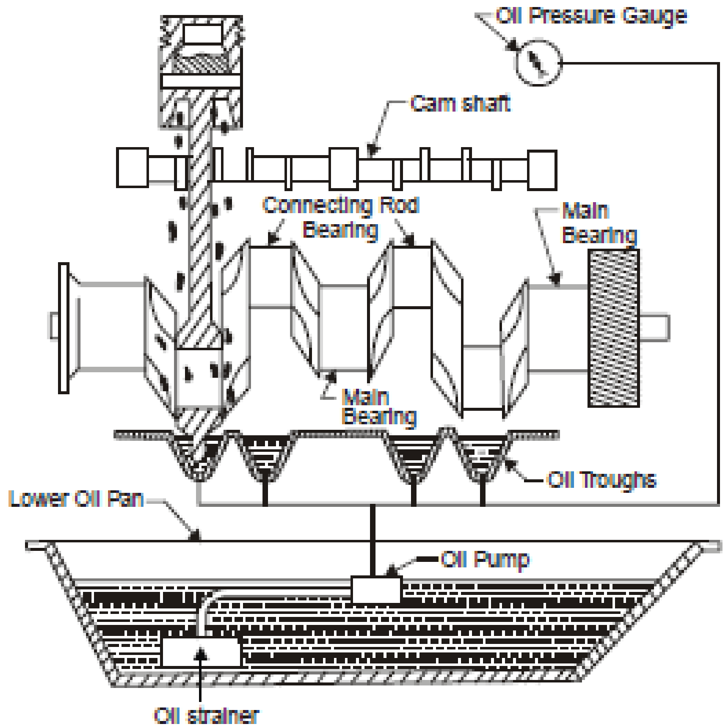


Fig. 6.7 Semi pressure Lubrication System

It incorporates the advantages of both. In this case main supply of oil is located in the base of crank chamber. Oil is drawn from the lower portion of the sump through a filter and is delivered by means of a gear pump at pressure of about 1 bar to the main bearings. The big end bearings are lubricated by means of a spray through nozzles. Thus oil also lubricates the cams, crankshaft bearings, cylinder walls and timing gears. An oil pressure gauge is provided to indicate satisfactory oil supply. The system is less costly to install as compared to pressure system. It enables higher bearing loads and engine speeds to be employed as compared to splash system.

References

Power Plant Engineering - by A K Raja

5. HYDRO ELECTRIC POWER PLANT

5.1 Introduction

- When rain water falls over the earth's surface, it possesses potential energy relative to sea or ocean towards which it flows. If at a certain point, the water falls through an appreciable vertical height, this energy can be converted into shaft work. As the water falls through a certain height, its potential energy is converted into kinetic energy and this kinetic energy is converted to the mechanical energy by allowing the water to flow through the hydraulic turbine runner. This mechanical energy is utilized to run an electric generator which is coupled to the turbine shaft. The power developed in this manner is given as:

Power = W.Q.H.η watts

where W = Specific weight of water, N/m3
Q = rate of water flow, m3/sec.
H = Height of fall or head, m
η = efficiency of conversion of potential energy into mechanical energy.

- The generation of electric energy from falling water is only a small process in the mighty heatpower cycle known as "Hydrological cycle" or rain evaporation cycle". It is the process by which the moisture from the surface of water bodies covering the earth's surface is transferred to the land and back to the water bodies again. This cycle is shown in Fig. 11.1. The input to this cycle is the solar energy.
- Due to this, evaporation of water takes, lace from the water bodies. On cooling, these water vapours form clouds. Further cooling makes the clouds to fall down in the form of rain, snow, hail or sleet etc; known as precipitation. Precipitation includes all water that falls from the atmosphere to the earth's surface in any form. Major portion of this precipitation, about 2/3rd, which reaches the land surface is returned to the atmosphere by evaporation from water surfaces, soil and vegetation and through transpiration by plants.
- The remaining precipitation returns ultimately to the sea or ocean through surface or underground channels. This completes the cycle. The amount of rainfall which runs off the earth's land surface to form streams or 'rivers is useful for power generation. The precipitation that falls on hills and mountains in the form of snow melts during warmer weather as run-off and converges to form streams can also be used for power generation.
  Hydro projects are developed for the following purposes:
  1. To control the floods in the rivers.
  2. Generation of power.
  3. Storage of irrigation water.
  4. Storage of the drinking water supply.

5.2 Selection Of Site For A Hydro-Electric Power Plant

While selecting a suitable site, if a good system of natural storage lakes at high altitudes and with large catchment areas can be located, the plant will be comparatively economical. Anyhow the essential characteristics of a good site are: large catchment areas, high average rainfall and a favorable place for constructing the storage or reservoir. For this purpose, the geological, geographical and meteorological conditions of a site need careful investigation. The following factors should be given careful consideration while selecting a site for a hydro-electric power plant:

1. Water Available.

To know the available energy from a given stream or river, the discharge flowing and its variation with time over a number of years must be known. Preferably, the estimates of the average quantity of water available should be prepared on the basis of actual measurements of stream or river flow. The recorded observation should be taken over a number of years to know within reasonable, limits the maximum and minimum variations from the average discharge. the river flow data should be based on daily, weekly, monthly and yearly flow ever a number of years. Then the curves or graphs can be plotted between tile river flow and time. These are known as hygrographs and flow duration curves. The plant capacity and the estimated output as well as the need for storage will be governed by the average flow. The primary or dependable power which is available at all times when energy is needed will depend upon the minimum flow. Such conditions may also fix the capacity of the standby plant. The, maximum of flood flow governs the size of the headwords and dam to be built with adequate spillway.

2. Water-Storage.

As already discussed, the output of a hydropower plant is not uniform due to wide variations of rain fall. To have a uniform power output, a water storage is needed so that excess flow at certain times may be stored to make it available at the times of low flow. To select the site of the dam ; careful study should be made of the geology and topography of the catchment area to see if the natural foundations could be found and put to the best use.

3. Head of Water.

The level of water in the reservoir for a proposed plant should always be within limits throughout the year.

4. Distance from Load Center.

Most of the time the electric power generated in a hydro-electric power plant has to be used some considerable distance from the site of plant. For this reason, to be economical on transmission of electric power, the routes and the distances should be carefully considered since the cost of erection of transmission lines and their maintenance will depend upon the route selected.

5. Access to Site.

- It is always a desirable factor to have a good access to the site of the plant. This factor is very important if the electric power generated is to be utilized at or near the plant site. The transport facilities must also be given due consideration.

5.3 Elelments Of Hydro Electric Power Plants

A simplified flow sheet of a water power plant is shown in Fig. The essential features of a water power plant are as below:
1. Catchment area.
2. Reservoir.
3. Dam and intake house.
4. Inlet water way.
5. Power house.
6. Tail race or outlet water way.

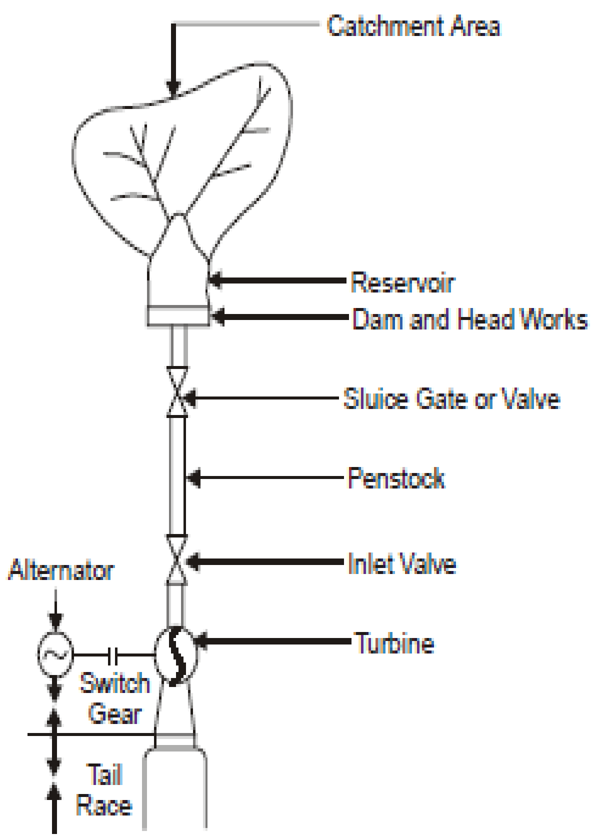


Fig. 5.1 Top schemetic view of Hydro Electric power plant

1. Catchment Area.

The catchment area of a hydro plant is the whole area behind the dam, draining into a stream or river across which the dam has been built at a suitable place.

2. Reservoir.

- Whole of the water available from the catchment area is collected in a reservoir behind the dam. The purpose of the storing of water in the reservoir is to get a uniform power output throughout the year. A reservoir can be either natural or artificial. A natural reservoir is a lake in high mountains and an artificial reservoir is made by constructing a dam across the river

3. Dam and Intake House.

- A dam is built across a river for two functions: to impound the river water for storage and to create the head of water. Dams may be classified according to their structural materials such as: Timber, steel, earth, rock filled and masonary. Timber and steel are used for dams of height 6 m to 12 m only. Earth dams are built for larger heights, upto about 100 m. To protect the dam from the wave erosion, a protecting coat of rock, concrete or planking must be laid at the water line. The other exposed surfaces should be covered with grass or vegetation to protect the dam from rainfall erosion. Beas dam at Pong is a 126.5 m high earth core-gravel shell dam in earth dams, the base is quite large as compared to the height. Such dams are quite suitable for a pervious foundation because the wide base makes a long seepage path. The earth dams have got the following advantages.

  (*a*) Suitable for relatively pervious foundation.
  (*b*) Usually less costlier than a masonary dam.
  (*c*) If protected from erosion, this type of dam is the most permanent type of construction.
  (*d*) It fits best in natural surroundings.

  The following are the disadvantages of earth dams :
  (*a*) Greater seepage loss than other dams.
  (*b*) The earth dam is not suitable for a spillway, therefore, a supplementary spillway is required.
  (*c*) Danger of possible destruction or serious damage from erosion by water either seeping through it or overflowing the dam.

4. Inlet Water Ways.

- Inlet water ways are the passages, through which the water is conveyed to the turbines from the dam. These may include tunnels, canals, flumes, forebays and penstocks and also surge tanks. A forebay is an enlarged passage for drawing the water from the reservoir or the river and giving it to the pipe lines or canals. Tunnels are of two types:
- pressure type and non-pressure type.
- The pressure type enables the fall to be utilized for power production and these are usually lined with steel or concrete to prevent leakages and friction losses. The non-pressure type tunnel acts as a channel. The use of the surge tank is to avoid water hammer in the penstock. Water hammer is the sudden rise in pressure in the penstock due to the

shutting off the water to the turbine. This sudden rise in pressure is rapidly destroyed by the rise of the water in the surge tank otherwise it may damage or burst the penstock.

5. Power House.

The power house is a building in which the turbines, alternators and the auxiliary plant are housed.

6. Tail Race or Outlet Water Way.

Tail race is a passage for discharging the water leaving the turbines, into the river and in certain cases, the water from the tail race can be pumped back into the original reservoir.

5.4 Classification Of Hydro-Plant

In hydro-plants, water is collected behind the dam. This reservoir of water may be classified as either storage or pondage according to the amount of water flow regulation they can exert. The function of the storage is to impound excess river flow during the rainy season to supplement the low rates of flow during dry seasons. They can meet the demand of load fluctuations for six months or even for a year. Pondage involves in storing water during low loads so that this water can be utilized for carrying the peak loads during the week. They can meet the hourly or weekly fluctuations of load demand. With poundage, the water level always fluctuates during operations It rises at the time of storing water, falls at the time 'off drawing water, remains constant when the load is constant.

The hydro-power plants can be classified as below:

Storage plant

(*a*) High head plants
(*b*) Low head plants
(*c*) Medium head plants.

Run-of-river power plants

(*a*) With pondage
(*b*) Without pondage.
(c)Pumped storage power Plants.

5.4.1 Storage Plants

- These plants are usually base load plants. The hydro-plants cannot be classified directly on the basis of head alone as there is no clear line of demarcation between a high head and a medium head or between medium head and low head. The power plant can be classified on the basis of head roughly in the following manner:

a) **High head plants.** About 100 m and above.
b) **Medium head plants.** about 30 to 500 m.
c) **Low head plants.** Upto about 50 m.

5.4.1.1 High Head Plants.

Fig. shows the elevation of a high head plant. The water is taken from the reservoir through tunnels which distribute the water to penstock through which the water is conveyed to the turbines. Alternately, the water from the reservoir can be taken to a smaller storage known as a forebay, by mans of tunnels. From the forebay, the water is then distributed to the penstocks. The function of the forebay is to distribute the water to penstocks leading to turbines. The inflow to the forebay is so regulated that the level in the forebay remains nearly constant. The turbines will thus be fed with under a constant static head. Thus, the forebays help to regulate the demand for water according to the load on the turbines. Trash racks are fitted at the inlets of the tunnels to prevent the foreign matter from going into the tunnels. In places; where it in not possible to construct forebays, vertical constructions known as `surge tanks' are built. The surge tanks are provided before the valve house and after the tunnel from the head works. The function of the surge tank is to prevent a sudden pressure rise in the penstock when the load on the turbines decreases and the inlet valves to the turbines are suddenly closed. In the valve house, the butterfly valves or the sluice type valves control the water flow in the penstocks and these valves are electrically driven. Gate valves are also there in the power house to control the water flow through the turbines. after flowing through tile turbines . The water is discharged to the tail race.

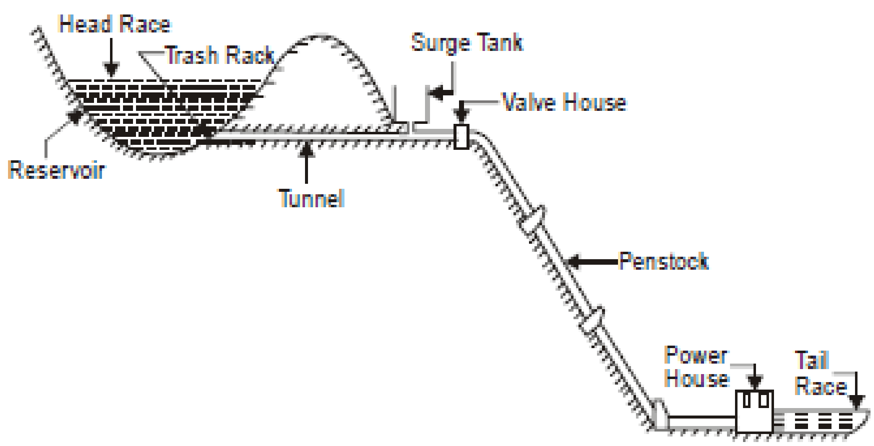


Fig. 5.2 Schematic of high head power plant

5.4.1.2 Low Head Power Plants.

These power plants are also known as Canal power plants. Such a plant is shown in Fig. A dam is built on the river and the water is diverted into a canal which conveys the water into a forebay from where the water is allowed to flow through turbines. After this, the water is again dischargedinto the river through a tail race. At the mouth of the canal, head gates are fitted to control the flow in the canal. Before the water enters the turbines from the forebay. It is made to flow through screens or trash-racks so that no suspended matter goes into the turbines. If there is any excess water due to increased flow in the river or due to decrease of load on the plant, it will flow over the top of the dam or a *waste weir can be constructed* along the forebay so that the excess water flows over it into the river. For periodic cleaning and repair of the canal and the forebay, a drain gate is provide on the side of the waste weir. The head gate is closed and the *drain gate* is opened so that whole of the water is drawn from the forebay and the canal for their cleaning and repair.

5.4.1.3 Medium Head Plants.

If the head of water available is more than 50 m., then the water from the forebay is conveyed to the turbines through pen-stocks. Such a plant will then be named as a medium head plant. In these plants, the river water is usually tapped off to a forebay on one bank of the river as in the case of a low head plant. From the forebay, the water is then led to the turbines through penstocks. Such a layout is shown in Fig.

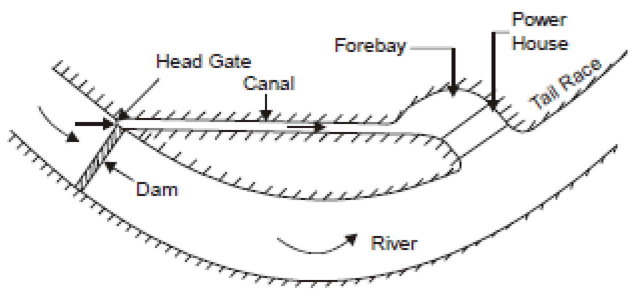


Fig. 11.7

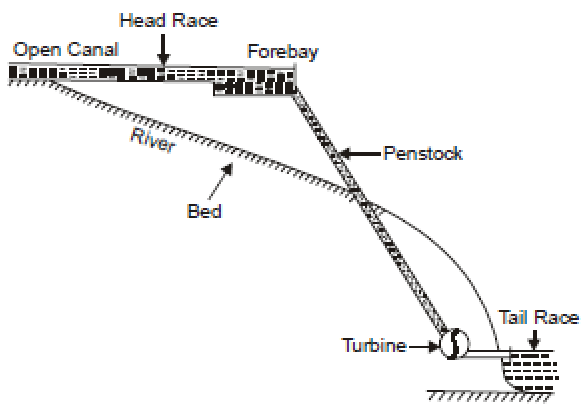


Fig. 5.3 Schematic of low head power plant

5.5 Prime-Movers

- The prime-mover in the hydraulic power plant converts the energy of water into mechanical energy and further into electrical energy. These machines are classified on the basis of the action of water and moving blades.
- As per the action of water on the prime-mover, they are classified as impulse turbine and reaction turbine. In impulse type turbine, the pressure energy of the water is converted into kinetic energy when passed through the nozzle and forms the high velocity jet of water. The formed water jet is used for driving the wheel.
- In case of reaction turbine, the water pressure combined with the velocity works on the runner. The power in this turbine is developed from the combined action of pressure and velocity of water that completely fills the runner and water passage. The casing of the impulse turbine operates at atmospheric: pressure whereas the casing of the reaction turbine operates under high pressure.
- The pressure acts on the rotor and vacuum underneath it. This is why the easing of reaction turbine is made completely leak proof. The details of few turbines which are commonly used in hydro-electric power plants are given below.

5.5.1 Pelton Turbine.

- Figure shows the layout of the Pelton turbine. This was discovered by Pelton in 1880.This is a special type of axial flow impulse turbine generally mounted on horizontal shaft, as mentioned earlier A number of buckets are mounted round the periphery of the wheel as shown in Fig. 5.4.

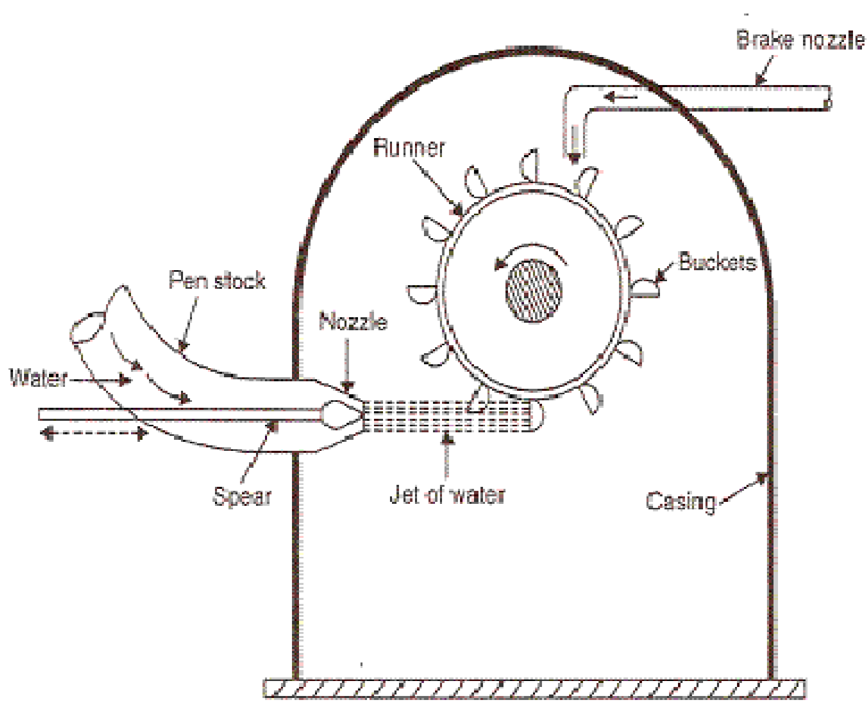


Fig. 5.4 Pelton Turbine

- The water is directed towards the wheel through a nozzle or nozzles. The flow of water through the nozzle is generally controlled by special regulating system.
- The water jet after impinging on the buckets is deflected through an angle of 160° and flows axially in both directions thus avoiding the axial thrust on the wheel.
- The hydraulic efficiency of Pelton wheel lies between 85 to 95%. Now-a-days, Pelton wheels are used for very high heads upto 2000 meters.
- Arrangement of jets. In most of the Pelton wheel plants, single jet with horizontal shaft is used.
- The number of the jets adopted depends upon the specific speed required. Any impulse turbine achieves its maximum efficiency when the velocity of the bucket at the center line of the jet is slightly under half the jet velocity.
- Hence, for maximum speed of rotation, the mean diameter of the runner should be as small as possible. There is a limit to the size of the jet which can be applied to any impulse turbine runner without seriously reducing the efficiency.
- In early twenties, a normal ratio of D/d was about 10 : I. In a modern Turgo impulse turbine, it is reduced upto 4.5 to I. The basic advantage of Turgo impulse turbine is that a much larger jet could be applied to a runner of a given mean diameter.
- The jet of pelton turbine strikes the splitter edge of the bucket, bifurcates and is discharged at either side.

5.5.2 Francis Turbine.

- In Francis turbine, the water enters into a casing with a relatively low velocity, passes through guide vanes located around the circumference and flows through the runner and finally discharges into a draft tube sealed below the tailwater level.
- The water passage from the headrace to tail race is completely filled with water which acts upon the whole circumference of the runner.
- A large part of the power is obtained from the difference in pressure acting on the front and back of the runner buckets, and only a part of totalpower is derived from the dynamic action of the water. There are mainly two types of Francis turbines known as open flume type and closed type.
- In open flume type, the turbine is immersed under water of the headrace in a concrete chamber and discharges into the tailrace through the draft tube. The main disadvantage of this type is that runner and guide-vane mechanism is under the water and they are not open either for inspection or repair without draining the chamber.
- In the closed type, the water is led to the turbine through the penstock whose end is connected to the spiral casing of the turbine.
- The open flume type is used for the plants of 10 meters head whereas, closed type is preferred above 30 meters head.

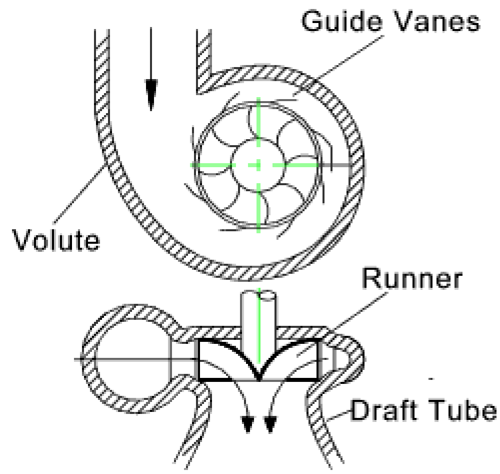


Fig.5.5 Francis Turbine

- The guide vanes are provided around the runner to regulate the water flowing through the turbine The guide vanes provide gradually decreasing area of flow for all gate openings, so that no eddies are formed, and efficiency does not suffer much even at part load conditions.

5.5.3 Kaplan Turbine

- Great strides are made in last few decades to improve the performance of propeller turbine at part load conditions.
- The Kaplan turbine is a propeller type having a movable blade instead of fixed one. This turbine was introduced by Dr. Vitkor Kaplan. This turbine has attained popularity and rapid progress has been made in recent years in the design and construction of this turbine:
- The rotor of the Kaplan turbine is shown in Fig. 11.23. The blades are rotated to the most efficient angle by a hydraulic servo-motor.
- A cam on the governor is used to change the blade angle with the gate position so that high efficiency is always obtained at almost any percentage of full load.
- These turbines are constructed to run at speeds varying from 60 to 220 r.p.m. and to work under varying head from 2 to 60 meters. These are particularly suitable for variable heads and for variable flows and where the ample quantity of water is available.
- The specific speed of Kaplan lies in the range of 400 to 1500 so that the speed of the rotor is much higher than that of Francis Turbine for the same output and head or Kaplan turbine having the same size as Francis develops more power under the same head and flow quantity.

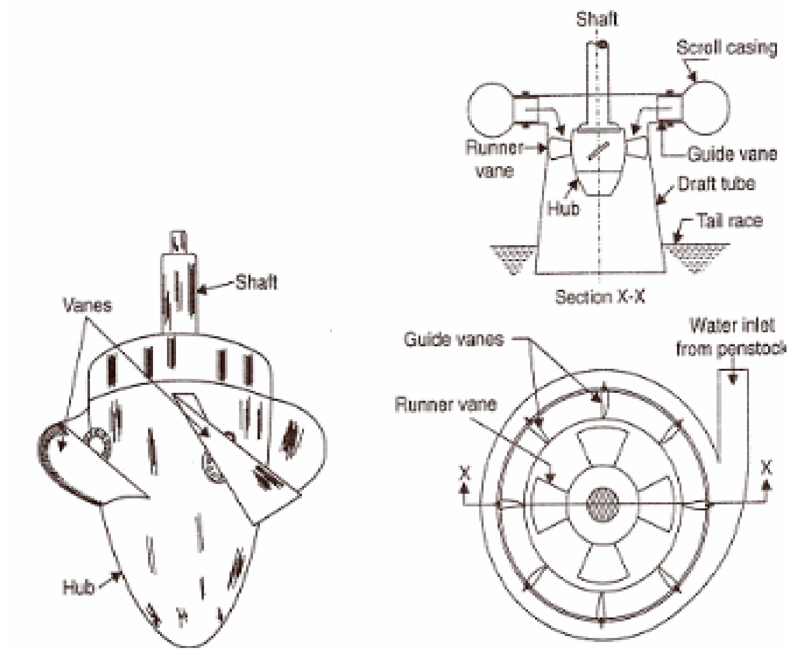


Fig. 5.6 kaplan Turbine

- The velocity of water flowing through Kaplan turbine is high as the flow is large and, therefore, the cavitation is more serious problem in Kaplan than Francis Turbine. The propeller type turbines have an outstanding advantage of higher speed which results in lower cost of runner, generator and smaller power house substructure and superstructure. The capital and maintenance cost of Kaplan turbine is much higher than fixed blade propeller type units operated at a point of maximum efficiency.
- For a low head development with fairly constant head and requiring a number of units, it is always advisable to install fixed blade propeller type runners for most of them and Kaplan type for only one or two units.
- With this combination, the fixed blade units could be operated at point of maximum efficiency and Kaplan units could take the required variations in load. Such combination is particularly suitable to a large power system containing a multiplicity of the units.

6. NUCLEAR POWER PLANT

6.1 Introduction

- Steam, diesel and gas turbine power plants are based on conventional sources of energy.
- Availability of this fuels are fast depleting while power demand is ever increasing.
- Thermal power plants also based on coal.
- We have to seek for large alternative source of energy like solar energy, geothermal energy, nuclear energy, tidal energy.
- Nuclear has bright future due availability of uranium and thorium in earth crest.
- Uranium and Thorium in earth crest are estimated to be 10^{11} tones at a depth 5km.
- 20 x 10^6 tons of Uranium, 1x 10^6 tones of Thorium can economically extracted.
- Fission of 1 kg of uranium can produce the energy equivalent to burning about 4x 10^6 of high grade coal.
- Initial cost is high but operating cost is low as compare to thermal power plant.

6.2 Advantages of Nuclear Power Plant

- Reduce demand of on depleting source of energy and rising cost of fuels like coal, oil and gas.
- Reduce transportation of fuels.
- Load shading and fluctuation in energy production is eliminated.
- Fuel storage facilities are not needed and less space is required.
- Power produce as well as fissile material also produce.
- Less pollution.
- Hige performance as compare to thermal power plants

6.3 Disadvantages

- Capital cost is high.
- Required trained man power.
- Radioactive waste disposal problem.
- High degree of safety needed.

6.4 Structure of Atom.

- Atom is a element of a smallest particle.
- Structure of a element decides chemical properties of an element.
- An atom consists of nucleus at the center and number of electrons orbiting around the nucleus.

- Nucleus of atom of protons and neutrons which are tightly bounded together and are called nucleons.
- Protons are positively charged.
- Electrons are negatively charged.
- Neutrons are charge less.
- For zero charge no of protons and no of electrons must be equal.
- Two nuclei of particular element have same number of protons but different number of neutrons such nuclei are called ISOTOPS of an element.

6.4.1 Atomic Number (Z)
It is defined as Total number of proton in nuclear of an element.
Uranium we can find naturally in earth crest which have higher atomic number (92) and other elements we can make likes plutonium (Z=94), curium(Z=96),fermium(Z=100).

6.4.2 Mass Number (A)
It is defined as total number of proton and neutron in nuclear of an element.

6.4.3 Neutron Number (N)
It is defined as total number of neutron in nuclear of an element.

6.5 Nuclear Fission Reaction

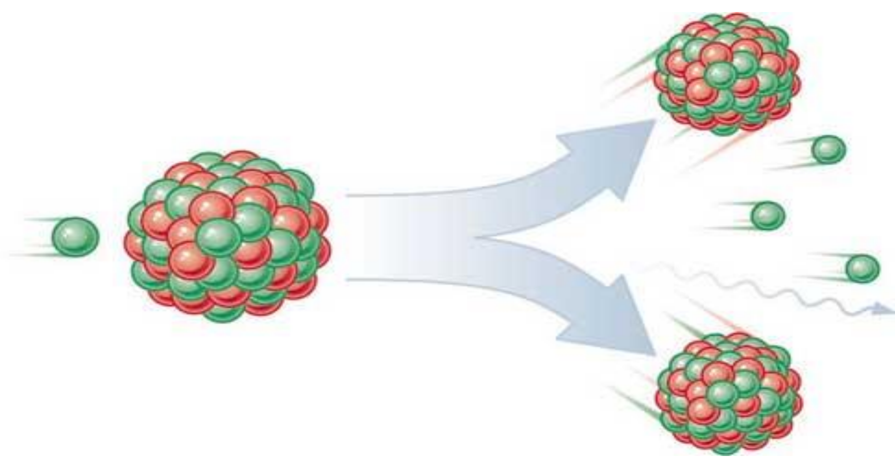


Fig. 6.1 Pictorial View Of Nuclear Fission Reaction

- A heavy nucleus splits in to two or more lighter nuclei.
- This process is possible at room temperature.
- Fission can be caused by bombarding with high energy alpha particles, protons, electrons, deuterons, x-rays as well as neutrons.
- However neutrons are most suitable for fission because of electrically neutral and thus no require high kinetic energy to overcome electrical repulsion for positively charged nuclei.

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2\ {}_{0}n^{1}$$

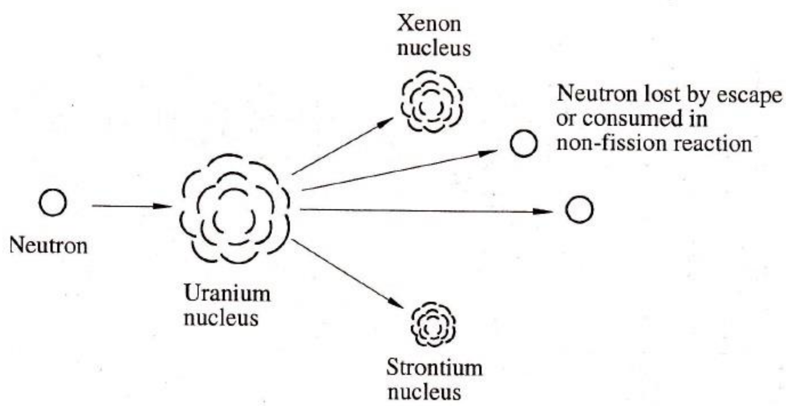


Fig. 6.2 Nuclear Fission Reaction

- Nucleus of heavy electrons like U^{233} , U^{235} , Pu^{239} has ability to capture and absorbs neutrons where upon its get converted to a compound nucleus sometimes this compound nucleus is highly unstable undergoing spontaneous fragmentation in several equal lighter nuclei or two to three neutrons this whole phenomenon called nuclear fission reaction.

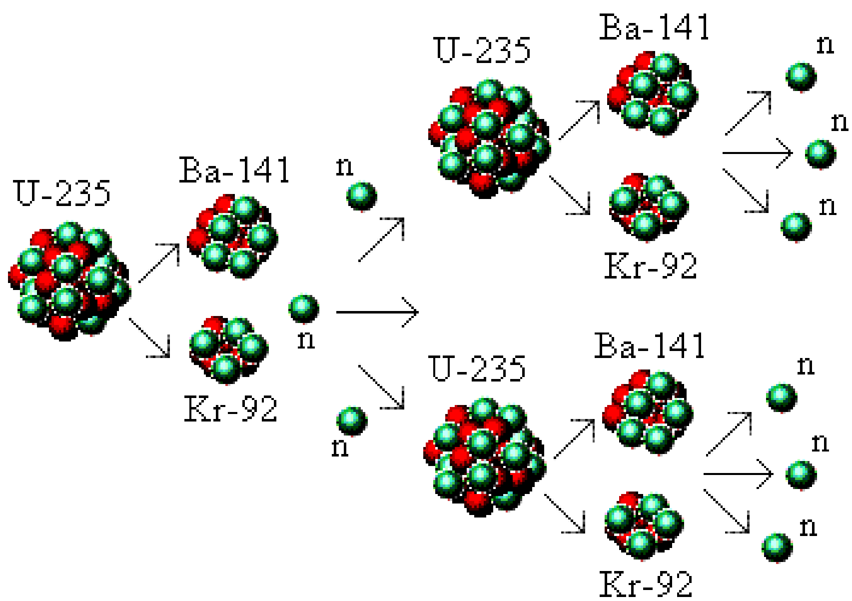
6.6 Nuclear Fusion Reaction

- It is process in which two light nucleuses makes heavy nucleus called fusion reaction.
- Its require high temperature (1.2×10^{9} K).
- High particle density.
- High particle confinement.
- It is not possible in earth.
- Sun generates heat and energy is a best example of fusion process.
- There is a 1.6×10^{7} K temp. Middle of the sun and pressure is more 10^{5} times then earth.

<u>Comparison with Fission Reaction..,</u>

- In fusion we can get isotops (duration) by naturally which is fissionable.
- The byproduct of fusion reaction is not radioactive so no problem of dispose of nuclear waste.
- We can get 7 times more energy in fusion reaction.
- The control of fusion reaction is very hard.
- The generation energy by fusion reaction may be or will be possible in up next future.

6.7 Nuclear Chain Reaction



6.3 Nuclear Chain Reaction

- Essential condition for the practical condition of nuclear energy is that self sustaining chain reaction should be maintained.
- The neutrons released have very high velocity of the order of 1.5 X 10^7 m/s.
- The energy liberated in chain reaction is according to Einstein law $E=MC^2$.
- To maintain continues chain reaction it should be leakage of neutrons is less.

6.8 Nuclear Fuels

- Nuclear fuels which are generally used in reactor are like U^{233} , U^{235} , Pu^{239} .
- Natural uranium are consists of three isotopes of uranium U^{238} , U^{235} , U^{234} .
- In natural uranium availability U^{238} is largest up to the extent of 99.28%.
- U^{235} is only 0.715% which is most unstable and fissionable and the remainder 0.006% is U^{234} .
- The other two fuels 94 Pu^{239} and 92 U^{233} are formed in nuclear reactor during fission process from 94 Pu^{239} and 90 Th^{232} . Respectively due to absorption of neutron without fission.

Fissionable Materials: This kind of materials is those which are capable of sustaining a fission chain reaction.

- U 235 is the only fissionable isotope found in nature.

Fertile Materials: The non fissionable materials and they can be converted in to fissionable materials.

- U- 238 and Th -232 can be converted in to fissionable materials.
- The chain reaction cannot be maintained In some reactors with natural uranium having only 0.7% fissionable u-235 therefore it is necessary to increase the percentage of u-235 in the fuel if it is used in reactor.
- The process used to increase the percentage of u-235 is known as enrichment of fuel.
- Enrichment also reduces size of the reactor.

Enrichment method

- Gaseous diffusion method.
- Thermal diffusion method.
- Centrifugal method.
- Electromagnetic method.
- Estimation of all resources of uranium in USA is 33%, South Africa 20%, Canada 20% largest reserve of most economical and low of cost uranium lies in Australia.

6.9 Components of Nuclear Reactors

Components of nuclear power plant categorize as under..,

1.FUELS
2.MODERATOR
3. CONTROL RODS.
4.COOLENT
5.REFLECTOR
6.SHIELDING
7. REACTOR VESSEL.

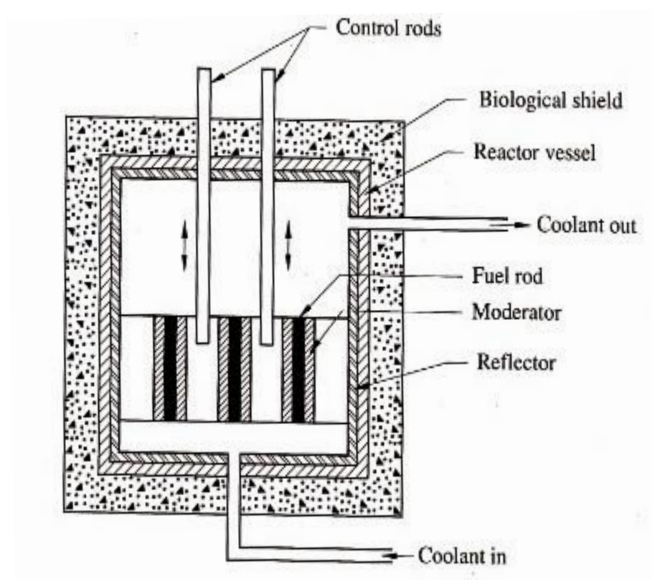


Fig.6.4 components of Nuclear Power Plants

1. **Fuel**

- Nuclear reactors use fissionable materials like U^{233}, U^{235} , Pu^{239} .
- Natural uranium found in earth crest has 0.714% which unstable and capable of sustainable chain reactions.
- The fuel is shaped in various shapes like roads, plates, pallets, tins etc. and located in the reactor in such a manner that the heat production within the reactor is uniform.
- The fuel elements are designed taking account the heat transfer, corrosion and structural strength.

- Homogeneous reactors and heterogeneous reactor.

2. Moderator

- The function of the moderator is to slow down the neutrons from high kinetic energy to low kinetic energy in a fraction of the second.
- The main function of the moderator is to increase the probability of the reaction.
- The fission chain reaction in the nuclear reactor is maintained due to slow neutrons when ordinary uranium used as a fuel.
- Moderators are lighter then fuel.
- Water, heavy water. Graphite and beryllium.
- Graphite and heavy water is used as a moderator with natural uranium.
- For enriched uranium ordinary water is used.

Characteristic of moderator

- It must be as light as possible.
- It must not absorb the neutrons.
- It must be work under high temperature and pressure with good corrosion resistance.
- It must have high chemical stability.
- It must have high heat conductivity.
- If it is in form of solid then it must have high melting point and good machinability.

3. Control Rods

- The control road controls the rate of energy which is generated.
- Function of control rod is ..,
- When we need to start the reactor.
- It is also used to increase, decrease and stop the reaction.
- The rod may be shaped like fuel rod them selves and are interspersed throughout the reactor core.
- The control is necessary to prevent the melting of fuel rods, disintegration of the of coolant and destruction of reactor as the amount of energy released is enormous.
- Control rod materials like cadmium, boron etc..,

4. Coolant

- The main purpose of the coolant in the reactor is to transfer the produced heat in to the reactor and keep fuel assembly at a safe temperature to avoid their melting and destruction.
- The heat carried away of coolant by using heat exchanger and use to generation of steam or hot gas.
- As a coolant generally water, heavy water carbon dioxide helium gas, liquid metal like sodium (Na) potassium (k) or organic liquid.
- CHARECTERISTICS OF COOLANT.
- It must have high chemical and nuclear stability.
- It must have high corrosion resistance.

- It must have high boiling point and low melting point.
- It should be non toxic.
- It must have high sp.heat and high thermal heat transfer co efficient.
- It should have high density and low viscosity.

5. Reflector

- It is important to conserve the neutrons as much as possible for reducing consumption of fissile material and keep the size of reactor small.
- This is possible by surrounding the reactor core with a material which reflects escaping neutrons back in to the core
- This material is called reflectors.
- The require properties of good reflectors should have low absorption and high reflection for neutrons .
- It should have high resistance to oxidation and high radiation stability.
- Materials are used for moderators are also used for reflectors.

6. Shielding

- Shielding is the radioactive zones in the reactor from possible radiation hazard are essential to protect the human life from harmful effects.
- To prevent effects those radiation on the human life it is necessary to absorb them before emitting to atmosphere.
- Shielding consists of inner lining of 50 to 60cm thick steel plate on the reactor core called thermal shield.
- With a few meters of thick concrete wall surrounding the inner shield called biological shield.
- Thermal shield cooled by circulation of water.

7. **Reactor Vessel**

- It is enclose the reactor core, reflector and shield.
- It also provides coolant inlet and outlet passages.
- It has to with stand the pressure at 200 bar or above.
- The reactor core, fuel and assembly are generally placed at the bottom of the vessel.

6.10 Classification of Reactors

On the basis of neutron energy

Fast reactors: In these reactors, the fission is affected by fast neutrons with out any use of moderator.

Thermal reactors: In these reactors the fast moving neutrons are slowed down with help of moderator.

Intermediate reactors: In this reactor velocity of the neutrons is kept between fast reactors and thermal reactors.

On the basis of fuel used
Natural uranium fuel reactors.
Enriched uranium fuel reactor.

On the basis of coolant used
Water /heavy water cooled reactors.
Gas cooled reactors
Liquid metal /organic liquid cooled reactors.

On the basis of moderator:
Water moderated.
Heavy water moderated.
Graphite moderated.
Beryllium moderated.

On the basis of reactor core used
Homogeneous reactor.
Heterogeneous reactor.

6.10.1 Pressurized Water Reactor

- In a PWR the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy generated by the fission of atoms. The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spins an electric generator.

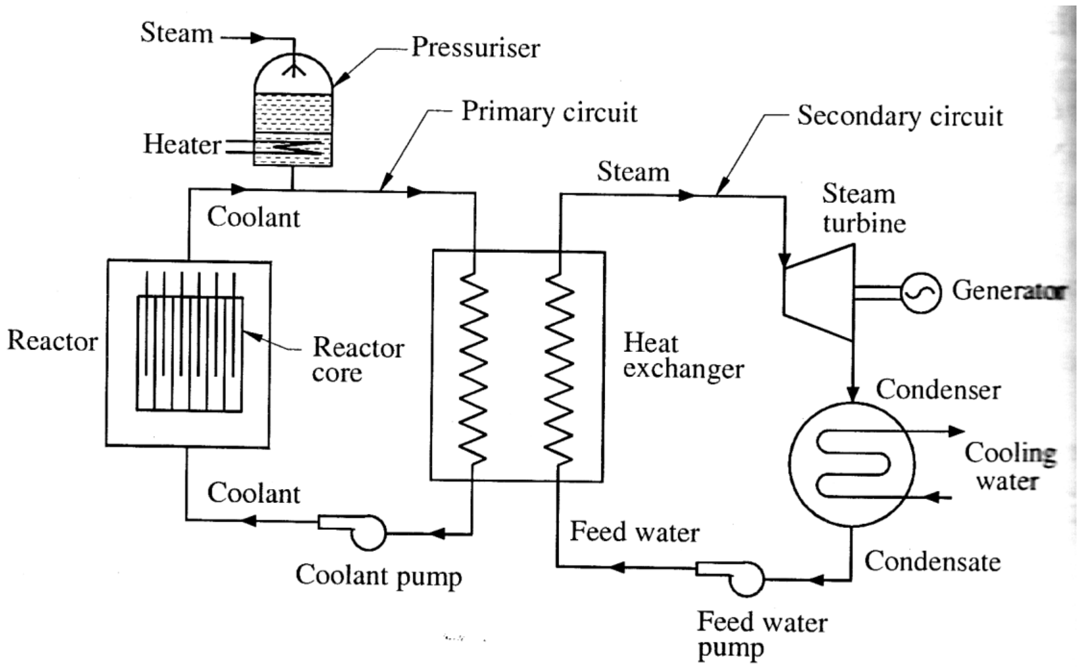


Fig. 6.5 Pressurized Water Reactor.

- Nuclear fuel in the reactor vessel is engaged in a fission chain reaction, which produces heat, heating the water in the primary coolant loop by thermal conduction through the fuel cladding.
- The hot primary coolant is pumped into a heat exchanger called the steam generator, where it flows through hundreds or thousands of tubes (usually 3/4 inch in diameter).
- Heat is transferred through the walls of these tubes to the lower pressure secondary coolant located on the sheet side of the exchanger where it evaporates to pressurized steam. The transfer of heat is accomplished without mixing the two fluids, which is desirable since the primary coolant might become radioactive. Some common steam generator arrangements are u-tubes or single pass heat exchangers. In a nuclear power station, the pressurized steam is fed through a steam turbine which drives an electrical generator connected to the electric grid for distribution.
- After passing through the turbine the secondary coolant (water-steam mixture) is cooled down and condensed in a condenser. The condenser converts the steam to a liquid so that it can be pumped back into the steam generator, and maintains a vacuum at the turbine outlet so that the pressure drop across the turbine, and hence the energy extracted from the steam, is maximized.

- Before being fed into the steam generator, the condensed steam (referred to as feed water) is sometimes preheated in order to minimize thermal shock.

Advantages

- PWR reactors are very stable due to their tendency to produce less power as temperatures increase; this makes the reactor easier to operate from a stability standpoint.
- It uses ordinary water as a coolant, moderator and reflector since water is available near the plant location this is great savings in cost.
- Reactor is compact and high power density.
- As steam is not effected by radiation so the inspection and maintenance of the turbine condenser and feed pump is possible.
- Small numbers of control road are required.
- PWR turbine cycle loop is separate from the primary loop, so the water in the secondary loop is not contaminated by radioactive materials.

Disadvantages

- Its capital cost is high due to heavy and strong pressure vessel is required in the primary circuit.
- Thermodynamic efficiency is less 20% due to low pressure in secondary circuit.
- Its required enriched uranium fuel cost of enriched uranium is high.
- It is necessary to shutdown the reactor for fuel charging.
- Because water acts as a neutron moderator, it is not possible to build a fast neutron reactor with a PWR design.

6.10.2 Boiling Water Reactor

- The BWR uses dematerialized water as a coolant and neutron moderator.
- Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam.
- The steam is directly used to drive a turbine, after which it is cooled in a condenser and converted back to liquid water.
- This water is then returned to the reactor core, completing the loop.

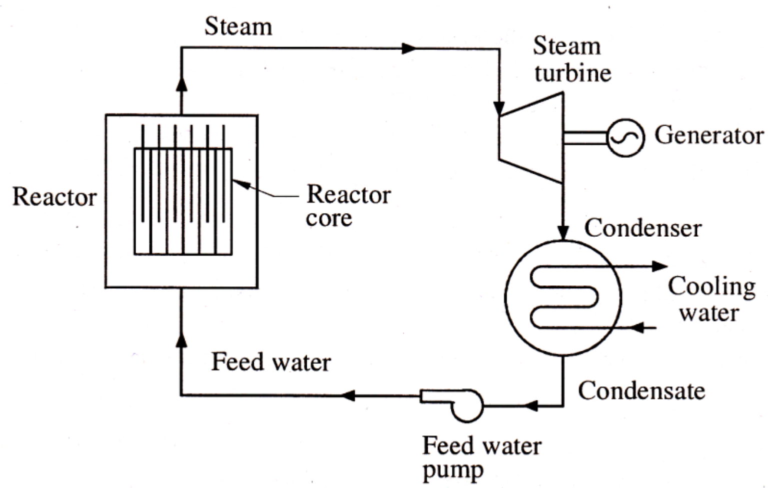


Fig.6.6 Boiling Water Reactor

Advantages

- The pressure inside the reactor is less then PWR as water is allowed to boil inside the reactor. Therefore the reactor vessel can be much lighter then PWR and reduce the cost of pressure vessel considerably.
- It eliminates the use of heat exchanger pressure equalizer circulating pump and piping therefore the cost of further reduced.
- The thermal efficiency of this reactor is 30% is considerably higher then PWR plant.
- The metal temperature remains low for given output conditions.

Disadvantages

- The steam leaving the reactor is slightly radioactive. Therefore light shielding of turbine and piping is necessary.
- It cannot meet the sudden changes in load the plant.
- The size of vessel is comparatively large as compare to PWR.
- Its required enriched uranium as a fuel.

6.10.3 Candu Reactor

- The **CANDU**, short for **Canada Deuterium-Uranium reactor** is a Canadian-invented, pressurized heavy water reactor.
- The acronym refers to its deuterium-oxide (heavy water) moderator and its use of (originally, natural) uranium fuel.

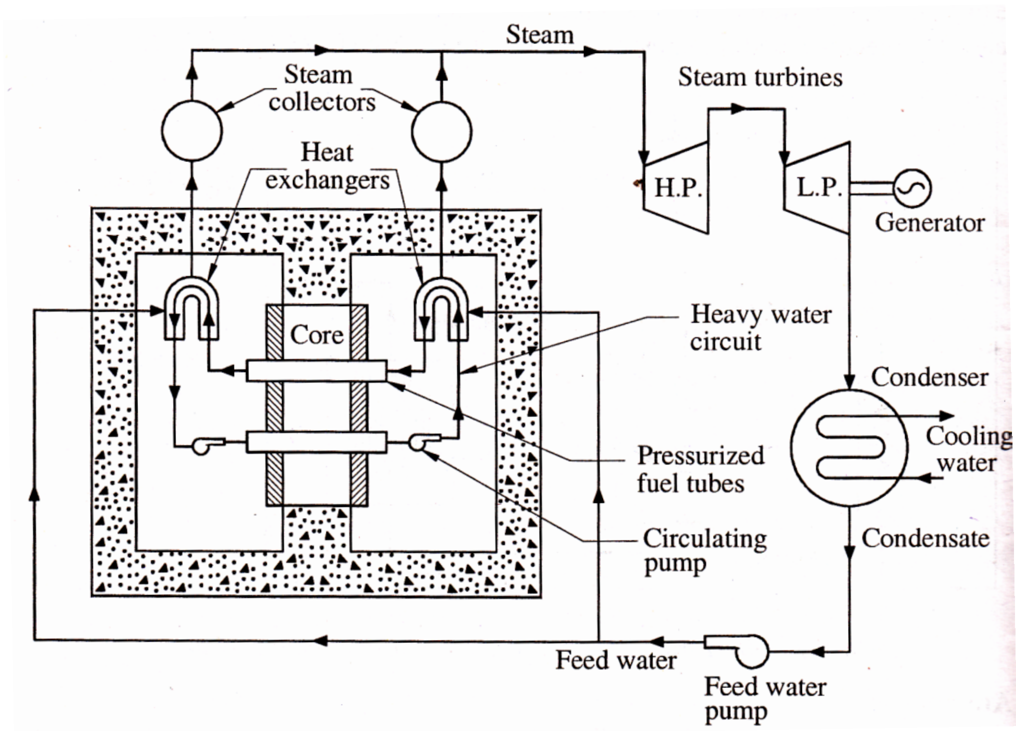


Fig. 6.7 Candu Reactor

- These reactors are more economical to those nations which do not produce enriched uranium as the enrichment of uranium very costly.
- In this reactor the fuel is normal uranium oxide as small cylinder pallets the pallets are packed in corrosion resistance zirconium alloy tube.
- The coolant heavy water is passed through the fuel pressure tubes and heat exchanger.
- The heavy water is circulated in the primary circuit and the same way the steam is generated as PWR in secondary circuit due to circulate heat in to it from primary circuit.
- The control of the reactor is achieved by varying the moderator level in the reactor so no control rod is needed.

Advantages

- Fuel not needs to be enriched.
- The reactor vessel may be built to withstand low pressure compared with PWR and BWR and only fuel tubes designed to withstand high pressure there fore cost of vessel is very less.
- No control rods required.
- The moderator can be kept low temp. which increases its effectiveness in slowing down neutrons.
- Shorter period require site construction as compare to PWR and BWR.

Disadvantages

- The cost of heavy water is high.
- Leakage is a major problem.
- Very high standard design, manufacture inspection and maintenance required.
- Power density is low as compare to PWR and BWR so its require large size of reactor.

6.10.4 Gas Cooled Reactor

- It is also called Gas Cooled Graphite Moderated (GCGM) Reactor.
- A **gas-cooled reactor (GCR)** is a nuclear reactor that uses graphite as a neutron moderator and carbon dioxide (helium can also be used) as coolant.

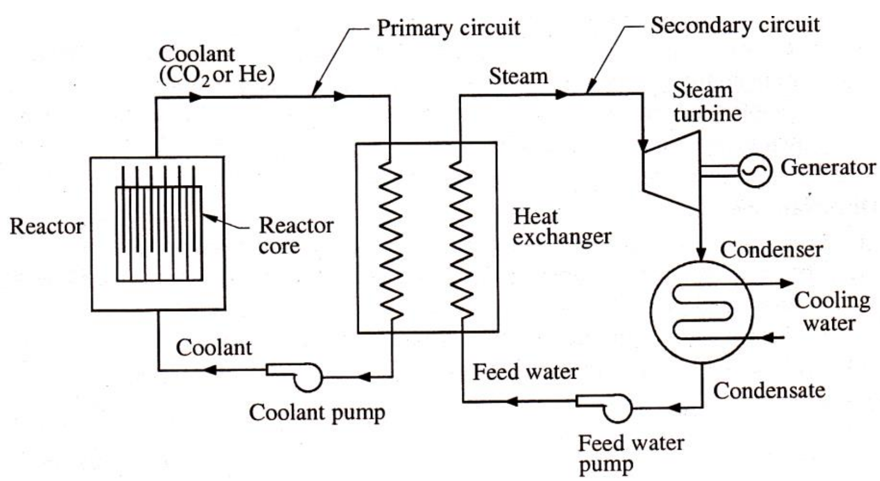


Fig.6.8 Gas Cooled Reactor

- Fuel used is U^{233} as fissile material and thorium as fertile material. Because of high melting point of graphite.

- In the primary circuit, coolant circulated is (CO)2 for GCGM reactor or (He) for HTGC reactor.
- The coolant transfers the heat energy to feed water in the heat exchanger and the steam generated is used to generate power in steam turbine.

Advantages

- The gases do not react chemically with the structural material like water hence there is no corrosion problem.
- Graphite remains stable at high temperature and radiation problem are minimum.
- Gases are safe and easy to handle.
- *The gas coolant provides best neutron economy.*

Disadvantages

- Gases have poor heat transfer properties that are why it requires large heat exchanger.
- The more pumping power is required.
- Leakage is major problem.

6.10.5 Fast Breeder Reactor

- THE PROCESS OF CONVERTING MORE FERTILE MATERIAL IN TO FISSILE MATERIAL IN A REACTOR IS CALLED BREEDING.
- In fast breeder reactor the core containing U^{235} is surrounded by a blanket of fertile material U^{238} .
- In this reactor no moderator is used the fast moving neutrons liberated due to fission of U^{235} are absorbed by U^{238} which gets converted in to Pu^{239} a fissile material.
- This reactor also uses two liquid metal coolants in which sodium is used as primary coolant and sodium potassium as secondary coolant.(sodium boils at 850^{O} C under atmospheric pressure and freeze at 95^{O} C).

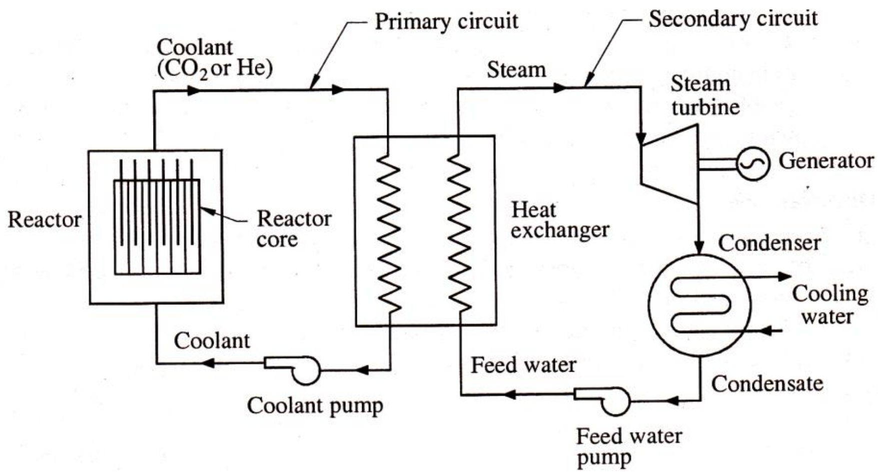


Fig. 6.9 Fast Breeder Reactor

- The reactor also used two liquid metal coolants in which sodium is used as primary coolants and sodium potassium as secondary coolants.
- Liquid sodium is circulated through the reactor to carry the heat produced.
- The heat produced by the sodium is transferred to secondary coolant sodium potassium In the primary heat exchanger which in turn transfer the heat in secondary heat exchanger called steam generator.

Advantages

- It gives high power density than any other reactor therefore small core is sufficient.
- Moderator is not required.
- Secondary fusible materials by breeding are obtained.
- Absorption of neutrons is slow.

Disadvantages

- It require highly enriched uranium fuel.
- Safety must be provided against melt down.
- Neutron flux is high at the center of the core.
- Thick shielding is necessary.

6.11 Nuclear Waste and its Disposal

- The radioactive emission during the operation of the plant is negligible but the emission intensity is very high which comes out from the waste. Therefore, safe nuclear waste disposal is major problem before the nuclear industry.
- It is estimated that the radioactive products of 400MW power plants would be equivalent to 100 tons of radium daily and the radioactive effect of this plants products if exposed to atmosphere would kill all the living organism with in the area about 160 square kilometers.
- The waste produced in a nuclear power plant may be in the form of liquid, gas and solid and each is treated in different water.

- **Solid waste**
  - It will arise used filters, sludge from the cooling ponds, pieces from discarded fuel element cans, splitters control rods etc..,
  - The combustible solid waste is burnt and flue gases formed are filtered and then exposed to the high level of atmosphere.
  - Active solid wastes are stored in water for about 100 or more days to allow radioactivity to decay then these are disposed off to deep salt mines or an ocean floor or in deep wells drilled in stable geological strata.

- **Liquid waste**
  - Radioactive effluents will arise from the laundry, personal decontamination etc.., together with activity accumulating from the corrosion of the irradiated fuel elements in the storage ponds.
  - The disposal of liquid waste has done in two ways.

Dilution

- The liquid waste are diluted with large quantity of water and then released in to the ground.
- The major drawback of this method there is a chance of contamination of underground water if dilution factor is not adequate.

Concentration to small volumes and storage

- If the dilution of water in not possible then liquid will store in leakage proof and high strength material storage can or tank and then stored in deep drilled salt mines.

- **Gaseous Waste**

- Gaseous waste are generally diluted with air passed through filters and then released to the atmosphere through large chimneys.
- Krypton is removed by cryogenic treatment of dissolved off gas stream and packed in gas cylinder under pressure.

- Generally gaseous waste filtered in filter and then allows escaping to the atmosphere or stored in pressure tanks and then stored in deep drilled salt mines.
- **6.12 Nuclear Power Plants In India**

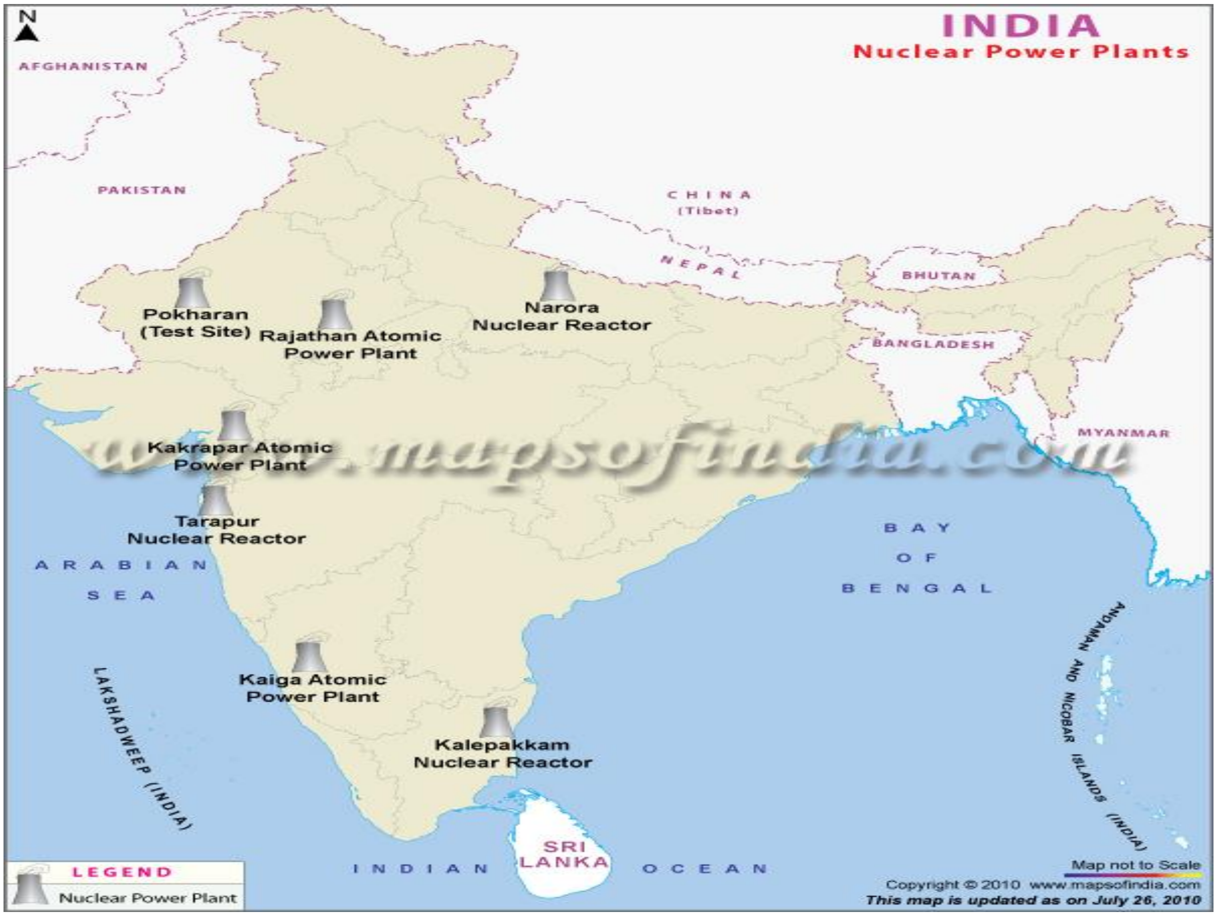


Fig.6.10 Nuclear Power Plants In India

TARAPUR NUCLEAR POWER PLANT

- It is India's first nuclear power plant.
- It has been built at TARAPUR 100 km north of Mumbai in collaboration with U.S.A.
- It has two BWR each of 200 MW capacity and uses enriched uranium as its fuel ordinary water as a coolant and moderator.
- It's first unit was established in 1961 and second was 1966.
- Its supply power to Maharashtra and Gujarat.
- Total cost of plant was Rs.65 Crores on the basis of prize line in 1964 and out of that Rs.45.25 Crores was financed by U.S.A.

RANA PRATAP SAGAR NUCLEAR POWER PLANT.

- Second nuclear power plant installed in 1971 of India.
- It has been built at 67km south west of kota in Rajasthan in collaboration with Canada.
- It has two CANDU type reactors with 200MW capacity.
- It uses natural uranium as a fuel in the form of oxide and heavy water as moderator and coolant.

KALPAKKAM NUCLEAR POWER PLANT.

- It is a third nuclear power plant in India installed in 1983 and 65kmaway from Chennai in tamilnadu state.
- It is the first nuclear power plant which has been wholly designed and constructed by indian scientists and engineers using indigenous materials.
- It has PWR water reactor and uses natural uranium as a fuel.
- Capacity 235MW.

NARORA NUCLEAR POWER PLANT

- It is India's fourth nuclear power plant built at narora in utter Pradesh.
- This plant has two units each of 235MW and with provision of extension up to 500MW.
- Plant has CANDU water reactor.
- The fuel used is natural uranium and heavy water is used as moderator and coolant.
- This plant supplies power to Uttar Pradesh, Delhi, Haryana, Punjab, Chandigarh, Jammu and Kashmir, and Himachal Pradesh.

KAKRAPAR NUCLEAR POWER PLANT

- India's 5th nuclear power plant is located at kakrapar near surat in Gujarat.
- This power station has four reactors each of 235MW capacity.
- It has Candu Reactor.
- It has similar design as Narora nuclear power plant.

KAIGA ATOMIC POWER PLANT

- The sixth atomic power plant of India is located at kaiga in Karnataka.
- It has two CANDU type reactor of 235MW each.
- This reactors have modern systems to prevent accidents.

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7. ECONOMICS OF POWER GENERATION

❖ 7.1 Load Duration Curve:-

- Load duration curve is simply a rearrangement of daily load curve with loads set-up in the descending order of magnitude.
- The area under the load duration curve and corresponding load curve are equal and measure kW-hr of energy for that period.
- To get the load duration curve from chronological load curve, we cut the daily load curve into many vertical strips and then arrange them in descending order.
- The graphical method for constructing load duration curve from the load curve is described as shown in fig.
- For plotting the load duration curve, make the abscissa at any load ordinate equal to the length of abscissa intercepted by that load ordinate on the load curve.
- Thus the intercept is one point at the maximum demand (kW_{max}) and it is plotted at zero hours as shown in fig b
- At load kW1, the intercept is a_1 hours and is plotted accordingly shown in fig.
- At minimum load kW_{min}; the intercept covers the entire period of 24 hours and plotted accordingly.
- Any point of the load duration curve is a measure of the number of hours in a given period during which the given load has prevailed.
- Load duration curve offers the advantage of summarizing loads foe a day, a week, a month, or a year.
- This is advantageous for power plant design as in one simple curve, a whole year can be summarized showing peak demand, the variations in demand down to minimum, the length of the time they existed, and total energy involved.

❖ 7.2 Effect of variable load on Power Plant Design & operation:-

- The necessity of supplying a variable load influences the characteristics and method of use of power plant equipments.
- The generation of power must be regulated according to the demand and governing is necessary to achieve the same.
- Another requirement of a power plant is a quick response to the load.
- In all variable load problems, the major problem is, the generator (and prime mover) must be able to take varying load as quick as possible without change in voltage and frequency.
- When the load on the generator increases, the first effect is to slow down the rotor and prime mover and therefore to reduce the frequency.
- With the decrease in speed of the prime mover which is due to the increase load on generator, the governor must act, admitting more fuel in case of thermal plants and more water in case of hydro power plant, enough to bring the speed back to normal and pick up the load.
- The frequency stabilizers are used to maintain the frequency constant which may change due to response of the equipments.
- The raw materials used in thermal power plant are fuel, air, and water and to produce variable power from the thermal power plant according to requirement is to vary the raw material correspondingly.
- With an increase in load on the plant, the governor admits more steam and maintains the turbine speed.
- The governor response to this point has followed rapidly the change of load but beyond this point, changes are not rapid.
- Because, the steam generator operates with unbalance between heat transfer and steam demand long enough to suffer a definite decrease of steam pressure.
- With fluctuating steam demand, it becomes difficult to secure good combustion and steady steam pressure, because efficient combustion requires the co-ordination of so many services.
- The co-ordination between the different components and processes is not as simple as supplying of more raw materials but the reason being that there is certain time lag present in combustion and heat transfer that is not present in electrical generators.
- The design of thermal plants for variable loads is always more difficult then diesel or hydraulic plants and it is always desirable to allow the thermal plant to operate as base load plant.
- It is necessary in case of power plants to keep the reserve capacity to meet the peaking loads.
- This reserve is particularly required for an individual or isolated plant.
- This reserve capacity always increases the charges of electrical energy supplied.

Therefore, it is always desirable to keep the reserve capacity as small as possible.

❖ 7.3 Cost of Electrical Energy:-

- The cost of electrical energy generated consists of fixed cost and running cost.

A. Fixed Cost:-

- The fixed cost is the capital invested in the installation of complete plant.
- This includes the cost of land, buildings, equipments, transmission, and distribution lines, cost of planning and designing of the plant substations and many others.
- It further includes the interest on the invested capital, insurance, maintenance cost, and depreciation cost.

1. Land Building and Equipment Cost:-

- The cost of land, building, does not change much with different types of plants but the cost of equipment changes considerably.
- The cost of the equipment or the plant investment cost is usually expressed on the basis of kW capacity installed.
- The capital cost per kW installed capacity does not change much for thermal plant but it changes a lot in case of hydro-plants.
- Because the cost of hydro-plant depends upon the foundation available, type of dam and spillways used available head and quality of water.
- The capital cost of hydro-plant may vary from Rs.18000/kW to Rs.30000/kW.
- The capital cost of thermal plant is about Rs.10000/kW on the basis of 1970.

2. Interest:-

- The interest on the capital investment must be considered because otherwise if the same capital is invested in some other profitable business could have equal the interest considered.
- A suitable rate of interest must be considered on capital investment.

3.Depreciation Cost:-

- It is the amount to get aside per year from the income of the plant to meet the depreciation caused due to wear and tear of equipments.
- The capital investment for the plant installation must be recovered by the time the life span of the plant is over, so that it can be replaced by a new plant.
- Some amount from the income is set aside per year as depreciation cost of the plant which accumulates till the plant is in operation.
- The amount collected by the way of depreciation by the time the plant retires is equal to the capital invested in the installation of the plant.
- Different methods are used for finding out the depreciation cost of the power plant.
- Few of them which are commonly used are listed below:

a) Straight Line Method
b) Sinking Fund Method
c) Diminishing Value Method

P = Initial investment to install the plant.
S = Salvage value at the end of the plant life.
n = Life of plant in years.
r = annual rate of compound interest on the invested capital.
A = the amount set aside per year for the accumulation of the depreciable investment at the end of n^{th} year.

a) Straight Line Method:-

- According to this method, annual/amount to be set aside is calculated using the following formula:

$$A = \frac{P-S}{n}$$

~ In this method, the amount set aside per year as depreciation fund does not depend on the interest it may draw.
~ The interest earned by the depreciation amount is taken as income.
~ This method is commonly used because of its simplicity.

b) Sinking Fund Method:-

- In this method, the amount set aside per year consists of annual installments and the interest earned on all the installments.
- This method is based on the conception that the annual uniform deduction from income for depreciation will accumulate to the capital value of the plant at the end of life of the plant or equipment.
- 'A' is the amount set aside at the end of year for 'n' years, then

Amount set aside at the end of first year = A

Amount at the end of second year = A + interest on A
= A + A*r
= A (1+r)

Amount at the end of third year = A (1+r) + interest on A (1+r)
= A (1+r) + A (1+r)*r
= $A (1+r)^2$

Amount at the end of n^{th} year = $A (1 + r)^{n-1}$

Total amount accumulated in n years
= Sum of the amounts accumulated in n years

$y = A + A (1+r) + A (1+r)^2 +\ldots\ldots.+ A (1+r)^{n-1}$

$= A [1+ (1+r) + (1+r)^2 +\ldots\ldots+ (1+r)^{n-1}]$……………………..(i)

Multiplying the above equation by (1+r), we get

$y (1+r) = A [(1+r) + (1+r)^2 + (1+r)^3 +\ldots\ldots+ (1+r)^n]$…………………(ii)

Subtracting equation (i) from equation (ii), we get

$y*r = [(1+r)^n – 1] A$

$y = [\{(1+r)^n -1\}/r] A$ (where y = (P-S))

So, $(P-S) = [\{(r+1)^n-1\}/r] A$

$A + [r/\{(1+r)^n-1\}] (P-S)$

c) <u>Diminishing Value Method:-</u>

- In this method, the amount set aside per year decreases as the life of the plant increases.
- This can be explained by the following example.

- Say the equipment cost is Rs.20000/-.
- The amount set aside is 10% of the initial cost at the beginning of the year and 10% of the remaining cost with every successive year.
- Therefore,

The amount set aside during first year

= 20000 – (10/100)*20000

= 18000 balance

The amount set aside during second year

= 18000 – (10/100)*18000

= 18000-1800

= 16200 balance

The next installment during third year

= 16200 – (10/100)*16200

= 14580 balance

▪

~ This method requires heavy installment in the early years when the maintenance charges are minimum and it goes on decreasing as the time passes but the maintenance charges increases.

~ This is the main disadvantage of this method.

3. Insurance:-

- it becomes necessary many times to insure the costly equipments specially for the fire issues.
- A fixed sum is set aside per year as insurance charges.
- The annual premium may be 2-3% but the annual installment is quite heavy as the capital cost of the plant is considerably high.

4. Management Cost:-

- This includes the salaries of the people working in the plant.
- This must be paid whether the plant is working or not.
- Therefore, this is included in fixed charges of the plant.

B.Operating Costs:-

- The operating cost of the electrical power generation includes the cost of fuel, cost of lubricating oil, grease, cooling water, and number of consumable articles required.

- The wages required for supplying the above material are also included in the operating cost of the power plant.

1. Fuel Cost:-

- The fuel cost is proportional to the amount of energy generated.
- The rate of fuel consumption per unit of energy generated also varies according to the load on power plant.
- The consumption of fuel per unit of energy generated is minimum at full load on power plant because the prime mover works at maximum efficiency at full load conditions.

2.Oil, Grease and Water Cost:-

- The cost of these materials is also proportional to the amount of energy generated.
- This cost increases with an increase in life of power plant as the efficiency of the power plant decreases with the age.
- The common way to representing the cost of power plant is given below:

$$C = x \text{ Rupees/kW} + y \text{ N.P./kW-hr}$$

❖ 7.4 TERMS:-

CONNECTION LOAD:-

It is defined as sum of the ratings of all the equipment installed in a given space which consumes the electrical energy ratings of all the equipments given in KW.

MAXIMUM DEMAND:-

It is defined as a maximum load which customers consume at a given time.

DEMAND FACTOR:-

It is defined as the ratio of maximum demand to the connected load of a consumer.

LOAD CURVE:-

A diagram showing consumption of energy of a consumer in a given time/duration is termed as load curve.

Load curve can be prepared on daily basis, monthly basis or even a yearly basis.

AVERAGE LOAD:-

It is defined as the ratio of energy consumed by the consumers in KWhr to the duration of consumption (i.e. 24 hrs).

Average load = KWhr/hr =____KW.

LOAD FACTOR:-

It is defined as the ratio of average load to the maximum load consume by the consumer.

Load factor = Average load/ Maximum load.

EXAMPLE:-

Time(hr)	0-6	6-10	10-12	12-16	16-20	20-22	22-24
Load(MW)	20	50	60	40	80	70	40

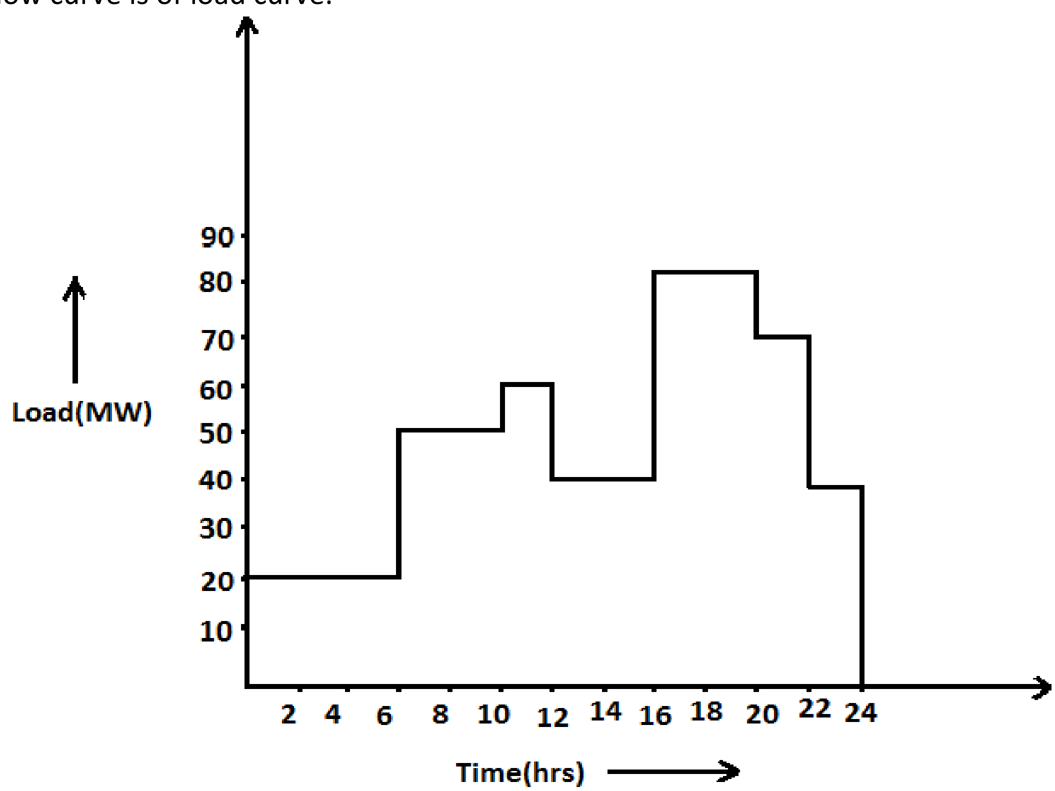
A power station supplies following load to the consumers listed in the table. Find (a) Load factor of the power plant.

(b) What is the load factor of a stand by equipment of 20MW capacity if it takes all the load above 60MW?

Also draw load curve.

- **ANSWER:-**

Below curve is of load curve.



(a)Total energy consumption

=(6*20) + (4*50) + (2*60) + (4*40) + (4*80) + (2*70) + (2*40)

=1140MWhr.

Average load = 1140/24

= 47.5MW

Load factor = Average load/ Maximum load

=47.5/80

=0.59375

≈0.594………………………………………………………………………………………… (ANS)

(b) The energy supplied by the stand by unit in the duration (16-20) and (20-22).

The energy supplied by energy is consumption by stand by unit

= (20*4) + (10*2)

= 80 + 20

= 100MWhr

Average load = 100/6

= 16.67MW

Load factor of stand by unit = Average load/ Maximum load

= 16.67/20

= 0.8335…………………………………………………… (ANS)

❖ 76.5 Performance & Operating Characteristics Of Power Plant:

The performance of generating power plant is compared by their average efficiencies over a period of time. The average efficiencies of power plant is the ratio of useful energy output to the total energy input during the period considered. This measure of performance varies with uncontrolled conditions such as cooling-water temperature. Shape of load curve &quality of fuel. Therefore, it is not a satisfactory standard of comparison unless all plant performances are corrected to the same controlling conditions.

Plant performance can be precisely represented by the input-output curve from the tests conducted on individual power plant. The input-output can be represented as:

$$I= a+bL+cL^2+dL^3$$

Where I is input expressed in millions of kJ per hour in case of thermal plants & in case of hydro plants & L is the output or load either in MW or kW, a, b, c & dare constants.

The input-output curve for a power plant is shown in Fig (A). At zero load (L=0), the positive intercept for I measures the amount of energy required to keep the plant in running condition. Any additional input over no-load input produces a certain output which is always less than input.

The efficiency of the power plant is defined as the ratio of output to input.

$$Efficiency = L/I$$

$$Efficiency = L/(a+bL+cL^2+dL^3)$$

For the given load, the efficiency can be calculated with the help of above formula.
The efficiency curve (output versus efficiency) can be drawn as shown in fig.

Input-output curve & corresponding efficiency heat rate & incremental rate curves.

The heat rate curve & the incremental rate curve may be derived from the basic input-output curve. The heat rate is defined as the input per unit output.

$$HR\ (heat\ rate) = I/L\ kJ/kW\text{-}hr$$

$$= (a+bL+cL^2+dL^3)/L$$

$$HR\ (heat\ rate) = (a/L) + b + cL + dL^2$$

The heat rate curve is derived by taking at each load the corresponding input. This curve is drawn as shown in Fig(c).

The relation between efficiency & heat Rate is given by

$$Efficiency = 1/HR$$

The incremental rate is defined as the ratio of additional Input (dI) required increasing additional output.

$$IR\ (incremental\ rate) = dI/dL\ kJ/kW\text{-}hr$$

The Incremental rate curve (L versus IR) is derived from the input output curve by finding at any load the additional input required for a given additional output & is drawn as shown in Fig (c).

Mathematically the incremental rate is the slope of the input-output curve of the given load. The incremental rate expresses the amount of additional energy required to produce an additional unit of output at any given load.

From the above equation, we can write

$$dI = IR*dL$$

$$I_2-I_1 = \int_{L1}^{L2} IR*dL$$

This indicates that the area under the incremental rate curve gives the total input to the plant to increase the output from L1 to L2.

The total input from no-load to full load is given by

$$I_f - I_0 = \int_{L_0}^{L_f} IR \cdot dL$$

Where the suffix ‘F’ indicates full load & suffix ‘0’ indicates no-load on the power plant.

$$IR = (dI)/(dL)$$

Substituting the value of I in the above equation,

$$IR = d/d\,(a+bL+cL^2+dL^3)$$
$$IR = b+2cL+3dL^2$$

This is known as incremental rate curve.
The incremental load curve can be considered a straight line for relatively small increase in output. This is not true for large increment of load because of the measured curvature of the incremental rate curve.

It is obvious from Fig(c) that the incremental rate curve crosses the heat rate curve at the lowest value of heat rate when both curves are plotted on the common coordinates. The reason for this is explained mathematically as given below.

At minimum heat rate, the slope of the heat rate curve must be zero.

$$d/dL\,(HR) = d/dL\,(I/L)$$
As $HR = I/L$
$$(LdI - IdL)/L^2 = 0$$
$$(dI/dL) = (I/L)$$
IR= HR when HR is minimum.

This indicates that the heat rate of continuous input-output curve is minimum when it equals the incremental rate. The incremental rate curve has a continuous increasing characteristics, therefore two curves CHR versus load and IR versus load must cross at load L_m when $IR_m=HR_m$.

From fig.(c), it can be stated that for the load between zero and L_m

$$IR<HR \text{ or } (dI/dL)<(I/L) \text{ or } (I/L)<(I+dI/L+dL)$$

For the loads above L,

$$IR<HR \text{ or } (dI/dL)>(I/L) \text{ or } (I/L)>(I+dI/L+dL)$$

In other words, starting from zero load, the relatively low rate of additional input per unit of additional output helps to decrease the heat rate as the load increase until the heat rate equals the incremental rate. After the minimum heat rate us reached, the increment rate causes a continuous risw in heat rate.

❖ 7.6 TERIFF METHODS FOR ELECTRICAL ENERGY:-

The rates of energy sold to the consumers depend on the type of consumers as domestic, commercial, and industrial. The rates depend upon the total energy consumed and the load factor of the consumer.

Whatever may be the type of consumer, all forms of energy rates must cover the following items:

(1) Recovery of capital cost invested for the generating power plant.
(2) Recovery of the running costs as operation cost, maintenance cost, metering the equipment cost, billing cost and many others.
(3) Satisfactory profit on the invested capital as the power plant is considered a profitable business for the government.

Although the determination of each cost item is simple but the allocation of these items among the various classes of consumers is rather difficult and requires considerable engineering judgement.

GENERAL RATE FORM:

The general type of tariff can be represented by the following equation.

$$Z=ax+by+c$$

Where, Z=Total amount of bill for the period considered
x=Maximum demand in KW
y=Energy consumed in KW-hrs during the period considered
a=Rate per KW of max demand
b=Energy rate per KW-hr
c=Constant amount charged to the consumer during each billing period. This charge is independent of demand or total energy because a consumer that remains connected to the line incurs expenses even if he does not use energy.

(1)Flat demand rate:

This type of charging depends only on the connected load and fixed number of hours of use per month or year. This rate expresses the charge per unit of demand (KW) of the consumer. This system eliminates the use of metering equipments and manpower required for the same.

This can be expressed as,

$$Z=ax$$

Under this system of charging the consumer cam theoretically use any amount of energy up to that consumed by all the connected load at 100% use factor continuously at full load.

The unit energy cost decreases progressively with an increased energy usage since the total cost remains constant. The variations in total cost and unit cost are shown in fig. (a).

(3)Block meter rate method: -

The straight line metre rate charges the same unit price for all magnitudes of energy consumption . the increased generation spreads the item of fixed charge over a greater number of units of energy and therefore the price of energy should decrease with an increase of consumption. To overcome this difficulty, the block metre rate is used. In this method the charging energy is done as stated below:

$$Z1 = b1y1+b2y2+b3y3+\_ \_ \_ \_$$

Where $b3<b2<b1$ and $y1+y2+y3+\_ \_ \_ = y$ (total energy consumption)

In gross metre rate system, the rate of unit charge decreases with increasing consumption of energy . the level y1,y2,y3 and so on is decided by the management to recover the capital cost of the plant. The variation of bill according to this method is shown in fig(C).

(4)Hopkinson demend rate of – Two part Tariff:

This method of charging was proposed by dr. John Hopkinson in 1892. This method charges consumer according to record the maximum demand and the energy consumption. This can be expressed as

$$z=a+by$$

This method required two metres to record the maximum demand and the energy consumption of the consumer. This method is generally used for industrial customers. The variation of z with respect to y taking x as parameter is shown in fig(d).

(5)Dohetry rate or Three part Tariff:

This rate of charging was suggested by Henry L. dohetry at the beginning of the twentienth century. According to this method of charging , the customer has to pay some fixed amount in addition to the charges for maximum demand and energy consumed . the fixed amount to be charged depends upon the occasional increase in prices and wage charges of the workers and so on. This is expressed as

$$X=ax+by+c$$

The Dohetry rate is sometimes modified by specifying the minimum demand and minimum energy consumption that must be paid for they are iess than the minimum values specified.

When the generating capacity is less than the actual demand , then the customers are discouraged to use more power. Upto the certain power consumption , the charging rate is fixed(say Rs.1.5/KW-hr up to 50KW-hr units and if it exeeds than this, the charge is rapidly increased as Rs.2.5/KW-hr.) this is unfortunate but very common in india.

Eample 1: Peak load on a thermal p.p of 12MW capacity is 10MW. The annual load factor 0.7. Taking the following data consideration design two part tariff and find overall cost of generation in P/KWHr.

1. Cost of the plant Rs. 700/KW of install capacity.
2. Interest, Depriciation & Insurance 10%.
3. Cost of transmission & distribution system Rs. $300*10^3$
4. Interest, Depriciation & Insurance on the transmission & distribution system is 5%
5. Operating cost Rs. . $300*10^3$ per year.
6. Cost of the coal Rs. 50 per ton
7. Plant maintenance cost
    i. Rs. 25000 per year fix in nature
    ii. Rs. 35000 per year running or variable
8. Consumption cost . $300*10^3$ /ton/year.

Assuming transmission distribution cost are charged to the generation.

Answer:

Fixed cost.

- Installation cost = 700*1200
  = $8.4*10^6$ Rs.

- Interest, depreciation and insurance
  = 10% of the installation cost
  = 10* $8.4*10^6/100$
  = $8.4*10^5$ Rs.
- Interest depreciation & insurance of the transmission & distribution
  = 5% of ($300*10^3$)
  = $5*300*10^3/100$
  = $15*10^3$ Rs.
- Fixed maintenance cost = Rs.25000
- Fixed cost = ($8.4*10^5$)+ ($15*10^3$) + 25000
  =$1500*10^3$
  =Rs. $150*10^4$

- Operating cost = Rs. $300*10^3$

- Variable maintenance cost = Rs. 35000

Total variable cost
=$1500*10^3 + 300*10^3 + 35*10^3$
= $1835*10^3$ rs.

Energy generated
= peak load*load factor*8760
=1000*0.7*8760
= $61.32*10^6$ KWH

Unit energy cost
= F.C+V.C\Energy generated
=($880*10^3$)+($1835*10^3$)\$61.32*10^6$
= 4.43 p/KW.hr

Two part tariff
Z= fixed cost \maximum load + variable cost\Energy generated
=$880*10^3$\ $10*10^3$ + $1835*10^3$ \ $61.32*10^6$
= 88 + 0.0299
= 88 rs\ KW + 29.9p\ KWh