B.E. 7th SEM

POWER PLANT ENGINEERING

(2171910)

Department of Mechanical Engineering

Darshan Institute of Engineering & Technology

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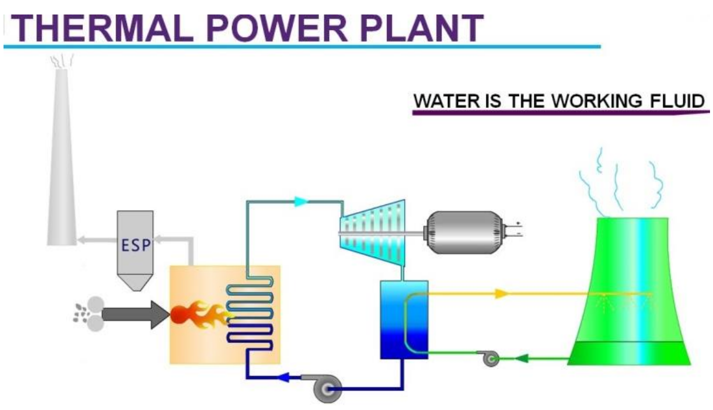
INTRODUCTION TO THERMAL POWER PLANT



Course Contents

1.1 Introduction

The availability of electrical energy and its per capita consumption is regarded as index of national standard of living in the present day civilization and for development of any country, energy is the basic input.

Next to the food, fuel and power are the most important items on which national standard life depends. That's why once the food requirement is fulfilled; next task for any country is to increase the power generation. The production of food also increases with increases of power generation. Therefore, the increase in power potential of a nation is considered most important among all.

The energy in the form of electricity is most desired as it is easy to transport, easy to control, clean in its surroundings and can be easily converted in heat or work as per requirements. If we see the data of last ten years, we can realize that consumption of power increases continuously, not only in India but worldwide and it will increase with development of industries and the improvement of living standard. As the coal is easily available in India, large percentage of electricity is developed by thermal power plant in which coal is used as fuel.

1.2 Working of Steam Power Plant

Steam power plant basically works on the Rankine cycle in which steam and water is used as working fluid. In Rankine cycle high pressure and temperature steam is generated in the boiler by burning of fuel. That high pressure and temperature steam is then expanded in the turbine to produce power which in turn used to drive the generator to produce electricity. After the expansion of steam low pressure and temperature steam is condensed in the condenser and the condensate is fed back to the boiler with the help of the feed water pump and cycle is repeated.

1.3 Rankine Cycle

The main components of cycle are boiler, turbine, condenser and feed pump. The cycle consists of following four processes:

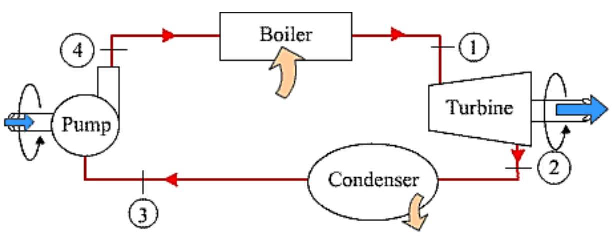


Fig. 1.1 Schematic diagram of Rankine cycle

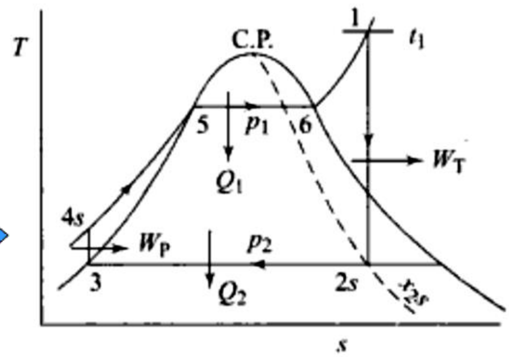


Fig. 1.2 T-S diagram of Rankine cycle

Process 1-2 isentropic expansion: Steam at high pressure and temperature is expanded in turbine isentropically. Pressure of the steam is decreases from P1 to P2. During the process work is done by the turbine.

Process 2-3 constant pressure heat rejection: exhaust steam from the turbine is condensed at constant pressure in the condenser so steam is condensed into water. During the process latent heat of steam is rejected to cooling water.

Process 3-4 isentropic compression: Condensate from the condenser is pumped back to the boiler. During with work is done on the water by the pump

Process 4-1 constant pressure heat addition: in the boiler heat is supplied at constant pressure by burning of the fuel.

1.4 General Layout of Thermal Power Plant

The general layout of the thermal power plant consists of mainly 4 circuits as shown in figure 1.3. The four main circuits are:

1) Coal and ash circuit
2) Air and gas circuit
3) Feed water and steam flow circuit
4) Cooling water circuit

1.4.1 Coal and ash circuit

Coal from the coal storage is fed to the boiler through coal handling system to generate the steam. Ash produced due to combustion of coal is removed and dump into ash sump through ash handling system.

1.4.2 Air and gas circuit

Air from the atmosphere is supplied to the boiler either through F.D. or I.D. fan or by using both. The dust from the air is removed with the help of air filter. Air preheater is used to utilize the heat of exhaust gases which increase the efficiency of the plant. To remove fly ash from the gases electrostatic precipitator is used. Exhaust gases from the boiler is discharge to the atmosphere through chimney.

1.4.3 Feed water and steam flow circuit

High pressure and high temperature steam is generated in the boiler by burning of the fuel. That high pressure and temperature steam is then expanded in the turbine to produce mechanical work which in turn is used to drive generator to produce electrical power. The steam coming out from the turbine is condensed in the condenser and then fed back to the boiler with the help of feed pump. The condensate may be heated in feed water heater using the steam tapped from the different points of the turbine.

Some of the steam and water may be lost due to leakage through different components. To compensate the loss, make up water is supplied to the boiler through feed water treatment plant to remove the impurities.

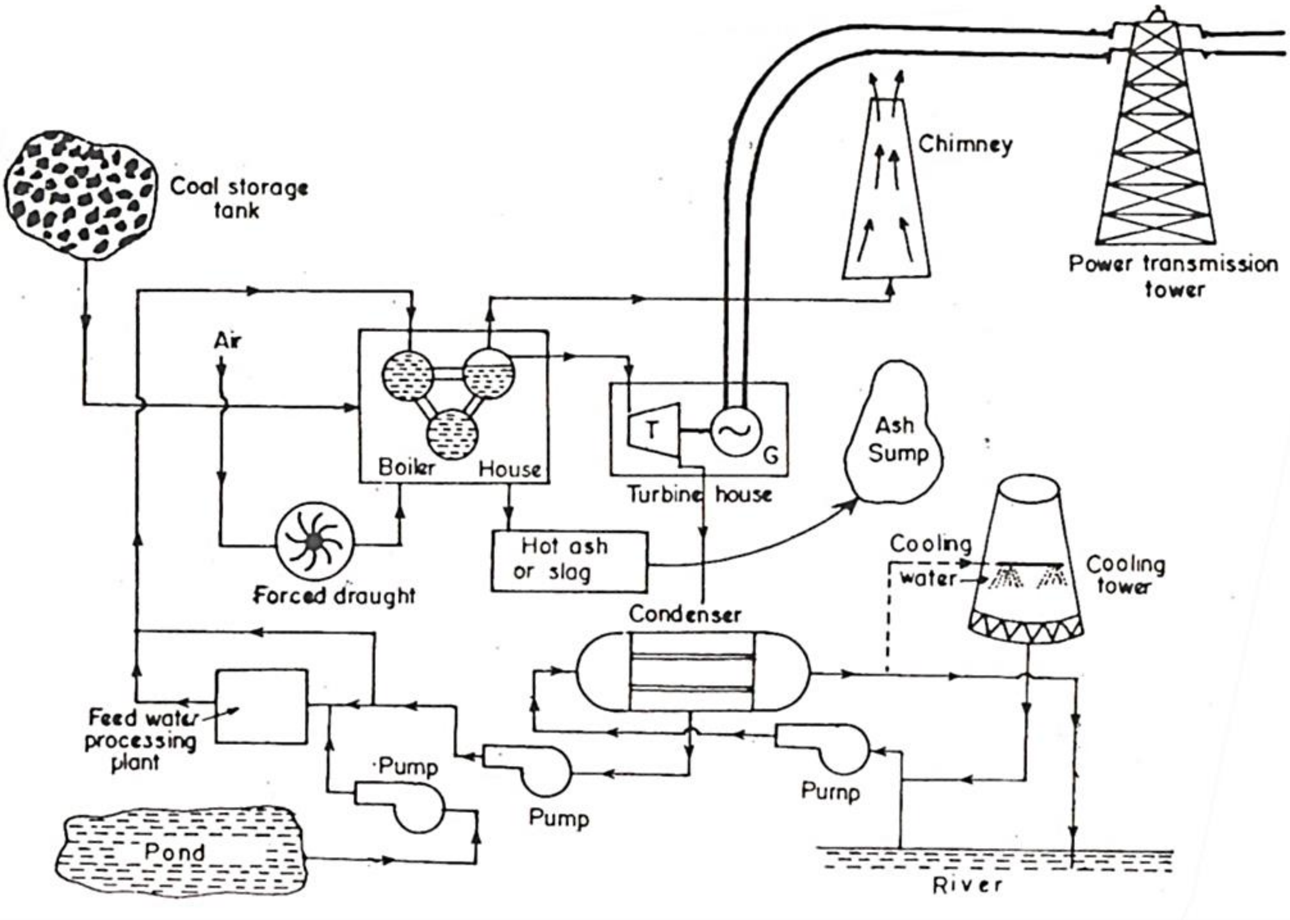


Fig. 1.3 General layout of thermal power plant

1.4.4 Cooling water circuit

The considerable amount of cooling water is required to condense the steam in condenser. It is taken either from lake, river or sea. If adequate water is available throughout the year, then cooling water is taken from the upstream of the river, passed through the condenser and discharge to downstream of the river.

If adequate water is not available, then hot water from the condenser is cooled in the cooling tower and cold water from the cooling tower is passed through the condenser.

- The different types of system and components of the thermal power plant:

1. Coal handling system
2. Ash handling system
3. Air preheater
4. F.D. fan
5. I.D. fan
6. Electrostatic precipitator
7. Boiler
8. Steam turbine

9. generator
10. Condenser
11. Feed pump
12. Feed water treatment plant
13. Cooling water circulating pump
14. Cooling tower

1.5 Site Selection of Thermal Power Plant

The following factors should be considered while selecting the site for a steam power station

1.5.1 Availability of Coal:

The major source of energy which is available in India for thermal power plant is coal. Therefore, it is necessary to concentrate for the best use of coal for power generation.

For the large capacity power plant, the huge amount of coal is required. Therefore, it is necessary to install such power plant near the coal mines. In this case, the electricity must be transported to the long distances, so, location of the plant is such that it will give minimum cost considering the coal transportation and power transmission.

1.5.2 Ash Disposal Facilities:

The ash removal problem has become more serious particularly in India, because Indian coal contains large percentage of ash. The removal of ash is more difficult than coal handling because it comes out from the boiler in hot condition and it is highly corrosive and it also contains poisonous gases.

Ash can be easily disposed off to river, sea or lake if such facilities are available. But in present day the ash from the power plant is used for many industrial processes, so it is better to utilize the ash for such process.

1.5.3 Space Requirement:

Space is required not only for construction of the plant but it also required for coal storage, ash disposal, staff colony and market facilities. To reduce the initial cost of the plant, land should be available at low cost.

1.5.4 Nature of Land:

The selected should have good bearing capacity to withstand the dead load of the plant and the forces transmitted to foundation due to operation of the machinery.

1.5.5 Availability of Water:

The large quantity of water is required for condenser, for disposal of ash, and as feed water to boiler and drinking water for the working staff. Large quantity of ash is also required for ash disposal if hydraulic system is used. Therefore, it is necessary to install the plant near the water source.

1.5.6 Transport Facilities:

Transportation facilities should be available for transportation of coal as well as transportation of heavy machinery.

1.5.7 Availability of Labour:
Cheap labour should be available at the proposed site as enough labour is required for construction of the plant.

1.5.8 Public Problem:
The proposed should be far away from the town to avoid the nuisance from smoke, fly ash and heat discharged from the power plant.

1.5.9 Size of the Plant:
In small power plant cost of transportation of coal and water is insignificant compare to transmission of electricity. Therefore small plant can be located away from the coal mines to minimize the total cost of power generation. Similarly large size plant should be located near the coal mines to minimize the coal transportation cost.

1.5.10 Future Extensions:
Space should be available for future expansion of the plant.

1.6 Things to Think About
- List the share of electricity generated in India and USA by different types of power plants.
- Compare the per capita energy consumption of India with west and USA.
- What is the effect of climate (winter and summer) on efficiency of power plant?
- What are the future sources of energy for mankind?

Assignment
1. Draw general layout of a thermal power plant and explain the working of different circuits.
2. Name factors to be considered for selection of site for thermal power station.
3. Select power plant and its location in Gujarat with its justification

2

HIGH PRESSURE BOILER

Course Contents

2.1 Introduction

Efficiency of any cycle can be increased by increasing the temperature of source or temperature of heat supplied. So, efficiency of the thermal power plant can be increased by increasing temperature of the steam supplied to the turbine. With development of the material, it is possible to supply high temperature steam to turbine. So to increase the efficiency of the plant it is necessary to use high pressure boiler.

2.2 Unique Features of High Pressure Boiler

2.2.1 Method of water circulation

The water may be circulated through the boiler by natural circulation due to density difference or by forced circulation with the help of pump.

In all modern thermal power plants forced circulation is used. But with increase of pressure, density difference decreases and at critical pressure it becomes zero. Thus the natural circulation ceases. Therefore, in high pressure boiler, it is necessary to use forced circulation. Further, heat transfer rate can also be increased by increasing the velocity of water with the help of pump.

2.2.2 Types of Tubing

In most of high pressure boiler, the water is circulated through the tubes and outer surface of tubes are exposed to the gases. If the water is circulated through the one continuous tube, large pressure drop will take place. To minimize the pressure drop, water is circulated through parallel system of tubing.

2.2.3 Improved Method of Heating

The heat transfer from the hot gases to water can be increased by using following methods:

i. At critical pressure, water is directly converted into steam. So, by increasing the pressure above the critical pressure latent heat of vaporization can be saved.
ii. If water is supplied to the boiler at high temperature, then efficiency of heat supplied can be increased. So, by using the feed water heater, temperature of feed water can be increased.
iii. The overall heat transfer coefficient can be increased by increasing velocity of water inside the tube or by increasing the velocity of gases.

2.3 Advantages of High Pressure Boiler

i. Scale formation is avoided due to the use of high velocity of water.
ii. Light weight tubes can be used.
iii. Reduction in number of tubes used.
iv. Boilers are capable of meeting rapid load changes.
v. Completely eliminates the high head which is needed for natural circulation.
vi. Since all parts are heated uniformly, eliminates danger of overheating and setting up thermal stresses.

vii. Construction time required is less

2.4 La-Mont Boiler:

Construction and Working

The arrangement of water circulation and different components is shown in figure 2.1.

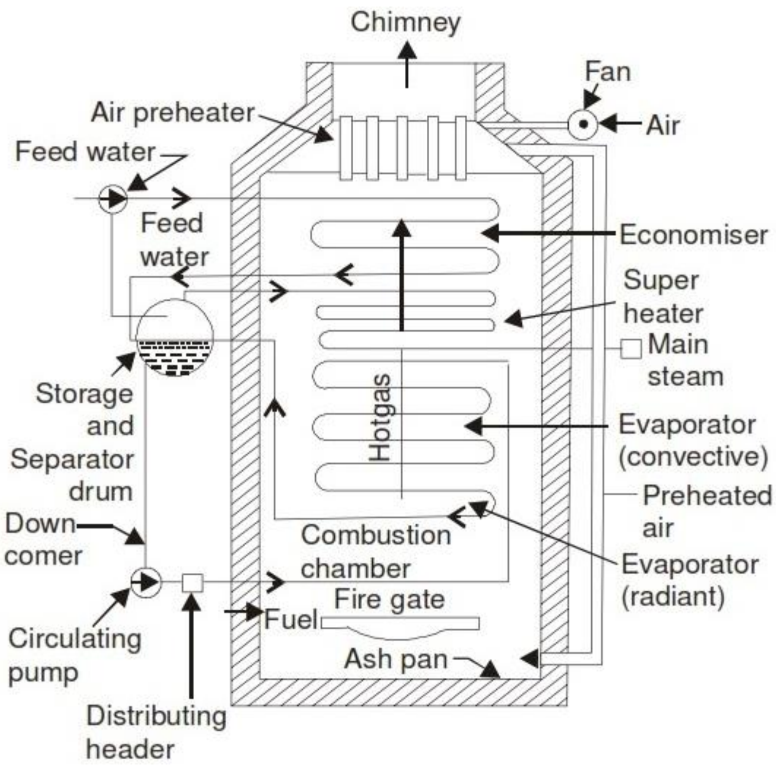


Fig. 2.1 La-Mont Boiler

The feed water from the hot well is supplied to a storage and separating drum through economizer. The most of the sensible heat is supplied to feed water through economizer. Water from the storage drum is circulated through the radiant evaporator and convective evaporator with the help of circulating pump. Circulation of water through evaporator is 8 to 10 times the weight of steam evaporated. Such large quantity of water circulation through evaporator tubes prevents the tube from overheating. Part of the water evaporated, as it pass through evaporator, is separated in the separating drum. Dry and saturated steam from the separating drum is passed through the super-heater before supply to prime mover. Distributing headers are used to distribute the water into radiant evaporator through nozzles.

Note: - In the radiant evaporator, heat is transferred by radiation so it is called radiant evaporator, whereas in convective evaporator, heat is transferred by convection. In modern high pressure boiler, furnace wall is covered with the water tube, so heat transfer in furnace is by radiation. This water tubes also protect the furnace wall from overheating.

Problem with La Mont Boiler and its Solution

The main difficulty experience in the La Mont boiler is the formation and attachment of bubbles on the inner surface of the heating tubes. As the attached bubbles offers high thermal resistance to heat transfer compare to water film, it reduce the heat transfer and steam generation. It also increases the thermal stresses.

This problem can be reduced by increasing the pressure inside the boiler upto the critical pressure. At the critical pressure, water and steam have same density, so formation of bubble can be eliminated.

2.5 Benson Boiler:

To avoid the formation and attachment of bubbles inside the water tube, Benson boiler is operated at critical pressure. The arrangement of the boiler components is shown in figure 2.2.

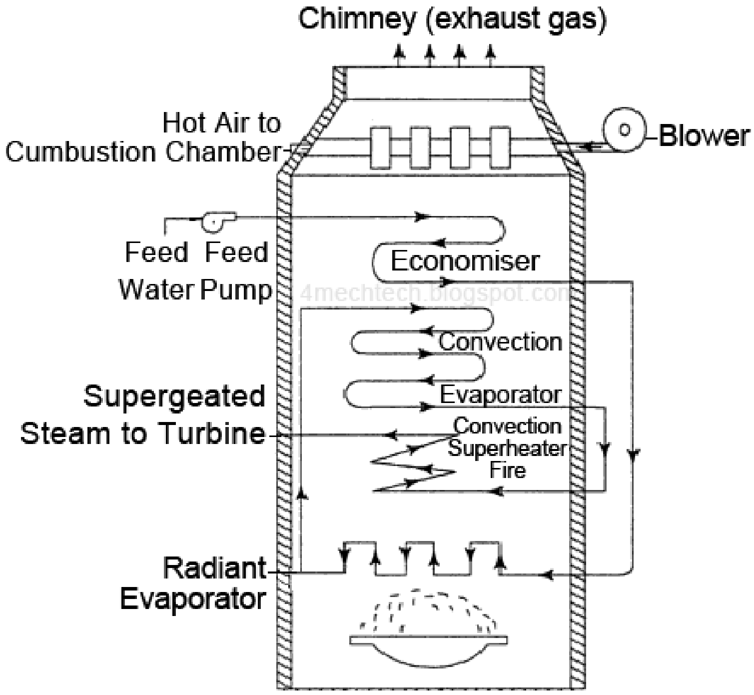


Fig. 2.2 Benson Boiler

Construction and Working

Water from the hot well is passed through the economizer where sensible heat is supplied to the water. Part of the water is evaporated when it passes through the radiant evaporator and remaining water is evaporated as it passes through the convective evaporator. Then dry and saturated steam from the convective evaporator is passed through the super-heater before supply to prime mover.

Starting of the Benson Boiler

First circulating pumps are started then burners are started. During starting water from super heater is supplied back to economizer with the help of valve A. During starting valve B is closed. Once generation of superheated steam starts, valve A is closed and valve B is opened.

Advantages

i. No drum so light weight

ii. Transportation of boiler is easy

iii. Erection is easy and can be carried out at plant site
iv. Furnace wall can be protected by small diameter tubes
v. Quick start because of the welded joint

Problem with Benson Boiler and its Solution

Major problem with the Benson boiler is deposition of salt in the transformation zone when all remaining water is converted into steam. This deposited salt offers the resistance to heat transfer and reduces the steam generation. It also causes the overheating of the tube.

To avoid this difficulty, the boiler is normally flashed out after every 4000 working hours to remove the salt.

2.6 Loeffler Boiler:

The major difficulty experienced in Benson boiler is deposition of salt on the inner surface of the tubes. This difficulty was solved in Loeffler boiler by preventing the circulation of water through the tubes. The arrangement of the components of boiler is shown figure 2.3.

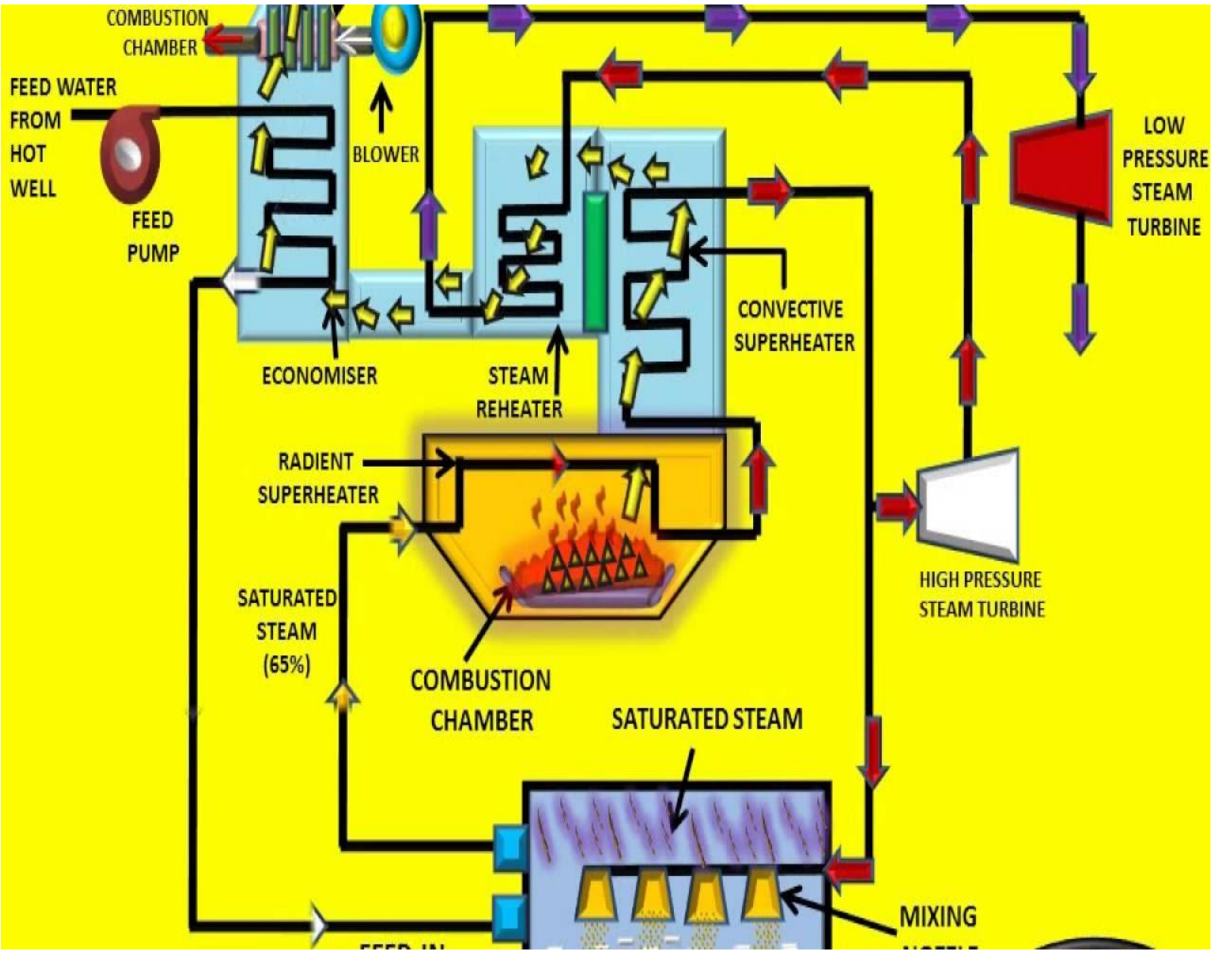


Fig. 2.3 Loeffler Boiler

Construction and Working

The water from the hot well is supplied to the evaporating drum through economizer. About 65% of the steam coming from the super-heater is supplied to the evaporating drum for evaporation of the feed water from the economizer. Steam is generated by mixing of the super-heated steam to the feed water in evaporating drum. Dry and saturated steam generated in the evaporating drum is circulated through the radiant super-heater and convective super-heater with the help of steam circulating pump. About 35% of super-heated steam generated in the super-heater is supplied to the H.P. turbine and remaining is supplied to evaporating drum. Exhaust steam from the H.P. turbine is reheated in the re-heater before supplied to the L.P. turbine.

For distribution of super-heated steam throughout the water into evaporator, special design nozzles are used which reduce the priming and noise. Higher salt concentration water can be used in this boiler.

2.7 Schmidt-Hartmann Boiler:

The operation of the boiler is similar to an electric transformer. The arrangement of the boiler components are shown in figure 2.4.

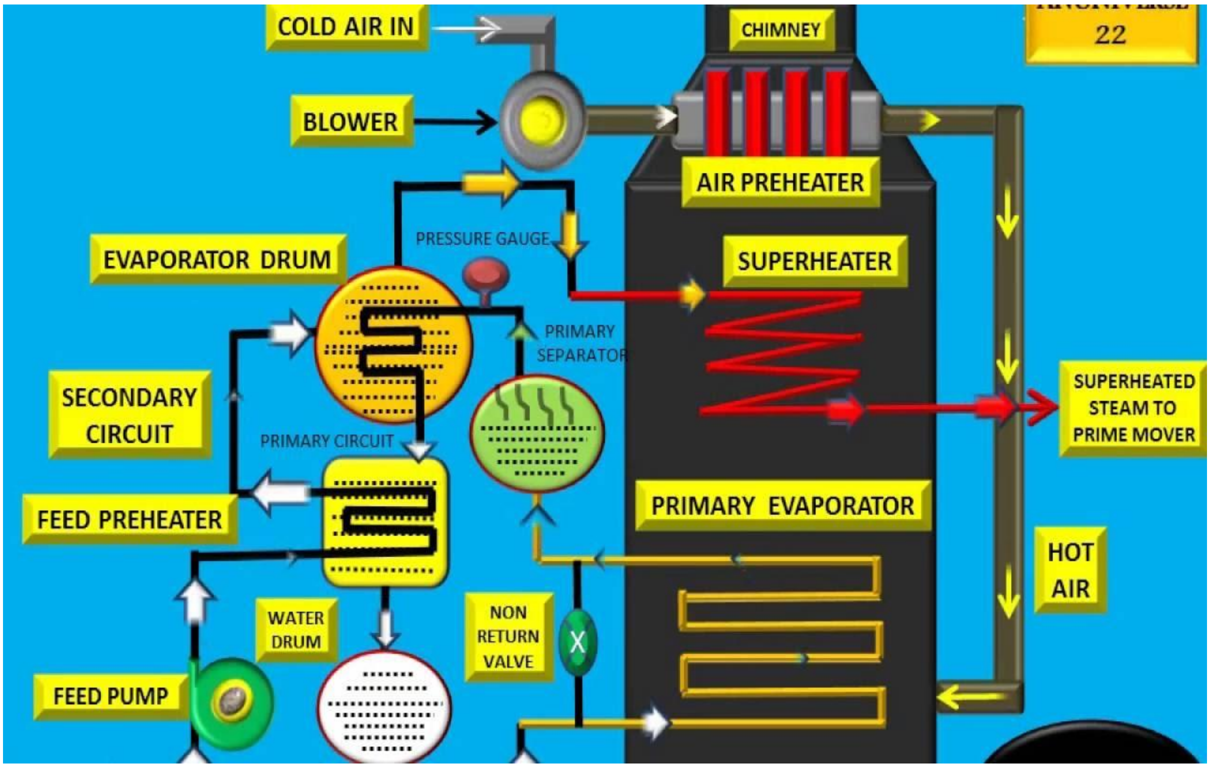


Fig. 2.4 Schmidt-Hartmann Boiler

Construction and working

The boiler consists of two circuits. In the primary circuit, steam is generated from the distilled water at 100 atm. The generated steam is passed through the coil submerged in the evaporating drum. Evaporating drum contains the impure water at 60 atm. so, in the evaporating drum, steam is generated at 60 atm. and high pressure steam is condensed. Steam generated in evaporating drum is passed through the super-heater before supply to the prime mover.

The high pressure condensate produced in the submerged coil is passed through the feed pre-heater to raise the temperature of impure water to its saturation temperature. So, only latent heat is supplied in the evaporator drum.

Natural circulation is used in the primary circuit and this is sufficient for desired rate of heat transfer and to overcome the thermo-siphon head of about 2 to 10 m.

Every care is taken in design and construction to prevent the leakage of distilled water in the primary circuit, so in normal circumstances, make up water is not required. For safety of operation pressure gauge and safety valve are fitted in the primary circuit.

Advantages

i. There is a rare chance of overheating or burning the highly heated components of primary circuit as there is no chance of obstruction to the circulation by impurities.
ii. The salt deposited in the evaporator drum due to the circulation of impure water can be easily brushed off just by removing the submerged coil from the drum or by blowing off the water.
iii. The wide fluctuations of load are easily taken by this boiler without priming problem.
iv. The absence of water risers in the drum, and moderate temperature difference across the heating coil allows evaporation to proceed without priming.

2.8 Velox Boiler:

High rate of heat transfer can be achieved by increasing the velocity of the flue gases over the velocity of the sound. In the velox boiler, velocity of the gases is more than velocity of the sound. The arrangement of components of the boiler is shown in figure 2.5.

Construction and Working

Air is compressed to 2.5 bar with the help of the compressor driven by the turbine. That high pressure air is supplied to combustion chamber to get supersonic velocity of the gases. The supersonic gases are passed through the combustion chamber and gas tubes to achieve high heat transfer rate.

The burned gases in the combustion chamber are passed through the annulus of the tubes as shown in figure 2.5. Heat is transfer from the gases to water while passing through the annulus to generate the steam. The mixture of water and steam formed in the water tube is passed to the separator which is design so that the mixture enters with spiral flow. Due to the centrifugal force, heavier water particles are thrown outward on the wall which separates the steam from water.

The gases coming out from the annulus at the top is further passed over the super-heater to super heat the steam. The gases coming out from the super-heater is passed through the turbine to utilize the kinetic energy of the gases. The power output of the turbine is used to run the compressor. The exhaust gases coming out from the turbine are passed through the economizer to utilize the heat of exhaust gases. The extra power required to drive the compressor is supplied with the help of electric motor.

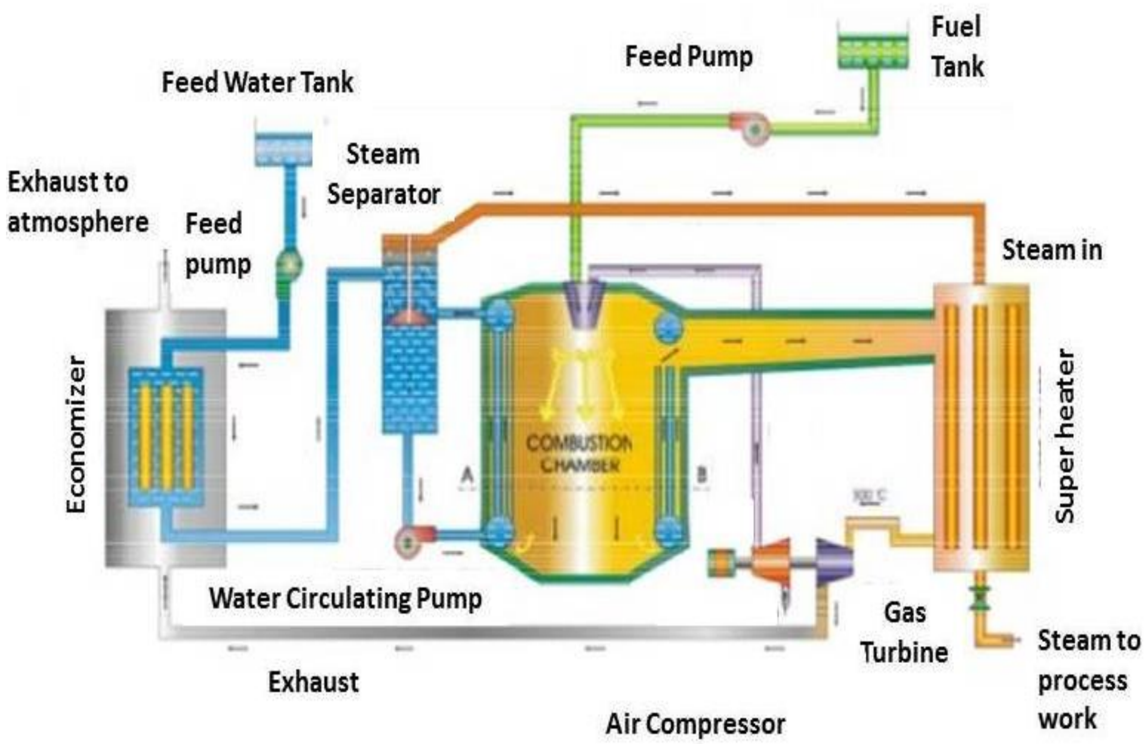


Fig. 2.5 Velox Boiler

Advantages

i. Very high rate of combustion is possible.
ii. It is very compact and has greater flexibility.
iii. Low excess air is required as pressurized air is used and draught problem is simplified.
iv. It can be quickly started from the cold.

2.9 Super Critical Boiler:

The efficiency of the plant can be increased by increasing the pressure of the steam. So in the modern power plants super critical boilers are used. Boiler which operates above the critical pressure is called super critical boiler.

Note:-

Critical state: State of a substance beyond which there is no clear distinction between the liquid and gaseous phase

A point where saturated liquid and dry saturated vapour lines meet so that latent heat is zero, is called Critical Point (figure 2.6).

For water, Critical Point is given by:

Pressure: 221 bar Temperature: 374.15 0C

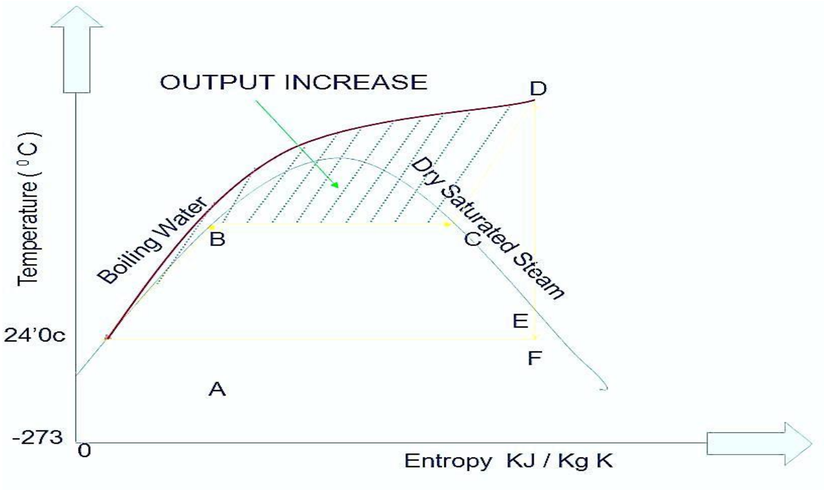


Fig. 2.6 T-S Diagram of Rankine Cycle

Super critical boiler is also called once through boiler as the water is converted into super-heated steam in single continuous pass. It does not required steam separating drum.

Design consideration of super critical boiler

Above super critical pressure, there is no density difference between the steam and water so forced circulation is necessary.

There is no steam drum so no blow down therefore extremely pure water must be used for which require high quality water treatment plant.

Boiler tubes must be made of high strength austenitic steels or super alloys to withstand high temperature.

Normally 3 steps of feed heating are required due to high pressure and to avoid excessive moisture at turbine exhaust.

Advantages

i. The heat transfer rate is considerable large compare to sub critical boiler.
ii. The pressure level is more stable due to less heat capacity of the boiler therefore give better response.
iii. Higher thermal efficiency of power plant can be achieved.
iv. The problems of erosion and corrosion are minimized in as two phase mixture does not exist.
v. The turbo generators connected to super-critical boilers can generate peak loads by changing the pressure of operation.
vi. It gives better response to load fluctuation.

Disadvantages

i. Feed pump is necessary.
ii. More reheats are required, hence increased complexity of the plant and maintenance.
iii. High capital involved.

2.10 Super-Charged Boiler:

In the super-charged boiler combustion of the fuel is carried out under the high pressure.

Construction and working

The arrangement of the different components is shown in figure 2.7. Air from the atmosphere is supplied to combustion chamber at high pressure with the help of the compressor. In the combustion chamber, combustion is carried out under the high pressure. The exhaust gases from the combustion chamber are used to run the gas turbine as they are exhausted at high pressure and the power produced by the gas turbine is used to run the compressor to compressor the air. The exhaust gases from the turbine are further used to preheat the feed water in the economizer.

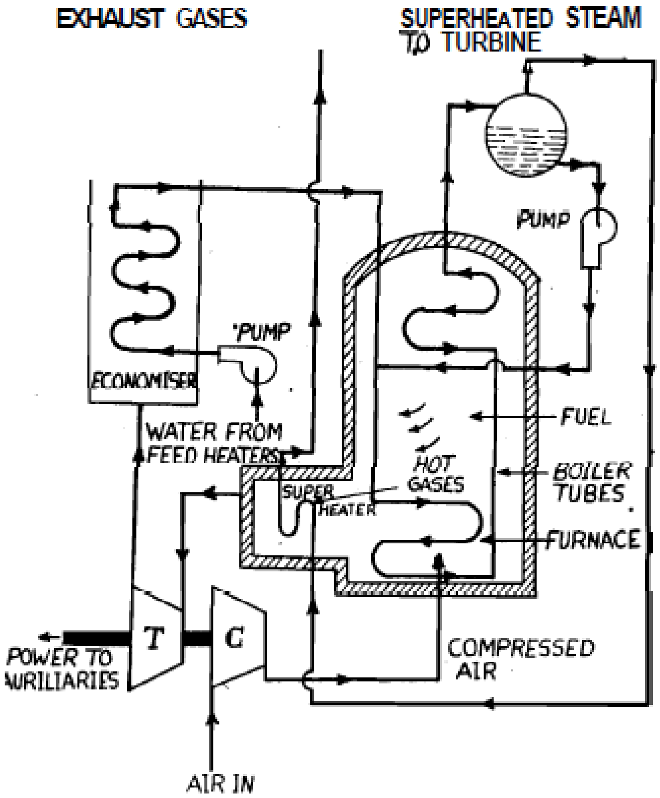


Fig. 2.7 Super charged Boiler

Advantages

i. High heat transfer rate can be achieved as combustion is carried under the high pressure.
ii. Rapid start of the boiler is possible as the boiler is compact.
iii. It gives the better response to load fluctuation due to small heat storage capacity.
iv. The part of the gas turbine output can be used to drive other auxiliaries.

Disadvantages

i. The tightness of high pressure gas passage is essential.
ii. Capital cost of the boiler is high.

2.11 Things to Think About

- List the different types of boilers and its application
- Compare the unique features of the different types of boilers

Assignment

1. Explain the constructional difference between Low pressure and High pressure boiler.
2. Explain with neat sketch construction and working of La Mont Boiler.
3. Draw a neat line diagram of a Benson boiler. State the main difficulty experienced in the La Mont boiler and how it is prevented. Explain its advantages.
4. Explain construction and working of Loeffler boiler. Also explain starting of Loeffler boiler.
5. With neat sketch explain construction and working of Schmidt-Hartmann boiler.
6. Draw line diagram of Velox boiler. Indicate all part of it. How it different from the other type of high pressure boiler?
7. What is subcritical and supercritical boiler?
8. Explain the working of pressurized fluidized bed combustion boiler with help of neat sketch. List its advantages and limitations.
9. Convection and radiant super heaters have opposite characteristics of temperatures v/s load- Explain.
10. With neat sketch explain different types of super heaters.
11. Write different methods of controlling temperature of superheated steam.
12. Distinguish between superheater, reheater and air preheater.

3

Coal and Ash Handling Systems

Course Contents

3.1 Introduction

Different types of fuels used for steam generation- Generally there are three types of fuels can be burnt in any type of steam power plant. They are 1) Solid fuels 2) Liquid fuels 3) Gaseous fuels.

Gaseous fuels:

The gaseous fuels widely used in steam power plants are natural gas, Blast furnace gas. Gaseous fuels may be either natural gases or manufactured gases. Since the cost of manufactured gases is high only natural gases are used for power generation. Natural gas is colorless, odorless and is non-poisonous its calorific value lies between 25000KJto 50000 KJ/m^3.

The various manufactured gases are coal gas, Coke oven gas, Blast furnace gas and producer gas. These manufactured gases plays less important role in the steam generation.

Advantages:

1) Excess air required is less
2) Uniform mixing of fuels and air is possible
3) Handling is much more easier compared to the coal
4) The load changes can be met easily
5) There is no problem of ash disposal. 6) Operational labourer required is less.

Disadvantages:

1) Storage of gaseous fuels is not easy compared to liquid fuels due to the risk of explosions.
2) The plant must be located near the natural gas field otherwise transportation cost increases.

Liquid fuels:

The liquid fuels used in the thermal plant to generate the steam instead of coal as it offers the following advantages over the coal.

1) The calorific value of liquid fuels is about 40% higher than that of coal or solid fuels
2) The storage space required for liquid fuels is less
3) Instantaneous ignition and extinction of fire is possible
4) Stand by losses are minimum
5) Efficiency of the boiler is high
6) Ash handling system can be eliminated
7) Oil can be easily metered. The rate of fuel supply to furnace is easy to control.

Disadvantages

1) The overall combustion efficiency of the liquid fuel fired power plant is less compared to the coal fired power plants
2) The availability of the liquid fuel resources are very limited as compared to the coal resources

Ex. Heavy oils, Bunker Coil, Viscous residue oil, Petroleum and its byproducts.

Solid Fuels:

Example for solid fuels is Coal. The term coal refers to the rocks in the earth's crust, produced by the decaying of the plant materials accumulated over the millions of years ago. Different types of coals that are used for steam generation are

1) Lignite
2) Sub Bituminous
3) Bituminous coal
4) Semi Anthracite coal
5) Anthracite coal.

1) Lignite:

It is lowest grade of coal. Its having 30% of moisture calorific value is about 14650 to 19300 KJ/ Kg. Due to the high moisture content and low calorific value lignite is not easy to transport over long distances. It is usually burnt by the utilities at the mine sites.

2) Sub Bituminous:

Its calorific value is slightly less than that of the Bituminous coal. Its calorific value is in between 193000 to 26750 KJ / Kg. The moisture content is about 15 to 30%. It is brownish black in colour. These coals usually burned in the pulverized form.

3) Bituminous coal:

Bituminous coal is widely used in all purposes. It is used in steam generation and in the production of the coal gas and producer gas. Its moisture content may vary from 6 to 12 %. Its calorific value ranges from 25600 KJ/Kg to 32600 KJ /Kg. Bituminous coal burn easily especially in pulverized form.

4) Semi Anthracite

It is an intermediate coal between Bituminous and Anthracite coal. It ignites more easily than anthracite to give a short flame changing from Yellow to Blue. It is having the following properties:

Moisture content = 1 to 2%

Volatile matter = 10 to 15 %

Calorific value= 36000 to 36960 KJ / Kg

5) Anthracite:

It is the most mature and hard form of solid fossil fuel. It is having a fixed Carbon content ranging from 92 to 98%. Anthracite is good domestic fuel for heating and is sometimes used for steam generation.

Selection of coal for steam generation

Selecting a suitable coal for steam generation is an very difficult task. The firing qualities of coal are every important when we are considering a combustion equipments. Slower burning coal generates high fuel bed temperature s and therefore requires forced draught fan. The fast burning coals require large combustion chamber. Such coals are suitable for meeting a sudden demand for steam. The most important factors which are to be considered in the selection of coal are sizing and caking, Swelling properties and ash fusion temperature. Sometimes the selection of coal depends on the ash content also.

The following properties of the coal are to be considered for the selection of the coal for steam generation in steam power plants.

1) Burning rate of coal
2) Sizing, Caking, Swelling properties of coals
3) Finess of coal

3.2 Coal handling

The coal handling plant needs extra attention, while designing a thermal power station, as almost 50% to 60% of the total operating costs consists of fuel purchasing and handling. Fuel system is designed in accordance with the type and nature off fuel. Plants may use coal oil or gas as the fuel. The different stages in coal handling are shown below.

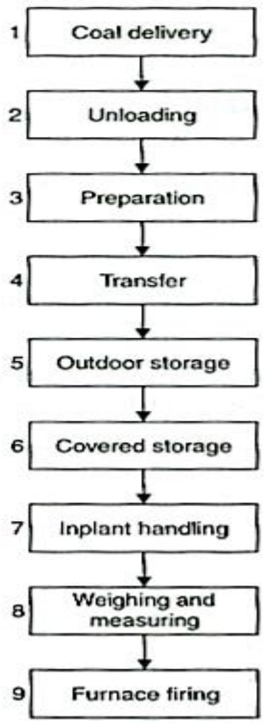


Fig. 3.1 Coal Handling

1. Coal delivery

The method of transporting coal to a power station depends on the location of the plant, but may be one or more of the following: rail, road, river or sea. Plants situated near river or sea may make use of the navigation facilities. Stations which cannot make use of these facilities may be supplied coal either by trucks or by rail. Transportation of trucks is usually used in case the mines are not available. In case rail transport is to be adopted, the necessary siding for receiving the coal should be brought as near the station is possible.

2. Unloading

Just what kind of equipment will do the best job for unloading depends first of all on how the coal is received. If the coal is delivered in dump trucks and if the plant site is favorable we may not need additional unloading equipment. When coal transported by using by sea or rivers unloading bridge or tower and portable conveyors are used. In case the coal received by rail in hoppers cars, again the coal may be unloaded quickly by using any of the facilities such as car shakers, Car throwing equipments, Car dumpers (Rotary), coal accelerators.

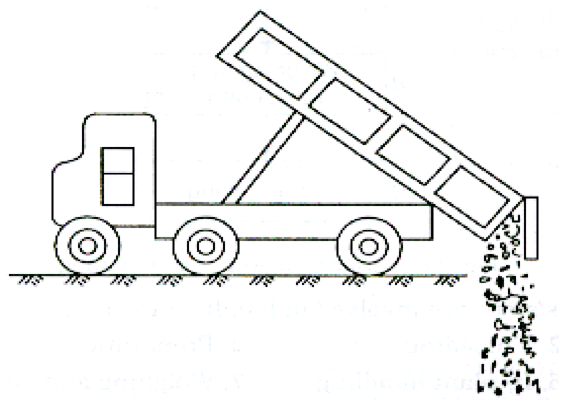


Fig. 3.2 Lift truck with scoop

3. Preparation

If the coal is brought to the site unsized and sizing is desirable for storage or firing purposes. The coal preparation plant may be located either near the coal receiving point or at the point of actual use. The coal preparation plant may include the following equipments:

a. Crushers
b. Sizers
c. Dryers
d. Magnetic separators

Coal preparation plant is as shown below in fig. 3.3.

The raw coal is crushed in to required size using crushers. The crushed coal is passed over the sizer who removes unsized coal and feeds back to the crusher. The crushed coal is further passed to the drier to remove the moisture from the supplied coal. Before supplying the coal to the storage hopper, the iron scrap and particles are removed with the help of magnetic separators.

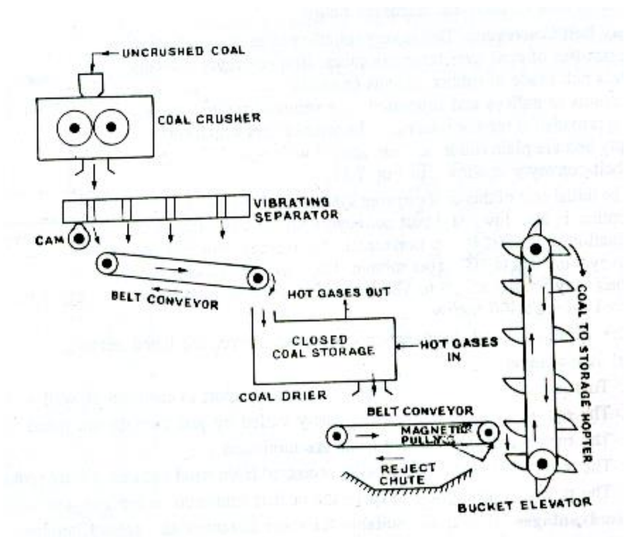


Fig. 3.3 Coal Preparation Plant

4. Transfer

Transfer means the handling of the coal between the unloading point and the final storage point from where it is discharged to the firing equipment. The equipments used for the transfer of coal may be any one of the following or a suitable combination thereof:

a) Belt conveyors
b) Screw conveyors
c) Bucket Elevators
d) Grab bucket Elevators
e) Skip hoists and
f) Flight conveyors

Belt conveyor

The belt conveyors are suitable for transporting large quantities of coal over large distances. It consists of endless belt made up of rubber, canvas or balata running over a pair of end drums or pulleys and supported by series of rollers provided at regular intervals. The return idlers which support the empty belt are plain rollers and are spaced wide apart. Belt conveyors can be used successfully up to 20 degree inclination to the horizontal. The load carrying capacity of the belt may vary from 50 to 100 tons /h and it can easily be transported through 400 meters.

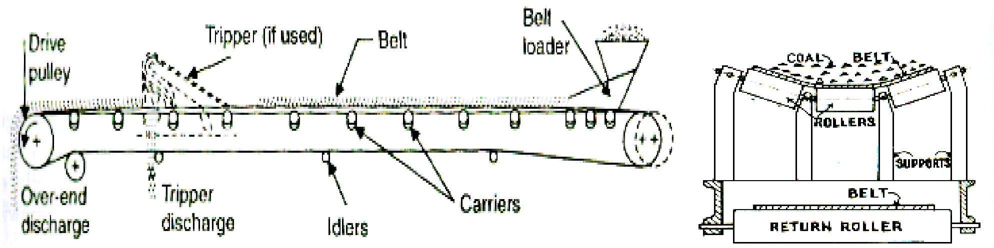


Fig. 3.4 Cross section of belt drive

Advantages

It is most economical method of coal transfer.

The rate of coal can be regulated by varying the speed of the belt.

The repair and maintenance charges are minimum

The coal can be protected.

The power consumption is minimum

Disadvantages

It is not suitable for short distances and greater heights.

Screw conveyor

It consists of a helicoids screw fitted to a shaft as shown in the figure. The driving mechanism is connected to one end of the shaft and the other end of the shaft is supported in an enclosed ball bearing. The screw while rotating in a trough transfers coal from one end to the other end as shown in figure. The diameter of screw is 15 cm to 50 cm and its speed varies from 70 to 120 rpm and the maximum capacity is 125 tones per hour.

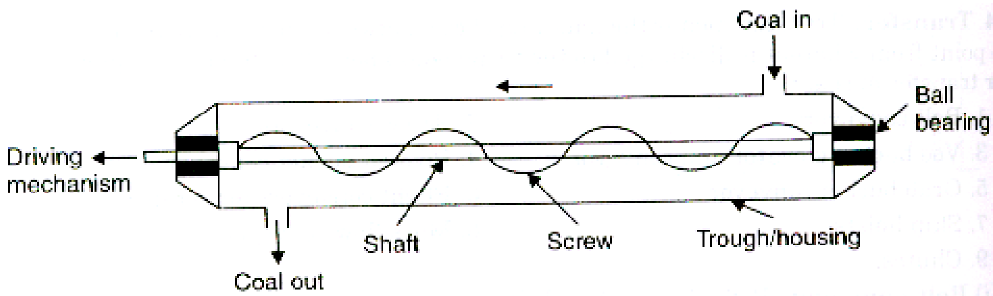


Fig. 3.5 Screw Conveyor

Advantages:

It requires minimum space and is cheap in cost

It is most simple and compact

It can be made dust tight

Disadvantages:

The power consumption is high

The maximum length limited to 30 meters

The wear and tear is very high therefore life of the equipment is less

Bucket elevators

These are used extensively for vertical lifts, through the horizontal runs is not ruled out. These elevators consist of relatively small size buckets closely spaced on an endless chain. The coal is carried by the buckets from the bottom and discharged at the top. Centrifugal type and continuous type bucket elevators are most commonly used. The maximum height of the elevator is limited to 30.5 m and maximum inclination to the horizontal is limited to 60 degree. The speed of the chain required in first case is 75 m/min and continuous type is 35 m/min for 60 tones capacity per hour.

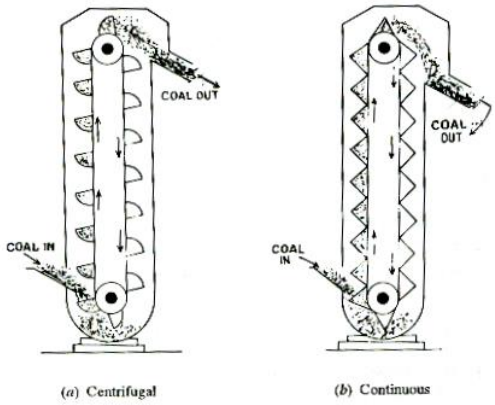


Fig. 3.6 Bucket elevators

<u>Advantages:</u>

Less power is required

Coal can be discharged at elevated places

Less floor area is required

<u>Disadvantages:</u>

Its capacity is limited to 60 tons per hour and hence not suitable for large capacity stations

Grab bucket

Grab bucket conveyor is form of hoist which lifts and transfers the load on a single rail or track form one point to another. This can be used with crane or tower as shown in figure A 2-3 cu-m bucket operating over a distance of 60 m transfer nearly 100 tons of coal per hour. Its initial cost is high but operation cost is less.

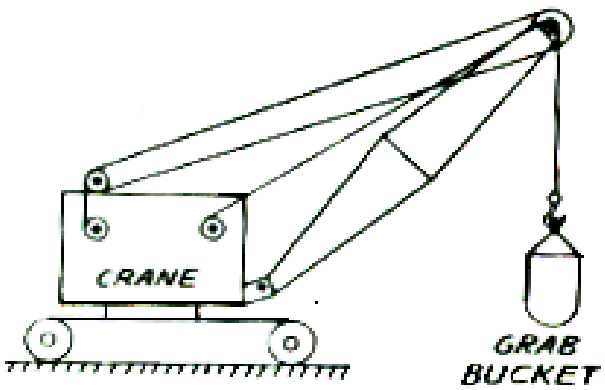


Fig. 3.7 Grab Bucket

Flight conveyor

This type of conveyor is generally used for transfer of coal when filling of number of storage bins situated under the conveyor is required. It consists of one or two strands of chain to which steel scrappers are attached the scraper scraps the coal through a trough and the coal is discharged in the bottom of the trough as shown in fig. 3.8.

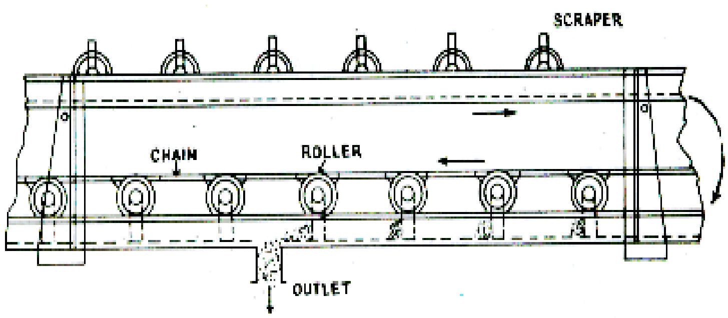


Fig. 3.7 Flight conveyor

Advantages:

It requires small head room

The speed can be regulated.

It can be used for as well as coal transfer.

It requires less attention.

Disadvantages:

There is excessive wear and tear and hence the life of the conveyor is less.

The repair and maintenance charges are high.

The restricting the operating speed to 300m/min is required to reduce the abrasive action.

Power consumption is high per unit of coal or ash handled.

Skip hoist:

It is used in high lifts and handling is not continuous. It consists of vertical or inclined hoist way, a bucket or a car guided by the frame, and a cable for hoisting the bucket.

Advantages:

It requires very low maintenance.

Power requirement is low.

It can handle larger size clinkers.

It can be used for handling ash as well as coal

It needs minimum floor area.

Disadvantages:

The initial cost is high

This is not suitable for continuous supply of coal.

There is excessive wear of skips and ropes which need frequent replacements.

5. Outdoor storage

Whether the storage is large or small, it needs protection against losses by weathering and by spontaneous combustion. With proper methods adopted even larger outdoor storage can remain safe. In order to avoid the oxidation of coal the compact layers are formed. To avoid spontaneous combustion air is allowed move evenly through the layers.

6. Indoor storage or live storage

This is usually a covered storage provided in plants, sufficient to meet day's requirement of the boiler. Storage is usually done in bunkers made of steel or reinforced concrete having enough capacity to store the requisite of coal. From the coal bunkers coal is transferred to the boiler grates.

7. Weighing

A frequent part of in plant handling is keeping tabs on quantity and quality of coal fired. For weighing weigh bridge is used. Coal is weighed in transit also by using belt scale.

8. Fuel firing methods

Selection of firing method adopted for a particular power plant depends on the following factors.

a) Characteristics of fuel available
b) Capacity of the plant
c) Load factor of the power plant
d) Nature of load fluctuations
e) Reliability and efficiency of the various combustion equipments

Depending upon the combustion equipments used boilers can be classified as:

a) Solid fuel fired
b) Liquid fuel fired
c) Gaseous fuel fired

Solid fuel firing

The classification of combustion system used for coal burning given below:

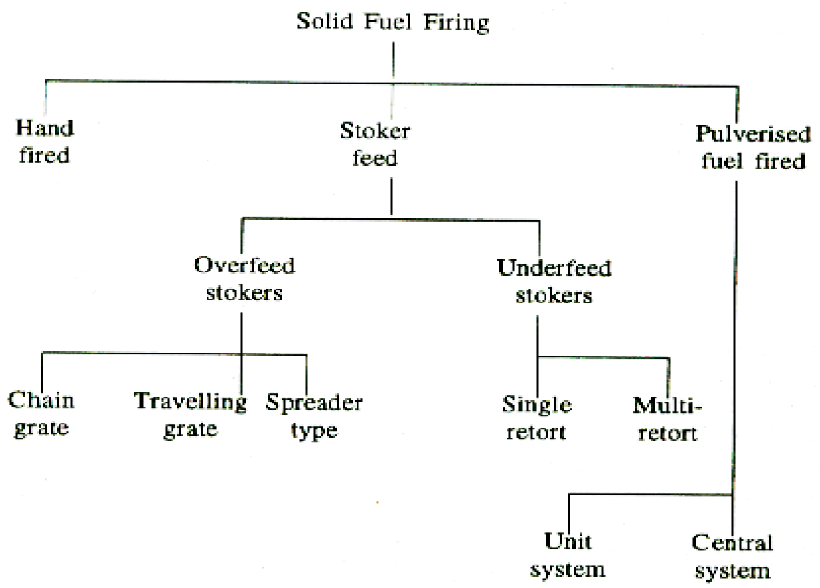


Fig. 3.8 solid fuel firing

Hand firing system is the simplest method for solid fuel firing but it cannot be used in modern power plant. The most commonly used methods for firing the coal are:

1) Stoker fire
2) Pulverized fire

Stoker fire:

Stoker is fuel burning mechanism used for burning fuel on grate. This type of burning mechanism is suitable where the coal is burned. Stokers are classified as

a. Over feed stokers
b. Under feed stoker.

In over feed stoker the direction of air and coal are opposite to one another. The coal is supplied on to the grates above the point of air admission.

In under feed stoker coal is fed from underneath the grate between the two tuyers. The direction of fuel and air is same.

Over feed stoker

Typical overfeed stoker is as shown in the fig. 3.9. Coal is fed on to the grate above the point of air admission.

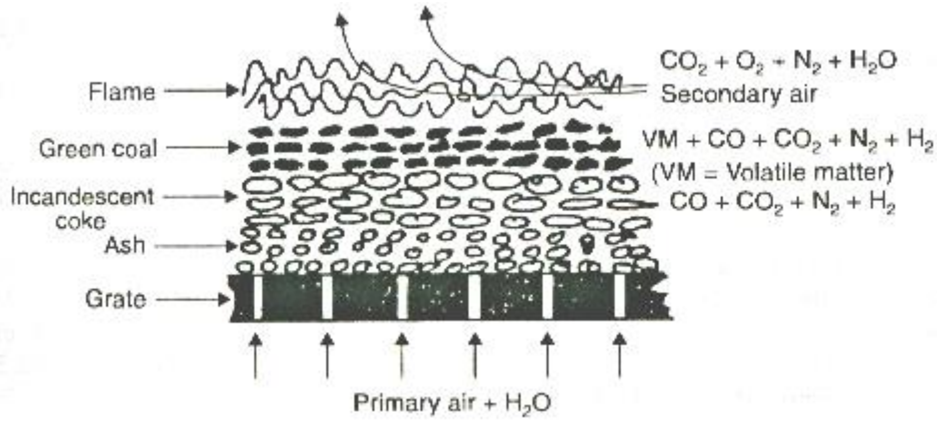


Fig. 3.9 Principle of overfeed stoker

The pressurized air coming from the FD fan enters under the bottom of the grate. The air passing through the grate opening is heated by absorbing the heat from the ash and grate itself, whereas the grate and ash get cooled.

As hot air passes through the incandescent coke layer O_2 reacts with Carbon to form Carbon dioxide. This is an exothermic reaction and releases heat required for continuation of combustion process. It continues till all the oxygen is consumed. If the incandescent layer thick, CO_2 may be partly reduced to CO (CO_2 + C – 2CO). The gasses leaving the incandescent layer are N_2, CO, CO_2, H_2.

A slight water reaction may take place with the moisture in air (H_2O + C – H2 + CO). This is an endothermic reaction and may bring down the temperature of the bed and gas. Stream of gases then passes through the distillation zone where volatile matter is added from raw coal and then moisture is picked up in the drying zone and finally emerges above the fuel bed. The gases leaving the upper surface of the fuel bed contain combustible volatile matter, N_2, CO_2, CO, H_2 and H_2O, if the combustion of Carbon, Hydrogen and volatile matter is to be completed following have to provide.

a. Sufficient fresh air or secondary air is supplied.
b. Ignition point should be in the range 1000^0C – 1300^0 C.
c. Creating turbulence by supplying secondary air at right angles to the up flowing gas stream from fuel bed.

It does not help supplying if the secondary air supplied along with primary air, since more primary air produces only more carbon monoxide. The presence of the Carbon monoxide in the exhaust gases indicates the in complete combustion leads to decrease in the efficiency of combustion equipments.

Types of over feed stoker

A. Traveling grate stoker
B. Spreader stoker

Traveling grate stoker

The traveling grate stoker is as shown in the figure. This type of stoker has the grate which is moving from one end of the furnace to the other end. This grate may be chain grate type or bar grate type chain grate stoker is made up of series of Cast Iron chain links connected by pins to form an endless chain.

The bar grate stoker is made up of a series of Cast Iron sections mounted on a carrier bars. The carrier bars are mounted and ride on two endless drive chains.

The traveling grate stoker consist of an endless chain which forma support for the fuel bed. The chain travels over the two sprocket wheels which are at the front and rear end of the furnace. The front end sprocket wheel is connected to variable speed drive mechanism.

The grate can be raised or lowered as needed. Simultaneous adjustment of great speed, fuel bed thickness, and air flow control, the burning rate so that nothing but ash remains on the grate by the time it reaches furnace rear.

The ash falls on to the ash pit, as the grate turns to make the return trip. A coal gate at the rear of the coal hopper regulates coal. As the raw coal or green coal on the grate enters the furnace, surface coal gets ignited from heat of furnace flame and radiant heat rays reflected by ignition arch.

The fuel bed becomes thinner towards the rear of furnace as combustible matter burns off. The secondary air supplied helps in mixing the gases and supplies oxygen to complete combustion. The coal should have minimum ash content which will form a layer on the grate. It helps in protecting grate from overheating.

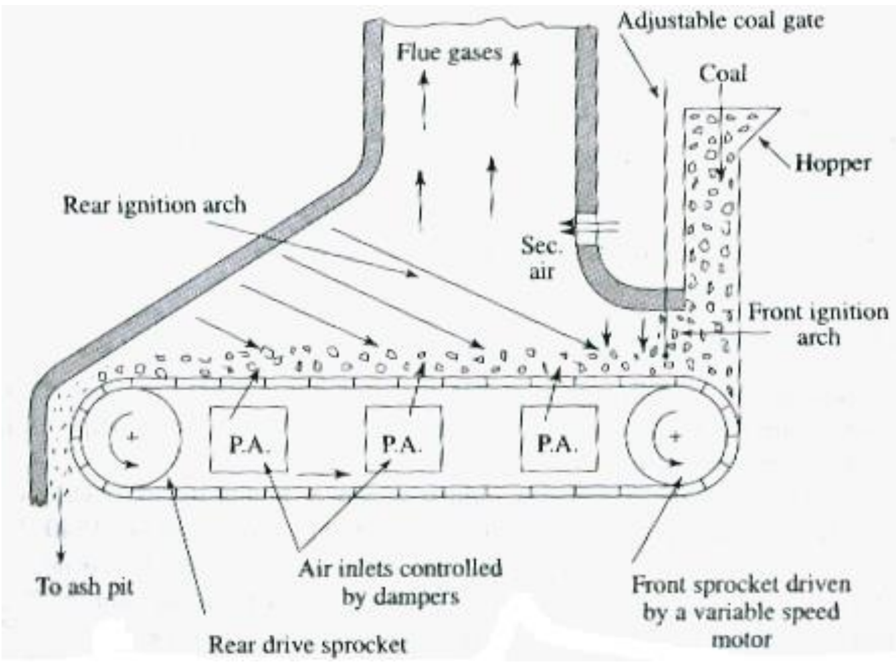


Fig. 3.10 Travelling grate stoker

Advantages:

Simple and initial cost is low

Its maintenance costs are low

It is self-cleaning stoker

Heat releases rates can be easily controlled

It gives high heat release rates per unit volume of furnace

Disadvantages

This ca not is use for high capacity boilers 200 t / hr or more

The temperature of preheated air is limited to 1800c

The clicker troubles are common

The ignition arches are required

The loss of fuel in ash cannot be avoided

Spreader Stoker

The coal from coal hopper is fed by a rotating feeder, a drum fitted with short blades on its surfaces, to the spreader or distributor below. Which projects the coal particles on to the grate holding an ignited fuel bed? The finer particles burn in suspension and the coarse Particles are consumed on the grate.

The speed of the feeder directly proportional to the steam output of the boiler. The secondary air helps in creating turbulence and completing combustion. In high capacity boilers may have traveling grate stoker in addition to spreader stoker.

The grate consists of Cast Iron links underneath the grate connect all the bars to a lever. Moving lever makes the ash fall through to the ash pit below. Spreader stokers are capable of burning any type of coal.

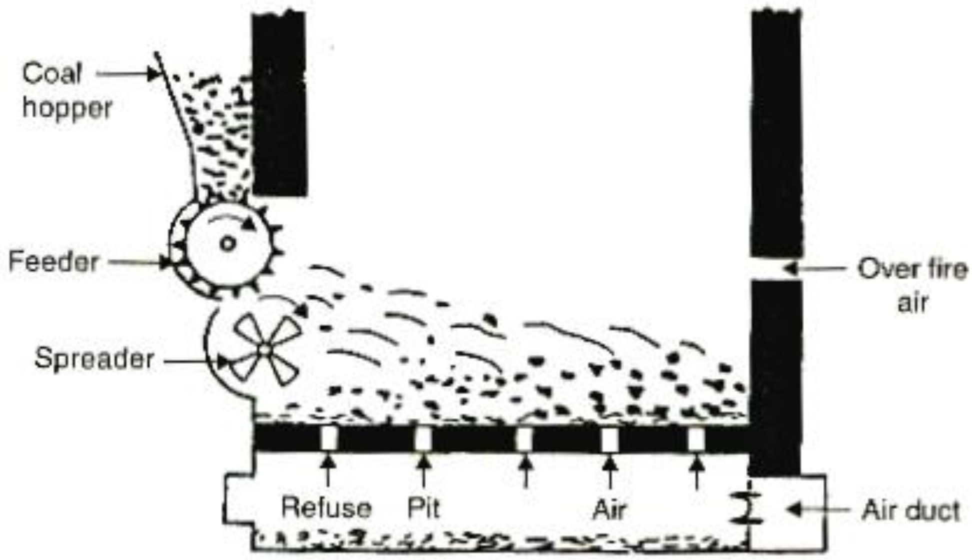


Fig. 3.11 Spreader stoker

Advantages:

Almost any type of the coal can be burnt
Clinkering problem is less
It is having quick response to varying load
The quantity of excess air required is less
The operation cost is low

Disadvantages:

The problem of fly ash is high. It requires a dust collector to prevent the environment pollution
Coal particles trapping mechanism is necessary to prevent their escape with excess air
Its operating efficiency decreases with varying sizes of coal

Under feed stoker

In this type of stokers the fuel and air move in the same direction. In this case coal is fed from underneath the grate by screw conveyor or by a ram.

Primary air after passing through the holes in the grate meets the raw coal. As the air diffuse through the bed of raw coal picks up moisture and then pass through the distillation zone where volatile matter is added.

When gas stream next passes through the incandescent coke region, volatile matter burns readily with the secondary air fed at the top. The gases in this type stoker are at higher temperature than over feed stoker.

The under feed method is best suited for burning semi Bituminous and Bituminous coals high in volatile matter.

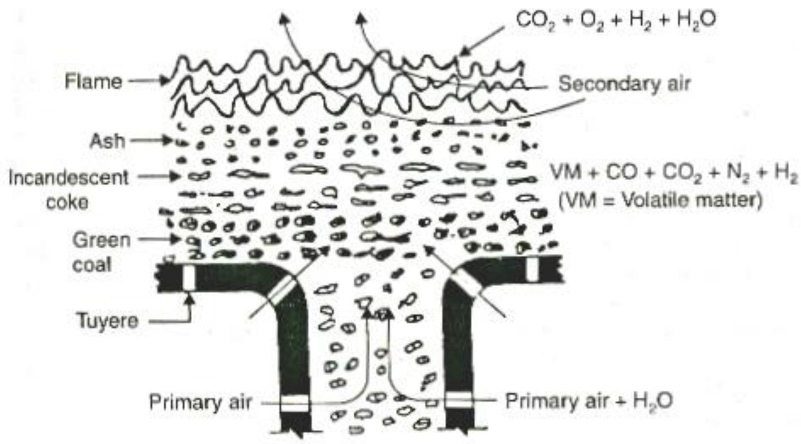


Fig. 3.12 Principle of underfeed feeders

Types of under feed stokers

A. Single retorts Stoker
B. Multi retort stoker

Single retort stoker

The arrangement of single retort stoker is shown in figure in the form of two views. The fuel is placed in large hopper on the front of the furnace and then further fed by reciprocating ram or screw conveyor in to the bottom of the horizontal trough. Air is supplied through the tuyers provided along upper edge of the grate. The ash and clicker are collected on the ash plate provided with dumping arrangement. The coal feeding capacity of a single retort stoker varies from 100 to 2000 Kg / Hr.

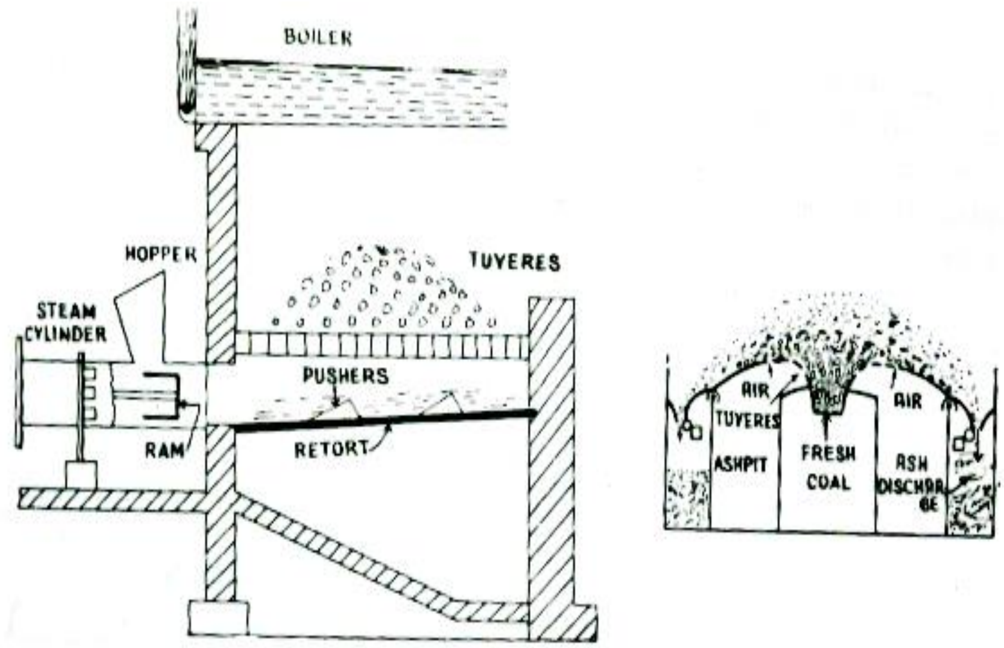


Fig. 3.13 Single retort stoker

Multi retort stoker

Multi retort stoker is as shown in figure. It consists of series of alternate retorts and tuyers boxes for supply of air. Each retort is fitted with reciprocating ram for feeding and pusher plates for uniform distribution of coal. Coal falling from hopper is pushed forward during inward stroke of the stoker ram. Then distributing ram pushes the entire coal down length of the stoker. The ash formed is collected at the end as shown in the figure. The number of retorts may be varying from 2 to 20 with burning capacity varying from 300 kg to 2000 Kg /hr/retort.

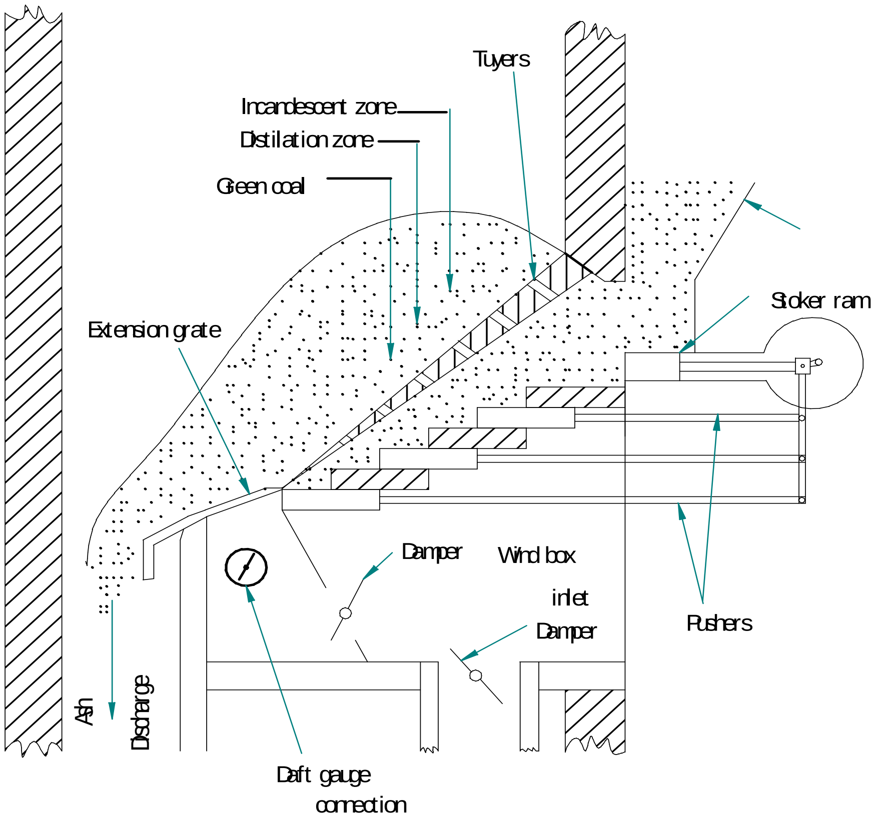


Fig. 3.14 Multi retort stoker

Advantages

High thermal efficiency compared to chain grate stoker

Combustion rate is high

Combustion is continuous

Grate is self-cleaning

Smoke less operation

Stokers are suitable for non- clinker high volatile and low ash content coal

Disadvantages

It requires large building space

Clicker problems are high

Low grade coals with high ash content cannot be burn economically

Initial cost of the unit is high

Pulverized fuel firing system

In pulverized fuel firing system the coal is grinded in to a fine powder form with the help of grinding mill and then projected in to the combustion chamber with the help of hot air current. This hot air is known as the primary air.

The amount of the air required for complete combustion is supplied separately in the combustion chamber. It helps in creating turbulence, so that uniform and intimate mixing of coal particles and air can take place inside combustion chamber.

The efficiency of the pulverized fuel firing system mostly depends upon the size of the particles of the coal in the coal powder. The finesse of the coal particles should be such that 70% of it would pass through 200 mesh sieve and 98% through a 50 mesh sieve.

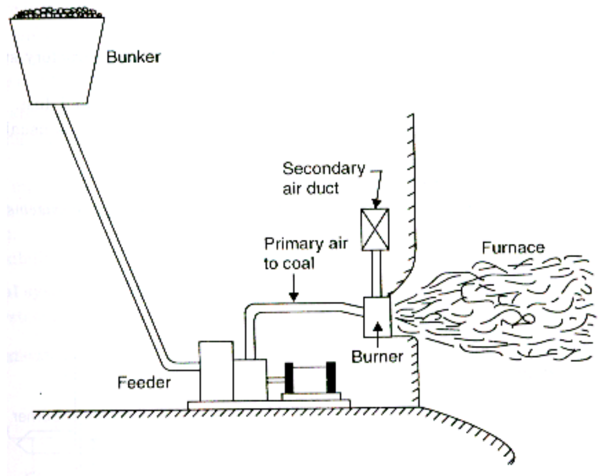


Fig. 3.15 Elements of pulverizing coal system

Advantages:

- Any grade of coal can be used
- Stand by losses are reduced and banking losses are eliminated
- Efficiency of combustion is high compared to other methods of solid fuel firing methods.
- Boiler unit can be started up from cold rapidly and efficiently
- Practically free from slagging and clinker troubles
- Furnace has no moving parts subjected high temperatures
- The furnace volume required is less
- This system works successfully with or in combination with gas and oil
- Greater capacity to meet the peak loads
- Practically no ash handling problems
- The structural arrangements and flooring are simple
- The external heating surfaces are free from corrosion

Disadvantages:

- Coal preparation plant is necessary
- High capital cost
- Handling of fly ash makes the system uneconomical
- Special equipment is needed to start this system
- Larger building space is needed especially with central system
- Skilled operators are required
- Refractory material surfaces are affected by high furnace temperatures
- Atmospheric pollution created by the fly ash is cannot be completely eliminated

- The possibility of explosion is more as coal burns like gas
- The maintenance of furnace brick work is costly

There are two methods of pulverized fuel firing.

1) Unit system
2) Central or Bin system.

In unit system each burner of the plant has its own Pulveriser and handling units. In central or Bin system fuel is pulverized in the central plant and then distributed to each burner with the help of high pressure air current.

Unit system

In unit system each burner of the plant has its own Pulveriser and handling units. The Pulveriser an together with feeder, separator and fans may be arranged to form an complete unit or mill.

The number of units required depends on the capacity of the boiler. Raw coal from coal hopper fed to the pulverizing mill through feeder. Hot air from or flue gases passed through the feeder to dry the coal before feeding to the Pulveriser.

The pulverized coal is carried from the mill with the help of induced draught fan as shown in figure. This further carries the coal through the pipes to the burner.

Secondary air supplied to the burner before fuel entry in to the combustion chamber is as shown in figure helps in creating the turbulence as well as supplying additional air required for completing the combustion of the coal particles in the furnace.

Advantages:

- It is simple in layout and cheaper than central system
- It allows direct control of combustion rate from the Pulveriser
- Maintenance charges are less
- The coal transportation is simple

Disadvantages:

- The performance of pulverizing mill is poor.
- Degree of flexibility is less than central system.
- The fault in the preparation unit may put entire steam generator out of use.
- There is excessive wear and tear of the blades of fan as it handles air and coal particles.
- Strict maintenance of the mill is required because the entire plant operation depends on it

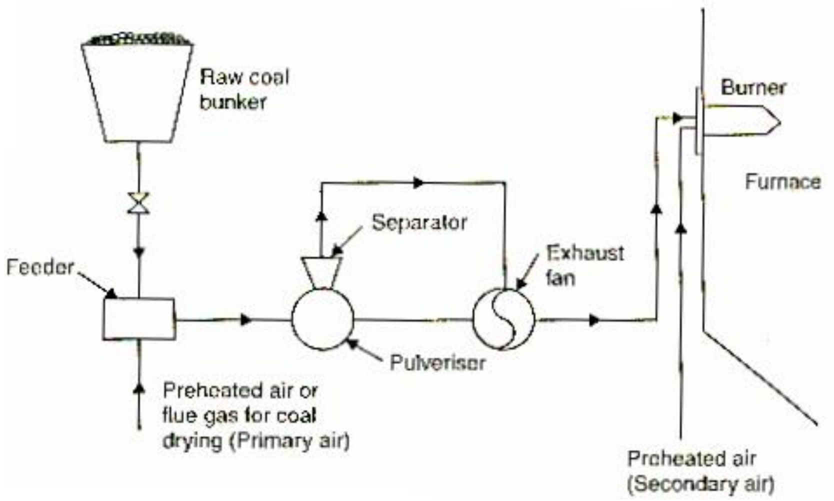


Fig. 3.16 Unit System

Central or Bin system

The central system or Bin system fuel is pulverized in the central plant and then distributed to each burner with the help of high pressure air current. Crushed and sized coal is fed to the drier from coal bunker by gravity as shown in fig. 3.17.

The dried coal fed to the pulverizing mill with the help of air, as shown in figure, separated in the cyclone separator. The separated pulverized coal is transferred to the central bunker using conveyor as shown in fig. 3.17.

Oversized coal particles are fed back to the pulverizing mill for further processing. The storage bin may contain 12 to 24 hours of supply of pulverized coal. The energy consumption is 15 to 25 KW-Hr / Ton of coal pulverized.

<u>Advantages:</u>

- The reliability of plant is high
- The central system is flexible. Supply of the coal can be maintained to the burners without any interruption.
- Burner operation is independent of coal preparation
- The pulverizing mill may work at the part load because of storage capacity available in the storage bin.
- Power consumption per ton of coal handled is less
- As the fans handle only air there is no problem of excessive wear and tear
- The laborers required is less

<u>Disadvantages:</u>

- Initial cost is high and occupies a larger space
- The overall power consumption per ton of coal handled is higher than unit system due to high power consumption by auxiliaries.
- The operation and maintenance charges are higher than unit system of same capacity.

- There is possibility of fire hazard due to the stored pulverized coal

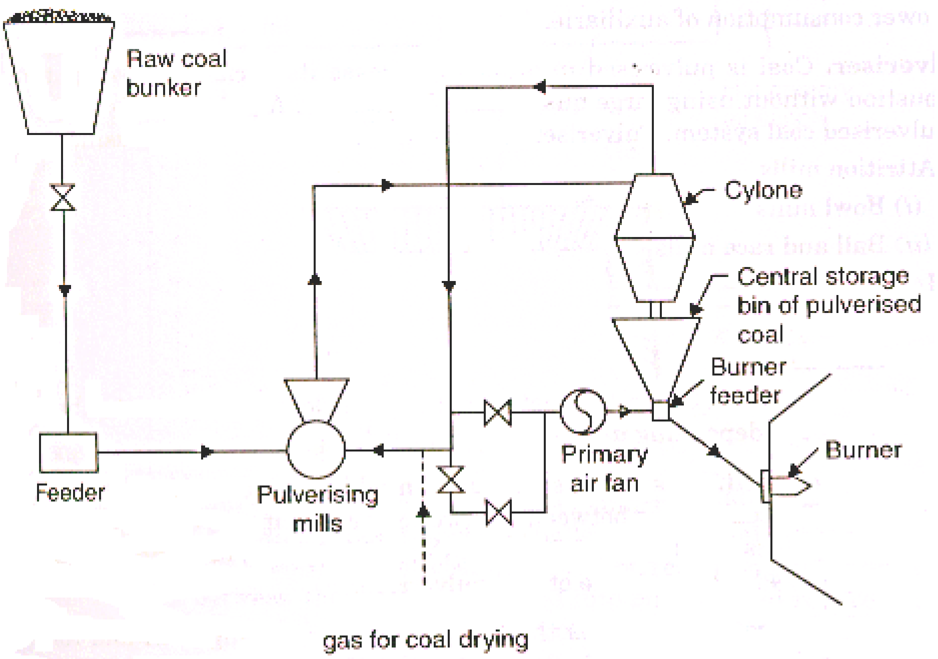


Fig. 3.16 Central System

3.3 Components of the pulverized coal fired plant

The main equipments used in the pulverized coal fires plant are

1. Primary crushers
2. Magnetic separators
3. Coal driers
4. Pulverizing mill
5. Burners

1. Primary crushers

Crushing of coal is required when we are handling un sized coal. Plant using pulverized coal generally specifies the top size, larger than what cannot be handled by the pulveriser, making crushing necessary to prepare coal for pulverization following types of crushers are used.

a) Ring crushers
b) Hammer mill crushers
c) Bread ford breaker
d) Rotary breaker
e) Single roll crushers

Ring crushers

In this type of crushers coal is fed at top of crushers and is crushed by the action of ring that pivots off centre on a rotor. Adjustable plate helps in varying the size of discharge coal. It can be used as off or on plant site.

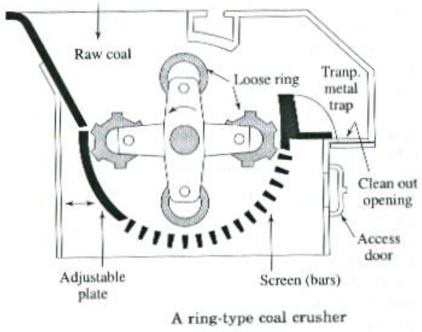


Fig. 3.17 Ring crusher

Hammer coal crusher

In this type of coal crusher also the coal is fed from the top and is crushed by the action of swinging hammers that are pivoted on a rotor. Swinging hammers are attached to the central drum. As the drum rotates coal particles coming in between the swinging hammers and adjustable plates crushed. The crushed sized coal falls out of the crusher through the opening provided at the bottom. The adjustable plates used to vary the size of discharge coal.

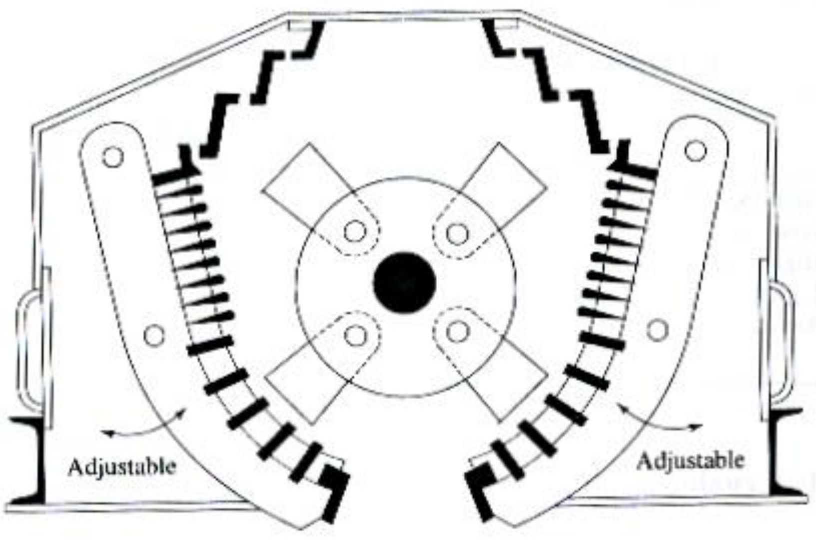


Fig. 3.18 Hammer coal crusher

Brad ford crushers

It is used in large capacity plant. It comprises of large cylinder consisting of perforated steel screen plates to which lifting shelves are attached inside. The cylinder rotates slowly at about 20 rpm and receives feed at the one end. The coal is lifted by the shelves, the breaking action is accomplished by the repeated lifting and dropping of the coal until its size permits it to discharge through the perforation made. The size of the perforation determines the size of crushed coal. The main advantage is rejection of the foreign matter and to produce relatively uniform size coal particles.

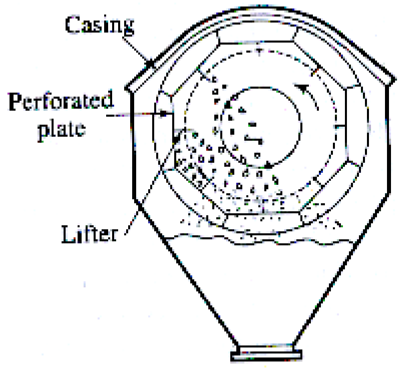


Fig. 3.19 Bradford crusher

Rotary breakers

The crushing of coal takes place between the rotating cylinder and rollers. The crushing action is combination of both lifting and dropping of the coal and also by the crushing action of coal between rollers and rotating cylinder.

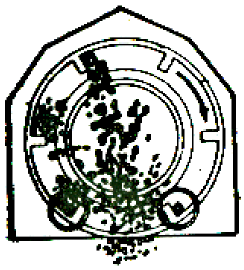


Fig. 3.20 Rotary crusher

Single roll crushers

The crushing of coal takes place between adjustable plate and rotating single roller having teeth on the circumference. The size of the coal particle can be varied by varying the gap between adjustable plates and rotating roller.

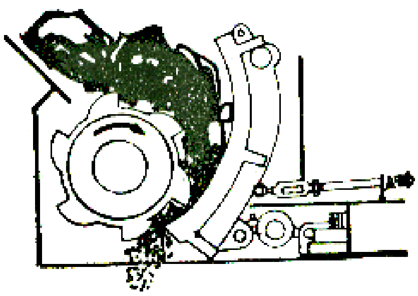


Fig. 3.21 Single roll crusher

2. Pulveriser

Pulverisers are devices that are used to produce coal in the powder form. They are also called as pulverizing mills. The pulverizing process consists of three stages namely i) Feeding ii) Drying iii) Grinding.

Feeding system controls automatically air required for drying and transporting pulverized fuel to the burner depending on the boiler demand. For pulverization of coal has to be dry and dusty. Dryer are an integral part of the pulverizing equipment. For drying coal part of primary air passing through the air preheated at 3500c is utilized. The third stage of pulverization process is the grinding and equipment used for this action is known as the grinding mill.

Four different types of pulverizing mills are used.

a) Ball and race mill
b) Bowl mill
c) Ball mill
d) Hammer mill

Ball and race mill

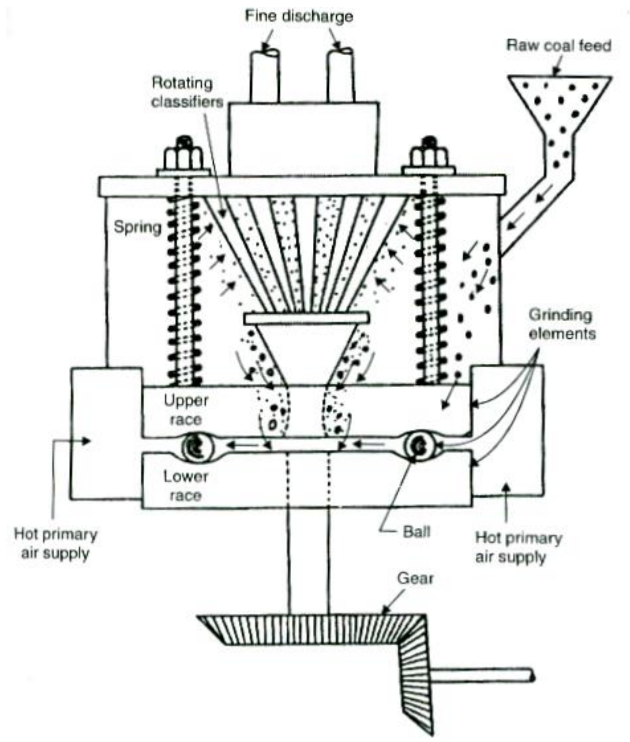


Fig. 3.22 Ball and race mill

This is also known as the contact mill.

The coal is crushed between two moving surfaces ball and race. The upper race is stationary and the lower race is driven by worm and gear, holds the steel balls between them. The coal is allowed to fall on the inside of the race from feeder or hopper.

Moving balls and race catches coal between them to crush in to a powder. Springs are used to hold down the upper race and adjust the force needed for crushing.

Hot air supplied picks up the coal dust as it flows between the ball and races and then enters in to the classifier, moving and fixed vanes make the entering air to form a cyclonic flow which helps to through the oversized particles on to the wall of classifier.

The oversized particles slide down for further grinding in the mill. The coal particles of required size carried to burners with air from the top of the classifier.

Bowl mill

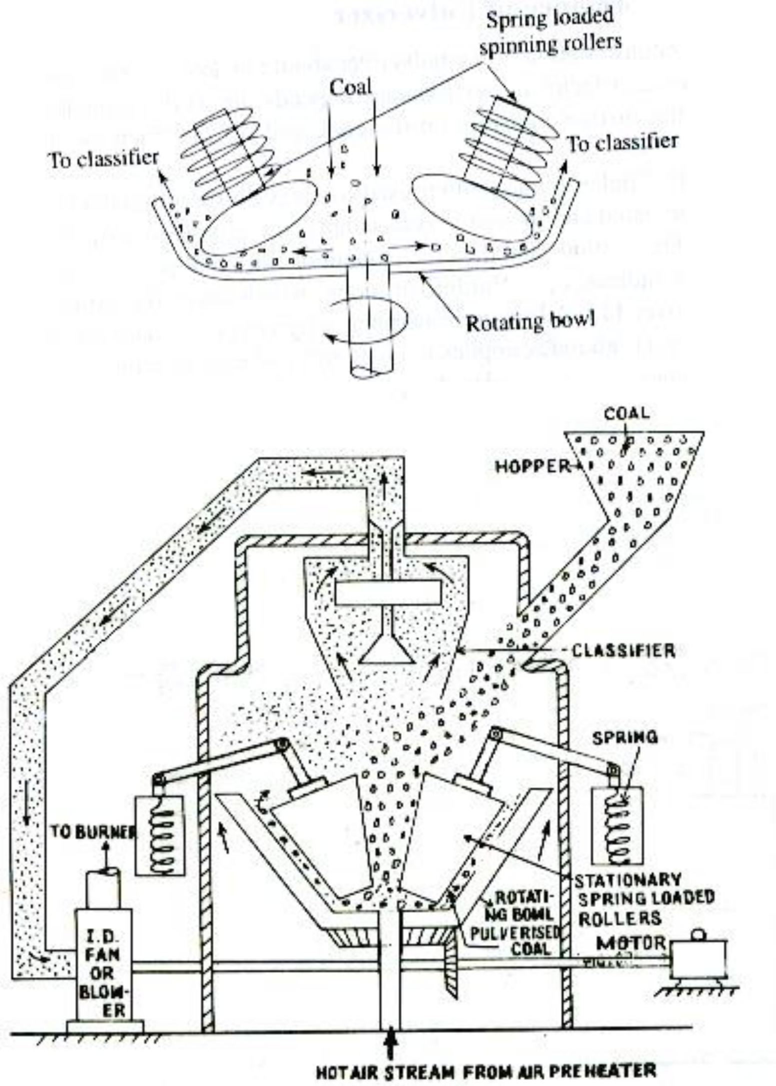


Fig. 3.23 Bowl mill

The bowl mill grinds the coal between a whirling bowl & rollers mounted on pivoted axis.

The Pulveriser consists of stationary rollers and power driven balls in which pulverization takes place as the coal passes between the bowl and rollers.

The hot primary air supplied in to the bowl picks up coal parcels and passes through the classifier. Where oversized coal particles falls back to bowl for further grinding. The required size coal particles along the primary air supplied to the burner.

Ball Mill

The line diagram of the ball mill is as shown in fig. 3.24. It consists of a large cylinder partly filled with varying sized steel balls.

The coal from coal hopper fed in to the cylinder with the help of crew conveyor. At the same time required quantity of hot air from air preheater is also enters. As the cylinder rotates pulverization takes place between the balls and the coal. The streams of hot air pick up the pulverized coal and pass through the classifier.

The oversized coal particles thrown out of the air stream in the classifier and fine coal particles are passed to the burner through exhaust fan.

Ball mill capable of pulverizing 10 tons of coal / hr containing 4% moisture requires 28 tons of steel balls and consumes 20- 25 KW – Hr energy per ton of coal pulverized.

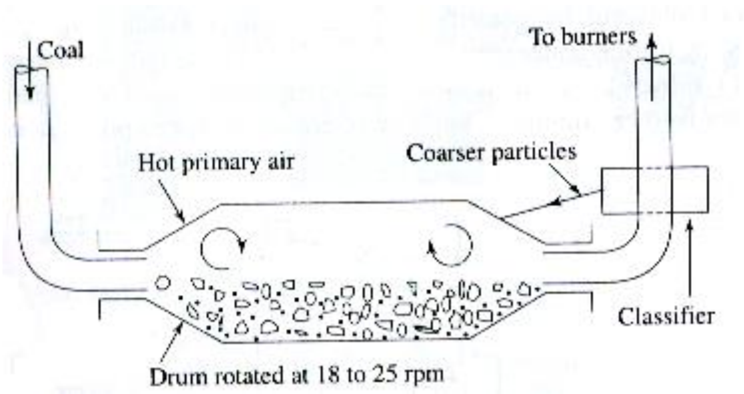


Fig. 3.24 Ball mill

Hammer mill

The hammer mills have swinging hammers connected to an inner ring and placed within the rotating drum. The coal to be pulverized is fed in to the path of hammers.

Grinding is done by the combination of impact on large particles and attrition on small particles. The hot air is supplied to dry the coal as well as carrying coal particles to burners.

It is compact low in cost and simple in operation. However its maintenance is costly and its capacity is limited. The power consumption is high when fine powder is required.

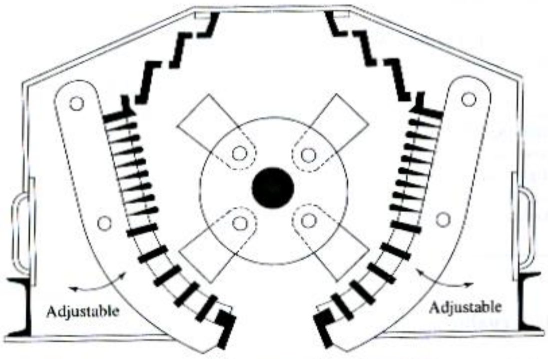


Fig. 3.25 Hammer mill

3.4 Pulverised fuel burners

Burners are devices use to burn coal particle by uniform mixing of coal and air and creation of turbulence within the furnace. The air which carries pulverized coal in to the furnace through the burner is primary air. The secondary air required for completing combustion is supplied separately around the burner or elsewhere in the furnace.

The main requirements of pulverized fuel burners are.

a. It should mix thoroughly primary air with coal particles and secondary air.
b. It should create turbulence and maintain stable combustion.
c. It should control the flame shape and it travel in the furnace.
d. The velocity of primary air and coal particles should be same as that of flame velocity to avoid flash back.
e. The burner should have ability to with stand overheating due internal fires and excessive abrasive wear.

Types of pulverized burners are

1) Long flame or U- Flame burners or streamlined burners.
2) Turbulent burners
3) Tangential burners
4) Cyclone burners

Long flame burners

The tertiary air supplied around the burner to provide better mixing of primary air and fuel.

The burner discharges air and fuel mixture vertically down wards with no turbulence to provide long flame. Heated secondary air supplied at right angles to the flame creates turbulence that required rapid combustion.

These types of burners are suitable for burning low volatile slower burning coal particles.

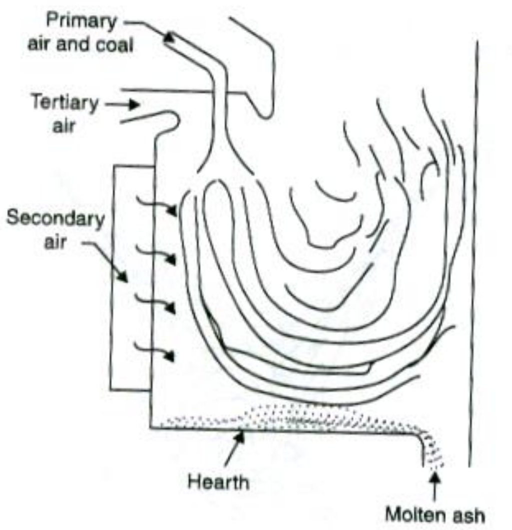


Fig. 3.26 Long flame burner

Turbulent Burners

These burners are also called as short flame burners. Turbulent burners can project flame horizontally or at small inclination to the furnace.

The fuel – primary air mixture and secondary hot air are arranged to pass through the burner in such a way that there is good mixing and the mixture is projected in highly turbulent form in to the furnace.

The mixture burns intensely and combustion is completed in a short distance. The burning rate of turbulent burners is high compared to other types of burners. Turbulent burners are preferred for high volatile coal and they are used in modern power plants.

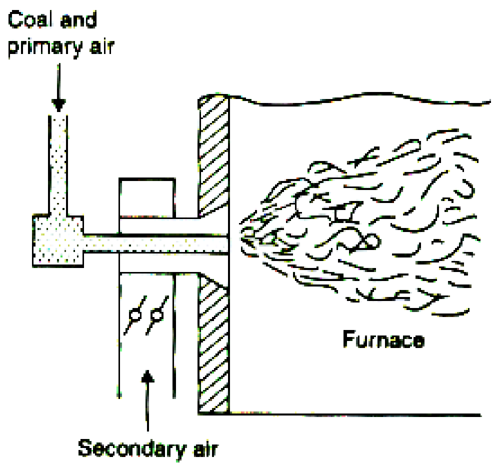


Fig. 3.27 Turbulent burner

Tangential burners

It consists of four different burners located at 4 corners of the furnace. The discharge of fuel and air mixture directed tangentially to an imaginary circle in the centre of the furnace.

The swirling action creates necessary turbulence required for completing the combustion in short period. The tips of the burners can be angled through a small vertical arc. So raise or lower the position of turbulent combustion region in the furnace. It helps in maintaining constant super heat temperature of steam as load varies. This arrangement can provide 100^0c difference in furnace gas exit temperature.

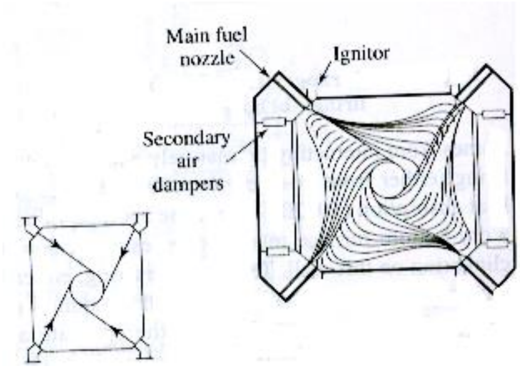


Fig. 3.28 Tangential burner

Cyclone Burner

It consists of horizontal cylinder of water cooled construction, 2 to 3 meters in diameter and 2.5 m in length. The horizontal axis of the burner is slightly deflected downward towards the boiler. These burners are externally attached to the furnace.

The cyclone burner receives pulverized coal carried by the primary air tangentially to the cylinder at outer end creates strong and highly turbulent Vortex. Secondary air enters in to the cylinder tangentially to complete the combustion. These burners can be rotated by ± 30 degree up and down it helps in controlling the super heater temperature.

The fuel supplied burns quickly with high heat liberate rates with temperature around 2000 0C. The ash forms the molten film over the inner wall surface and molten ash flows to an ash disposal system. The cyclone burners give best results with low grade fuel.

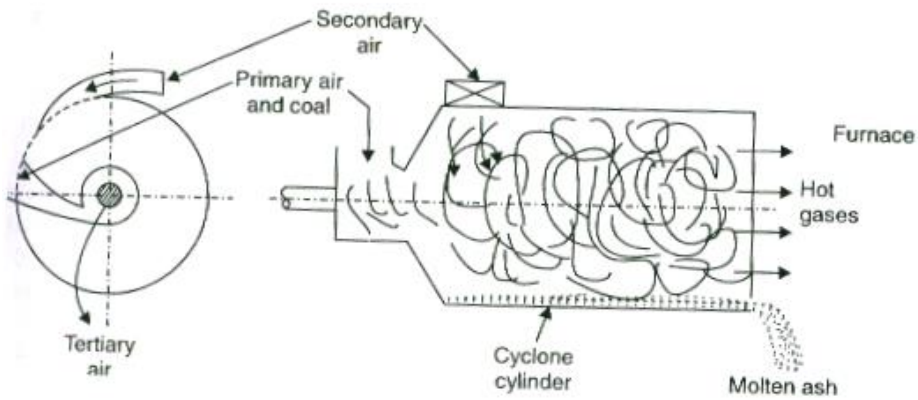


Fig. 3.29 Cyclone burner

3.5 Ash handling system

Large quantity of ash is produced by the power plants due to burning coals having high ash content. The ash should be discharged and dumped at sufficient distance from the power plant because of the following reasons.

a) The ash content is dusty
b) It is very hot when it comes out of the furnace
c) It produces poisonous gases and corrosive acids when mixed with water

The amount of ash produced is as large as 20% of total coal burnt during the day. In order to handle this large quantity of ash use of mechanical handling equipment becomes necessary. Any ash handling system consists of the following operations.

a) Removal of ash from the furnace.
b) Carrying of ashes from ash hopper to storage with the help of conveyor.
c) Quenching of hot ash before carrying is desirable and necessary as it offers the following advantages.
   i. Reduces the temperature.
   ii. Reduces dustiness of ash.
   iii. Reduces the corrosive action.
   iv. Disintegrate large clinkers in to smaller one.
   v. It act as sealing against the air entering in to boiler.

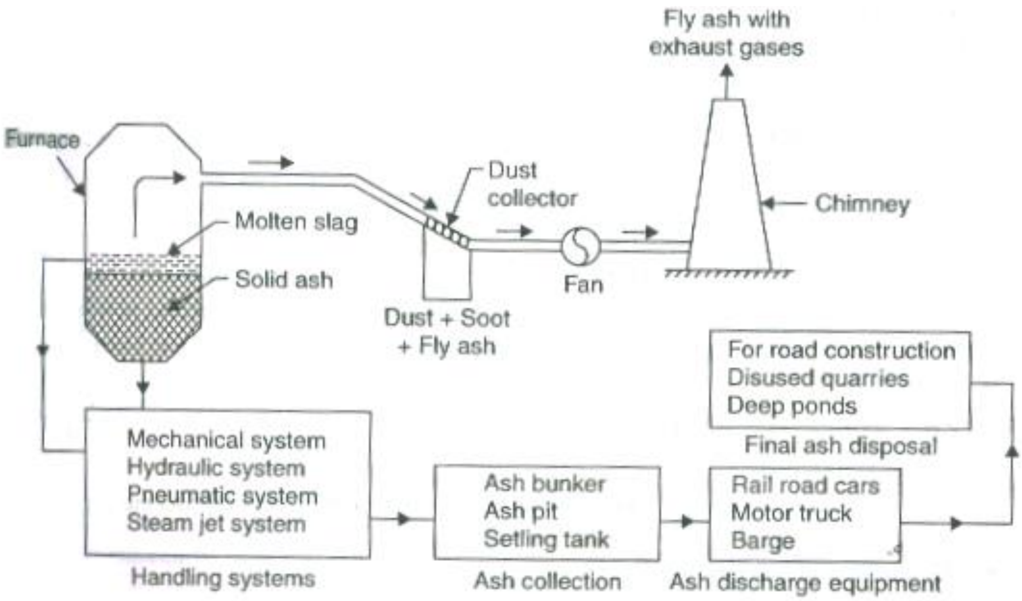


Fig. 3.30 Ash handling system

Requirements of Ash handling equipment

The main requirements of good ash handling plants are listed below:

1. It should be capable of handling large volume of ash.
2. It should be capable of handling large clickers with minimum attention.
3. The plant should have high rates of handling.
4. The operation should be noise less as much as possible.

5. It should deal effectively both hot and wet ash.
6. The initial cost, operating and maintenance charges should be minimum as per as possible.

The generally used ash handling systems are classified in to four groups:
1) Mechanical handling system
2) Hydraulic handling system
3) Pneumatic handling system
4) Steam jet system

Mechanical ash handling system

This system of handling ash is used in low capacity power plants. The hot ash coming out of furnace allowed falling on to the belt conveyor moving through the water trough.

Cooled ash carried continuously by belt conveyor to the ash bunker. The ash is removed from the ash bunker to the dumping site with the help of trucks.

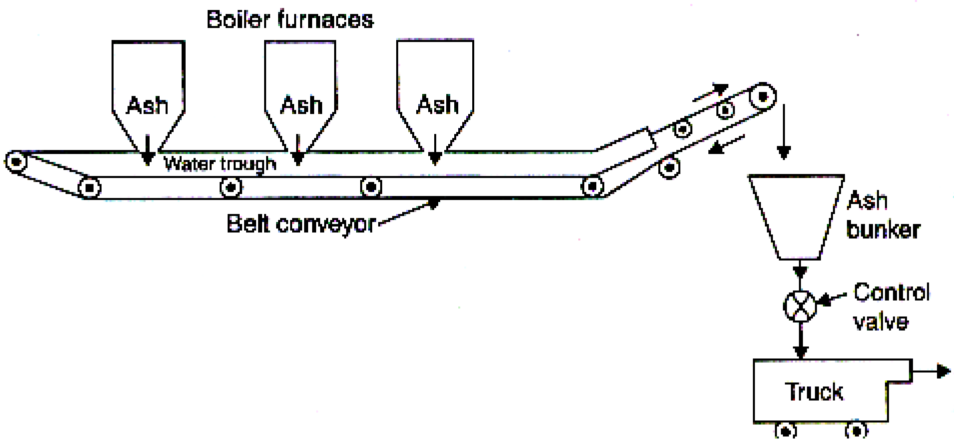


Fig. 3.31 Mechanical Ash handling system

Hydraulic handling system

In this system ash is carried with the flow of water. The hydraulic system, is subdivide in to low velocity system and high velocity system

Low velocity system

In this system water trough is provided just below the boiler and water is made to flow through the trough. The ash falling directly in to the drain and it is carried by water to the sump. In the sump ash is separated from water, separated water is used again while the ash collected in the sump is removed to the dumping yard. The capacity of this system is 50 tons/ hr.

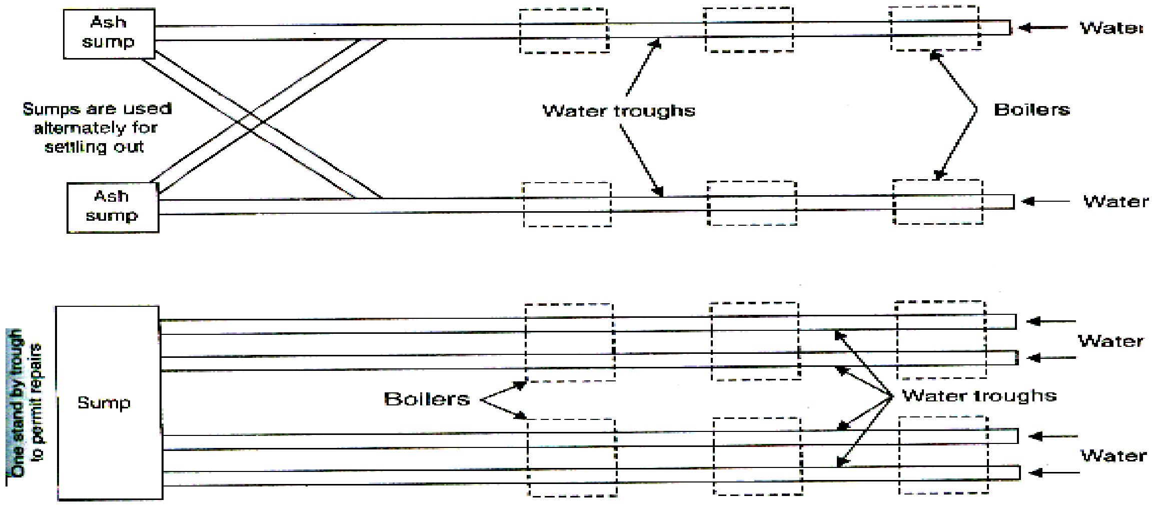


Fig. 3.32 Hydraulic low velocity Ash handling system

High velocity or high pressure system

The ash hoppers below the boilers are fitted with water nozzles at the top and on the sides. The top nozzle quench ash and side nozzle provide driving force to carry the ash through a trough.

The cooled ash with high velocity water is carried to the sump. The water is re circulated again after separating it out from the ash. Capacity of the system is 120 tons /hr and distance is 1000 meters.

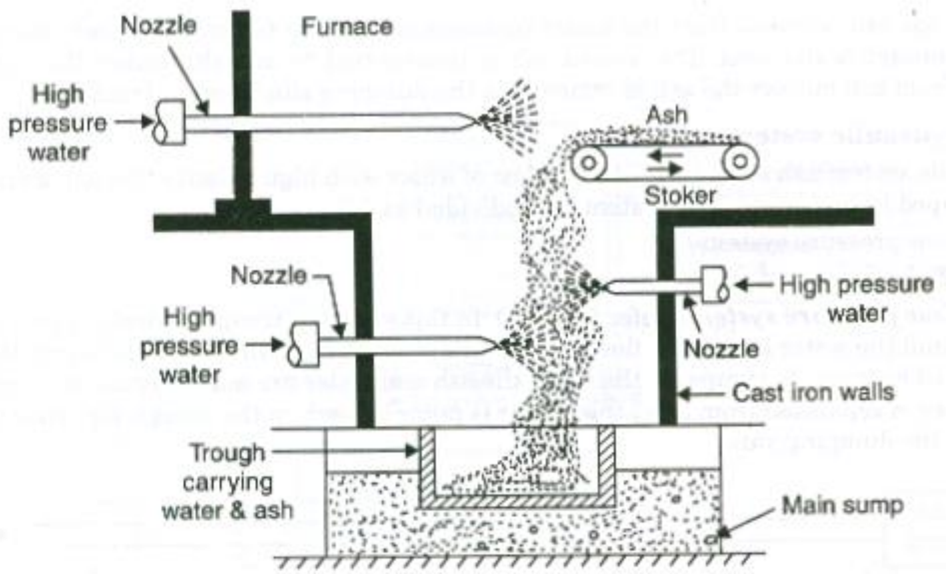


Fig. 3.33 Hydraulic high velocity Ash handling system

Pneumatic handling system

In primary and secondary separation working on cyclone principle and then it is collected in the ash hopper as shown in the figure. The clean air is discharged from the top of the secondary air separator in to the atmosphere through the exhauster.

Exhauster may be mechanical type with filter or washer to ensure that the exhauster handles clean air or it may use steam jet or water jet for its operation.

Mechanical exhausters are used in large power stations. While steam exhausters are used in small and medium power stations. The pneumatic system can handle abrasive as well as fine materials such as fly ash as soot.

The capacity of system varies from 15 -25 tons/hr.

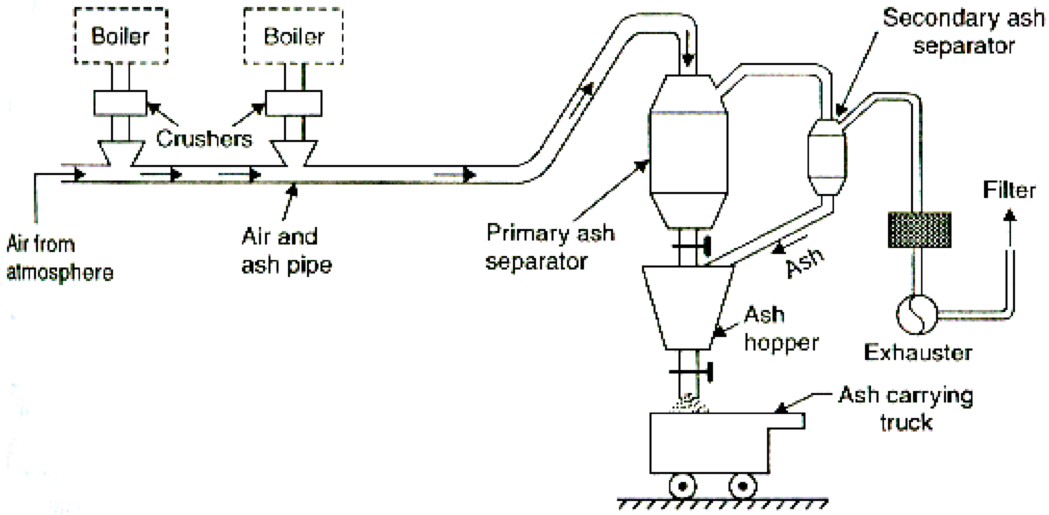


Fig. 3.34 Pneumatic Ash handling system

<u>Advantages:</u>

- The system is flexible.
- There is no spillage and re handling.
- No chances of ash freezing and sticking of the materials, ash can be discharged freely by gravity.
- Dustless operation as the system is totally closed.
- Cost / ton of ash handled is comparatively less.

<u>Disadvantages:</u>

- Wear and tear of pipes is high and hence the maintenance costs are high.
- The operation is noisy compared to other systems

Steam jet system

In this type of ash handling system, a jet of high pressure steam is passed in the direction of ash travel through a conveying pipe in which ash from the boiler ash hopper is fed. The ash is deposited in the ash hopper. The velocity is given to the steam by forcing it through the pipe under pressure greater than that of atmosphere.

<u>Advantages:</u>

- It does not requires any auxiliary drivers

- Capital coat and maintenance costs are low
- It requires less space
- Equipment can be installed in any position

Disadvantages

- Noisy operation
- Wear and tear of pipes is high
- Capacity of this system is limited to 15 tons/hr.

3.6 Dust Collection

Any gas borne matter larger than 1 micron (0.001mm) in diameter we called it as dust. If the particles are mainly ash particles then it is called fly ash. If the particles are in turn mixed with some quantity of carbon, then the matter is known as the cinders. The size of cinders is usually greater than 100 micron. Incomplete combustion volatile components of fuel produces smoke, consists of particles smaller than 10 micron. The removal of dust and cinders from flue gas can be achieved by using dust collectors. These are classified as

1) Mechanical dust collectors
2) Electrical dust collectors

Mechanical dust collectors

The basic principle used in the mechanical dust collection is as shown in the fig. 3.35.

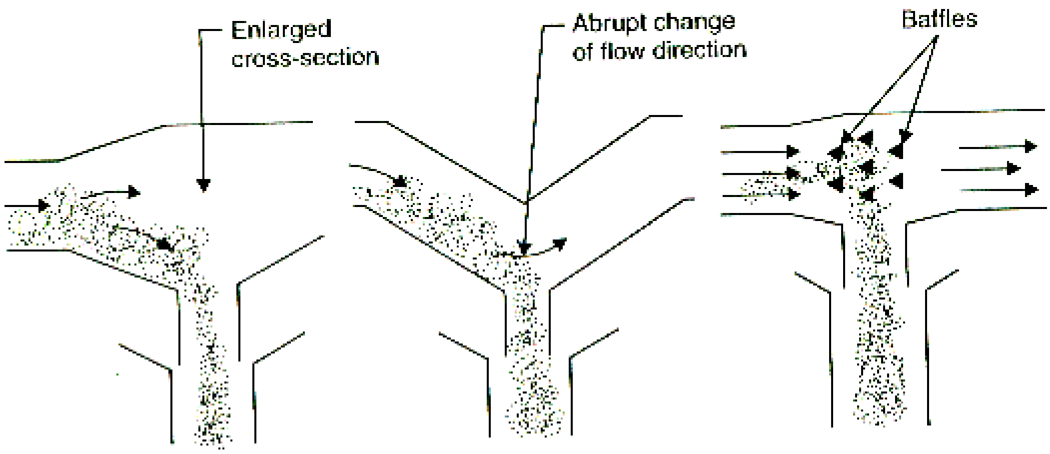


Fig. 3.35 Mechanical dust collector

a) Sudden velocity decreasing method: Enlarging cross sectional area off the dust carrying pipe helps in slow down of the gas so that dust particles will have the chance to settle out are allowed to fall down.
b) Abrupt change of flow direction. When gas makes a sharp change in flow direction the heavier particles tend to keep going in original direction and so settle out.

c) Impingement upon small baffles: The larger dust particles may be knocked out of the gas stream by impingement on baffles. These are used to drop large cinders from the gases.

Mechanical dust collectors can be further classified as wet type and dry type. The wet type dust collectors are also called as scrubbers. Scrubbers operate with water sprays to wash dust from the air. Large quantity of wash water is required for central power stations and this system is rarely used. This also produces waste water that may require chemical neutralization before it may be discharged in to the natural water bodies. Scrubbers may be 1) Packed type 2) Spray type 3) Impingement type.

Electrostatic precipitator

Electrostatic precipitators are extensively used in removal of fly ash from electric utility boiler emissions.

The dust laden gas is passed between oppositely charged conductors and it becomes ionized. As the dust laden gas passed through these charged electrodes, both negative and positive ions are formed. The ionized gas is further passed through the collecting unit which consists of set of vertical plates.

Alternates plates are charged and earthed. As the alternate plates are grounded, high intensity electrostatic field exerts a force on positively charged dust particles and drives them towards the grounded plate.

The deposited dust particles are removed from the plates by giving the shaking motion to the plates. Dust removed collected in the dust hoppers.

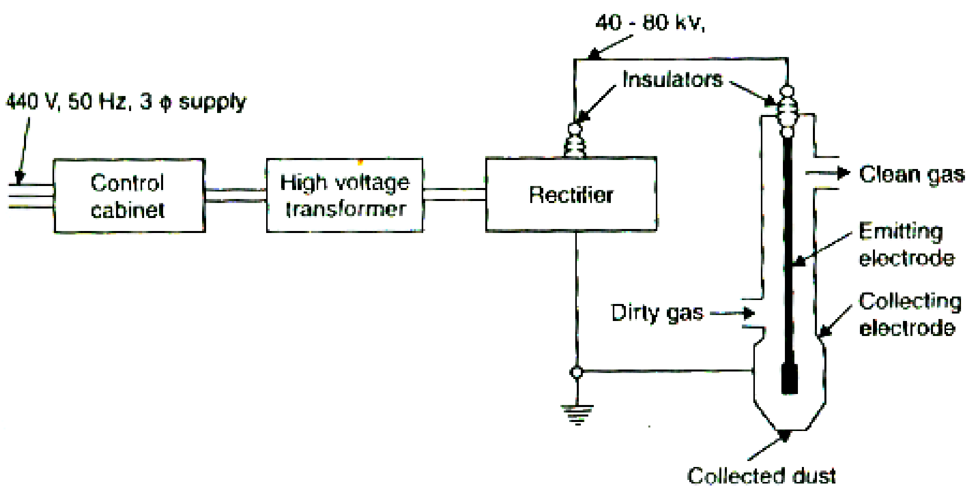


Fig. 3.36 Electrostatic precipitator

<u>Advantages</u>

- It is more effective in removing small particle
- Its efficiency s high
- The drought losses are least

- It provides ease of operation.

Disadvantages:

- Use of electrical equipment for converting AC in to DC is necessary
- The space required is larger than wet system
- Collectors must be protected from sparking
- The running costs are high

4

Draught system

Course Contents

4.1 Introduction

Draught is mechanism of creation of small pressure difference that is required maintain the constant flow of air for combustion of fuel and to discharge the gases through the chimney to atmosphere. Draught can be produced by using chimney, fans, steam or air jet or combination of these.

The purpose of draught is to,

1) Helps in allowing desired volume of air flow in to the furnace.
2) Helps in overcoming the resistances offered to the flow of air through the furnace.
3) Discharge gases at sufficient height to avoid pollution to atmosphere.

4.2 Natural draught- Estimation of height of chimney

If the draught is produced only with the help of chimney it is known as natural draught. The natural draught is produced by chimney or stack. It is caused by the density difference between the atmospheric air and the hot gas in the stack. This type of draught is useful for small capacity boiler and it does not play much important role in the high capacity thermal power plant.

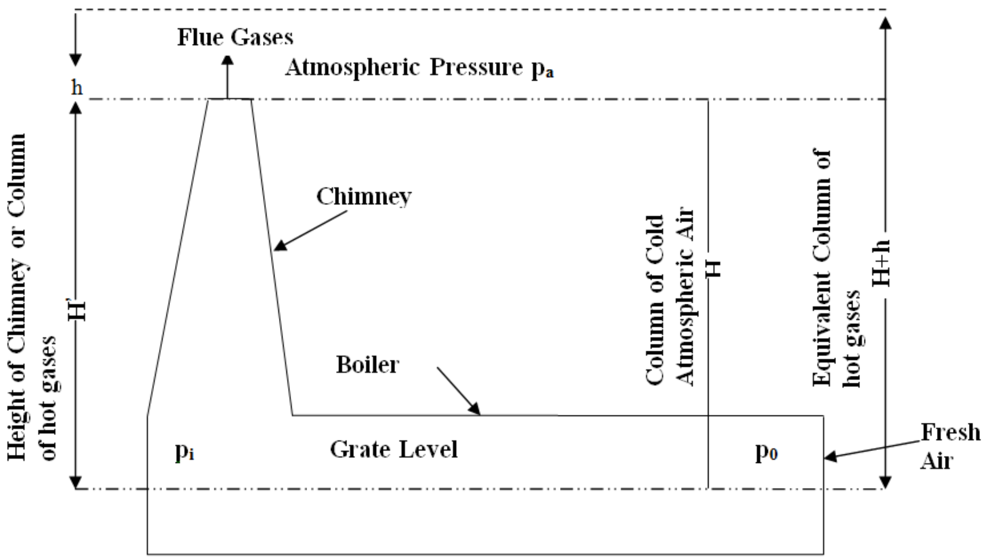


Figure 4.1 Natural draught

Consider the chimney above grate level is H. The pressure acting on the grate from chimney side,

P_0 = Pa + Wg H

= Pa + ρ_g gH………………..1)

Where, Pa= Atmospheric pressure at chimney top.

ρ_g gH =Pressure due to the column of hot gas of height H meters.

ρ_g = Average mass density of hot gas Kg/m^3

Similarly the pressure acting on the grate on open side

P_i= Pa + ρ_a gH ………………2)

ρ_a gH – Pressure acting on the grate on open side by the column of cold air outside the chimney of height H meters.

ρ_a – Average mass density of cold air outside the chimney.

The net pressure acting on the grate P = $P_i - P_o$

= $gH(\rho_a - \rho_g)$………………………3)

If the acting pressure is in terms of mm of water (head),

h_w x Ww = H (Wa – Wg)

$h_w \ \rho_w g = gH(\rho_a - \rho_g)$

(h_w x 1000x g)/1000 = $gH(\rho_a - \rho_g)$

$h_w = H(\rho_a - \rho_g)$ mm of water………………………4)

Draught in terms of hot column of gas,

Let Hg is the hot column of gas in meters.

H_g x Wg = H (Wa – Wg)

$H_g \times \rho_g g = gH(\rho_a - \rho_g)$

Hg = H(ρa/ρg - 1) Meters of hot column of gas……………..5)

If m kg be the mass of air supplied per kg of fuel. Then m+1 will be the mass of flue gases. Assuming volume of air and gas is same at same temperature, at 0^0c or 273^0 K and at atmospheric pressure one kg of air occupies volume equal to

v = RT/P = 287 x 273 / 1.013 x 10^5 = 0.7734 m^3

The volume of the gases at higher temperature can be calculated as follows.

Let Tg – Mean absolute temperature of flue gases ^{0}K

Ta – Mean absolute temperature of outside air ^{0}K.

Volume of one kg of air at temperature Ta = (0.7734 x Ta) / 273

Volume of m kg of air at temperature Ta= (0.7734 x Ta x m) / 273

Volume of m+1 kg of flue gases at temperature Tg = (0.7734 x Tg x m) / 273

Hence density of air at temperature Ta = Mass / Volume (air)

ρ_a = (m x 273) / (0.773 x Ta x m)

= 353 / Ta……………6)

Similarly density of gases at temperature Tg = Mass of hot flue gas / Volume of hot flue gas,

ρ_g = (m+1) x 273 / (0.7734 x m x Tg)

= [353/Tg] x [(m+1) / m]……………………7)

Substituting values of equation 6 and 7 in equation 3,

$$P = 353gH\ [\frac{1}{T_a} - \left(\frac{m+1}{m}\right)\frac{353}{T_g}]$$

If h_{mm} be the draught measured in water column then,

h = H(ρ_a - ρ_g) mm of water.

$$= 353\ H\ [\frac{1}{T_a} - (\frac{m+1}{m})\frac{1}{T_g}]$$

If Hg is the height of a column of hot gas expressed in meters which would produce the pressure P in N/ m^2 then,

$$H_g = H[\ \frac{T_g}{T_a}\left(\frac{m}{m+1}\right) - 1\ ]$$

4.3 Maximum discharge condition

Theoretical velocity of flue gases produced by static draught is,

C = $(2gH_g)^{1/2}$

$$= \left\{2gH\left[\ \frac{T_g}{T_a}\left(\frac{m}{m+1}\right) - 1\ \right]\right\}^{1/2}$$

The mass of gas discharged per second is given by,

$$m_g = A \times C \times \rho_g$$

$$= A \times \left\{2gH\left[\ \frac{T_g}{T_a}\left(\frac{m}{m+1}\right) - 1\ \right]\right\}^{1/2} \times \frac{p}{R\,T_g}$$

$$= K \times \left\{\left[\ \frac{1}{T_g T_a}\left(\frac{m}{m+1}\right) - \frac{1}{{T_g}^2}\right]\right\}^{1/2}$$

Where, $K = A\frac{p}{R}(2gH)^{1/2}$

For maximum discharge, differentiating above equation with respect to Tg and equating it to zero, we get

$$\frac{d(m)_g}{d(T)_g} = \frac{d}{d(T_{g)}} \left\{ K \times \left\{ \left[\frac{1}{T_g T_a} \left(\frac{m}{m+1} \right) - \frac{1}{{T_g}^2} \right] \right\}^{1/2} \right\} = 0$$

$$\left(\frac{m}{m+1} \right) \frac{1}{T_a} \times \left(-\frac{1}{{T_g}^2} \right) + \frac{2}{{T_g}^3} = 0$$

$$\therefore \frac{T_g}{T_a} = \frac{2(m_a + 1)}{m_a} \quad \ldots\ldots\ldots\ldots..8)$$

Above equation is the condition for maximum discharge through the chimney and the temperature of flue gases is slightly greater than twice the atmospheric temperature.

4.4 Forced, Induced and balanced draught

Those are the types of artificial draught in which draught can be produced either by using fan or using steam jet.

4.4.1 Forced Draught

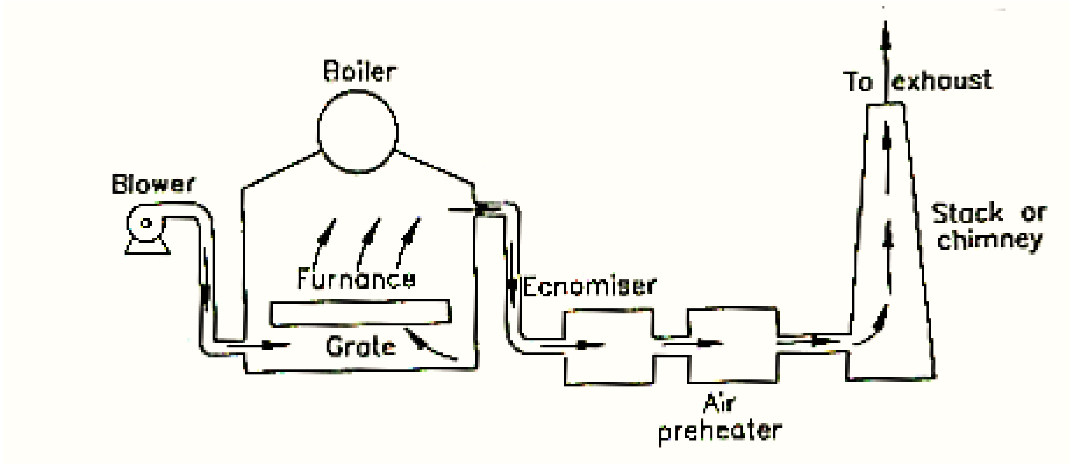


Figure 4.2 forced draught

The forced draught system fans are installed at the base of the boiler. This draught system is known as the positive draught system. The fans or blowers installed at the base of the boiler forces the air through the fuel bed, Economiser, air preheater and to the chimney. The furnace has to be gas tight to prevent the leakage of gases in the boiler house. Since the FD fans handle cold air, so they consume less power and less maintenance problems.

4.4.2 Induced Draught

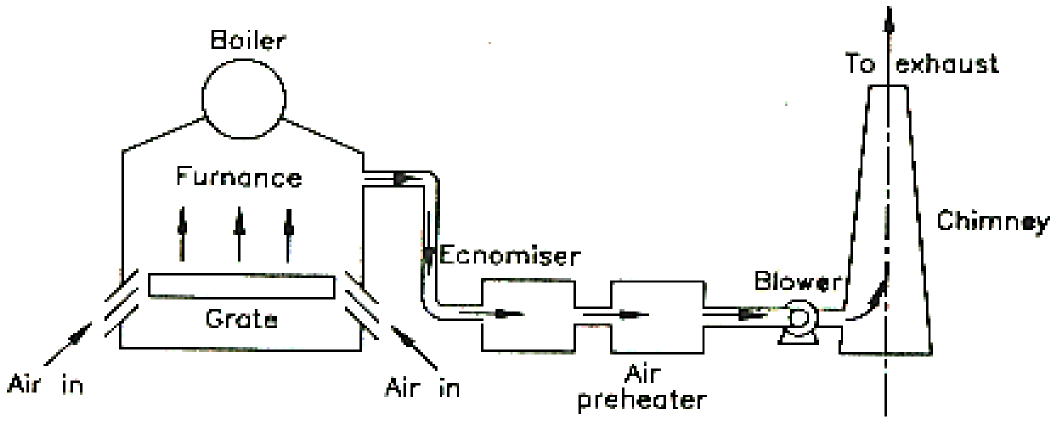


Figure 4.3 Induced draught

In this type of draught system a fan or blower is located at the base of the chimney. The ID fan sucks the burned gases from furnace and the pressure inside the furnace is reduced below atmosphere and induces the atmospheric air to flow through the furnace. The draught produced is independent of the temperature of the gases. This draught is similar to the natural draught system in action but the total draught produced is the sum of draught produced by the fans and chimney.

Advantages of Forced draught over induced draught:

1) Forced draught fans does not require water cooled bearing.
2) The tendency of air leak in to the furnace reduced.
3) The life of the FD fan blades is high.
4) The power required for FD fans is less compared to Induced draught fans.

4.4.3 Balanced draught.

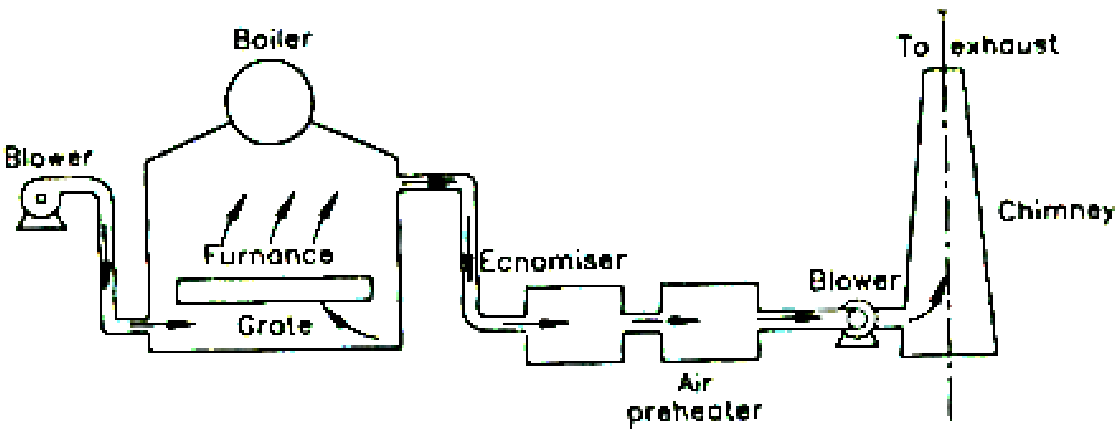


Figure 4.4 Balanced draught

It is the combination of the both forced draught and induced draught system. In this system FD fan over comes the resistance of fuel bed and air pre heater. The induced draught fan removes the gases from the furnace maintaining the pressure in the furnace just below atmosphere.

4.5 Power requirement by fans

Let us consider,

V = Volume of the flow gases through the fan m^3/min.

H= Draught produced by the fan mm of water.

P = Draught in N/m^2

η= Efficiency of fan.

We have,

P = $\rho_w gh$ =1000 x g x (h/1000) N/m^2

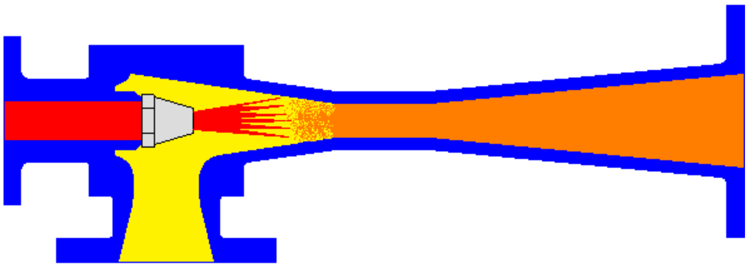
The work done on the gas,

W = PV / 60 = (gh) V/60 Watts

Power required to drive the fan $= \frac{ghV}{60} \times \eta$ watts

5

Steam Nozzle



Course Contents

5.1 Introduction

A nozzle is often a pipe or tube of varying cross sectional area, and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them. In a nozzle, the velocity of fluid increases or decrease at the expense of its pressure energy

Its major function is to produce steam jet with high velocity to drive steam turbines.

5.2 Application of nozzle

- To produce high velocity jet to impinge on curved blade of driving turbine shaft.
- Jet engines to produce thrust.
- Rocket motors to produce thrust.
- Artificial Fountains.
- Flow measurements.
- Injectors for pumping feed water.
- Ejectors for removing air from condensers.
- Fire hose to produce

5.3 Types of Nozzle

There are mainly three types of nozzle.

1) Convergent nozzle
2) Divergent nozzle
3) Convergent-divergent nozzle

5.2.1 Convergent nozzle

If the c/s of the nozzle decreases continuously from the entrance to exit, it is called a convergent nozzle. It is used, when back pressure is equal to or greater than critical pressure. It is also used for non-compressible fluids.

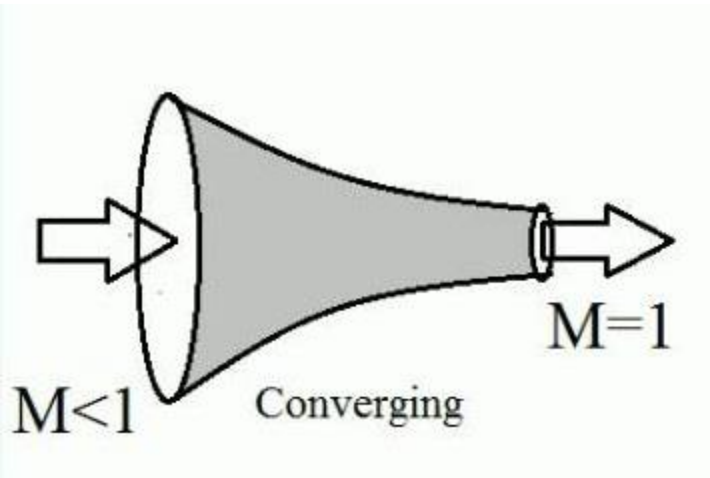


Figure 5.1 Convergent nozzle

5.2.2 Divergent nozzle

If the c/s of the nozzle increases continuously from the entrance to exit, it is called a divergent nozzle. It is used when back pressure is less than critical pressure.

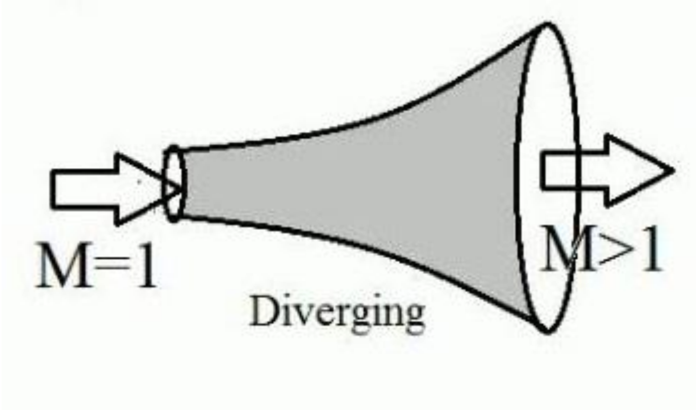


Figure 5.2 Divergent nozzle

5.2.3 Convergent-divergent nozzle

If the c/s of the nozzle first decreases and then increases, it is called convergent-divergent nozzle. The convergent-divergent nozzle is used when back pressure is less than the critical pressure. It is widely used in steam and gas turbine.

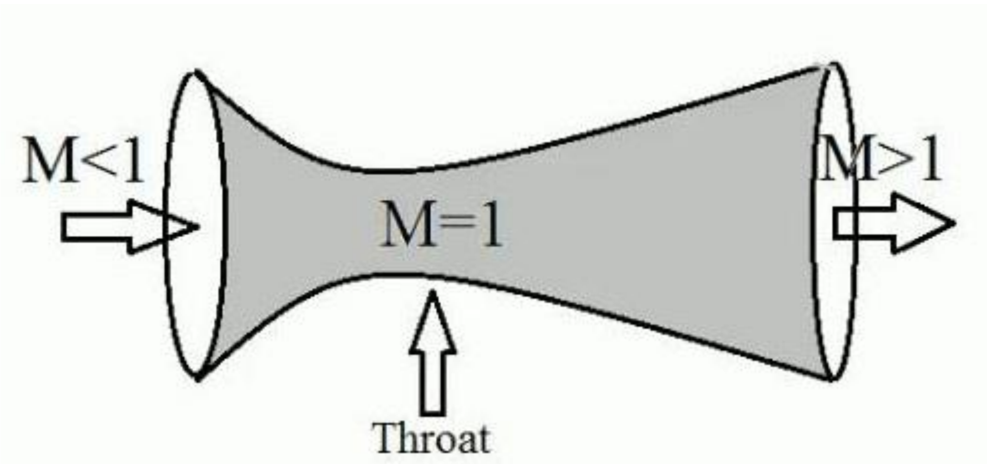


Figure 5.3 Convergent-divergent nozzle

5.4 Velocity of Steam

Steam flow through nozzle maybe assumed as adiabatic flow since during expansion of steam there is no any heat transfer. It can be calculated by following formula. Consider 1 at inlet section and 2 as outlet section.

By applying energy equation at section 1 and 2 we get

$$h_1 + \frac{{c_1}^2}{2 \times 1000} = h_2 + \frac{{c_2}^2}{2 \times 1000}$$

As the velocity of steam entering the nozzle is very small, C_1 can be neglected and finally by simplifying equation we obtain,

$$C_2 = 44.72\sqrt{((h_1 - h_2) \times \eta_n}$$

Where,
$h_1 = Enthalpy\ at\ inlet$
$h_2 = Enthalpy\ at\ outlet$
$\eta_n = Nozzle\ efficiency$

5.5 Discharge through nozzle

The steam flow through the nozzle is isentropic and is represented by $pv^{\gamma}=C$. Neglecting the initial velocity, gain in kinetic energy becomes $V_2^2/2$.

Heat drop = h_1-h_2. = Work done during Rankine cycle.

$$\therefore \frac{{V_2}^2}{2} = \frac{n}{n-1}(p_1v_1 - p_2v_2)$$

$$= \frac{n}{n-1}\, p_1v_1\left[1 - \frac{p_2v_2}{p_1v_1}\right] \_\_\_\_\_\_\_\_\_\_1)$$

But, $\frac{v_2}{v_1} = \left(\frac{p_2}{p_1}\right)^{-1/n}$

Substituting this value in equation 1)

$$\frac{{V_2}^2}{2} = \frac{n}{n-1}\, p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$V_2 = \sqrt{\frac{2n}{n-1}\, p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

Mass of steam discharged through nozzle per second,

$$m = \frac{Volume\ of\ steam\ flowing\ per\ secong}{Volume\ of\ 1\ Kg\ steam\ at\ pressure\ p_2}$$

$$= \frac{AV_2}{v_2} = \frac{A}{v_2}\sqrt{\frac{2n}{n-1}\, p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1}\left(\frac{p_2}{p_1}\right)^{1/n}\sqrt{\frac{2n}{n-1}\, p_1v_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= A\sqrt{\frac{2n}{n-1} \times \frac{p_1}{v_1}\left[(\frac{p_2}{p_1})^{\frac{2}{n}} - (\frac{p_2}{p_1})^{\frac{n+1}{n}}\right]}$$

5.6 Critical pressure ratio and condition for maximum discharge

Nozzle is usually designed for maximum steam flow rate. By designing certain pressure at throat this is achieved.

Let us consider,
P_1 = Initial pressure of steam
P_2 = Pressure of steam at throat
V_1 = Specific volume of steam at pressure P_1
V_2 = Specific volume of steam at pressure P_2

Mass of steam discharged through nozzle is given by,

$$m = A\sqrt{\frac{2n}{n-1} \times \frac{p_1}{v_1}\left[(\frac{p_2}{p_1})^{\frac{2}{n}} - (\frac{p_2}{p_1})^{\frac{n+1}{n}}\right]}$$

There is only one value of the ratio P_2/P_1, which produces maximum discharge from the nozzle. In above equation except P_2/P_1, all other values are constant. Therefore only that portion of equation which contains P_2/P_1 is differentiated and equated to zero for maximum discharge.

$$\therefore \frac{d}{d\left(\frac{p_2}{p_1}\right)}\left[(\frac{p_2}{p_1})^{\frac{2}{n}} - (\frac{p_2}{p_1})^{\frac{n+1}{n}}\right] = 0$$

$$\therefore \frac{2}{n}(\frac{p_2}{p_1})^{\frac{2-n}{n}} = \frac{n+1}{n}(\frac{p_2}{p_1})^{\frac{1}{n}}$$

$$\therefore \frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

This ratio shows critical pressure ratio for maximum discharge at throat.

Sr. no.	Steam condition	n	$\frac{p_2}{p_1}$
1	Initially dry saturated steam	1.135	0.5777
2	Initially superheated steam	1.3	0.546
3	Initially wet steam	1.035+0.1x	Depend on dryness fraction
4	For air entering in nozzle	1.4	0.528

5.7 Physical significance of critical pressure ratio

Velocity of steam at any section of nozzle is given by,

$$V_2 = \sqrt{\frac{2n}{n-1}\, p_1 v_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]}$$

And critical pressure ratio for maximum discharge,

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \qquad \text{1)}$$

Substituting this value in above equation,

$$V_2 = \sqrt{\frac{2n}{n-1}\, p_1 v_1 \left[1 - \frac{2}{n+1}\right]}$$

$$V_2 = \sqrt{\frac{2n}{n+1}\, p_1 v_1} \qquad \text{2)}$$

For isentropic expansion,

$$p_1 v_1^{\,n} = p_2 v_2^{\,n}$$

$$\frac{V_1}{V_2} = \left(\frac{p_2}{p_1}\right)^{1/n}$$

$$\therefore p_1 v_1 = p_1\, v_2 \left(\frac{p_2}{p_1}\right)^{1/n} = p_1 v_2 \frac{p_2}{p_2}\left(\frac{p_2}{p_1}\right)^{1/n} = p_2 v_2 \left(\frac{p_2}{p_1}\right)^{\frac{1-n}{n}}$$

Substituting equation 1 in above equation we get,

$$p_1 v_1 = p_2 v_2 \left(\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}\right)^{\frac{1-n}{n}} = p_2 v_2 \left(\frac{n+1}{2}\right)$$

Substituting above equation in equation 2 we get,

$$V_2 = \sqrt{n\, p_1 v_1}$$

This is the value of velocity of sound in the medium at pressure p_2 and is known as sonic velocity.

From above derivation following points are concluded,

1. The critical pressure gives the velocity of steam at the throat which is equal to the velocity of sound.
2. The steam flow in convergent portion of nozzle is subsonic and in the divergent portion it is supersonic.
3. When a nozzle operates with maximum mass flow rate, it is said to be chocked. A correctly designed convergent-divergent nozzle is always chocked.
4. To increase the velocity of steam above sonic velocity, it becomes necessary to expand steam below critical pressure. To effect this, the divergent portion for the nozzle becomes necessary.

5.8 Nozzle Efficiency

Expansion process in nozzle considered as isentropic expansion but in actual practice there is a friction loss in the nozzle, so actual flow in the nozzle is not isentropic flow.

Nozzle efficiency is defined as the ratio of actual heat drop to isentropic heat drop or heat drop due to isentropic expansion.

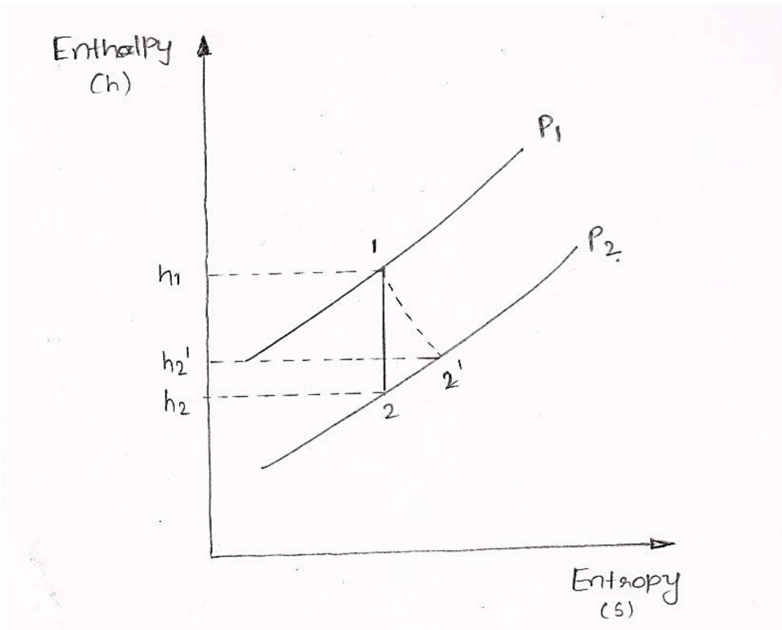


Figure 5.4 h-s diagram for nozzle

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

Where,

$$h_1 = Initial\ Enthalpy$$
$$h_2 = Final\ Enthalpy$$
$$h_2' = Actual\ final\ Enthalpy$$

Effect of Friction

When steam flows through a nozzle the final velocity of steam for given pressure drop is reduced due to following reason.

- The friction between the nozzle surface and steam.
- The internal friction of steam itself.
- The shock losses.

The convergent portion of nozzle is smaller than the divergent portion. Thus, the wall friction is small in the convergent portion as compared to divergent portion.

The fluid friction is also small in convergent portion than in the divergent portion, since the fluid velocity in the convergent portion is small.

Thus, most of the friction occurs in the divergent portion of the nozzle and h-s diagram plot as shown in following figure.

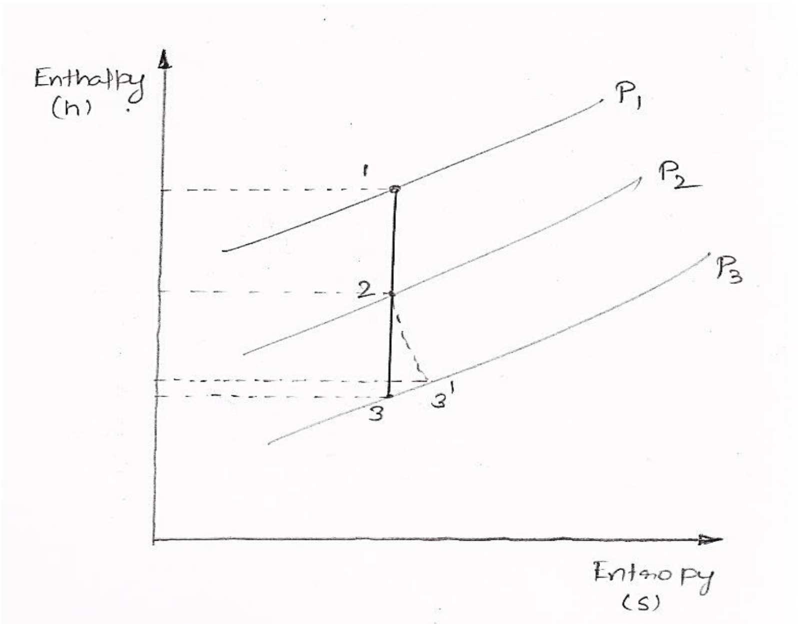


Figure 5.5 Effect of friction in divergent portion of nozzle

These frictional losses entail the following effects.

- The expansion is no more isentropic and the enthalpy and entropy of steam increasing during the process.
- The final dryness fraction of steam is increased as the kinetic energy gets converted into heat due to friction and is absorbed by steam.
- The specific volume of steam increased as the steam becomes drier due to this frictional reheating.

- Exit velocity is reduced as the kinetic energy gets converted into heat due to friction.
- Mass flow rate is decreased.

6

Steam Turbine

Course Contents

6.1 Principle of Operation

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.

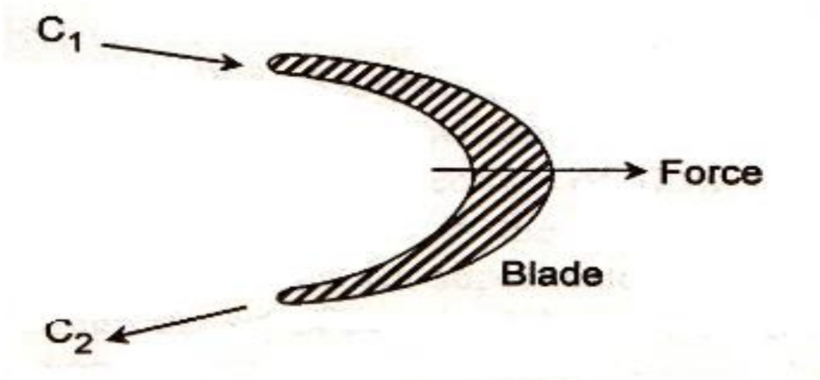


Figure 6.1 Principle of operation of steam turbine

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 as shown in fig 6.1.

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.

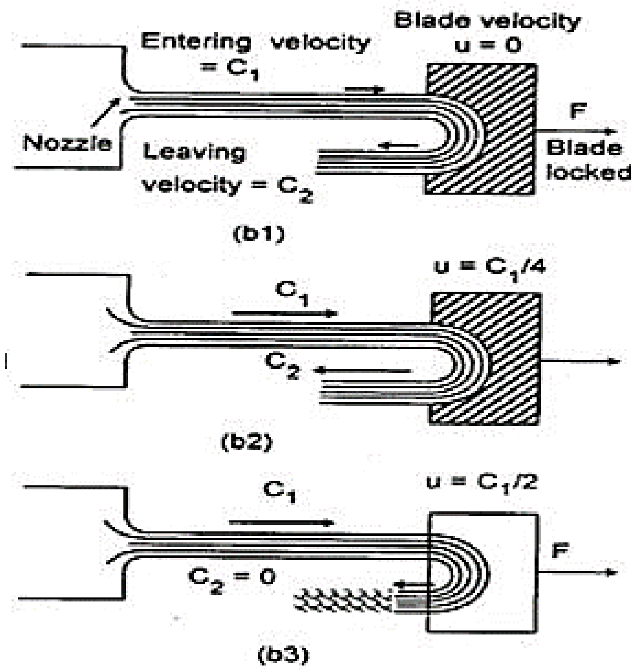


Figure 6.2 Effect of blade velocity

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 6.2. 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.

6.2 Types of steam turbines

(A) On the basis of the principle of operation

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*"

Impulse-Reaction Turbine: In this 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

Axial Flow Turbine: - In axial flow turbine, the steam flows along the axis of the shaft.

Radial Flow Turbine: In this turbine, the steam flows in the radial direction.

Tangential Flow Turbine: In this type, the steam flows in the tangential direction.

(C) On the basis of Means of Heat Supply

Single Pressure turbine: In this type of turbine, there is single source of steam supply.

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.

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

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.

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

Condensing Turbine: In this turbine, the exhaust steam is condensed in a condenser and the condensate is used as feed water in the boiler.

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.

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

Single Cylinder: - When all stages of turbine are housed in one casing,

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

Single Flow. In a single flow turbines, the steam enters at one end, flows once through the blading in a direction approximately parallel to this axis,

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

Tandem Compound. Most multi-cylinder turbines drive a single shaft and single generator.

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.

6.3 Compounding of steam turbines

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 30,000 RPM which is too high for practical use. 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

(a) Pressure-compounded impulse turbine

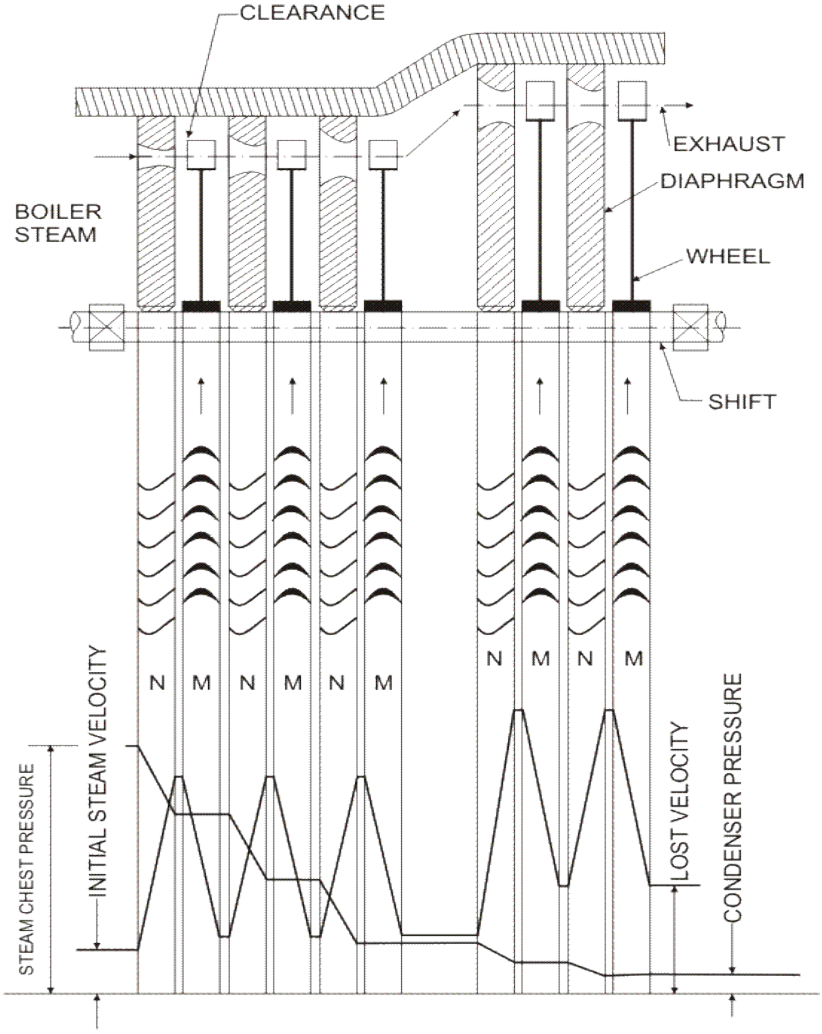


Figure 6.3 Pressure compounding impulse turbine

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 6.3. 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.

(b) Velocity compounded Impulse Turbine

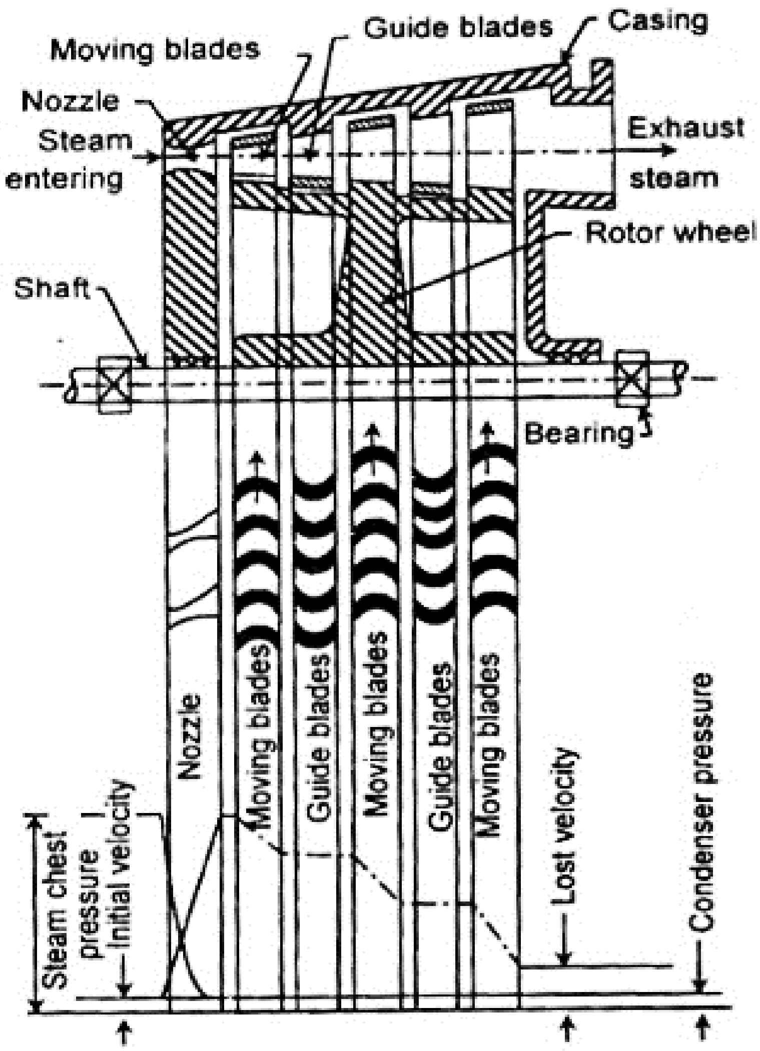


Figure 6.4 velocity compounded Impulse Turbine

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.

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.

(C) Pressure and velocity compounded impulse turbine

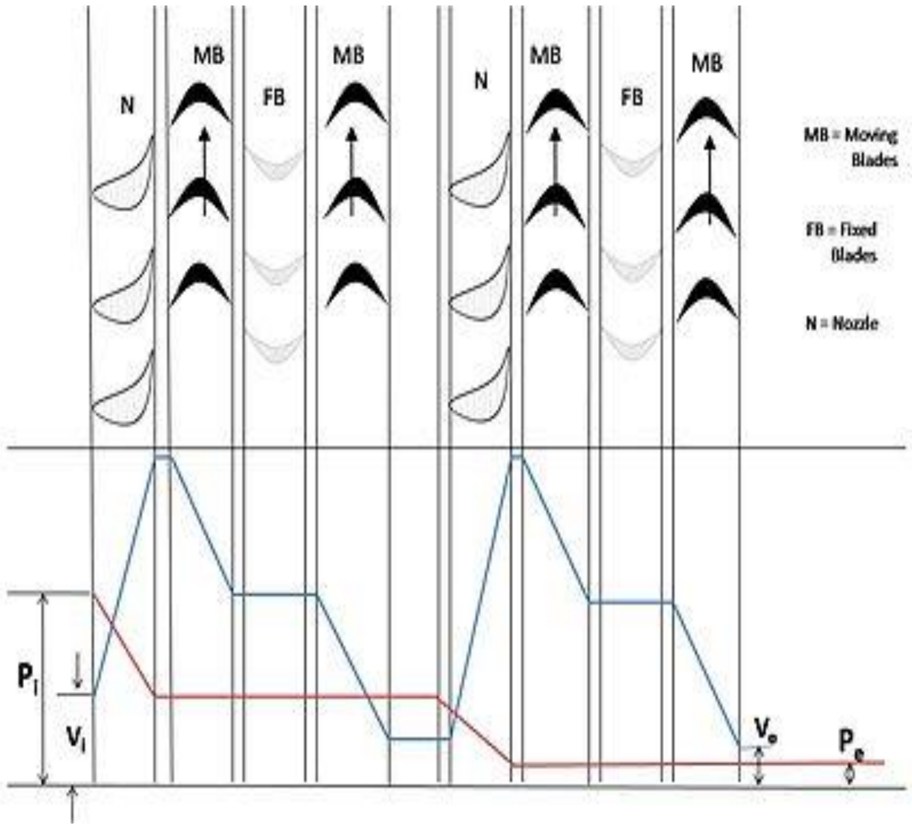


Figure 6.5 Pressure-velocity compounded impulse turbine

This type of turbine is a combination of pressure and velocity compounding and is shown diagrammatically in Fig. 6.5. 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. However It is, very rarely used now due to its low efficiency.

6.4 Impulse turbine – velocity diagram, calculation of work, power and efficiency

The expansion of steam in the nozzle produces a high velocity jet, the function of the blade is to change the direction and hence momentum of the jet of steam and so produce a force which will rotate the blade. Hence it is important to measure the amount of propelling force that is applied to a turbine rotor. This measurement is useful to find the work done and hence the power.

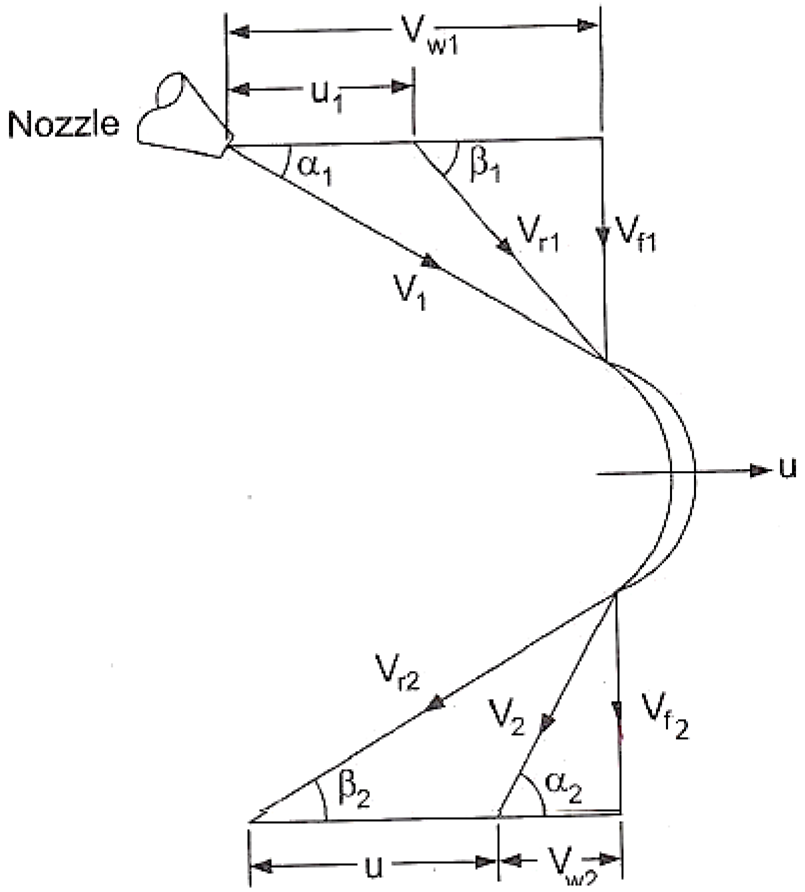


Figure 6.6 velocity diagram of simple impulse turbine

Notations used in the analysis are as below,

V_1 = Absolute velocity of steam at inlet in m/sec
U = Blade velocity in m/sec
D = Blade ring mean diameter in m
N = Speed in rpm
V_{r1} = Relative velocity of steam at inlet in m/sec
V_{W1} = Whirl velocity of steam at inlet in m/sec
V_{F1} = Flow velocity of steam at inlet in m/sec
α_1 = Nozzle inlet angle in degree
β_1 = Blade inlet angle in degree

V_2 = Absolute velocity of steam outlet in m/sec
V_{r2} = Relative velocity of steam at outlet in m/sec
V_{W2} = Whirl velocity of steam at outlet in m/sec
V_{F2} = Flow velocity of steam at outlet in m/sec
α_2 = Angle made by absolute velocity with the tangent of wheel at outlet in degree.
β_2 = Blade outlet angle in degree.

The steam supplied to a single wheel impulse turbine expands completely in the nozzle and leaves with high absolute velocity. The steam is directed on the rotor at a nozzle angle α_1. Therefore, the absolute inlet velocity has two components, tangential and axial. The tangential component is called the whirl velocity and is mainly responsible for useful work, while axial (vertical) component is called axial or flow velocity. It allows the flow of steam across the wheel.

Combined Velocity Diagram

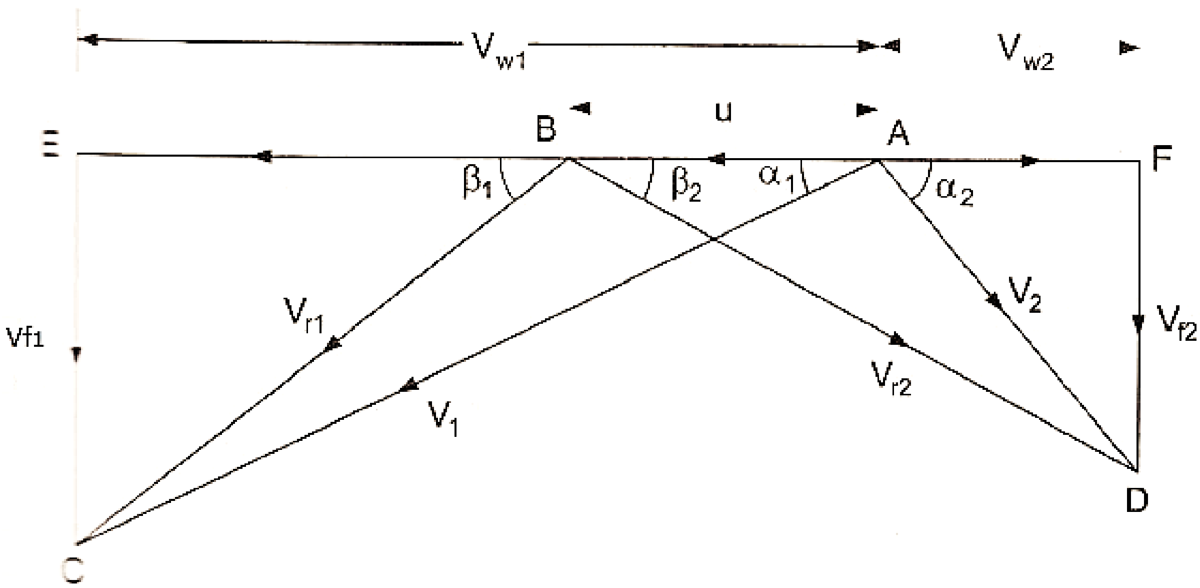


Figure 6.7 Combined velocity diagram

Procedure for drawing the combined velocity diagram.

1) Draw a horizontal line. Cut off AB equal to blade velocity, u to some suitable scale.

2) From point A draw a line AC inclined at nozzle angle α_1, and length equal to absolute velocity of steam V_1 to the scale.

3) Join B and C. The line BC represents the relative velocity, Vr1. The blade inlet angle β_2 is measured and its value is noted down.

4) From point C draw a perpendicular line CE on AB produced. CE represents flow velocity at inlet and AE represents the Whirl velocity at inlet.

5) From point B draw a line BD at an angle β_2. Calculate the relative velocity at outlet.

6) Join A and D. AD represents the absolute velocity at outlet. The angle α_2 is measured and noted down.

7) From point D draw a perpendicular DF on BA produced. Then AF represents the whirl velocity of steam at outlet, V_{w2}, and DF represents the flow velocity at outlet, V_{f2}. This completes the velocity triangle.

Calculation for work, power and Efficiency

Tangential Force on the blade:

By newton's second law of motion, the tangential force is proportional to the rate of change of momentum of steam as it flows over the blade surface.

$$F = m(V_{W1} \pm V_{W2}) \quad N$$

Work done by steam on blades:

Work done by steam = Force × Distance moved per second

$$m\,(V_{W1} \pm V_{W2}) \times u \quad Nm/s$$

Power developed by turbine:

$$P = \frac{m\,(V_{W1} \pm V_{W2}) \times u}{1000}$$

Axial Thrust:

The vertical component of the absolute velocity provides the axial thrust on the bearing. It is obtained due to difference between the velocities of flow at entrance and outlet of blade.

Axial thrust = mass × Change in the velocity of flow

$$= m\,(v_{f1} - v_{f2})$$

Diagram or blade efficiency:

$$\eta_{blade} = \frac{Work\ done\ by\ the\ blade}{Kinetic\ energy\ supplied\ to\ the\ blade} = \frac{mv_w u}{{mv_1}^2/2} = \frac{2uv_w}{{v_1}^2}$$

6.5 Condition for maximum efficiency of impulse turbine

The work done per kg of steam flow in a single impulse turbine is given by,

$$W = uv_w = (V_{W1} + V_{W2})$$

From the combined velocity diagram,

$$v_{w1} = v_1 \cos\alpha_1 = v_{r1}\cos\beta_1 + u$$

$$v_{w2} = v_2 \cos\alpha_2 = v_{r2}\cos\beta_2 - u$$

$$\therefore (V_{W1} + V_{W2}) = v_{r1}\cos\beta_1 + u + v_{r2}\cos\beta_2 - u$$

$$= v_{r1}\cos\beta_1\left[1 + \frac{v_{r2}\cos\beta_2}{v_{r1}\cos\beta_1}\right]$$

$$= v_{r1}\cos\beta_1 \ [1 + KC]$$

Where, $k = v_{r2}/v_{r1} = Blade\ velocity\ coefficient$

$$C = \frac{\cos\beta_2}{\cos\beta_1} = constanr\ for\ given\ inlet\ and\ outlet\ angles$$

Now, $v_{r1}\cos\beta_1 = BE = AE - AB = (V_1\cos\alpha_1 - u)$

$$\therefore W = (V_{W1} + V_{W2}).u = (V_1\cos\alpha_1 - u)\ [1 + KC]u$$

The blade or diagram efficiency is given by,

$$\eta_{blade} = \frac{2u\ (V_{W1} + V_{W2})}{{v_1}^2} = \frac{2u(V_1\cos\alpha_1 - u)\ [1 + KC]}{{v_1}^2}$$

$$= \frac{2(uV_1\cos\alpha_1 - u^2)\ [1+KC]}{{v_1}^2}$$

$$= 2\left(\frac{u}{v_1}\cos\alpha_1 - \frac{u^2}{{v_1}^2}\right)[1 + KC]$$

$$= 2(\rho\cos\alpha_1 - \rho^2)[1 + KC] \ldots\ldots\ldots\ldots 1)$$

Where $\rho = \frac{u}{v_1} = blade\ speed\ ratio$

Now in above equation if α_1, K and C are assumed constant, the blade efficiency depends upon the value of ρ. The optimum value of ρ for maximum blade efficiency is obtaining by differentiating equation 1 with respect to ρ and equating it to zero.

$$\therefore \frac{d\eta_{blade}}{d\rho} = \frac{d}{d\rho}[2(\rho\cos\alpha_1 - \rho^2)(1 + KC)] = 0$$

$$2\cos\alpha_1 - 4\rho = 0$$

$$\rho = \frac{\cos\alpha_1}{2}$$

Substituting this value in equation 1 we obtain following equation for maximum efficiency.

$$\eta_{max} = (1 + KC)\frac{cos^2\alpha_1}{2}$$

Furthermore assume that blades are symmetrical ($\beta 1 = \beta 2$) and friction is absent.

$$\therefore C = 1 \; and \; K = 1$$

$$\therefore \eta_{b(\max)} = cos^2\alpha_1$$

6.6 Reaction turbines – velocity diagram, degree of reaction and reheat factor.

It consist of number of rows of moving blades and attached to the rotor and an equal no of fixed blades attached to the casing. The fixed blades are set in reversed direction of moving blades. Here no nozzles are provided and fixed blade act as nozzle in reaction turbine.

Velocity diagram

In reaction turbines, the steam expands continuously while passing over the rings of fixed and moving blades. The effect of expansion of steam on the moving blade is to increase the relative velocity at the exit. Hence, relative velocity at outlet is always greater than relative velocity at inlet.

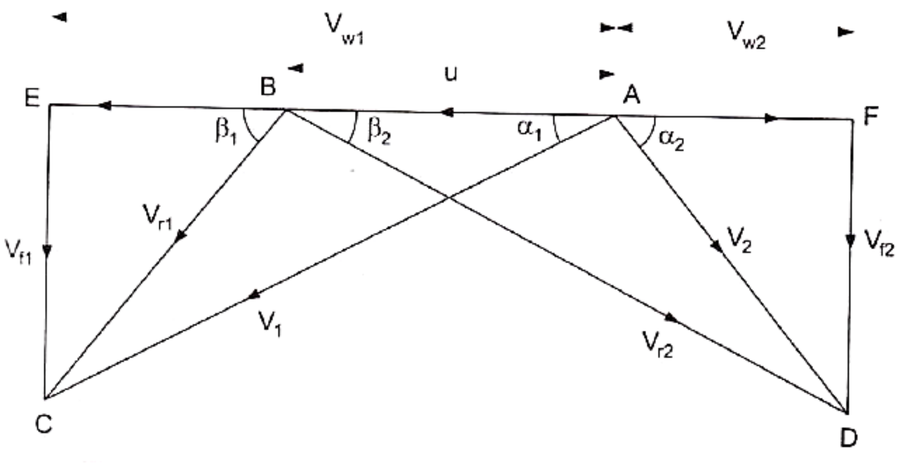


Figure 6.8 combined velocity diagram for reaction turbine

Degree of reaction

The degree of reaction of a reaction turbine is defined as the ratio of enthalpy drop in moving blades to the total enthalpy drop in a stage. It is denoted as R.

Mathematically,

$$R = \frac{Enthalpy\ drop\ in\ moving\ blades(\Delta h_m)}{Enthalpy\ drop\ in\ moving\ blades + Enthalpy\ drop\ in\ fixed\ blades\ (\Delta h_f)}$$

For pure impulse turbine, R=0 as there is no any heat drop in moving blades. For pure reaction turbine, R=1. Pure reaction turbines are not in general use. The reaction turbines in use are impulse-reaction turbine.

The heat drop in moving blades in reaction turbine is utilized in increasing the relative velocity of the steam from inlet to outlet.

$$\Delta h_m = \frac{{v_{r2}}^2 - {v_{r1}}^2}{2}$$

$$\Delta h_f + \Delta h_m = u(v_{w1} + v_{w2})$$

$$R = \frac{{v_{r2}}^2 - {v_{r1}}^2}{2u(v_{w1} + v_{w2})} \ldots\ldots\ldots\ldots\ldots\ldots 1)$$

From velocity triangle,

$$v_{r2} = v_{f2}\ cosec\beta_2$$

$$v_{r1} = v_{f1}\ cosec\beta_1$$

$$v_w = (v_{w1} + v_{w2}) = v_{f1}\ cot\beta_1 + v_{f2}\ cot\beta_2$$

The velocity of flow generally remains constant while the steam passes over the blade ring

$$v_{f1} = v_{f2} = v_f$$

Substituting this values in equation 1, we get

$$R = \frac{{v_f}^2(cosec^2{}_{\beta 2} - cosec^2{}_{\beta 1})}{2uv_f(cot\beta_1 + cot\beta_2)}$$

$$= \frac{v_f}{2u}\left[\frac{(1 + cot^2{}_{\beta 2}) - (1 + cot^2{}_{\beta 1})}{cot\beta_1 + cot\beta_2}\right]$$

$$= 2u(cot\beta_2 - cot\beta_1)$$

6.7 Governing of steam turbine.

Why governing?

The power output increases with speed, reaches a maximum (Rated) value at rated speed and after this decreases. The turbine speed is a function of electrical load. At lower the load, higher the speed due to accelerating torque. The load may not remain the same. 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 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:-

1. Throttle control governing
2. Nozzle control Governing
3. By-Pass governing
4. Combination of (a) and (b) or (a) and (c)

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 blading whenever there is a reduction of load compared to economic or design load for maintaining the speed of the turbine.

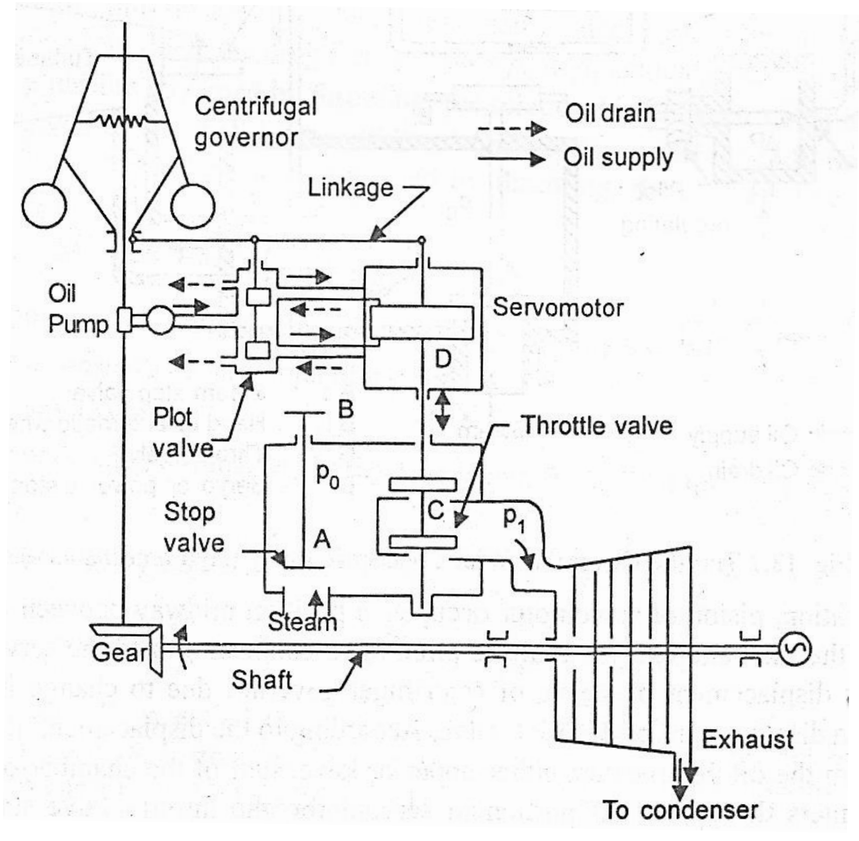


Figure 6.9 Throttle control governing

- The relay system consists of a pilot valve and a servomotor. Under normal operation, piston of servomotor occupies a position midway between its path 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. Nozzle control Governing

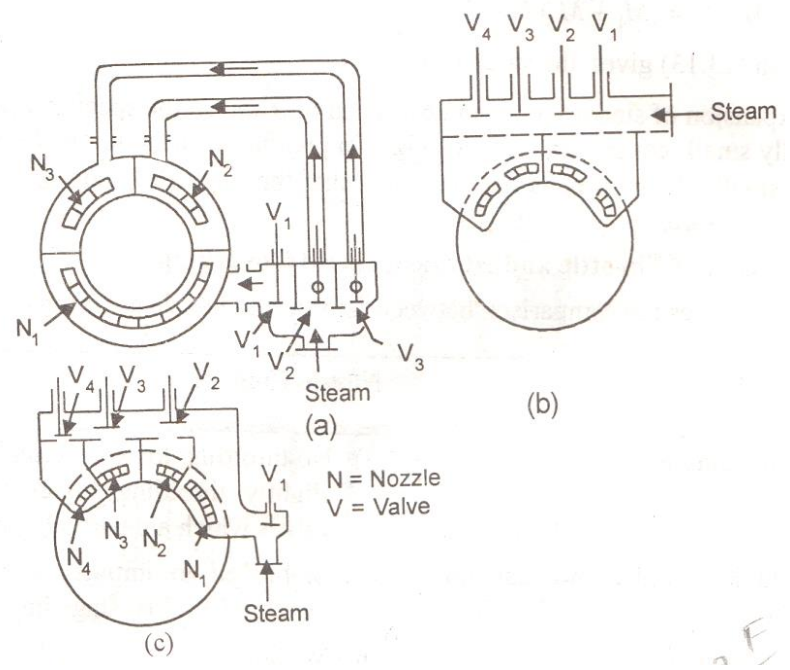


Figure 6.10 Nozzle control governing

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. 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.

Fig. (a) Shows an arrangement often employed in large steam turbines and turbines using high pressure steam. Here, the nozzles are divided into three groups N1, N2 and N3 under the control of three valves V1, V2 and V3 respectively. The number of nozzle groups may vary from three to five or more.

Fig. (b) shows 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˚C or less. The number of nozzles group may vary from 4 to 12.

Fig. shows (c) In this arrangement four groups of nozzles N1 is under the control of the valve V1, through which all the steam entering the turbine passes and further admission of steam is through the valves V2, V3, etc. in turn.

3. By-Pass governing

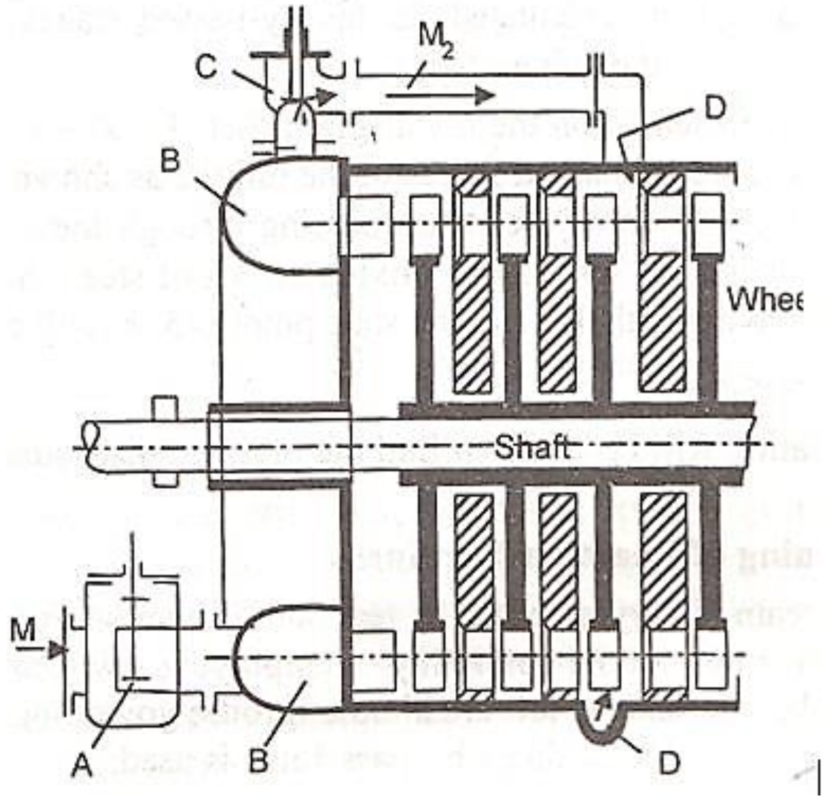


Figure 6.11 By-pass governing

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,

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.

6.8 Methods of attachment of blades to turbine rotor

The attachment of the turbine blades to the rotor is the most critical aspect of steam turbine design as it affects the reliability of the machine. All the forces are transmitted through the attachment to the rotor.

The blades of the turbine are subjected to centrifugal forces and bending. The centrifugal forces on the blade are very high which its mass is many times. Also there is always possibility of stress concentration at the sharp corners. Blades which are loosely fastened to the rotor will amplify the vibrations induced in the blades, causing fatigue failure. The failure of one blade may lead to the destruction of the entire turbine. Hence the form of attachment should be such that the centrifugal force on the blade is transmitted to the disc in the simplest and most direct manner. The design should be such that security of the attachment is independent of the skill of the mechanic. The various methods of blade attachment are as follows:

- De-Laval blade attachment
- Inverted-T attachment
- Fir tree or serrated blade root attachment
- Straddle attachment
- Side entry blade attachment

- Shrouding strip attachment
- Attachment of Parsons Reaction turbine blade.

De-Laval blade attachment

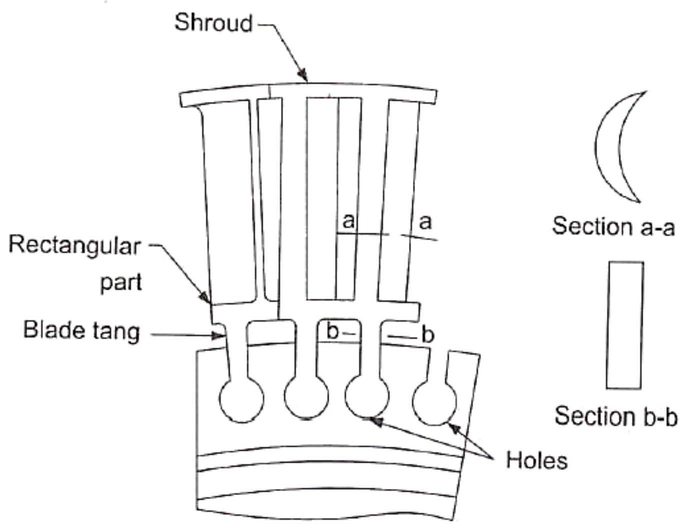


Figure 6.12 De Laval blade attachment

To attach the blades to the rotor, number of holes are drilled in the rim of the rotor parallel to the axis. The slot for the blade tang is then finished by milling. The tips of the blades have integral shrouding which forms a continuous ring. Shrouding is provided for stiffness against vibration and to give correct guidance to steam. At the bottom of the working section, rectangular part also forms a continuous ring when all the blades are inserted in the rotor. This method of fastening is suitable for low pressure impulse turbine.

Inverted-T attachment

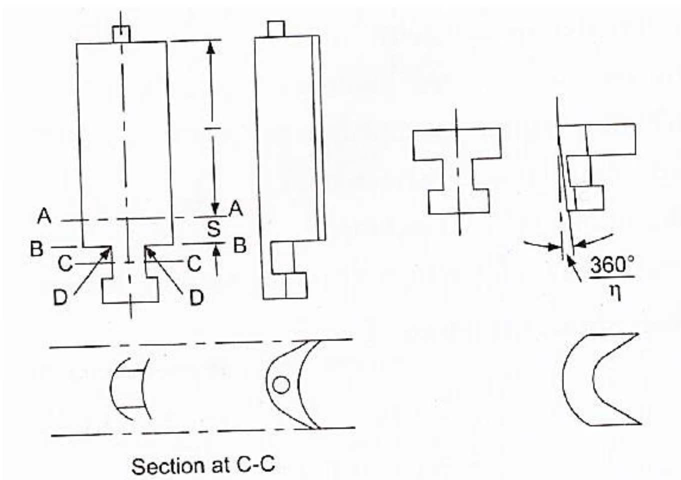


Figure 6.13 Inverted T attachment

As name implies, attachment is inverted T shaped as shown in above figure. This attachment may be with separate spacer or integral spacer. The blade are cut from bars or the strip of blade section is formed either by rolling, drawing through dies or by machining. S shows the length of spacer from rotor. When the stress across the section C-C becomes excessive the blade and spacer are made from one piece. Such blades are machined from bars and expensive to manufacture. It is used in high pressure impulse stage of large turbines.

Fir tree or serrated blade root attachment

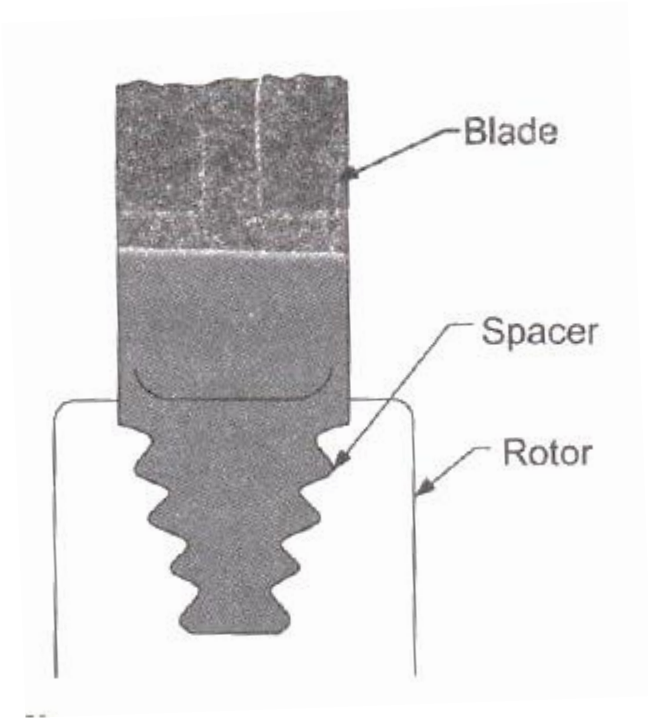


Figure 6.14 Fir tree or serrated blade root attachment

Figure shows fir-tree or of serrated blade attachment. This type blade attachment is used for high speed turbine with large centrifugal forces. The blade and spacer are made from one piece to withstand large centrifugal stresses. Serrations are machined on both side of the root and also in the blade groove. The depth of serration kept about 10 % of the width of the groove having an angle 45°. This attachment is extensively used in medium and large gas and steam turbines.

Straddle attachment

Fig. 6.15 shows the straddle attachment. For moderate speeds and short blades, arrangement shown in left of Fig 6.15 is used in which blade and spacer are machined from one piece of metal. The blade is forked and it fits tightly on a projecting tongue on the wheel. The rivets are staggered and are countersunk.

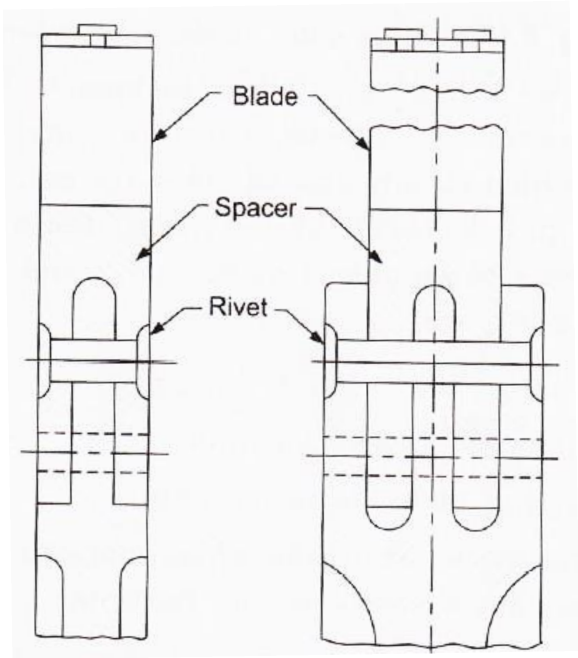


Figure 6.15 Straddle attachment

Attachment as shown in right of Fig. 6.17 is used for higher speeds or longer blades since the rivets are subjected to excessive shear stresses. In this attachment there is no necessity to cut any gap for the blade insertion. One or more blades may be removed from the wheel without disturbing the remaining blades.

Side entry blades attachment

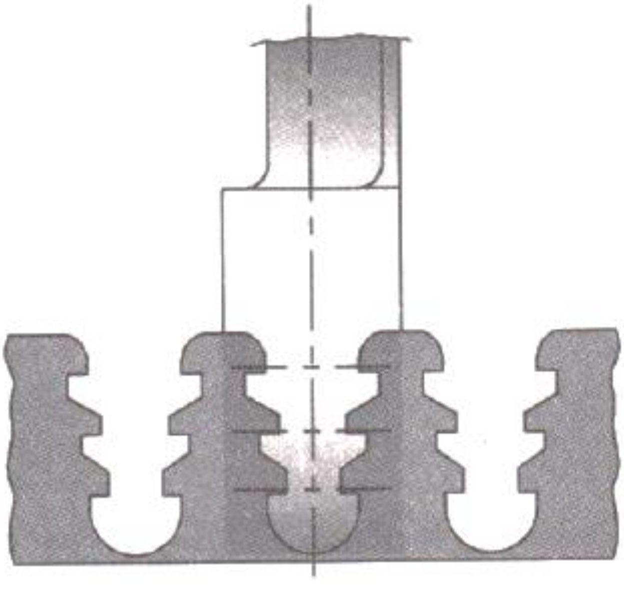


Figure 6.16 Side entry blade attachment

Fig. 6.16 shows side entry blade attachment. This attachment is used for high peripheral speeds. The rotor carries a comparatively heavy rim in which closely spaced slots are cut, one to each blade. A part of the pull is taken by outermost teeth of section 1-1, so smaller area may be employed at section 2 and 3. The advantage of this attachment are,

- Bending across section 1-1 is eliminated.
- Replacement of blades is simple.
- Complete ring of blade is possible.
- By making the width of the wheel more than the width of blade, maximum stress in the fastening can be reduced.

The disadvantage is that it is an expensive attachment.

Shrouding strip attachment

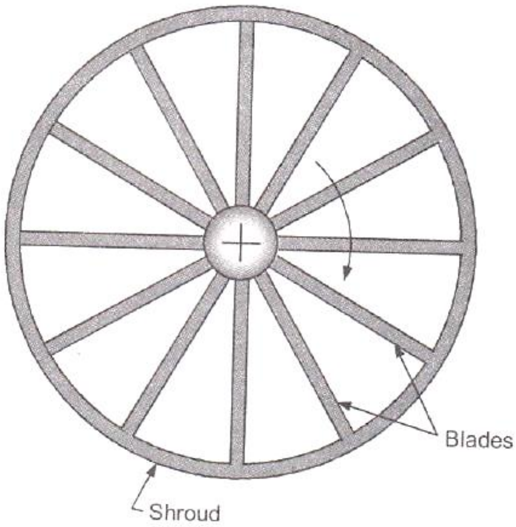


Figure 6.17 Shrouding strip attachment

As shown in Fig. 6.17 shroud is attached around the periphery the blade tips in order To stiffen the blades and prevent spillage of steam over the tips. Due to high speed of rotation often the centrifugal forces are large and hence thickness of the shrouding strip must be chosen with reference to bending stress. Shrouding is beneficial in high pressure impulse blades with partial admission, which are subjected to vibration. For shorter blades, shroud must be used and is omitted for longer blades as increase in weight of shrouds increase the centrifugal stresses at the blade root.

Parsons Reaction turbine blade

As shown in the Fig., the blade and spacer are made from one piece. The root of the blade is lozenge-shaped. These blades are made from a rectangular bar and are rolled by a discontinuous process. The blade is pickled, polished and serrated at the root by machining. They are suitable for long reaction turbine blades which run at high speeds.

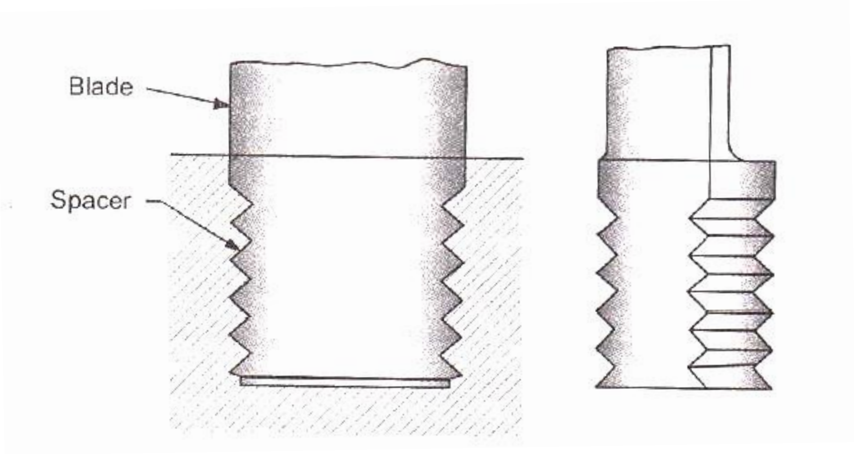


Figure 6.18 Parson integral blades

6.9 Labyrinth Gland

A small radial clearance is provided between rotating and stationary components to separate them. As some pressure difference exist across them, steam or air will leak through this clearance. Gland and seals are provided in steam turbines to reduce or prevent the leakage of steam or air between rotating and stationary components that have a pressure difference across them. There are three types of glands and seals mainly used in steam turbines.

1. Labyrinth gland
2. Carbon ring gland and
3. Water-sealed gland

Labyrinth and carbon ring glands restrict the steam and air leakage while water-sealed gland prevents the steam and air leakage completely. Labyrinth gland is superior to carbon ring gland as it can withstand higher steam temperature.

Working principle of plain labyrinth gland:

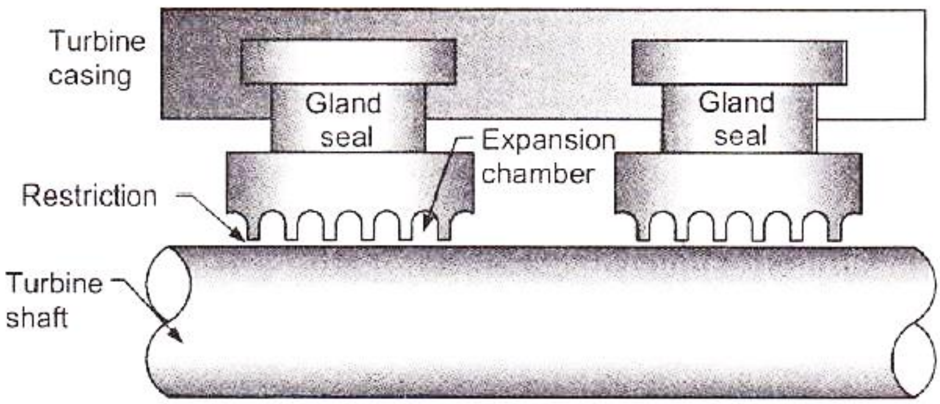


Figure 6.19 Plain labyrinth gland

Fig. shows plain form of labyrinth gland in which shaft is plain and it consists of number of rings arranged in series. There is a fine clearance or restriction between ring and rotating shaft.

There are number of restrictions and each restriction is followed by an expansion chamber. When the steam passes through the restriction and enters the expansion chamber, throttling process occurs. This results in increase in velocity and reduction in pressure, hence kinetic energy is developed. When the steam enters the expansion chamber, the kinetic energy is converted by turbulence into heat with no recovery of pressure energy. I.e. pressure falls progressively when the steam passes through restrictions resulting in reduction in leakage of steam or air. When the turbine is under vacuum, through the outlet of low pressure turbine, the atmospheric air may enter the turbine which is known as air ingress. To stop air ingress, steam is supplied between the rings some of which flows outwards and rest inwards, thus a seal is created and the ingress of air is prevented.

6.10 Losses in steam turbine

The energy contained in steam supplied to the steam turbine is not completely converted into mechanical energy. This is due to various losses which occur inside and outside of the turbine. All losses in an actual turbine are divided into two categories.

1. Internal losses
2. External losses

Internal losses

These losses are connected with steam conditions while steam flows through the turbine. These losses include,

- Losses in regulating valves
- Nozzle or fixed blade losses
- Moving blade losses
- Disc friction losses
- Blade windage or partial admission losses
- Gland leakage and clearance losses
- Carry-over losses
- Residual or leaving velocity losses
- Losses due to moisture
- Radiation and convection losses

Losses in regulating valves

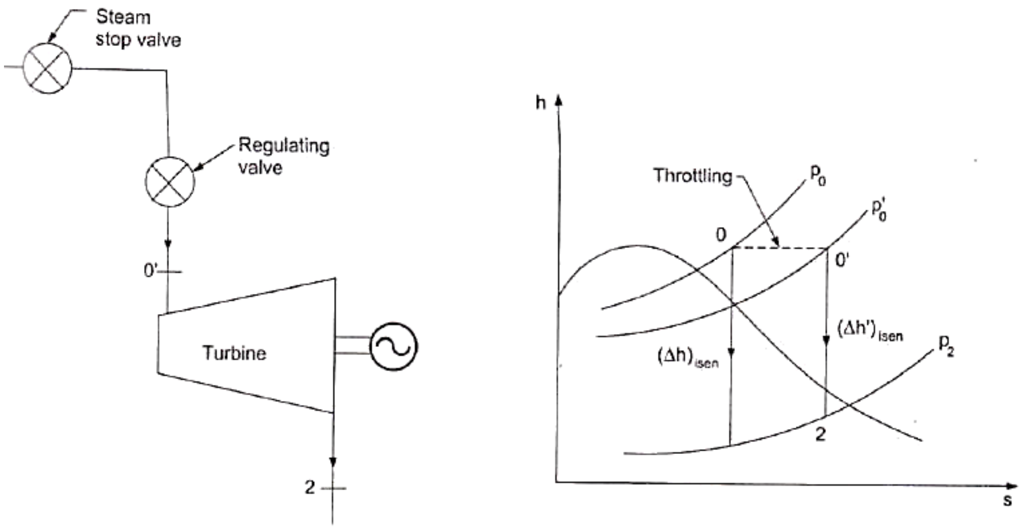


Figure 6.20 Regulating valve losses

The Steam produced in the boiler has to flow through the stop and regulating valves before entering to the steam turbine. As shown in Fig., at these valves the steam gets throttled and hence the pressure of steam at entry to the turbine is less than the boiler pressure. The isentropic heat drop decreases from $(\Delta h)_{isen}$ to $(\Delta h')_{isen}$ as shown in the Fig above. The loss of available energy is equal to

$$(\Delta h)_{valve} = (\Delta h)_{isen} - (\Delta h')_{isen}$$

Nozzle or fixed blade losses

This loss is due to friction between steam and nozzle wall surface, viscous friction between fluid particles, deflection of the flow, growth of the boundary layer and formation of eddies. Since losses produce heat, the heat content of steam at nozzle outlet will be more than the theoretical value. Thus, the actual heat drop in the nozzle be less than theoretical value resulting in reduction in velocity at nozzle outlet.

Moving blade Losses

It is due to,

<u>(i)Impingement losses:</u> Steam which leaves the nozzle meets the leading edge of the moving blades. Energy may be lost if entry is not smooth resulting in formation of eddies.

<u>(ii)Blade friction losses:</u> Steam encounters these losses in the blade passages which depends on the roughness of the blade surface.

(iii)Wake or trailing edge losses: Steam jets leaves the nozzles and before entering moving blades mix with each other and form a homogenous flow. This mixing causes formation of eddies and there is loss due to turbulence. These losses are known as wake or trailing edge losses.

(iv)Turning losses: These losses occur as the steam turns in the blade passages.

(v)Leakage through the annular space: steam leaks through annular space between nozzle and shrouding attached to the moving blades without doing work on moving blades.

(vi)Losses due to shrouding: Due to shrouding height of moving blades is larger than nozzle height. This result in thickening of boundary layer and increase in losses.

Disc friction losses

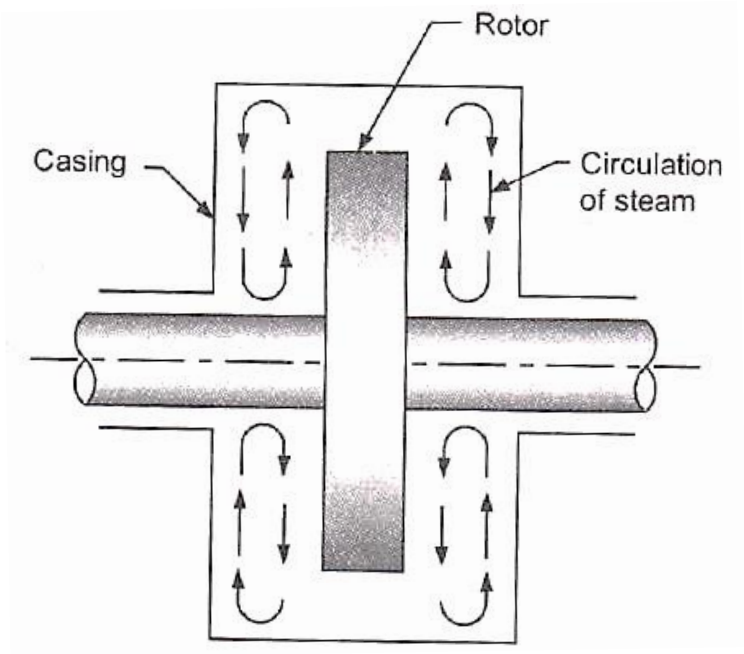


Figure 6.21 Disc friction losses

When the turbine disc (rotor) rotates in the viscous steam, there is surface friction loss due to relative motion between the disc and steam particles. Due to centrifugal force, steam is thrown radially outward. As a result, the moving surface exerts a drag force on the steam. The drag sets the steam in motion and produces a definite circulation of it. The nature of circulation depends on the shape of the space enclosing the disc as shown in the Fig above.

Blade windage or partial admission losses:
Impulse turbine are partial admission turbines as nozzles are provided only over a part of blade periphery. There is turbulence or churning of steam in the portion which doesn't receive steam. This loss is called Blade windage or partial admission loss.

Gland leakage and clearance losses

There is always clearance between the diaphragm and the shaft. The steam leaks through this clearance from one wheel chamber to other. Since the leaked steam does no work on the blade, it represents energy loss.

Carry-over losses

This occurs in multistage turbines, when steam passes from one stage to the next stage through the diaphragm, the kinetic energy of steam available at succeeding row of moving blades for utilization, is less than that at exit of preceding row. Due to this, some energy loss takes place known as carry-over loss. This loss is taken care by the term carryover coefficient, which is less than unity.

Residual or Leaving velocity losses:

The steam leaves the turbine with some absolute velocity. The energy loss due to absolute exit velocity is equivalent to $v^2_{exit} / 2000$. The residual velocity loss may be about 10 to 12 % in a single stage impulse turbine.

Loss due to moisture:

Near exit of turbine, usually steam is wet. This forms heterogeneous mixture of water droplets and steam. So water particles dragged along with steam and part of kinetic energy of steam is lost.

Radiation and Convection losses:

Some part of heat of steam is radiated or convected from the body of turbine to its surrounding. These losses are negligible and reduced by properly insulating the turbine.

External Losses

These losses do not affect the steam conditions while steam flows through the turbine. These losses include Mechanical losses and losses due to end leakage. Mechanical losses are caused due to the friction losses in the bearing of turbine shaft. There is leakage loss of steam from two ends of the turbine where the turbine shaft projects out from the turbine casing. Labyrinth packing are provided at ends to prevent the leakage.

7

Condensers and Cooling Towers

Course Contents

7.1 Introduction

In systems involving heat transfer, a condenser is a device or unit used to condense a substance from its gaseous to its liquid state, by cooling it. In so doing, the latent heat is given up by the substance, and will transfer to the condenser coolant.

The function of the condenser is to condense exhaust steam from the steam turbine by rejecting the heat of vaporization to the cooling water passing through the condenser.

Once the steam has passed through the turbine, it enters the condenser where heat is removed until it condenses back into liquid water.

This is done by passing the wet steam around thousands of small cold water tubes. The cold water is usually supplied from a nearby sea, lake, river, or from a cooling tower.

The condensed steam is collected at the bottom of the condenser and returned to the boiler using feed water pumps, to begin the water-to-steam, steam-to-water cycle again. The temperature of the condensate determines the pressure in the steam/condensate side of the condenser. This pressure is called the turbine backpressure and is usually a vacuum. Decreasing the condensate temperature will result in a lowering of the turbine backpressure and increasing turbine power output and efficiency.

The condenser also has the following secondary functions:

- The condensate is collected in the condenser hot well, from which the condensate pumps take their suction;
- Provide short-term storage of condensate;
- Provide a low-pressure collection point for condensate drains
- from other systems in the plant; and
- Provide for de-aeration of the collected condensate.

7.2 Types of condensers

The condensers are mainly classified as Mixing Type or Jet condensers and Non-mixing Type or Surface Condensers.

In mixing type condensers, the exhaust steam from prime mover and cooling water come in direct contact with each other and steam condenses in water directly. The temperature of the condensate (condensed steam + cooling water) is same as that of cooling water leaving the condenser. The condensate coming out from the mixing type condenser cannot be used as feed to the boiler as it is not free from salt and pollutants. These types of condensers are generally preferred where the good quality water as feed to boiler is easily available in ample quantity. Mixing condensers are seldom used in modem power plants.

a) Mixing or Jet type condensers

In such system exhaust steam and cooling water directly comes into contact. The heat transfer from steam to water is by direct conduction. Two mediums are mixed together and condensate contains impurities, so here cooling water has to be treated in water treatment plants. Jet condensers are less popular due conduction losses and power requirement.

It is classified as,

- Low level jet condensers (Parallel flow and Counter flow)
- High level jet condensers
- Ejector condensers

b) Non-mixing type condensers or Surface condensers

In non-mixing type of condenser, steam and cooling water do not come in direct contact with each other. The cooling water passes through the number of tubes attached to condenser shell and steam surrounds the tubes. These types of condensers are universally used in all high capacity modem steam power plants as the condensate coming out from the condenser is used as feed for the boiler.

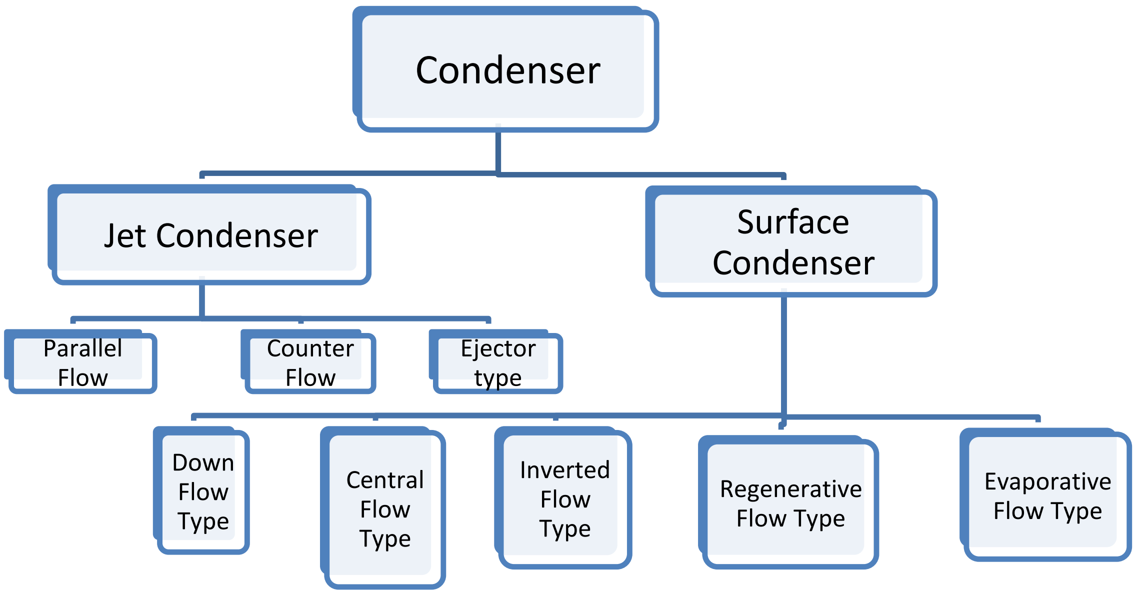


Figure 7.1 Types of condenser

7.2.1 Low level Parallel flow jet Condenser

Fig. 7.2 shows schematic arrangement of low level parallel flow jet condenser. In this type of condenser, the exhaust steam and cooling water both flow in the same direction and parallel to each other

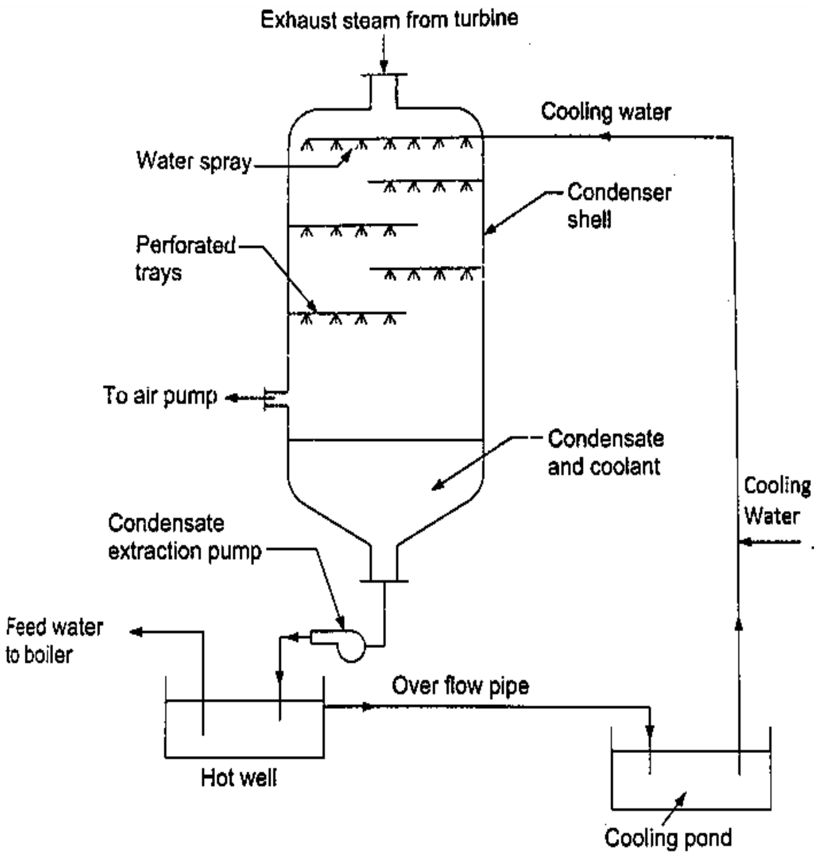


Figure 7.2 Low level Parallel flow jet Condenser

- Exhaust steam from the steam turbine is introduced from the top of the condenser while cooling water is sprayed on the steam through multiple jets. The cooling water is passed through series of perforated trays. This helps in breaking the water sprays and increases the heat transfer rate by providing more contact area. The cooling water condenses the exhaust steam and the condensate flows downwards and is collected from the bottom of the condenser.
- Vacuum is maintained in the condenser with the help of dry air pump which extracts the air present in the condenser. The condensate is removed by condensate extraction pump. The condensate extraction pump delivers the condensate into the hot well from where surplus water flows to the cooling pond through overflow pipe.
- No separate cooling water pump is required to supply cooling water ns the vacuum created in the condenser is sufficient to draw cooling water into the condenser. The height of the condenser top should be low level and should not exceed 10 meters from the cooling water tank surface otherwise water will not be drawn automatically.
- In this type of condenser, the coldest water is in contact with hot steam and hence it is less efficient than counter flow jet condenser. Low level condenser has a disadvantage that the water from hot well will flood the steam turbine, if the condensate extraction pump fails.

7.2.2 Low level Counter flow jet Condenser

Fig. 7.3 shows schematic arrangement of low level counter flow jet condenser in which cooling water and exhaust steam flow in opposite direction. The exhaust steam is supplied from the bottom side of the condenser and it flows upward while the cooling water is supplied from the top of the condenser. The water flows in downward direction through series of perforated trays. The steam gets condensed when it comes in contact with the cording water.

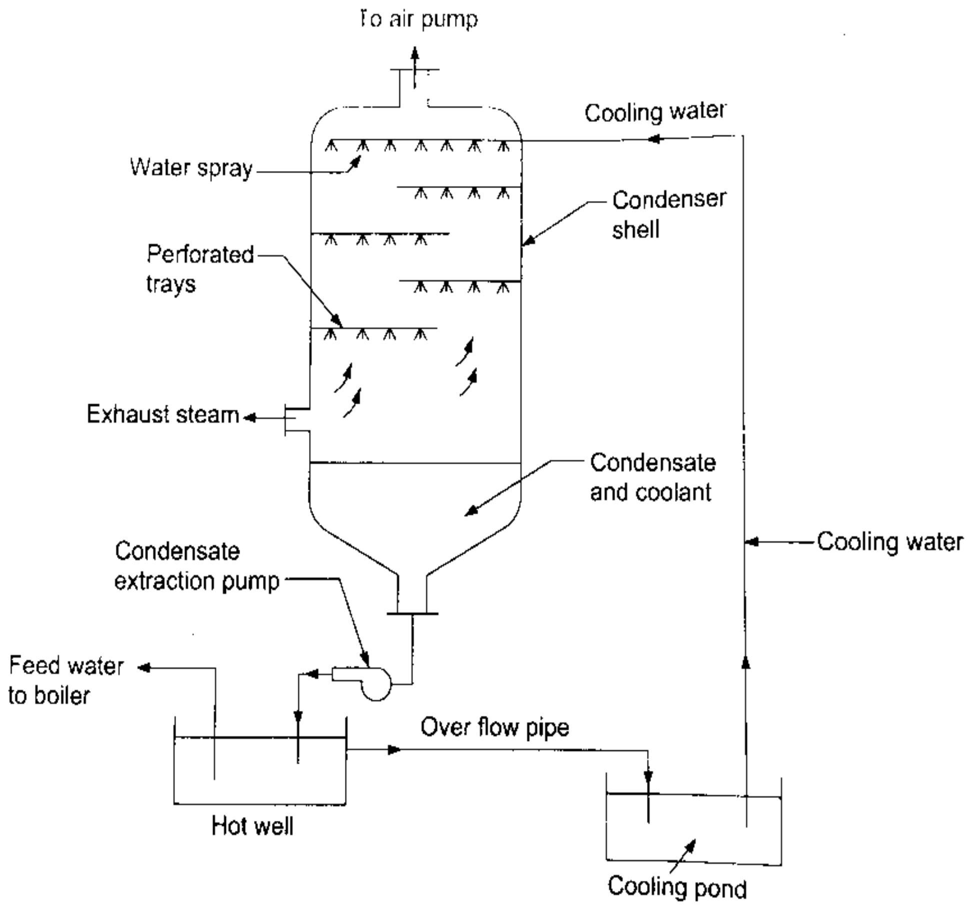


Figure 7.3 Low level counter flow jet Condenser

- The air extraction pump located at the top of the condenser shell, sucks the air and any uncondensed vapour. The air pump maintains the required vacuum in the condenser and causes the cooling water to be lifted to a height of approximately 5.5 meter. A pump for supply water is needed only if water is to be lifted greater than 5.5 meter height.
- The mixture of condensate and coolant is extracted with the help of condensate extraction pump and is discharged into the hot well. The excess amount of condensate is pumped into the cooling pond by an overflow pipe and remainder is pumped to the boiler as feed water.
- Counter flow jet condenser is more efficient than parallel flow type as the hottest steam comes In contact with hottest water.

7.2.3 High level Counter flow jet Condenser or Barometric Condenser

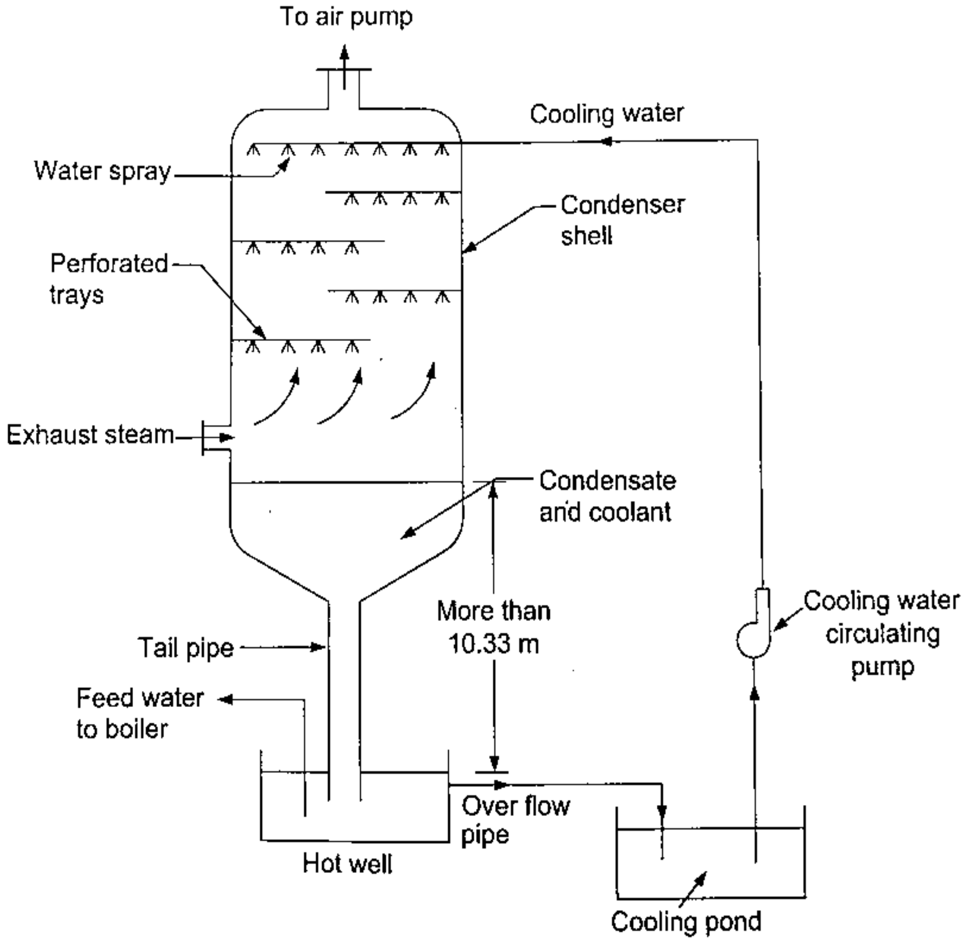


Figure 7.4 High level Counter flow jet Condenser

- Fig. 7.4 shows schematic arrangement of high level jet condenser. It is also called barometric condenser since the condenser shell is placed at height greater than that of atmospheric pressure in water column i.e. 10.33 m.
- A long tail pipe, more than 10.33 m in height, is attached between the bottom of the condenser and the hot well. This allows the condensate and coolant to fall from the condenser under gravity, hence condensate extraction pump is not needed.
- The exhaust steam enters at the bottom, flows upwards and meets the down coming cooling water in the same way as that of low level jet condenser. The vacuum is created by the air pump placed at the top of the condenser shell. This condenser requires a separate pump to supply the cooling water to the condenser as the height of the shell is above 10.33 m. The condensate and cooling water descends through the tail pipe by gravity and surplus water from the hot well flows to the cooling pond through the overflow pipe.
- Another advantage of this condenser is that water from the hot well will not be able to rise into the condenser and flood the turbine.

7.2.4 Ejector Condenser

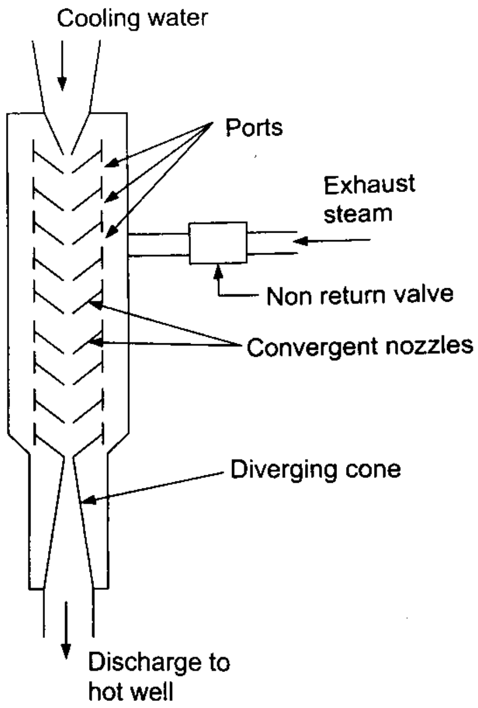


Figure 7.5 Ejector Condenser

- Here the exhaust steam and cooling water mix in hollow truncated cones. Due to this decreased pressure exhaust steam along with associated air is drawn through the truncated cones and finally lead to diverging cone. In the diverging cone, a portion of kinetic energy gets converted into pressure energy which is more than the atmospheric so that condensate consisting of condensed steam, cooling water and air is discharged into the hot well.
- The exhaust steam inlet is provided with a non-return valve which does not allow the water from hot well to rush back to the engine in case a failure of cooling water supply to condenser.

7.2.5 Double Pass Surface Condenser (Two-flow surface condenser)

- A surface condenser, as illustrated in fig. 7.6, consists of a cast iron shell, cylindrical in shape and closed at each end to form a water box. A tube plate is located between each cover head and the shell. A number of water tubes are fixed to the tube plates.

- The exhaust steam from the engine enters at the top of the condenser and is condensed by coming in contact with the cold surface of the tubes through which cooling water is being circulated. The cooling water enters at one end of the tubes situated in the lower half of the condenser and after flowing to the other end returns in the opposite direction through the tubes situated in the upper half of the condenser.

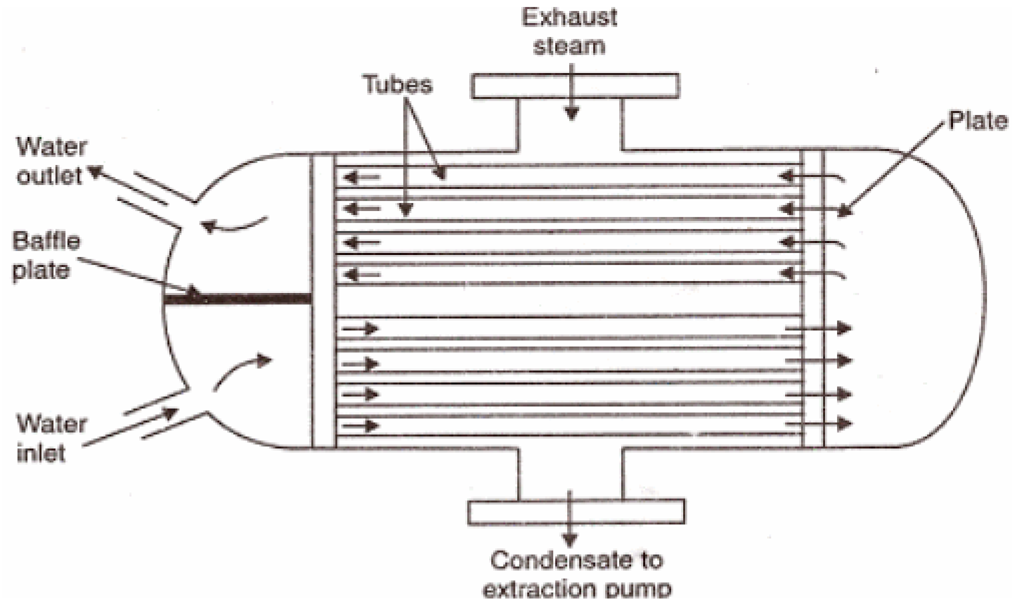


Figure 7.6 Double Pass Surface Condenser

- The resulting water from the condensation of the exhaust steam and the air associated with the uncondensed water vapour, are extracted from the bottom of the condenser where the temperature is the lowest, so that the work of the wet air pump is reduced. The surface condenser of this type requires two pumps, namely, wet air pump to remove air and condensate, and a water circulating pump to circulate the cooling water under pressure through the tubes of the condenser. Steam driven reciprocating pumps are used, but electric driven centrifugal pumps are used very extensively (commonly) for circulating water and condensate removal. Steam ejectors are also sometimes used for air removal.
- Surface condensers may be classified as, two-flow or multi-flow condensers. Surface condenser, as illustrated in fig. 7.6, is a two-flow condenser because the circulating water traverses (travels) the whole length of the ‘condenser twice. By introducing more partitions in the water boxes, the condenser may be converted into a three-flow condenser or even four-flow condenser.
- The velocity of cooling should be increased with the increase of number of flows. The rate of transmission of heat through the tubes to the circulating water, increases with the increase of number of flows, but the power required to circulate the water is increased.

7.2.6 Down flow condenser

Figure 7.7 shows a sectional view of a down flow condenser. The exhaust team enters at the top and flows downwards over the tubes through which the cooling water is flowing. The exhaust steam as a result is condensed and the condensate is extracted from the bottom by the condensate extraction pump.

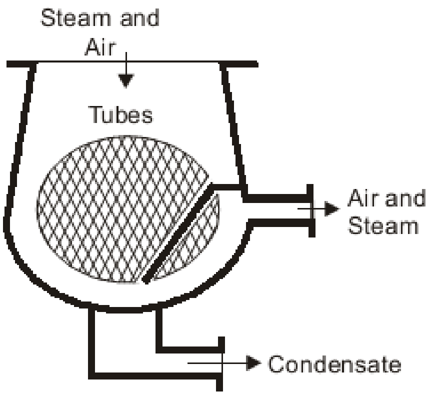


Figure 7.7 down flow condenser

- The cooling water enters at one end of the tubes situated in the lower half of the condenser and after flowing of the other end returns in the opposite direction through the tubes situated in the upper half of the condenser. The temperature of condensate, therefore, decreases as the exhaust steam passes downwards, and hence partial pressure of steam decreases from top to bottom of the condenser.
- The air exit is shielded from the downstream of the condensate by means of a baffle plate, and thus air is extracted with only a comparatively small amount of water vapour. As the air passes downwards, it is progressively cooled and becomes denser (partial pressure of air increases) and hence it is extracted from the lowest convenient point. In a condenser of this type, therefore, the partial pressure of steam decreases, the partial pressure of air correspondingly increases, as the mixture passes from top to the bottom of the condenser.
- The result of all these effects is that the condensate temperature falls below the exhaust steam temperature which enters at the top. Thus, by cooling the air, the capacity of the air pump is considerably reduced.

7.2.7 Central Flow Surface Condenser

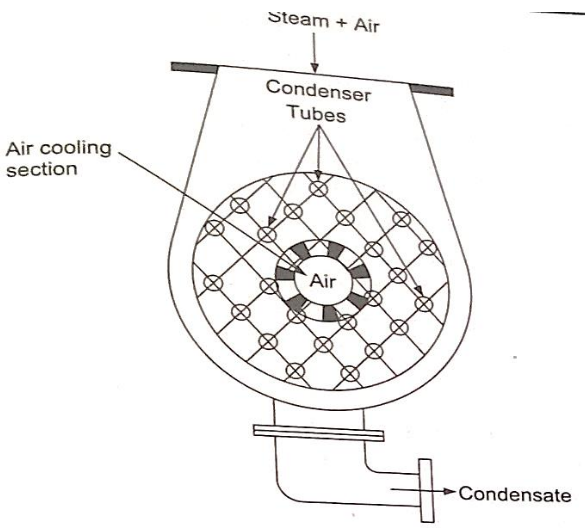


Figure 7.8 Central Flow Surface Condenser

- In Central Flow Surface Condenser (fig. 7.8), the suction pipe of the air extraction pump is placed in the center of the tubes nest; this causes the condensate to flow radially towards the center as shown by the arrows in the figure.
- The condensate leave sat the bottom where the condensate extraction pump is situated. The air is withdrawn from the center of the nest of tubes. This method is an improvement on the down flow type as the exhaust steam is directed radially inward by a volute casing around the tubes nest; it has thus access to the whole periphery of the tubes.

7.2.8 Evaporative condenser

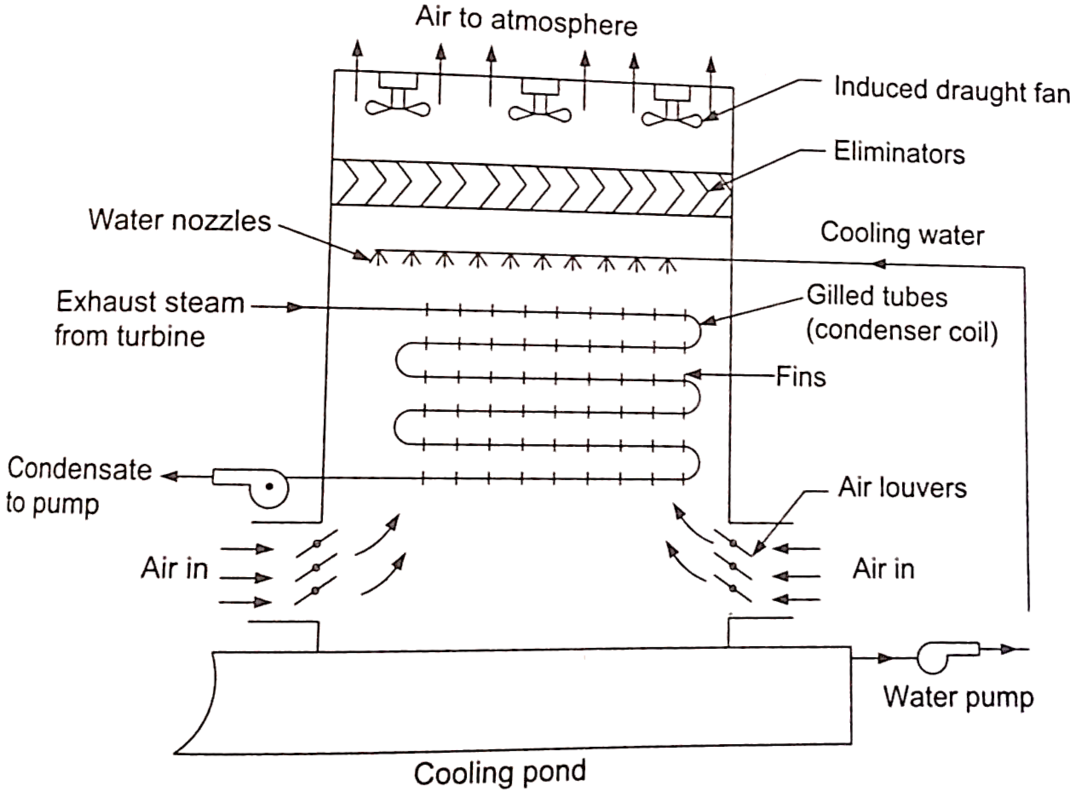


Figure 7.9 Evaporative condenser

- Where the supply of cold water is extremely limited, the evaporative condenser is the only suitable type which can be run on a minimum supply of cooling water, and even without cooling water in cold weather and on light loads. Exhaust steam from the engine is exhausted into a coil of grilled pipes or series of tubes, the outlet of which is connected to the wet air pump.
- Cooling water is allowed to flow in a thin film over the outside of the tubes. A natural or forced air current causes rapid evaporation of this film of water. The effect of this is that not only the steam inside the tubes is condensed but some of the cooling water is also evaporated on the outside of the tubes. The process of evaporation

cools the water. The film of water on the outside of the tubes is maintained by allowing water to trickle (fail) over them continuously.

- The water which is not evaporated falls into an open tank or collecting tank under the condenser, from which it can be drawn by circulating water pump and used over again. The evaporative condenser is placed outside in the open air. On account of nuisance which would result from the production of clouds of steam, this type of condenser is restricted to small power plants.

7.3 Sources of air leakage in condenser

The main sources of air through which air may enter into the condenser are,

1) The feed water contains dissolved air which is liberated in the boiler when the steam is formed. This dissolved air is carried along with the steam into the condenser.

(2) Air leaks through the joints, packings and glands into the condenser as the pressure inside the condenser is less than atmospheric pressure.

(3) In jet condensers, air dissolved in water is also carried to condenser. This dissolved air gets liberated in condenser at low pressure.

Usually the quantity of air leakage in surface condensers is around 0.05 percent of the steam condensed.

7.4 Effect of air leakage

The air leakage in a condenser will produce the following effects:

- Presence of air lowers the vacuum in the condenser, hence the back pressure in the condenser increases. This reduces the work output of the steam turbine and also the thermal efficiency of the plant.
- Presence of air in the condenser lowers the partial pressure of the steam which results in lower saturation temperature. This increases the latent heat of steam. Hence more cooling water is required to condense the steam.
- Air forms film adjacent to the pipe surface of the condenser. As air has poor thermal conductivity, the rate of heat transfer from vapour to cooling medium is reduced.
- Air leakage causes corrosion of condenser tubes which reduces the life of condenser.
- To remove air, large air pump is required, hence power consumption to drive the pump increases.

7.5 Method of obtaining maximum vacuum in condenser

The various methods for obtaining maximum vacuum in condensers used in modern steam power plants are mentioned below:

(1) Air pump:

The air pump is used to maintain the desired vacuum in the condenser by extracting the air and other non-condensable gases. They are classified as:

Wet air pump: It removes both air and condensate as well as non-condensable gases.

Dry air pump: It removes only air and other non-condensable gases.

(2) Steam air ejector:

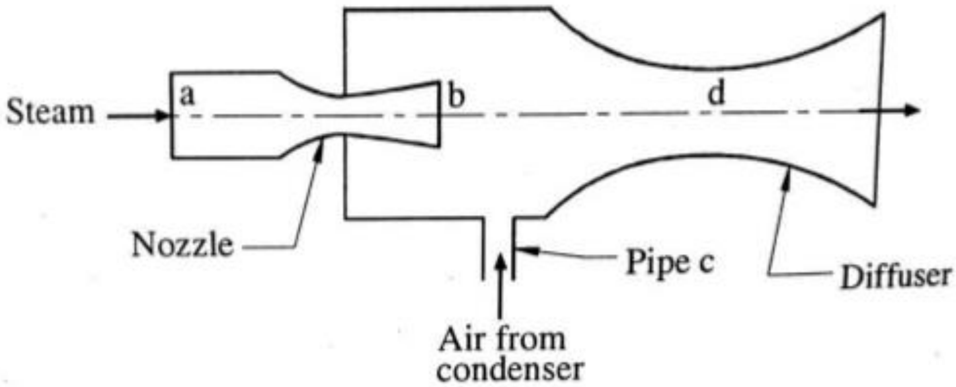


Figure 7.10 Steam jet air ejector

- The wet air pump uses the steam air ejector to remove the air from the mixture. Fig. 7.10 shows schematic arrangement of steam air ejector.
- It consists of convergent-divergent nozzle and a diffuser. High pressure steam from the boiler enters the nozzle at ‘A’, where its kinetic energy increases and pressure reduces. Pipe ‘C’ is connected to the condenser from where moist air is sucked by the low pressure steam at location B.
- The momentum of the steam jet carries the mixture of steam and air into the diffuser where its velocity decreases and pressure increases by the time it leaves the diffuser. Fig. shows only one ejector, but if more than one ejector are used, very low pressure can be obtained in the condenser.
- Steam ejector is simple in construction, cheap, highly efficient and without any moving parts. They are suitable for large power plants where high condenser vacuum is required.

(3) De-aerated feed water:

De-aeration is the process of removal of non-condensable gases from feed water. It helps both in maintaining better vacuum in the condenser and controlling corrosion of the steel shell and piping of the steam power plant.

(4) Air tight joints:

The joints of steam power plant can be made air tight by the use of suitable packing materials at the joints of piping. These joints should be periodically inspected.

7.6 Vacuum and condenser efficiency

Vacuum efficiency is defined as the ratio of actual vacuum to the maximum obtainable vacuum.

$$\eta_{vacuum} = \frac{Actual\ vacuum\ in\ the\ condenser}{Maximum\ obtainable\ \ vacuum}$$

$$= \frac{Barometric\ pressure - Total\ pressure\ in\ condenser}{Barometric\ pressure - saturation\ pressure\ of\ steam\ corresponding\ to\ condenser\ temperature}$$

$$= \frac{p_b - p_t}{p_b - p_s}$$

Maximum obtainable vacuum obtained when there is only steam and no air is present in the condenser. Vacuum efficiency will be 100 % when there is no air present in the condenser. But in a steam condenser, mixture of steam and air is present.

Condenser efficiency,

$$\eta_{condenser} = \frac{Rise\ in\ temperature\ of\ cooling\ water}{Maximum\ possible\ temperature\ rise\ of\ cooling\ water}$$

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

Where,

$t_o = Outlet\ temperature\ of\ cooling\ water$
$t_i = Inlet\ temperature\ of\ cooling\ water$
$t_s = Saturation\ temperature\ corresponding\ to\ absolute$ *Pressure in the condenser*

7.7 Mass of cooling water required

Approximately 30 to 50 kg of cooling water is required per kg of steam condensed. During condensation, steam release its latent heat and sometimes a portion of sensible heat also. So the temperature of condensate leaving the condenser is less than the saturation temperature of the condenser. This temperature difference is known as undercooling or subcooling of the condensate.

The rate of heat loss of exhaust steam,

$Q_s = Latent\ heat + Subcooling\ heat$

$Q_s = m_s[xh_{fg} + C_{pw}(t_s - t_c)]$

By rearranging,

$Q_s = m_s[C_{pw}t_s + xh_{fg} - C_{pw}t_c]$

Now, $C_{pw}t_c = h_{fc} = sensible\ heat\ of\ condensate\ leaving$

$Q_s = m_s[h_f + xh_{fg} - h_{fc}]$

The rate of heat gain by cooling water,

$Q_w = mass\ flow\ rate \times specific\ heat \times Temperauture\ rise\ of\ water$

$= m_w c_{pw}(t_o - t_s)$

Where, t_o and t_s are outlet and inlet temperature of circulating water.

In condenser heat lost by steam is gain by cooling water.

$\therefore Q_s = Q_w$

$\therefore m_w c_{pw}(t_o - t_s) = m_s[h_f + xh_{fg} - h_{fc}]$

$$\therefore m_w = \frac{m_s[h_f + xh_{fg} - h_{fc}]}{c_{pw}(t_o - t_s)}$$

This equation is applicable to both surface and jet condenser. However, in the jet condenser as the condensate and cooling water mix up, so the temperature of cooling water at exit will be same as that of the condensate.

7.8 Edward air pump

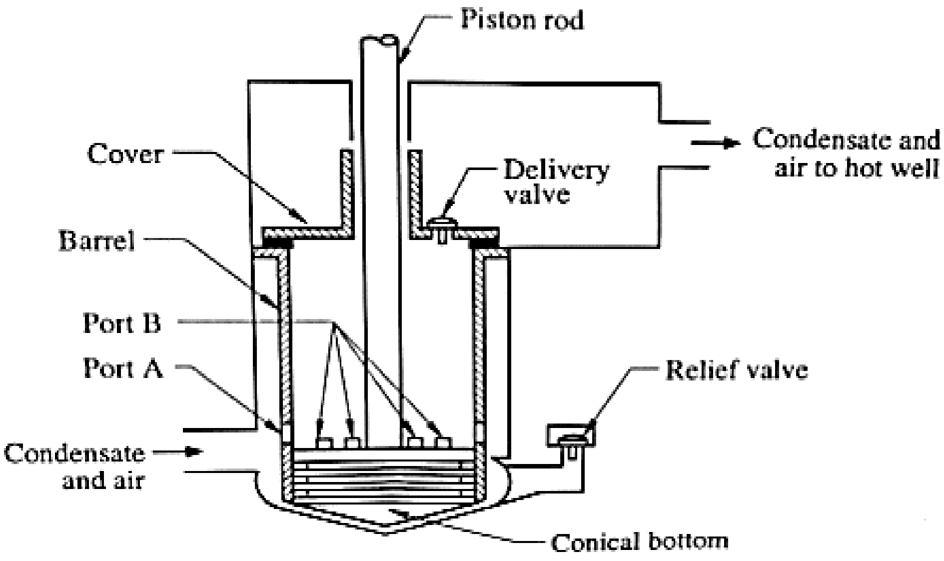


Figure 7.11 Edward air pump

- It is wet air pump of reciprocating type which is used to extract both condensate and non-condensable gases. Fig, 7.12 shows schematic diagram of Edward's air pump.
- It consists of number of delivery or head valves which are mounted on the cover which is placed at the top of the pump barrel. The reciprocating piston of the pump is flat on its upper surface and conical at the bottom as shown in Fig. 7.11. The bottom of the pump casing is also of conical shape in order that piston head can be easily seated. The piston has several ports along its periphery. These porta A and B as shown in Fig. 7.11 communicate with the condenser.
- When the piston is at the top of the barrel, the condensate and air from the condenser is collected in the conical portion of the barrel and enter through the ports above the piston. Consider the case when the piston is at the top and starts moving downwards. A partial vacuum will be created in the portion above the piston resulting in the closure of the delivery valve.
- Further motion of the piston in the downward direction causes its conical end to displace the condensate rapidly through the ports above the piston. Thus, a mixture of condensate, water vapour and air fills the space above the piston through the ports. This mixture is compressed when the piston goes up and raises the pressure above atmospheric pressure. This opens the delivery valve and discharges the condensate-air mixture above the cover.
- The condensate flows over the weir to the hot well, which is at atmospheric pressure. The weir maintains a certain head of water above the cover to avoid air being leaked into the barrel.
- A relief valve is provided at the base of the cylinder. If the pressure in the bottom of the pump exceeds the atmospheric value, the relief valve gets lifted and allows the condensate and air to escape through it.
- This pump is suitable for small power plants where there is requirement of low vacuum. Special feature of Edward's air pump is the absence of suction and bucket valve which is necessary in ordinary reciprocating air pumps.

7.9 Necessity of cooling pond and cooling towers

The principle of operation of cooling towers is very similar to that of the evaporative type of condensers, in which the warm water gets cooled by means of evaporation. Water evaporates as a result of the hot water droplet coming in contact with the air (which is being pumped out by means of a fan). This evaporating water also absorbs the latent heat from the water surrounding it. By losing latent heat, the water is cooled.

The purpose cooling tower is to cool the water used in the water cooled condenser of the refrigeration plant so that the same water can be reused to absorb the heat at the condenser. The basic principle of cooling of water is the evaporative cooling achieved by using atmospheric air. The condenser water is sprinkled through nozzles and air on passing over the water droplets creates evaporative cooling of water. The heat lost from the water is carried by the air which increases the enthalpy of air leaving the cooling tower. The temperature drop achieved depends on the following factors.

- Surface area of water exposed to air stream.
- Dry bulb and wet bulb temperature of the air.
- Velocity of air.
- Water inlet temperature
- Direction of air flow in relation to water
- Contact time period of air with water.

Theoretically, it is possible to cool the water up to wet bulb temperature of the air entering the cooling tower. Generally, the temperature of water coming out from the cooling tower is 3 ^{0}C to 5 ^{0}C above the WTB of the entering air. It is very important to operate the cooling tower at optimum efficiency to get water at lowest possible temperature for the condenser.

Cooling ponds are used where sufficient land is available, as an alternative to cooling towers or discharging of heated water to a nearby river or coastal bay, a process known as "once-through cooling." The latter process can cause thermal pollution of the receiving waters. Cooling ponds are also sometimes used with air conditioning systems in large buildings as an alternative to cooling towers. Cooling towers are not a good choice because their internal surfaces have been coated with a non-approved paint such as bitumen or epoxies, as a result cooling ponds are a better option.

The pond receives thermal energy in the water from the plant's condensers and the energy is dissipated mainly through evaporation. Once the water has cooled in the pond, it is reused by the plant. New water is added to the system ("make-up" water) to replace the water lost through evaporation.

7.10 Condenser water cooling system

Depending upon the availability of water, various condenser water cooling systems are classified as follows:

1) Open or once through system
2) Closed cooling system
3) Mixed cooling system

Open or once through system

This type of cooling system is used where required quantity of water is available throughout the year. The plant is usually located near a river or sea.

As shown in Fig. 7.12 water is drawn from upper side of river by pump, filtered and circulated through the condenser. The hot water is discharged to the lower side of the river at a temperature of 5 to 10 °C higher than the inlet temperature. The temperature of hot water should be kept within safe limits so that it is not harmful to life of fishes.

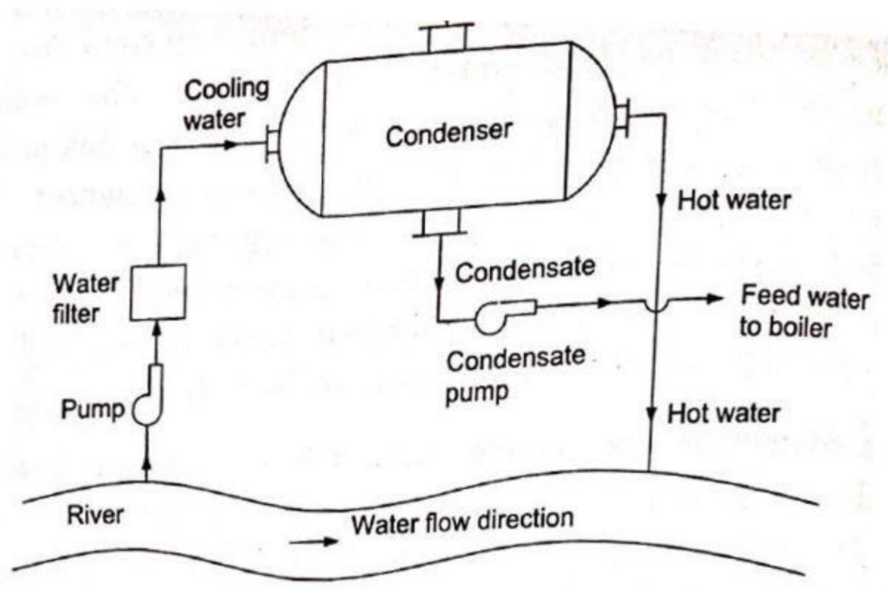


Figure 7.12 Open cooling system

Certain distance between inlet and outlet of water in the river should be maintained so that there is no recirculation of hot water otherwise it will reduce the efficiency of condensing plant.

Closed cooling system

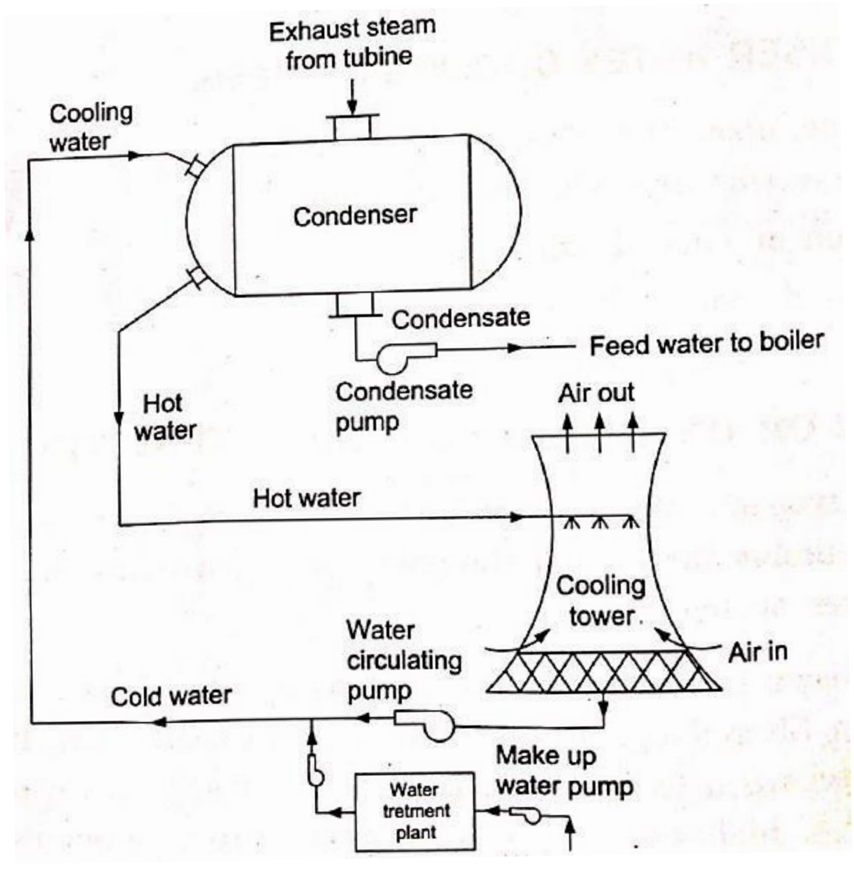


Figure 7.13 Closed cooling system

Fig. 7.13 shows schematic diagram of closed cooling system. This system is used when sufficient quantity of water for condensing the steam is not available from lake or river.

The hot water coming out of the condenser is cooled either in a spray pond or in a cooling tower and the cooled water is recirculated with the help of circulating pump to the condenser.

In this system some amount of water is lost by evaporation and windage in the cooling tower or spray pond, hence 2 to 5 percent make-up water is added to compensate this water loss.

Mixed cooling system

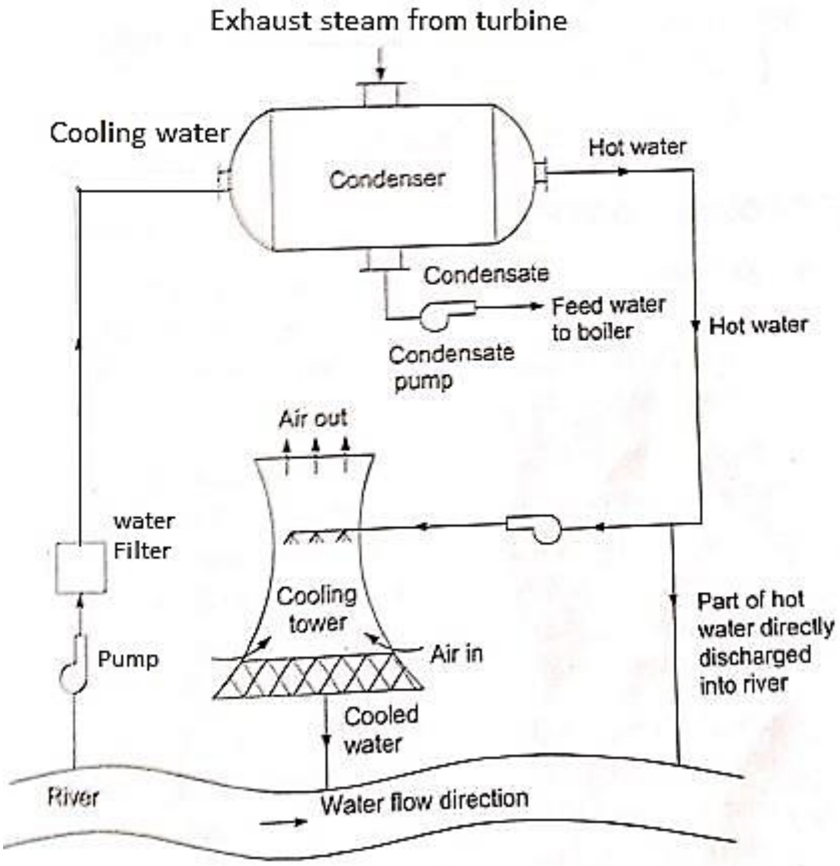


Figure 7.14 Mixed cooling system

Mixed cooling system is combination of both Open and Closed system. Fig. 7.16 shows schematic diagram of mixed cooling system.

In this system, hot water coming out of the condenser is divided into two parts, one part of it is discharged directly into the lower side of the river and remaining part of water is pumped to the cooling tower, where it is cooled and then discharged to the lower side of the river. In this way temperature of the discharged water into the river is maintained within safe limits so that it is not harmful to the life of fishes. The cooling water is supplied from the river directly to the condenser.

7.11 Types of cooling towers and cooling ponds

According to the method adopted to circulate the air, cooling towers may be classified as:

a) Natural draft cooling towers
b) Mechanical draft cooling towers.

Natural Draft Cooling Tower

As the name indicates, the air is circulated inside the cooling tower by natural convection. The natural draft cooling towers are further classified as:

- Natural draft cooling towers spray type
- Natural draft cooling towers splash deck type

SPRAY TYPE

The entire system is housed inside a box-shaped structure which also accommodates spray headers, spray nozzles, and louvers. The louvers (usually made of steel) are placed on the sides to enhance natural circulation of air inside the cooling tower. To prevent the carryover of water droplets to the atmosphere, the louvers are slanted towards the inside. Usually these types of cooling towers are located outside the building, so that the air can pass freely through the tower.

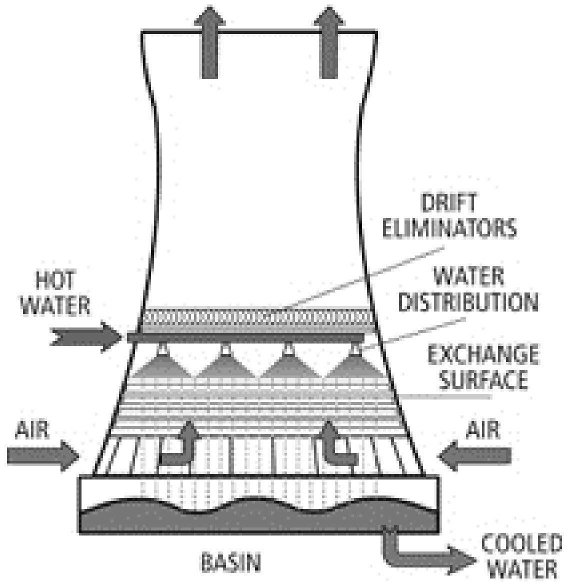


Figure 7.15 Natural draft cooling tower spray type

Warm water from the condenser is fed to the spray header by means of a pump. The spray header is located on top as shown in the sketch. The spray nozzles spray the warm water inside the tower. Air from the atmosphere comes in contact with the warm water, thereby causing some water droplets to evaporate. The evaporating water also absorbs some amount of latent heat from the surrounding water, which causes the remaining water to cool. The passing air also absorbs some amount of sensible heat from the warm water.

A make-up line, which may be controlled by a simple float, may be used to make up the loss of water due to evaporation. The cooled water may be then taken back to the condenser.

The size of the spray plays a vital role. If the spray is too fine, a greater amount of water will be taken away by the air. On the other hand, if the size of the spray is too large, the area of contact of water with the air will be reduced.

SPLASH DECK TYPE

This type of cooling tower is very similar to that of the spray type. Instead of a spray header, a water box is used. The water box has small holes at the bottom. It also contains decking inside the tower. The hot water from the condenser enters into the water box and splashes via holes in the water box on the decking. The main objective of the decking is to increase the surface area of contact of air with the warm water. This type of cooling tower is 20-30% more effective than the spray type.

Mechanical Draft Cooling Towers

The mechanical draft cooling towers are very much similar to that of the natural draft cooling towers. As the name indicates, air is circulated inside the tower mechanically instead of natural circulation. Propeller fans or centrifugal fans may be used.

According to the location of the fan, they are further classified as:

a. Forced draft cooling towers, and
b. Induced draft cooling towers.

Forced draft cooling tower

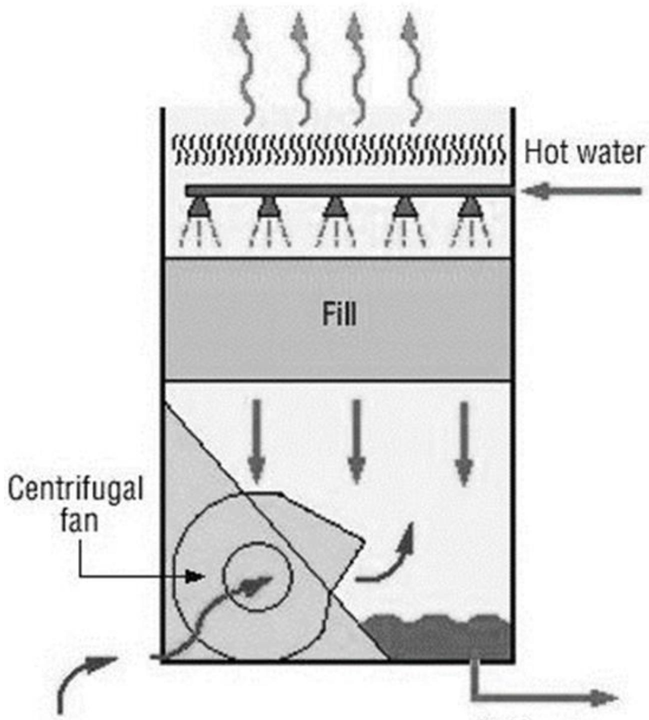


Figure 7.16 Forced draft cooling tower

In this system, fan is located near the bottom and on the side. This fan forces the air from bottom to top as shown in fig. 7.16. The hot water from the condenser is supplied at the top of the cooling tower which is sprayed through series of spray nozzles.

Around 3-5 % make up water is added to the pond to compensate the water lost due to evaporation. A drift eliminator is used to prevent loss of water droplets along with the forced air.

Induced Draft Cooling Towers

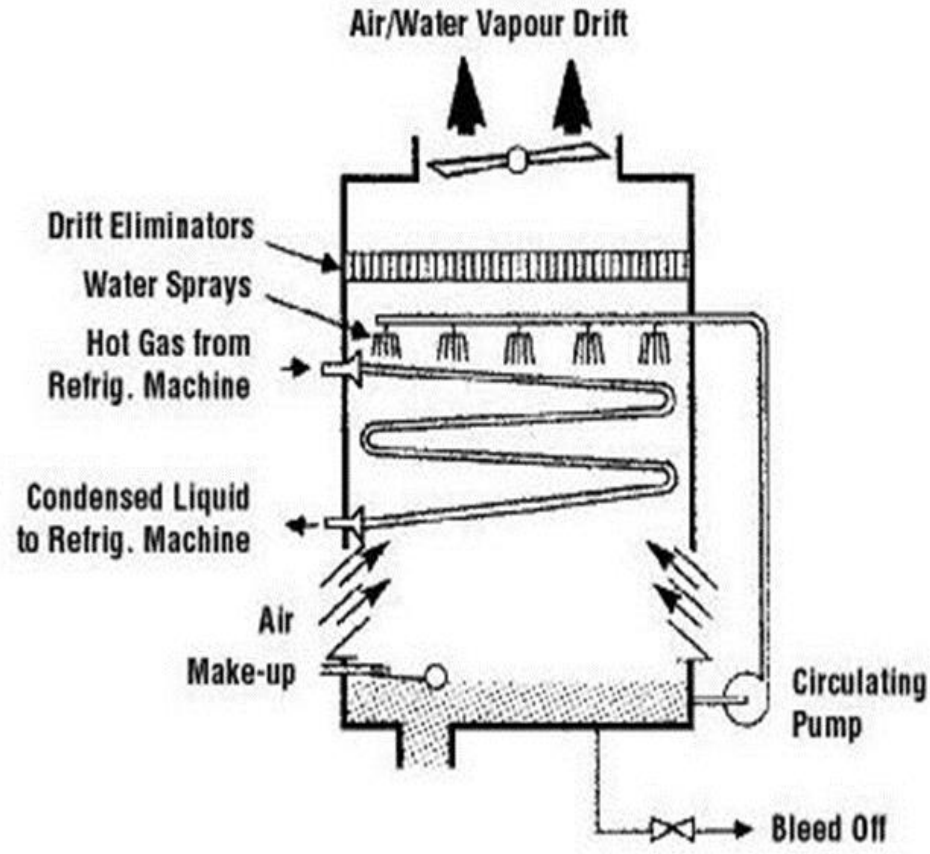


Figure 7.17 Induced Draft Cooling Towers

In this system, a centrally located fan at the top, takes suction from the tower and discharges it to the atmosphere. Line diagram of the same is shown in fig. 7.17.

The only difference between the induced draft cooling tower and forced draft cooling tower is that the fan is located at the top in the induced draft cooling tower.

Cooling pond

It is a simple method of cooling the condensate water but it is inefficient compared to cooling tower. In this method, water coming out of the condenser is discharged to a shallow pond of sufficient area, thus exposing the hot water to the atmosphere. The heat from the hot water is transferred to the air by convection and evaporation. Due to evaporation of water and absorption of latent heat by air, water gets cooled. The depth of water in cooling pond is around one meter.

Types of cooling pond:

Natural and directed flow Cooling pond

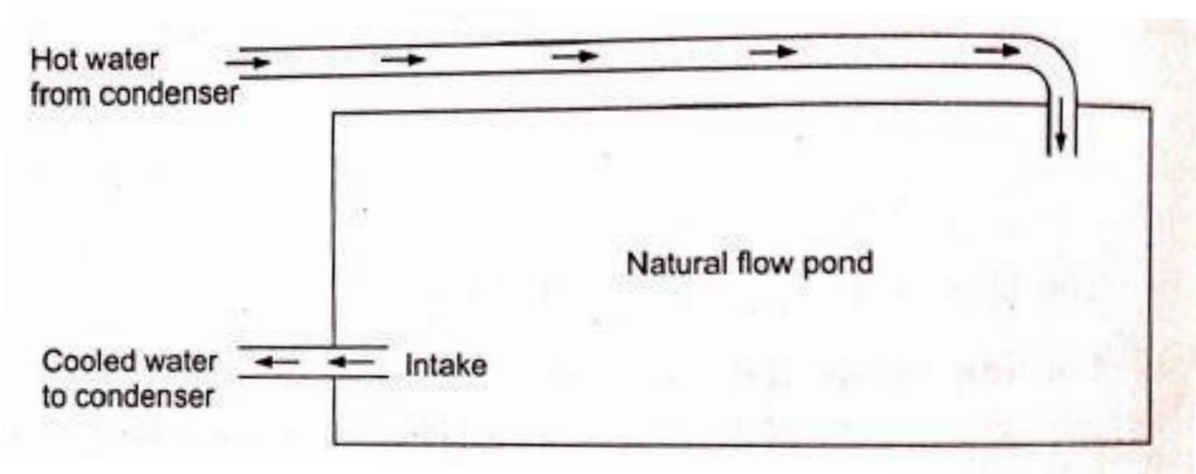


Figure 7.18 Natural flow cooling pond

In natural type, hot water coming out of the condenser is just allowed to flow in the pond as shown in Fig. 7.18. This system is rarely used now.

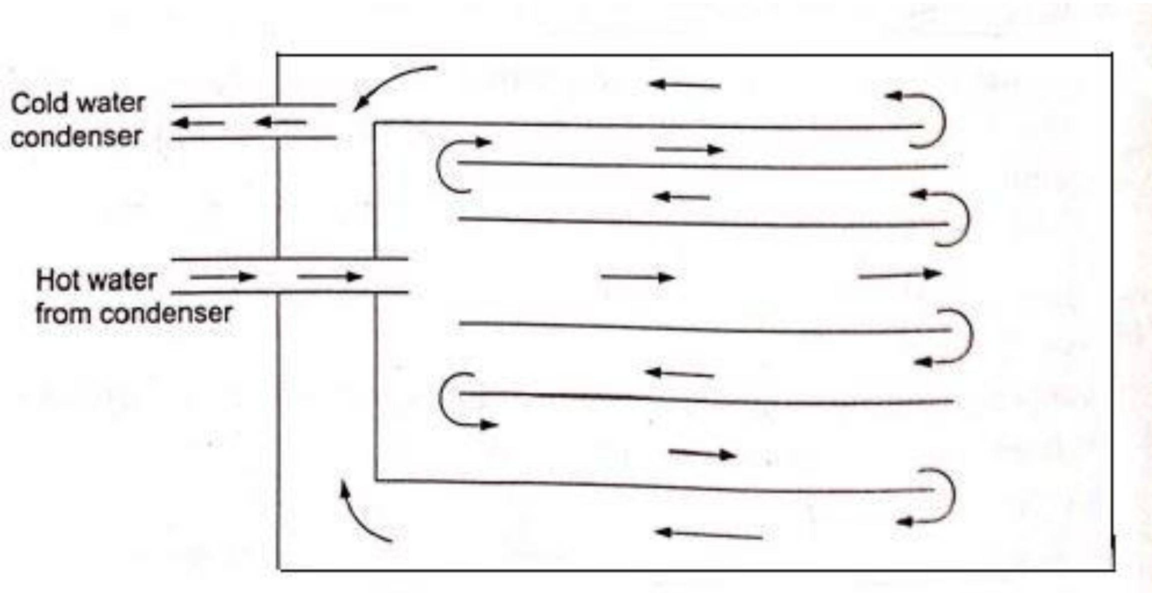


Figure 7.19 Directed flow cooling pond

Above fig. shows schematic diagram of directed flow cooling pond. The hot water coming out of the condenser enters the middle channel. On reaching the far end, it is divided in two direction by baffle. Water travels through the pond several times before uniting at intake point. Cooling in this case is more effective than natural type non directed cooling pond.

Single Deck and Double Deck Cooling pond:

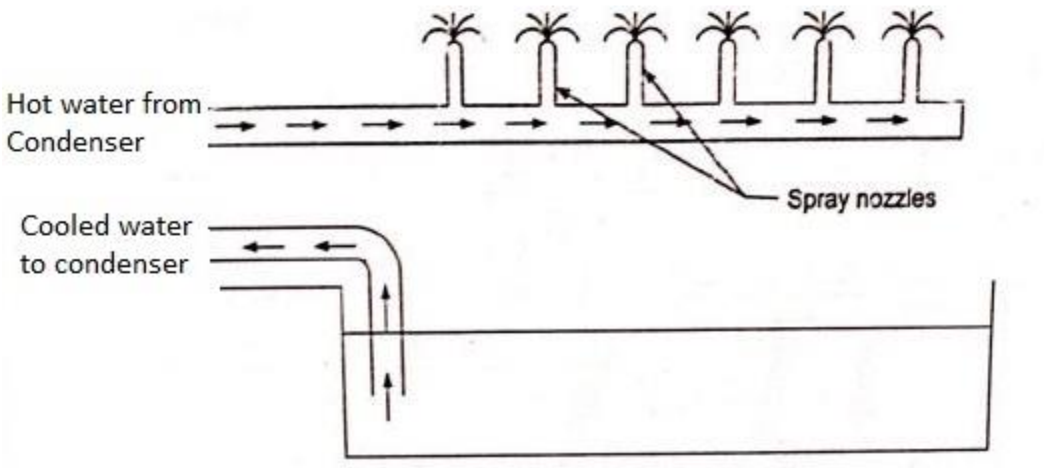


Figure 7.20 Single deck spray pond

In single deck cooling pond, spray nozzles are arranged at same elevation as shown in Fig. 7.20. The nozzles break the water into spray. Whirling motion can also be given to nozzles to produce better atomization of water. Nozzles are usually placed 1.2 to 2.4 m above the surface of the water and are arranged at sufficient distance to each other so that there is no interference between the sprays.

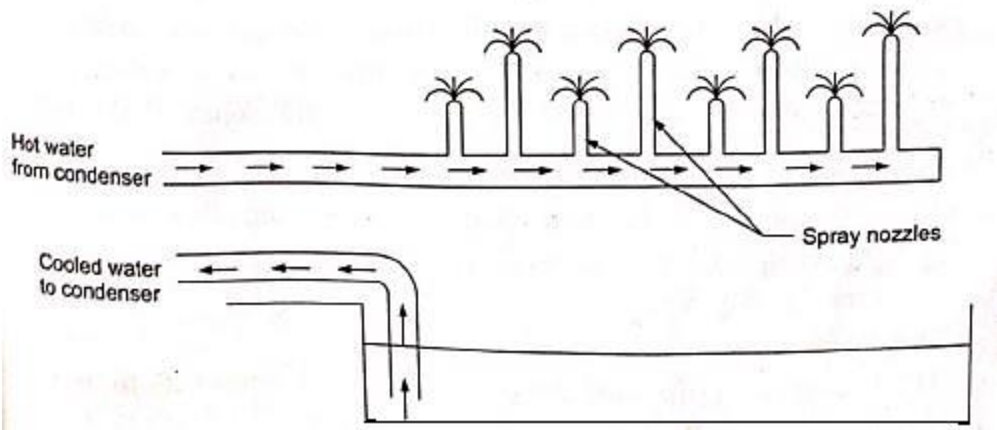


Figure 7.21 Double deck spray pond

In double deck cooling pond, spray nozzles are arranged at different elevations as shown in Fig. 7.21. Its cooling effect is more than single deck cooling pond as water comes in contact with air at lower temperature.

Open and Louvre fence cooling pond

Single or double deck cooling pond may be open type or provided with louvre fence. In open pond, drift losses are more as some water is carried away along with the wind when wind velocity is high. This can be prevented by providing louvre fence as shown in Fig. 7.21.

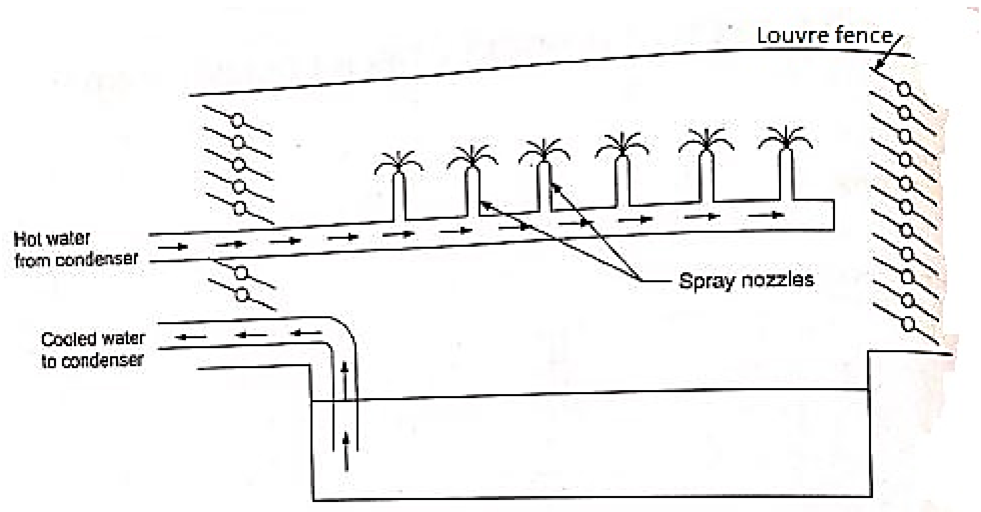


Figure 7.22 Spray pond with louvre fence

The factors which influence the rate of heat dissipation from cooling pond are: initial temperature of water entering the cooling pond, atmospheric temperature, relative humidity, wind velocity, solar radiation, shape and size of nozzle, area and depth of the pond.

8

Feed Water treatment

Course Contents

8.1 Necessary of Feed Water Treatment

Following are various reason which clearly indicate that feed water treatment is required in power plants before supply it into boiler.

- Natural water contains solid, liquid and gaseous impurities hence it cannot be used for steam generation in boiler.
- The boiler water needs to be alkaline and not acidic, so that it does not ruin the tubes.
- To prevent scale formation inside and outside the tubes.

8.2 Different impurities found in feed water and its effects

All natural waters contain various types and amounts of impurities. These impurities cause boiler problems and as such consideration must be given to the quality and treatment required of the water used for generating steam.

It is mainly classified in three parts

1. Undissolved and suspended solids.
2. Dissolved calcium and magnesium salts
3. Dissolved gases

Undissolved and suspended solids

i. **Turbidity and sediments**: It is suspended insoluble matter such as mud, sand etc. which settle down when there is no disturbance in water.

ii. **Sodium and Potassium salts:** They are alkaline in nature and accelerate the corrosion process.

iii. **Chlorides:** Increase the corrosive action in water.

iv. **Iron:** Ferrous bicarbonate is the most common soluble iron found in water. Such water becomes yellow in color and it is harmful as it forms soft scale.

v. **Manganese:** It is equally troublesome as iron.

vi. **Silica:** Natural water contains 1-100 ppm of silica. It accelerate hard scale in boiler tubes.

Dissolved calcium and magnesium salts

Calcium and magnesium salts are present in water in form of carbonates, bicarbonates, sulphates and clorides. The presence of these salts can be known as hardness of water. Hardness is further classified as temporary hardness and permanent hardness.

Temporary hardness is caused due to presence of dissolved bicarbonates of Calcium and magnesium and it is removed by boiling.

Permanent hardness is due to presence of chlorides, sulphides, nitrates of Calcium and magnesium. These salt cannot be removed by boiling and form hard scale on heating surface.

Dissolved gases

There are two gases which cause corrosion are oxygen and carbon dioxide which are present in dissolved form of water. Oxygen is corrosive to iron, Zinc, brass, and other metals.

Carbon dioxide is dissolved form in water forms weak carbonic acid. It cause corrosion of metal parts.

8.3 pH & its role in corrosion and scale formation.

pH value of water is the logarithm of reciprocal of hydrogen ion concentration in water. pH value varies from 0 to 14. pH value less than 7 indicates acidity of water and more than 7 indicates alkalinity of water.

Role of pH in corrosion

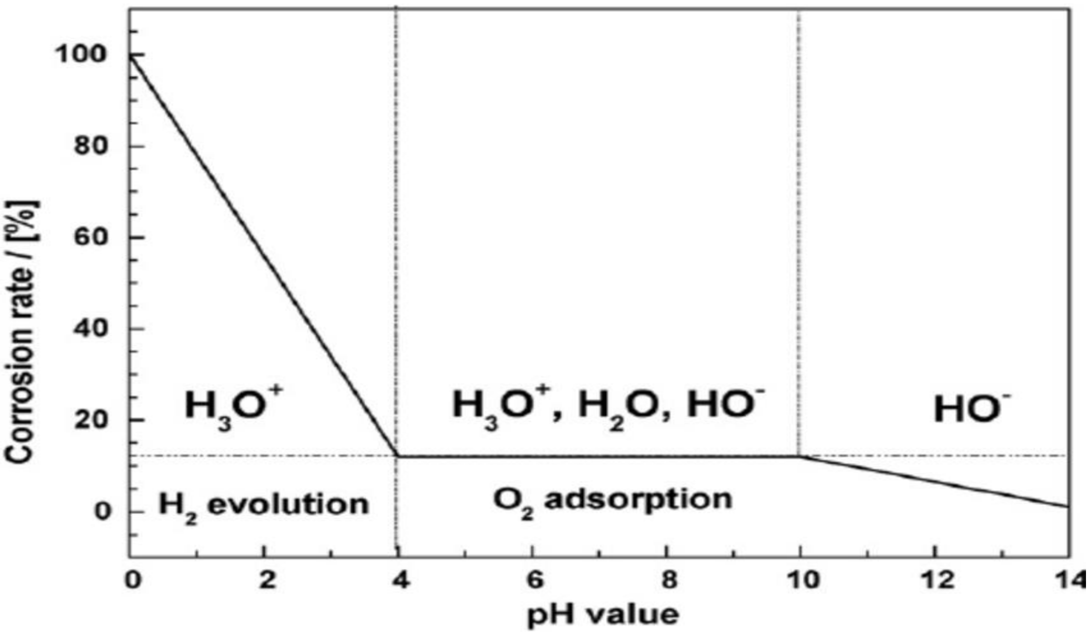


Figure 8.1 Role of pH in corrosion

The corrosion rate of iron in absence of oxygen is proportional to pH value upto 9.6. The pH value of water determines the solubility of iron and hence the rate of corrosion.

Corrosion rate increases due to presence of dissolved O2 and CO2 in water as concentration of H^+ ions increasing which increases the pH value of water.

Role of pH in Scale formation

Scale formation and corrosion are reciprocal phenomena. A decrease in pH value will make water more prone to corrosion whereas increase in pH value will increase the tendency of scale formation.

Calcium hardness, alkalinity and pH value are inter related variables in scale formation.

Calcium carbonates is the most troublesome deposits responsible for scale formation.

8.4 Methods of Feed Water Treatment

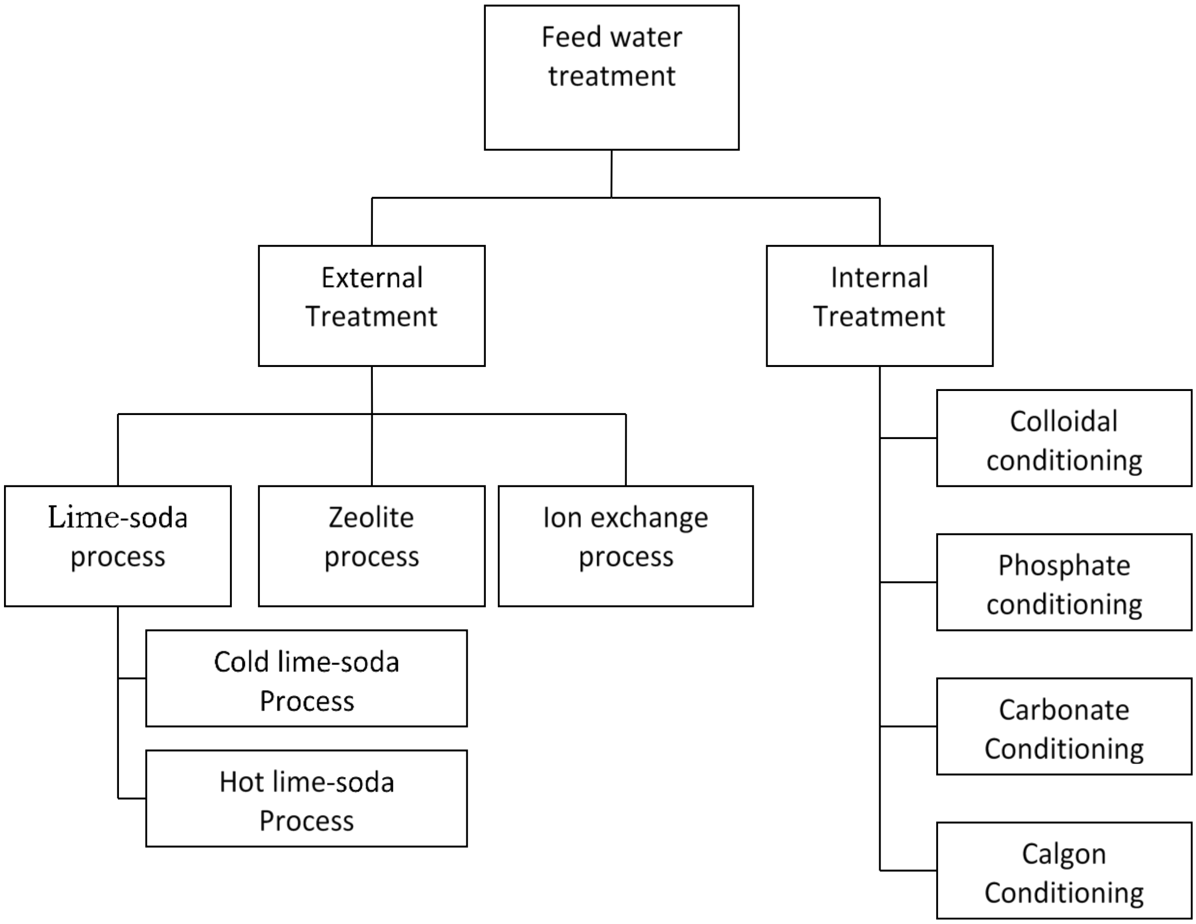


Figure 8.2 Methods of feed water treatment

8.5 Hot Lime soda Process

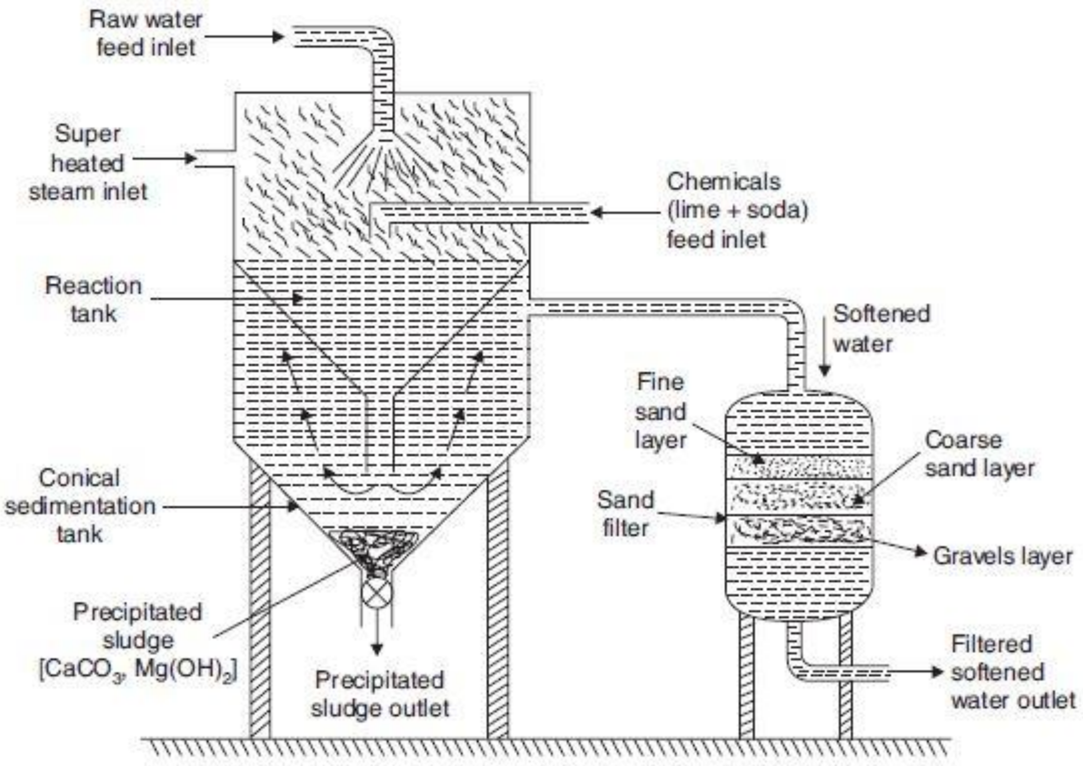


Figure 8.3 Hot lime soda process

Hot lime-soda plant consists essentially of three parts (a)'reaction tank' in which raw water, chemicals and steam are thoroughly mixed; (b)'conical sedimentation vessel' in which sludge settles down, and (c)'Sand filter' which ensures complete removal of sludge from the softened water.

In this method raw water and calculated quantities of chemicals (Lime + soda + coagulant) are fed from the top into the inner vertical circular chambers, fitted with a vertical rotating shaft carrying a number of paddles. As the raw water and chemicals flow down, there is a vigorous stirring and continuous mixing, whereby softening of water takes place.

Here the chemicals along with the water are heated near about the boiling point of water by exhaust steam.

Advantages of Lime soda process:

- It is a very economical.
- If this process is combined with sedimentation with coagulation, lesser amounts of coagulants shall be needed.
- The process increased the pH value of the treated water, thereby corrosion of the distribution pipes is reduced.

- Besides the removal of hardness, the quantity of minerals in the water are reduced.
- To certain extent, iron and manganese are also removed from the water.
- Due to alkaline nature of treated- water, amount of pathogenic bacteria's in water is considerably reduced.

Disadvantages of Lime soda process:

- Disposal of large amounts of sludge (insoluble precipitate) poses a problem. However, the sludge may be disposed of in raising low-lying areas of the city.
- This can remove hardness only up to 15ppm, which is not good for boilers.

8.6 Zeolite ion exchange Process

Zeolite is hydrated sodium alumino silicate capable of exchanging reversibly its sodium ions for Ca2+ and Mg2+, having the general formula $Na_2O.Al_2O_3.xSiO_2.yH_2O$ (where x=2-10 and y=2-6). Zeolite are two types,

1) Natural zeolites are non-porous for Ex; Natrolite Na2Al3O3.4sio22h2o
2) Synthetic zeolites possess gel structure. Synthetic Zeolites possess higher exchange capacity than natural Zeolites.

Process

For Softening of water by Zeolite process, hard water is percolated at a specified rate through a bed of zeolite; kept in a cylinder. The Hardness causing ions (ca^{+2}, Mg^{+2} etc.) are retained by the zeolite as CaZe and MgZe, while the outgoing water contains sodium salts. Reactions taking place during the softening process are,

$Na_2Ze + Ca(HCO_3)_2 \rightarrow CaZe + 2NaHCO_3$

$Na_2Ze + Mg(HCO_3)_2 \rightarrow MgZe + 2NaHCO_3$

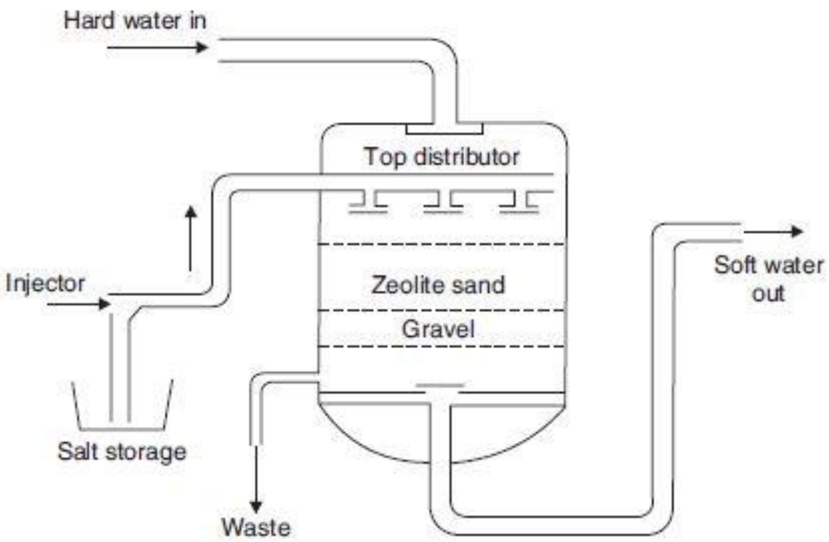


Figure 8.4 Zeolite ion exchange Process

Regeneration:

After Some time the zeolite is completely converted into calcium and magnesium Zeolites and it ceases to soften water i.e.; it gets exhausted. At this stage the supply of hard water is stopped and the exhausted zeolite is reclaimed by treating the bed with a concentrated NaCl solution,

$$CaZe \text{ (or } MgZe) + 2NaCl \rightarrow Na_2Ze + CaCl_2 \text{ (or } MgCl_2)$$

The washings are led to drain and the regenerated zeolite bed thus obtained is used again for softening process.

Advantages:

- If removes the hardness almost completely
- Equipment occupying a small space
- Requires less time
- It is quite clean

Disadvantages:

- Treated water contains more sodium salts than in time soda process
- The method only replaces Ca+2 and Mg+2 ions by Na+ ions leaves all the acidic ions.

8.7 Reverse Osmosis process

Reverse Osmosis is a technology that is used to remove a large majority of contaminants from water by pushing the water under pressure through a semi--permeable membrane.

Reverse Osmosis is the process of Osmosis in reverse. Whereas Osmosis occurs naturally without energy required, to reverse the process of osmosis we need to apply energy to the more saline solution. A reverse osmosis membrane is a semi---permeable membrane that allows the passage of water molecules but not the majority of dissolved salts, organics, bacteria and pyrogens. However, we need to 'push' the water through the reverse osmosis membrane by applying pressure that is greater than the naturally occurring osmotic pressure in order to desalinate (demineralize or deionize) water in the process, allowing pure water through while holding back a majority of contaminants. Following Figure shows the process of Reverse Osmosis. When pressure is applied to the concentrated solution, the water molecules are forced through the semi-permeable membrane and the contaminants are not allowed through.

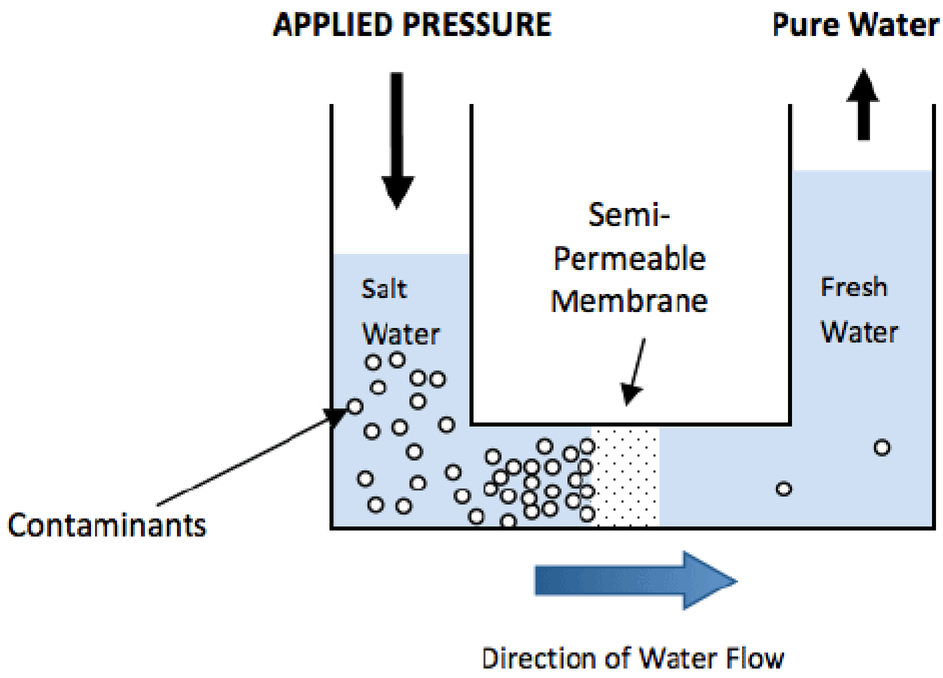


Figure 8.5 Reverse Osmosis process

Working

Reverse osmosis works by using a high pressure pump to increase the pressure on the salt side of the RO and force the water across the semi-permeable RO membrane, leaving almost all (around 95% to 99%) of dissolved salts behind in the reject stream. The amount of pressure required depends on the salt concentration of the feed water. The more concentrated the feed water, the more pressure is required to overcome the osmotic pressure.

In very simple terms, feed water is pumped into a Reverse Osmosis (RO) system and we end up with two types of water coming out of the RO system: good water and bad water. The good water that comes out of an RO system has the majority of contaminants removed and is called permeate. Permeate is the water that was pushed through the RO membrane and contains very little contaminants.

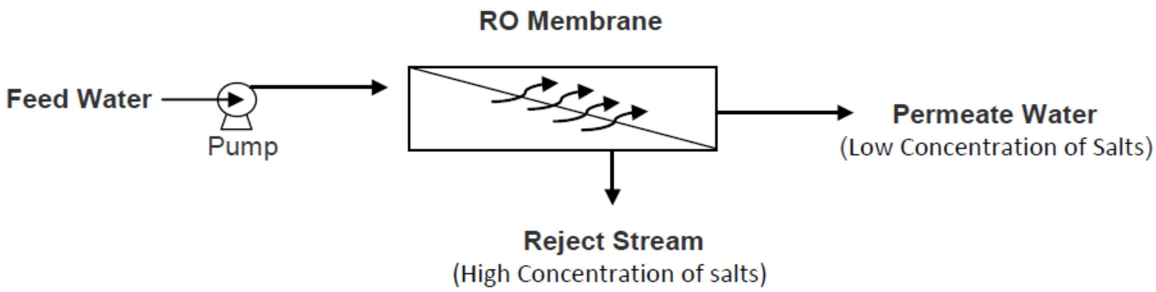


Figure 8.6 RO Pumping process

Figure 8.6 shows how an RO system works. As the feed water enters the RO membrane under pressure (enough pressure to overcome osmotic pressure) the water molecules pass through the semi---permeable membrane and the salts and other contaminants are not allowed to pass and are discharged through the concentrate stream, which goes to drain or can be fed back into the feed water supply in some circumstances to be recycled through the RO system to save water. The water that makes it through the RO membrane is called permeate or product water and usually has around 95% to 99% of the dissolved salts removed from it.

8.8 Sea water treatment using Reverse Osmosis

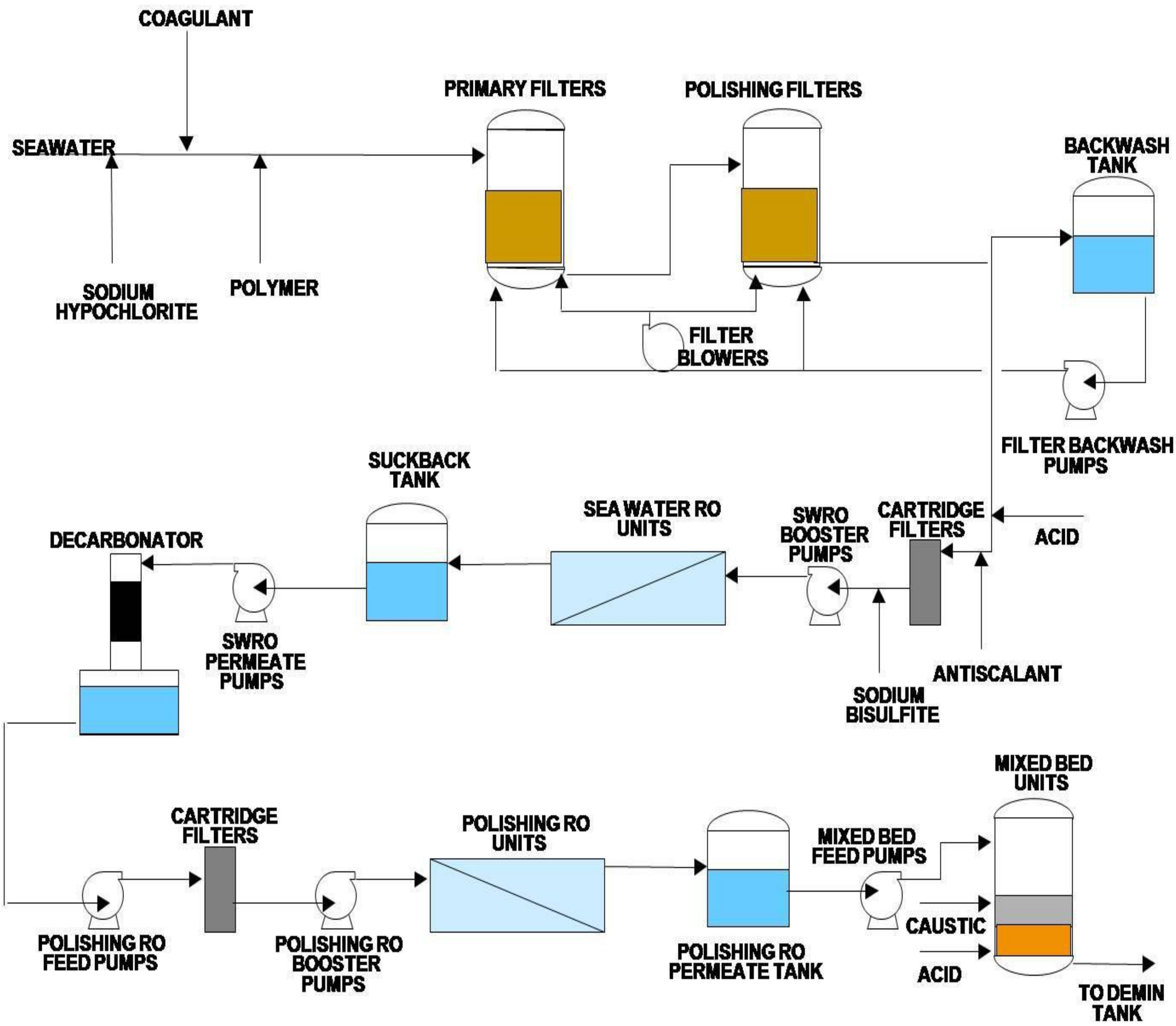


Figure 8.6 sea water treatment using RO

Above figure shows sea water treatment using reverse osmosis process. Depending on the clarity of sea water, pretreatment is required before passing it through RO system. Aluminum sulphate (coagulant) is added to precipitate colloidal material and color.

To reduce the pH value to around 6 and reduce calcium carbonate scaling, HCL or sulphuric acid is added to this water. The water is than filtered using filters commonly called as media filters. Water is than passed through cartridge filter to remove suspended matter. After it water passed through series of semi-permeable membranes to get pure boiler feed water.

The membrane of RO system consist of polymeric material film made of proper porosity and is made of material like acrylics, polyamides etc. As sea water is highly corrosive, the material for construction should be selected so that it can withstand corrosion.

This method is economically used when total dissolved solid present is the water is in the range of 2000 to 10,000 ppm or slightly more.

9

Gas turbine

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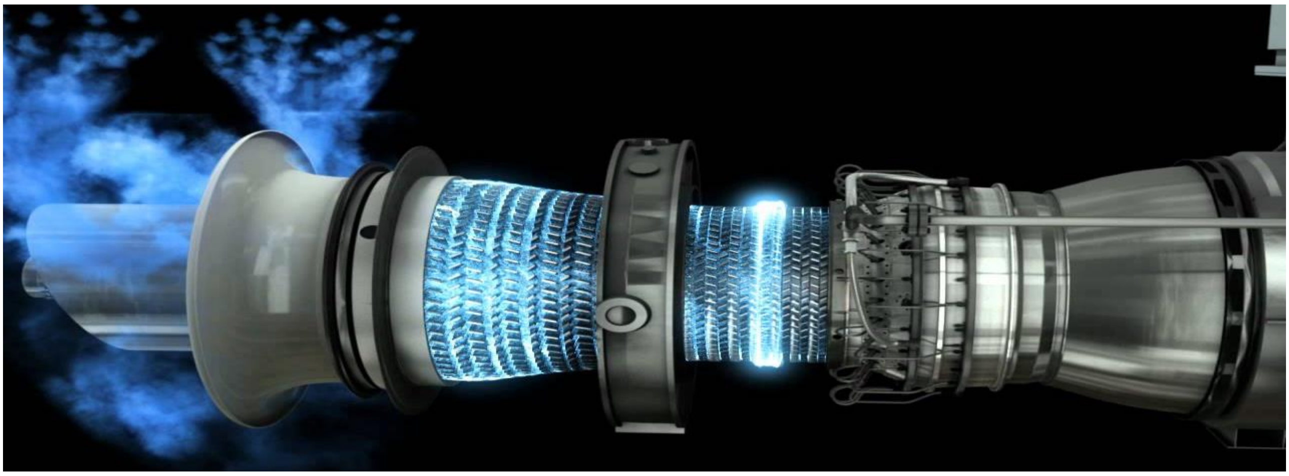


9.1 Classification of gas turbine

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

1. Compressor
2. Combustion chamber
3. 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 neat 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.

Classification

1. Combustion:

- Constant pressure gas turbine (Air fuel mixture take place at constant pressure)
- Constant volume gas turbine (Air-fuel mixture take place at constant pressure)

2. Action of expanding gases

- Impulse turbine
- Impulse-Reaction turbine

3. Path of working substance

- Open cycle gas turbine
- Close cycle gas turbine
- Semi-closed cycle gas turbine

4. Direction of flow

- Axial flow gas turbine
- Radial flow gas turbine

5. Arrangement of shaft

- Single shaft gas turbine
- Multi-shaft gas turbine

6. Thermodynamic cycle

- Simple cycle
- Cycle with regeneration
- Cycle with intercooling

- Cycle with reheating
- Cycle with intercooling, regeneration and reheating

7. **Fuel**
   - Liquid fuel
   - Gaseous fuel
   - Solid fuel

8. **Applications**
   - Power or industrial turbine
   - Aviation or aircraft turbine

9.2 Open and Closed cycle gas turbine

Open cycle gas turbine

The Open cycle gas turbine or Brayton cycle is the most idealized cycle for the simple gas turbine power plant as shown in fig 9.1.

Atmospheric air is compressed from p_1 to 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.

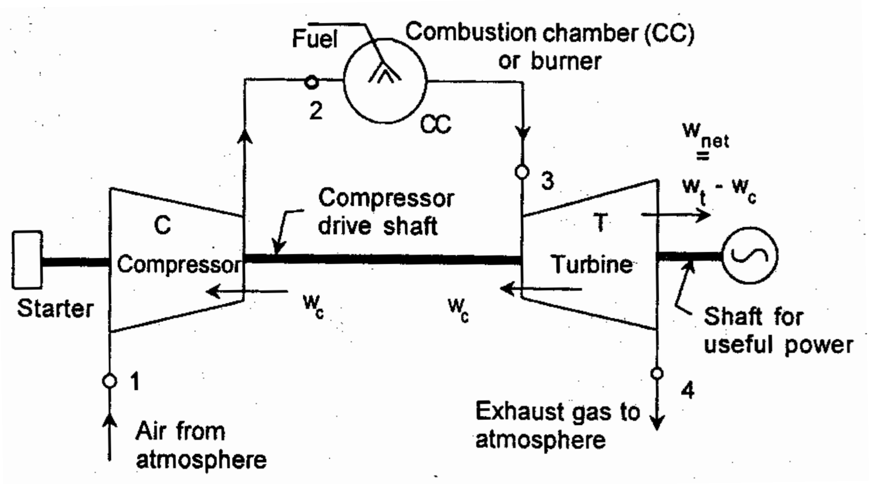


Figure 9.1 Simple Open Cycle Gas Turbine

Representation of ideal Brayton cycle on p-v and h-s (or T-s) diagrams are shown in following figure 9.2

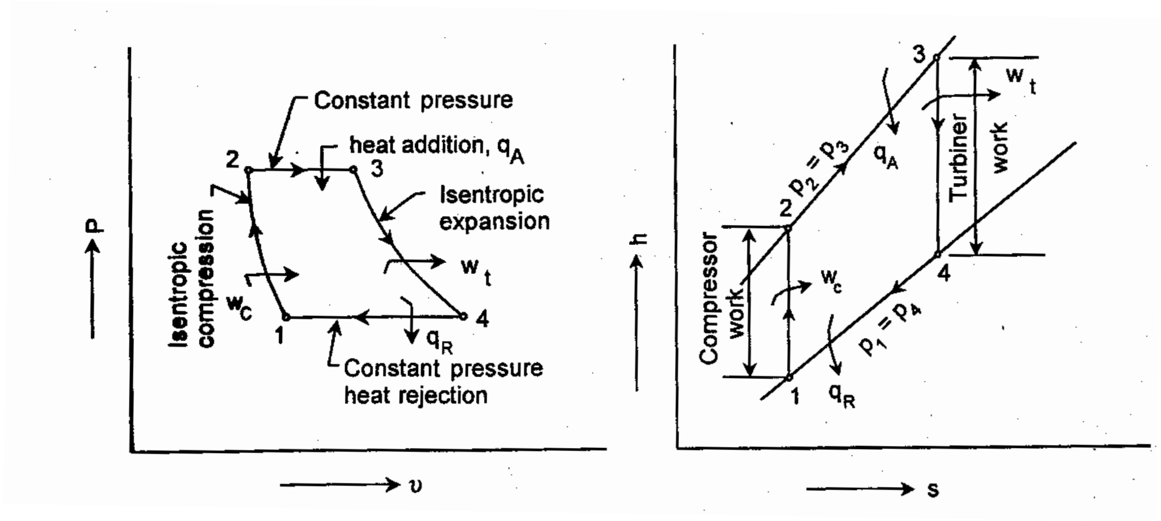


Figure 9.2 Representation of Ideal Brayton Cycle on P-v and h-s Diagram

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

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

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

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

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

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

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

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

Closed cycle gas turbine

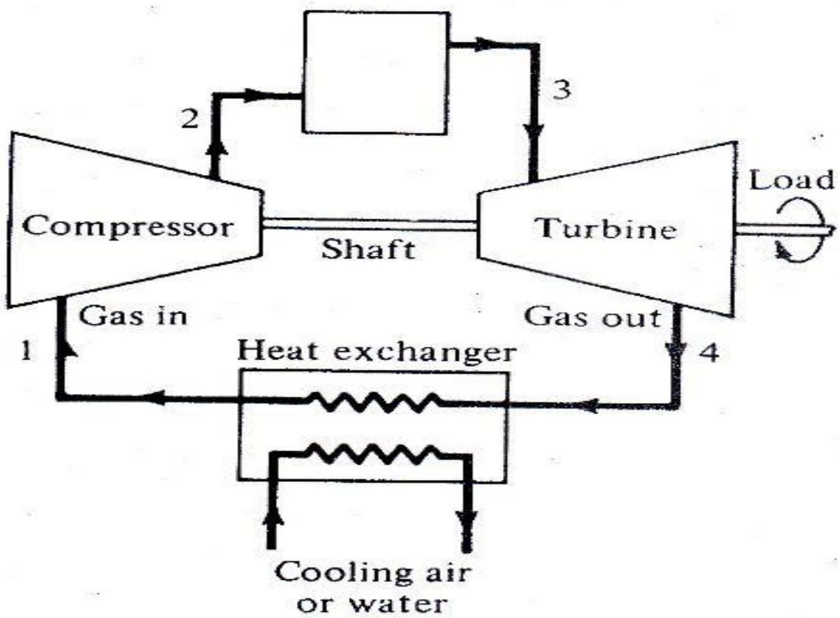


Figure 9.3 Close cycle gas turbine

Working:

A schematic diagram of a closed cycle gas turbine plant is shown in figure 9.3. The working fluid coming out from the compressor is heated in a heat exchanger by an external source at constant pressure. The working fuel is heated by burning the fuel using separate supply of air in CC and transfer this heat to the working fluid. The hot air, while flowing over the blades gets expanded. This air is cooled where it is cooled at constant pressure with the help of circulating water to its original temperature.

Following are the desirable properties of working fluid used in closed cycle.

- It should be perfectly inert.
- It should be stable, non-explosive and non-corrosive.
- It should be non-toxic and non-flammable.
- It should have high thermal conductivity.

Following are various **advantages** of closed cycle gas turbine over open cycle gas turbine plant:

- Working fluid is cooled and it decrease its specific volume. So size of compressor can be reduced.
- Gases other than air which have more favorable properties.
- External heating of air permits use of low quality fuel.
- Higher thermal efficiency obtained for same maximum and minimum temperature limits compared to open cycle.
- The Power output can be varied by changing the mass flow.
- No loss of working fluid.
- High heat transfer rate is possible compared to open cycle.

Following are various **disadvantages** of closed cycle gas turbine over open cycle gas turbine plant:

- Depends on cooling water. This eliminates use of this system in aircraft.
- Use of high pressure requires a strong heat exchanger.
- The load control of closed system is complex and costly compared to open cycle.
- Considerable quantity of cooling water is required in pre-cooler.

9.3 Gas turbine fuels

Liquid and gaseous fuel

Gaseous fuels such as natural gases are mainly used in gas turbines that power pumping stations along main gas pipelines. Liquid fuels are used in gas turbine powered transport vehicles and in large stationary gas turbines.

Gas turbine accept most commercial fuel such as petrol, natural gas, propane, and diesel as well as renewable such as biogas, biodiesel. However, when running on kerosene or diesel, starting sometimes requires the assistance of a more volatile product such as propane gas - although the new kero-start technology can allow even micro-turbines fuelled on kerosene to start without propane.

Solid Fuel

Also solid fuels like pulverized coal is normally used in closed cycle gas turbine plants. But problem facing in such fuel is that it increase the level of flyash in the gases leaving combustion chamber and entering in turbine. So additionally flyash collectors are used.

9.4 Actual Brayton cycle

The actual Brayton cycle differs from the ideal Brayton cycle because of 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 9.4.

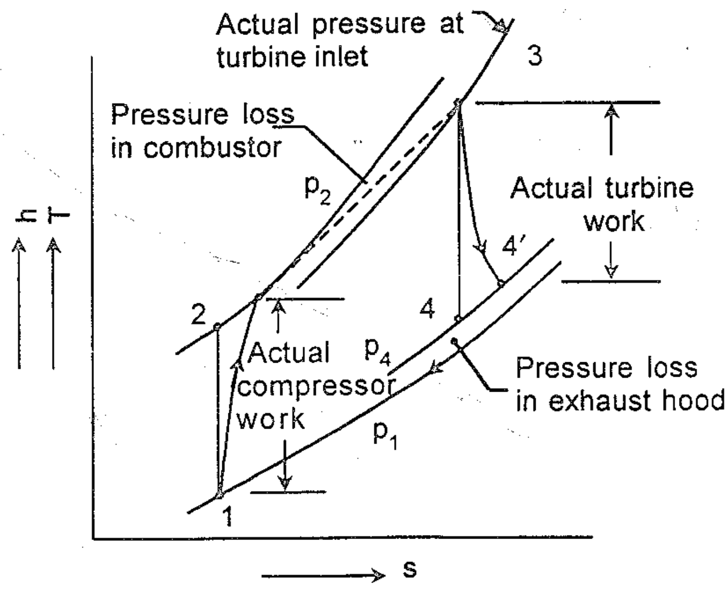


Figure 9.4 Actual Brayton cycle

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

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,

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

9.5 Optimum pressure ratio for maximum thermal efficiency

First of all,

$$\eta_c = \frac{\textit{Isentropic compressor work}}{\textit{Actual compressor work}} = \frac{c_p(T_{2'} - T_1)}{c_p(T_2 - T_1)}$$

$$\eta_t = \frac{\textit{Actual turbine work}}{\textit{Isentropic turbine work}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4'})}$$

Actual heat supplied per kg of air is given by,

$$Q = c_p(T_3 - T_2)$$

This can be approximately taken as $c_p(T_3 - T_{2'})$ without introducing appreciable error. Thermal efficiency of cycle is given by

$$\eta_{th} = \frac{W_{net}}{Q} = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_{2'})} = \frac{\eta_t\,(T_3 - T_{4'}) - \frac{(T_{2'} - T_1)}{\eta_c}}{(T_3 - T_{2'})}$$

$$= \frac{\eta_t \times T_3\left(1 - \frac{T_{4'}}{T_3}\right) - \frac{T_1}{\eta_c}\left(\frac{T_{2'}}{T_1} - 1\right)}{T_1\left(\frac{T_3}{T_1} - \frac{T_{2'}}{T_1}\right)}$$

Now, $\frac{T_{2'}}{T_1} = \frac{T_3}{T_{4'}} = r_p^{\frac{\gamma-1}{\gamma}}$

$$\therefore\ \eta_{th} = \frac{\eta_t \times T_3\left(1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}\right) - \frac{T_1}{\eta_c}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)}{T_1\left(\frac{T_3}{T_1} - r_p^{\frac{\gamma-1}{\gamma}}\right)}$$

For maximum thermal efficiency, $\frac{d\eta_{th}}{dr_p} = 0$

Differentiating above equation and equating to zero, we get

$$r_p = \left[\frac{T_3/T_1}{1 + \sqrt{\left(\frac{T_3}{T_1} - 1\right)\left(\frac{1}{\eta_c \eta_t} - 1\right)}} \right]^{\frac{\gamma-1}{\gamma}}$$

9.6 Work ratio and air rate

Work ratio is defined as the ratio of net work output to the work done by the turbine.

$$WR = \frac{W_{net}}{W_T} = \frac{W_T - W_c}{W_T}$$

Air rate is defined as the air flow required per kWhr output. Unit of air rate is kg/KWhr for following equation.

$$Air\ rate = \frac{Mass\ of\ air\ required}{KWhr\ output} = \frac{m_a}{m_a \times \frac{W_{net}}{3600}} = \frac{3600}{W_{net}}$$

9.7 Effect of operating variables on the thermal efficiency, work ratio and air rate

For thermal efficiency:

Thermal efficiency of actual open cycle depends on following operating variables:

- Compressor inlet temperature (T_1)
- Turbine inlet temperature (T_3)
- Pressure ratio
- Compressor and Turbine efficiency
- Regeneration, intercooling and reheating
- Specific fuel consumption

Compressor inlet temperature (T_1)

If the compressor inlet temperature T_1 is increased to $T_{1'}$, then corresponding compressor outlet temperature is increased. The effect of this is to reduced heat supplied. It also increase compressor input work which reduce net work output.

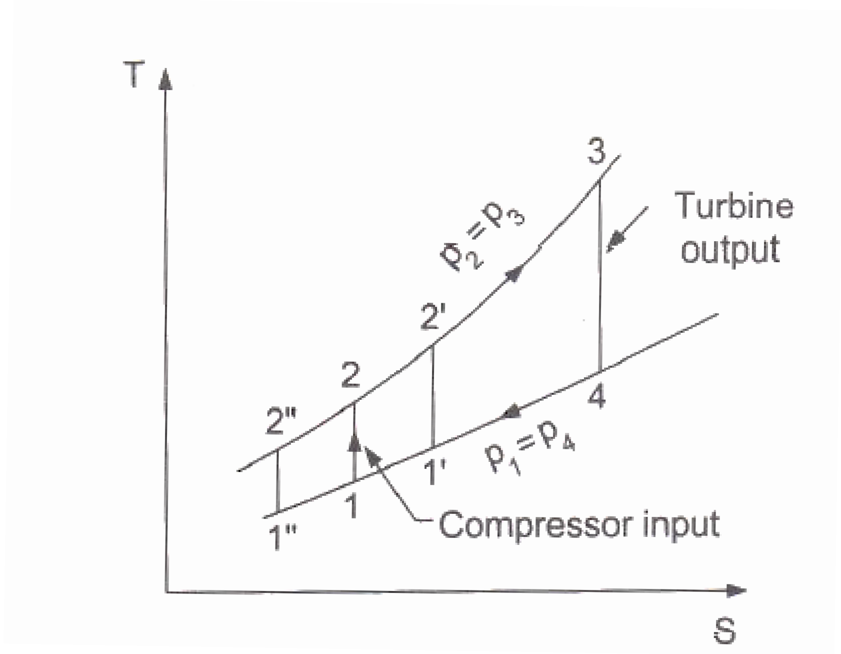


Figure 9.5 Effect due to compressor inlet temperature

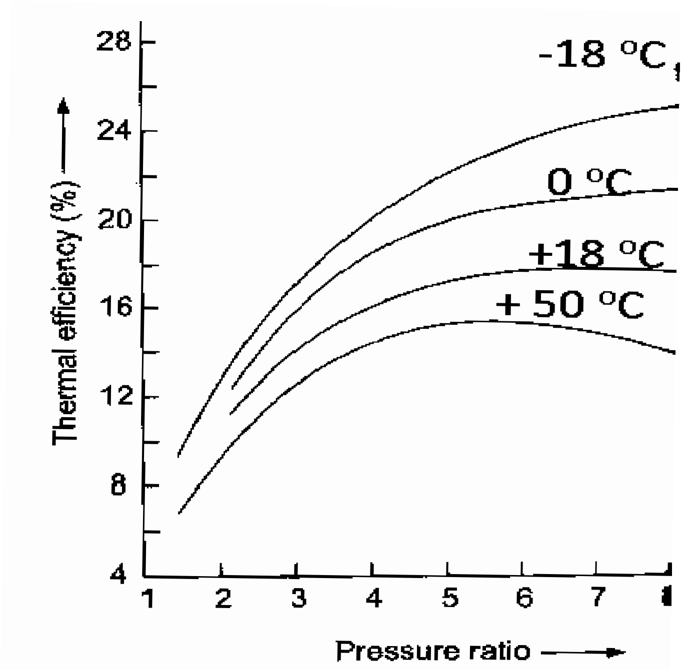


Figure 9.6 Effect of compressor inlet temperature on pressure ratio and Thermal efficiency

If compressor inlet temperature is reduced ($T_{1''}$) it decrease compressor outlet temperature. So as T_1 increase thermal efficiency reduced due to reduction in heat supplied and reduction in compressor inlet temperature increase plant efficiency as shown in 9.6

Turbine inlet temperature (T_3)

As the turbine inlet temperature increase, the work output from the turbine increases and this increase turbine efficiency at given pressure ratio.

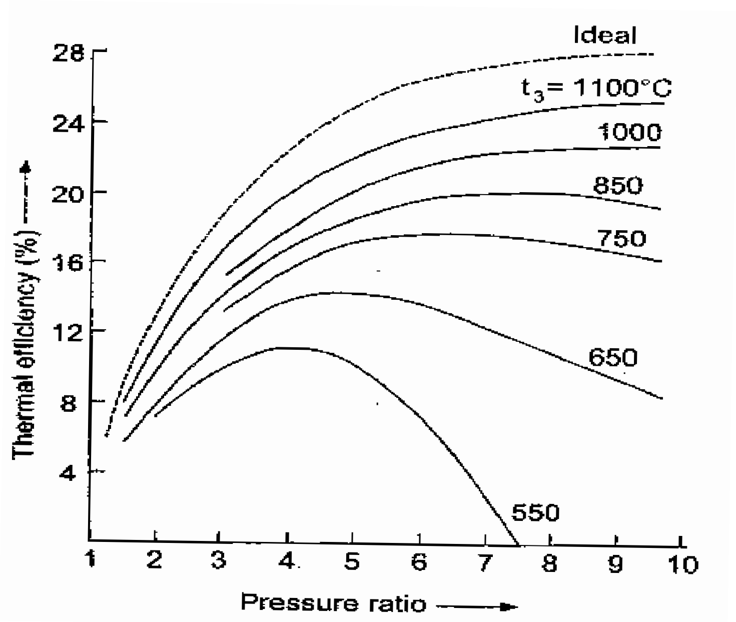


Figure 9.7 Effect of turbine inlet temperature on pressure ratio and Thermal efficiency

For higher turbine efficiency, it becomes necessary to increase turbine inlet temperature. So, high heat supplied by combustion chamber is required to increase turbine thermal efficiency.

Pressure ratio

As shown in fig. 9.8, for a given turbine inlet temperature as pressure ratio increases, the work done by turbine increase and compressor work also increase.

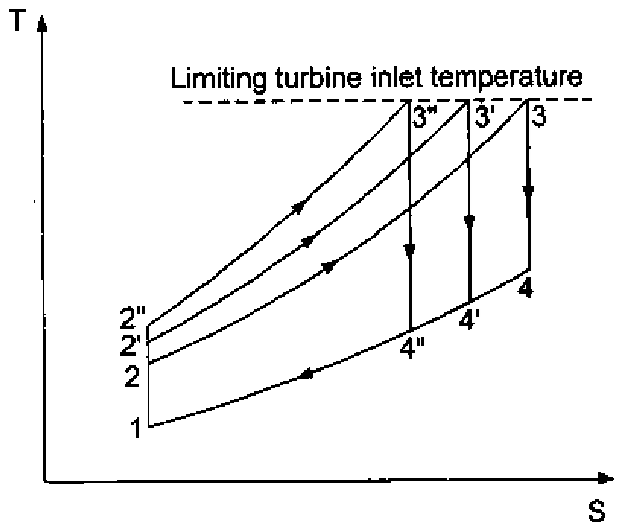


Figure 9.8 Effect of pressure ratio on gas turbine cycle.

Fig. 9.7 also indicates that there is an optimum pressure ratio for maximum thermal efficiency. Further increase in pressure ratio drops the thermal efficiency of cycle.

Compressor and Turbine efficiency

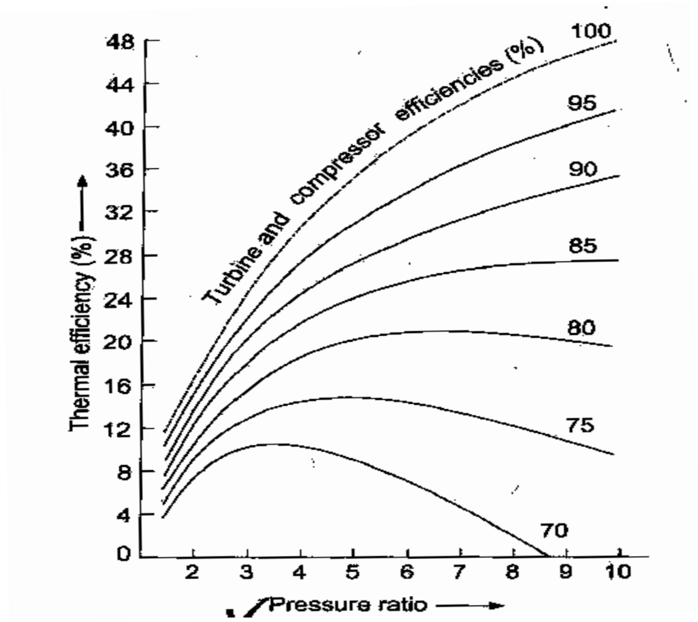


Figure 9.9 Effect of compressor and turbine efficiency on thermal efficiency

As shown in above figure, as the efficiencies of compressor and turbine increases, the thermal efficiency increases but there is an optimum pressure ratio at which maximum efficiency occur. Turbine is power producing device and products more power than compressor consumes. So turbine efficiency affect much compare to compressor efficiency.

Regeneration, intercooling and reheating

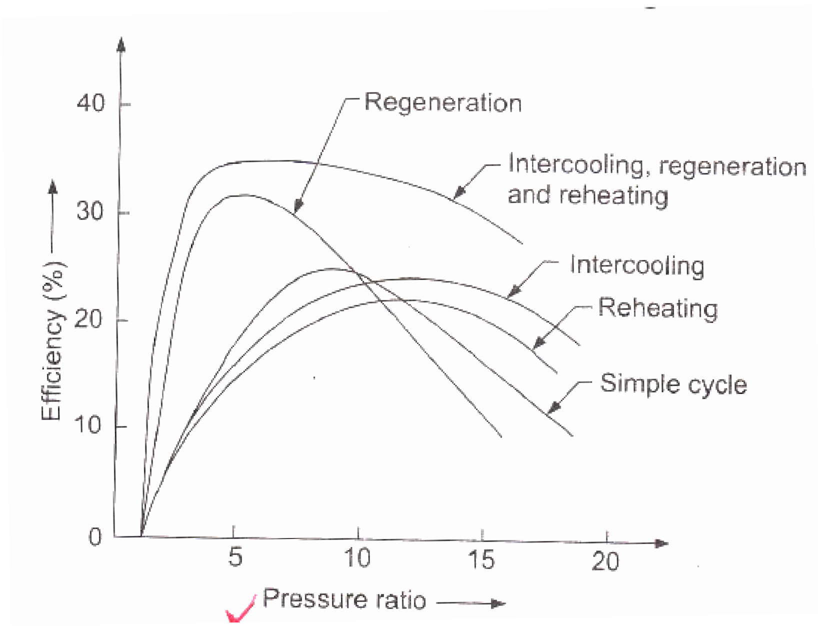


Figure 9.10 Effect of regeneration, intercooling and reheating on thermal efficiency

Due to addition of these three things peak value of thermal efficiency shifts towards lower pressure ratio compared to simple cycle. In all cases, thermal efficiency first increases with increase in pressure ratio, reaches a maximum value and then deceases.

Specific fuel consumption

As the specific fuel consumption increased, the thermal efficiency of the cycle decreases. As shown in below fig, for all value of pressure ratio, fuel consumption is minimum in complete cycle

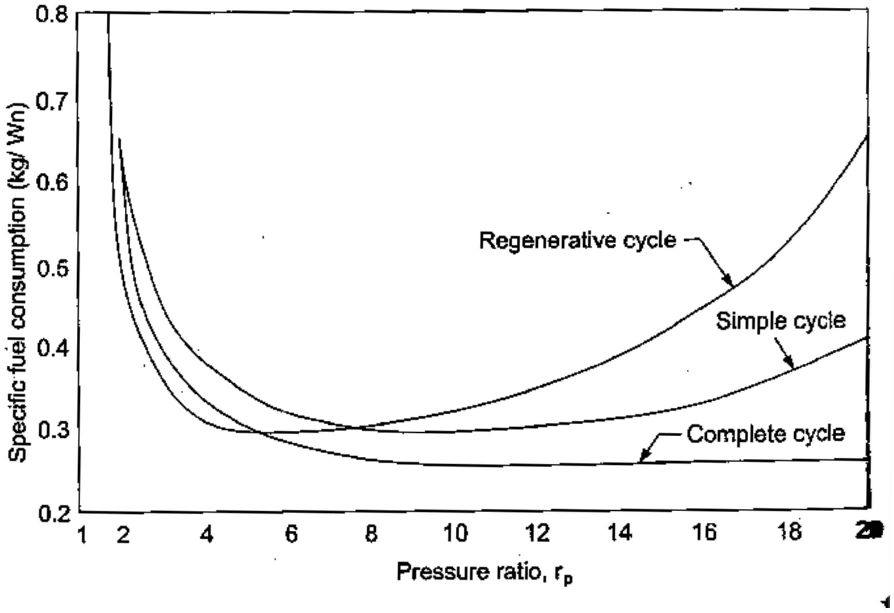


Figure 9.11 Effect of pressure ratio on specific fuel consumption

<u>For work ratio</u>

The parameters which affect the work ratio are,

- Compressor inlet temperature
- Turbine inlet temperature and pressure ratio
- Compressor and turbine efficiency
- Regeneration, intercooling and reheating

Compressor inlet temperature

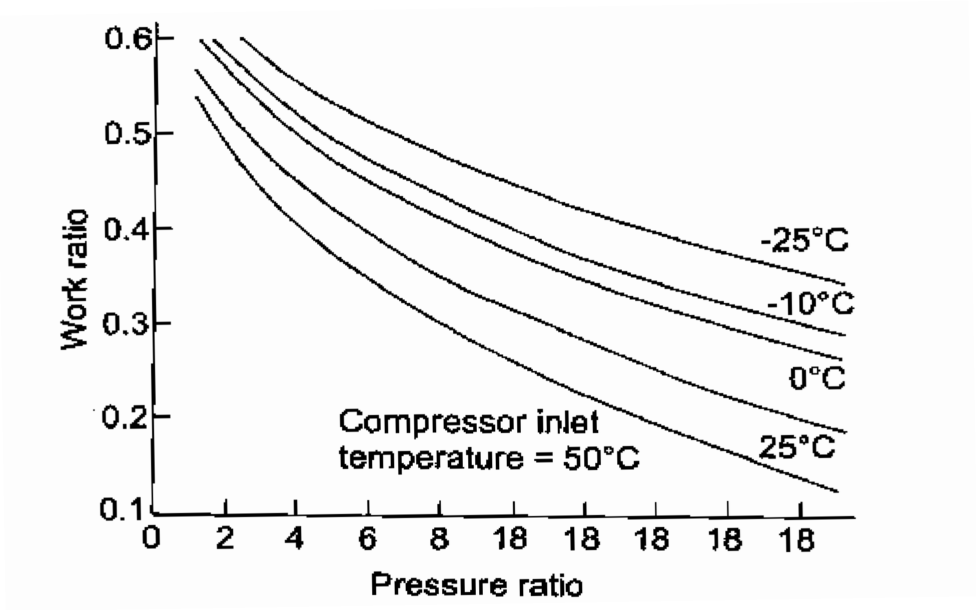


Figure 9.12 Effect of compressor inlet temperature
And pressure ratio on work ratio

As compressor inlet temperature desreases, the work ratio increases. This is due to decrease in the power required by the compressor.

Turbine inlet temperature and pressure ratio

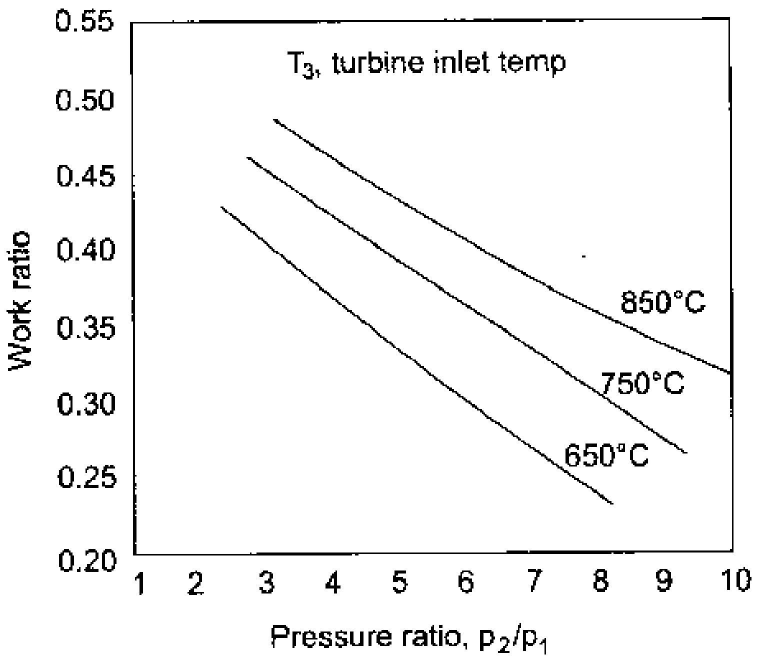


Figure 9.13 Effect of turbine inlet temperature
And pressure ratio on work ratio

As turbine inlet temperature increases, the work output increases for a given pressure ratio, hence the work ratio increases. Also as the pressure ratio increases, the work ratio decreases for a fixed value of turbine inlet temperature.

Compressor and turbine efficiency

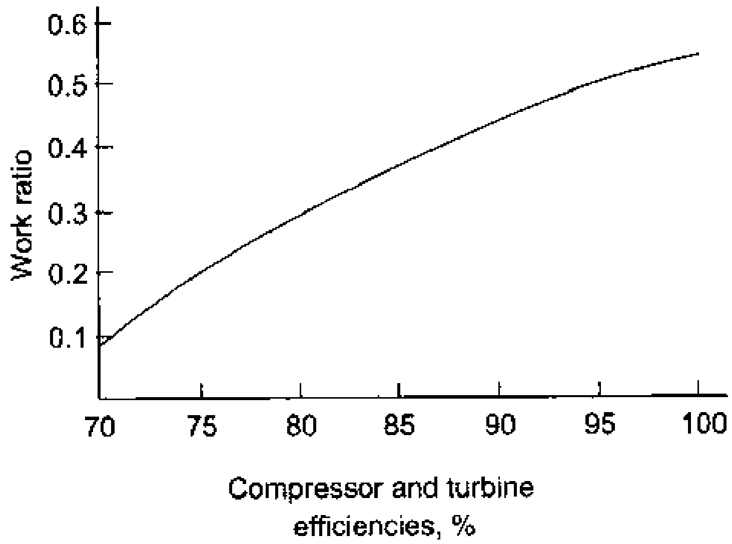


Figure 9.14 Effect of compressor and turbine efficiency on work ratio

As the compressor and turbine efficiencies increase, the work ratio also increase due to increase in work output of turbine and reduction in compressor work input.

Regeneration, intercooling and reheating

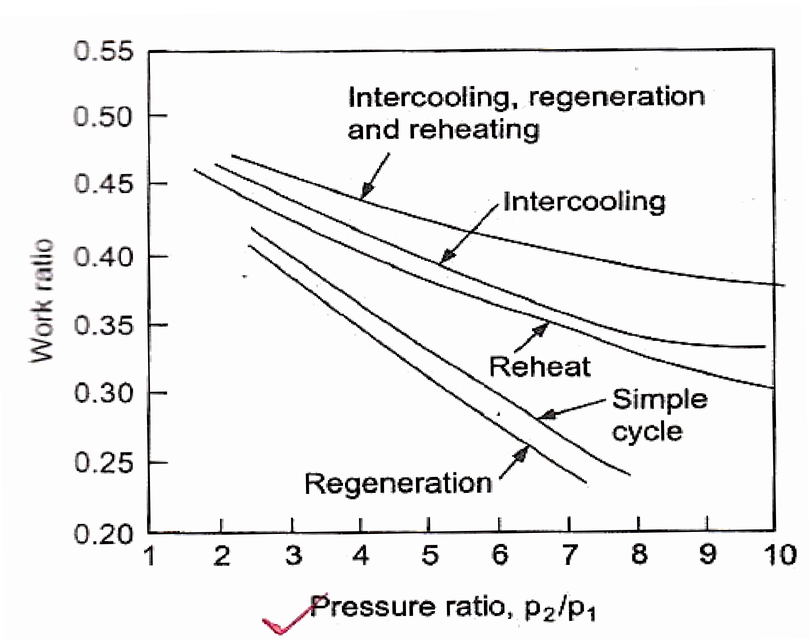


Figure 9.15 Effect of regeneration, intercooling and reheating On work ratio

Above fig shows Effect of regeneration, intercooling and reheating on work ratio with increase of pressure ratio. The maximum work ratio is obtained in cycle with regeneration, intercooling and reheating.

For Air rate

The parameters which affect the air rate are,

- Compressor inlet temperature
- Turbine inlet temperature and pressure ratio
- Compressor and turbine efficiency
- Regeneration, intercooling and reheating

Compressor inlet temperature

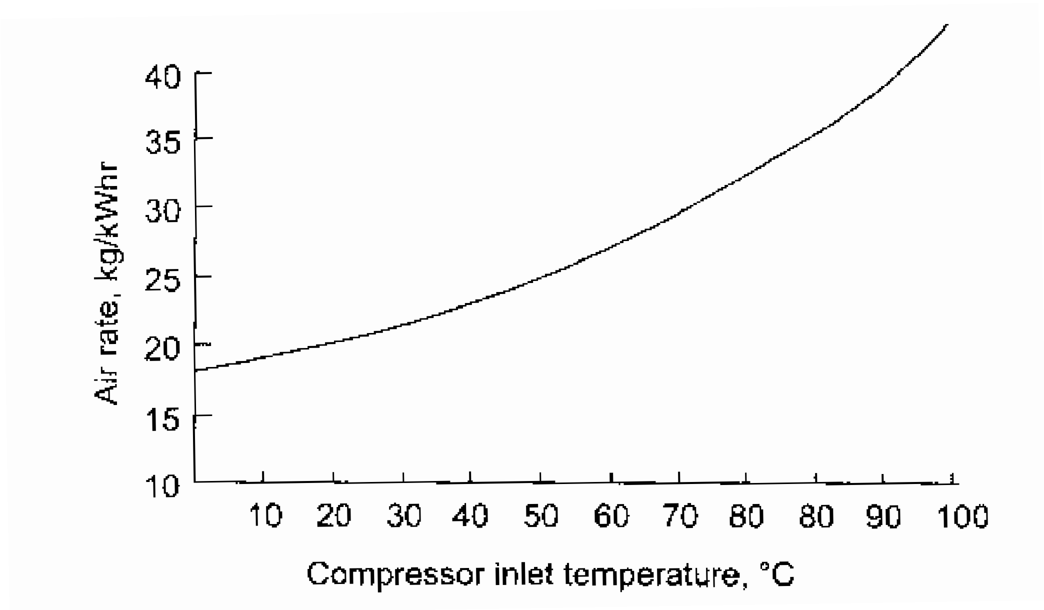


Figure 9.16 Effect of compressor inlet temperature on air rate

As compressor inlet temperature increases, the air density is reduced and hence the mass flow rate reduces. To maintain constant mass flow rate, the compressor will consume more power. Thus, increasing value of compressor inlet temperature reduces the net work output because the power consumed by the compressor increases while there is no change in turbine output.

Turbine inlet temperature and pressure ratio

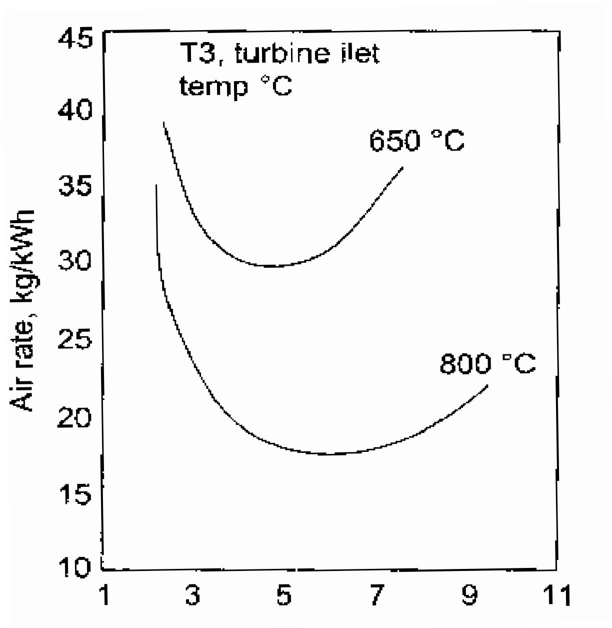


Figure 9.17 Effect of turbine inlet temperature
And pressure ratio on air rate

As turbine inlet temperature increases, the work output increases for a given pressure ratio, hence the air rate decreases. As the pressure ratio increases, the air rate decreases to a minimum value first and after that it again increases.

Compressor and turbine efficiency

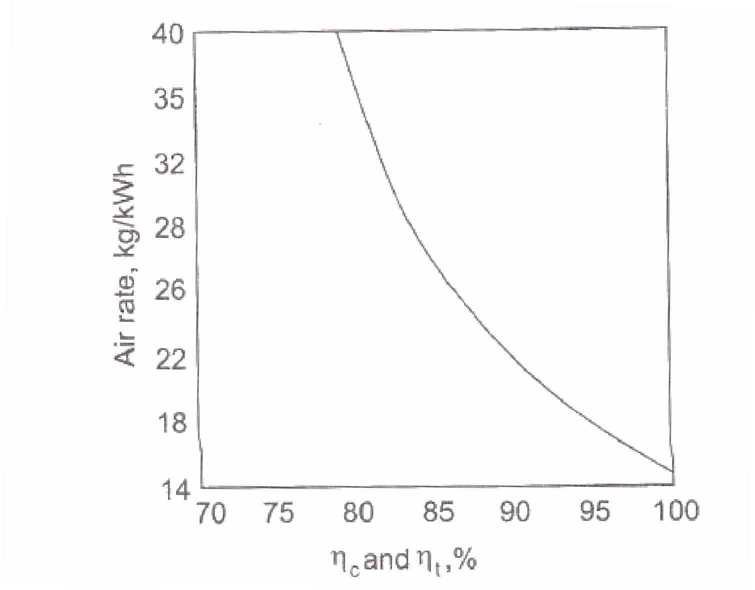


Figure 9.18 Effect of compressor and turbine efficiency on air rate

As the compressor and turbine efficiencies increase, the net work output increases at same mass flow rate of air. Hence mass flow rate of air per KW is reduced

Regeneration, intercooling and reheating

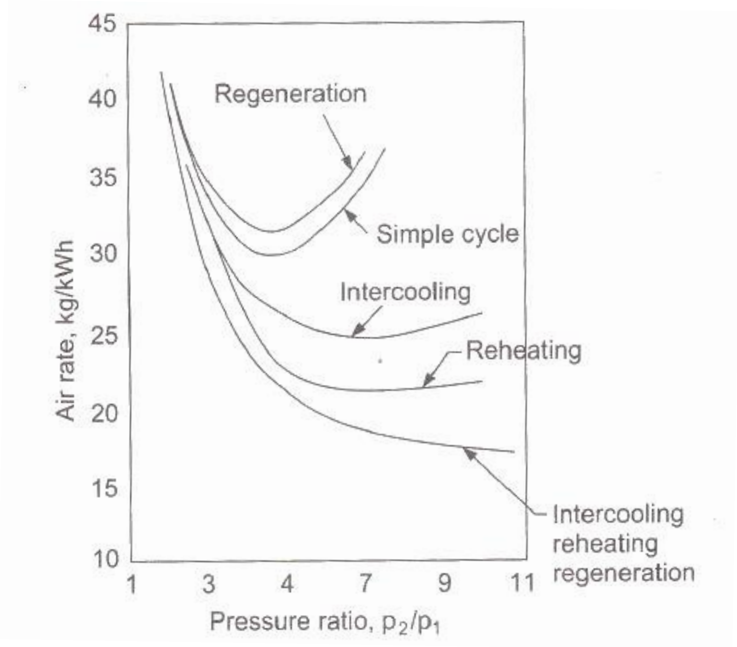


Figure 9.19 Effect of regeneration, intercooling and reheating on air rate

Comparison of curves shown in Fig 9.19 shows that air rate is lower in case of cycle with intercooling and reheating cycles and least in case of open cycle with complete cycle with regeneration, intercooling and reheating.

9.8 Combined steam and gas turbine plant

To overcome low cycle efficiency, gas turbine is used in conjuction with a steam turbine plant, to utilize the advantage of gas turbine as quick starting and stopping.

Hence gas turbine can be used as peak load or an emergency stand by plant. Folowing are the different arrangements of combined cycle power plant.

Gas turbine, Heat Recovery Steam Generator (HRSG) and steam turbine can be arranged in different combinations depending on size of gas turbine, electrical power generation requirements and economics of application as follows.

1. Gas and Steam turbine combined cycle without supplementary fuel firing

A gas turbine plant consists of air compressor, combustion chamber and gas turbine. The exhaust of the gas turbine goes to HRSG to produce superheated steam as shown in figure below.

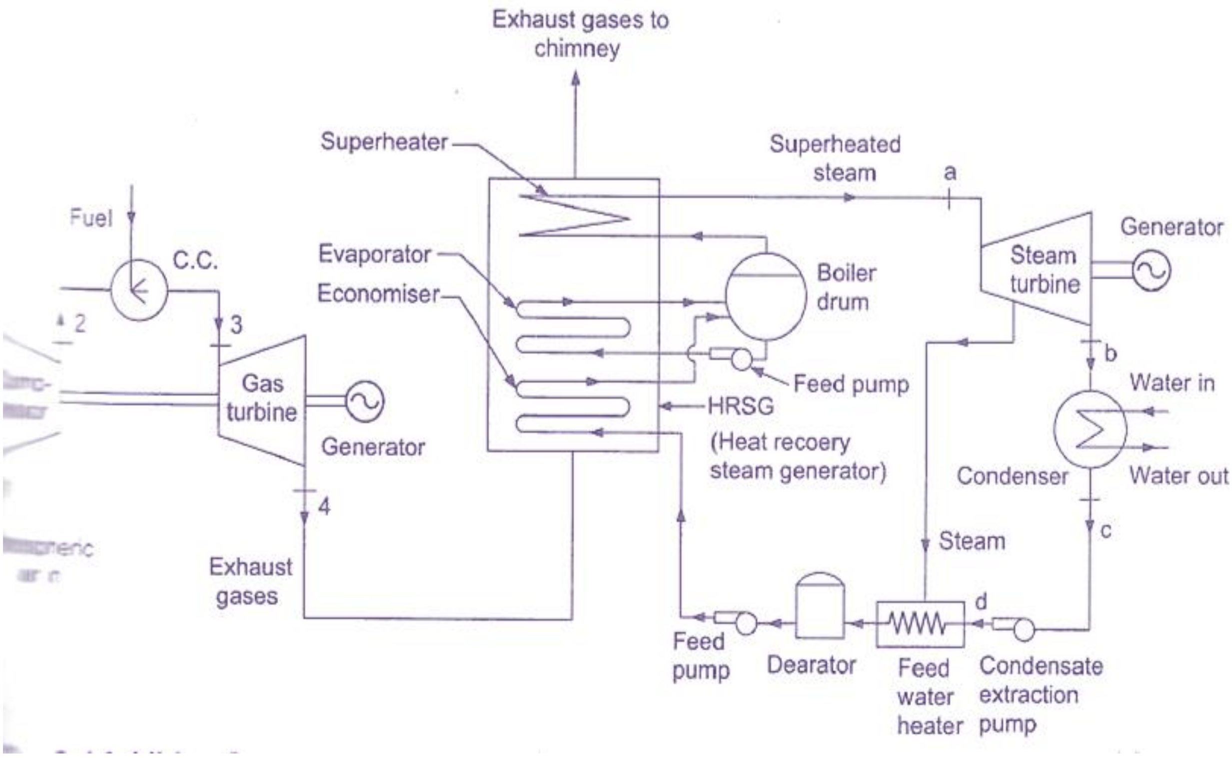


Figure 9.20 Gas and Steam turbine combined cycle without supplementary fuel firing

The generated steam is then used to generate power from a steam turbine Power plant which consists of steam turbine, Condenser, condensate and boiler feed pumps, feed water heater and deareator. The HRSG consists of economizer, evaporator and superheater. The exhaust gas goes to chimney after leaving HRSG. In this arrangement the oxygen contained in the exhaust gases is not utilized. Both steam and gas turbine drive electric generator.

2. Gas and steam turbine combined cycle with supplementary fuel firing

The temperature of exhaust gases coming out of the gas turbine which contains around 16% 02, is further increased by burning additional fuel in secondary combustion chamber as shown in Fig below. This is known as supplementary fuel firing. The exhaust gas temperature can be raised around 800-900 °C. High flue gas temperature increases the temperature of steam in HRSG, thereby improving the efficiency of Rankine cycle and increases the steam output. To limit the maximum gas turbine inlet temperature, high air fuel ratio (50:1 to 100:1) is used in gas turbine and due to this gas turbine exhaust contains more oxygen in which additional fuel is burned.

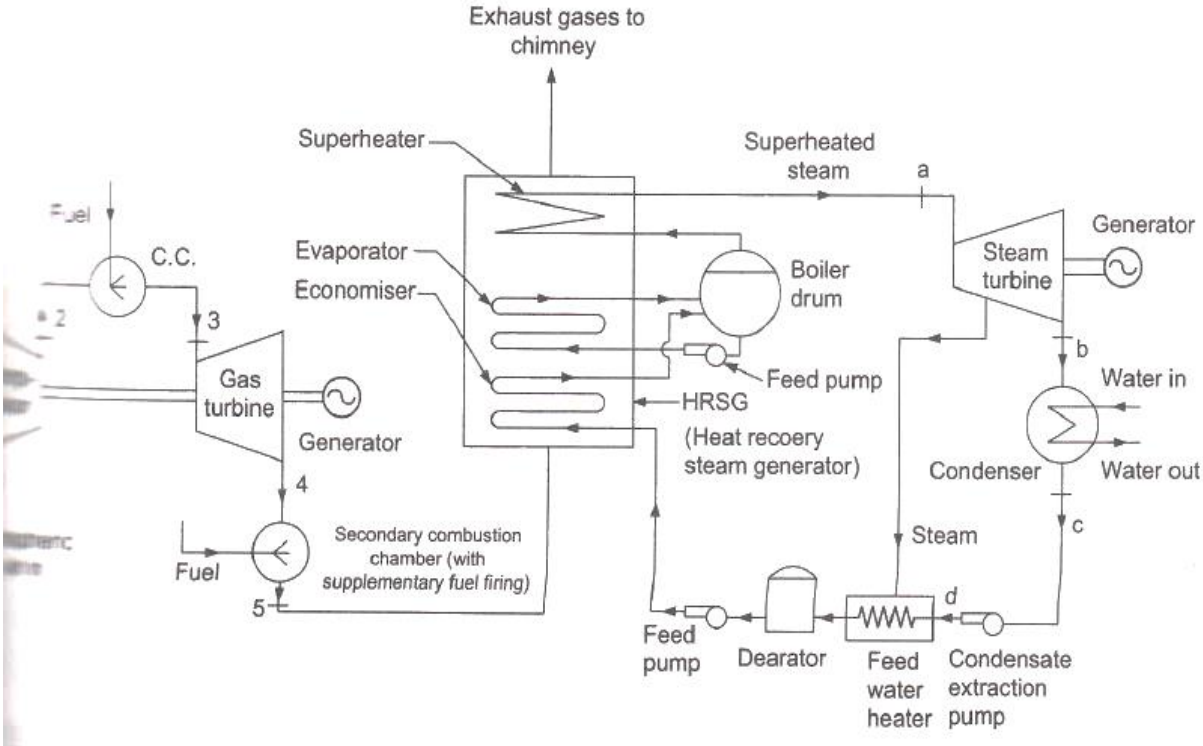


Figure 9.21 Gas and steam turbine combined cycle with supplementary fuel firing

3. **Combined cycle power plant with dual pressure steam cycle**

In this system there are two separate boilers. High pressure boiler which supplies steam to HP turbine and low pressure boiler in HSRG. Each boiler comprises the usual economizer, evaporator and superheater sections.

There is always some irreversibility during heat transfer from exhaust gas to water-steam in HRSG. More heat can be extracted if steam is generated at low pressure and temperature, but available energy for such low pressure steam will be low or there will be more losses during heat transfer in HRSG.

The temperature difference between gas side and steam side is considerably smaller than single pressure cycle which gives considerable thermodynamic advantages to dual pressure cycle.

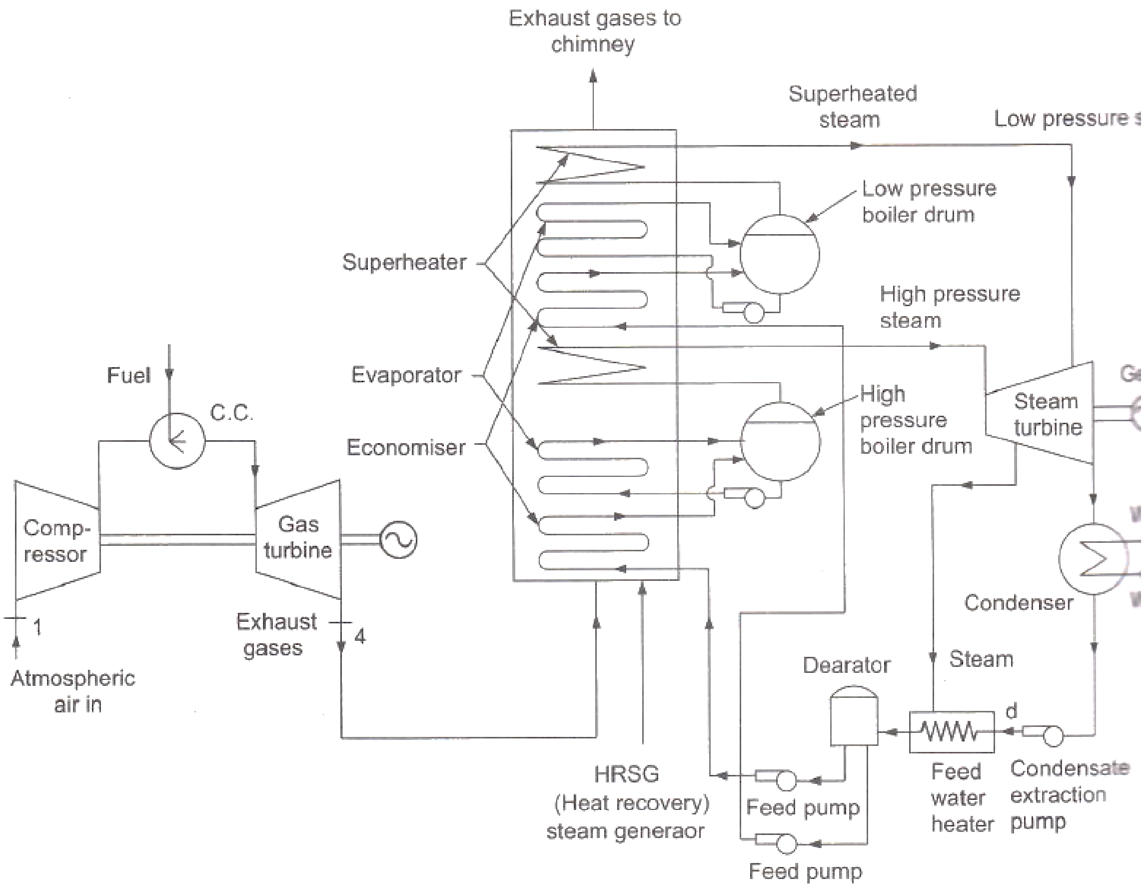


Figure 9.22 Combined cycle power plant with dual pressure steam cycle

9.9 Gas turbine blade cooling

At a constant pressure ratio, thermal efficiency increases as the maximum are under large centrifugal stresses and materials are weaker at high temperature. So, turbine blade cooling is essential.

Blade cooling mainly classified as external cooling and internal cooling.

1) External Cooling

External cooling can be achieved by either film cooling or Effusion cooling.

Film cooling

Film cooling can be achieved by drilling holes on precision cast blades by EDM. Holes of 0.15 mm diameter can be drilled by EDM for film cooling.

Film cooling is a widely used type, allows for higher heat transfer rates than either convection or impingement cooling. This technique consists of pumping the cooling air out of the blade through multiple small holes in the structure. A thin layer (the film) of cooling air is then created on the external surface of the blade, reducing the heat transfer from main flow. The air holes can be in many different blade locations, but they are most often along the leading edge.

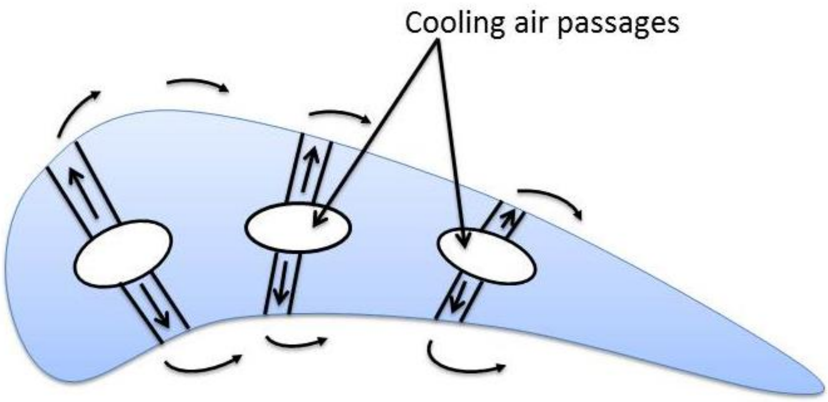


Figure 9.23 Film Cooling

Effusion cooling or Transpiration cooling

In transpiration cooling, the air is allowed to effuse from the pores of the porous blade material. Small holes along the blade surface provides envelope of cool air, thus insulating the material from hot gas.

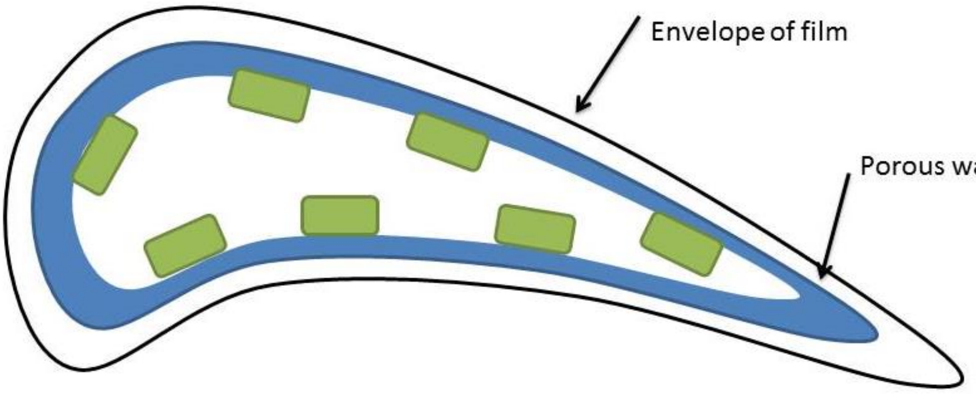


Figure 9.24 Effusion cooling

2) Internal cooling

It works by passing cooling air through passages internal to the blade. Heat is transferred by conduction through the blade, and then by convection into the air flowing inside of the blade. A large internal surface area is desirable for this method, so the cooling paths tend to be serpentine and full of small fins. The internal passages in the blade may be circular or elliptical in shape. Cooling is achieved by passing the air through these passages from hub towards the blade tip.

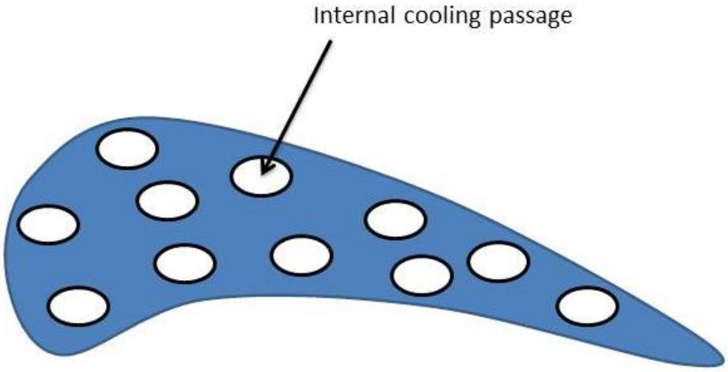


Figure 9.25 Convection cooling

Impingement cooling

The blades used for Impingement cooling are manufactured with a core and internal cooling passage as shown in figure below.

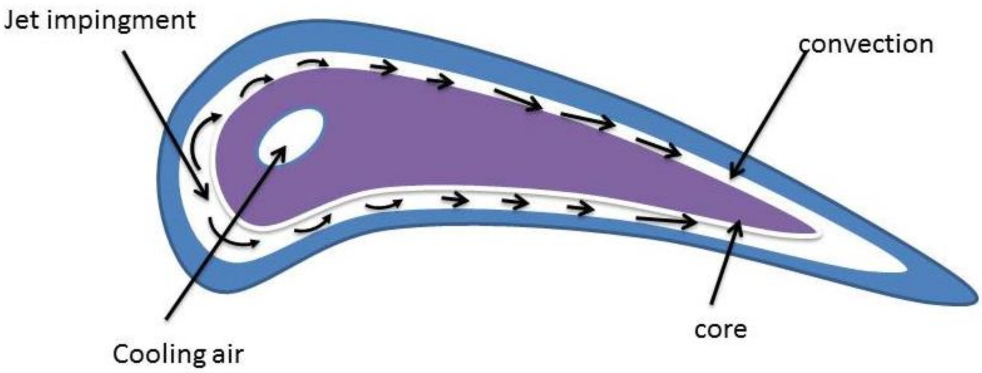
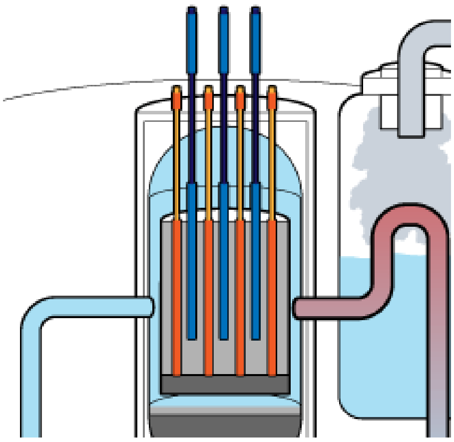


Figure 9.26 Impingement cooling

It works by hitting the inner surface of the blade with high velocity air. This allows more heat to be transferred by convection than regular convection cooling does. Impingement cooling is used in the regions of greatest heat loads. Cooling air enters from the leading edge region and turns towards the trailing edge.

10

Nuclear Power Plant



Course Contents

10.1 Nuclear Fission and Fusion

Nuclear Fission

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.

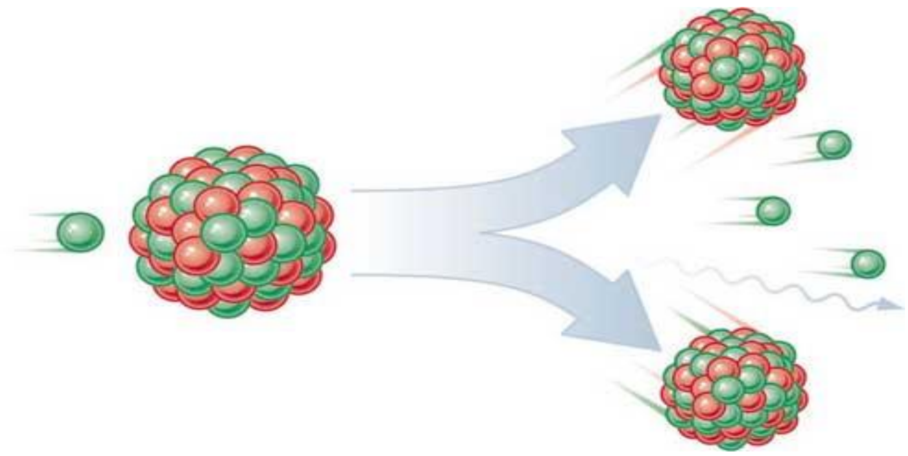


Figure 10.1 Pictorial view of nuclear fission reaction

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. A heavy nucleus splits in to two or more lighter nuclei. This process is possible at room temperature.

$$_{92}U^{235} + {_0}n^1 \longrightarrow {_{54}}Xe^{140} + {_{38}}Sr^{94} + 2\,{_0}n^1$$

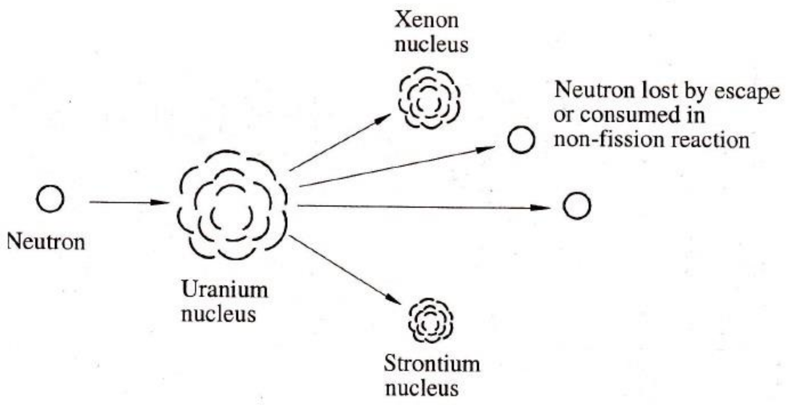


Figure 10.2 Nuclear fission reaction

Nuclear Fusion

It is process in which two or more light nucleuses fuse together and make one heavy nucleus called fusion reaction. It required very high temperature (1.2 X 109 K). Following figure shows one example of nuclear fusion reaction.

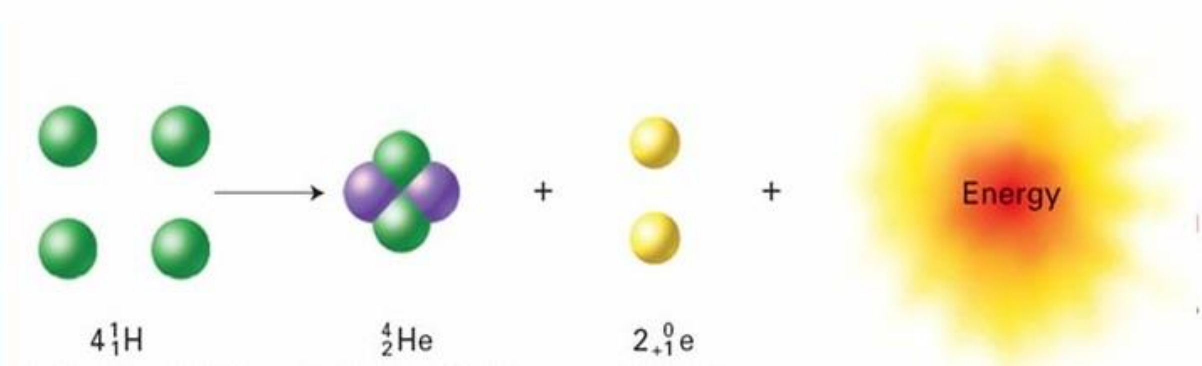


Figure 10.3 Nuclear Fusion reaction

In above reaction four light nucleuses of hydrogen atom fuse together and make helium nucleuses and release tremendous amount of energy as per E= mc^2. Sun generates heat and energy is a best example of fusion process. There is a 1.6 X 10^7 K temperature at the middle of the sun and pressure is more 10^5 times then earth.

10.2 Chain reaction

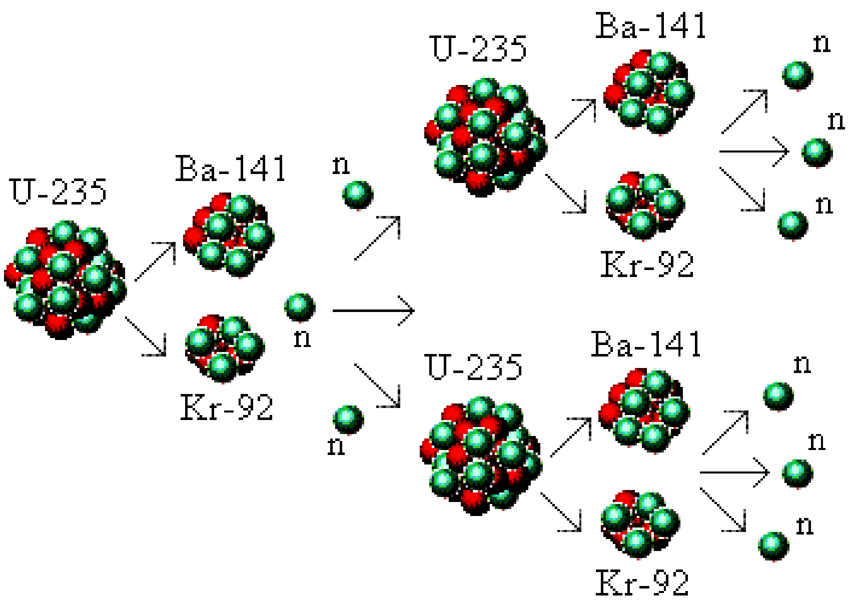


Figure 10.4 Nuclear chain reaction

A nuclear chain reaction occurs when one single nuclear reaction causes an average of one or more subsequent nuclear reactions, thus leading to the possibility of a self-propagating series of these reactions.

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 and it is several million times more energy per reaction than any chemical reaction. To maintain continues chain reaction it should be less leakage of neutrons.

10.3 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 nature, 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. Nuclear fuels are mainly classified in two parts

1. Fissionable material
2. Fertile material

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: It is non fissionable material which can be converted into 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.

10.4 Components of nuclear reactor

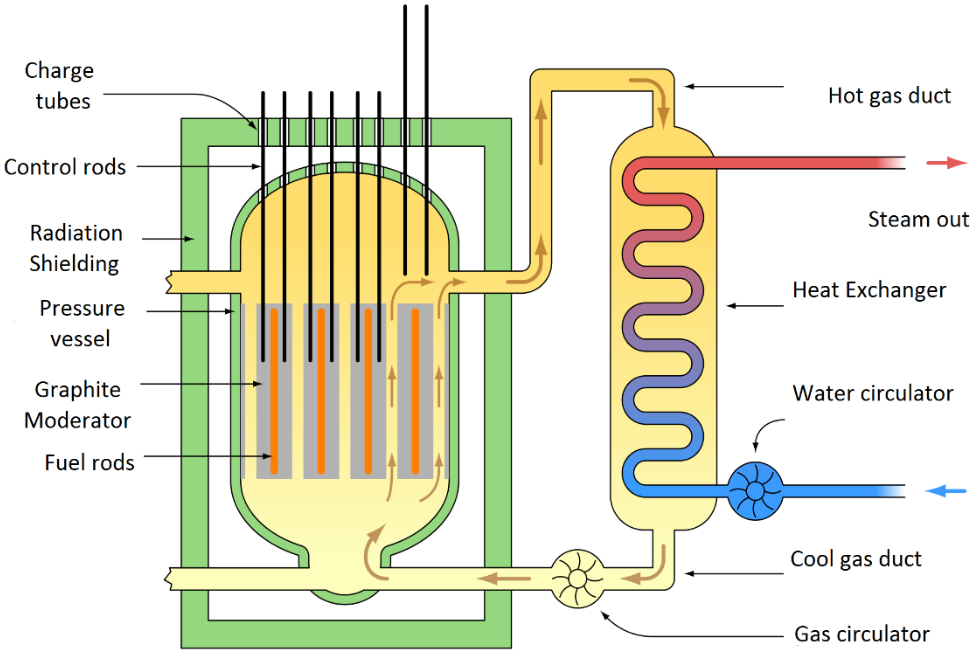


Figure 10.5 Components of nuclear reactor

Following are the components of nuclear reactor.

- FUELS
- MODERATOR
- CONTROL RODS.
- COOLENT
- REFLECTOR
- SHIELDING
- REACTOR VESSEL

10.4.1 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.

10.4.2 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 like 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. Following are few

Characteristics of moderators

- 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.

10.4.3 Control Rods

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

10.4.4 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.

Characteristics 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 specific heat and high thermal heat transfer co efficient.
It should have high density and low viscosity.

10.4.5 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.

10.4.6 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.

10.4.7 Reactor Vessel

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

10.5 Classification of reactors

On the basis of neutron energy

1. **Fast reactors:** In these reactors, the fission is affected by fast neutrons without any use of moderator.
2. **Thermal reactors:** In these reactors the fast moving neutrons are slowed down with help of moderator.
3. **Intermediate reactors:** In this reactor velocity of the neutrons is kept between fast reactors and thermal reactors.

On the basis of fuel used

1. Natural uranium fuel reactors
2. Enriched uranium fuel reactor

On the basis of coolant used

1. Water /heavy water cooled reactors
2. Gas cooled reactors
3. Liquid metal /organic liquid cooled reactors

On the basis of moderator:

1. Water moderated
2. Heavy water moderated
3. Graphite moderated
4. Beryllium moderated

On the basis of reactor core used

1. Homogeneous reactor
2. Heterogeneous reactor

10.6 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.

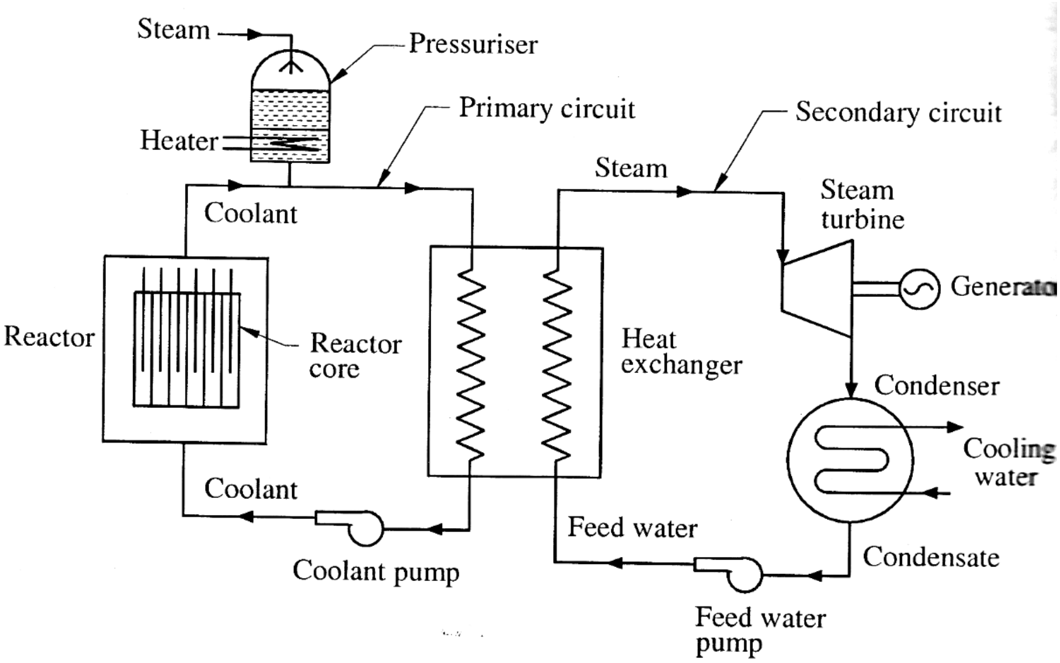


Figure 10.6 Pressurized Water Reactor

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 shut down 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.

10.7 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.

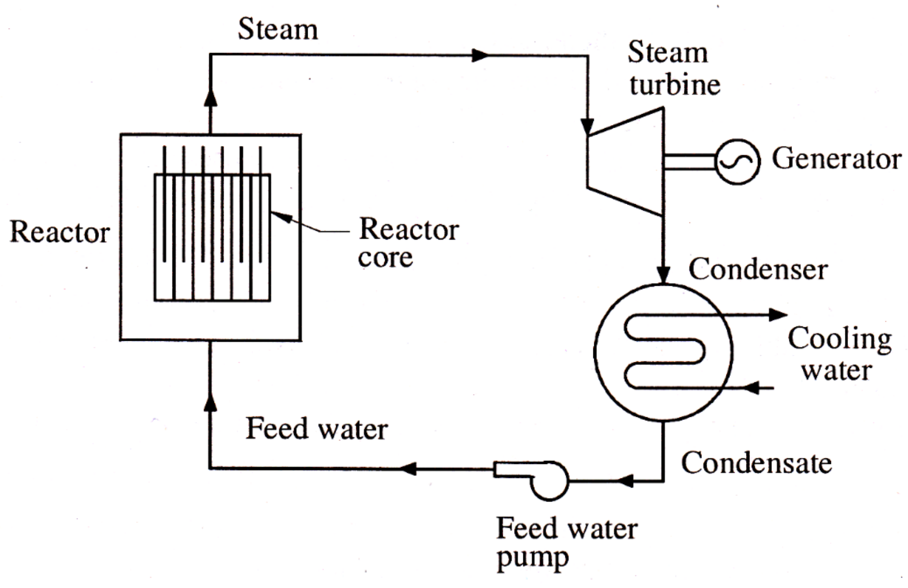


Figure 10.7 boiling water reactor

Advantages

- The pressure inside the reactor is less than PWR as water is allowed to boil inside the reactor. Therefore the reactor vessel can be much lighter than 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 than 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.
- It required enriched uranium as a fuel.

10.8 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. 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 H_e 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.

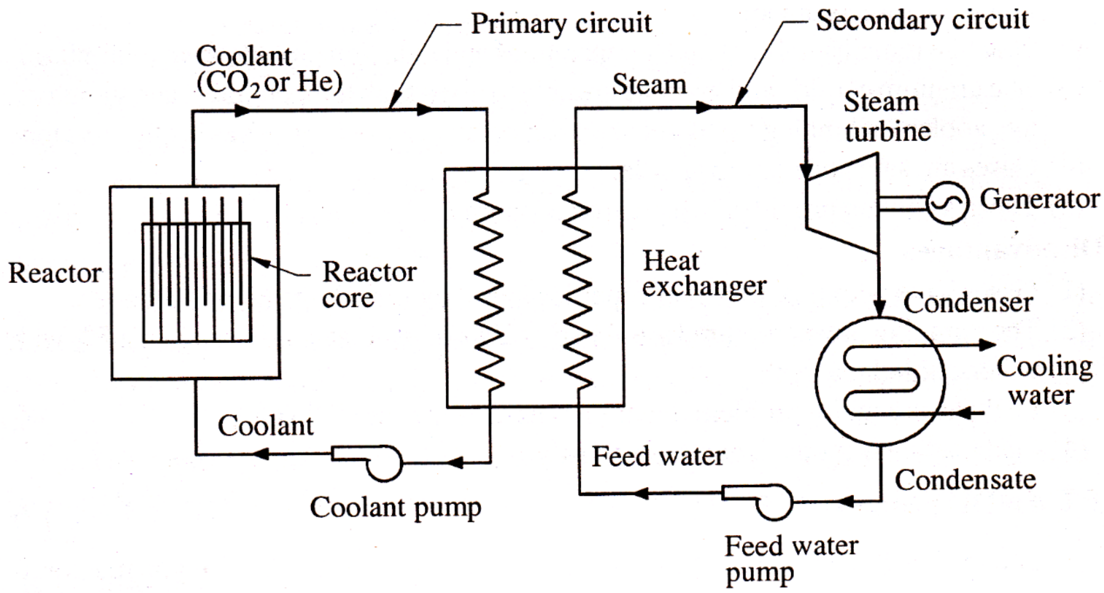


Figure 10.8 Gas cooled reactor

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.

10.9 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.

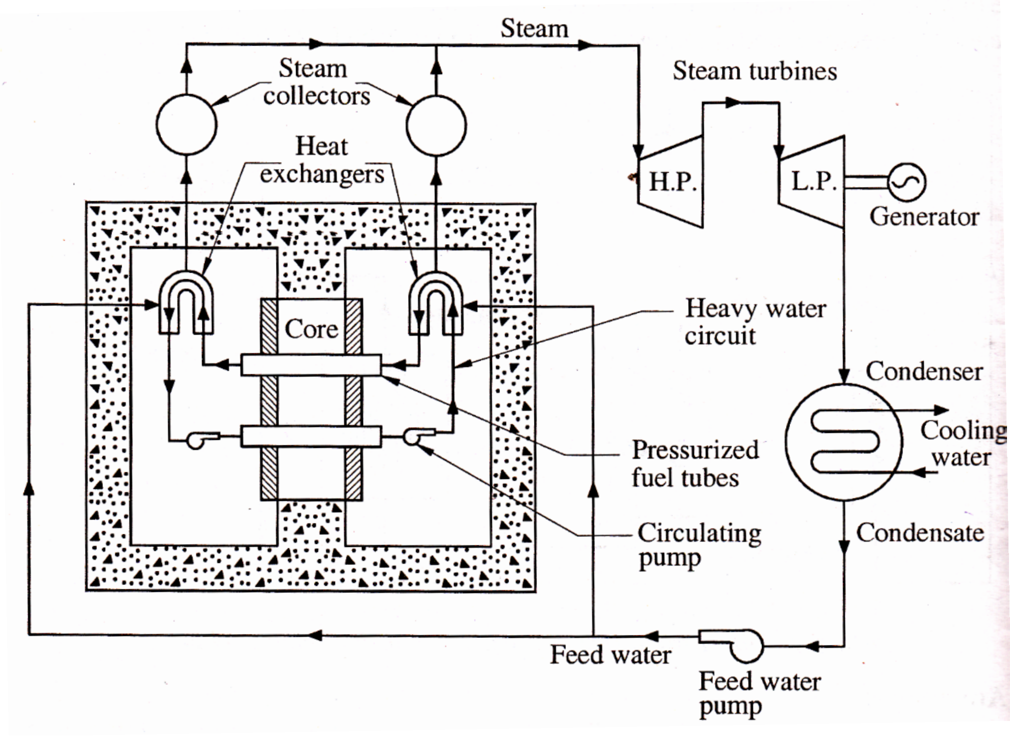


Figure 10.9 CANDU reactor

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 therefore cost of vessel is very less.
- No control rods required.
- The moderator can be kept low temperature 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 it required large size of reactor.

10.10 Fast Breeder Reactor

The process of converting more fertile material into 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).

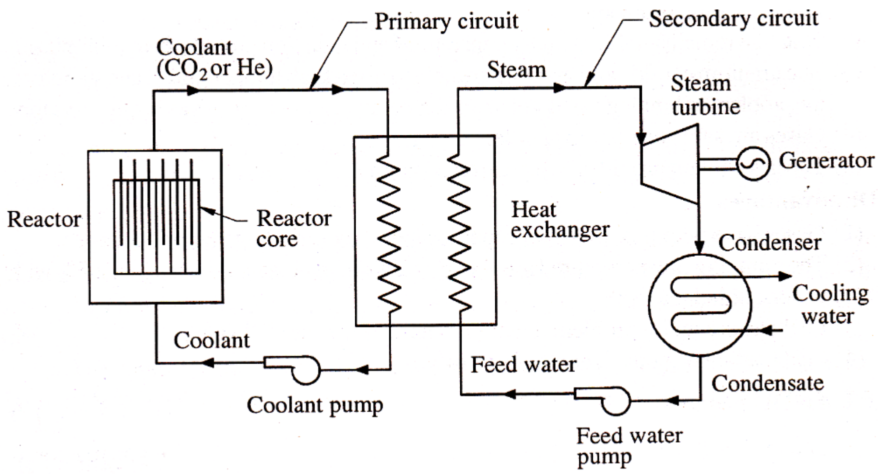


Figure 10.10 Fast Breeder reactor

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.

Disadvantage

- 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.

10.11 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 400 MW 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 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.

1. **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.
2. **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.

10.12 Nuclear Power Plants In India

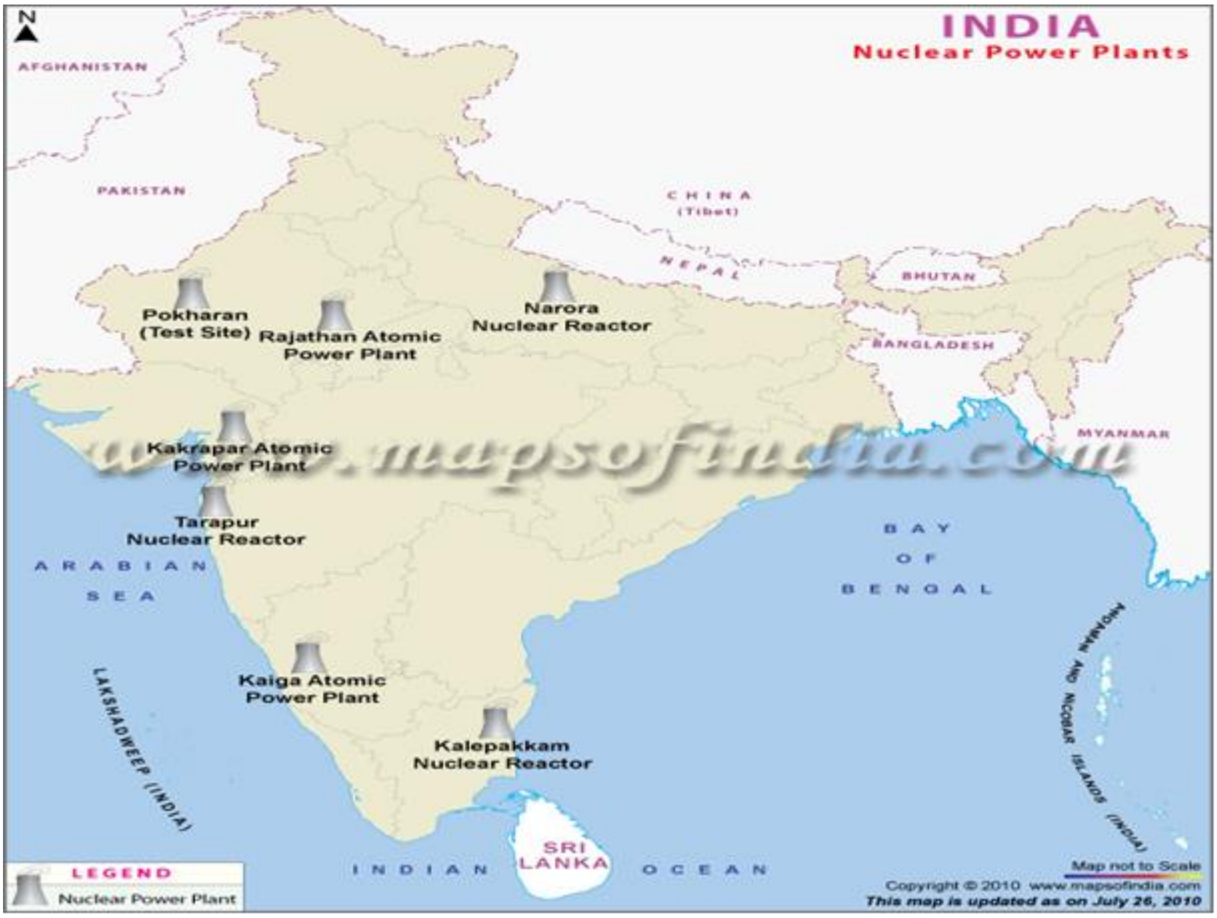


Figure 10.11 Nuclear power plant in India

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. Its first unit was established in 1961 and second was 1966. It supplies 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 65 km away 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. Its Capacity is 235 MW.

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

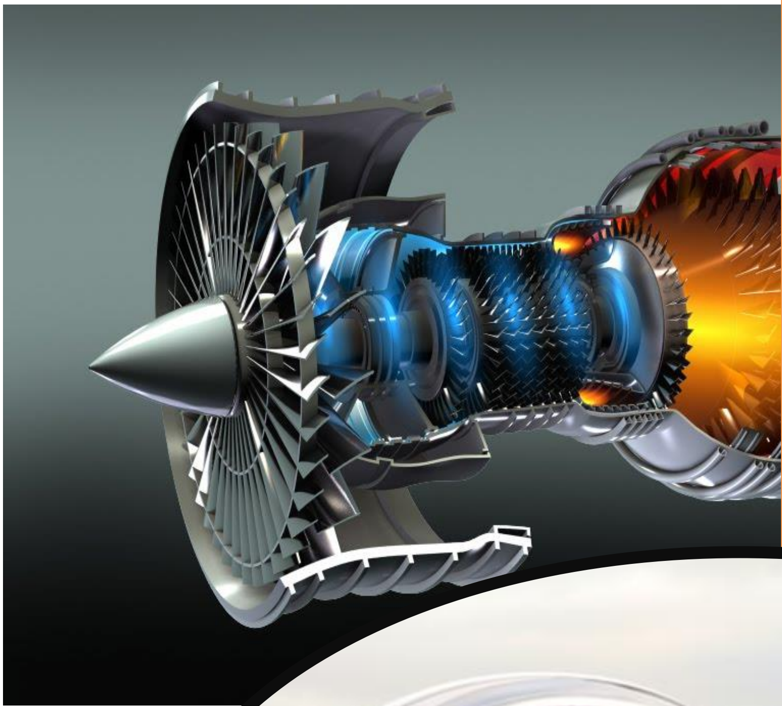
India’s 5th nuclear power plant is located at kakrapar near Surat in Gujarat. This power station has four reactors each of 235MW capacity. It has Candu Reactor. It has similar design as Narora nuclear power plant.

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.

11

Jet Propulsion



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11.1 Introduction

Jet propulsion, similar to all means of propulsion, is based on Newton's Second and Third laws of motion.

The jet propulsion engine is used for the propulsion of aircraft, missile and submarine (for vehicles operating entirely in a fluid) by the reaction of jet of gases which are discharged rearward (behind) with a high velocity. As applied to vehicles operating entirely in a fluid, a momentum is imparted to a mass of fluid in such a manner that the reaction of the imparted momentum furnishes a propulsive force. The magnitude of this propulsive force is termed as thrust.

For efficient production of large power, fuel is burnt in an atmosphere of compressed air (combustion chamber), the products of combustion expanding first in a gas turbine which drives the air compressor and then in a nozzle from which the thrust is derived. Paraffin is usually adopted as the fuel because of its ease of atomization and its low freezing point.

Jet propulsion was utilized in the flying Bomb, the initial compression of the air being due to a divergent inlet duct in which a small increase in pressure energy was obtained at the expense of kinetic energy of the air. Because of this very limited compression, the thermal efficiency of the unit was low, although huge power was obtained. In the normal type of jet propulsion unit a considerable improvement in efficiency is obtained by fitting a turbo-compressor which will give a compression ratio of at least 4 : 1.

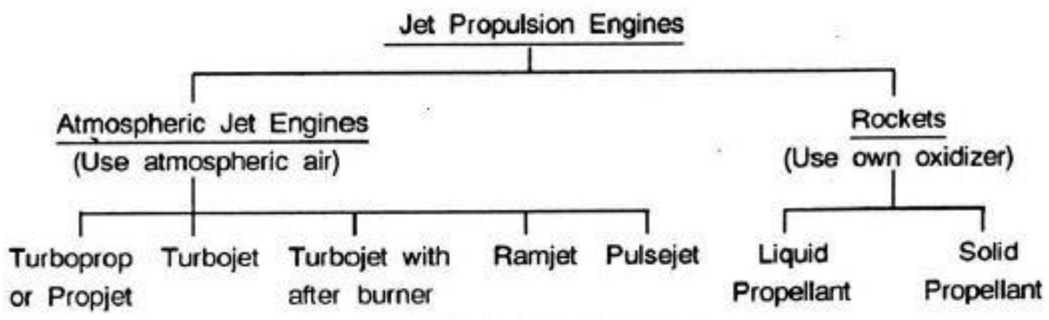


Figure 11.1 Classification of Jet propulsion Engines

11.2 Turbojet Engine

The turbojet engine is similar to the simple open cycle constant pressure gas turbine plant, except that the exhaust gases are first partially expanded in the turbine to produce just sufficient power to drive the compressor. The exhaust gases leaving the turbine are then expanded to atmospheric pressure in a propelling (discharge) nozzle. The remaining energy of gases after leaving the turbine is used as a high speed jet from which the thrust is obtained for forward movement of the aircraft

The essential components of a turbojet engine are:

An entrance air diffuser (diverging duct) in front of the compressor, which causes rise in pressure in the entering air by slowing it down. This is known as ram. The pressure at entrance to the compressor is about 1-25 times the ambient pressure.

A rotary compressor, which raises the pressure of air further to required value and delivers to the combustion chamber. The compressor is the radial or axial type and is driven by the turbine.

The combustion chamber, in which paraffin (kerosene) is sprayed, as a result of this combustion takes place at constant pressure and the temperature of air is raised.

The gas turbine into which products of combustion pass on leaving the combustion chamber. The products of combustion are partially expanded in the turbine to provide necessary power to drive the compressor.

The discharge nozzle in which expansion of gases is completed, thus developing the forward thrust.

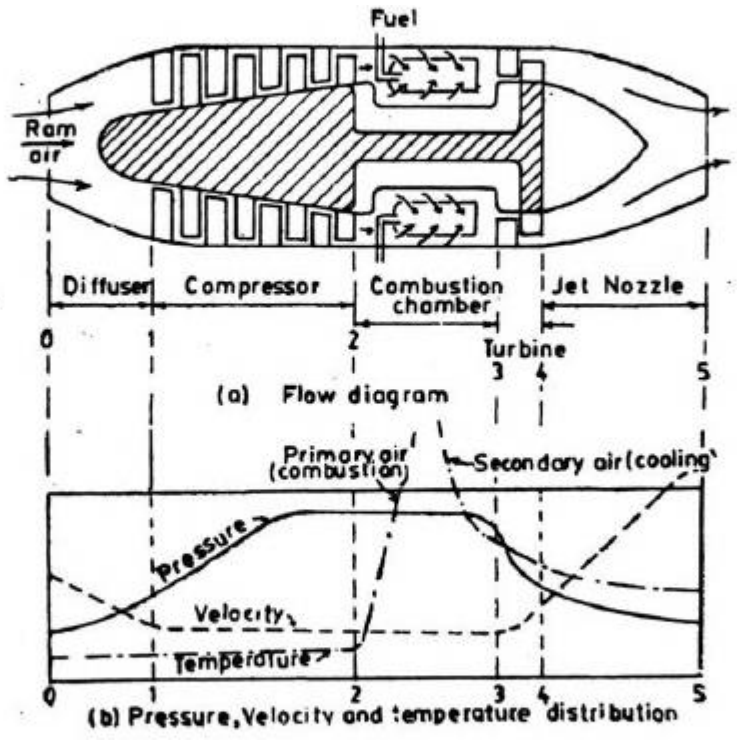


Figure 11.2 Turbojet engine

Working Cycle:

Air from surrounding atmosphere is drawn in through the diffuser, in which air is compressed partially by ram effect. Then air enters the rotary compressor and major part of the pressure rise is accomplished here. The air is compressed to a pressure of about 4 atmospheres.

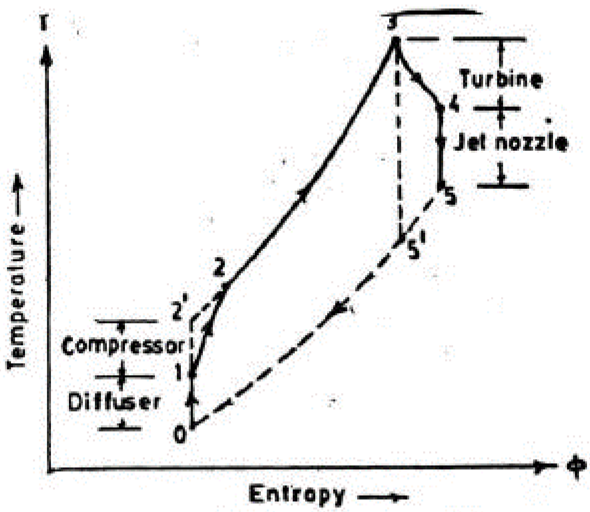


Figure 11.3 T-S diagram of turbojet engine

From the compressor the air passes into the annular combustion chamber. The fuel is forced by the oil pump through the fuel nozzle into the combustion chamber. Here the fuel is burnt at constant pressure. This raises the temperature and volume of the mixture of air and products of combustion.

The hot gases from the combustion chamber then pass through the turbine nozzle ring. The hot gases which partially expand in the turbine are then exhausted through the discharge (propelling nozzle) by which the remaining enthalpy is converted into kinetic energy. Thus, a high velocity propulsion jet is produced.

11.3 Thrust power, propulsive efficiency and thermal efficiency

The jet aircraft draws in air and expels it to the rear at a markedly increased velocity. The action of accelerating the mass of fluid in a given direction creates a reaction in the opposite direction in the form of a propulsive force. The magnitude of this propulsive force is defined as thrust. It is dependent upon the rate of change of momentum of the working medium i.e. air, as it passes through the engine. The basis for comparison of jet engines is the thrust. The thrust, T of a turbojet engine can be expressed as,

T = m (Vj - Vo)

Where,
M = mass flow rate of gases, kg/sec
V_i = exit jet velocity, m/sec
Vo = vehicle velocity, m/sec

The above equation is based upon the assumption that the mass of fuel is neglected. Since the atmospheric air is assumed to be at rest, the velocity of the air entering relative to the engine, is the velocity of the vehicle, Vo. The thrust can be increased by increasing the mass flow rate of gas or increasing the velocity of the exhaust jet for given Vo. Thrust power is the time rate of development of the useful work achieved by the engine and it is obtained by the product of the thrust and the flight velocity of the vehicle. Thus, thrust power TP is given by

$$TP = Tv_0 = m\,(v_j - v_0)\,v_o \text{ Nm/s}$$

The kinetic energy imparted to the fluid or the energy required to change the momentum of the mass flow of air, is the difference between the rate of kinetic energy of entering air and the rate of kinetic energy of the exist gases and is called propulsive power. The propulsive power PP is given by,

$$PP = m\frac{(v_j^2 - v_o^2)}{2} \text{ Nm/s}$$

Propulsive efficiency is defined 'as the ratio of thrust power and propulsive power and is the measure of the effectiveness with which the kinetic energy imparted to the fluid is transformed or converted into useful work. Thus, propulsive efficiency is given by,

$$\eta_p = \frac{TP}{PP} = \frac{m\,(v_j - v_o)}{1} \times \frac{2}{m\,(v_j^2 - v_o^2)}$$

Thermal efficiency of a propulsion is an indication of the degree of utilization of energy in fuel (heat supplied) in accelerating the fluid flow and is defined as the increase in the kinetic energy of the fluid (propulsive power) and the heat supplied. Thus,

$$\text{Thermal efficiency} = \eta_T = \frac{Propulsive\ power}{heat\ supplied} = \frac{Propulsive\ power}{Fuel\ flow\ rate \times C.V.of\ fuel}$$

The overall efficiency is the ratio of the thrust power and the heat supplied. Thus, overall efficiency is the product of propulsive efficiency and thermal efficiency. The propulsive and overall efficiencies of the turbojet engine are comparable to the mechanical efficiency and brake thermal efficiency respectively, of the reciprocating engine.

11.4 Ramjet engine

A french engineer, Rane Lorin invented and patented the first ram jet in 1913. It is a steady combustion or continuous flow engine. It has the simplest construction of any propulsion engine consisting essentially of an inlet diffuser, a combustion chamber, and an exit nozzle or tailpipe.

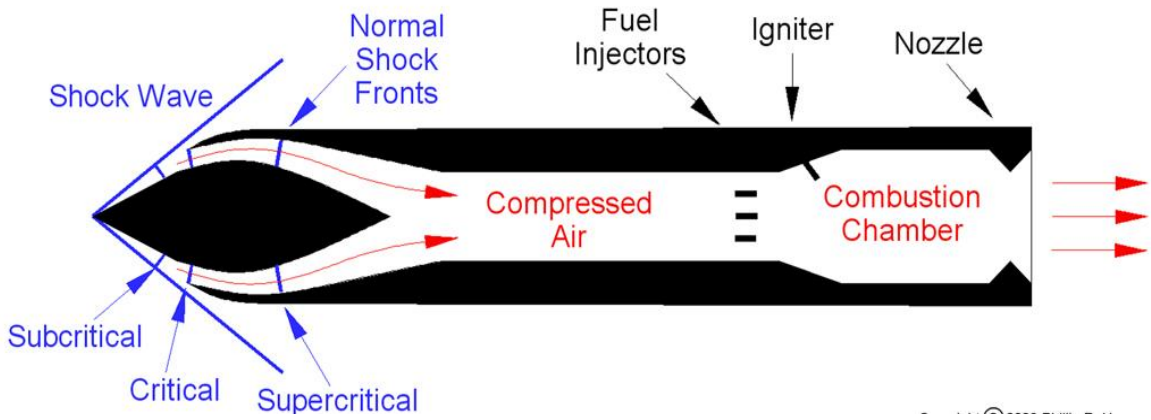


Figure 11.4 Ramjet engine

Since the ram jet has no compressor, it is dependent entirely upon ram compression. Ram compression is the transformation of the kinetic energy of the entering air into pressure energy. After the ram jet is boosted, the- velocity of the air entering the diffuser is decreased and is accompanied by an increase in pressure. This creates a pressure barrier at the after end of the diffuser. The fuel that is sprayed into the combustion chamber through injection nozzles is mixed with the air and ignited by means of a spark plug.

The expansion of the gases toward the diffuser entrance is restricted by the pressure barrier at the after end of the diffuser; consequently, the gases are constrained to expand through the tail pipe and out through the exit nozzle at a high velocity. Sometimes, the pressure barrier is not effective and that there are pulsations created in the combustion chamber which affect the air flow in front of the diffuser.

The cycle for an ideal ram jet, which has an isentropic entrance diffuser and exit nozzle, is the Joule cycle as shown by the dotted lines in fig.

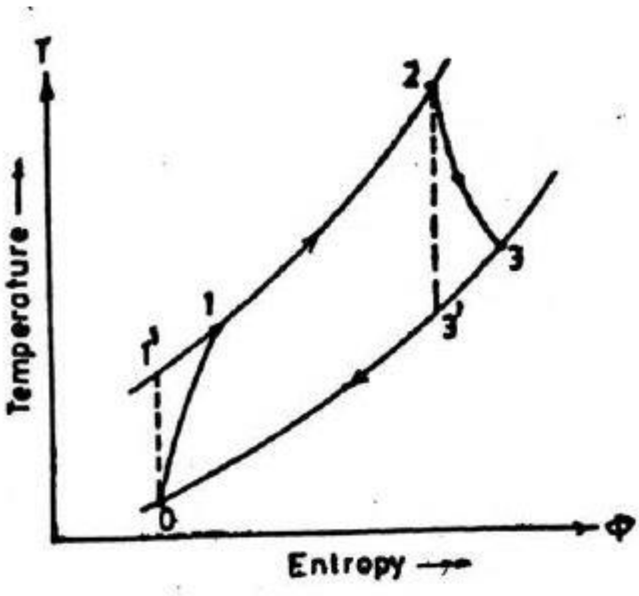


Figure 11.5 T-S diagram of ramjet engine

The difference between the actual and ideal jet is due principally to losses actually encountered in the flow system. The sources of these losses are:

- Wall friction and flow separation in the subsonic diffuser and shock in the supersonic diffuser.
- Obstruction of the air stream by the burners which introduces eddy currents and turbulence in the air stream.
- Turbulence and eddy currents introduced in the flow during burning.
- Wall friction in the exit nozzle.

11.5 Pulsejet engine

Paul Schmidt patented principles of the pulse jet engine in 1930. It was developed by Germany during World-War-II.

The pulse jet engine is somewhat similar to a ram jet engine. The difference is that a mechanical valve arrangement is used to prevent the hot gases of combustion from flowing out through the diffuser in the pulse jet engine.

The turbojet and ram jet engines are continuous in operation and are based on the constant pressure heat addition (Bryton) cycle. The pulse jet is an intermittent combustion engine and it operates on a cycle similar to a reciprocating engine and may be better compared with an ideal Otto cycle rather than the Joule or Bryton cycle.

The compression of incoming air is accomplished in a diffuser. The air passes through the spring valves and is mixed with fuel from a fuel spray located behind the valves. A spark plug is used to initiate combustion but once the engine is operating normally, the spark is turned off and residual flame in the combustion chamber is used for ignition. The engine walls also may get hot enough to initiate combustion.

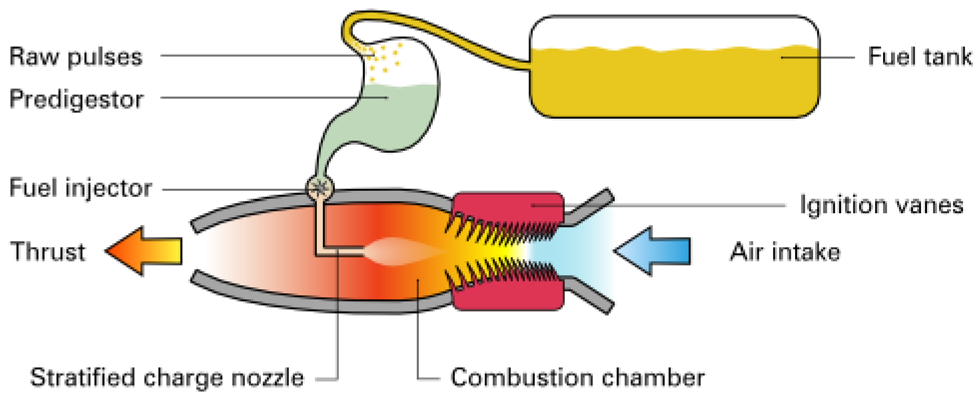


Figure 11.6 Pulsejet engine

The mechanical valves which were forced open by the entering air, are forced shut when the combustion process raises the pressure within the engine above the pressure in the diffuser. As the combustion products cannot expand forward, they move to the rear at high velocity. The combustion products cannot expand forward, they move to the rear at high velocity. When the combustion products leave, the pressure in the combustion chamber drops and the high pressure air in high pressure air in the diffuser forces the valves open and fresh air enters the engine.

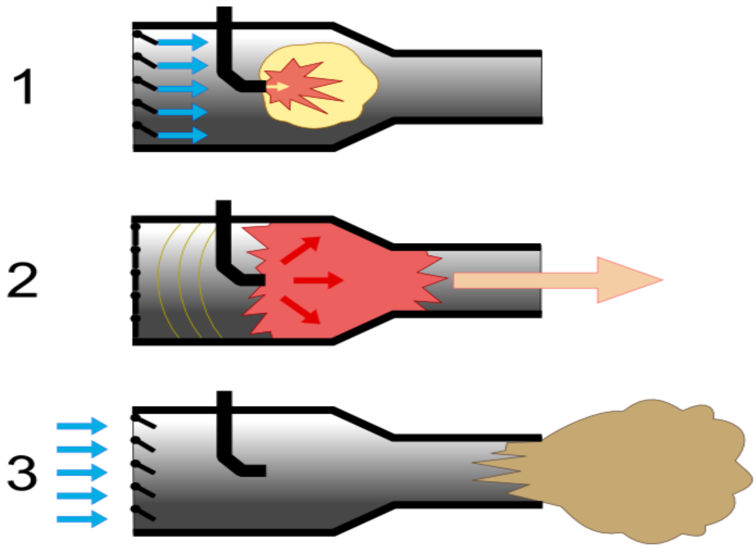


Figure 11.7 Valves position for Pulsejet engine

Since the products of combustion leave at a high velocity there is certain scavenging of the engine caused by the decrease in pressure occasioned by the exit gases. There is a stable cycle set up in which alternate waves of high and low pressure travel down the engine. The alternating cycles of combustion, exhaust, induction, combustion, etc. are related to the acoustical velocity at the temperature prevailing in the engine.

Despite the apparent noise and the valve limitation, pulse jet engines have several advantages when compared to other thermal jet engines.

- The pulse jet is very inexpensive when compared to a turbojet.
- The pulse jet produces static thrust and produces thrust in excess of drag at much lower speed than a ram jet.
- The potential of the pulse jet is quite considerable and its development and research may well bring about a wide range of application.

11.6 Rocket engine

A rocket engine is a type of jet engine that uses only stored rocket propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines, obtaining thrust in accordance with newton's third law. Most rocket engines are internal combustion engines. Vehicles propelled by rocket engines are commonly called rockets.

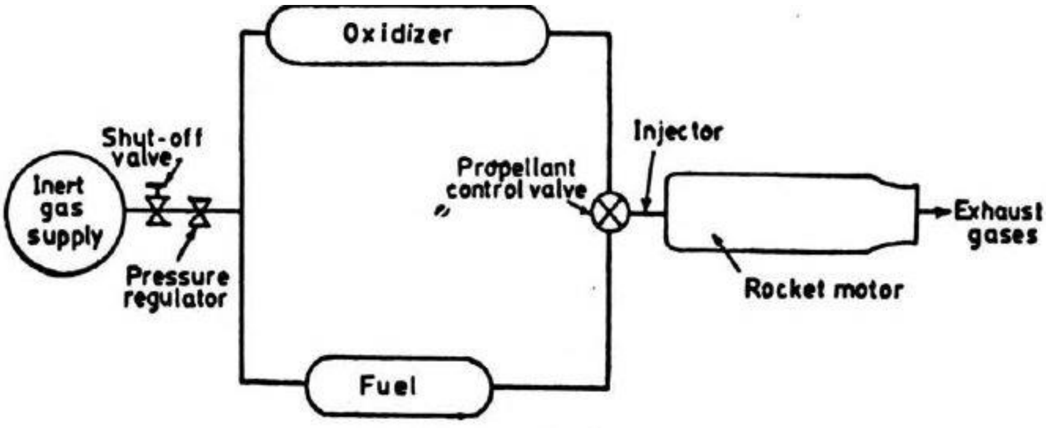


Figure 11.8 Pressure feed rocket jet

Principle of operation:

Rocket engines produce thrust by the expulsion of an exhaust fluid which has been accelerated to a high speed through a propelling nozzle. The fluid is usually a gas created by high pressure combustion of solid or liquid propellants, consisting of fuel and oxidiser components, within a combustion chamber. The nozzle uses the heat energy released by expansion of the gas to accelerate the exhaust to very high (supersonic) speed, and the reaction to this pushes the engine in the opposite direction.

Propellant

Rocket propellant is mass that is stored, usually in some form of propellant tank, or within the combustion chamber itself, prior to being ejected from a rocket engine in the form of a fluid jet to produce thrust. Chemical rocket propellants are most commonly used, which undergo exothermic chemical reactions which produce hot gas which is used by a rocket for propulsive purposes.

Rocket engines are classified as to the type of propellant used in them. Accordingly, there are two major groups: One type belonging to the group that utilizes liquid type propellants and other group that uses solid type propellants. The basic theory governing the operation of rocket motor is applied, equally to both the liquid and the solid propellant rocket.

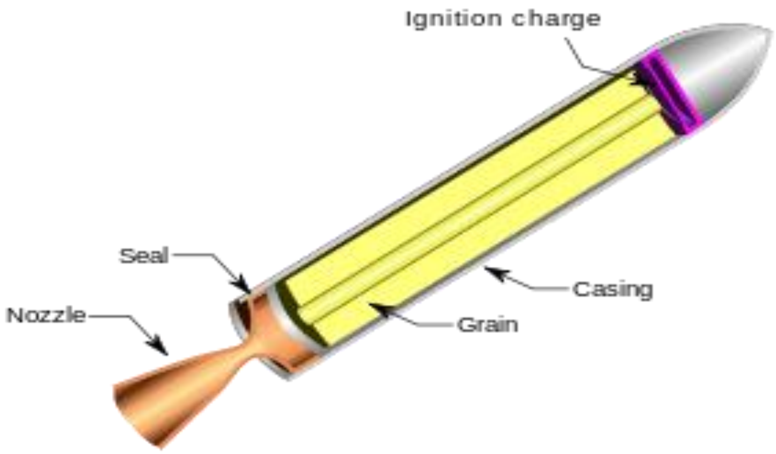


Figure 11.9 Rocket motor

The particular **advantages** of the rocket are,

- Its thrust is practically independent of its environments
- It requires no atmospheric oxygen for its operation.
- It can function even in a vacuum.
- It appear to be the simplest means for converting the thermochemical energy of a propellant combination (fuel plus oxidizer) into kinetic energy associated with a jet flow gases.

Applications:

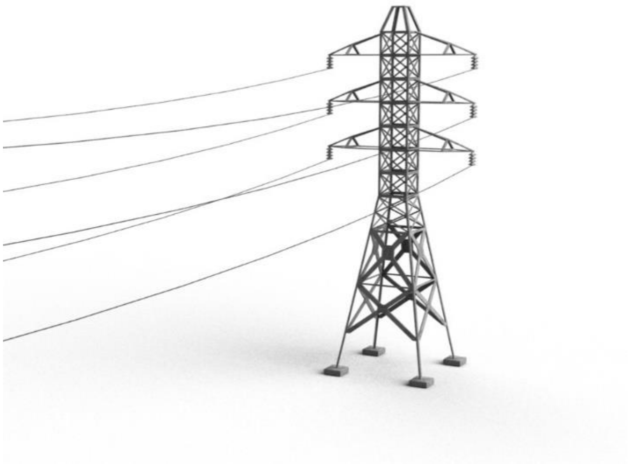
- Artillery barrage rockets
- Anti-tank rockets
- All types of guided missiles
- Aircraft launched rockets
- Jets assisted take-off for airplanes
- Engines for long range, high speed guided missiles and pilotless aircrafts
- Main and auxiliary propulsion engines on transonic airplanes

Despite its apparent simplicity, the development of a reliable rocket system must be light in weight and the rocket motor must be capable of sustained operation in contact with gases at temperature above 2800° C and at appreciable pressures. The -problem of materials in consequently a major one. Furthermore, owing to the enormous energy releases involved, problem of ignition, smooth start up, thrust control, cooling etc. arise.

A major problem of development of rocket is selection of suitable propellant to give maximum energy per premium total weight (propellant plus containing vessels) and convenience factors such as a safety in handling, dependability, corrosive tendencies, cost, availability and storage problems. In general, it can be stated that there is a wide variety of fuels that are satisfactory for rocket purpose, but choice of oxidizers is at present distinctly limited.

12

Economics of Power Generation



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12.1 Load curves and Load duration curves

The curve showing variation of load or power consumption with time is known as load curve. If time is in hours, then it is called daily load curve. If the time in days, it is called monthly load curve and f time is in month it is called yearly load curve.

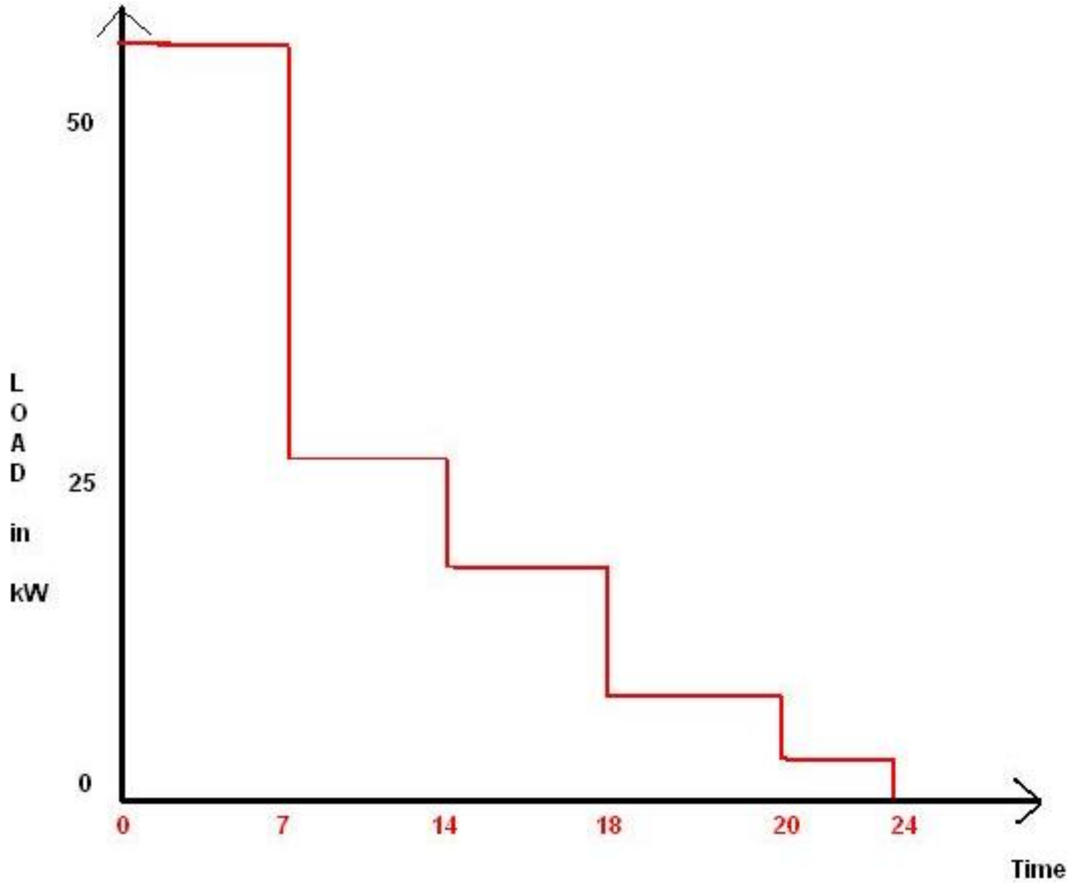

Figure 12.1 Load curve

Following information obtained from the load curve

- The area under the load curve gives the total energy consumption.
- Peak load and its duration can be known from load curve.
- The average load during day, month or year can be determined from load curve by dividing total energy consumption by time.

Load duration curve

A load duration curve is a rearrangement of daily load curve with load set up in descending order of magnitude. The area under the load curve and the area under load duration curve are equal.

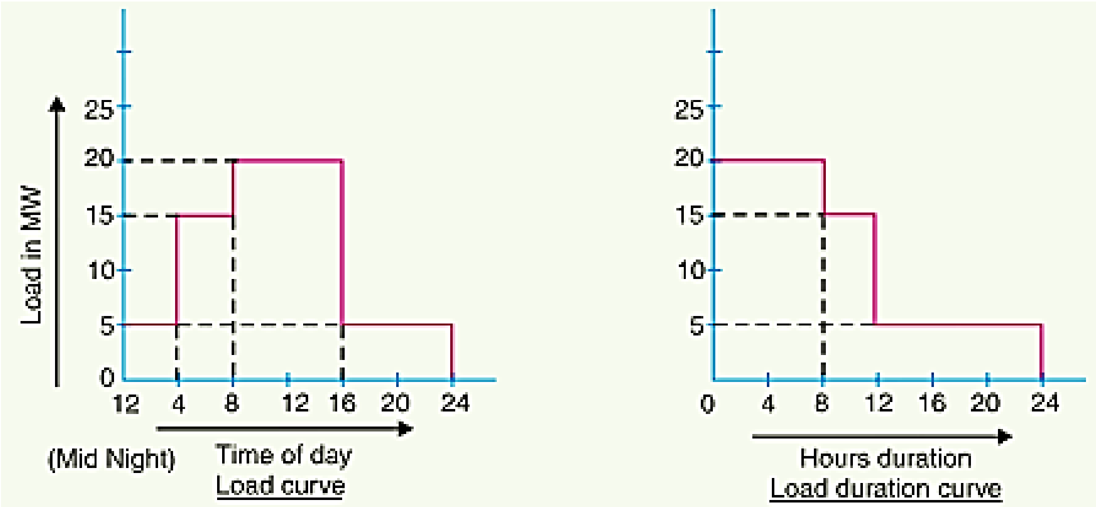

Figure 12.2 Load curve and Load duration curve

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 area under the load duration curve and corresponding load curve are equal and measure kWhr of energy for that period.

12.2 Different terms used in Economics of power generation

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 hours). It is also calculated by multiplication of load factor and peak load.

Load factor

It is defined as the ratio of average load to the maximum load consume by the consumer.

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum load}}$$

Diversity factor

It is the ratio of sum of individual maximum demand of the load to the maximum demand of entire group of loads.

Plant capacity factor

Capacity factor shows how close a plant runs to its full rating.

$$Plant\ capacity\ factor = \frac{E}{C \times t}$$

Where,

E= Actual energy generated in KWhr in given period

C= Capacity of the plant in KW

t= Total number of hours in the given period

Plant use factor

It is defined as the ratio of energy produced in a given time to maximum possible energy that could have been produced during the actual number of hours the plant was in operation. High value of plant use factor indicates that the plant is used more efficiently.

$$Plant\ use\ factor = \frac{E}{C \times t1}$$

Where,

E= Actual energy generated in KWhr in given period

C= Capacity of the plant in KW

t_1= Actual number of hours the plant is in operation.

12.3 Cost of Power Plant

The cost of electrical energy generated in power plant consists of fixed cost and running cost.

1. <u>Fixed Cost</u>

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.

- **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.

- **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.

- **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

Let us consider,

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

$P-S = A + A (1+r) + A (1+r)^2 + \ldots\ldots + A (1+r)^{n-1}$
$= A [1+ (1+r) + (1+r)^2 + \ldots\ldots + (1+r)^{n-1}]$……………………….(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

$(P-S)r = [(1+r)^n - 1] A$
$P-S = [\{(1+r)^n - 1\}/r] A$

So finally,

$$A = \left[\frac{r}{(1+r)^n - 1}\right](P - S)$$

c) Diminishing value method

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.

- **Insurance**

It becomes necessary many times to insure the costly equipments especially 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.

- **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.

2. <u>Running cost</u>

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.

- **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.

- **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.

12.4 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:

$$\mathbf{I = a + bL + cL^2 + dL^3}$$

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/($a+bL+cL^2+dL^3$)

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

= $(a+bL+cL^2+dL^3)/L$

HR (heat rate) = $(a/L) +b+cL+dL^2$

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

$$\therefore dI = IR \times dL$$

$$\int_{I1}^{I2} dI = \int_{L1}^{L2} IR\,.\,dL$$

$$\therefore I2 - I1 = \int_{L1}^{L2} IR\,.\,dL$$

$$IR = \frac{dI}{dL}$$

$$= \frac{d(\text{ a} + \text{bL} + \text{cL2} + \text{dL3})}{dL}$$

$$= b + 2cL + 3dL^2$$

Above equation is known as the incremental rate equation. 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.

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.

12.5 Tariff for electric 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 KWh during the period considered

a=Rate per KW of max demand

b= Energy rate per KWh

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

(2) Straight line meter rate

In this type of tariff, the charge is based on amount of energy consumed and the charge per unit is constant. It is expressed as

$$Z = by$$

The main drawback of this tariff is that a customer who does not use energy will not pay any amount.

(3) Block meter rate method

The straight line meter 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 meter 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 meter 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.

(4) Hopkinson demand rate or 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,

$$z=ax + by$$

This method required two meters to record the maximum demand and the energy consumption of the consumer. This method is generally used for industrial customers.

(5) Doherty rate or Three part Tariff

This rate of charging was suggested by Henry L. Doherty at the beginning of the twentieth century. According to this method of charge, 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 Doherty rate is sometimes modified by specifying the minimum demand and minimum energy consumption that must be paid for they are less than the minimum values specified.