UNIT-I B

B) Thermal Power Plant: General layout of modern thermal power plant with different circuits, site selection criteria, classification of coal, coal blending, coal beneficiation, selection of coal for thermal power plant, slurry type fuels, pulverized fuel handling systems, fuel burning methods, FBC systems, high pressure boilers, ash handling system, Rankine cycle with reheat and regeneration (Numerical Treatment), steam power plants with process heating (Numerical Treatment)
Power Plants and Types of Power Plant

• What is Power Plant?
• A power plant or a power generating station, is basically an industrial location that is utilized for the generation and distribution of electric power in mass scale, usually in the order of several 1000 Watts. These are generally located at the sub-urban regions or several kilometers away from the cities or the load centers, because of its requisites like huge land and water demand, along with several operating constraints like the waste disposal etc. For this reason, a power generating station has to not only take care of efficient generation but also the fact that the power is transmitted efficiently over the entire distance. And that’s why, the transformer switch yard to regulate transmission voltage also becomes an integral part of the power plant.
• At the center of it, however, nearly all power generating stations has an AC generator or an alternator, which is basically a rotating machine that is equipped to convert energy from the mechanical domain (rotating turbine) into electrical domain by creating relative motion between a magnetic field and the conductors. The energy source harnessed to turn the generator shaft varies widely, and is chiefly dependent on the type of fuel used.
The **electric power generation plant** must be constructed at such a place where the cost of land is quite reasonable.

The land should be such that the acquisition of private property must be minimum.

A large quantity of cooling water is required for the condensers etc of **thermal power generation plant**, hence the plant should preferably situated beside big source of natural water source such as big river.

Availability of huge amount of fuel at reasonable cost is one of the major criterion for choosing plant location.

The plant should be established on plane land.

The soil should be such that it should provide good and firm foundation of plant and buildings.

The **thermal power plant** location should not be very nearer to dense locality as there are smoke, noise steam, water vapors etc.

There must be ample scope of development of future demand.

Place for ash handling plant for thermal power station should also be available very near by.

Very tall chimney of power station should not obstruct the traffics of air ships.
Advantages and Disadvantages of Thermal Power Station

• **Advantages:**
  • Economical for low initial cost other than any generating plant.
  • Land required less than [hydro power plant](#).
  • Since coal is main fuel and its cost is quite cheap than petrol/diesel so generation cost is economical.
  • Maintenance is easier.
  • Thermal power plant can be installed in any location where transportation & bulk of water are available.

• **Disadvantages:**
  • The running cost for a thermal power station is comparatively high due to fuel, maintenance etc.
  • Large amount of smoke causes air pollution. The thermal power station is responsible for Global warming.
  • The heated water that comes from thermal power plant has an adverse effect on the aquatic lives in the water and disturbs the ecology.
  • Overall efficiency of thermal power plant is low like less 30%.
Thermal Power Station

A thermal power station or a coal fired thermal power plant is by far, the most conventional method of generating electric power with reasonably high efficiency. It uses coal as the primary fuel to boil the water available to superheated steam for driving the steam turbine. The steam turbine is then mechanically coupled to an alternator rotor, the rotation of which results in the generation of electric power. Generally in India, bituminous coal or brown coal are used as fuel of boiler which has volatile content ranging from 8 to 33 % and ash content 5 to 16 %. To enhance the thermal efficiency of the plant, the coal is used in the boiler in its pulverized form. In coal fired thermal power plant, steam is obtained in very high pressure inside the steam boiler by burning the pulverized coal.

This steam is then super heated in the super heater to extreme high temperature. This super heated steam is then allowed to enter into the turbine, as the turbine blades are rotated by the pressure of the steam. The turbine is mechanically coupled with alternator in a way that its rotor will rotate with the rotation of turbine blades. After entering into the turbine, the steam pressure suddenly falls leading to corresponding increase in the steam volume. After having imparted energy into the turbine rotors, the steam is made to pass out of the turbine blades into the steam condenser of turbine. In the condenser, cold water at ambient temperature is circulated with the help of pump which leads to the condensation of the low pressure wet steam. Then this condensed water is further supplied to low pressure water heater where the low pressure steam increases the temperature of this feed water, it is again heated in high pressure. This outlines the basic working methodology of a thermal power plant.
• **Advantages of Thermal Power Plants**
  • Fuel used i.e coal is quite cheaper.
  • Initial cost is less as compared to other generating stations.
  • It requires less space as compared to hydro-electric power stations.

• **Disadvantages of Thermal Power Plants**
  • It pollutes atmosphere due to production of smoke & fumes.
  • Running cost of the power plant is more than hydro electric plant.
• Types of Power Generation

• As mentioned above, depending on the type of fuel used, the power generating stations as well as the types of power generation are classified. Therefore the 3 major classifications for power production in reasonably large scale are :-
• **Thermal power generation.**
• Nuclear power generation.
• Hydro-electric power generation.
• Apart from these major types of power generations, we can resort to small scale generation techniques as well, to serve the discrete demands. These are often referred to as the alternative methods or non conventional energy of power generation and can be classified as :-
• Solar power generation. (making use of the available solar energy)
• Geo-thermal power generation. (Energy available in the Earth’s crust)
• Tidal power generation.
• Wind power generation ( energy available from the wind turbines)
• These alternative sources of generation has been given due importance in the last few decades owing to the depleting amount of the natural fuels available to us. In the centuries to come, a stage might be reached when several countries across the globe would run out of their entire reserve for fossil fuels. The only way forward would then lie in the mercy of these alternative sources of energy which might play an instrumental role in shaping the energy supplies of the future. For this reason these might rightfully be referred as the energy of the future.
Methods of Firing Steam Boiler

• For obtaining maximum fuel combustion efficiency it is required to have proper and complete combustion of fuel inside the **boiler furnace**. For that, proper and sufficient supply of air and proper mixing of air with fuel are primary requirements.

• Adequate supply of fuel particles for proper burning of particles also to be maintained. The combustion should produce designated temperature of the **steam boiler** and maintains it consistently. In addition to these, the method of firing steam boiler is such that, the system may be easily handled and also, operation and maintenance should be minimum. There are mainly two **methods of firing steam boiler** with coal as fuel.

• One is solid fuel firing other is pulverized fuel firing. Let us discuss one by one. There are mainly two types of solid fuel firing system
  - Hand firing
  - Mechanical stoker firing
• Smaller size boiler can be operated by hand firing system. This system was commonly used to drive coal engine locomotive in past. Here, coal chips are put into the furnace frequently by shovels.
• **Mechanical Stoker Firing**

• When fuel i.e. coal is put into the steam boiler furnace by means of mechanical stoker, the firing of boiler method is referred as mechanical stoker firing.

• There are mainly two types of mechanical stoker firing systems.

• **Under Feed Mechanical Stoker Firing**: Here, combustion takes place on the grate. The primary air is fed below the grate. The secondary air is allowed at the top. when the coal is burnt, it is pushed down by fresh coal. The fresh coal is pushed on the grate by means of rams as shown.
The ignition occurs downwards against the primary air flow. The volatile matter filters through the bed and is completely burnt. The combustion rate is high. The light ash contents and combustion gases fly away to the atmosphere along with primary air. Heavier ash content comes down over the grate and ultimately falls into ash pit.
• **Travel Grate Stoker Solid Coal Firing**

• Here, the coal is burnt on a chain grate which continuously travel forwards slowly, combustion takes place during the journey of coal from first end to last end of the furnace. At the end of the combustion heavier ash content falls into ash pit by gravitational force as the grate chain moves like conveyor belt. The lighter ash particles and combustion gases fly away with primary air.
• **Pulverized Fuel Firing**

For getting most calorific value of coal, the coal is pulverized in fine powder and then mixed with sufficient air. The mixture of coal powder and air is fired in the steam boiler furnace to achieve most efficient combustion process. This is the most modern and efficient method of boiler firing. Due to pulverization, the surface area of coal becomes much larger, and in this method air required for combustion is much less.

• As the quantity of required air and fuel both are less, loss of heat in this method of boiler firing is much less, hence temperature can easily be reached to the designated level. As the combustion is most efficient, pulverized coal firing increases the overall efficiency of steam boiler. As handling of lighter coal dust is much easier than handling of heavier coal chips, it is quite easy to control the output of the boiler by controlling supply of fuel to the furnace. Hence fluctuation of system load can smoothly be met. In addition these advantages, pulverized coal firing system has may disadvantages. Such as
• The initial cost of installing this plant is very high.
• Running cost of this plant is quite high as separate pulverization plant to be installed and run additionally.
• High temperature causes high thermal loss through flue gas.
• This method of boiler firing has always a risk of explosion.
• This is also difficult and expensive to filter fine ash particles from fine gas. Moreover, the quantity of ash particles in the flue gas is more in pulverized system.
• **Pulverization Process**

• Process of pulverization is discussed here in brief.

• First the coal is crushed by preliminary crusher. The coal is crushed to 2.5 cm. or less.

• Then this crushed coal is passed through magnetic separator to separate any iron content in the coal. Iron must be removed, otherwise during pulverizing iron particles will cause spark which results in unwanted fire hazard.

• After that, crushed coal is dried properly before pulverization. The moisture content must be less than 2% after drying operation.

• Then the coal is crushed again in fine particles in ball mill. This process is referred as pulverization.

• This pulverized coal is then puffed with air and put into furnace as fluid.
Steam Boiler Furnace [Grate Firebox Combustion Chamber of Furnace]

• The heat required for producing **steam** in a **boiler** is generated at **boiler furnace** by combustion of fuel.

• **What is Combustion?**

• **Combustion** is a chemical process during which oxygen is combined with different elements of fuel. During this combination, a definite amount of heat is produced per unit mass of combustible element depending upon the element with which the oxygen combines.

• The elements participate in combustion process are oxygen, hydrogen, carbon and sulfur. There are various other elements in the fuel (coal) which do take part in combustion process such as iron, silicon etc. They usually exist in small amount and are classed as impurities of fuel.

• These impurities produce certain waste during combustion of coal and remain in the form of ash and stored in the ash pit of steam **boiler furnace**, after combustion. The combustion of fuel including coal requires three stages to be completed.
• The absorption of heat to rise the temperature of the fuel to the point of ignition.
• The distillation and burning of volatile gases.
• Combustion of fixed carbon.

While the coal is fed to the **boiler furnace** in a pulverized form, the temperature of the coal is first raised to its ignition point the volatile matters of the coal so called hydrocarbons, such as marsh gas, tar, pitch, naphtha are separated from the coal and driven of in the gaseous form. These gases then combine with oxygen of air which is supplied through the bed of the hot bed of fuel (coal) of the **steam boiler furnace**.

After the hydrocarbons are driven off from the coal, the solid carbon unites with oxygen of air and forms carbon monoxide and carbon dioxide. Any substances of the coal which are not combustible fall through the grate into the pit below the **boiler furnace** in form of ash.
• So far combustion process, sufficient air to be supplied in furnace. Generally approximately 1.2 pound of air is required to complete combustion of one pound of coal. But in practice twice or more of this quantity of air is supplied in the furnace by forced draft since ideal condition of combustion can not be achieved practically.

• It is always quite difficult to supply air to the all part of the steam boiler furnace uniformly. on the other hand, too much air should not be supplied to the furnace. If air is supplied in very higher rate than specified then there may be a chance of blowing off the hydrocarbon gases before the combustion process is completed. So the air should be supplied to the furnace in high but with controlled rate.
The main design and operation of the boiler furnace is to obtain combustion with minimum smoke. Smoke less combustion is preferred for mainly two reasons,
• The smoke is a main cause of air pollution.
• Smoke is the indication of incomplete combustion. The unburned visible gases are in the form of smoke.

The principle of complete combustion is quite simple but is not always possible to carry out in **steam boiler furnace**. Introducing coal into the boiler furnace, rising the temperature to the burning point, and supplying enough air for the combustion may not be sufficient for a successful combustion. There is another factor which to be kept in mind during designing a furnace. It is equally important to mix up the air with combustible gases thoroughly and that is to be maintained at a sufficiently high temperature during the process. When fresh bituminous coal is fired, on the fuel bed of boiler furnace, the combustible gases are driven off and large portion of which remain unburned and are carried into the chimney if air is not mixed up with them properly.

There are many air mixing processes developed for steam boiler furnace. One of the popular methods of boiler furnace is to provide fire brick lined combustion chamber of ample size with suitable baffles for proper mixing the gases with the air.

the introduction of sufficient heated air in the combustion to consume the combustible gases before reaching the heating surface of the boiler.
• **Construction of Boiler Furnace**
• For successful combustion, a boiler furnace has some essential parts in its construction, such as
• A grate for supporting fuel (coal).
• Combustion chamber – in which the combustion takes place.
• Means of supplying fresh air.
• An ash pit for collecting and catching the refuse from the fuel during combustion.

**Boiler Furnace Grate**

![Grate Diagram]
• **Grate** is provided in a steam boiler furnace for supporting the solid fuel in the furnace. Grate is so designed that it can also allow air to admit in the solid fuel for combustion. The openings of the **grate** must not be so large that they allow the unburned fuel partials to fall through and on the other hand these openings must not be so narrow that they obstruct sufficient amount of air to pass through the fuel.

• **Firebox and Combustion Chamber of Furnace**

  • **Firebox** of boiler furnace is the place just above the grate and **combustion chamber**. It is the extension of this where combustion of volatile hydrocarbons take place. The heat is produced due to combustion is absorbed by the **steam boiler** surface at the top of the **combustion chamber**. Different fire bricks wall and baffles are provided in the combustion chamber proper mixing of air with combustible gases.
• **Ash Pit**

• **Ash pit** of steam boiler furnace is a chamber provided below the grate to catch the refuse (ash) from the fire above.

• **Ash pit** also functions as supply chamber of air through the grate. There must be sufficient height between the bottom floor of the ash pit and the grate to give plenty of air space. It is common practice to slope the pit floor towards the front, to facilitate the removal of ashes.
Combustion is a rapid chemical reaction between fuel and oxygen. When combustible elements of fuel combine with O$_2$, heat energy comes out. During combustion combustible elements like Carbon, Sulfur, Hydrogen etc. combine with oxygen and produce respective oxides. The source of oxygen in fuel combustion is air. By volume there is 21 % of Oxygen presents in air and by weight it is 23.2 %. Although there is 79 % (by volume) nitrogen in air but it plays no role in combustion. Actually Nitrogen carries heat produced during combustion to steam boiler stack. As per combustion theory the quantity of air required for combustion is that which provides sufficient O$_2$ to completely oxidize combustible elements of fuel. This quantity of air is normally known as STOICHIOMETRIC AIR requirement. This amount of air depends upon the nature of fuel. STOICHIOMETRIC AIR requirements for different fuels are obtained by analysis of fuel and they are given in tabular form below,
<table>
<thead>
<tr>
<th>Fuel</th>
<th>STOICHIOMETRIC AIR mass / unit mass of fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous Coal</td>
<td>11.18</td>
</tr>
<tr>
<td>Anthrasite Coal</td>
<td>10.7</td>
</tr>
<tr>
<td>Coke</td>
<td>9.8</td>
</tr>
<tr>
<td>Liquite</td>
<td>7.5</td>
</tr>
<tr>
<td>Peat</td>
<td>5.7</td>
</tr>
<tr>
<td>Residual Fuel Oil</td>
<td>13.85</td>
</tr>
<tr>
<td>Distillate Fuel Oil(Gas Oil)</td>
<td>14.48</td>
</tr>
<tr>
<td>Natural Gas(Methane Base)</td>
<td>17.3</td>
</tr>
</tbody>
</table>
• **Coal Content in Proximate Analysis**

  - Moisture = 8 %, volatile material = 20 to 25 %, fixed carbon = 40 %, ash = 30 %. Fixed carbon's combustion temperature = 900°C.

  - Basic component of ash is Si, Al and others. Now fusion temperature of Si is 1200°C. If the furnace temperature raises above 1100°C then Si will be fused and deposited on the tubes, as slag, causing improper heat transfer. Now to dilute the temperature excess air and complete combustion are required. Now, the volatile material plays important role in combustion. Less the volatile material flame will be high which may be chance for flame impingement of S/H coil. For fulfilling the point some practical steps to taken. In practice it is always necessary to supply more air to the combustion system than it is theoretically required. Reason for that air and fuel mixing process in any combustion system, as it is not possible to ensure complete and intimate mixing of the fuel with the necessary oxygen at the point of injection. So some excess air is required for proper combustion to a reasonable minimum power, stack loss and unburnt carbon in ash. Generally 20% excess air is allowed.
Fluidized Bed Combustion | Types and Advantages of Fluidized Bed Combustion

Fluidization is a method of mixing fuel and air in a specific proportion, for obtaining combustion. A fluidized bed may be defined as the bed of solid particles behaving as a fluid.

It operates on the principal that when an evenly distributed air is passed upward through a finely divided bed of solid particles at low velocity, the particles remain undisturbed, but if the velocity of air flow is steadily increased, a stage is reached when the individual particles are suspended in the air stream.

If the air velocity is further increased, the bed becomes highly turbulent and rapid mixing of particles occur which appear like formation of bubbles in a boiling liquid and the process of combustion as a result is known as fluidized bed combustion.

The velocity of air, causing fluidization depends on a number of parameter, like :-

Size of fuel particles.

Density of air fuel mixture.
• The main **advantage of fluidized bed combustion** system is that municipal waste, sewage plant sludge, biomass, agricultural waste and other high moisture fuels can be used for heat generation.

• A fluidized furnace has an enclosed space with a base having openings to admit air. Crushed coal, ash and crushed dolomite or limestone is mixed in the bed furnace and high velocity combustion air is then passed through the bed, entering from the furnace bottom.

• With the steady increase in the velocity of air, a stage will be reached when the pressure drop across the bed becomes equal to the weight per unit cross-section of the bed, and this particular critical velocity is called the **minimum fluidizing velocity**. With further increase in velocity of air, the bed will begin to expand and allow passage of additional air, in the form of bubbles. When the air velocity becomes 3 to 5 times the critical velocity, the bed resembles to that of a violently boiling liquid.
A pictorial representation of fluidized bed combustion is given in the figure below :-
• The evaporator tubes of boiler are directly immersed in the fluidized bed and the tubes, being in direct contact with the burning coal particles, produce very high heat transfer rates. Because of this, the unit size is reduced to a great extent, and also produces combustion with very high efficiency.

• **Types of Fluidized Bed Combustion (FBC)**
  • Fluidized Bed combustion can be in 2 variants, namely :-
  • **Vertical type FBC:** These are generally used in smaller plant, and has the capacity to produce steam of up to 6 tonnes per hour only. Their vertical shape reduces the overall dimension of the steam boiler, and is extremely efficient in plants, where space provision is limited.
  • **Horizontal type FBC:** There are almost 10 times in capacity when compared to vertical type fluidized bed combustion. They can produce as much as 60 tonnes of steam per hour, and are placed horizontally with respect to the boiler tubes. The high capacity of the horizontal type Fluidized boilers coupled with their high efficiency, makes them an extremely desirable choice for the coal fired thermal power generating station.
Advantages and Dis-advantages of Fluidized Bed Combustion

- FBC is being used exhaustively these days in all major power stations all over the globe, owing to numerous advantages that it offers over the other predominant methods of combustion. Few of those are:-
- High thermal efficiency.
- Easy ash removal system, to be transferred for made cement.
- Short commissioning and erection period.
- Fully automated and thus ensures safe operation, even at extreme temperatures.
- Efficient operation at temperatures down to 150° C (i.e. well below the ash fusion temperature).
- Reduced coal crushing etc. (pulverised coal is not a necessity here).
- The system can respond rapidly to changes in load demand, due to quick establishment of thermal equilibrium between air and fuel particles in the bed.
- The operation of fluidized bed furnace at lower temperature helps in reducing air pollution. The low temperature operation also reduces the formation of nitrogen oxides. By adding either dolomite (a calcium-magnesium carbonate) or lime stone (calcium carbonate) to the furnace the discharge of sulphur oxides to the atmosphere can also be reduced if desired.
• **Disadvantages of fluidized bed combustion**

• The major drawback of this system is that the fan power has to be maintained at a considerably high value, since the air has to be supplied continuously at a very high pressure for supporting the bed.

• This in turn increases the operating cost of the auxiliary units of the plant. But it is more than compensated by the high values of efficiency that FBC provides.
Rankine Cycle

• **Ideal Rankine Cycle**

• Principles of **thermodynamics** are useful for power cycle for of **electrical power generation** (i.e. net power output) and to study refrigeration & heat pump which requires input of net power. Classification of thermodynamics power cycles can be done into two types:

• Vapor cycle working fluid exists in liquid phase during one part of the cycle (i.e. from condenser outlet to Boiler) and mixed phase with in the **steam boiler** and in vapor phase at the Boiler outlet.

• Gas cycle working fluid during the cycle remains in gas phase.

• **Steam** power generation units run on vapor power cycle using water as the working fluid. Under this section attempt is made to familiarize the readers with the concepts of ideal vapor cycle called **Rankine cycle**.
• Typical Ideal Rankine Cycle

• In a vapour cycle if the working fluid in a vapor cycle passes through various components of the power plant without irreversibility and frictional pressure drop, then the cycle is called as **Ideal Rankine Cycle**. The Rankine cycle is the basic operating cycle for all power plants where an working fluid is continuously changing its phase from liquid to vapour and vice-versa.
The (p-h) and (T-s) diagrams are useful in understanding the working of **Rankine cycle** along with the description given below:
1-2-3 Isobaric Heat Transfer or Constant pressure heat addition in a boiler **Boiler** is a large heat exchanger where heat liberating fuel like coal, lignite or oil transfers the heat indirectly to water at constant pressure. Water enters the steam boiler from boiler feed pump as a compressed liquid at state-1 and is heated to the saturation temperature as shown in the T-s diagram as state-3. The energy balance in the boiler is or energy added in steam generator, \( q_{in} = h_3 - h_1 \)

3-4 Isentropic Expansion in a turbine Vapor from the boiler outlet enters the turbine at state 3, where it expands isentropically over the turbine fixed and moving blade to produce work done in the form of mechanical rotation of the turbine shaft which in turn is connected to the electrical generator.
• Work delivered by turbine, (Neglecting heat transfer with the surroundings)

• $W_{turbine\;out} = h_3 - h_4$

• 4-5 Isobaric Heat Rejection or Constant pressure heat rejection in a condenser At state-4 vapor enters the condenser and the change of phase occurs as vapor is condensed to liquid at constant-pressure in the condenser by transferring the heat of the steam to the circulating water flow through the tubes of the condenser. Change of phase occurs in condenser and the working fluid leaving the condenser is in liquid state and marked as point 5. Energy rejected in the condenser,

• $q_{out} = h_4 - h_5$
• 5-1 Isentropic Compression in a pump Water exits the condenser at state 5 and enters the pump. This pump raises the pressure of the water by imparting work during the processes. It is of smaller size and because of low specific volume this small work can be neglected when compared to work-output of steam turbine. Work done on pump, per kg of water,

\[ W_{\text{pump-in}} = h_1 - h_5 \]

The thermal efficiency of the Rankine cycle is given by,

\[ \eta = \frac{q_{\text{in}} - q_{\text{out}}}{q_{\text{in}}} \]
Rankine Cycle and Regenerative Feed Heating

• Rankine Cycle
• From the T-s diagram of **Rankine cycle** it is evident that at the state 2-2’ working fluid enters the **boiler** and this temperature is very low temperature at which water is entering the boiler. As a result of its efficiency of the cycle is lower.
• **Regeneration**

• There is a way to overcome this problem by raising the temperature-of the working fluid (water) before it enters into the boiler and this process is called **regeneration** in steam **power plants**.

• Conventional way of doing **regeneration** in a power plant is by extracting the steam from the turbine after partial expansion or partial work done. This **steam** is used to heat the feed water and the device in which it happens is called a feed water heater or a regenerator.
• Regeneration improves the cycle efficiency by increasing the initial feed water temperature before the water enters the boiler and also helps in controlling the large flow rate of steam at the turbine exhaust.

• Regeneration is commonly used in all power plants where efficiency is of importance and fuel saving is the motto. A feed water heater is basically a heat exchanger where heat is transferred to the feed water by extracting the partially expanded steam from the turbine to heat the feed water. Heating of feed water can be done by:

• Directly heating (in a tank, Open type) - Direct heating of feed water is performed in tanks or vessel also called open feed water heaters; or

• By indirect heating (in shell and tube type heat exchanger, closed type) - Indirect heating of steam and water is performed on shell and tube type closed heaters
• Regeneration with Open Feed Water Heaters

• Open or direct feed water heating comprises of the vessel were extracted steam and feed water directly mix with each other. Heated mixture leaves the tank at a temperature which is in line with the pressure of the mixing chamber. An example of the power plant operating with single stage regenerative cycle on the T-s diagram given below.
In a Rankine regenerative cycle steam enters the turbine at the boiler outlet pressure at (5). After entering the turbine the steam expands isentropically in the turbine till the point (6) or intermediate pressure (6), where it is extracted.
• At the state (6) some steam is taken out or extracted and directed towards the feed water heater while the rest of the steam continue to expand in the remaining stages of the turbine till the end i.e. condenser at a pressure corresponding to condenser pressure at state (7).
• The condensate in the condenser is at the saturation temperature corresponding to the condenser pressure at (7). From condenser Condensate leaves as a saturated liquid at condenser pressure (1). Condensate or feed water from here enters into the open feed water water heater via pump (1), where it comes in direct contact with the steam extracted from the turbine at (6).
• Mixture leaves the open feed water water heater as saturated liquid corresponding to heater pressure at (3). Second pump raises the feed water pressure equal to boiler pressure (4), in boiler change of state from water to steam and then superheating of steam took place to match the turbine inlet parameters.
• For every 1 kg of steam coming out of the boiler, some amount of steam (y) kg expands partially in the turbine up to (6) and extracted to heat the feed water. Remaining quantity of steam (1-y) kg worked completely over the rest of the turbine stages to condenser pressure.

• If the boiler generates m kg of steam, then it is (1-y)m steam enters the condenser. Analysis of the heat and work interaction for single feed water heater per unit mass of steam flowing through the boiler is given by:
Regeneration helps in boosting the **thermal-efficiency** of the cycle and also the boiler heat input requirement by enhancing/improving the feed water temperature entering the boiler.

\[ q_{in} = h_5 - h_4 \quad q_{out} = (1 - y)(h_7 - h_1) \]

\[ W_{turb, out} = (h_5 - h_6) + (1 - y)(h_6 - h_7) \]

\[ W_{pump, in} = (1 - y)W_{pumpI, in} + W_{pumpII, in} \]

Where

\[ y = \frac{n_6}{n_5}, \text{(fraction of steam extracted)} \]

\[ W_{pumpI, in} = V_1(P_2 - P_1) \]

\[ W_{pumpII, in} = V_3(P_4 - P_3) \]
Rankine Cycle for Closed Feed Water Heaters and Rankine Cycle Cogeneration

- **Rankine Cycle with Closed Feed Water Heaters**
- **Rankine cycle** with closed feed water heaters are having its benefits and is most commonly used in all modern power plants. Closed feed water heater employs indirect mode of heat transfer, i.e. extracted steam or bleed steam from the turbine transfers its heat indirectly to feed water in shell and tube heat exchanger. Since the steam and water are not mixing directly, so both steam and water circuits are at different pressures. Close feed water heater in a cycle is represented on T-s diagram as shown below in Fig:1. Theoretically or ideally heat transfer in closed feed water heater should be in such a way that the temperature of the feed water should be increased to that of the saturation temperature of the extraction steam (heating the feed water)

- But in actual plant operation the maximum temperature which feed water can attain is normally slightly less than that of the saturation-temperature of the steam.
This condensate or condense steam from the heater shell shall be transferred to next heater (low-pressure) in the cycle or sometimes to the condenser.
• **Differentiate Between Open and Closed Feed Water Heater**

• The open and closed feed water heaters can be differentiated as follows:

<table>
<thead>
<tr>
<th>Open feed water heater</th>
<th>Closed feed water heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open and simple</td>
<td>More complex in design</td>
</tr>
<tr>
<td>Good heat transfer characteristics</td>
<td>Less effective heat transfer</td>
</tr>
<tr>
<td>Direct mixing extraction steam and feed water in a pressure vessel</td>
<td>In-direct mixing feed water and steam in a shell and tube type heat exchanger.</td>
</tr>
<tr>
<td>Pump is required to transfer the water into next stage in the cycle.</td>
<td>Closed feed water pumps don’t require pump and can operate with the pressure difference between the various heaters in the cycle.</td>
</tr>
<tr>
<td>Requires more area</td>
<td>Requires less area</td>
</tr>
<tr>
<td>Less expensive</td>
<td>More expensive</td>
</tr>
</tbody>
</table>
• All Modern power plants are employing the combination of open and closed feed water heaters to maximize the thermal efficiency of the cycle.
• **Cogeneration Phenomenon**

Art of converting the valuable form of energy called heat to work is **thermodynamics**, this is done by transferring it to the working fluid called water (in power plants).

• So the purpose is to avoid the wastage of heat of steam in the **steam turbine** condensers. This is possible if find the means to use the low pressure steam going into the condenser.

• **Cogeneration** is the concept meant for utilizing the heat of the steam which is getting waste in the condensers. **Cogeneration means Combined Heat and Power (CHP)**, that is generation of heat and power simultaneously for the industry requiring process heating steam. In cogeneration plant both heat-and-power are judiciously utilized so the efficiency of it can be as high as 90% or more. Co-generation offers **energy savings**.
The Co-generation Principle

- Vegetable Oil
- Bioethanol
- Heating Oil
- Natural Gas
- Coal
- Biomass
- Bio Gas
- Municipal Waste

Co-Generation Plant

Gas Turbine/Generator

Steam Turbine/Generator

Power

Heat
• Cogeneration offers the reduction in wasting of large amount of steam and the same can be utilized in many devices in the form of heat. Most of the industries like paper and pulp, chemical, textile & fiber and cement are depending upon co-generation plant for process heating steam. Process heat steam requirement in above industries are in the order of 4 to 5 kg/cm² at temperature around 150 to 180 degree C.
• Paper, chemical and textile industries require both electric power and process steam to accomplish their objective. So this requirement can be easily met through by installing cogeneration power plant.

• Temperature inside the boiler is of the order of 800 to 900 Degree C and the energy is transferred to the water to produce steam of pressure 105 bar and temperature around 535 deg C for co-generation power plants. Steam at these parameters are considered as of very good quality source of energy and is thus first utilized in steam turbine for producing power and the turbine exhaust (low quality energy) is used to meet the requirement of process steam. Cogeneration plant is known for meeting the requirement of power while meeting the process steam requirement of Industrial processes.
• Ideal steam-turbine cogeneration is shown in the figure above.
• Let us say that the process heat requirement $Q_p$ is at 5.0 Kg/cm$^2$ at around 100 KW. In order to meet the process steam requirement at 5.0 Kg/cm$^2$ steam is expanded in the turbine till the pressure of the steam drop to 5.0 Kg/cm$^2$ and thus produces the power around 20 KW. The condensate from process heater is recycled back to boiler for cyclic operation.
• Pump work required to raise the pressure of the feed the water in the cycle is considered as small so not considered.
• All energy transferred to the working fluid in the boiler is used either in steam turbine or in process plant, thus utilization factor of the cogeneration plant is:
\[ \epsilon_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} \]

\[ \epsilon_u = 1 - \frac{Q_{\text{out}}}{\dot{Q}_{\text{in}}} \]

Where, \( Q_{\text{out}} \) Heat rejected in the process. Thus in the absence of the condenser the heat utilization factor of the cogeneration plant is 100%.
Given below Fig. 1-a and Fig 1-b represents the Rankine cycle on P-v and T-s diagram.

<table>
<thead>
<tr>
<th>Rankine Cycle Representation are as follows on P-v &amp; T-s diagrams:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ideal Rankine Cycle</strong></td>
<td>1-2'-b-3'-4'-1</td>
</tr>
<tr>
<td><strong>Actual Rankine Cycle</strong></td>
<td>1-2-b-3-4-1</td>
</tr>
</tbody>
</table>
• Critical Point (CP) is in centre of the curve as shown in Fig 1-a & 1-b above. The curved lines on the left side of the CP are saturated- liquid lines and the region/area to the left of these lines are called as sub-cooled liquid regions. Similarly curved lines on the right side of the CP are saturated- vapour lines and the region/area to the right of these lines are called as super-heat vapour regions.

• **Energy Analysis of Ideal Rankine Cycle**

• All components of Rankine cycle (Boiler, turbine, condenser and pump) are examples of steady flow process and to be analysed accordingly. Energy balance for the Ideal cycle is as follows:
Ideal Rankine Cycle Components | Heat | Work
---|---|---
Boiler feed Pump $W_{pump-in}$ | $q = 0$ | $W_{pump-in} = h_2' - h_1'$, or $W_{pump-in} = V(P_2')$
Boiler | $q_{in} = (h_3' - h_2')$ | $W = 0$
Turbine | $q = 0$ | $W_{turbine-out} = (h_3' - h_4')$
Condenser | $q_{out} = (h_4' - h_1')$ | $W = 0$

Thermal efficiency of Ideal Rankine cycle

$$\frac{W_{net}}{q_{in}} = \left\{ \frac{q_{in} - q_{out}}{q_{in}}, \text{or} \left(1 - \frac{q_{out}}{q_{in}}\right), \text{or} \left\{ 1 - \frac{h_4'}{h_3' - h_2'} \right\} \right\}$$
• Energy Analysis of Actual Rankine Cycle
• The actual vapour cycle differs from the ideal Rankine Cycle, as a result of irreversibility in various components. Two major factors of irreversibility are Fluid friction and the heat loss.
<table>
<thead>
<tr>
<th>Actual Rankine Cycle Components</th>
<th>Heat</th>
<th>Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler feed Pump $W_{\text{pump-in}}$</td>
<td>$q = 0$</td>
<td>$W_{\text{pump-in}} = (h_2 - h_1)$, or $W_{\text{pump-in}} = V(1 - \frac{h_4}{h_3})$</td>
</tr>
<tr>
<td>Boiler</td>
<td>$q_{\text{in}} = (h_3 - h_2)$</td>
<td>$W = 0$</td>
</tr>
<tr>
<td>Turbine</td>
<td>$q = 0$</td>
<td>$W_{\text{turbine-out}} = (h_3 - h_4)$</td>
</tr>
<tr>
<td>Condenser</td>
<td>$q_{\text{out}} = (h_4 - h_1)$</td>
<td>$W = 0$</td>
</tr>
</tbody>
</table>

**Thermal efficiency of Ideal Rankine cycle**

$$\frac{W_{\text{net}}}{q_{\text{in}}}$$

$$\frac{|q_{\text{in}} - q_{\text{out}}|}{q_{\text{in}}}$$, or $$\left(1 - \frac{q_{\text{out}}}{q_{\text{in}}}\right)$$, or $$\left\{1 - \frac{h_4}{h_3}\right\}$$
• While calculating the overall cycle efficiency, Turbine and pump irreversibilities need to be given due importance. For small units usually pump work are negligible and can be neglected but in larger units pump work is appreciable and can’t be neglected like that. Actual/Practical Rankine cycle is based on the deviation of flow in turbine and pressure requirement in pump from the isentropic one and is defined as follows:

\[
\frac{\eta_p}{W_s} = \frac{h_{2s} - h_1}{h_{2a} - h_1}, \quad \frac{\eta_T}{W_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}
\]

Where \(h_{2a}\) Actual enthalpy at the pump exit \(h_{4a}\) Actual enthalpy at the turbine exit \(h_{2s}\) Ideal isentropic enthalpy at the pump exit \(h_{4s}\) Ideal isentropic enthalpy at the turbine exit.
• **Other factors Irreversibility are:**
• Other factors responsible for irreversibility of actual vapour power cycle are:
• Sub-cooling of condensate in condenser
• Losses associated with bearings
• Steam leakages
• Condenser air-leaks
Rankine Cycle Efficiency Improvement Techniques

- **Steam power plants** are still the backbone of the total power generation in the Asia pacific. Thus even a small improvement in the form of increasing the efficiency has a tremendous effect on the fuel saving and also reduction in emission of green house gases. Thus one should not miss out any opportunity to find out the ways and means to increase the efficiency of the steam power cycle. The ideal behind any improvement or modification is to increase the thermal efficiency of the **power plant**. Thus thermal efficiency improvement techniques are:

- By decreasing average temperature at which heat is rejected from the working fluid (**steam**) in the condenser. (Lowering condenser Pressure)
- By increasing steam temperature entering the turbine
- **Lowering The Condenser Pressure**

Steam leaves the turbine and enters the condenser as saturated mixture in line with the corresponding pressure of steam in the condenser. Lowering the **condenser pressure** always helps in delivering more net work in the turbine as more expansion of steam in turbine is possible. By the help of T-s diagram the effect of lowering the condenser pressure on the performance of the cycle can be seen and understood.
• **Positive Effects of Lowering the Condenser Pressure**

• To make the advantage of higher efficiency **Rankine Cycle** has to operate on lower condenser pressure usually below atmospheric. But the limit for lower condenser-pressure is defined by the cooling water temperature corresponding to saturation-pressure of the area. In the above T-s diagram it can be easily seen that the coloured area is the increase in net work output on account of lowering the condenser pressure from $P_4$ to $P_4'$. 
• **Negative Effects of Lowering the Condenser Pressure**

• The effect of lowering the condenser-pressure is not comes without any side effects. Thus following are the adverse effects of lowering the condenser pressure:

• Additional heat input in the boiler on account decreased condensate re-circulation temperature (effect of lower condenser pressure)

• With lower condenser pressure the possibility of increase of moisture content in steam at the final expansion stage of the turbine increases. Decreases in dryness fraction of steam in later stages of the turbine is undesirable as it results in slight decrease in efficiency and erosion of turbine blades.
• Net Effects of Lowering the Condenser Pressure
  The over all net effect is more towards positive side, since the increase in heat input requirement in the boiler is marginal but the increase in net work out put is more on account of decrease in condenser pressure. Also the dryness fraction of the steam in the latter stages of the turbine are not allowed to drop beyond 10-12%.

• Super Heating The Steam to Higher Temperature
  Superheating of steam is the phenomenon in which heat is transferred to the steam to super heat the steam to higher temperature by maintaining the constant pressure in the boiler.
The shaded area in the above T-s diagram clearly showing the increase in net work (3-3’-4’-4) on account of increase in superheat temperature of steam. Additional heat input in the form of energy, leaves the cycle as work i.e increase in work output surpass the additional heat input and heat rejection. Thermal efficiency of the rankine cycle increases on account of increase in steam temperature.
• **Positive Effects of Increasing the Steam Temperature**
  One desirable effect of increasing the steam temperature is that it doesn’t allow to the last stage moisture % of steam to increase. This effect can be easily seen on the T-s diagram (Fig:2) above.

• **Negative Effects of Increasing the Steam Temperature**
  Increasing the steam temperature results in small increase in heat input. There is a limit to which the steam can be superheated and used in the power cycle. These limiting factors are related to metallurgical proveness at high temperature and economical viability. Presently in supercritical power generating units, steam temperature at turbine inlet is around 620°C. Decision of any further increase in steam temperature can be judiciously taken only after doing the metallurgical due diligence and evaluation of the cost-implications.
• **Net Effects of Increasing the Steam Temperature**

From the T-s diagram (Fig:2) the net effect of temperature increase is more towards positive side, because the gain from the network output surpasses the increase in heat input and slight increase in heat rejection. So it is always beneficial to increase the steam temperature after accessing the reliability and economic viability.

• **Increasing Boiler Pressure With Sub Critical Parameters**

Alternative way of increasing the *Rankine cycle efficiency* is by increasing the boiler operating pressure and thus in a way related with the temperature at which boiling is taking place in the boiler. Thus the thermal efficiency of the cycle increases. By the help of T-s diagram the effect of Increase in boiler pressure on the performance of the cycle can be clearly seen and understood.
Because of increase in boiler pressure, Rankine cycle shifts slightly towards left as shown in the Fig:3 on T-s diagram and thus following can be concluded from it:

Substantial increase in net-work, as shown in the pink colour shaded area of the above figure.

As the cycle shift slightly towards left, so their is decrease in net work during the expansion of steam in the turbine. (as shown in above fig:3 sheded in grey colour.

Reduction in the heat-rejection to the cooling water in the condenser.

Thus net-effect is marked increases in the thermal efficiency of the cycle on account of these measures.
• Increasing the Boiler Pressure with Super Critical Parameters
• In order to increase the thermal efficiency of the Rankine cycle, super-critical pressure is used in steam-generators used in the present time. When the steam generators operates above 22.06Mpa then the steam generators are called super-critical steam-generators and the plant is called super-critical power generation plant. Because of the higher operating pressures these plants are know for giving higher efficiencies.
fig-4 Super Critical Power Cycle
• Re-Heat Rankine Cycle
• **Re-heat Rankine cycle** is for taking the advantage of increased cycle efficiency at higher boiler pressure without compromising on moisture content of the steam in the last stages of the turbine. Higher cycle efficiency is possible with re-heating cycle that too without compromising on dryness fraction this is possible by expanding the steam in turbine in two stages by re-heating it in between. Re-heating is practically acceptable way of tackling the problem of excessive moisture in the last stages of the turbine.
• Theoretical Way of Reducing the Last Stage Moisture

Theoretically one way is to superheat the steam to a higher temperature before steam enters the turbine but there is a limit above which metallurgical limitations of handling high steam temperature prevents it from further increase beyond 620°C. Super critical power plants are running in India are running with inlet steam temperature of around 593°C.

• Modified Rankine Cycle

Practical way of successfully reducing the last stage moisture in large turbine (200 MW and above) is by slightly modifying the simple Rankine cycle with re-heat cycle as shown below in Figure:5
fig-5a-re-heat cycle
fig-5b-re-heat cycle
• **Re-Heat Cycle Differs from Rankine Cycle in Following Aspects**
  
  Expansion of steam in reheat cycle happens in two stages. In the first stage steam expands in the High Pressure turbine (HP turbine) and the exhaust of the HP turbine is then send back to the steam generator for re-heating. Steam outlet from the re-heater in the 2nd stage steam generator re-heating is directed to the Low-pressure-turbine (LP Turbine) for final-expansion over the last stages of the turbine with high dryness fraction then exhaust to the condenser.

• **Analysis of Re-Heat Cycle is as Follows**
  
  • Heat input during the cycle (2-3-4-5) is
    \[ q_{\text{in}} = q_{\text{primary}} + q_{\text{reheat}} = (h_3 - h_2) + (h_5 - h_4) \]
  
  • Turbine work output for the cycle is
    \[ W_{\text{turb,out}} = W_{\text{turb,I}} + W_{\text{turb,II}} = (h_3 - h_4) + (h_5 - h_6) \]
  
  • Thus by adopting a single reheat cycle in a **thermal power plant** cycle efficiency can easily is enhanced by another 4 to 5 percentage.
• **What is Practical Limit of Re-Heating ????**

• Theoretically if we increase the number of reheating stages then the number of expansion in the turbine can also be increased in order to get the more turbine output and thus higher cycle efficiency. But practically more than two stages of reheat is not practical. It has been seen and experienced that the theoretical improvement in the efficiency of the cycle from 1st to 2nd reheat is reduced from 5 percent to less than 2.5 percent. Also it is observed that with a sub-critical pressure double reheat cycle are having a more super-heated exhaust loss in the condenser than with super-critical-cycle-parameters. So double-reheat cycles are avoided with sub-critical parameters. From third reheat cycle onwards the gain of cycle efficiency starts diminishing, so not justifiable to incurred additional cost and complexity.
• Cogeneration | Combined Heat and Power
• Cogeneration is also called as combined heat and power or combine heat and power. As it name indicates cogeneration works on concept of producing two different form of energy by using one single source of fuel. Out of these two forms one must be heat or thermal energy and other one is either electrical or mechanical energy. Cogeneration is the most optimum, reliable, clean and efficient way of utilizing fuel. The fuel used may be natural gas, oil, diesel, propane, wood, bagasse, coal etc. It works on very simple principle i.e the fuel is used to generate electricity and this electricity produces heat and this heat is used to boil water to produce steam, for space heating and even in cooling buildings. In conventional power plant, the fuel is burnt in a boiler, which in turn produces high pressure steam. This high pressure steam is used to drive a turbine, which is in turn is connected to an alternator and hence drive an alternator to produce electric energy.
The exhaust steam is then sent to the condenser, where it gets cool down and gets converted to water and hence return back to boiler for producing more electrical energy. The efficiency of this conventional power plant is 35 % only. In cogeneration plant the low pressure steam coming from turbine is not condense to form water, instead of it its used for heating or cooling in building and factories, as this low pressure steam from turbine has high thermal energy. The cogeneration plant has high efficiency of around 80 - 90 %. In India, the potential of power generation from cogeneration plant is more than 20,000 MW. The first commercial cogeneration plant was built and designed by Thomas Edison in New York in year 1882.
As shown in above diagram, in traditional power plant, when we gave fuel as input we get electrical energy and losses as output but in case of cogeneration with fuel as input, the output is electrical energy, heat or thermal energy and losses.
In conventional power plant, with 100% energy input, only 45% of energy is used and rest 55% is wasted but with cogeneration, the total energy used is 80% and energy wasted is only 20%. It means with cogeneration the fuel utilization is more efficient and optimized and hence more economical.
• **Need for Cogeneration**

• Cogeneration helps to improve the efficiency of the plant.

• Cogeneration reduce air emissions of particulate matter, nitrous oxides, sulphur dioxide, mercury and carbon dioxide which would otherwise leads to greenhouse effect.

• It reduces cost of production and improve productivity.

• Cogeneration system helps to save water consumption and water costs.

• Cogeneration system is more economical as compared to conventional power plant.
• **Types of Cogeneration Power Plants**

• In a typical Combined heat and power plant system there is a *steam* or gas turbine which take steam and drives an alternator. A waste heat exchanger is also installed in cogeneration plant, which recovers the excess heat or exhaust gas from the electric generator to in turn generate steam or hot water. There are basically two types of cogeneration power plants, such as-

• Topping cycle power plant

• Bottoming cycle power plant
• **Topping cycle power plant** - In this type of Combine Heat and Power plant electricity is generated first and then waste or exhaust steam is used to heating water or building. There are basically four types of topping cycles.

• **Combined-cycle topping CHP plant** - In this type of plant the fuel is firstly burnt in a **steam boiler**. The steam so produced in a boiler is used to drive turbine and hence **synchronous generator** which in turn produces electrical energy. The exhaust from this turbine can be either used to provide usable heat, or can be send to a heat recovery system to generate steam, which maybe further used to drive a secondary steam turbine.
• Steam-turbine topping CHP Plant- In this the fuel is burned to produce steam, which generates power. The exhaust steam is then used as low-pressure process steam to heat water for various purposes.

• Water- turbine topping CHP Plant- In this type of CHP plant a jacket of cooling water is run through a heat recovery system to generate steam or hot water for space heating.

• Gas turbine topping CHP plant- In This topping plant a natural gas fired turbine is used to drives a synchronous generator to produce electricity. The exhaust gas is sent to a heat recovery boiler where it is used to convert water into steam, or to make usable heat for heating purposes.
• **Bottoming cycle power plant** - As its name indicate bottoming cycle is exactly opposite of topping cycle. In this type of CHP plant the excess heat from a manufacturing process is used to generate steam, and this steam is used for generating electrical energy. In this type of cycle no extra fuel is required to produce electricity, as fuel is already burnt in production process.
Configuration of Cogeneration Plant

- Gas turbine Combine heat power plants which uses the waste heat in the flue gas emerging out of gas turbines.
- Steam turbine Combine heat power plants that use the heating system as the jet steam condenser for the steam turbine.
- Molten-carbonate fuel cells have a hot exhaust, very suitable for heating.
- Combined cycle power plants adapted for Combine Heat and Power.
Line Diagram of Power Plant
• Efficiency of Thermal Power Station or Plant
• Overall efficiency of steam power plant is defined as the ratio of heat equivalent of electrical output to the heat of combustion of coal. The overall efficiency of a thermal power station or plant varies from 20% to 26% and it depends upon plant capacity.
<table>
<thead>
<tr>
<th>Installed plant capacity</th>
<th>Average overall thermal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>upto 1MW</td>
<td>4%</td>
</tr>
<tr>
<td>1MW to 10MW</td>
<td>12%</td>
</tr>
<tr>
<td>10MW to 50MW</td>
<td>16%</td>
</tr>
<tr>
<td>50MW to 100MW</td>
<td>24%</td>
</tr>
<tr>
<td>above 100MW</td>
<td>27%</td>
</tr>
</tbody>
</table>
• Thermal Power Plant
• https://youtu.be/Chvl2v85fsU
THANK YOU