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ASPIRE TO EXCEL

ISO 21001

DEPARTMENT OF MECHANICAL ENGINEERING

SUBJECT NOTES

SUB NAME: POWERPLANT ENGINEERING

SUBCODE : MET81 **YEAR & SEM : IV/VIII**

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UNIT-I

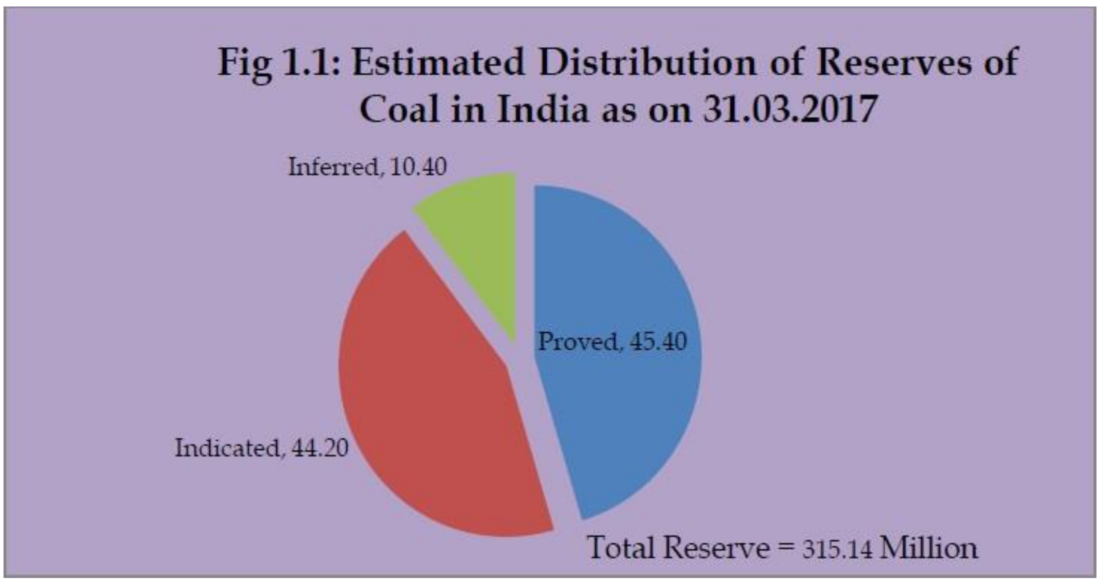
APOUR POWER CYCLE
AND
STEAM GENERATORS

POWER SCANERIO IN INDIA
RESERVES AND POTENTIAL FOR GENERATION

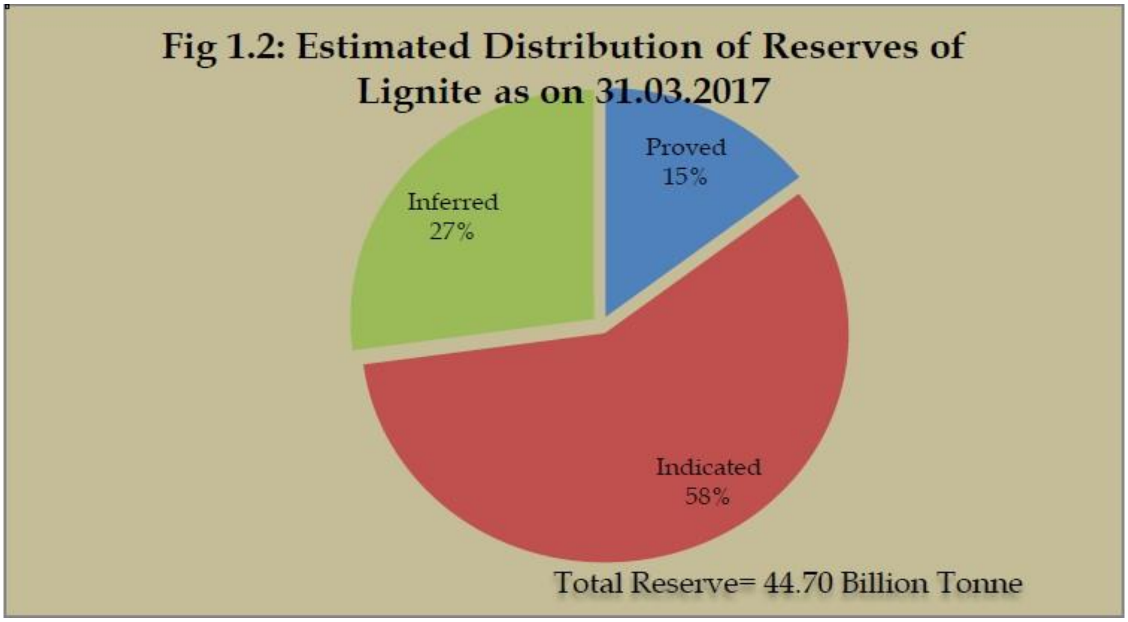
Coal and Lignite

Coal deposits are mainly confined to eastern and southcentral parts of the country. The states of Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Telangana and Maharashtra account for 98.20% of the total coal reserves in the country. The State of Jharkhand had the maximum share (26.16%) in the overall reserves of coal in the country as on 31st March 2017 followed by the State of Odisha (24.52%)

As on 31.03.17, the estimated reserves of coal were 315.14 billion tonnes, an addition of 6.34 billion tonnes over the last year (Table 1.1). There has been an increase of 2.05% in the estimated coal reserves during the year 2016-17 with Maharashtra accounting for the maximum increase of 7.15%.



The estimated total reserves of lignite as on 31.03.17 was 44.70 billion Tonnes against 44.59 billion tonnes on 31.03.16.



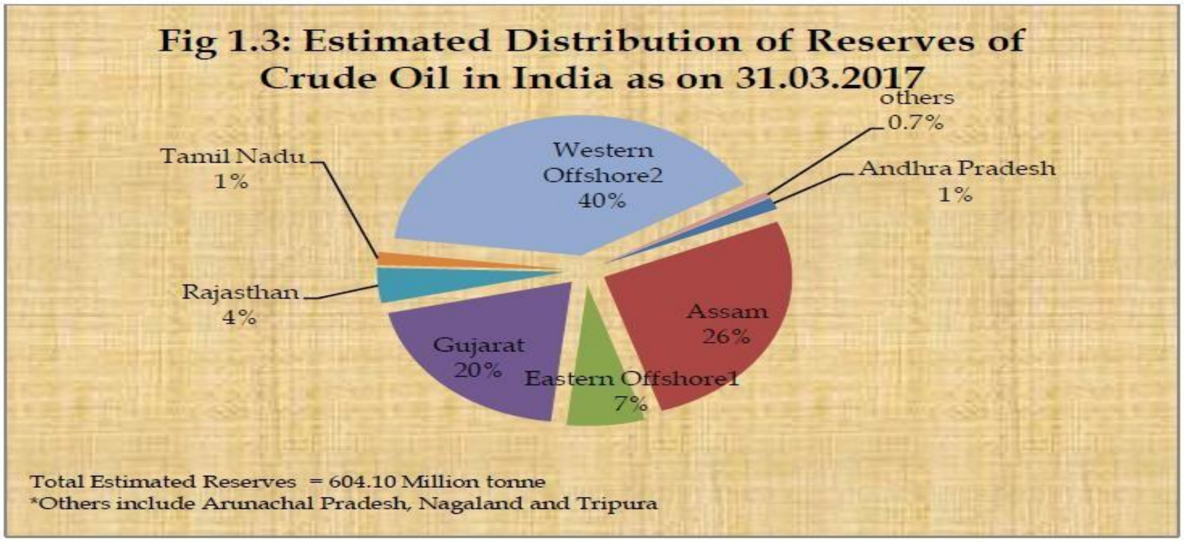
Petroleum and Natural gas

The estimated reserves of crude oil in India as on 31.03.2017 stood at 604.10 million tonnes (MT) against 621.28 million tonnes on 31.03.2016.

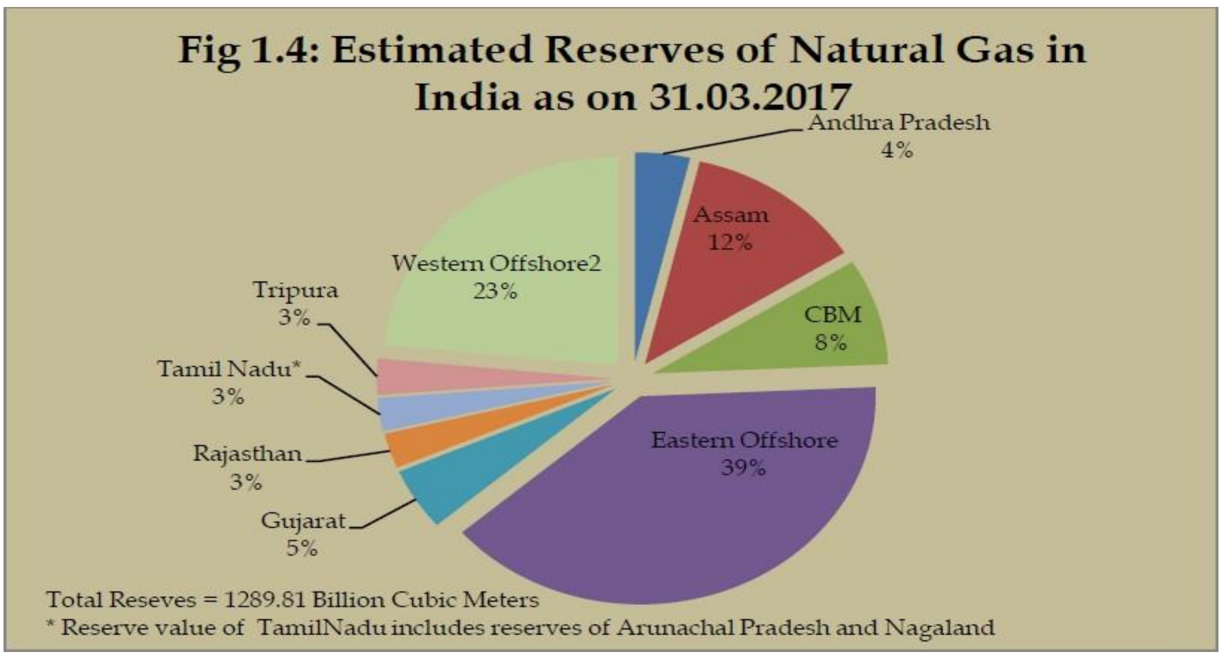
Geographical distribution of Crude oil indicates that the maximum reserves are in the Western Offshore (39.60%) followed by Assam (26.48%), whereas the maximum reserves of Natural Gas are in the Eastern Offshore (39.37%) followed by Western offshore (23.44%).

There was decrease of 2.76% in the estimated reserve of crude oil for the country as a whole during 2016-17 as compared to the position a year ago. During the same period, estimated reserves of crude oil in Andhra Pradesh, Rajasthan, Arunachal Pradesh, Western Offshore, Gujarat and Assam decreased by 25.19, 22.60, 12.48, 3.21, 2.11 and 0.51% respectively, while the same in Eastern Offshore and Tamil Nadu increased by 11.75% and 0.04% respectively.

 The estimated reserves of Natural Gas in India as on 31.03.2017 stood at 1289.81 Billion Cubic Meters (BCM) as against 1227.40 BCM as on 31.03.2016



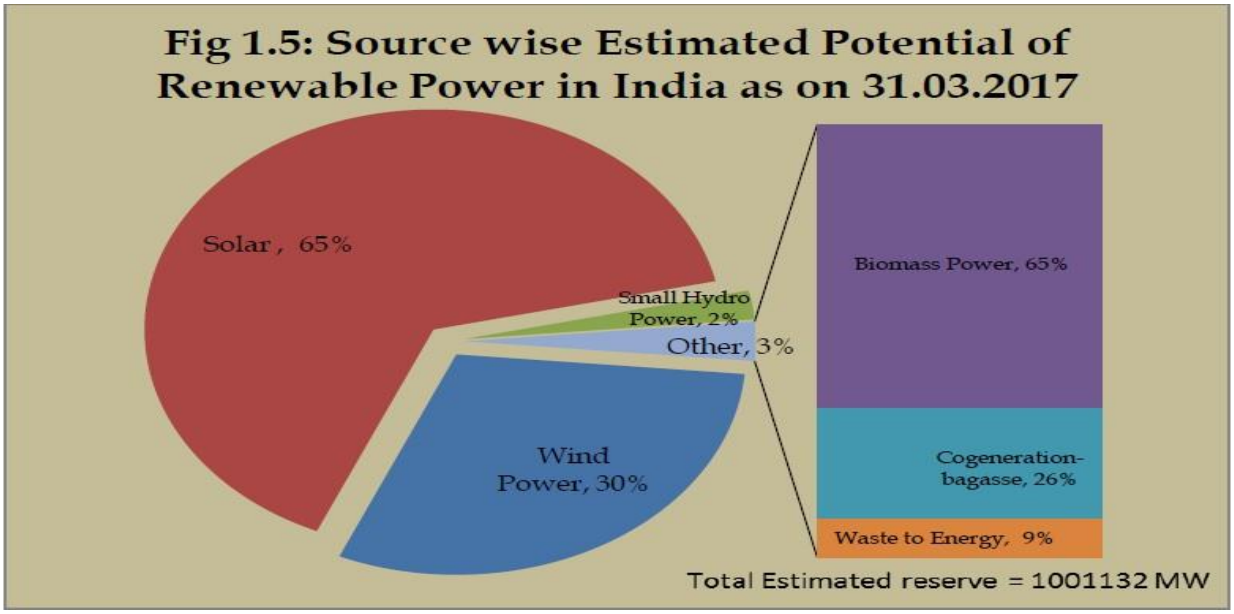
The estimated reserves of Natural Gas increased by 5.08% over the last year. The maximum contribution to this increase has been from Tripura (27.65), followed by Andhra Pradesh (14.95).



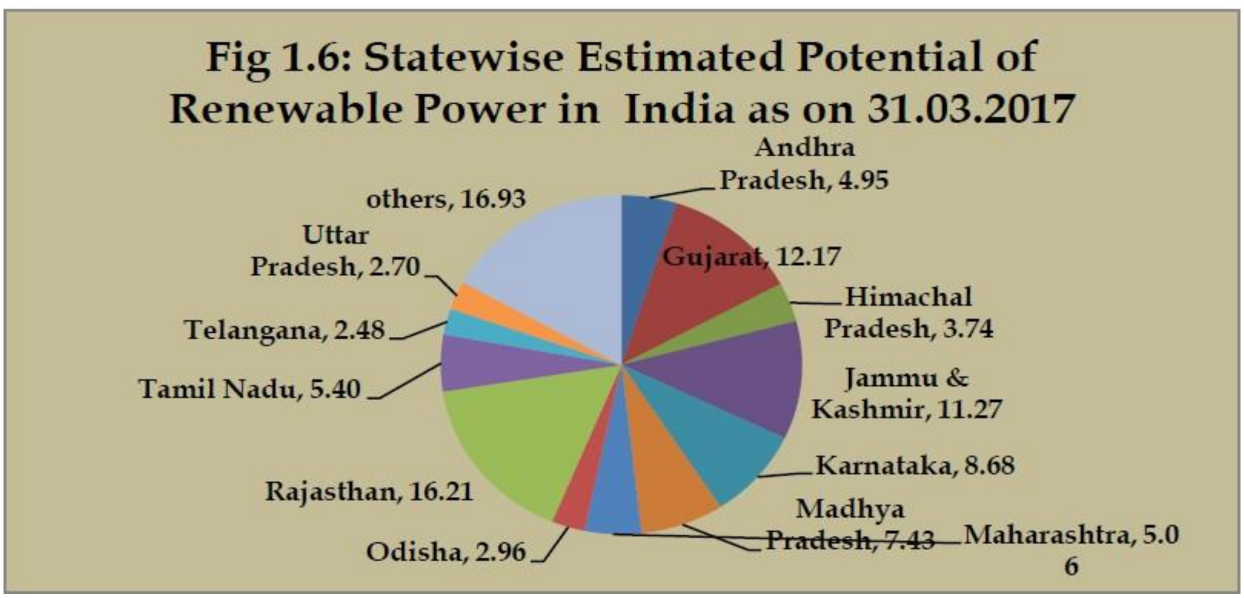
Renewable energy sources

There is high potential for generation of renewable energy from various sources- wind, solar, biomass, small hydro and cogeneration bagasse.

The total potential for renewable power generation in the country as on 31.03.17 is estimated at 10,01,132MW (Table 1.3). This includes solar power potential of 649342 MW (64.86%).wind power potential of 3,02,251 MW (30.19%) at 100 m hub height,SHP (small-hydro power) potential of 21,134 MW (2%), Biomass power of 18,601 MW (1.86%), 7,260 MW (0.73%) from bagasse-based cogeneration in sugar mills, 2554 MW (0.26%) from waste to energy



The geographic distribution of the estimated potential of renewable power as on 31.03.2016 reveals that Rajasthan has the highest share of about 14% (167276 MW), followed by Gujarat with 13% share (157158 MW) and Maharashtra with 10% share (119893MW), mainly on account of solar power potential.



AVAILABILITY OF ENERGY SOURCES

Availability of Coal and Lignite

The total availability of raw coal in India in 2016-17 stood at 863.90 MTs and that of lignite at 47.30 MTs

The availability of coal in the year 2016-17 increased by 1.93% compared to 2015-16. The availability of lignite increased by 4.03% during the same period.

The availability of coal has increased at a CAGR of about 5.46% during the period from 2007-08 to 2016-17. This increased availability might be attributed to the increase in the coal production (507.68 MTs during 2007-08 to 863.90 MTs during 2016-17) supplemented by imports

The availability of lignite has increased at a CAGR of about 4.03% during the period from 2007-08 to 2016-17

Availability of Natural Gas

The availability of natural gas has steadily increased from a mere 39.80 BCM during 2007-08 to 50.53 BCM during 2016-17, registering a CAGR of 2.42%. Most of this increase in the indigenous production is due to discovery of new reserves..

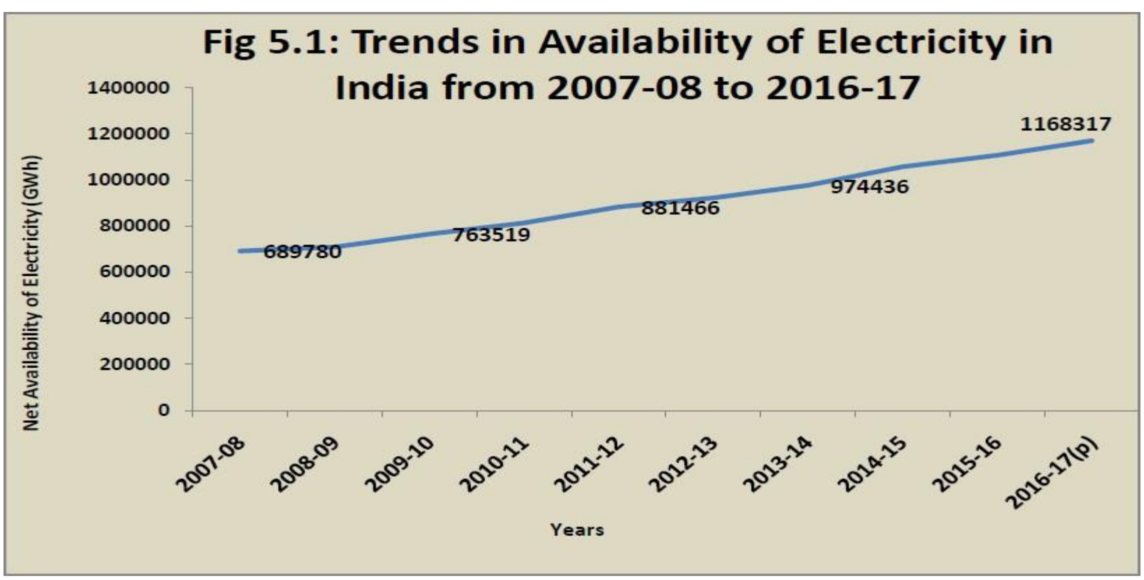
Availability of Crude Oil and Petroleum Products

The availability of crude oil in the country increased from 155.79 MTs in 2007-08 to 249.94 MTs during 2016-17 .

During this period, crude oil production increased from 34.12 MTs to 36.01 MTs and the net import increased from 121.67 MTs to 213.93 MTs between 2007-08 and 2016-17. There was increase of 5.46% in availability of crude oil during 2016-17 over 2015-16.

Availability of Electricity

Electricity available for supply increased from 6,89,780Gwh in 2007-08 to 11,68,317 Gwh in 2016-17, thus recording a CAGR of 5.41% during this period. The availability of electricity increased at 5.80% in 2016-17 over its value in 2015-16.



CONSUMPTION OF ENERGY RESOURCES

Consumption of Coal and Lignite

The estimated total consumption of raw coal by industry has increased from 502.82 MT during 2007-08 to 841.56 MT during 2016-17 with a CAGR of 5.29% (Table 6.1). The annual growth rate from 2015-16 to 2016-17 is 0.58%.

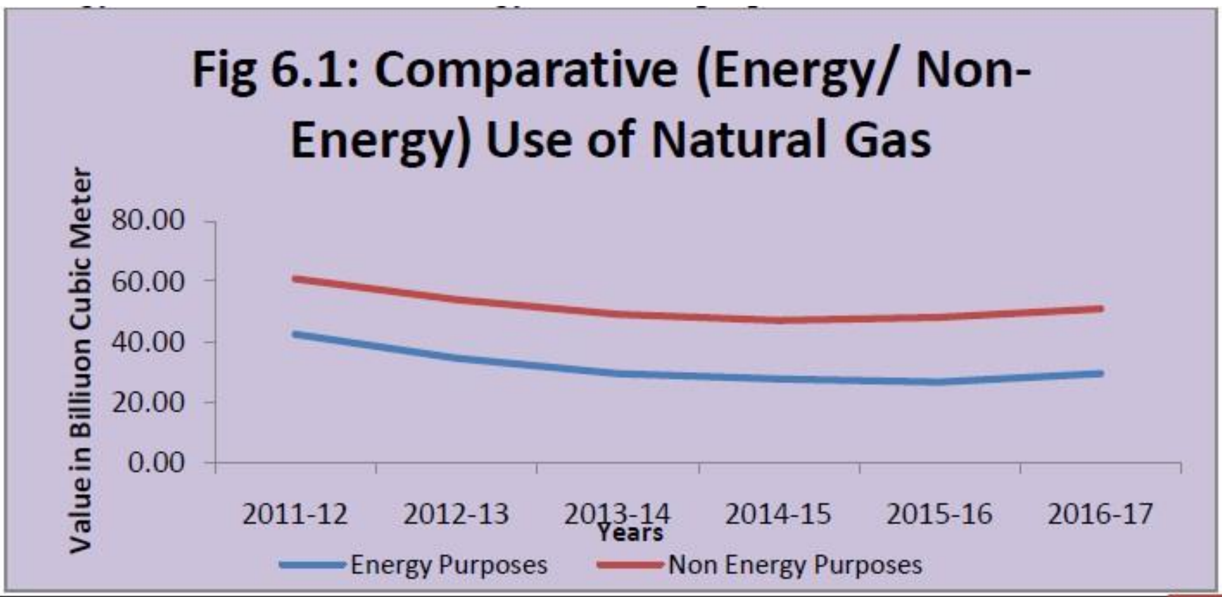
Consumption of Lignite increased from 34.65 MT in 2007-08 to 43.16 MT in 2016-17 registering a compound growth of 2.22%.

The maximum consumption of raw coal is in Electricity generation, followed by steel industries. Industry-wise estimates of consumption of coal(Table 6.4) shows that during 2016-17, electricity generating units consumed 527.26 MT of coal, followed by steel &washery industries (54.15 MT), cement industries (6.43 MT) and sponge iron industries (5.68 MT).

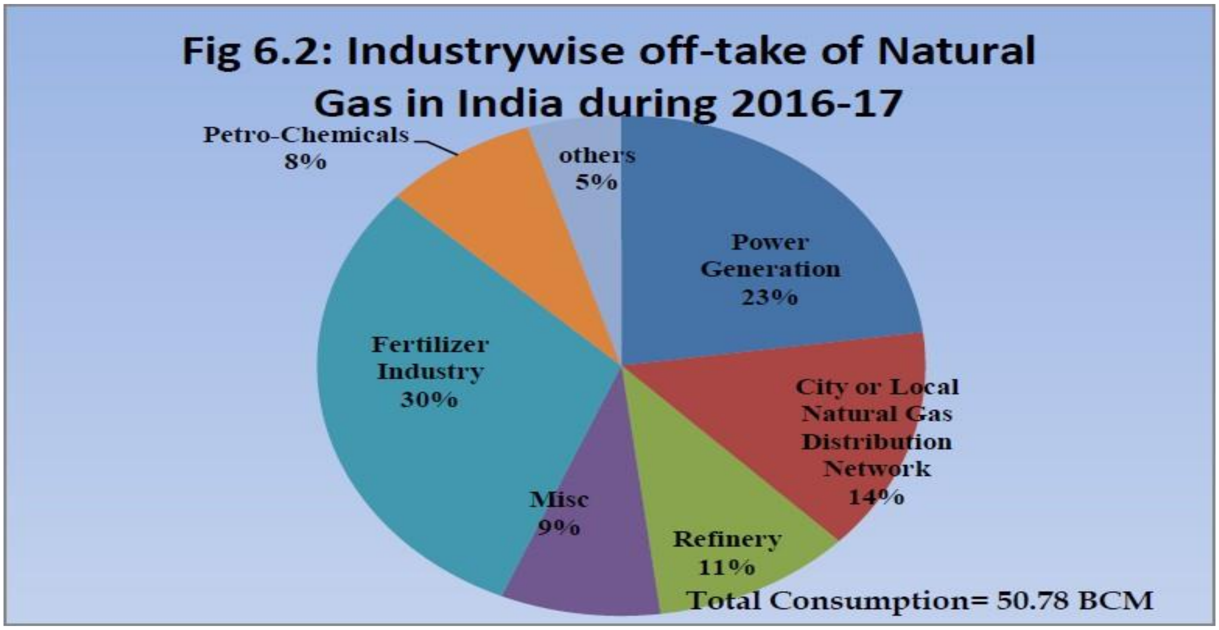
Consumption of Lignite in Electricity Generation sector is the highest, accounting for about 89.96% of the total lignite consumption

Consumption of Crude Oil and Natural Gas

The estimated consumption of crude oil has a steady increase, from 156.10 MMT during 2007-08 to 245.36 MMT during 2016-17 with CAGR of 4.63%. It increased from 232.86 MMT in 2015-16to 245.36 MMT in 2016-17 registering a growth rate of 5.37%



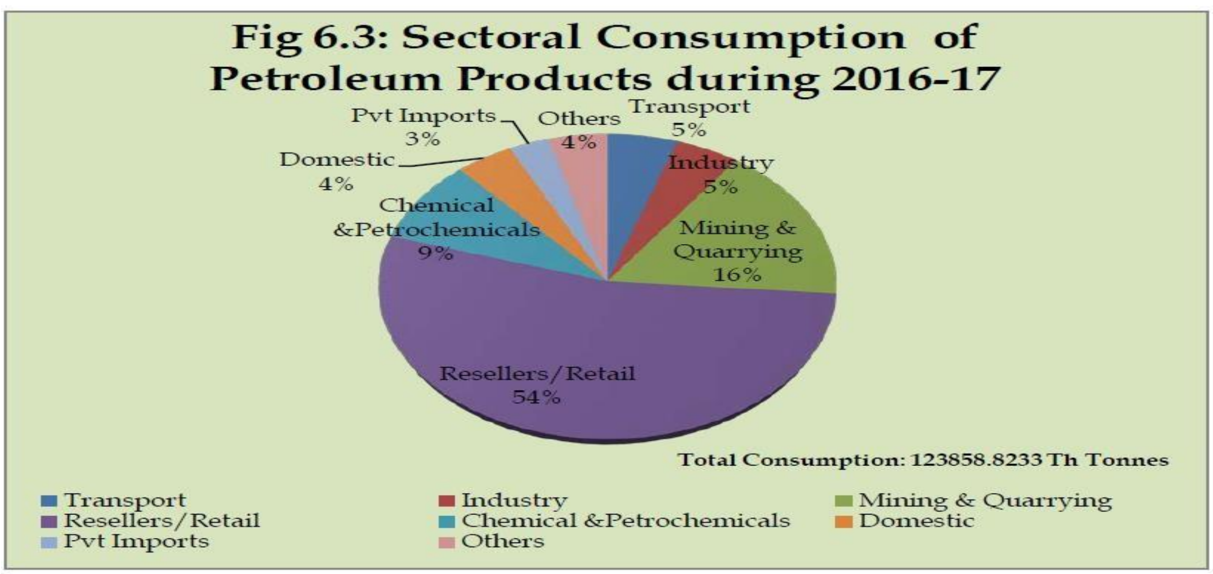
The maximum use of Natural Gas is in fertilizers industry (30.38%) followed by power generation (24.28%) and 14.47% natural gas was used for domestic fuel .



Industry wise off-take of natural gas shows that natural gas has been used both for Energy (58.16%) and Non-energy (41.84%) purposes

Consumption of Petroleum Products

High speed diesel oil accounted for 39.06% of total consumption (Excluding refinery fuels and losses) of all types of petroleum products in 2016-17. This was followed by Petroleum Coke (12.31%), Petrol (12.21%), LPG (11.11%) and Naphtha (6.80%). Consumption of Light Diesel oil continuously decreased from 2007-08 (0.67 MT) to 2016-17 (0.45 MT)

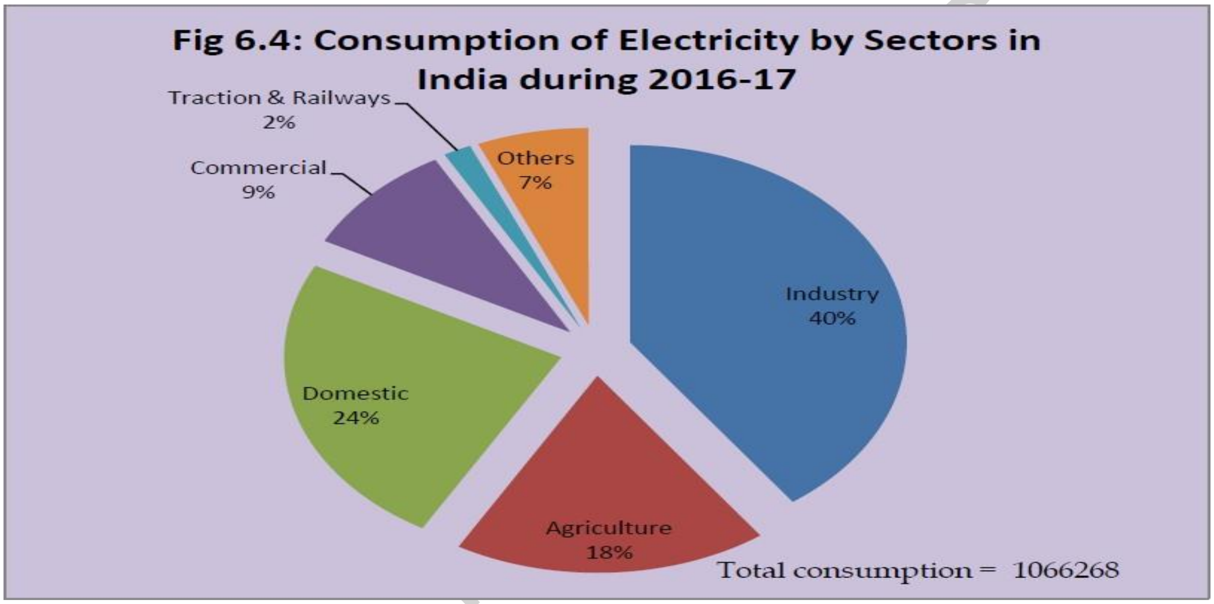


Sector-wise consumption of different petroleum products reveals that Reseller/Retail contributes 53% in the total consumption followed by Domestic sector with contribution 19%

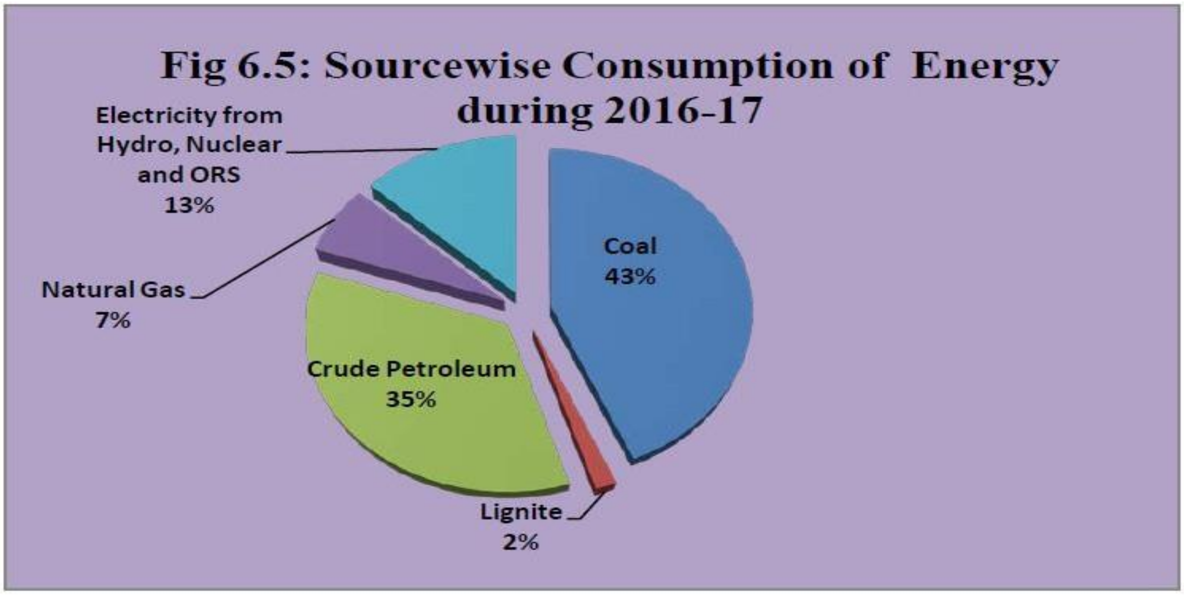
Consumption of Electricity

The estimated electricity consumption increased from 5,01,977GWh during 2007-08 to 10,66,268 GWh during 2016-17, showing a CAGR of 7.82% . The percentage increase in electricity consumption from 2015-16 (10,01,191GWh) to 2016-17 (10,66,268 GWh) is 6.50%. Of the total consumption of electricity in 2016-17, industry sector accounted for the largest share (40.01%), followed by domestic (24.32%), agriculture (18.33%) and commercial sectors (9.22%).

The electricity consumption in Industry sector and domestic sector has increased at a much faster pace compared to other sectors during 2007-08 to 2016-17 with CAGRs of 8.46% and 7.93% respectively



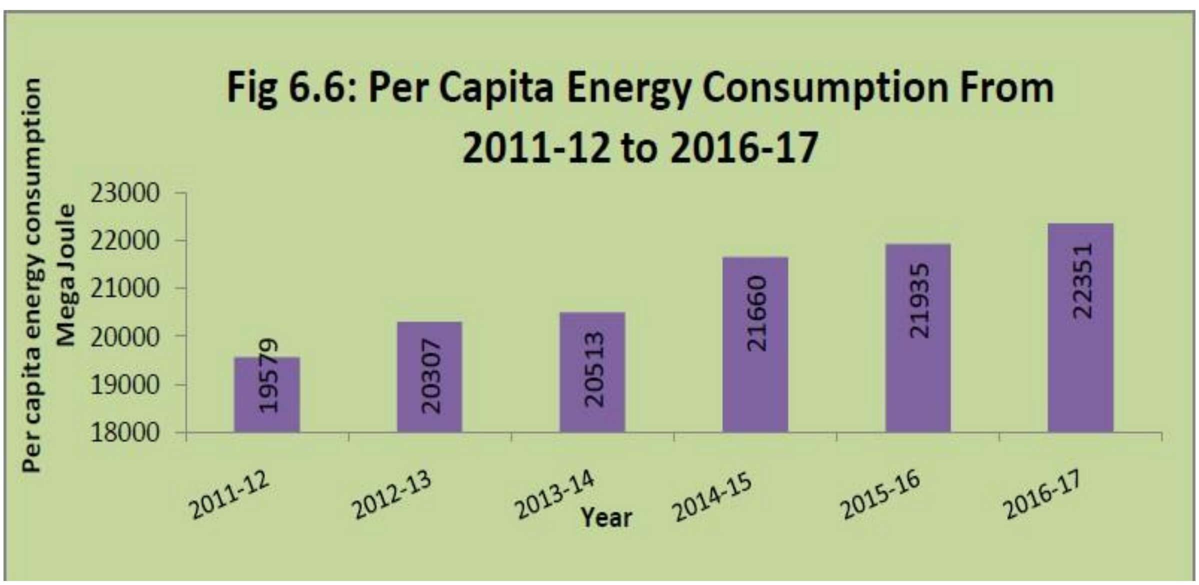
Loss of electricity due to transmission has decreased from 27.18% during 2007-08 to 21.30% during 2016-17



Per-Capita Energy Consumption & Energy Intensity

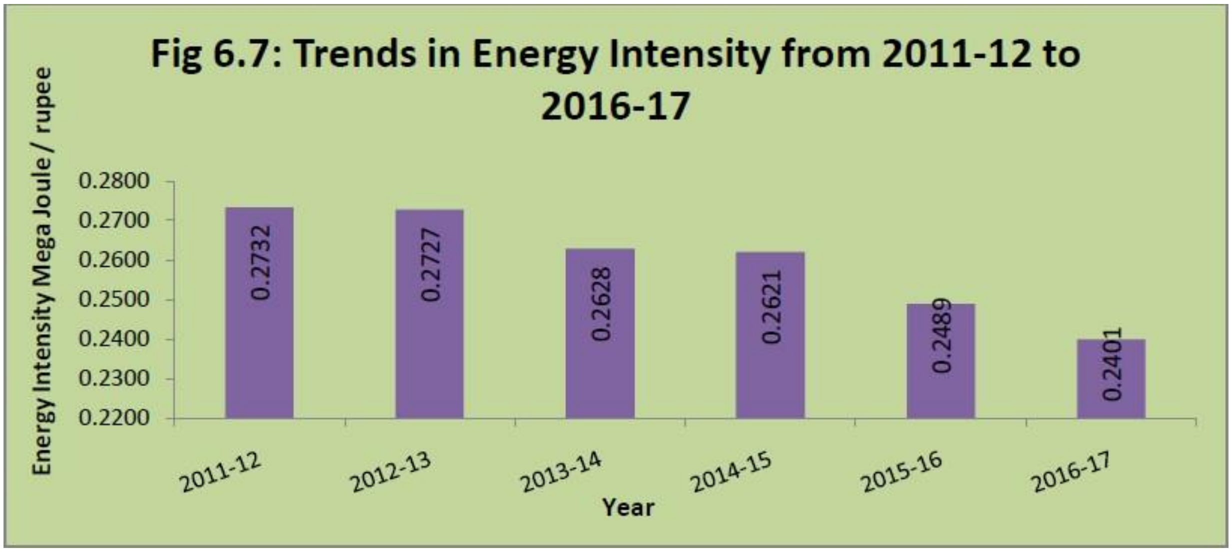
The consumption of energy in petajoulesin the form of Coal and Lignite which accounted for about 45.16% of the total consumption during 2016-17. Crude Petroleum was second (35.05%), while Electricity (13.11%) was third.

The total consumption of energy from conventional sources increased from 28,337petajoules during 2015-16 to 29,279petajoules during 2016-17, showing an increase of 3.32%.



Per-capita Energy Consumption (PEC) during a year is computed as the ratio of the estimate of total energy consumption during the year to the estimated mid-year population of that year.

Per-capita Energy Consumption (PEC) increased from 19579 Mega Joules in 2011-12 to 22351 Mega Joules in 2016-17. The annual increase in PEC for 2015-16 over 2014-15 was 1.89% .



Energy Intensity is defined as the amount of energy consumed for generating one unit of Gross Domestic Product (at constant prices).

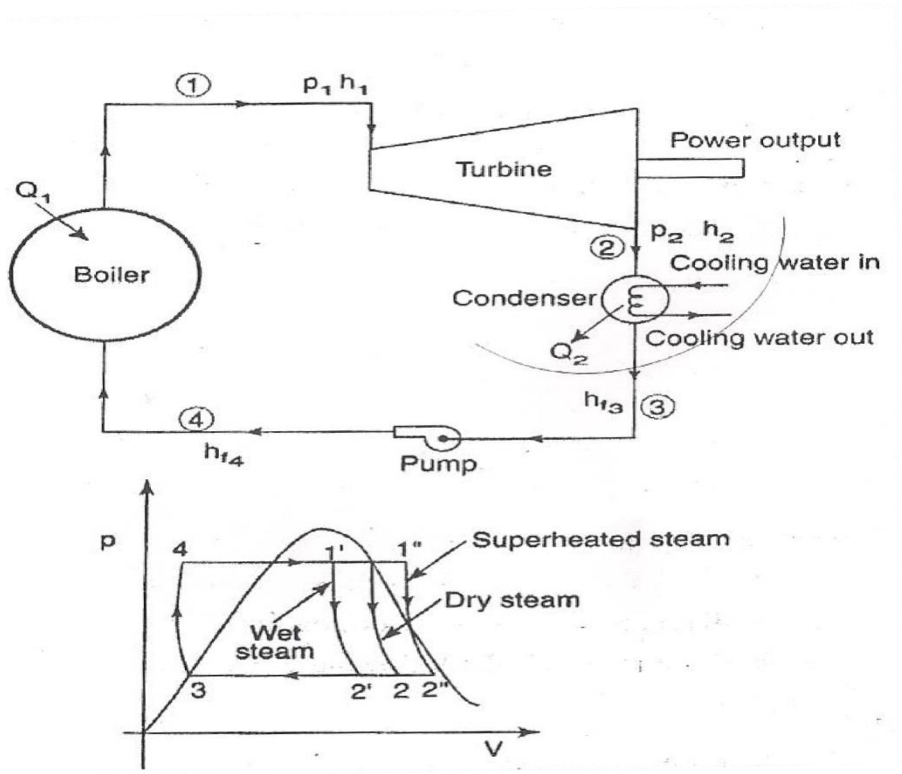
PEC and Energy intensity are the most used policy indicators, both at national and international levels. In the absence of data on consumption of non-conventional energy from various sources, particularly in rural areas these two indicators are generally computed on the basis of consumption of conventional energy.

The Energy Intensity (at 2011-12 prices) decreased from 0.2732 Mega Joules per rupee in 2011-12 to 0.2401 Mega Joules per rupee in 2016-17

Energy intensity has decreased over the last decade. This decline may be attributed to faster growth of GDP than energy demand, the services sector having a growing share of the economy, use of energy efficiency programmers, etc.

Rankine Cycle and the Efficiency of cycle.

Rankine cycle is the theoretical cycle on which the steam turbine works. The line diagram of the plant working on the cycle is shown in fig. The Rankine cycle has the following processes.



Rankine cycle

Processes:

1 -2 ➔ Reversible adiabatic expansion in the turbine.

2-3 ➔ Constant pressure heat transfer in the condenser.

3- 4 ➔Reversible adiabatic pumping process in the feed pump.

4-1 ➔ Constant pressure heat transfer in the boiler.

To analyze the cycle we take 1 kg of fluid and applying steady flow energy equation to boiler, turbine, condenser and pump:

1. Boiler (as constant volume)
   $h_1 = Q1 + h_{f4}$

   $$Q1 = h_1 - h_{f4}$$

Where Q1= Heat supplied in boiler.

2. For turbine (as constant volume)
   $h_1 = WT + h_2$

   $$\therefore \; W_T = h_1 - h_2$$

   Where, WT = Turbine work

3. For condenser
   $h_2 = Q_2 + h_{f3}$

   $$\therefore Q_2 = h_2 - h_{f3}$$

   Where, Q2 = Heat rejection in condenser

4. For pump
   $H_{f3} + W_p = h_{f4}$

   $$\therefore \quad W_p = hf_4 - h_{f3}$$

   $$W_p = V_3 (p_1 - p_2)$$

Where, Wp = Pump work, and

V in m^3/kg

P in *bar*

The efficiency of Rankine cycle is given by

$$\eta_{Rankine} = \frac{Workoutput}{Heat\,supplied} = \frac{W_{net}}{Q1}$$

$$= \frac{W_T - W_P}{Q_1}$$

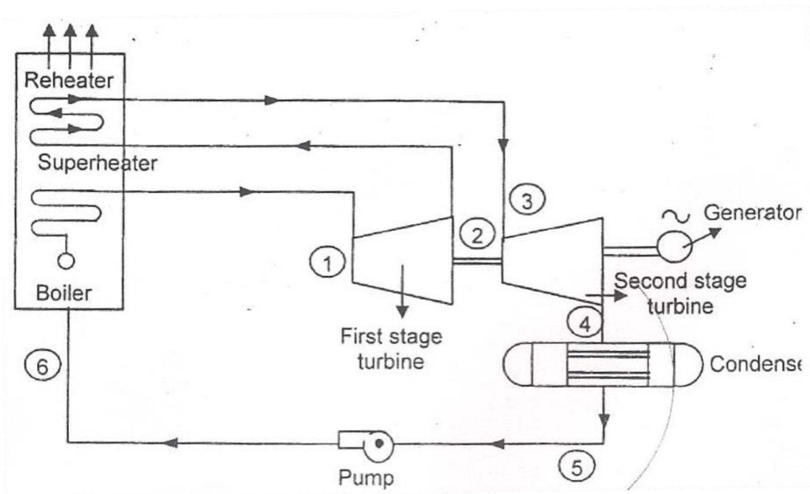
$$\eta_{Rankine} = \frac{(h_1 - h_2) - (hf_4 - hf_3)}{(h_1 - hf_4)}$$

$$\therefore \eta_{Rankine} = \frac{h_1 - h_2}{h_1 - hf_4}$$

The pump work is very small when compared to turbine work.

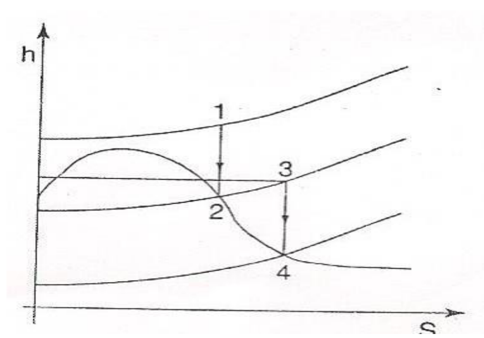
Reheat Cycle and the Efficiency of cycle.

The efficiency of the ordinary Rankine cycle can be improved by increasing the pressure and temperature of the steam entering into the turbine. This is shown in fig 1.20. In reheat cycle, the steam is extracted from a suitable point in the turbine and is reheated with the help of flue gases in the boiler furnace.



Reheat cycle

The main purpose of reheating is to increase the dryness fraction of steam and improve the cycle efficiency by 5%. But the dryness fraction of steam coming out of turbine should not fall below 0.88. The cost of reheat cycle is about 5 to 10% more than that of the conventional boilers.



By using the reheat cycle, the specific steam consumption decreases and thermal efficiency become increases. Normally, the reheat pressure is 20% of the initial pressure of the steam.

The reheat cycles are preferred for high capacity plants (above 50, 000kw) only and practically one stage reheater is used in power plants.

From the above figures, the efficiency of the reheat cycle is

$$\therefore \eta_{Rankine} = \frac{Workdone}{Heat\,\text{sup}\,plied} = \frac{W}{Q_5}$$

Where, Qs = (h1-h6) + (h3-h2)

Work done, W = $(h_1-h_2) + (h_3-h_4) - (h_6-h_5)$

Where, $h_6 - h_s$ = Pump work

$h_1 - h_2$ = First steam turbine work

$h_3 - h_4$ = Second steam turbine work

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

Neglecting pump work.

$$\therefore \eta_{Rankine} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_6) + (h_3 - h_2)}$$

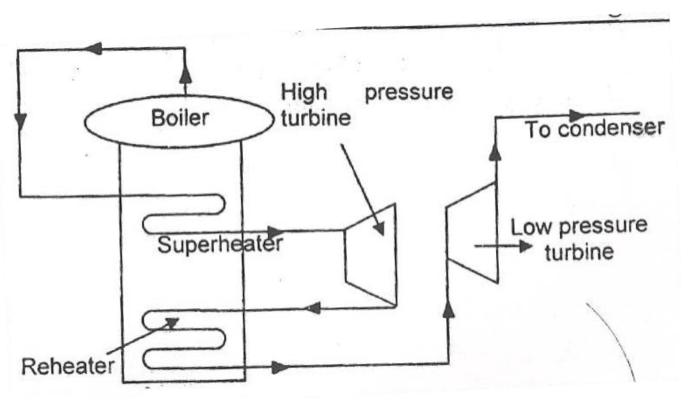
Where, $h_6 = h_5$

Types of reheating:

(a) Flue gas reheating
(b) Live steam reheating
(c) Combined flue gas and live steam reheating

(a). Flue gas reheating:

In this, the flue gas out from the boiler is used to heat the steam. The reheater is always placed behind the high-pressure super – heater. The steam can be reheated to initial throttle temperature and reheating normally employs the counter flow heat exchanger.



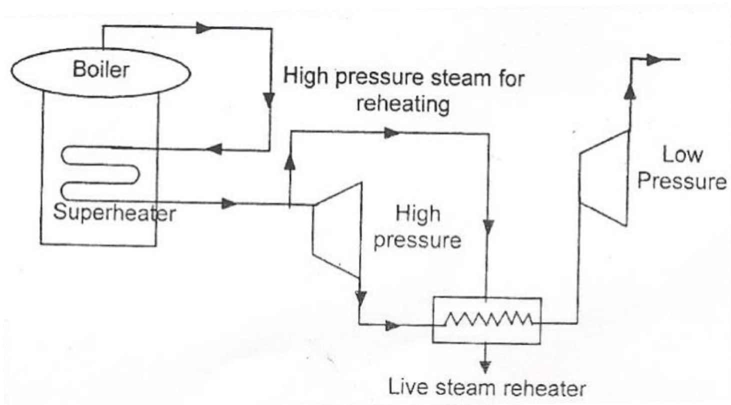
Flue gas reheating

(b). Live-steam reheating:

In this process, the high-pressure steam from the boiler is used for reheating the steam coming out from H.P. turbine in a specially designed heat exchanger.

The main advantages in this process are

1. The reheater can be placed near the turbine thus avoiding the use of large piping.
2. It is possible to reheat the wet steam also.
3. Simple in operation.

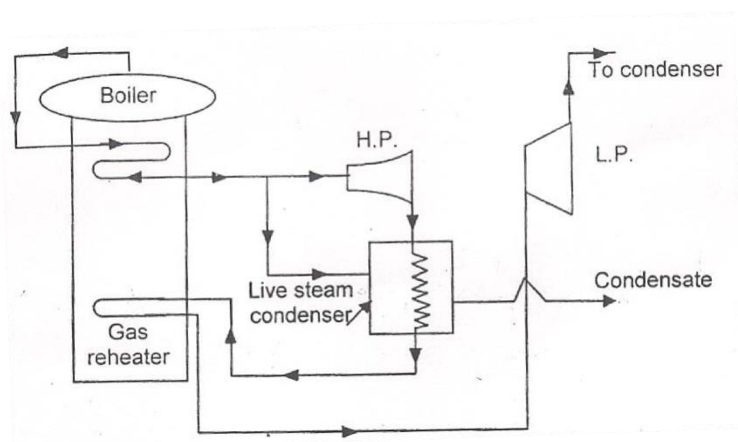


Live steam reheating

(c) Combined gas and live steam reheater:

In the combined heating system, the disadvantage that the steam cannot be reheated to its initial throttle temperature and the live steam reheating is eliminated.

The steam coming out from the H.P. turbine is first passed through the live steam reheater and then to gas reheater. It is clearly shown in the fig. 1.24.



Combined gas and live steam reheating

After reheating in the gas reheater, the steam is put through the low-pressure turbine. Initially, the steam from the boiler is superheated in the super heater.

Regenerative Cycle , Reheat-Regenerative Cycle and the Efficiency of cycle.

Regenerative Cycle:

In the Rankine cycle, it is observed that the condensate which is coming out has very low temperature and it mixes with hot water boiler. This results in decrease of cycle efficiency.

To avoid this, the condensate coming out is heated with the help of steam in a reversible manner. The temperature of steam and water is same at any section. This type of heating is known as regenerative heating.

Fig. shows a layout of a condensing steam power plant in which a surface condenser is used to condense all the steam that is not extracted for feed water heating. The boiler is equipped with a super heater and turbine is double extracting type.

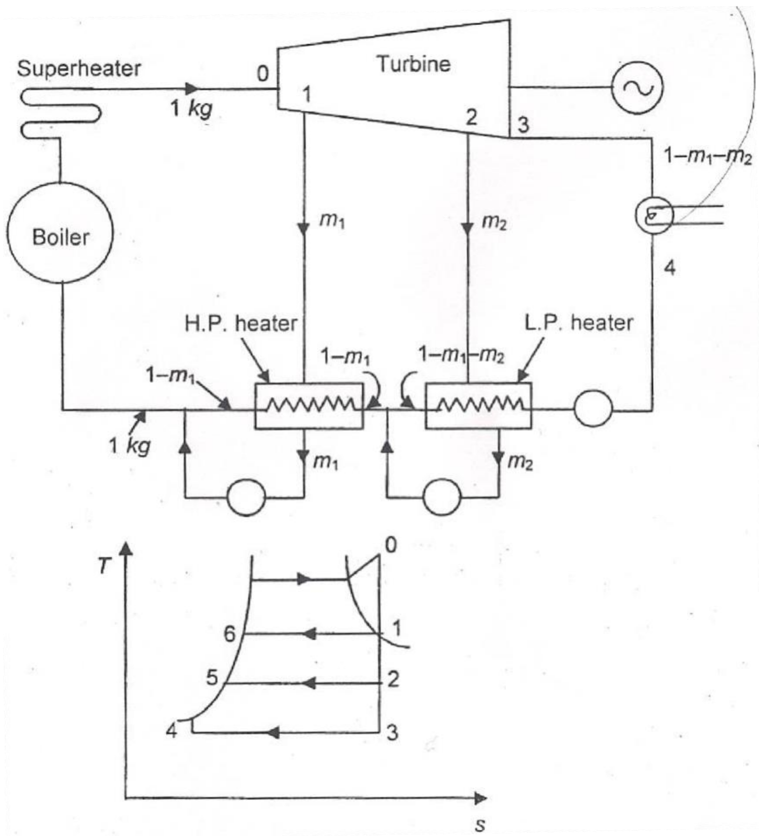
The conditions of steam bled for each heater are so selected that the temperature of saturated steam will be 4 to 10˚C higher than the final condensate temperature.

Let, m_1 = kg of high pressure steam per kg of steam flow.

m_2 = kg of low pressure steam extracted per kg of steam flow.

$1-m_1 - m_2$ = kg of steam entering condenser per kg of steam flow.

Heat supplied externally in the cycle = $(h_o - h_{f6})$



Regenerative cycle

Isentropic work done.

= (h_0 - h_1) + (1 – m_1) (h_1- h_2) + (1 – m_1 – m_2) (h_2 – h_3) Thermal efficiency,

$$= \frac{Workdone}{Heat\,\mathrm{sup}\,plied}$$

$$= \frac{(h_0 - h_1) + (1 - m_1)(h_1 - h_2) + (1 - m_1 - m_2)(h_2 - h_3)}{(h_0 - hf_6)}$$

Where, m1 $= \dfrac{hf_6 - hf_5}{h_1 - hf_5}$

$$m2 = \frac{(1 - m_1)(hf_5 - hf_3)}{(h_2 - hf_3)}$$

Advantages of regenerative cycle:

1. The thermal stresses set up in the boiler are minimized.
2. The heating process in the boiler tends to become reversible.
3. Heat rate is reduced.
4. A small size condenser is required.

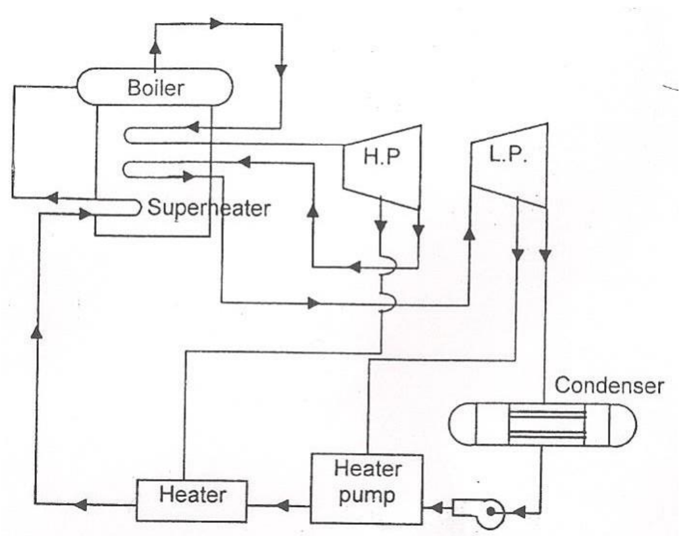
Disadvantages:

1. Due to addition of heaters, greater maintenance is required.
2. The plant becomes more complicated.
3. Large capacity boiler is required.

Reheat-Regenerative Cycle:

Reheat-Regenerative cycle is used in actual thermal power plant with high steam pressure to increase the overall efficiency of the cycle. The figure is shown the Reheat-Regenerative cycle.

The thermal efficiency of the reheat-regenerative cycle is higher than only reheat or only regenerative cycle.



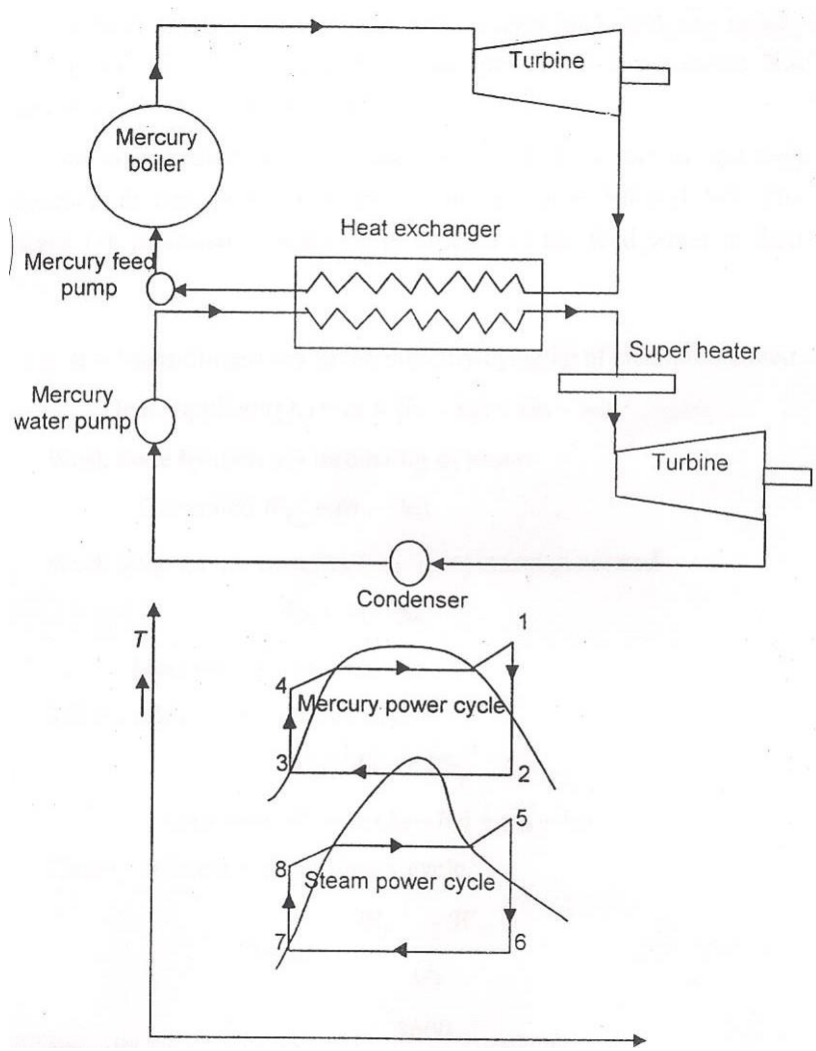
Reheat-Regeneration cycle

***Binary Vapour Cycle* and the Efficiency of cycle.**

It is one type of combined cycles in which usually two working fluids mercury and water are used to improve the overall thermal efficiency of the power plant.

For getting the best performance of vapour power cycle, the working fluid should have the following characteristics.

1. High enthalpy of vaporization.
2. Good heat transfer characteristics.
3. High critical temperature with a low corresponding saturation temperature.
4. High condenser temperature.
5. Freezing temperature should be below room temperature.

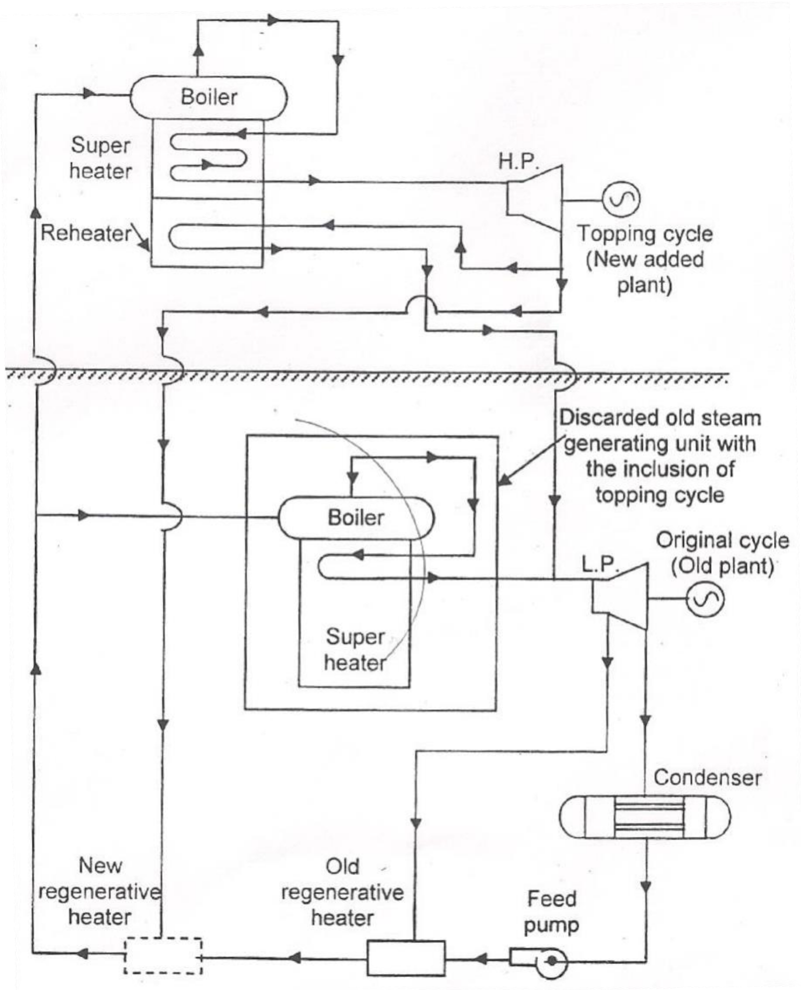


Binary vapour cycle

The cycle has one high temperature region and one low temperature region. This is called a binary vapour cycle. In this cycle, the condenser of the high temperature cycle called topping cycle, and the low temperature cycle termed as bottoming cycle.

1. Topping cycle:

In the above figure, the process 1 – 2 shows the expansion of the mercury vapour in the mercury turbine. Process 2 – 3 represents the condensation of the mercury in the condenser or heat exchanger where the heat exchanges from mercury vapour to water. Process 3 – 4 shows the pumping work and process 4 – 1 represents heating of the liquid mercury to the saturation temperature.



Topping cycle

2. Bottoming cycle:

The heat removed from the mercury is used for heating the liquid. It is shown by the process 8 – 9. The process 9 – 5 represents the super heated steam in the super heater.

The super heated steam is expanded in the steam turbine and then condensed in condenser. It is shown by the curve 5 – 6 and 5 – 7. The process 7 – 8 represents the pumping process of the feed water in feed pump.

Let m = Mass of mercury in the mercury cycle/kg of steam circulated.

Heat supplied (Q_s) = m x (h_1-h_4) + (h_5-h_9)

Work done by mercury turbine/kg of steam

Generated W_{Tm} = (h_1 – h_2)

Work done by the steam turbine/kg of steam generated

$W_{Ts} = h_5 - h_6$

Heat rejected, $Q_R = h_6 - h_7$

Total work done in binary cycle

$W_T = W_{Tm} + W_{Ts}$

Pump work W_P = m (h_4 – h3) + (h_8 – h_7)

Overall efficiency of the binary cycle,

$$\eta_{Rankine} = \frac{W_{Tm} + W_{ST}}{Q_S}$$

Specific steam rate (SSR) $= \dfrac{3600}{W_T - W_P} kg / kwhr$

Thermal efficiency of the mercury cycle,

$$\therefore \eta_{Rankine} = \frac{m \times W_T m}{m.h_1} = \frac{W_{Tm}}{h_1}$$

The efficiency of steam cycle,

$$\therefore \eta_{Rankine} = \frac{W_{Ts}}{h_5 - h_8}$$

The value of m can be determined from energy balance equation.

$$m(h_2 – h_3) = (h_9 – h_8)$$

mass flow rate of mercury required/kg stem flow rate

$$m = \frac{h_9 - h_8}{h_2 - h_3}$$

3. Superposed or Topping cycle:

Whenever the demand increases, the capacity of the existing thermal power plant may be expanded either by increasing the capacity of existing plant or by purchasing additional equipment.

Similar to that the superposed or topping cycle, it is included to the existing unit to increase the power demand. The arrangement is shown in fig. 1.28.

By supplying the sufficient steam by the superposed unit into original plant header, the excellent qualities of existing turbines are retained. The economics of plant operation are increased by the help of topping cycle.

Lamont Boiler.

Introduction:

This boiler works on a forced circulation and the circulation is maintained by a centrifugal pump. This centrifugal pump is driven by a steam turbine using steam from the boiler.

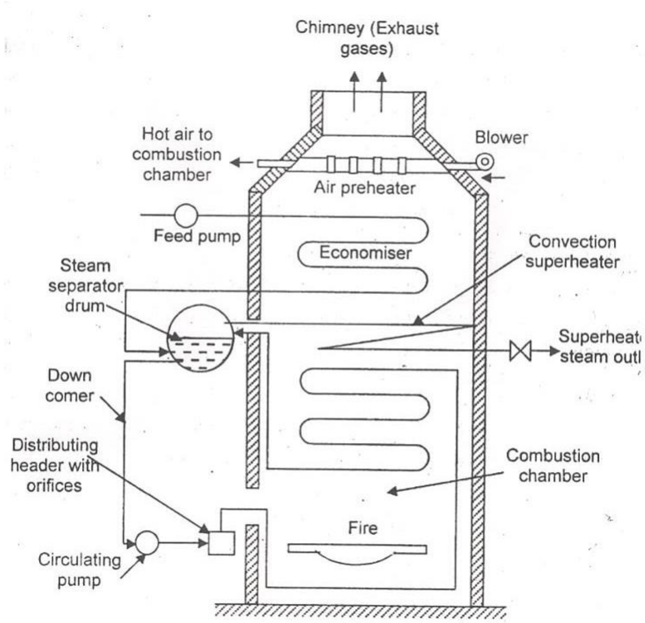
Description:

The arrangement of water circulation and different components are shown in fig. 1.43.

a. ***Steam separator drum:***

It is placed outside the boiler assembly. The drum receives a mixture of steam and water from the evaporator tubes and feeds water from the economizer. The water particles in the steam are separated here.

b. ***Water circulating pump:*** The centrifugal pump is used to draw the water from the drum through the down-comer. The pump circulates water by forced circulation and equal to 8 to 10 times the weight of steam evaporated which prevents the overheating of tubes.



La-Mont Boiler

c. ***Distributing header:***

It is used to control the flow of water to the evaporator tubes.

d. Evaporator:

It is used to evaporate the water into steam.

e. Convection super heater:

The stem produced in the boiler is in the state of saturated condition. The moisture in the steam will affect the turbine blades and cause corrosion. To avoid this, the super heater is used. It is used to increase the temperature of steam and to improve the efficiently.

f. Economizer:

The main purpose of economizer in the boiler is to preheat the feed water using the exhaust gases flowing out from the boiler to the atmosphere. The preheated water requires only a small amount of heat to be supplied in the boiler. This will increase the efficiency of the boiler. In this, the feed water supplied by the feed pump is heated in the economizer on its way to the steam separator drum.

g. Air preheater:

It is used to preheat the air by using exhaust gases flowing out from the boiler. The preheated air is supplied to the furnace for combustion.

Working:

The feed water passes through the economizer to the drum, from which it is drawn to the circulation pump. The pump delivers the feed water to the tube evaporating section. The circulating of water is about 8 to 10 times the steam evaporated in the boiler. The steam in the drum is a mixture of steam and water and the steam is drawn through a convection superheater. The superheated steam is supplied to the prime mover through steam outlet. The working pressure of Lamont boiler is about 170 bar and capacity up to 50,000kg of steam per hour at 500˚C temperature.

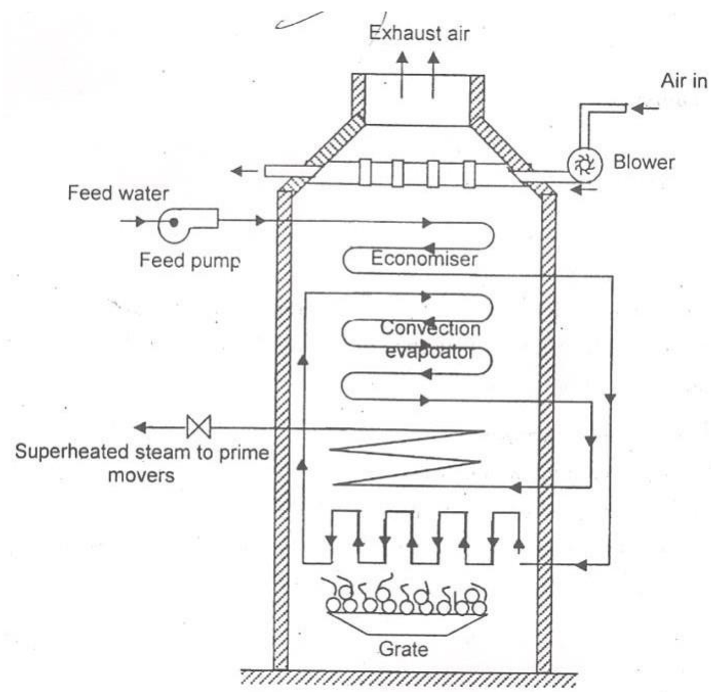
Advantages:

- It is forced circulation boiler.
- High working pressure.

Disadvantages:

- The salt and sediment are deposited on the inner surfaces of water.
- Danger of overheating of tubes.

Benson Boiler



Benson Boiler

Introduction:

In the Lamont boiler, the main difficulty experienced is the formation and attachment of bubble on the inner surfaces of the heating tubes. The attached bubbles to the tube surfaces reduce the heat flow and steam generation as it offers high thermal resistance than water film. This difficulty is overcome in Benson Boiler. This is the first drumless boiler.

Description:

The arrangement of different components is shown in fig. 1.44. The entire process takes place in a single continuous tube. This is also called once through boiler.

a. Economizer:

The feed water from the feed tank is supplied to the economizer. The economizer used in this boiler is used to preheat the feed water.

b. Radiant evaporator:

The feed water from the economizer flows into the radiant evaporator in which the water gets evaporated and is party converted into steam. The radiant evaporator receives heat from the burning fuel through radiation process.

c. ***Convection evaporator:***

The remaining water in the radial evaporator is evaporated in the convection evaporator. The heat required is absorbed from the hot gases by convection. Thus, the saturated high-pressure steam at a pressure of $210kgf/cm^2$ is produced.

d. **Convection super heater:**

The saturated steam is available in the convection evaporator. It is super heated in convection super heater and the super heated steam is supplied to the steam turbine.

Working:

In Benson boiler, all heating, steam generation and super heating are done in a single continuous tube. The feed water after circulation through the economic tubes flows through the radiant parallel tube section to evaporate partly. The remaining water in the radiant evaporator is evaporated into steam in the convection evaporator by the hot gases. The saturated steam available from the evaporator is passed through the convection super heater where the steam is superheated. Finally, the super heated steam is supplied to the steam turbine through stem outlet. The capacity of Benson boiler is about 750 tonnes/hr.

Salient features:

- It can be erected in a comparatively smaller floor area.
- As there are no drums, the total weight of Benson boiler is 20% less than other boiler.
- It can be started very quickly.
- Circulating pump and down comers are dispensed with.
- The furnace walls of the boiler can be more efficiently protected by using smaller diameter and closed pitched tubes.
- Easy transportation.
- It can be operated most economically by varying the temperature and pressure at partial loads and overloads.
- Blow down losses only 4%
- No special starting arrangement super heater is required.

Loeffler Boiler.

Introduction:

The major problem experienced in Lamont boiler is the deposition of salt and sediment on the inner surfaces of the water tubes. To rectify this problem the forced circulation is used.

The boiler can carry higher salt concentrations than any other type. The principle operation in the evaporating of the feed water by means of superheated steam from the super heater, the hot gases from the furnace is being primarily used for superheating purposes. The steam is used as a heat-absorbing medium.

Description:

Fig.1.45 shows the various components of a Loeffler boiler.

a. Economizer:

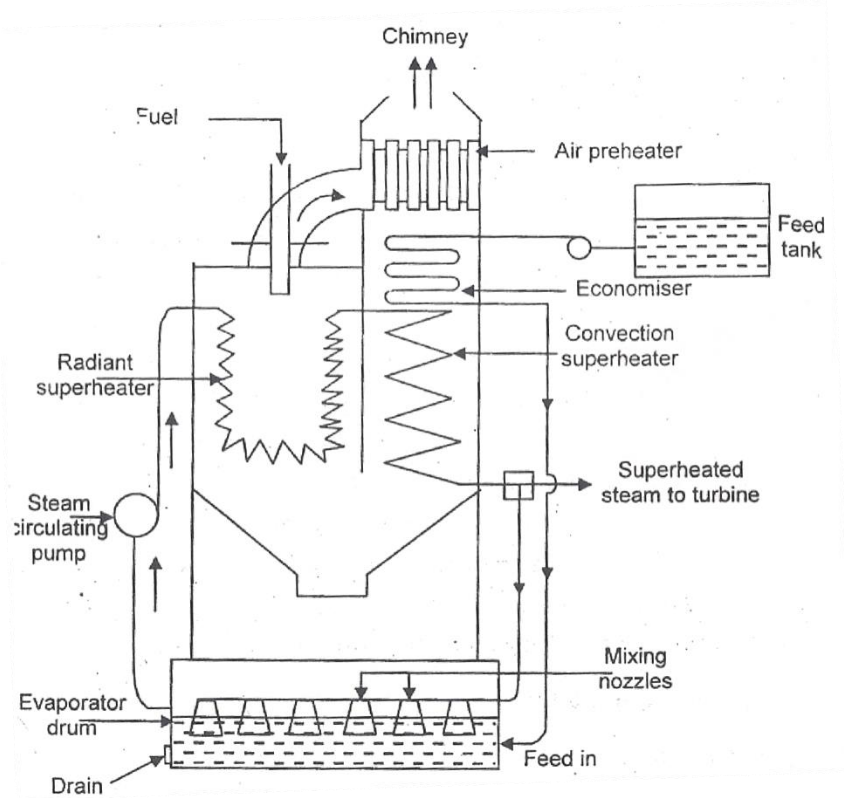
The feed water from the feed tank is supplied to the economizer by feed pump. The economizer is used to preheat the water before it is going to the boiler. There is a heat exchanger from the hot gases to the feed water.

b. Evaporator drum:

The evaporator drum contains steam and water. The feed water from the economizer tube enters the evaporator drum into which is also passed two-thirds of the superheated steam is used to heat the water in the drum and evaporates it to saturated steam.

c. Mixing nozzles:

It is used to distribute and mix the superheated steam throughout the water in the evaporator drum.



Loeffler boiler

d. Steam circulating pump:

It is used to force the steam from the evaporator drum to the radiant super heater.

e. Radiant super heater:

It is placed in the furnace. The hot gases in the furnace are used for superheating the saturated steam from the drum.

f. Convection super heater:

Steam from the radiant super heater enters the convection super heater where it is finally heated to the desired temperature of 500˚C. Both radiant and convection super heaters are arranged in series in the path of the flue gases.

g. Steam outlet:

One third of the superheated steam from the convection super heater passes to the steam turbine and remaining two-thirds is passed on the evaporator drum.

Working:

The high pressure feed pump draws water through the economizer and is delivered to the evaporating drum, the steam circulating pump draws saturated steam from the drawn and passes it through radiant and convective super heaters.

About one third of super heated steam from the convection and radiant super heaters is passed to the turbine and remaining two-third is passed through the water in the evaporating drum to evaporate the feed waster.

Advantages of the boiler:

- Higher salt concentrations ratio than any other type of high-pressure boiler.
- More compact.
- Easy transportation.
- Capacity of about 100tonnes/hr and operating at 140bar.

<u>Velox Boiler</u>

Introduction:

This boiler makes use of pressurized combustion. This boiler can generate a pressure of about $84 kg/cm^2$. Fig. 1.46 shows the Velox boiler and its components.

Description:

a. Economizer:

It is used to preheat the water from the feed pump.

b. Axial flow compressor:

It is used to raise the air pressure from the economizer to tube evaporating section.

c. Water circulating pump:

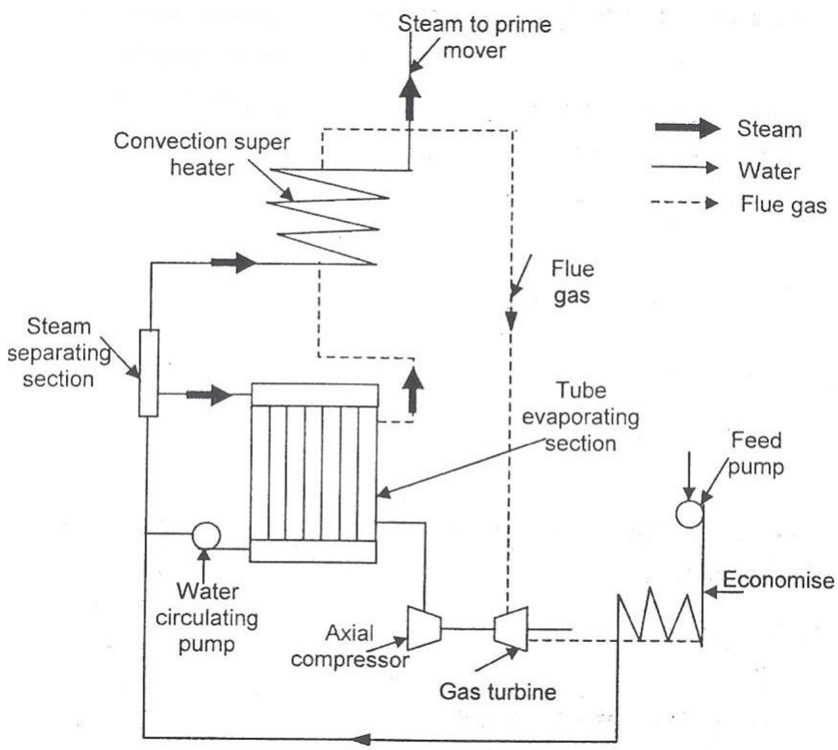
It is used to pump the water from the economizer to tube evaporating section.

d. Convection super heater:

It is used to super heat the steam through convection principle.

Working:

The feed water after passing through the economizer is pumped by a water-circulating pump to the tube evaporating section.



Velox boiler

e gas turbine drives the axial flow compressor which raises the incoming air from atmosphere pressure to furnace pressure. The combustion gases after heating the water and steam flow through the gas turbine to the atmosphere. Steam separated in steam separating section flows to the superheat and then it passes through the steam turbine.

Advantages:

- High combustion rates are possible.
- Quick starter.
- Compact in size and has greater flexibility.
- Excess air requirement is less.

<u>Supercritical Boilers</u>

The most of the large number of steam generating plants are designed between working ranges of 125atm and 510˚C to 300atm and 660˚C.

These types of boilers are basically classified into sub-critical and super-critical boilers.

The sub-critical boiler consists of

- Economizer
- Evaporator
- Super heater

But in case of super critical boiler, it requires only economizer and super heater. Now a days, the super critical boilers are above 300MW capacity units available.

Advantages of super critical boilers:

- High thermal efficiency.
- Heat transfer rate is high.
- The erosion and corrosion are minimized.
- More stable pressure level is maintained.
- Easy operation.
- It can be used as peak load boilers.
- More adaptable load fluctuations.

Boiler Accessories:

The boilers are equipped with some more components other than mountings. They are installed to increase the efficiency of the boiler plants or help in proper working of the boiler unit. These components are known as boiler accessories. A modern boiler has the following accessories attached to it.

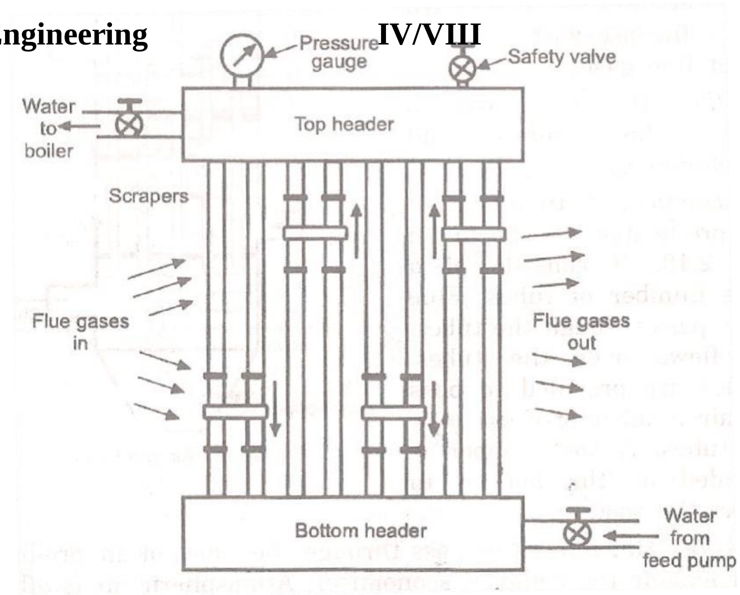
1. Economizer,
2. Air pre-heater,
3. Super heater,
4. Injector,
5. Feed pump,
6. Stem separator,
7. Steam trap etc.

(1) Economizer:

Function: An economizer preheats (raise the temperature) the feed water by the exhaust flue gases. This pre-heated water is supplied to the boiler from the economizer.

Location: The economizer is placed in the path of the flue gases in between the boiler and the air pre-heater or chimney.

Construction: An economizer used in modern high pressure boiler is shown by a line sketch in Fig. 2.17. It consists of series of vertical tubes. These tubes are hydraulically pressed into the top and bottom headers. The bottom header is connected to feed pump. Top header is connected to the water space of the boiler. It is provided with a safety valve which opens when water pressure exceeds a certain limit. To keep the surface of the tubes clean from soot and ash deposits, scrapers are provided in the tubes. These scrapers are slowly moved up and down to clean the surfaces of the tubes. The action of adjacent pairs of scraper is in opposite direction. i.e., when one scraper moves up, the other moves down.



Economizer

Economizers may be parallel or counter flow types. When the gas flow are in the same direction, it is called parallel flow economizer. In counter flow, the gas flow and water flow are in opposite direction.

Working: The feed water is pumped to the bottom header and this water is carried to the top header through number of vertical tubes. Hot flue gases are allowed to pass over the external surface of the tubes. The feed water which flows upward in the tubes is thus heated by the flue gases. This pre-heated water is supplied to the boiler.

Advantages:

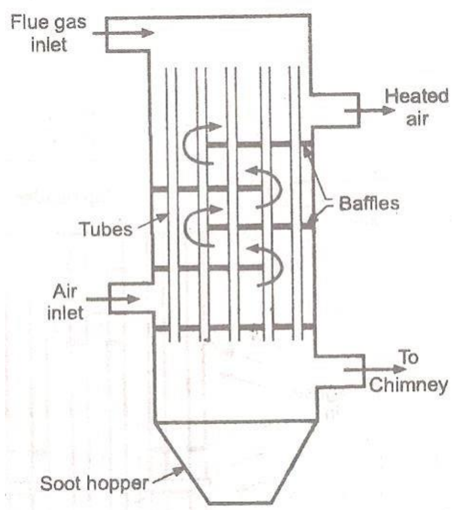
- ❖ Feed water to the boiler is supplied at high temperature. Hence heat required in the boiler is less. Thus fuel consumption is less.
- ❖ Thermal efficiency of the plant is increases.
- ❖ Loss of boiler is increased
- ❖ Steaming capacity is increased.

(2.) Air Pre-Heater:

Function: Air pre-heater pre-heats (increases the temperature) the air supplied to the furnace with the help of hot flue gases.

Location: It is installed between the economizer and the chimney.

Construction: A tubular type air pre-heater is shown in Fig. 2.18. It consists of a large number of tubes, flue gases pass through the tubes. Air flows over the tubes. Baffles are provided to pass the air number of times over the tubes. A soot hopper is provided at the bottom to collect the soot.



Air pre-heater

Working: Hot flue gases pass through the tubes of air pre-heater after leaving the boiler or economizer. Atmospheric air is allowed to pass over these tubes. Air and flue gases flow in opposite directions. Baffles are provided in the air pre-heater and the air passes number of times over the tubes. Heat is absorbed by the air from the flue gases. This pre-heated air is supplied to the furnace to aid combustion.

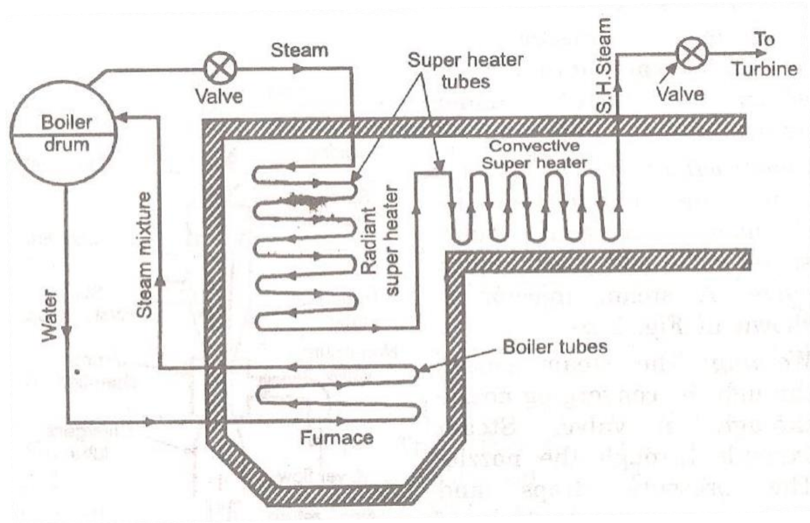
Advantages:

- Boiler efficiency is increased.
- Evaporative rate is increased.
- Combustion is accelerated with less soot, smoke and ash.
- Low grade and inferior quality fuels can be used.

(3.) Super Heater:

Function: it superheats the steam generated by the boiler and increases the temperature of the steam above saturation temperature at constant pressure.

Location: Super heaters are placed in the path of flue gases to recover some of their heat. In bigger installations, the super heaters are placed in an independently fired furnace. Such super heaters are called separately fired or portable super heaters.



Super heat (radiant and convective)

Construction: there are many types of super heaters. A combination type of radiant and convective super heater is shown in Fig. 2.19. Both these super heaters are arranged in series in the path of flue gases. Radiant super heater receives heat from the burning fuel by radiation process. Convective super heater is placed adjacent to the furnace walls in the path of flue gases. It receives heat by convection.

Working: Steam stop valve is opened. The steam (wet or dry) from the evaporator drum is passed through the super heater tubes. First the steam is passed through the radiant super heater and then to the convective super heater. The steam is heated when it passes through these super heaters and converted into super heated steam. This superheated steam is supplied to the turbine through a valve.

Applications: This type of supper heaters are used in modern high pressure boilers.

Advantages of superheated steam (super heaters) :

- *Work output is increased for the same quantity of steam.*
- *Loss due to condensation of steam in the steam engine and in the steam mains is minimized.*
- *Capacity of the plant is increased.*
- *Thermal efficiency is increased since the temperature of superheated steam is high.*

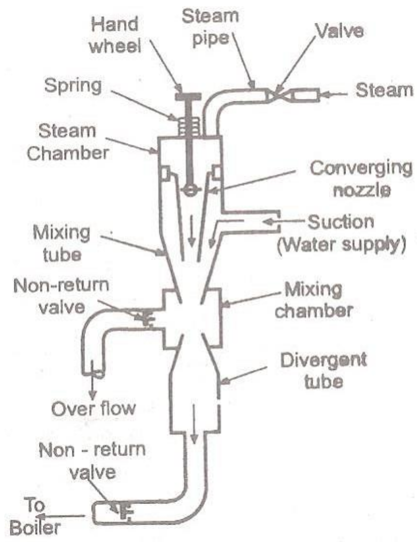
(4) Injector:

Function: An injector lifts and forces water into a boiler which is operating under pressure.

Construction: It consists of a converging nozzle, mixing chamber, divergent tube, steam valve and a non-return valve. A steam injector is shown in Fig. 2.20.

Working: The steam passes through the converging nozzle. The pressure drops and consequently velocity of steam increases. This steam mixes with water in the mixing chamber. In the mixing chamber steam condenses and vacuum is created. Due to this vacuum, more water is sucked into the mixing chamber. The jet of water is converted into pressure energy. Due to this increased pressure, feed water is forced into the boiler through feed check valve.

Application: they are commonly used in vertical and locomotive boilers.

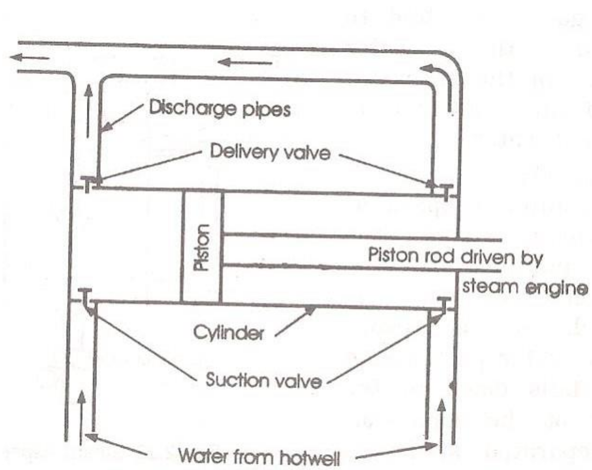


Steam injector

(5.) Feed Pump:

Function: It delivers feed water into the boiler drum.

Location: It is placed in between boiler and water supply source (hot well).



Feed pump (reciprocating type)

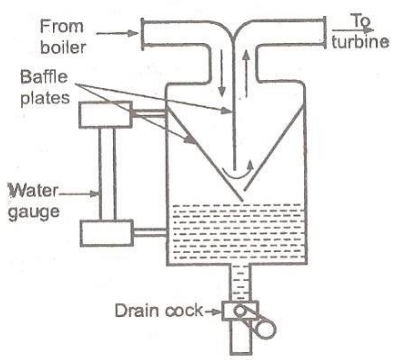
Construction: The feed pumps used may be of reciprocating type or rotary type (centrifugal pump). The reciprocating pump may use plunger or piston. It is driven by a steam engine or electric motor. The piston rod of the steam engine is connected directly with the piston rod of the pump.

Working: When the piston moves to the right, vacuum is created in the right, vacuum is created in the left side of the piston. The water from the hot well is the piston returns (moves to the left), vacuum is created in the right side of the piston. The liquid from the well is sucked into the cylinder through the right side suction valve. At the same time, the liquid in the left side of the piston is forced out through the left side delivery valve into the delivery pipe. The operations are repeated. During each stroke, suction takes place on one side of the piston and delivery takes place on the other side. Thus, the water is delivered continuously into the boiler.

(6.) Steam Separators (Steam Driers):

Function: It separates water particles form steam before it is supplied to a steam engine or turbine. Thus it prevents the damaging of turbine blades due to moisture present in steam.

Location: It is located in the supply line near the turbine or engine.



Steam separator

Construction: There are different types of steam separators. A separator with baffle plates is shown in Fig. 2.22. It consists of a cylindrical vessel. The vessel is fitted with baffle plates. A water gauge is fitted to indicate the water collected in the separator to drain away to separated water.

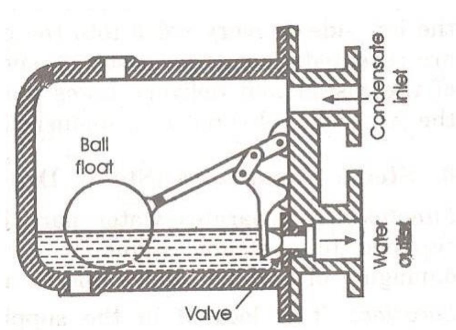
Working: the steam is allowed into the separator. The steam strikes the baffle plates and the direction of flow is changed. As a result, heavier water particles in steam falls down to the bottom of the separator. The separated steam is free from water particles. It is passed to the turbine or engine through the outlet pipe.

(7.) Steam, Trap:

Function: In any steam system, water may be formed due to partial condensation of steam in the piping system. This may cause water hammer and reduction in efficiency. A steam trap removes the condensed water, without allowing the steam to escape out.

Location: They are located on the steam mains, headers etc.

Working: The condensed water enters the steam trap by gravity. When the water level in the trap rises high enough, the ball float is lifted. This causes the valve to open and the water is discharged through the outlet. After the discharge of water, the float moves down. This causes the valve to close again.



Ball float steam trap

2. Differences Between Boiler Mountings and Accessories:

Boiler mountings	Boiler accessories
1. Mountings are fitted in a boiler for the safety of boiler and complete control of steam generation process. 2. They form integral parts of the boiler. 3. They are usually mounted on the boiler shell. 4. A boiler should not be operated without mountings.	1. Accessories are fitted to increase the efficiency of the boiler plant or help in proper working of the boiler unit. 2. They are not integral parts of the boiler. 3. They are usually installed outside the boiler shell. 4. A boiler can be operated without accessories.

5. Examples of mountings are safety valves, water level indictor, fusible plug, pressure gauge, steam stop valve etc.	5. Example of accessories are economizer, air pre-heater, super heater etc.

3. Feed Water Treatment:

Natural water contains solid, liquid and gaseous impurities. Hence this water cannot be used directly for steam generation in the boilers. The impurities present in the feed water should be removed before it is supplied to the boiler. Even though the condensate is returned to the boiler as the feed water, make up water is needed to replace the losses.

4. Impurities Present in Water:

The impurities are present in natural water (raw water) in the following forms.

1. *Undissolved and suspended materials:* They are turbidity in the water (mud, sediment sand etc.,) sodium and potassium salts, iron, manganese, silica etc.
2. *Dissolved salts and minerals:* Calcium and magnesium salts are present in the water in the water in the form of chlorides (Calcium chloride, Magnesium chloride), bicarbonates (Calcium bicarbonate) and sulphates (Calcium and magnesium sulphates).
3. *Dissolved gases:* Oxygen and carbon di-oxide are present in water.
4. *Other materials:* They include free mineral acid and oil.

5. Effects of Impurities:

- *Scale formation:* scale formation may be caused in the boiler drums or heater tubes and feed water piping system. This may result in poor heat transfer rate and chocked flow. The scale formation is mainly due to salts of calcium and magnesium.
- *Corrosion:* Corrosion is the eating away of boiler materials. Corrosion occurs in the boiler shell, tubes, economizers and piping systems. Corrosion causes pitting on metal surfaces. This reduces the life of the material used in the boiler construction. It may even lead to total failure of the system. Corrosion is mainly due to acids, dissolved oxygen and carbon di-oxide present in the feed water.
- *Foaming, priming and carry over:* Foaming is the formation of small and stable bubbles at the surface of water. It prevents the free escape of steam bubbles from water. Foaming is caused by the dissolved solids, excessive alkalinity (Alkali is a compound having the property of neutralizing acids such as soda lime) and presence of oil.
- Priming is the escape of more water particles with steam as it leaves the boiler. This steam cannot be used in turbines or engines since it contains more water particles.

Priming is due to improper boiler design, a high water level, improper method of firing, overloading, sudden load changing etc.

- Carry over is the escaping of water solids in the form of mist or fog (moisture) mixed with steam. The carryover of boiler water solids disrupts operation of the boiler equipments such as steam pipes, valves, super heaters and turbine blades. Carry over is caused by improper boiler deign, high water level etc.
- *Caustic embrittlement:* Boiler metal becomes weaker and brittle due to inner crystalline cracks. This is due to free hydroxide alkalinity and some silica in boiler feed water, leakage of boiler waster through a joint, highly stressed boiler metals at the point of leakage (caused by faulty riveting, misalignment and expansion) etc.

6. Methods of Feed Water Treatment:

The water supplied to the boiler should be free from any impurities. Hence the impure water is treated to remove suspended solids, dissolved solids and dissolved gases. The treatment methods are as given below.

1. Internal treatment
2. External treatment

1. Internal treatment:

The impurities are removed by treating the water in the boiler itself during evaporation and it is known as internal treatment. In this method, chemicals are added to the water in the boiler to precipitate the impurities. These can be removed in the form of sludge (mud) or salts. The common internal treatments given to the boiler feed water are

(a) Sodium carbonate (soda ash)
(b) Phosphate treatment
(c) Colloidal treatment
(d) Blow down

(a) Sodium carbonate treatment: Sodium carbonate is added to the boiler water. It reacts with sulphates of calcium and magnesium in the boiler water and produces calcium and magnesium bicarbonates as sludge which can be removed easily.
(b) Phosphate treatment: Sodium phosphate is added in the boiler waster. It reacts with calcium sulphate and precipitates tricalcium phosphate which can be easily removed.
(c) Colloidal treatment: Colloidal materials such as starch (gruels used to stiffen clothes), linens are added to the boiler water. They absorb the inorganic sludges formed. They prevent precipitating particles from sticking to each other or to the boiler drum surfaces.
(d) Blow down: Draining off some quantity of water in the boiler through the bottom drain of the boiler is known as blowing down. The water thus discharged is known as blow down.

By blowing down, the concentration of dissolved solids (which causes foaming and priming) can be reduced.

2. *External Treatment:*

Removal of impurities present in water before it is supplied to the boiler, is known as external treatment. The different external treatments given to the boiler feed water are as follows.

(a) Mechanical treatment
(b) Thermal treatment,
(c) Chemical treatment and
(d) Demineralization

(a) Mechanical treatment: Suspended materials can be removed by this treatment. It involves three stages namely sedimentation, coagulation and filtration.

Sedimentation: Water is allowed to stand quietly for some time in big tanks. The solid materials settle down and they are removed periodically.

Coagulation: The settling of solid materials is accelerated by adding coagulants like aluminum sulphate or ferrous sulphate. The coagulants react with alkalinity (soda lime) in the water and it forms a flock (gather together) which makes small particles adher to each other. Thus larger particles are formed and settle down easily.

Filtration: During filtrastion, the waster is passed through fine strainers or other porous medium. The suspended solids adhere to the filter materials and they can be removed.

(b) Thermal Treatment: in this treatment, dissolved gases (oxygen, carbon di-oxide, air, etc.) in the water are removed. This is done by heating the3 water to about 110˚C with subsequent agitation while heating.

(c) Chemical Treatment: In this treatment, chemicals are added to the feed waster to remove impurities. Lime (calcium hydroxide) and soda ash (sodium carbonate) are added to the boiler feed water in a tank. They react with impurities present in water (calcium and magnesium salts) and precipitate them.

Sodium zeolite is used for softening the water (zeolite is a kind of mineral) having the property of ion exchange).

(d) Demineralisation: This is to remove mineral contents of waster. Raw water is passed through the hydrogen zeolite exchangers where cast ion is removed. Then this waster is passed through an ion exchange and degassifer and finally through silica absorber. The water thus obtained is soft water.

7. Starting the Boiler from Cold Condition:

The following is the procedure for starting the boiler from cold condition.

- Boiler mountings are checked for their proper functioning.
- All the joints and fittings are checked.

- ❖ The doors, stokers, controls, fuel supply systems etc., are tested for their proper functioning.
- ❖ Then, the boiler is filled with feed water upto the specified level. The drains and blow-off cocks are opened and waster is allowed to escape and then they are closed again.
- ❖ The boiler is again refilled with feed water upto the working level.
- ❖ Steam valve is opened to connect the pressure gauge.
- ❖ Firing is done to heat the water in the boiler. The steam is raised to a predetermined pressure.
- ❖ The steam valves are opened to allow steam into the super heater. Chemicals are introduced into the boiler with feed water.
- ❖ Boiling of waster is continued and the pressure is brought to half of the working pressure till the blow down is obtained. Then the pressure is raised to the working pressure.

8. Safety precautions in Boiler Operation:

The following safety precautions should be adopted during boiler operation.

- ❖ The boiler should be fitted with all the necessary mountings and they should be checked for proper functioning.
- ❖ Danger of explosion or fire should be avoided. Fire fighting equipments must be kept in ready condition for use at any time.
- ❖ Safety devices must be used by the workers to avoid cuts, burns, falls and bruises (injuries) to workmen.
- ❖ Guards, railings, steps and floors must be kept clean.
- ❖ Constant watch on the mountings such as water level indicator is necessary.

9. Indian Boiler Act:

The Indian Boiler Act was passed in 1923. Later it was amended in 1953. Some of its important clauses are given below.

1. Boiler mountings: The following mountings should be fitted with each boiler for the safety of boiler. Safety valves (2 Nos), water lever indicators (2 Nos), steam pressure gauges (2 Nos), steam stop valve, blow-off cock, feed pump, fusible plug, valve after superheater, man hole, hand holes and sight holes for cleaning and inspection.

2. Boiler registration: The boiler should not be operated unless it is registered. The registration certificate should be obtained from chief inspector of boilers.

Restrictions in boiler registration:

(a) If the boiler has been transferred from one state to another state, it should not be operated until the transfer has been reported as prescribed.

(b) The boiler should not be operated at a pressure higher than the maximum pressure specified in the boiler certificate.
(c) Boiler should be operated by a person holding competency certificate (Boiler operator certificate).

Renewal of certificate: The certificate should be renewed under the following conditions.

(a) The due date (for which it was certified) expires.
(b) Any accident occurs to the boiler or person.
(c) The boiler is shifted from one state to another state.
(d) Any alteration in structure, addition or renewal made in the boiler.
(e) The feed pipe or steam pipes are in dangerous condition.

3. Transfer of a boiler: When a boiler is transferred from one state to another state, it must be noted in the register. The owner of the boiler should apply to the chief inspector of boiler of the state in which the boiler is to be installed for the registration of transfer and obtain a a fresh certificate of registration.

4. Accident report: If any accident occurs to the boiler owner or operator, it should be informed within 24 hours of the accident to the chief inspector of boilers in writing. All details about the accident and injuries caused to the boiler or any person should be given. The chief inspector of boiler will inspect the accident site and decide whether the boiler can be reused. During investigation, he can ask questions from anybody and every person are bound to answer truly.

5. Boiler repairs: Any repair of the boiler should be carried out only after obtaining sanction from the chief inspector of boilers.

6. Alterations and renewals: Any alteration in the boiler structure and additions or renewals should be made only after obtaining permission from the chief inspector of boilers.

7. Penalties: The owner shall be liable to be fined for the following offences.

- Using a boiler without obtaining a certificate.
- Refusing to surrender a certificate.
- Using a boiler which has been transferred from one state to another state without reporting.
- Operating the boiler at a higher pressure than the allowed pressure.
- Doing alterations in the boiler or steam pipe without informing.
- Failing to mark the registration number on the boiler.
- Failing to report any accident occurred to the boiler or person.
- Tampering the safety valves of the boiler.
- Marking a fraudulent registration number on the boiler.

Fluidized bed boilers

It is used to produce steam from fossil and waste fuels by using technique fluidized bed combustion.

- It can use solid, liquid or gaseous fuel or mix as well as domestic and industrial waste.
- Solid mixing is rapid. So high heat transfer rates can be obtained to surfaces owing to its immersion within the bed. This can lead to a saving of 75% in tube required power.
- Combustion temperature can be controlled actually and it can be low enough to minimse volatisation of ash constituents like alkali materials because the temperature is well below the melting point of most gas – borne solid particles.
- Simplicity of arrangement, small size of the plant and reduced corrosion or erosion of gas turbine blades.
- Higher sulphur content coals can be used due to THE presence of SO_2 by combustion of sulphur.
- High ash containing coal can be efficiently burnt in FBC.

Types of fluidized bed boilers:

The fluidized bed boilers are of two types.

- Bubbling fluidized bed boilers (BFB)
- Circulating fluidized bed boilers (CFB)

Bubbling fluidized bed boilers

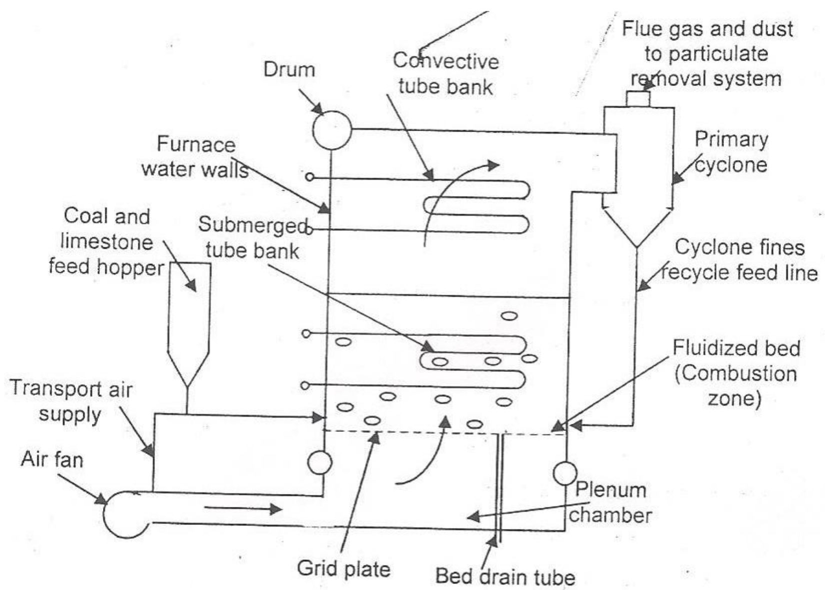
In this boiler, the crushed coal (about 6-20mm) is injected into the fluidized bed of limestone just above air distribution grid which is located at the bottom of the bed.

Working:

The air from the air fan flows upwards through the grid from the air plenum into the bed where combustion of coal occurs.

The combustion products leaving from the combustion chamber is having a large number of carbon particles and it is collected in cyclone separator and it is again fed back to the bed.

The gases can be cooled to a lower temperature before leaving the stack with less formation of H_2SO_4 acid due to the sulphur in coal is retained in the bed by the bed material used (limestone).

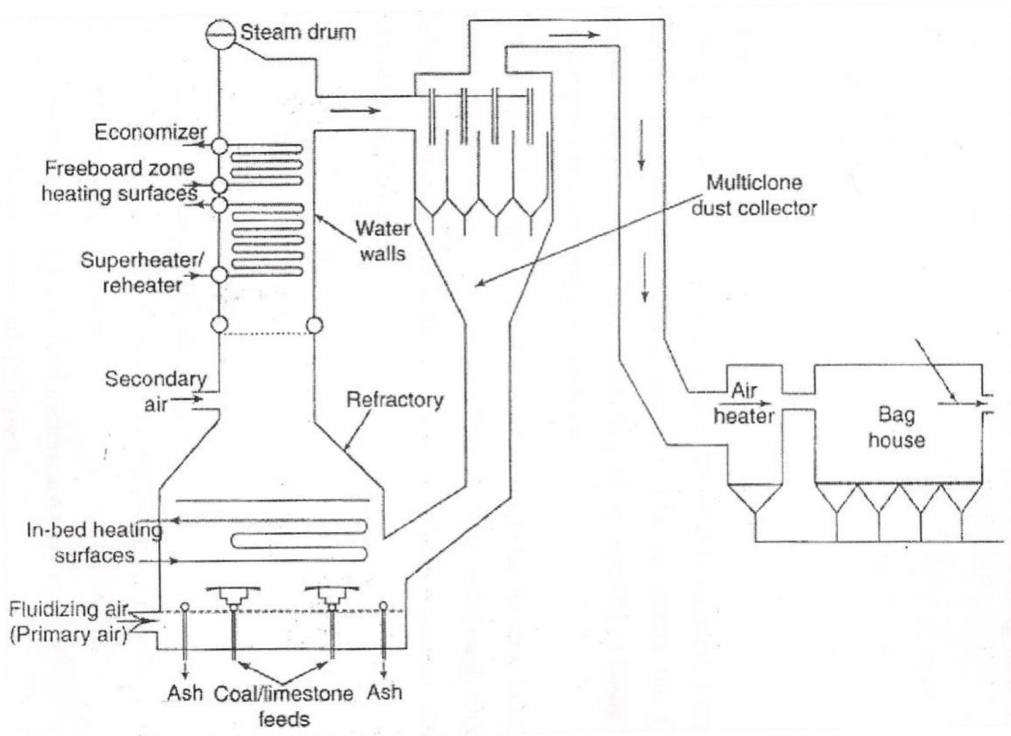


Schematic of bubbling fluidized bed boiler

As a result of low combustion temperatures (800 - 900˚C), it is possible to use inferior grades of coal without slogging problems and less NO_x.

The volumetric heat release is about 10 to 15 times higher and surface heat transfer rates are 2 to 3 times higher than a conventional boiler.

The below fig. shows the bubbling fluid bed boiler system operating at atmospheric pressure.



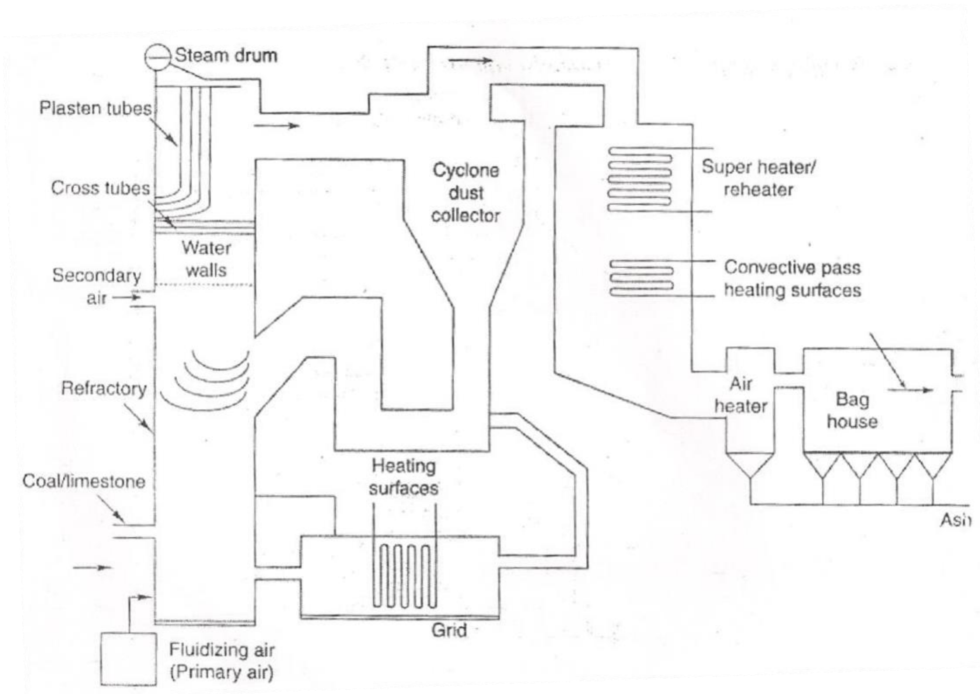
An atmosphere bubbling fluid bed boiler system

<u>Circulating fluidized bed (CFB) Boilers</u>

The circulating fluidized bed boiler is divided into two sections.

The first section consists of

- Furnace or fast-fluidized bed.
- Cyclone separator
- Solid recycle device, and
- External heat exchanger



An atmosphere bubbling fluid bed boiler system

This second section is the back-pass. Here, remaining heat from the flue gas is absorbed by

- Reheater
- Super heater
- Economizer
- Air preheater

Working:

At the lower section of the furnace, the coal is injected. Limestone is fed into the bed in a similar manner. The air enters the furnace through an air distributor. The secondary air is injected at some height above the grate to complete the combustion.

The bed solids are well mixed throughout the furnace height and the bed temperature is about 800-900˚C. The unburned char and particles of limestone are collected in the cyclone separator and it is again fed to the furnace.

The ash and sorbents (limestone) having the cyclones are collected in the electrostatic precipitator.

Advantages of CFB boilers:

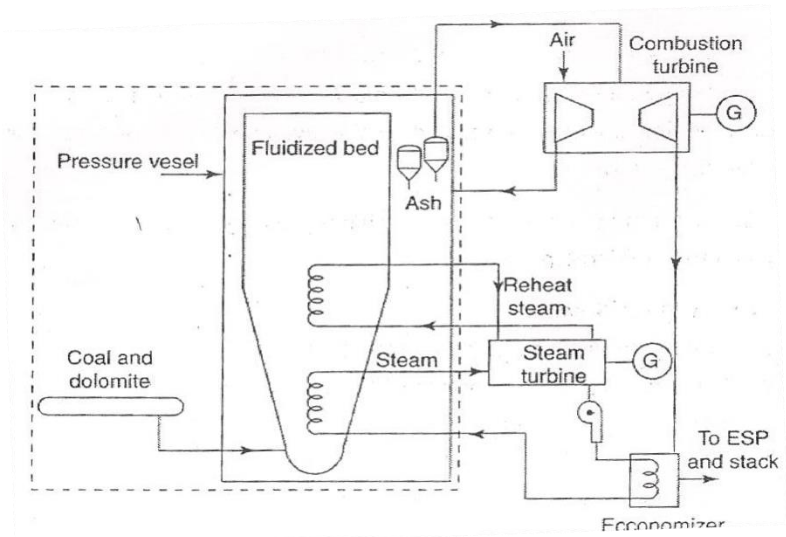
- High combustion efficiency (about 99%).
- The most attractive features of CFB boilers is fuel flexibility.
- Efficient sulphur removal
- The fuel handling and feed system are very simple.
- Low NOx emission (50-150ppm).
- The availability records of CFB boilers are very impressive.
- Furnace cross section is very small.
- High fluidizing gas velocity.
- Heat release rate is high.
- Sulphur capture efficiency is maximum (depending on combustor temperature).

Disadvantages:

- Erosion of particles.
- Reactor wall erosion.
- Material immersing is not possible.

Pressurized fluidized bed boiler

The combustion efficiency is improved by using pressurized combustion process. The process allows the use of a gas turbine, driven by pressurized hot combustion gases. Like atmospheric fluidized bed combustion fluidized bed combustion furnace, the pressurized fluidized bed combustors are classified into two types. The fig. 1.50 shows the schematic of a pressurized bubbling bed combustor.



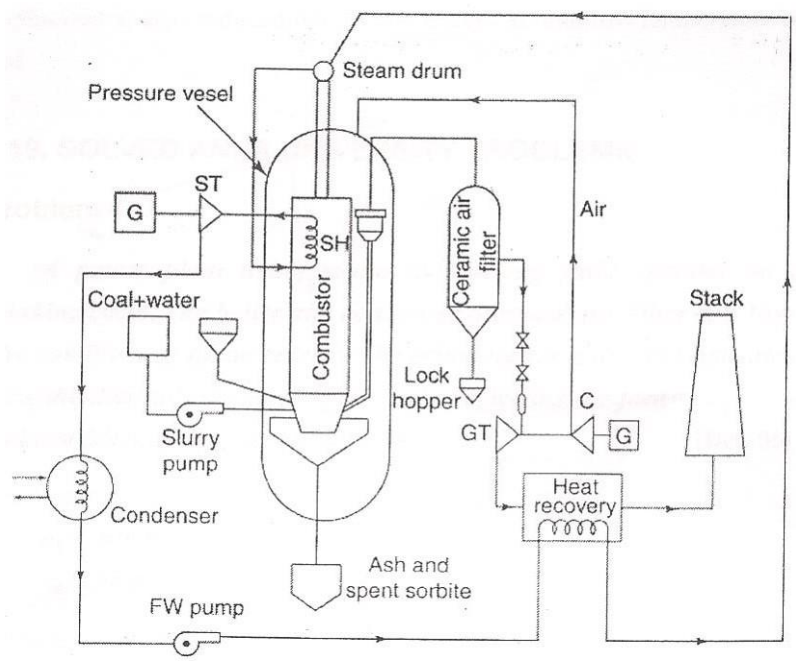
Schematic of a pressurized bubbling fluidized bed combustor

In this, the granular solids are fluidized in bubbling fluidized mode. A part of the heat generated in the fluidized bed is extracted by waster carrying tubes in the bed. The cleaned hot gas is expanded through the gas turbine. The steam produced in the combustor or heat recovery exchanger is used to produce power through steam turbine.

Pressurized circulating fluidized bed combustor

The fig. 1.51 shows the pressurized circulating fluidized bed combustor. The advantage of this type of combustor is that the solids are fully mixed throughout the combustor.

The primary air enters the combustor through the grid at the bottom of the combustor. The secondary air enters at some distance above the grid. The solids in a pressurized circulating fluidized bed are kept in "fast fluidized" condition. The boiler tubes are located above the sub-stoichiometric condition. It will reduce NOx and corrosion of the boiler tubes.



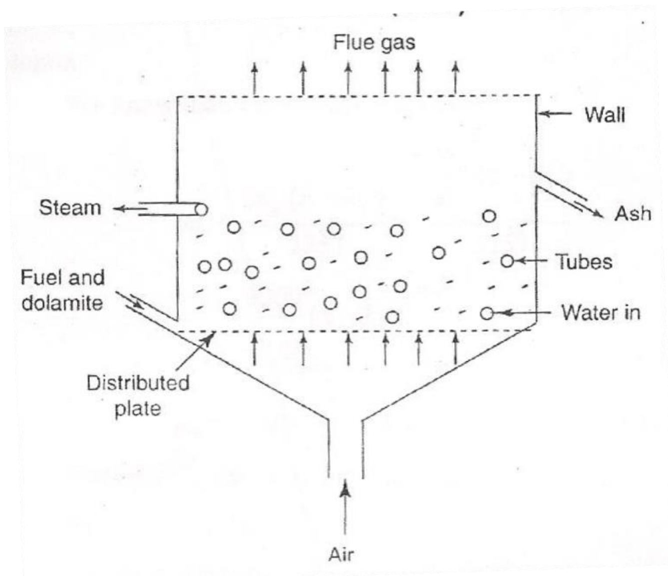
A pressurized circulating fluidized bed combustor

Advantages of pressurized circulating fluidized bed combustor over pressurized bubbling fluidized bed combustor:

- The exhaust gas temperature from this boiler is high and this gas is used in gas turbine.
- Lower NOX emission.
- It does not require a bed material handling system.
- Less corrosion and erosion.
- Space requirement is less.

- Simple and more reliable system.
- Higher velocity and higher heat release rate per unit area.
- Quick response to load changes.
- It uses more readily available limestone.
- Easy inspection and maintenance.

Fluidized bed combustion (FBC)



Fludised bed combustion

When air is passed through a fixed or packed bed of particles, the air flow rate gradually increases and at a maximum point the pressure drop across the bed becomes equal to the particles weight/unit cross sectional area of the bed.

So, this velocity of the particles is known as fluidization velocity and the high degree of particle mixing and equilibrium between gas and particles is known as fluidized bed.

The basic principle of fluidized bed combustion (FBC) is shown in fig. 1.52.

The fuel and dolomite are fed on a distribution plate and air is supplied from the bottom of distribution plate. Due to the high velocity of air, the feed material remains in suspension condition during burning. The bed temperature is about 800-900˚C and the SO_2 emission is controlled by the addition of limestone or dolomite. The NOx production is also reduced due to low excess air and low temperature of be.

UNIT–II

AIR AND FUEL HANDLING SYSTEMS

COAL HANDLING

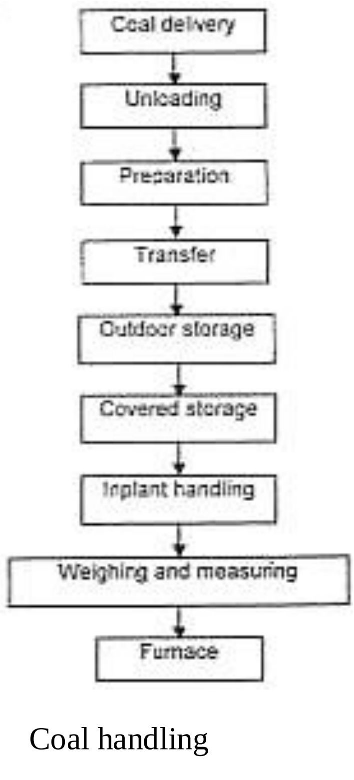
Coal handling is the very important factor in the power plant, coal handling is done by two ways.

1. out plant handling of coal
2. in plant handling of coal

The out plant handling of coal is done by

1. Transportation by sea or river.
2. Transportation by ropes.
3. Transportation by rail.
4. Transportation by road.
5. Transpiration coal by pipeline

The various steps involved in coal handling are as follows and it is explained in detail



Coal handling

1. coal delivery:

Coal from the supply points is delivered to the power stations by the way of sea transportation or by pipe line transportation or by trucks.

2. unloading:

The requirement of unloading equipment depends on the type of coal received at the power station. If it is by trucks, there is no need of unloading equipments. In this case, the coal is brought by railway wagons, ships or boats. It means, the unloading is done by cranes, car shakes, grab buckets and by coal accelerators.

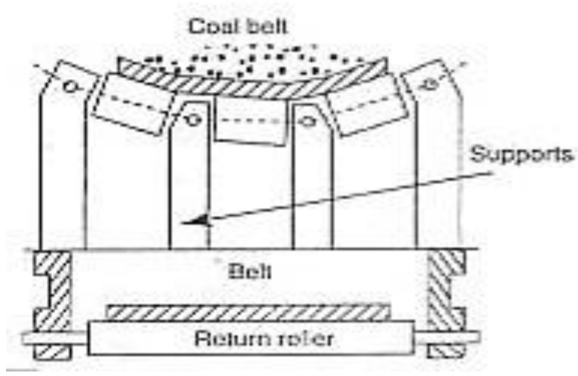
3. Preparation:

The coal cannot be in proper size, when it is delivered in the form of big lumps. The preparation of coal can be achieved by sizes, crushers, and breakers.

4. Transfer coal transfer is done by the following systems.

   1. Belt conveyors
   2. Bucket elevators
   3. Screw conveyors
   4. Grab bucket elevators
   5. Flight conveyor
   6. Skip hoists

(i) Belt conveyor:



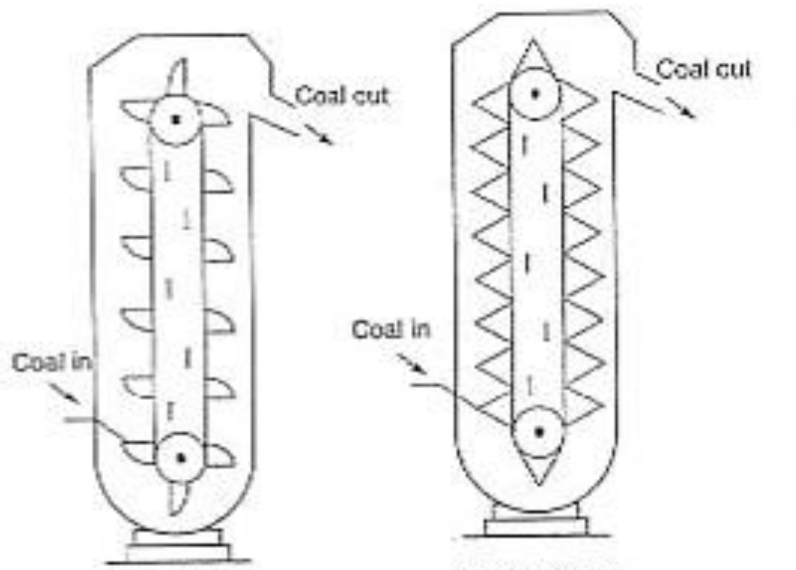
Belt conveyor

This method is more suitable for transporting large quantities of coal. It consists of an endless belt moving over a pair of end drums (pulleys) and supported by a series of rollers. The belt is made up of rubber or canvas.

The load carrying capacity of the belt may vary from 50 to 100 tonnes/hr and average speed of belt conveyors is 60m to 100m per minute.

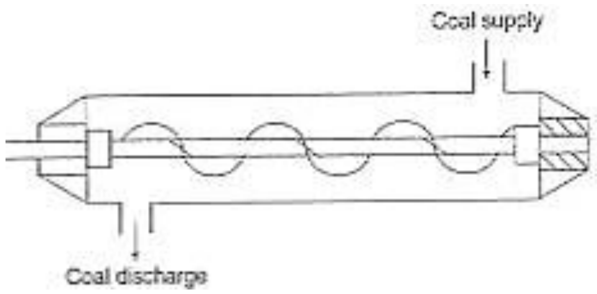
(ii) Bucket elevator:

It is used for vertical lifts. It consists of buckets fixed to a chain. The chain moves over two wheels. The coal is carried by the buckets in the bottom and discharged at the top.



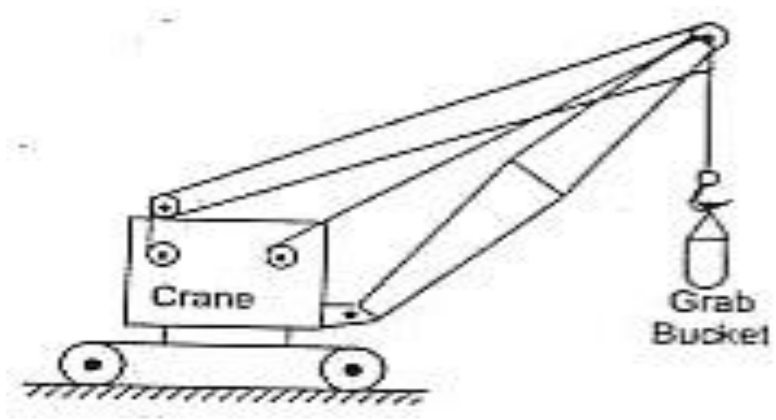
(a) Centrifugal (b) Continuous

(iv) Screw conveyers:



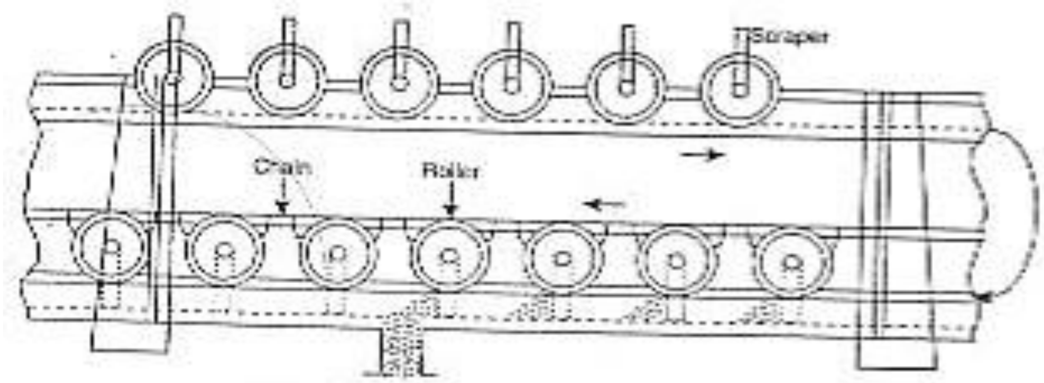
It consists of an endless helicoids screw fitted to a shaft. The one end of the shaft is connected to the driving mechanism and the other end is connected to the bearing. The screw while rotating in a trough transfers the coal from feeding end to the discharge end. The rotational speed of the screw varies from 75. to 125 rpm.

(iv) Grab bucket conveyor :



It is used to transfer the coal from one point to another. The coal lifted by grab buckets is transferred to overhead bunker. The grab conveyor can be used with crane or tower. A 2 to 3 cu-m bucket over a distance of 6m transfers nearly 100 tonnes of coal per hour.

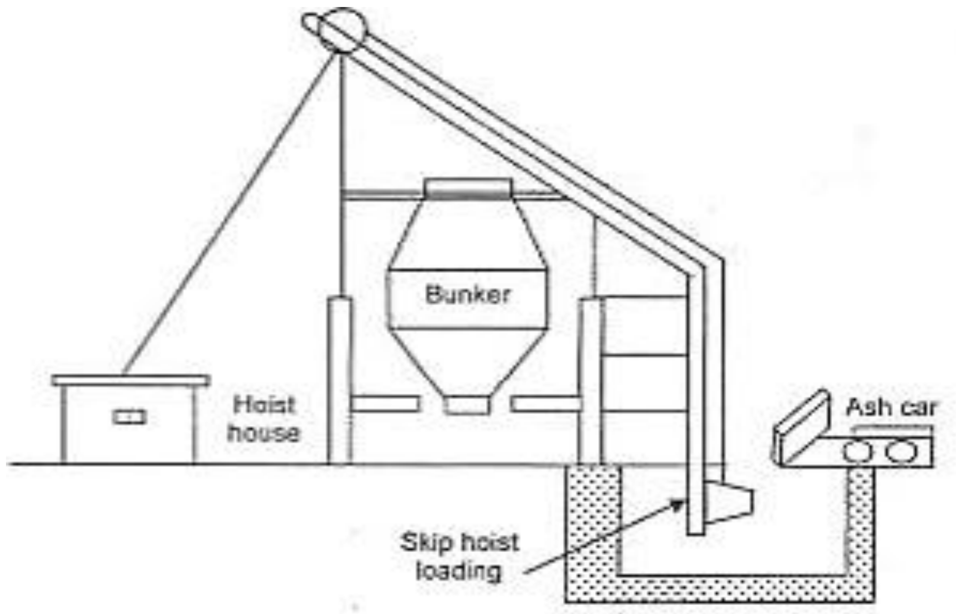
(v) Flight conveyor :



It is used for transferring the coal when filling of number of storage bins situated under the conveyor is required. It consists of one or two stands of chain to which steel or flights are attached.

(vi) Skip hoist :

Skip hoist consists of a vertical or inclined hoist way a bucket or a car guided by a frame and a cable for hoisting the bucket.



DRAUGHT

Large amount of air is needed for combustion of the fuel. The purpose of draught is to supply the required quantity of air for combustion and remove the burnt products from the system.

Draught is defined as the movement of air through full bed and to produce a flow of hot gases through the boiler and chimney requires a pressure difference between gas pressure and atmospheric pressure. This difference in pressure required to maintain the constant flow of air and to discharge the gases is known as draught.

The function of draught is

1. To supply the required quantity of air to the furnace.
2. To remove the burnt gases from the furnace.

There are two ways of producing draught.

1. Natural draught
2. Artificial draught

The natural draught is obtained by the use of chimney only. The artificial draught is produced by forced or induced fans and without chimney.

Natural Draught

Natural draught is produced by a chimney or a stack. Natural draught is created by the difference between the atmospheric air and the hot gas in the furnace. The natural draught depends upon the height of chimney and average temperature of the hot gases in the chimney.

The difference in pressure of the natural draught is calculated by

Advantages:

1. No external power is required.
2. Long life of chimney.
3. It prevents the contaminations and maintains the cleanliness.
4. Maintenance cost is nil.
5. Less capital investment.

Limitations:

1. Less pressure difference is only created.
2. Draught will decrease when the outside air temperature increase.

Mechanical Draught

It is produced by fans. There are two types of fans

1. Forced draught fan
2. Induced draught fan

In large size boilers, the fans are employed to create the necessary draguth in order to reduce the height of chimney.

1. Forced draught:

In this system, a blower is installed near the base of the boiler and air is forced to pass through the furnace. The pressure throughout the system is above atmospheric pressure and air is forced to flow through the system.

The forced draught fans are handled cold air. So, the maintenance problem is less. A stack or chimney is also used in this system. The arrangement of forced draught system is shown in fig.

The power required to drive the FD fan is given by

Where, W_f = Fuel burning rate

U = Specific volume of inlet air

A/F = Air fuel ratio

ΔP = Pressure head developed by fan.

η_{FD} = Efficiency of the forced draught fan

For the better operating conditions, the two forced draught fans in paralled are normally used.

2. Induced draught:

In induced draught systems, the fan is located near the base of the chimney instead of near the grate. The suction pressure in this system is below atmospheric.

It sucks the burnt gases from the furnace and pressure inside the furnace is reduced to below atmospheric pressure. Induced draught fans are handled hot combustion gases. The power requirement is greater than the forced draught fans.

The Chimney is also used in this system but the total draught is produced by fan only. The arrangement of induced draught fan is shown in fig.

The power input in induced draught fan is calculated by

Where, W_f = Fuel burning rate

A/F = Air fuel ratio

U_g = Specific volume of the flue gases

ΔP_{ID} = Pressure head developed.

η_{ID} = Efficiency of induced draught fan.

3. Balanced draught:

It is the combination of induced and forced draught systems. If forced draught only is used in the furnace, it is not possible to open the furnace for either firing or inspection. IF induced draught only is used in the furnace, the furnace cannot open for either firing or inspection because of high pressure inside the furnace.

To avoid this difficulty, the balanced draught is sued. The forced draught is used to force the air through the bed and induced draught is used to such the gases from the boiler and discharges them to the chimney. The arrangement of balanced draught is shown in fig. 2.49.

Advantages of mechanical draught over natural draught:

1. Draught pressure can be easily changed.
2. Rate of combustion is high.
3. Low – grade fuel can be used in combustion chamber.
4. It is independent of atmospheric pressure.
5. The efficiency of artificial draught is nearly 7% but in natural draught is 1%
6. Height of the chimney is reduced.
7. Fuel consumption is less (about 15% less than natural draught).
8. It prevents the formation of smoke inside the furnace.
9. Fuel burning capacity is high.
10. Overall thermal efficiency of the plant is increased.

DUST COLLECTOR

The type of dust collectors and their classification are given below. It is very important to clean the dust before; it is discharged to the atmosphere.

Mechanical Dust Collectors

1. Gravitational separators:

The basic principle of gravitational dust collectors is shown in fig. 2.41. By increasing the cross-sectional area of duct, the dust gages are passing and the heavy dust particles fall down when the direction of the flow of flue gages is changed. It may be wet or dry type. Sometimes, the baffles are provided to separate the heavier particles.

In we type dust collectors, the water is used to remove the dust from flue gas. The wet type dust collectors are also called scrubbers.

The dry type dust collectors include gravitational, baffle dust collectors and cyclone dust collectors.

2. Cyclone separator;

It uses a downward flowing vortex for dust gases along the inner walls. The high velocity gas stream carrying the dust particles enters at high velocity and tangential to the conical shell. It will produce a whirling motion within the chamber and heavier dust particles are thrown to the sides and are collected at the bottom of the separator.

The multi-tubular type cyclone separation is particularly used in power plants. The overall efficiency of the cyclone separator is depending on the dust particle size. Some of these values are given.

Particle size in microns	Collection efficiency at pressure drop 5 cm
Less than 10	67
10-20	97.8
20-45	99.1
Above 45	99.5

Advantages of cyclone separator:

1. Higher efficiency when large size particles are collected.
2. Maintenance cost is less.
3. Efficiency increases with increasing load.

Disadvantages:

1. It requires more power than other collectors.
2. The efficiency will decrease when very fine particles are collected.
3. The pressure loss is high.
4. It is not suitable for high volumes of dust collection.

3. Packed type scrubber:

The figure 2.43 shows the wet type collector. The water is prayed through the spray nozzles against the dust particles for breaking up into fine drops and may be divided into thin films by passing through the bed of tower packing.

The thickness of packing material becomes 1 to 3 metres. The slurry which comes out of scrubber becomes highly corrosive therefore, it is necessary to select the high resistant scrubber material. The polyethylene is used as a packing material.

4. Spray type wet collector:

The working principle of spray type wet collector is through the spray nozzles. The water is sprayed by using the towers. The water particles are wet the dust and it is removed. This type of collectors is limited to particles size of 10 microns or above 10 microns

5. Electrostatic precipitator (ESP)

It has two sets of electrodes insulated from each other. The first set is composed of rows of vertical parallel plates and the second set consists of wires, and the wires are located between each pair of parallel plates.

The two sets of electrodes maintain an electrostatic field between them at high voltage and the flue gases are made to pass between these two sets of electrodes. The dust particles are ionized when passing in between the electrodes and attracted them to the electrode of opposite charge. The dust particles are removed from the collecting electrodes. The voltage maintained between the electrodes is 30000 it 60000 volts.

Advantages of ESP:

1. Very small particles (0.01μ to 1.00μ) are being removed by using ESP.
2. Maintenance cost is less.
3. The collection efficiency is about 99.5%.
4. Easy operation.
5. The removed dust particles are either dry or wet.
6. The draught loss is very less.

Disadvantages:

1. The capital cost is high.
2. Large space is required
3. Running cost is also high.
4. The efficiency is not maintained, if the velocity of flue gas is high.

ASH REMOVAL

The following methods are used for removing the ash.

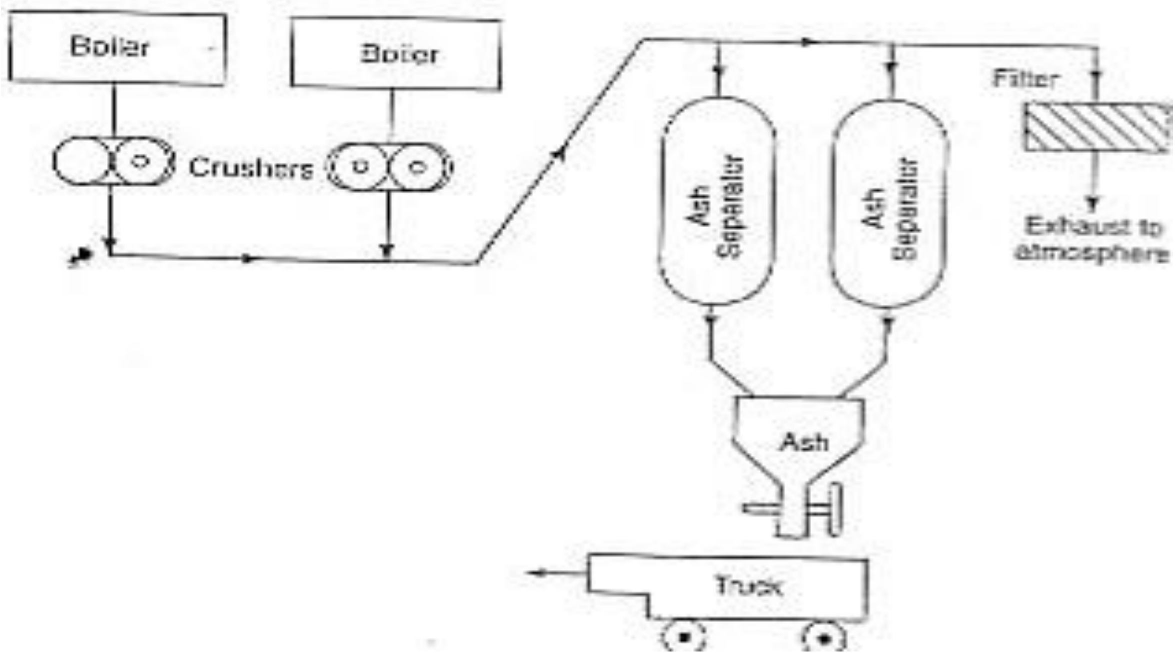
1. vacuum extraction plant
2. hydraulic system
3. mechanical conveyors
4. steam jet system

1. Vaccum extraction plant :

This type is used in both stoker and pulverized fuel installations. This system is more suitable to the boiler plants from which ash transported to some considerable distance.

Working :

Working of vacuum extraction plant is show in fig 2.15. The ash and dust from all discharge points are picked by a high velocity air passed through ash crushers into the air steam.



The crushed ash carrying air is separated in the ash separators and the separated ash is collected in the hopper. The separated ash from the ash separators is exhausted to the atmosphere through air filter and exhauster.

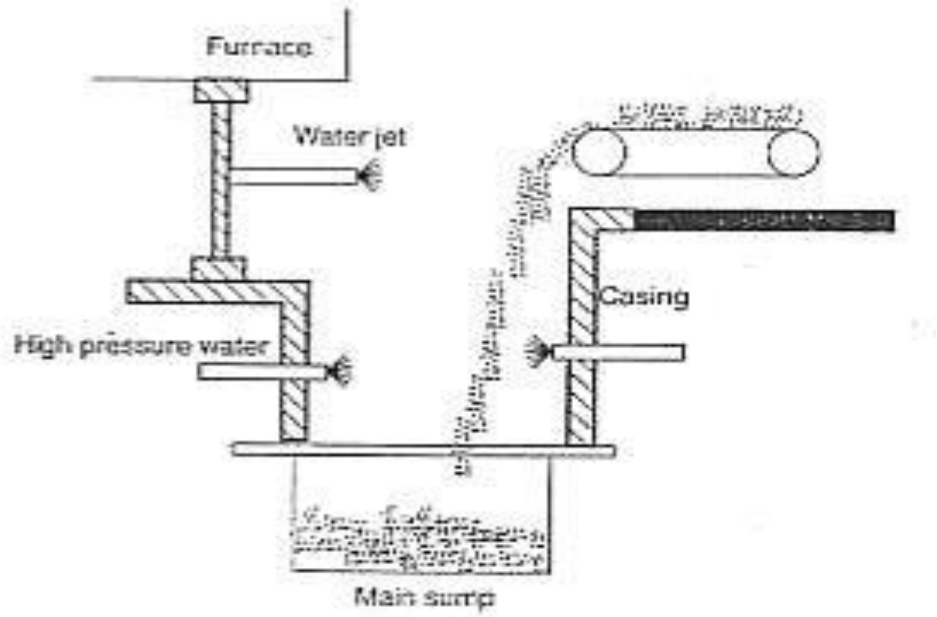
2. Hydraulic system:

In hydraulic systems, the ash is removed by using the water through a channel and finally dumped to the sump. It can be divided into two groups.

(1) Low Velocity system

(2) High velocity system.

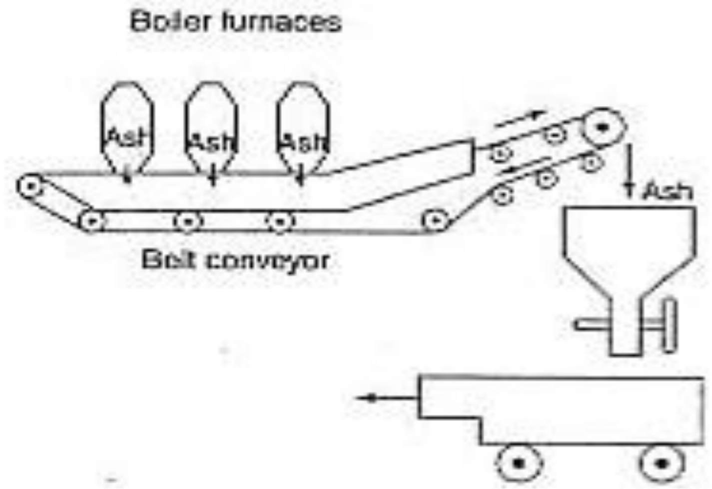
The fig 2.16 shows the high velocity system. The hoppers below the boilers are fitted with nozzles, at the top and on the sides. The top nozzle is used tot quench the water and side nozzle is used ot force the ash. Finally. The quenched ash at high velocity is collected on the sump.



Advantages:

1. Ash carrying capacity is high.
2. The whole system is clean
3. total system is enclosed
4. Discharge if ash is at considerable distance.
5. working parts are not contact with ash.

3. Mechanical system :



It is used for low capacity system. The working principle is shown in fig. the ash coming out of boiler is collected over the belt conveyor through a water seal for cooling the ash form the boiler. The cooled ash is carried by the conveyor continuously to the duping size. The life of the system is about 5to 10.

4. Steam jet system.

In a steam jet system, the ash is carried by high celocity steam which is capable of carrying dry solid materials. In this system, the high celocity steam is passed through a pipe opposite to the movement of ash.

Advantages of this system :

1. It requires less Space
2. Capital cost is less
3. In this system, the ash removal is very economical.
4. The boiler steam is used for removing the ash.

Disadvantages :

1. The operation is noisy.
2. High wear in the pipes.
3. Limited capacity.

EQUIPMENT FOR BURNING COAL

Coal may be fed into the furnace for combustion in lump pieces (or) in powder form. Combustion of coal may occur in

1. Fuel bed furnaces (coarse particles)
2. Fluidized bed furnaces (crushed small particles)
3. Cyclone furnaces (crushed particles)
4. pulverized coal furnaces (fine particles)

1.Fuel Bed furnace :

It is used for burning coarse particles. In fuel bed furnaces, there are tow ways of feeding coal on to the grate.

a) over feeding
b) under feeding

2. Fluidized bed furnace :

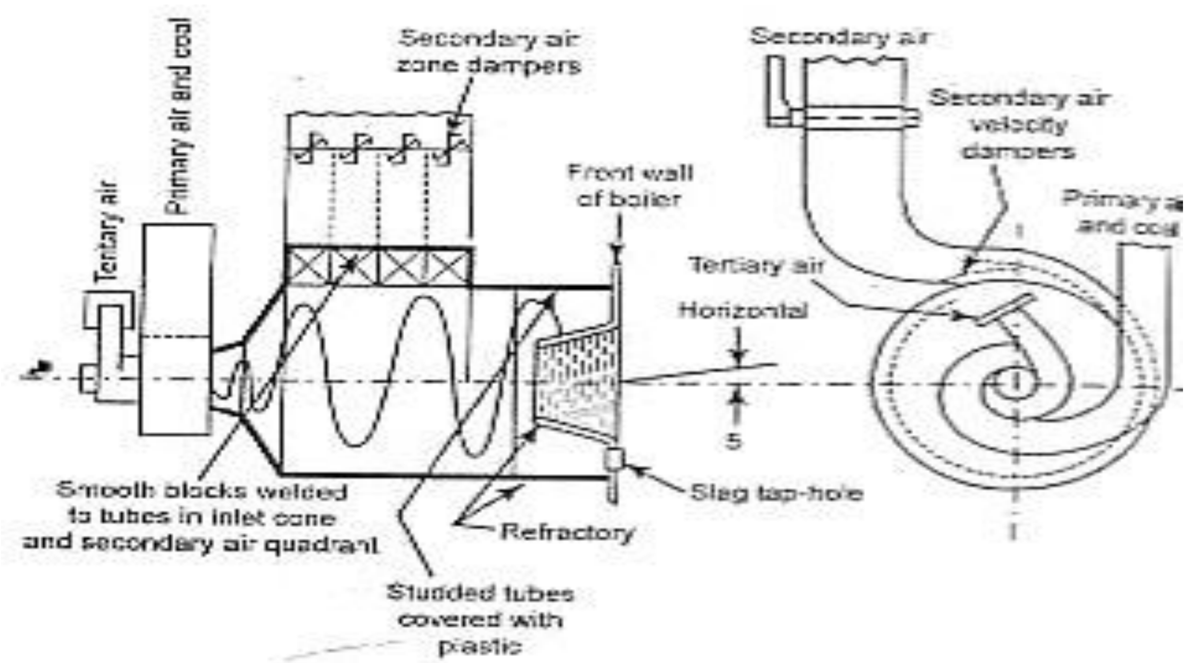
The fluidized bed furnaces are used for burning fine particles. It is classified into

a) A atmospheric fluidized bed combustor
b) Pressurized fluidized bed combustor

3. Cyclone furnace :

The cyclone furnaces are used for firing crushed coal particles. The cyclone is essentially water cooled horizontal cylinder located outside the main boiler furnace, in which crushed coal is fed and fired with very high rates of heat release. The crushed coal is fed into the cyclone along with primary air which is about 20% of combustion or secondary air. The coal air mizture enters tangentially and produces a centrifugal motion in the coal particles. The secondary air enters tangentially at the top of the eyclone at 80-120 *M/s* and produces further centrifugal motion in the coal mizture.

A small quantity of air called tertiary air is admitted at the centre combustion of the coal is complete before the resulting hot gases enter the boiler furnace. The swirling motion of coal and air results in the release of large volumetric heat with high combustion temperature. The cyclone is made with a diameter of 1.8 to 4m and its length is about 1.3 time of its diameter.



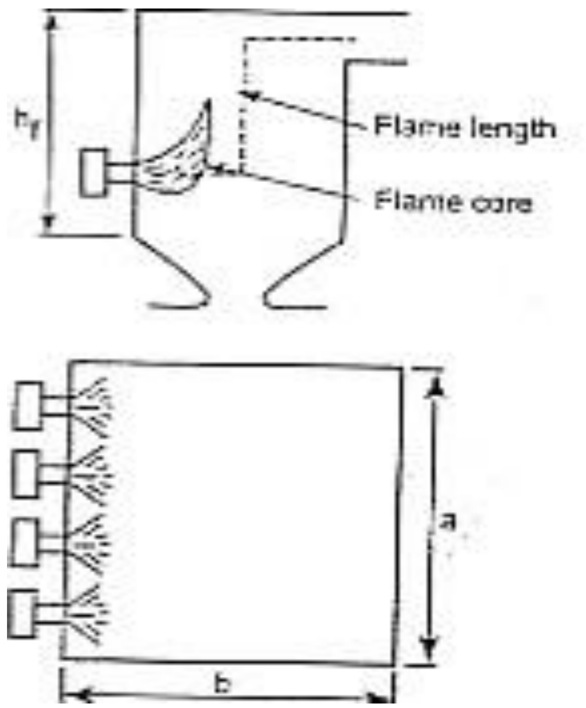
1. The removal of ash is about 60% and only 40% ash leaves with flue gases.
2. No pulverization equipment is needed because of the use of crushed coal.

Disadvantages :

1. High power requirement for running the forced draught fan pressures.
2. More NOz formation.

3. pulverized coal furnace :

The pulverized coal furnaces are used for buring fine particles of coal. Pulverized coal burns in suspension in the furnace space. Heat released by combustion is transferred to the water wall tubes around the furnace by radiation. Water walls consist of vertical tubes arranged mostly in tangent connected with the boiler drum at the top and headers at the bottom. These vertical tubes receive water form the drum via down comer tubes and discharges the water steam mixture to the drum. Pulverized coal furnace can be characterized by its linear dimensions.



(i) furnace description :

Front width = a

Depth = b

Height = h_f

Cross sectional area of the furnace $a_f = a \times b$

The heating power of the furnace

The heating power of the furnace $Q_f = HHV \times W_f$

Where, W_f = fuel consumption rate in kg/s

HHV = Higher heating value in kJ/kg

The heat release rate per unit bed cross section

$$g_f = \frac{W_f \times HHV}{a_f} \; kW/m^2$$

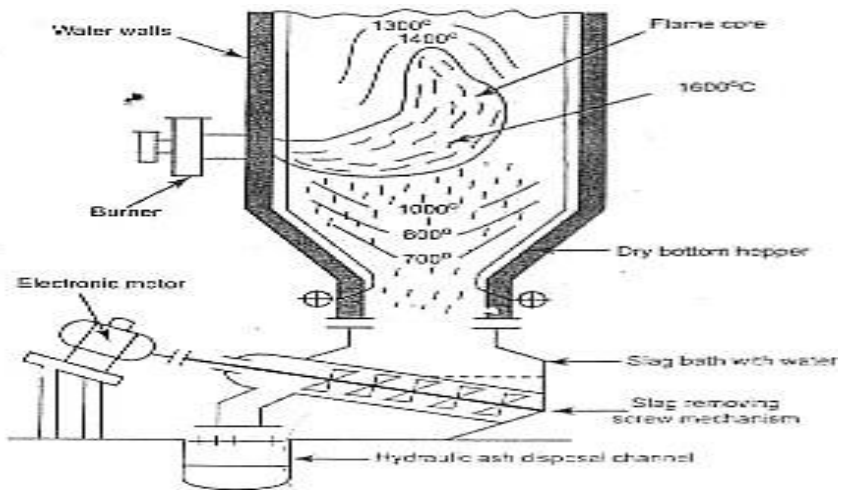
(ii) furnace types:

Depending upon the condition of ash coming out from the furnace bottom, pulverized coal furnaces are of two types they are

a) Dry- bottom furnace

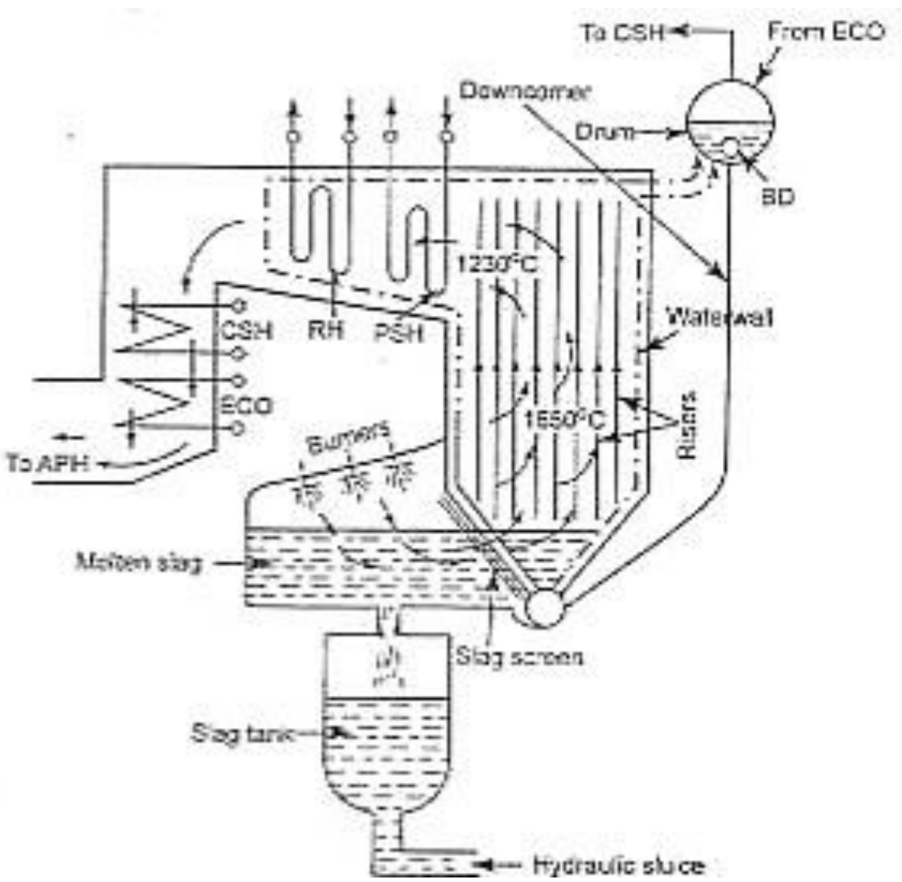
b) Wet- bottom or slag furnace

a) Dry- bottom furnace



In this type of furnace, the ash or slag is removed in the solid or dry state. The exit temperature of gases leaving the furnaces must be below the ash fusion temperature. A about 85% of the ash in coal flows with the flue gases and it is collected in the dust collectors and electrostatic precipitator before the ID fan. The remaining ash falls through furnace bottom and it is cleaned with dust collectors and electrostatic precipitator. The furnace has a hopper at the bottam which cools the furnace gases at the furnace bottom, so that molten slage particles are cooled quickly and fallen along the hopper sides into a slag pit containing water. The water bath also serves as the hydraulics seal into a slag pit containing water. The water bath also serves as the hydraulic seal preventing the suction of cold air form beneath into the furnace.

b) Wet- bottom furnace



In this type of furnace, 90-60% of the ash in coal moves with the flue gases due to ID fan suction, and the rest falls through furnace bottom in a continuous molten stream.

The temperature of gases at the walls in the lower portion of the furnace should be higher than the melting temperature of ash to increase its fluidity. The molten ash is discharged into a slag tank containing water, quenched and shattered into granular form. In wet a furnace, coals having high ash content and low ash fusion temperature are only consumed.

MECHANICAL STOKERS

For more uniform operating conditions, higher burning rate stokers are employed. The stokers are used to feed solid fuels into the furnace in medium and large size power plants.

According to the feed system, the stokers are classified into two types.

(1) Overfeed stokers
(2) Under feed stokers.

The working principle of stokers and types of overfeed and underfeed stokers is given below.

1. OVERFEED STOKERS

In case of overfeed stokers; the coal is fed on the grate above the point of air admission.

Working Principle:

In this type of fuel firing, the primary air enters the grate from the bottom. The air passing through the grate is heated by absorbing the heat from the ash and grates itself. Some the grate is cooled. Then the air passes through a layer of incandescent coke and the oxygen in the air is reacted with coke to form CO_2. The rate of carbon oxidation depends upon the rate of air supply.

The water vapour present in the air also reacts with coke to form CO, CO_2 and H_2. The gases leaving the fuel bed contain the N_2, CO_2, CO, H_2 and H_2O. Then additional air is supplied to urn the combustible gases.

The burnt gages entering the boiler contain N_2, CO_2, O_2 and HO and some CO, if the fuel burning is not completed.

Over feed stokers classification:

1. A chain grate stoker:

It consists of an endless chain which forms a support for fuel bed. The chain travels over two sprocket wheels one at the front and the other at the rear of finance. The front sprocket is connected with variable speed mechanism. The traveling chain receives coal at its front end through a hopper and carriers it into the furnace. The ash containing a small amount of combustible materials is carried over the rear end of the stoker and deposited in the ash pit. The air required for combustion enters through the air inlets situated below the grate. The secondary air is supplied above the grate. The combination of primary and secondary air produces a high turbulence for complete combustion.

2. Spreader stoker:

In this system, the coal is fed through the feeder. The feeder arrangement has rotating drum with blades. The speed of the feeder can be changed as per the level of the plant. From the feeder, the coal is dropped over the spreader distributor which spreads the coal over the furnace.

The spreader consists of a rapidly rotating shaft carrying blades. These fast rotating blades with the coal particles are coming from the feeder and throw it into the furnace.

Advantages:

1. Variety of coal can be used to burn in this stoker.
2. Cooling of ash is easier because of incoming air is under the ash.
3. Less operating cost.
4. It is very useful for fluctuating loads.

Disadvantages:

1. It is not suitable for large sixe coal
2. It requires dust collecting equipment.

2. Under Feed Stokers

In this type of stokes, the fuel and air move in the same direction. In this type of stokers, the air entering the holes in the grate comes in contract with the raw coal. Then the air is mixed with formed volatile matter and passed through the ignition and then entered into the region of incandescent coke. The reactions takes place in under feed stokers similar to the overfeed stokers.

After the gases coming out of raw fuel bed, it passes through a region of incandescent ash on the surface of the fuel and finally is discharged to the furnace. It is very much suitable for semi-bituminous and bituminous coals having high volatile matter.

Underfeed Stokers Classification

1. Single retort stoker:

In this type, the fuel is placed in large size hopper at the front of the furnace. The coal fed from the hopper goes to the horizontal trough. Through the tuyers the air is supplied for mixing the coal with air.

The ash and clinkers are collected on the ash plate. The feeding capacity of this type is about 100 to 2000kg per hour. To increase the burning capacity, the multi retort stoker is used.

2. Multi retort stoker:

In this, the coal falling from the hopper is pushed forwarded during the inward stroke of stoker arm. Each rotor is filled with a reciprocating ram for feeding and pusher plates for the uniform distribution of coal. The distributing rams (pushers) slowly move the entire coal down the length of stoker. The ash formed is collected at the other end.

The length of stroke of pushers can be varied according to the load. The primary air enters the fuel bed through the wind box which is below the stoker. The partly burnt coal moves on the extension grate. The low pressure air is entered into the extension grate. A thinner fuel bed on the extension requires low-pressure air. So, the air from the main wind box is regulated through dampers.

The numbers of retorts may vary from 2 to 20 and burning capacity of about 300kg to 2000kg per hour per retort.

Advantages of underfeed stokes:

1. Part load efficiency is high.
2. It has high thermal efficiency
3. Self cleaning grates
4. Variety of coals can be used.
5. It is more suitable for variable load conditions
6. Tuyers, grate bars and retorts are hot subjected to high temperature.
7. Smokeless operation.
8. It is more suitable for high volatile and low ash content coals.
9. It can be sued for all refractory furnaces.
10. The fuel bed is free from clinker.

Disadvantages of underfeed stokes:

1. Space requirement is high.
2. Initial cost is high.
3. Troubles due to clinkers.
4. It is not suitable for low-grade feeds.

PULVERISER

Coal is pulverized to increase its surface exposure and complete combustion. This is done by using the pulverizing mills.

The various types of pulverizing mills are

(1) Ball mill
(2) Hammer mill
(3) Ball and race mill
(4) Bowl mill.

1. Ball Mill:

It consists of a large cylinder partly filled with various sized steel balls. Raw coal is supplied to the classifiers and then the coal is moved to the drum by means of a screw conveyor. The coal is pulverized when the drum rotates. This is because of combined between coal and steel balls. Then the hot air is supplied to the drum. The powdered coal is picked up by the air and the mixture of coal and air enters the classifiers. Here, the oversized particles are removed and returned to the drum. The remaining coal air mixture is supplied to the burners.

2. Hammer or Impact mill:

In an impact mill, the pulverization takes place due to impact. The grinding wheel and air fan are mounted in a single shaft. The air supplied through the pulveriser carries the coal to the primary stage of grinding. In this primary stage, the coal is reduced to fine granular stage by the application of impact force using hammers.

The final stage grinding consists of pegs carried on a rotating disk and traveling between stationary pegs. The pulverized coal in the final stage is carried with the air to the burner.

3. Ball and Race mill:

In this type of mill, the coal is passed between the rotating elements again and again. There is two moving surfaces named ball and race is used to crush the coal. The base is held between the upper stationary race and lower rotating race. The traces are driven by worm gear.

The raw coal is supplied in between the races and due to the action of ball against the coal is used to powder the coal. The hot air is supplied in between the ball and races. Then, the air plus coal mixture goes to the classifier. Here, the oversized particles slide down. They are further taken to the burners with air from the top of the classifier.

4. Bowl mill:

In this type of mills, the coal passes between the sides of bowl and the roller. This pulveriser consists of stationary rollers and a power driven bowl in which pulverization takes place. The primary air is from air preheater supplied in between the rollers. The coal and air are mixed and crushed in between the rollers. Then, it goes to the classifier where the coal dust and large size particle are removed. The fine coal powder plus air mixture goes to the burner.

Advantages of using pulverized coal:

1. It has more heating surface area.

2. It requires less percentage of excess air.
3. Low grade fuel can also be used.
4. Free from clinker troubles.
5. High temperature can be produced.
6. High rate of combustion.
7. Preheated air is used to improve the pulverization process.
8. No cooling equipment is required.

PULVERISED COAL FIRING

The pulverized coal firing is done by two systems.

1. Direct system of Unit system
2. Central or Bin system.

1. Direct System:

Working:

The raw coal is fed to the feeder and hot air is passed through the feeder to dry the coal. IT is then transferred to the pulverizing mill, where it is pulverized. The fan is used for supply the primary air to the mill. The air and coal power mixture flow to the burner where secondary air is added.

2. Central System

In this system, the crushed coal from the coal burner is fed to a dryer by gravity force and hot air is passed through the coal to dry it. Then the dry cal is transferred to the pulverising mill.

The supplied air is separated in the cyclone separator. Finally, the primary air is mixed with the coal in the feeder and the mixture supplied to the burner.

3. Pulverised fuel burners:

It is used to burn the pulverized coal. The burner should satisfy the following requirements.

1. Through mixture of coal and air
2. Air delivery in right proportions.
3. Coal air mixture should move away at a rate equal to flame movement.

The fig. 2.35 given below shows the pulverized coal handling plant of unit and central system.

Types of burners:

1. U flame burner
2. Turbulent burner
3. Tangential flow burner
4. Cyclone burner

(i) U Flame burner or Long flame burner:

In this type, the air and coal mixture travel considerable distance and give sufficient time for complete combustion. It discharges the primary air and fuel mixture vertically and heated. Secondary air is introduced at right angles to the flame for better mixing. Tertiary air is supplied around the burner to make an envelope around the primary air and fuel to provide better mixing.

(ii) Turbulent burner or short flame burner:

The flow of air and coal are in turbulent way and the flame enters the furnace horizontally. Due to high turbulence in the burner, the mixture before entering the furnace burns very quickly. This burner gives a high rate of combustion when compared to other types. The bituminous coal is successfully used this burner.

(ii) Tangential burner:

In this system, the burner is fitted at the corner of the furnace. The inclination of the burner will make imaginary circle at the center due to the tangential flame movement. The swirling action produces sufficient turbulence in the furnace to complete the combustion in shorter period and it avoids the necessity of producing high turbulence. When the burners are tilted downwards, the furnace gets filled completely with the flame and the furnace exit gas temperature reduces the furnace absorption is greater.

(iv) Cyclone burner:

It uses crushed coal instead of pulverisied coal. It saves the cost of pulverization. Also the problem of fly ash is reduced and the cyclone burner is a horizontal cylinder of water-cooled construction. The inside part of the cyclone cylinder is lined with chrome ore. The coal with air moves from the front to rear. Secondary air is introduced tangentially to complete the combustion.

The advantages of cyclone burner are

1. The incombustibles are retained in cyclone burner.
2. Rate of combustion is completely controlled.
3. Equipment requirement is simplified.
4. The cyclone furnace gives best results with low grade fuels.
5. The slag recovery performance rate is 82%

UNIT-III

STEAM INJECTORS AND STEAM TURBINES

STEAM NOZZLES

Introduction:

Nozzle is a duct of varying cross-sectional area in which the velocity increases with the corresponding drop in pressure.

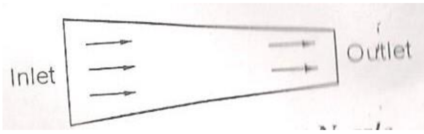
Its main function is to produce a jet of steam with high velocity. For example, nozzles are used in steam turbines, gas turbines, in jet engines, rocket motors, flow measurement and many other applications.

Shapes of nozzles:

Following three types of nozzles are important from the subject point of view:

- ***Convergent Nozzle***

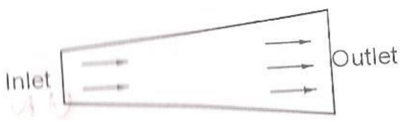
In convergent nozzle, the cross sectional area decreases from the inlet section to the outlet section.



Convergent Nozzle

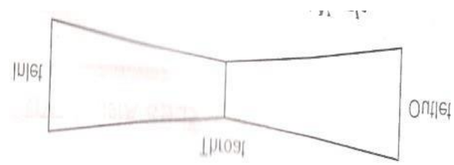
- ***Divergent nozzle***

In divergent nozzle, the cross sectional area increases from the inlet section to the outlet section.



Divergent Nozzle

- ***Convergent – Divergent nozzle***



Convergent divergent Nozzle

When the cross section of a nozzle first decreases form the inlet section to throat and then increases from its throat to outlet section, it is called a *Convergent-divergent nozzle*.

STEAM FLOW THROUGH NOZZLES

The steam flow through the nozzle may be assumed as adiabatic flow. Since no heat is supplied or rejected by the steam during flow through a nozzle and there is no work done during the flow of steam. i.e.,

$$Q = 0 \quad \text{and} \quad W = 0$$

VELOCITY OF STEAM

Steam enters the nozzle with high pressure and low velocity, and leaves with high velocity and low pressure.

The outlet velocity (V_2) of steam can be found as follows.

Consider a unit mass flow of steam through a nozzle.

Let,

V_1 ➔ Velocity of steam at the entrance of nozzle – m/s

V_2 ➔ velocity of steam at any section considered – m/s

h_1 ➔ Enthalpy of steam entering the nozzle – KJ/kg

h_2 ➔ Enthalpy of steam at any section considered – KJ/kg.

For steady flow process:

The steady flow energy equation can be written as,

$$h_1 + \frac{1}{2} m V^2{}_1 = h_2 + \frac{1}{2} m V^2{}_2 + Losses$$

We know that for unit mass flow rate of steam,

m = 1 and Neglecting Losses in Nozzle

So,

$$h_1 + \frac{1}{2} V^2{}_1 = h_2 + \frac{1}{2} V^2{}_2$$

$$h1 + \frac{V^2{}_1}{2000} = h_2 + \frac{V^2{}_2}{2000}$$

$$h_1 - h_2 = \frac{1}{2000}\left[V^2{}_2 - V^2{}_1\right]$$

$$V^2{}_2 - V^2{}_1 + 2000(h_1 - h_2)$$

$$V_2 = \sqrt{V^2{}_1 + 2000(h_1 - h_2)}$$

Inlet velocity V1 is negligible as compared to outlet velocity V_2.So,

$$\boxed{V2 = \sqrt{2000(h_1 - h_2)}} \quad \text{..........................(1)}$$

$$\boxed{V2 = 44.72\sqrt{(h_1 - h_2)}} \quad \text{- - - - - - - - - - - - - - - (2)}$$

MASS OF STEAM DISCHARGED THROUGH NOZZLE

The isentropic process in nozzle may be approximately represented by an equation

Pv^n = Constant

Where

n = 1.135 for saturated steam and

n = 1.3 for superheated steam

let

P_1 ➔ Initial Pressure of steam

v_1➔ Specific volume of steam at entry

P_2 ➔ Pressure of steam at the throat or exit

v_2 ➔ Specific volume of steam at pressure P2

v_1 ➔ Velocity of steam at entry

v_2 ➔ Velocity of steam at exit or throat

As the steam passes through the nozzle its pressure is dropped. So the enthalpy is also reduced. This reduction of enthalpy must be equal to the increase in kinetic energy. Hence the work done by the steam upon itself is equal to the enthalpy drop. We know that for the process Pv^n = Constant, the work done is given by the equation $\frac{n}{n-1}(P_1 v_1 - P_2 v_2)$.

Gain in kinetic energy = Work done during isentropic process

$$\frac{V_2^2}{2} - \frac{V_1^2}{2} = \frac{n}{n-1}(P_1 v_1 - P_2 v_2)$$

Since V_1 is very less as compared to V_2, it can be neglected. So the equation reduces to

$$\frac{V_2^2}{2} = \frac{n}{n-1} P_1 v_1 \left(1 - \frac{P_2 v_2}{P_1 v_1}\right) \quad \text{--------------------- (a)}$$

We know that, for the process Pv^n = Constant

$$P_1 v_1^n = P_2 v_2^n$$

$$\frac{v_2}{v_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} \quad \text{------------ (3)}$$

Substituting $\frac{V_2}{V_1}$ value in Equation (A),

$$\frac{V_2^2}{2} = \frac{n}{n-1} P_1 v_1 \left[1 - \frac{P_2}{P_1} \left(\frac{P_1}{P_2} \right)^{\frac{1}{n}} \right]$$

$$\frac{V_2^2}{2} = \frac{n}{n-1} P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right) \left(\frac{P_2}{P_1} \right)^{-\frac{1}{n}} \right]$$

$$\frac{V_2^2}{2} = \frac{n}{n-1} P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right] \quad \text{--------- (4)}$$

$$V_2 = \sqrt{\frac{2n}{n-1} P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]}$$

We know that,

Mass of steam discharged through nozzle per second

$$m = \frac{Volume of steam flowing per second}{specific volume of steam} \quad \text{---------- (B)}$$

Volume of steam flowing per second

= Area x Velocity of steam

= $A \times V_2$

Specific volume of Steam = v_2

$$m = \frac{A \times V_2}{v_2}$$

Substituting V_2 value of equation (4) in the above equation,

$$m = \frac{A}{v_2} \sqrt{\frac{2n}{n-1} P_1 v_1 \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right]}$$

We know that,

Specific volume, $v_2 = v_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$

Substituting v_2 value in "m" equation

$$m = \frac{A}{v_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}}\sqrt{\frac{2n}{n-1}P_1v_1\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]}$$

$$m = \frac{A}{v_1}\times\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}\times\sqrt{\frac{2n}{n-1}P_1v_1\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]}$$

$$m = \frac{A}{v_1}\times\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}\times\sqrt{\frac{2n}{n-1}P_1v_1\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]}$$

$$m = \frac{A}{v_1}\sqrt{\frac{2n}{n-1}P_1v_1\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1}\sqrt{\frac{2n}{n-1}P_1v_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}}-\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}+\frac{n-1}{n}}\right]}$$

$$= \frac{A}{v_1}\sqrt{\frac{2n}{n-1}P_1v_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{n}}-\left(\frac{P_2}{P_1}\right)^{\frac{n+1}{n}}\right]}$$

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

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

CONDITION FOR MAXIMUM DISCHARGE

We know that the mass of steam discharged through the nozzle.

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

There is only one value of the ratio (called critical pressure ratio)

$\frac{P_2}{P_1}$ which will produce the maximum discharge. This can be obtained by differentiating 'm' with respect to $\left(\frac{P_2}{P_1}\right)$ and equating it to zero. Other quantities except the ratio $\frac{P_2}{P_1}$ are constant.

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

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

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

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

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

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

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

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

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

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

$$\boxed{\frac{P2}{P1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}}$$

Substituting $\frac{P_2}{P_1}$ value in Equation (5),

$$m \max = A \sqrt{\frac{2n}{n-1} \frac{P1}{v1} \left[\left[\frac{2}{n+1}\right]^{\frac{n}{n-1} \times \frac{2}{n}} - \left(\frac{2}{n+1}\right)^{\frac{n}{n-1} \times \frac{n+1}{n}} \right]}$$

$$\boxed{m_{\max} = A\sqrt{\frac{2n}{n-1} \times \frac{P1}{v1} \left[\left[\frac{2}{n+1}\right]^{\frac{2}{n-1}} - \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}} \right]}}$$

Substituting n = 1.135 and n = 1.3 for saturated steam and superheated steam respectively in the above equation, we get

$m_{\max} = 0.6356 A\sqrt{\frac{P_1}{v_1}}$ for saturated steam

$m_{max} = 0.667 A\sqrt{\frac{P_1}{v_1}}$ for superheated steam

When the flow is isentropic $n = \gamma = 1.4,$ substituting this value in the above equation (7), then $m_{max} = 0.685 A\sqrt{\frac{P_1}{v_1}}$

NOZZLE EFFICIENCY (OR) EFFECT OF FRICTION IN A NOZZLE

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

1. Due to the friction between the nozzle surface and steam.
2. Due to the internal fluid friction in the steam
3. Due to shock losses

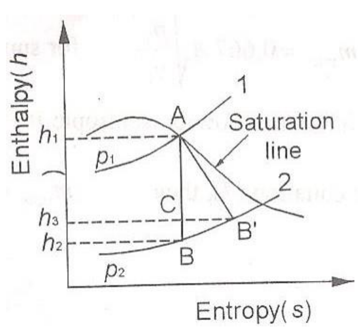
Most of these frictional losses occur between the throat and exit in convergent-divergent nozzle. The effects of these frictional losses are listed below:

1. The expansion is no more isentropic and enthalpy drop is reduced resulting in lower exit velocity.
2. The final dryness fraction of the steam is increased as the part of the kinetic energy gets converted into heat due to friction and is absorbed by steam with increase in enthalpy.
3. The specific volume of steam is increased as the steam becomes drier due to this frictional reheating.

The can be best understood with the help of h-s diagram or mollier chart as shown in fig. 3.4

The point a represents the initial condition of steam. It is a point, where the saturation line meets the initial pressure (P1) line.

If the friction is neglected, the expansion of steam from entry to throat is represented by the vertical line AB. This is done, as the flow through the nozzle is isentropic.



Nozzle efficiency

The enthalpy drop (h_1 - h_2) is known as isentropic enthalpy drop.

Due to friction in the nozzle, the actual enthalpy drop in the steam will be less than (h1 – H2). This enthalpy drop is shown as AC instead of AB. Final condition of steam is obtained by drawing a horizontal line through C to meet the final pressure (P2) line at B. Now, the actual expansion of steam in the nozzle is expressed by the curve AB (adiabatic expansion) instead of AB (Isentropic expansion). So, the actual enthalpy drop is (h_1 – h_3).

Co-efficient of Nozzle or Nozzle efficiency is defined as the ratio of actual enthalpy drop to the isentropic enthalpy drop.

$$\eta = \frac{Actualenthalpydrop}{Isentropicdropenthapy} = \frac{AC}{AB} = \frac{h_1 - h_3}{h_1 - h_2}$$

CRITICAL PRESSURE RATIO

There is only one value of the ratio (P_2/P_1), which produces maximum discharge from the nozzle. This ratio is called critical pressure ratio.

Where

P_1 ➔ Inlet pressure

P_2 ➔ Throat Pressure

(i) For saturated steam n = 1.135
We know that the critical pressure ratio

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

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

Critical pressure ratio, $\boxed{\frac{P_2}{P_1} = 0.577}$

(ii) For super heated steam n = 1.3

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

Critical pressure ratio, $\boxed{\frac{P_2}{P_1} = 0.546}$

(iii) For gases n = 1.4

Critical pressure ratio, $\frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$

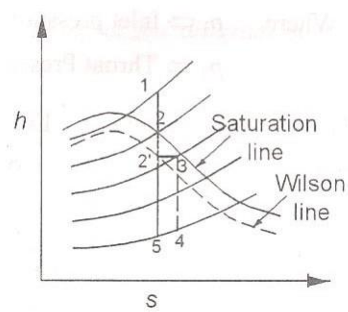
$$\frac{P_2}{P_1} = \left(\frac{2}{1.4+1}\right)^{\frac{1.4}{1.4-1}}$$

$$\frac{P_2}{P_1} = 0.5282$$

$$\boxed{\frac{P_2}{P_1} = 0.5282}$$

SUPERSATURATED FLOW OR METASTABLE FLOW OF STEAM IN A NOZZLE

When the superheated steam expands in the nozzle, the condensation will occur in the nozzle. Since, the steam has more velocity, the condensation will not take place at the expected rate. So, the equilibrium between the liquid and vapour phase is delayed and the steam continues to expand in a dry state.



Super Sataurated flow

The steam in such set of condition is said to be supersaturated or metastable flow. (Fig. 3.5)

The ideal expansion of the super heated steam from pressure P_1 to P_4 can be represented by a line 1-5 on mollier diagram as shown in fig. 3.5. During the expansion, the change of phase must start to occur at pressure P_2 as shown, where the expansion line meets the saturation line (Point2).

But in nozzles, under certain conditions, this phenomenon of condensation does not occur at point 2, as the time available is very short due to high velocity of steam passing through the nozzle.

The equilibrium between the liquid and vapour phase is therefore delayed and the vapour continues to expand in dry state even beyond point (2). This is represented by 2-2 in fig (3.5). The pressure at the point 2 can be found by extending the superheated constant pressure line (p_3) up to 2 as shown in diagram by dotted line. The steam during the expansion of 2-2 remains dry and its conditions are suppressed.

The vapour between the pressures P_2 and P_3 is said to be supersaturated and this type of flow in nozzle is known as supersaturated or metastable flow of steam. A limit to the supersaturated state was observed by Wilson and 2 line drawn on the chart through the observed point is known as Wilson line.

The flow is also called as super cooled flow because at any pressure between P_2 and P_3 the temperature of vapour is always lower than the saturation temperature corresponding to that pressure. The differancein this temperature is known as degree of under-cooling.

STEAM TURBINE

Introduction

Steam turbine is a device which is used to convert kinetic energy of steam into mechanical energy. In this, enthalpy of steam is first converted into kinetic energy in nozzle or blade passages. The high velocity steam impinges on the curved blades and its direction of flow is changed. This causes a change of momentum and thus force developed drives the turbine shaft.

The steam turbine has been used as a prime mover in all steam power plants. Now-a-days, a single steam turbine of 1000MW capacity is built in many countries. In larger sizes, it is used for driving electric generators. In small sizes, it is used to drive pumps, fans, compressors etc.

CLASSIFICATION OF STEAM TURBINES

Steam turbines are classified as follows:

1. On the basis of method of steam expansion

    a. Impulse turbine
    b. Reaction turbine
    c. Combination of impulse and reaction turbine

2. On the basis of number of stages

    a. Single stage turbines
    b. Multi-stage turbines

3. On the basis of steam flow directions

    a. Axial turbine
    b. Radial turbine
    c. Tangential turbine
    d. Mixed flow turbine

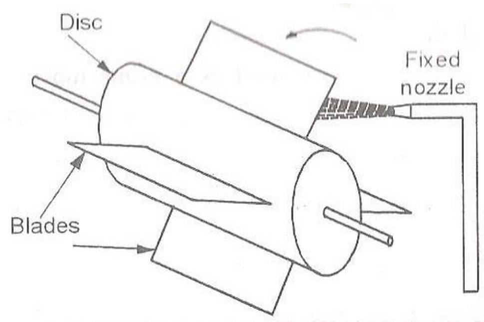
4. On the basis of pressure of steam

    a. High pressure turbine
    b. Low pressure turbine

c. Medium pressure turbine

PRINCIPLE OF OPERATION

1. Impulse turbines.

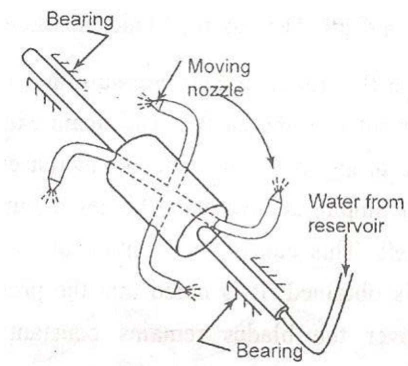


Impulse turbine

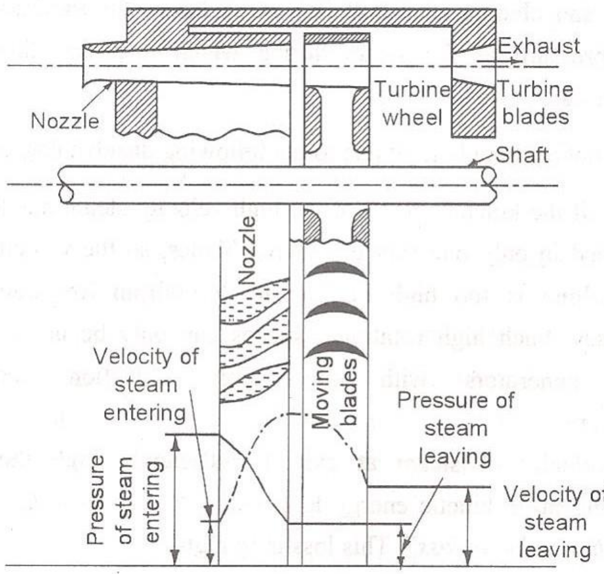
In impulse turbine, the steam at high pressure and temperature with low velocity expands through nozzles where the pressure reduces and velocity increase. This high velocity jet of steam which is obtained from the nozzle impinges on the blades fixed on a rotor. The blades change the direction of the steam flow without changing its pressure. This causes change in momentum and the force developed drives the turbine rotor. Here, the nozzles are stationary and fitted in a casing. The principle of operation of impulse turbine is shown in fig. 3.11. The examples of impulse turbine are De-Laval, Curtis and Rateau turbines.

2. Reaction turbines

In reaction turbines the steam expands both in fixed and moving blades continuously as the steam passes over them. As it expands, there is some increase in steam velocity thereby resulting reaction force. The pressure drop occurs gradually and continuously over both moving and fixed blades. The working principle of a reaction turbine is shown in fig. 3.12. The examples of such turbine are parson's turbine.



SIMPLE IMPULSE TURBINE



Simple Impulse Turbine

Fig. shows an arrangement of a simple impulse turbine. It consists of one set of nozzle followed by one set of moving blades. A rotor is mounted on a shaft. The moving blades are attached to the rotor.

The steam from the boiler at high pressure and low velocity enters the nozzle which is fitted in the casing. The stem expands in the nozzle where the pressure drops to P1 and velocity increases to V1. This high velocity steam jet impinges over the blades mounted on the rotor attached to the shaft. This causes the rotation of the turbine shaft and thus useful work is obtained. It is noted that the pressure of the steam when it moves over the blades remains constant but the velocity decreases.

The upper portion of the fig. 3.13 shows a longitudinal section of the upper half of the turbine. The middle portion shows the development of the nozzles and blading. The bottom portion shows the variation of velocity and pressure of the steam during which it passes through nozzles and blades.

This turbine is not commonly used due to the following disadvantages.

- Since all the kinetic energy of the high velocity steam has to be absorbed in only one ring of moving blades, so the velocity of the turbine is too high i.e., up to 30,000rpm for practical purposes. Such high rotational speeds can only be utilized to drive generators with only large reduction gearing arrangements.
- The velocity of steam at exit is sufficiently high thereby resulting in an kinetic energy loss called “Carry over loss” or “Leading velocity loss”. This loss is so high.

VELOCITY DIAGRAM FOR IMPULSE TURBINE

The velocity of steam relative of the blades, work down on the blades, etc., can be easily found out from the velocity diagrams. Fig. shows the velocity diagram of a single stage impulse turbine.

Let

V_1 ➔ Absolute velocity of steam entering the moving blade

V_{f1} ➔ Velocity of flow at entrance of moving blade

V_{r1} ➔ Relative velocity of jet at entrance of moving blade. It is the vertical difference between Vb and V1.

V_b ➔ Linear velocity of moving blade.

V_{w1} ➔ Velocity of whirl at the entrance of moving blade

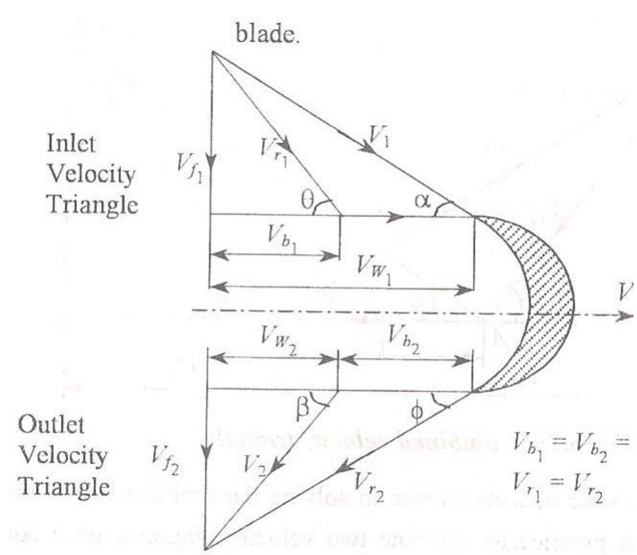
α ➔ Angle with the tangent of the wheel at which the steam with velocity, V1 enters. This is also called nozzle angle.

θ ➔ Entrance angle of moving blade

ϕ ➔ Exit angle of moving blade

β ➔ Angle which the discharging steam makes with the tangent of the wheel at the exit of moving blade.

V_2, V_{f2}, V_{r2}, V_{w2} ➔ the corresponding values at exit of the moving blade.

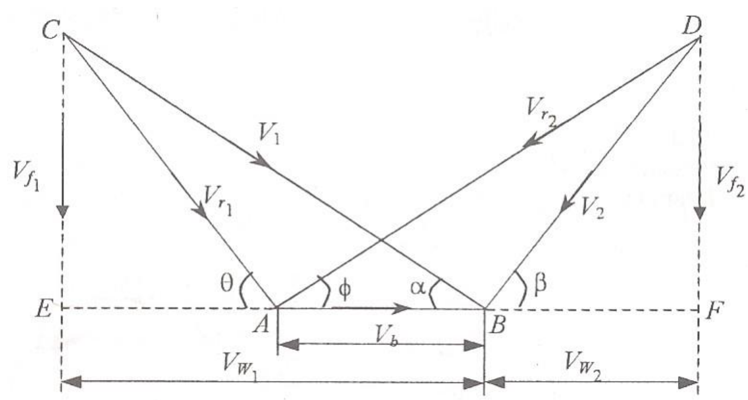


Velocity diagram for simple impulse turbine

The steam jet with absolute velocity V_1 impinges on the moving blade at an angle of α . The tangential component of this jet (V_{w1}) performs work on the blade which is called as velocity of whirl (V_{w1}).

The axial component of velocity (Vf1) of the jet V1 does no work on the blade but causes the steam to flow through the turbine. This component is known as velocity of flow (Vf1). As the blades move with a tangential velocity Vb1, the entering steam jet has a relative velocity V+1 which make an angle ϕ with the tangent of the blades. The absolute velocity (V2) of leaving steam makes and angle β to the tangent at the wheel.

Combined velocity diagram:



Combined velocity triangle

For the sake of convenience in solving the problems on turbines, it is a common practice to combine two velocity diagrams on a common base representing the blade velocity V_b as shown fig. 3.19. Here, the outlet velocity triangle is turned triangle so that the blade velocity line V_b coincides.

When there is no friction, $V_{r1} = V_{r2}$ and $\theta = \phi$ then $V_{f1} = V_{f2}$

WORK DONE ON BLADES OF IMPULSE TURBINE

As stated earlier, the work is done on the blades by the velocity of whirl which produces tangential force on the blades. The velocity of flow is responsible for producing the axial thrust on the wheel.

From Newton's second law of motion,

Tangential force on the wheel = mass of steam x acceleration

= mass of steam/s x change of velocity

Driving force, $F_x = m \times (V_{w1} + V_{w2})$

The value of V_{w2} is actually negative as the steam is discharged in the opposite direction to the blade motion. Therefore, the values of Vw1 and Vw2 are added together while solving problems.

Work done on blades/s = Forced $\times$ Distance traveled

$$= m \times (V_{w1} + V_{w2}) V_b$$

$\therefore$ Power developed per wheel,

$$\boxed{P = m \times (V_{w1} + V_{w2}) V_b}$$

Since available energy of the steam entering the blade,

$$= \frac{mV_1^2}{2}$$

The efficiency of the blade alone or blade efficiency

$$\eta_b = \frac{Workdoneontheblade}{Energy \sup pliedtotheblade}$$

$$= \frac{m(V_{w1} + V_{w2})V_b}{\frac{mV_1^2}{2}}$$

$$\boxed{\eta_b = \frac{2V_b(V_{w1} + V_{w2})}{V_1^2}}$$

This is also known as diagram efficiency.

If h1 and h2 be the total enthalpy before and after expansion through the nozzle, then (h1-h2) is the heat drop in the nozzle ring.

Then Stage efficiency,

$$\eta_b = \frac{Workingbyblade}{Totalenergy \sup pliedperstage}$$

$$\eta_{stage} = \frac{V_b(V_{w1} + V_{w2})}{h_1 - h_2}$$

Stage efficiency can also be given by,

$$\eta_{stage} = \text{blade efficiency} \times \text{nozzle efficiency}$$

If there are no losses, then the stage efficiency shall be the same as blade efficiency.

The axial thrust on the wheel is due to the difference between the velocities of flow at entrance and outlet.

Axial force on wheel = mass of steam × acceleration in axial velocities

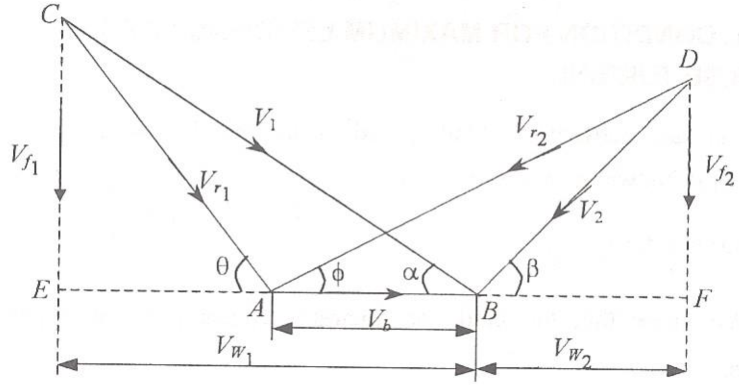
= mass of steam/s × change in axial velocities

Axial thrust, $F_x = m(V_{f1} - V_{f2})$

The axial force must be balanced or must be taken by axial bearings.

EFFECT OF FRICTION ON VELOCITY DIAGRAM

As stated earlier, if the friction is neglected $V_{r1} = V_{r2}$. But in actual practice, there is always some frictional resistance to the flow of steam over blades. The effect of this friction is to reduce the relative velocity of steam as it passes over the blades. The loss in relative velocity is generally taken as 10 to 15%. The ratio of V_{r2} to Vr1 is known as blade velocity coefficient or coefficient of velocity or friction factor (K).



Effect of friction on velocity diagram

Friction factor,

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

Effect of friction on the combined velocity diagram will be to reduce the relative velocity at outlet (V_{r2}).

$$\therefore AC \neq AD$$
$$V_{r2} \neq V_{r1}$$

The value of K varies from 0.75 to 0.85 depending upon the shape of the blade.

In this case, it may be noticed that the effect of blade friction is to reduce V_{w2} which will consequently result in the reduction of work done per kg of steam.

Heat due to blade friction = loss of kinetic energy during flow over blades.

$$\frac{m\left(V_{r1}^{2} - V_{r2}^{2}\right)}{2}$$

CONDITION FOR MAXIMUM EFFICIENCY OF AN IMPULSE TURBINE

The ratio between the blade speed V_b and the absolute velocity of steam V_1 is known as speed ratio (p).

Speed ratio, $p = \frac{V_b}{V_1}$

We know that the blade or diagram efficiency of an impulse turbine,

$$\eta b = \frac{2V_b\left(V_{w1} + V_{w2}\right)}{V_1^{2}}$$

From fig. 3.20, we have

$$Vw1 + Vw2 = EB + BF$$

$$= EA + AB + (AF - AB)$$
$$= EA + AF$$
$$= V_{r1} Cos\theta + V_{r2} Cos\phi$$
$$= V_{r1} Cos\theta \left(1 + \frac{V_{r2}}{V_{r1}} \frac{Cos\phi}{Cos\theta}\right)$$
$$V_{w1} + V_{w2} = V_{r1} Cos\theta (1 + KC) = EA$$

Where, $\frac{V_{r2}}{V_{r1}} = K$ and $\frac{Cos\phi}{Cos\theta} = K$

$$EA = EB - AB = V_1 Cos\alpha - V_b$$

Substituting EA value in equation (i)

$$\eta_b = \frac{2V_b (V_1 Cos\alpha - V_b)(1 + KC)}{V_1^2}$$
$$\eta_b = 2\frac{V_b}{V_1}\left[\left(Cos\alpha - \frac{V_b}{V_1}\right)(1 + KC)\right]$$
$$\eta_b = 2\rho(Cos\alpha - \rho)(1 + KC) \left(\because \rho = \frac{V_b}{V_1}\right)$$

The efficiency will be maximum, when

$\frac{d}{d\rho}(\eta_b) = 0.$ Considering α, K and C as constants.

$$\frac{d}{d\rho}[2\rho(Cos\alpha - \rho)(1 + KC)] = 0; Cos\alpha = 0$$

Or $\rho = \frac{Cos\alpha}{2}$.

$$\eta_{b\max} = 2.\frac{Cos\alpha}{2}\left(Cos\alpha - \frac{Cos\alpha}{2}\right)(1+KC)$$

$$\eta_{b\max} = (1+KC)\frac{Cos^2\alpha}{2}$$

It will be sufficiently accurate to assume that the blades are symmetrical $(\theta = \phi)$ and C = 1 and that there is no friction in the fluid passage (K = 1)

$$\boxed{\eta_{b\max} = Cos^2\alpha}$$

The work down per kg of steam is given by

$$W = (V_{w1} + V_{w2})V_b$$

Substituting the value of $(V_{w1} + V_{w2})$ from equation (ii),

$$W = (V_1 Cos\alpha - V_b)(1+KC)V_b$$

$$\boxed{W = 2V_b\left(V_1 Cos\alpha - V_b\right)} \qquad \text{(If K = 1 C = 1)}$$

The maximum value of work done can be determined by substituting the value of cosα from equation (iii) as,

$$\rho = \frac{Cos\alpha}{2} \implies 2\rho = \frac{2V_b}{V_1}$$

$$Wm_{ax} = 2V_b\left(V_1 \times \frac{2V_b}{V_1} - V_b\right)$$

$$= 2V_b\left(2V_b - V_b\right)$$

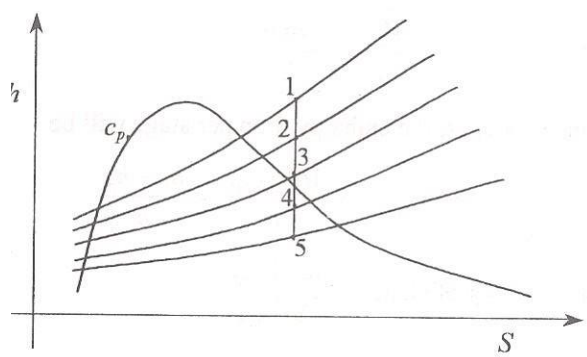
$$\boxed{W_{\max} = 2V_b^{\,2}}$$

From above equation, it is clear that for maximum work to be developed, the blade speed 'V_b' should be half of the absolute velocity V1 of the steam jet for the fixed value of nozzle angle.

VELOCITY DIAGRAMS FOR MULTI STAGE TURBINES

Pressure Compounding

When four simple impulse turbines are connected in series, the total enthalpy drop is divided equally among the stages. So, the pressure drop only occurs in the nozzle whereas there is no pressure drop in blades. Therefore, the corresponding h – s diagram for the four – stage pressure compounding steam turbine is given below:



h-S diagram

Enthalpy drop in each stage will be equal

$$\therefore h_1 - h_2 = h_2 - h_3 = h_3 - h_4 = h_4 - h_5$$

So

$$h_1 - h_2 = \frac{h_1 - h_5}{4}$$

$\therefore$ The velocity of steam at exit from the first row of nozzle is given by

$$V_1 = \sqrt{2000(h_1 - h_2)}$$ Where h1 and h2 in KJ/kg

$$= \sqrt{2000\frac{(h_1 - h_2)}{4}}$$

$$= \frac{1}{2}\sqrt{2000(h_1 - h_5)}$$

But for a single stage turbine, the velocity of steam at exit of the nozzle,

$$V_1 = \sqrt{2000(h_1 - h_5)}$$

From equation 1 and 2, we can infer that the velocity of steam leaving the nozzles in each stage of 4-stage turbine is half of that for a single stage turbine. For 9-stage turbine, it will be one-third.

So, each impulse turbine operating at its maximum blading efficiency is giving by

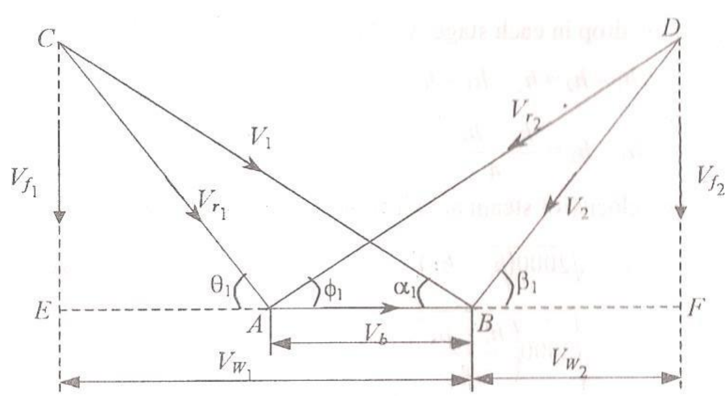
$$\frac{V_b}{V_1} = \frac{\cos\alpha}{2}$$

For n-stages, the enthalpy drop per stage will be

$$(\Delta h)_{stage} = \frac{(\Delta h)_{Total}}{n} = \frac{h_1 - h_n}{n}$$

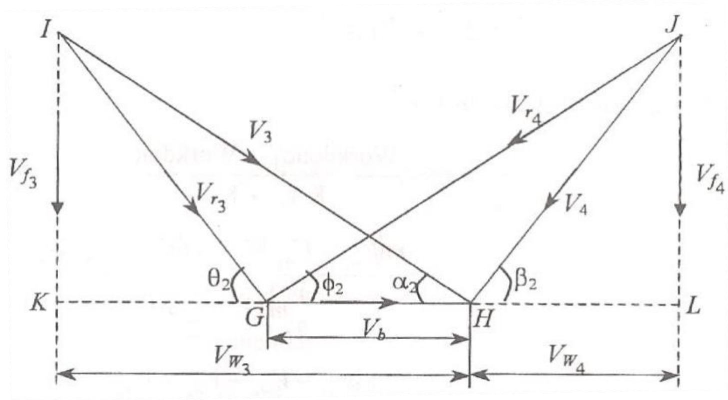
Or number of stages $= \frac{(\Delta h)_{Total}}{(\Delta h)_{State}}$

VELOCITY COMPOUNDING



Velocity diagram for the first row of moving blades

The kinetic energy of steam jets $\left(\frac{1}{2} mV_1^2\right)$ at nozzle exit is partially converted into work in the first row of moving blades with velocity difference from V_1 to V_2. Again kinetic energy $\left(\frac{1}{2} mV_3^2\right)$ of the exiting steam from the first row of moving blades is converted into work in the next row of moving blades and so on.



Velocity diagram for the second row of moving

Already, we know that, $\frac{V_{r2}}{V_{r1}} = K$

From this diagram, work done $_I$ = $m(V_{w1} + V_{w2})V_b$

Axial thrust, $Fy1 = m(V_{f1} - V_{f2})$

Kinetic energy of steam supplied for the first stage,

$$K.E_1 = \frac{1}{2} m V_1^2$$

The same friction factor is considered for the next row of moving blades.

$$\therefore \frac{V3}{V2} = K \text{ and also } \therefore \frac{V_{r4}}{V_{r3}} = K$$

$$Workdone_{II} = m(V_{w3} + V_{w4})V_b$$

Axial thrust, $F_{yII} = m(V_{f3} - V_{f4})$

Kinetic energy of steam supplied for the second stage,

$$K.E_{11} = \frac{1}{2} m V_3^2$$

$\therefore$ Total efficiency of steam turbine,

$$\eta = \frac{Workdone_1 + Workdone_{II}}{K.E_1 + K.E_{II}}$$

$$= \frac{m(V_{w1} + V_{w2})V_b + m(V_{w3} + V_{w4})V_b}{\frac{1}{2}mV_1^2 + \frac{1}{2}mV_3^2}$$

$$\therefore \eta = \frac{2V_b(V_{w1} + V_{w2} + V_{w3} + V_{w4})}{V_1^2 + V_3^2}$$

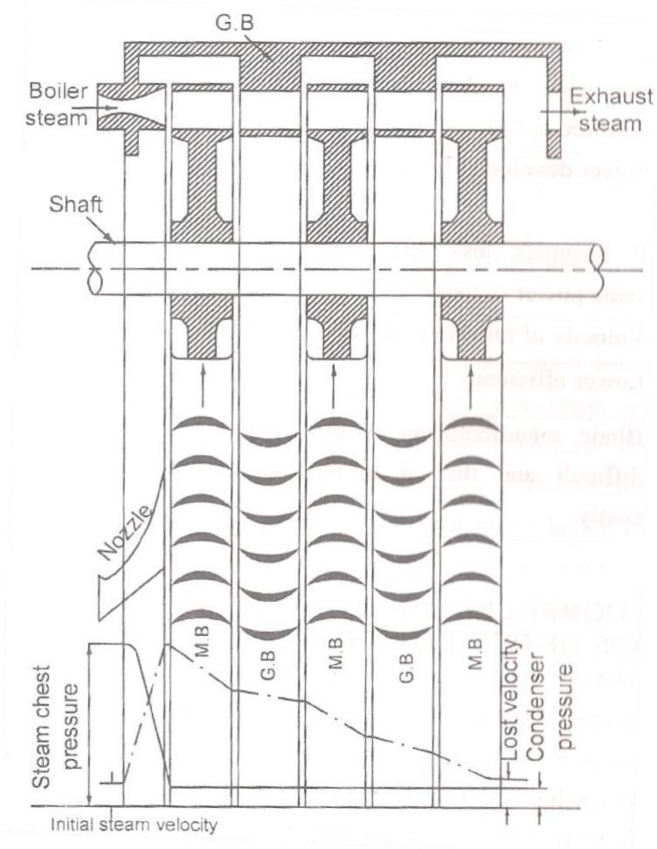
Similarly, total axial thrust, $F_y = F_{y1} + F_{yII}$

COMPOUNDING OF STEAM TURBINES OR METHODS OF REDUCING ROTOR SPEED

As already discussed in the heading "Simple impulse turbine", if the expansion of steam from the boiler pressure to condenser pressure takes place in a single stage turbine, the velocity of steam at the exit of turbine is very high. Hence, there is a considerable loss of kinetic energy (i.e. about 10 to 12%). Also, the speed of the rotor is very high (i.e. up to 30000rpm). There are several methods of absorbing the jet velocity in more than one stage when the steam flows over moving blades. The different methods of compounding are:

1. Velocity compounding
2. Pressure compounding
3. Pressure-velocity compounding

VELOCITY COMPOUNDING



Velocity compound impulse turbine

In this method, there are number of moving blades (M.B), separated by rings of fixed blades (G.B), keyed in series on a common shaft as shown in fig. The stem from the boiler is passed through the row of nozzles from boiler pressure to condenser pressure and attains high velocity.

The high velocity steam jet than passes over the rings of moving blades and fixed blades alternatively. During which, a part of kinetic energy is absorbed in each ring of moving blades. The direction of steam is changed without altering much its velocity in the rings of fixed blades. Thus, all the kinetic energy is utilized in moving blades. Since there is no pressure drop as the steam passes over the moving blades, the turbine is thus of impulse type.

Example of this type of turbine is Curtis turbine

Since the efficiency of this type of turbine is low. A three rows wheel is used for driving small machines. It may be noted that a two rows wheel is more efficient than the three row wheel turbines.

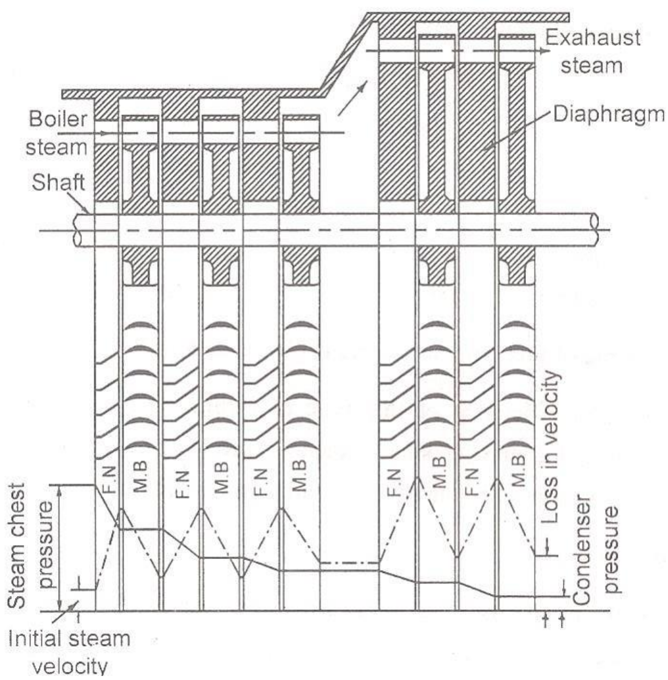
Advantages:

- ❖ Its initial cost is less because of few numbers of stages.
- ❖ Less space is required.
- ❖ The system is reliable and easy to start.
- ❖ There is a need of strong casing due to low pressure.

Disadvantages:

- ❖ Frictional losses are high due to high initial velocity. Hence, the efficiency is low.
- ❖ The ratio of blade velocity to steam velocity is not optimum for all wheels. It also reduces the efficiency.
- ❖ The power developed in later rows is only a fraction of the power developed in the first row. But, the space requirement of all the stages is still the same. This increases the cost and material requirement

PRESSURE COMPOUNDING



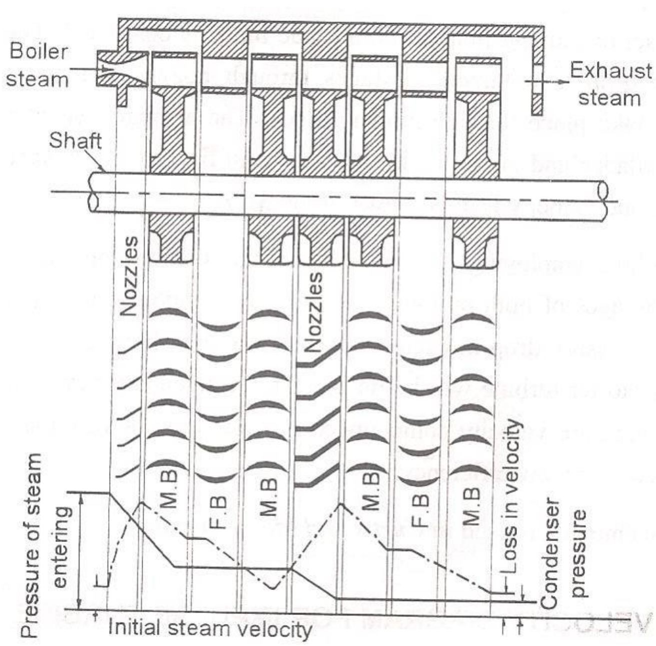
Pressure compound impulse turbine

In this method, a number of simple impulse turbine stages is arranged in series as shown in fig. Each of these simple impulse turbines consists of one set of nozzles (F.N) and one row of moving blades (M.B). The exhaust from each row of moving blades enters the succeeding set of nozzles. The steam from the boiler is passed through the nozzles and moving blades. The steam velocity increases when it passes through nozzles and pressure drops. The steam velocity decreases without much alteration in pressure as it flows over the moving blades. Finally, the pressure falls down to condenser pressure.

Both the variation in pressure and velocity will vary while the steam flows through the fixed nozzle and moving blades are shown in fig. 3.16. The pressure is reduced in each stage of nozzle rings and hence this is called as pressure compounding.

Examples of this type of turbines are Rate au turbine and Zoelly turbine.

PRESSURE – VELOCITY COMPOUNDING



Pressure – velocity compound impulse turbine

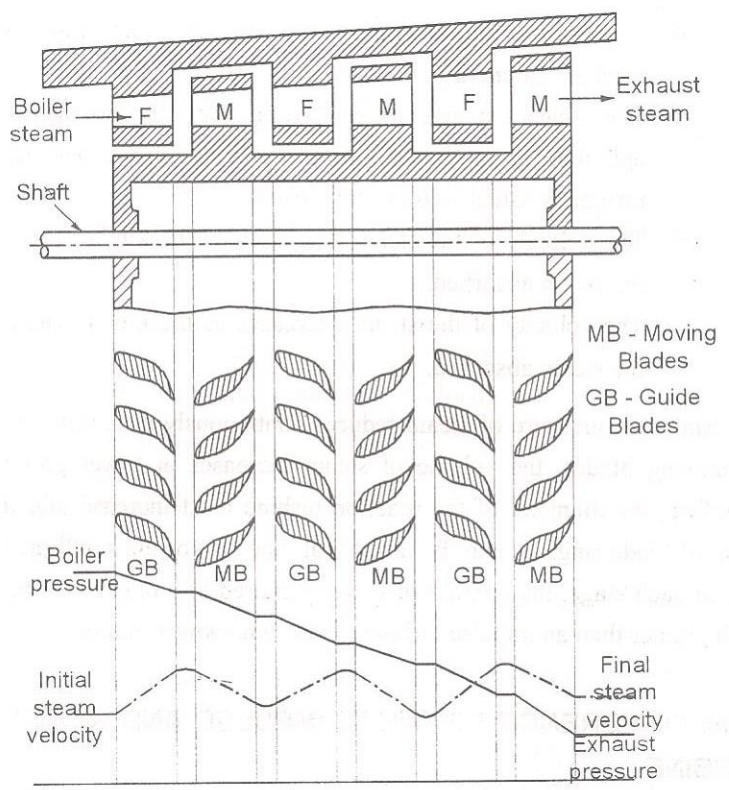
This method is a combination of pressure and velocity compounding. The total pressure drop is carried out in two stages and the velocity obtained in each stage is also compounded. Steam pressure from boiler pressure to condenser pressure is dropped in stages through convergent-divergent nozzles. Velocity compounding is done by using a guide blade rings in between every two moving blade rings.

High-pressure steam expands through first ring nozzles, does work on the first row of moving blades and enters guide blades. Through the guide blades the steam comes out with a changed direction of flow. Then the steam flows through the second row of moving blades where it does work. The remaining reduction of pressure up to condenser pressure takes place in the second set of nozzles and the process of doing work on two set of moving blades and a guide blade is continued. Thus, total pressure drop is obtained in stages through nozzle sets and velocity changes take place through moving blades. The arrangement of nozzles, moving blades and guide blades are shown in fig. The variation in pressure and velocity is also shown in fig.

Turbine employing this method may be said to said to combine many of the advantages of both pressure and velocity compounding. By allowing a larger pressure drop in each stage, less number of stages are used and hence a shorter turbine will be obtained for given pressure drop. Now-a-days, pressure-velocity compounded turbines are not very much in use because of very low efficiency.

This method is used in Curtis and Moore turbine

REACTION TURBINE



Compound reaction turbine diagrams

In reaction turbines, there is no sudden pressure drop. There is a gradual pressure drop and takes place continuously over the fixed and moving blades. A number of wheels are fixed to the rotating shaft. Fixed guide ways are provided in between such pair of rotating wheels as shown in fig.

The function of fixed blades (F) is that they guide the steam as well as allow it to expand in a larger velocity. It is similar to nozzles as in case of impulse turbine.

The moving blades serve the following functions:

- ❖ It converts the kinetic energy of the steam into useful mechanical energy.
- ❖ The steam expands while flowing over the moving blades and thus gives reaction to the moving blades. Hence, the turbine is called as Reaction turbine.
- ❖ The velocity of the steam decreases as the kinetic energy of the steam absorbed.
- ❖ The velocity of the steam decreases as the kinetic energy of the steam absorbed.

Since the pressure of steam reduces continuously as it follows over the moving blades, the diameter of the reaction turbine must increase after each group of blade rings. It may be noted that, because of the small pressure drop in each stage, the number of stages required in a reaction turbine is much greater than an impulse turbine of the same power output.

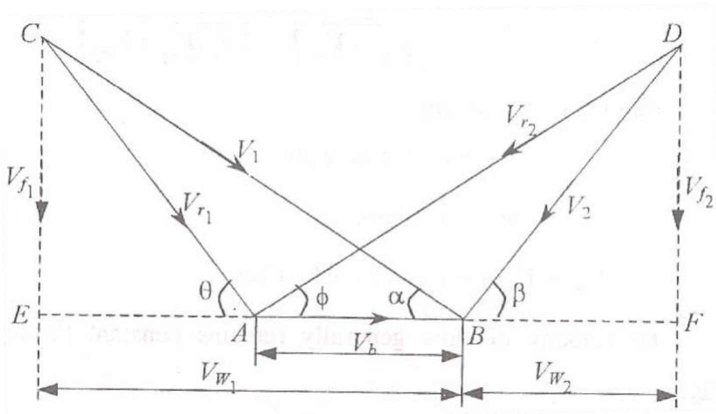
DIFFERENCE BETWEEN IMPULSE AND REACTION TURBINE

S. No.	Impulse Turbine	Reaction turbine
1.	It consists of nozzles and moving blades.	It consists of fixed blades and moving blades.
2.	Pressure drop occurs only in nozzles not in moving blades.	Pressure drop occurs in fixed as well as moving blades.
3.	Steam strikes the blade with kinetic energy.	Steam passes over the moving blades with pressure and kinetic energy.
4.	It has constant blade channels area.	It has varying blade channels area.
5.	Due to more pressure drop per blade, number of stages required is less.	Number of stages required is more due to more pressure drop.
6.	Power developed is less.	Power developed is considerable.
7.	It occupies less space for same power output.	It occupies more space for same power.
8.	Velocity of turbine is more.	Velocity of turbine is less.
9.	Lower efficiency.	Higher efficiency.
10.	Blade manufacturing is not difficult and thus it is not costly.	Blade manufacturing process is difficult.

VELOCITY DIAGRAM FOR REACTION TURBINE

In case of reaction turbines, since the steam expands continuously in both the fixed and moving blades, the relative velocity does not remain constant. It increases due to the expansion of steam i.e., V_{r2} is greater than V_{r1}.

Fig 3. 24. Shown a velocity diagram for the blades of a Parson's reaction turbine. In this turbine, the fixed and moving blades are made identical i.e., $\alpha = \theta = \beta$. Therefore, the velocity diagram for these blades is symmetrical about a vertical center line.



Velocity diagram for reaction turbine

Tangential force, $F_x = m(V_{w1} + V_{w2})V_b$

The work done per kg of steam/s $= mV_b(V_{w1} + V_{w2})$

$\therefore$ Power produced by the turbine, $P = m(V_{w1} + V_{w2})V_b$

Similarly, the axial thrust on the wheel

$$F_x = m(V_{f1} - V_{f2})$$

DEGREE OF REACTION (R)

It may be defined as the ratio of isentropic heat drop in the moving blades to isentropic heat drop in the entire stage of the reaction turbine.

Degree of reaction,

$$R = \frac{Enthalpy drap \text{ int } hemovingblade}{Enthalpy drop \text{ int } hestage} = \frac{h_2 - h_3}{h_1 - h_3}$$

$$R = \frac{Increase\ in\ the\ relative\ K.E.\ in\ the\ moving\ blade}{Stage\ work\ output}$$

$$= \frac{\frac{V_{r2}^2 - V_{r1}^2}{2}}{V_b(V_{w1} + V_{w2})} = \frac{V_{r2}^2 - V_{r1}^2}{2V_b(V_{w1} + V_{w2})}$$

From velocity diagram

$$V_{r2} = V_{f2} Cosec\phi \ and$$

$$V_{r1} = V_{f1} Cosec\theta$$

$$(V_{w1} + V_{w2}) = V_{f1} Cot\theta + V_{f2} Cot\phi$$

The velocity of flow generally remains constant throughout the stage

$$V_{f1} = V_{f1} = V_f$$

$$\therefore V_{w1} + Vw_2 = V_f\ (Cot\theta + Cot\phi)$$

Substituting the values of V_{r1}, V_{r2} and (V_{w1}, V_{w2}) in the equation (x),

$$\therefore R = \frac{V^2{}_f \left(Cosec^2\phi - Cosec^2\theta\right)}{2V_b V_f\left(Cot\theta + Cot\phi\right)}$$

$$= \frac{Vf}{2Vb}\left[\frac{\left(Cot^2\phi + 1\right) - \left(Cot^2\theta + 1\right)}{Cot\theta + Cot\phi}\right]$$

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

$$\boxed{R = \frac{V_f}{2V_b}\left(Cot\phi - Cot\theta\right)}$$

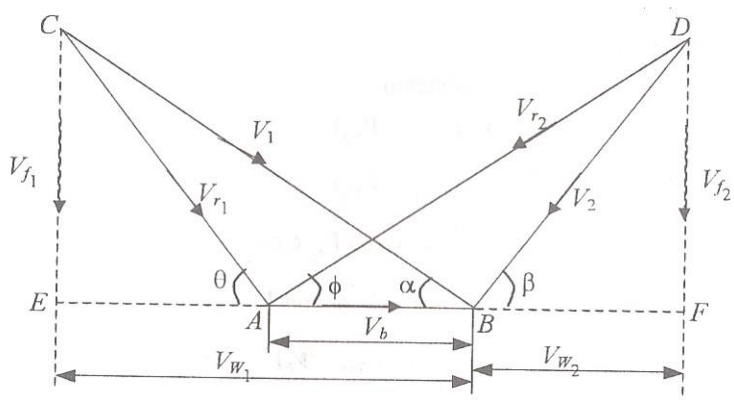
For 50% reaction turbine, R = 50% = ½

$$\frac{1}{2} = \frac{V_f}{2V_b}\left(Cot\phi - Cot\theta\right)$$

$$V_b = V_f\ \left(Cot\phi - Cot\theta\right)$$

Also, if we assume $V_{f1} = V_{f2} = V_f$, V_b can be written as

$$V_b = V_f\left(Cot\phi - Cot\beta\right)$$
$$V_b = V_f\left(Cot\alpha - Cot\theta\right)$$



Velocity diagram for Parson's reaction turbine

From equations (i), (ii) and (iii), we get

$$\theta = \beta and \phi = \alpha$$

Thus for a 50% reaction turbine the moving and fixed blades must have the same shape. This condition gives the symmetrical velocity diagram. This type of turbine is known as "Parson's reaction turbine".

When degree of reaction R = 0, we have simple impulse turbines.

When degree of reaction R = 1, we have pure reaction turbines.

Velocity diagram for the blades of this turbine is given in fig.

CONDITION FOR MAXIMUM EFFICIENCY FOR REACTION TURBINE

The following assumptions are made for deriving condition for maximum efficiency.

- The degree of reaction is 50%
- The moving and fixed blades are symmetrical.
- Velocity of steam leaving from preceding stage is same as velocity of steam at the entrance to the succeeding stage.

We know that,

Work done per kg of steam,

$$W = V_b(V_{w1} + V_{w2})$$
$$W = V_b(V_{w1} + V_{w2})$$
$$= V_b[V_1 Cos\alpha + V_2 Cos\phi - V_b]$$

From assumptions made, $\alpha = \phi$ and $V_{r2} = V_1$

$$\therefore W = V_b(2V_1 Cos\alpha - V_b) \quad \text{or}$$

$$W = V_1^2\left[\frac{2V_b V_1 Cos\alpha}{V_1^2} - \frac{V_b^2}{V_1^2}\right] \qquad \left(\because \rho = \frac{V_b}{V_1}\right)$$
$$W = V_1^2(2\rho Cos\alpha - \rho^2)$$

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

The K.E. supplied to the moving blade $= \frac{V_{r2}^2 - V_{r1}^2}{2}$

Total energy supplied to the stage, $\Delta h = \frac{V_1^2}{2} + \frac{V_{r2}^2 - V_{r1}^2}{2}$

For symmetrical blades, $V_{r2} = V_1$

$$\Delta h = V_1^2 = -\frac{V_{r1}^2}{2}$$

By considering the ΔABC of fig. 3.25,

$$V_{rf2} = V_1^2 + Vb_2 - 2V_f . V_b . Cos\alpha$$

Substituting this value in equation (a),

$$\Delta h = V_1 2 - \frac{V_1^2 + V_b^2 - 2V_1 V_b Cos\alpha}{2}$$
$$= \frac{V_1^2 + 2V_1 V_b Cos\alpha - V_b^2}{2}$$
$$= \frac{V_1^2}{2}\left[1 + \frac{2V_b}{V_1} Cos\alpha - \left(\frac{V_b}{V_1}\right)^2\right]$$
$$\Delta h = \frac{V_1^2}{2}(1 + 2\rho Cos\alpha - \rho^2)$$

The blade efficiency of the reaction turbine is given by

$$\eta_b = \frac{W}{\Delta h} = \frac{V_1^2\left[2\rho Cos\alpha - \rho^2\right]}{\frac{V_1^2}{2}\left[1 \quad 2 \quad Cos \qquad ^2\right.}$$

$$= \frac{2\left(2\rho Cos\alpha - \rho^2\right)}{\left(1 + 2\rho Cos\alpha - \rho^2\right)}$$

$$= \frac{2\left(1 + 2\rho Cos\alpha - \rho^2\right) - 2}{\left(1 + 2\rho Cos\alpha - \rho^2\right)}$$

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

The η_b become maximum when the value of $\left(1 + 2\rho Cos\alpha - \rho^2\right)$ becomes maximum.

The required equation is

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

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

$$\rho = Cos\alpha$$

Substituting ρ value in equation (b), the maximum blade efficiency becomes

$$\eta_{b\,\max} = 2 - \frac{2}{1 + 2Cos^2\alpha - Cos^2\alpha}$$

$$= 2\left(1 - \frac{1}{1 + Cos^2\alpha}\right) = 2\left(\frac{1 + Cos^2\alpha - 1}{1 + Cos^2\alpha}\right)$$

$$\boxed{\eta_{b\,\max} = \frac{2Cos^2\alpha}{1 + Cos^2\alpha}}$$

MASS OF STEAM FLOWING OVER THE BLADES OF A REACTION TURBINE

Let d – drum diameter in m

H – height of blades in m

Then total area available to steam for flow

$$= \pi\left(d + h\right)h = \pi d_m h \qquad \text{in } m^2$$

Where, $d_m = (d + h)$ = mean diameter measured from the centre of the blades.

If V_f is the velocity of flow in m/s

Then quantity of steam flowing/s

$$Q = \pi d_m h V_f \text{ in } m^3$$

If the pressure and dryness fraction of steam at the turbine pair considered are known, the volume of 1kg of steam may be obtained from the steam tables.

Mass of steam flowing per sec, $m = \dfrac{Q}{xv_3} = \dfrac{\pi d_m h V_f}{xV_3}$

GOVERNING OF TURBINES OR SPEED REGULATIONS

The method of maintaining the speed of the turbine is constant irrespective of variation of the load on the turbine known as governing of turbines. The governors regulate the supply of steam to the turbine in such a way that the speed of the turbine is maintained as far as possible a constant under varying load conditions. The principal methods of steam turbine governing are as following:

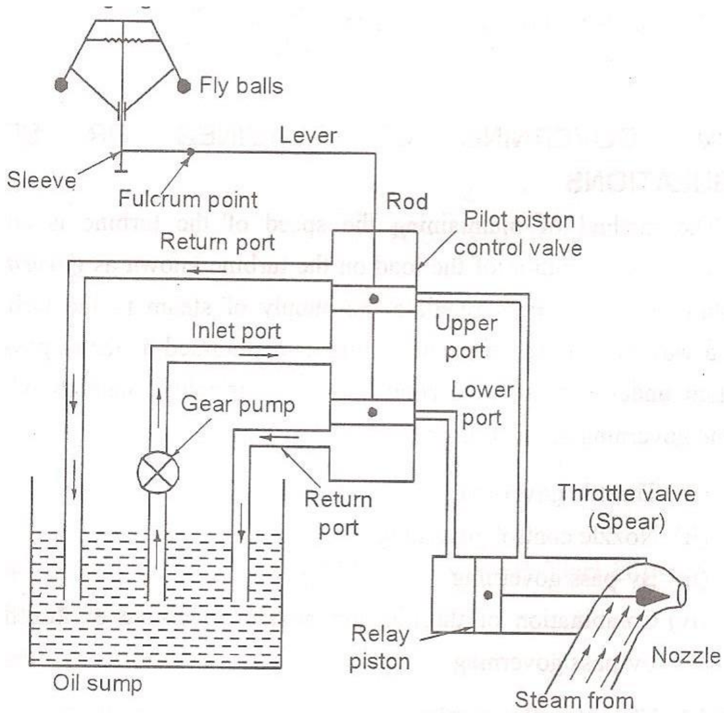
(i) Throttle governing
(ii) Nozzle control governing
(iii) By-pass governing
(iv) Combination of throttle and nozzle governing or throttle and by-pass governing.

THROTTLE GOVERNING

Steam pressure at inlet to a steam turbine is reduced by throttling process to maintain the speed of the turbine constant at part load and hence this method of governing is called "throttle governing".

Construction:

Throttle governing system consists of a centrifugal governor, a lever, an oil pump, a pilot piston, control valve, a relay piston and a throttle valve. Fig. 3.26 shows a simple throttle governing mechanism. The throttle valve is moved by a relay piston. The relay piston is actuated by pilot piston control valve. There are two piston valves covering ports in the pilot piston control valve without any overlap. These piston valves are operated by lubricating oil supplied by a gear pump at 2 to 4bar. The oil returns to the drain from this chamber.



Throttle governing

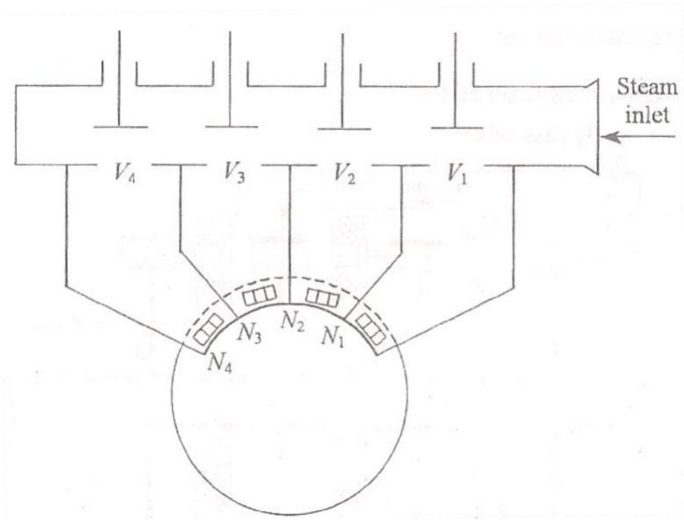
Working:

When the turbine works on full road, the throttle valve will remain open. When the load is decreased, the energy output of the turbine becomes in excess and the turbine shaft speed increases. Hence, the governor sleeve will lift. The upward movement of the sleeve will lower the control valve rod, opening the lower port to oil pressure and upper port to oil return.

The relay piston will move the piston and throttle valve towards the right which will partially close the area of the nozzle. As a result the steam flow rate into the turbine decreases which inturn brings the speed of the turbine to lower range.

Throttle governing is mechanically simple but thermodynamically it is inefficient and therefore, this method is used in small machines.

NOZZLE CONTROL GOVERNING



Nozzle control governing

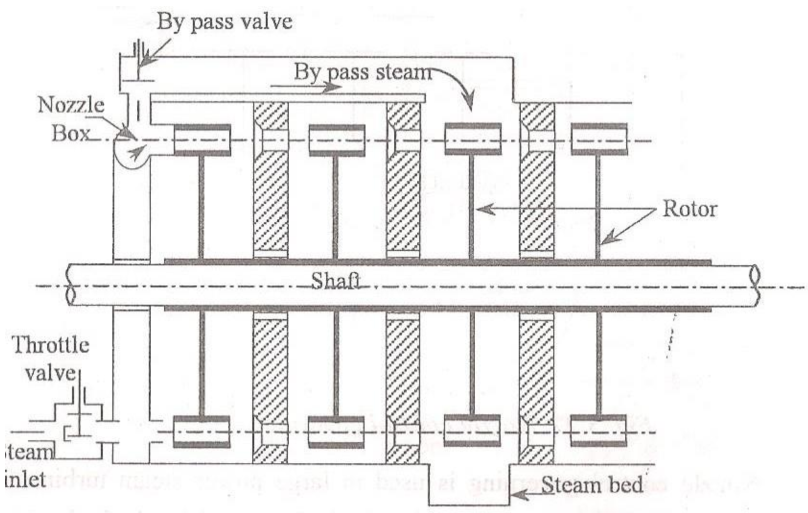
Nozzle control governing is used in large power steam turbines to which very high pressure steam is supplied. In this method, the total number of nozzles of a turbine is grouped in a number of groups varying from two to twelve groups and each group of nozzle is supplied steam controlled by valves. The valves are poppet valves and are opened or closed by automatic devices. Number of groups of nozzle in operation at a particular instant depends upon the load on the steam turbine.

Fig. 3.27 shows nozzle control governing system for high-pressure steam turbine. The nozzles are divided into four groups N1, N2, N3 and N4 and are controlled by control valves V1, V2, V3 and V4 respectively. At full load on the turbine, steam flows through nozzles of all groups. At part load, only the required number of groups of nozzles is operated. The arc of admission is limited to 180˚C or less.

The nozzle control governing is restricted to the first to the first stage of the turbine, the nozzle area in other stages remaining constant. It is suitable for simple impulse turbine.

BY-PASS GOVERNING

This method is adopted in modern high-pressure impulse steam turbines which contain a large number of stages of small mean diameter in high-pressure stages. Such turbines are usually designed for a definite load known as economic load at which the efficiency is maximum. This load is taken as about 80% of the maximum continuous rating. According to the principle of by-pass governing, some extra quantity of steam is by-passed to the far down stages of the turbine when the load exceeds the economic load.



By pass governing

Nozzle control governing is not preferable because of small enthalpy drop in the first stage of a high-pressure turbine. Further, in case of higher loads the extra steam required cannot be admitted through additional nozzles in the first stage due to many practical reasons. Those difficulties are overcome by using by-pass governing.

Fig. 3.28 shows an arrangement of by-pass governing system. Steam through a throttle valve enters the nozzle box or steam chest. The throttle valve is controlled by a speed regulator or governor. In general, upto economic load, the governing of steam turbine speed is done by throttling. For loads greater than the economical load, a bypass line is provide in such a way that steam passes directly from the first stage nozzle box into a latter stage. The by-pass of steam is automatically controlled by the lift of the valve. This valve is controlled by the speed governor for different loads within this range.

By-pass governing is most suitable for reaction turbine and a single by-pass valve.

LOSSES IN STEAM TURBINES

The energy supplied to steam turbine is not fully utilized to transform it into mechanical energy. This is due to various losses occurred in the turbine and energy dissipated away from the turbine. The losses which occur in steam turbines are given below.

- ***Loss in regulating valves***

Steam before entering the turbine passes through the main valve and regulating valves where it gets throttle adiabatically with constant enthalpy. As a result of this, some pressure drop occurs. Thus, some available energy of steam is lost. The pressure drop varies from 3 to 5% of the inlet steam pressure.

- ***Losses due to steam friction***

As stated earlier, friction occurs both in nozzles and blades. In nozzles, the effect of friction is considered by nozzle efficiency. Losses in moving blades are caused by various factors such as impingement losses, frictional losses frictional losses and turning losses. These losses are taken into account by the blade frication coefficient,

$$\left(K = \frac{V_b}{V_1} \right)$$

- ***Losses due to mechanical friction***

This loss occurs in the bearing, gears and governing mechanisms and may be reduced by proper lubrication.

- ***Losses due to leakage***

Leakage of steam can occur between stages and along the shaft at inlet and exit ends of the casing. In impulse turbines, the leakage occurs between the shaft and the stationary diaphragms carrying losses. In reaction turbines, the leakage may occur of the blade tips.

- ***Residual velocity losses***

Steam leaving the last stage of the turbine has a certain velocity which present an amount of kinetic energy that cannot be imported to the turbine shaft and it is thus wasted.

- ***Carry over losses***

Some energy loss takes place as steam flows from one stage to the next. The kinetic energy leaving one stage and available to the next is given by carry over efficiency.

- ***Losses due to wetness of steam***

In multi-stages turbines, condensation of steam may occur in the last stages, since water and stem have different velocities and will not form homogeneous mixture. The water particles will have to be dragged along with steam and in doing so a part of kinetic energy will be lost.

- ***Losses due to radiation***

As the turbines are heavily insulated, this loss is negligibly small.

UNIT-IV

GAS TURBINE PLANT CYCLE

AND

NUCLEAR POWER PLANT

GAS TURBINE POWER PLANT

A gas turbine is similar to the steam turbine but hot gas is used to run the turbine. It is mainly used in the aircraft engines, electric power generation, marine propulsion etc. In this chapter, the various types of gas turbines and its cycles will be considered in detail. The practical limitations and modifications of the ideal cycle will be discussed.

Classification of Gas Turbines

1. According to the cycle of operation
    a. Open cycle gas turbines
    b. Closed cycle gas turbines, and
    c. Semi closed cycle gas turbines

2. According to the process
    a. Constant pressure gas turbines, and
    b. Constant volume gas turbines

3. According to the use
    a. Industrial gas turbines, and
    b. Air craft gas turbines

4. According to the type of load
    a. Peak load
    b. Stand by
    c. Base load

5. According to the application
    a. Aircraft
    b. Marine
    c. Locomotive
    d. Transport

6. According to the type of fuel
    a. Liquid
    b. Gas
    c. Solid

7. According to the number of shafts
    a. Single shaft
    b. Multi-shaft

Application of Gas Turbine Power Plant

Gas turbine power plants are mainly used as peak load power plants, emergency stand-by unit or hydro-station stand-by unit and base load plant under specific conditions. It has relatively low installation cost per kW installed capacity commended attention throughout the world as excellent source of peaking or emergency power. The quick starting and good response characteristics of the gas turbine plant make the gas turbine as desirable peak load and essential stand-by plant. The gas turbine can be used as base load plant where the gas turbine fuel is relatively cheap.

The gas turbine power plant now-a-days is universally used as peak load, base load as well as stand-by power plant due to outstanding operational characteristics.

Fuels for Gas Turbine Plant

The advantages of increased gas turbine combustion temperatures i.e. increased efficiency, power and reduced fuel consumption are partially negated by increasing cost of fuels normally used by gas turbines.

Residual liquid fuels, the residue left after the profitable light fractions have been extracted from the crude, have been used in gas turbines to some extend. The following properties are identified for residual liquid fuels

(i) Viscous in nature
(ii) Tend to polymerise when overloaded
(iii) Their high carbon content leads to excessive carbon deposits in the combustion chamber
(iv) The contents of alkali metals, such as sodium, combine with sulphur to form sulphates that are corrosive
(v) They have other metals like vanadium with compounds that form during combustion also being corrosive
(vi) They have a relatively high ash content that deposits mostly on the fixed blades, that reducing gas flow and power output.

The rate of corrosion increase with increasing gas temperature. Early turbines designed for residual fuel use operated as temperature below 900K to avoid the problem. Ash deposition is not a problem with intermittent operation because of successive expansions and contractions, but it is a series problem with steady operation.

The ideal fuel for the gas turbine units is natural gas from the view point of efficient energy conversion operation and pollution control. The fuel being clean would not foul the gas turbine blades and as such, the availability of the unit would be highest. It is always advisable to use a gas turbine unit designed for multi-fuels (Gaseous as well liquid fuels such as LPG, Kerosene, landfill gas, or oil). This would be useful for operation of power station in case of non-availability one type of fuel due to some reasons.

The light distillates, such as light diesel oil, high speed diesel, naptha etc., would be the next preferred gas turbine fuels. These fuels can be used without treatment, if the contaminates are minimal. The gas turbine can also use heavy residual fuel oils as furnace oil and low sulphur heavy stock. The furnace oil has a viscosity of about 170 mm^2/sec at 50°C with maximum sulphur content of 4.5% whereas low sulphur heavy stock is waxy in nature and has a viscosity of about 500 mm^2/sec at 50°C with maximum sulphur content of 1.5% and its has a pour point of 72°C. The low sulphur heavy stock has higher calorific value about 3.5% more compared to furnace oil. Also it is cheaper by about 15% and has lower asphaltenses, ash and carbon residue. Both the furnace oil and low sulphur heavy stock could be used in the gas turbine, if pretreated properly to reduce contaminants within the acceptable limits.

Gas Turbine Material

The gas turbines are to be operated at high turbine inlet temperatures to achieve higher efficiencies and outputs. This also means higher pressure rations because optimum pressure increase with increasing turbine inlet temperatures for both efficiency and power.. The components that suffer most from a combination of high temperature; high stresses and chemical attack are those of the turbine first-stage fixed blades i.e, nozzles and moving blades. They must be weldable and castable and must resist corrosion, oxidation, and thermal fatigue. Heat resistance materials and precision casting are two recent advances, largely attributed to aircraft engine developments. Cobalt-based alloys have been used for the first stage fixed blades which are subjected to the highest temperatures (but not the high stress) moving blades. These alloys are now being supplemented by vacuum-cast-nickel based alloys that are strengthened through solution and precipitation-hardened heat treatment. For the moving blades, cobalt-based alloys with high chromium content are now used.

Ceramic materials are also being developed, especially for the turbine inlet fixed blades. Developmental problems here are inherent brittleness which causes fabrication problems are raises uncertainties about the mechanical properties of ceramic materials.

Advantages of Combined Cycles

1. The efficiency of the combined cycle plant is better than simple gas turbine cycle.
2. The capital cost of combined plant per kW output with supplementary firing is slightly higher than a simple gas turbine plant.
3. The combined plant is more suitable for rapid start and shutdown.
4. The cooling water requirement of a combined cycle is much lower than a pure steam plant having same output.
5. The combined system offers self-sustaining feature. If power station is down due to some fault, the gas turbine offers to start the station from cold condition. No outside power source is required.
6. It gives high ratio of power output to occupy ground space.
7. The environmental standards of many old fossil fuel plants are not acceptable and they are likely to be closed. These can be renovated by replacing the old boiler with a gas turbine unit and heat recovery boiler.
8. It provides more flexibility of operation due to multiple units.
9. Low operation manpower.
10. Less down time for maintenance.
11. Combined cycle power plant minimizes visual impact on the environment.

MAIN COMPONENTS OF GAS TURBINE

A gas turbine unit consists of the following essential parts:

1. **Compressor:**

   The air compressor used in gas turbines is of rotary type mainly axial flow turbines. It draws air from the atmosphere and compressed to the required pressure. This compressed air is then transferred to the combustion chamber.

2. **Combustion chamber:**

The compressed air from the air compressor is drawn to combustion chamber. The fuel is injected to the air and then ignited in the combustion chamber. It increases the pressure and temperature of the air instantaneously.

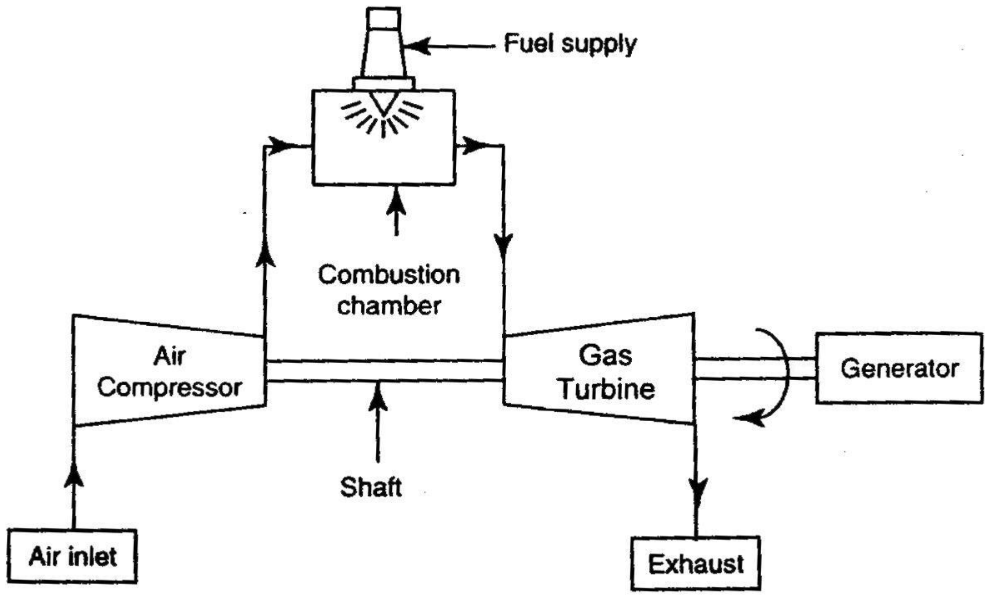
3. **Turbine:**

The high pressure and temperature air is expanded in the turbine. Turbine is also of rotary type. During the expansion, the heat energy in the gas is converted into mechanical energy. This mechanical energy is gain converted into electrical energy by using generator.

Working of Open Cycle Gas Turbine

The most basic gas turbine unit is one operating on the open cycle in which a rotary compressor and a turbine are mounted on a common shaft as shown in fig. 4.19.

Air is drawn from the atmosphere into the compressor and compressed to pressure of 300 to 400kN/m^2. The compressed air is then entered into the combustion chamber where the energy is supplied by spraying fuel into the air and ignited by hot gases. The hot gases expand through the turbine to produce the mechanical power. Then the burned gases are exhausted to the atmosphere. Then fresh air is drawn into the compressor for the next cycle. The process is repeated again and again. Here, the compressor is driven by turbine itself. In order to achieve the network

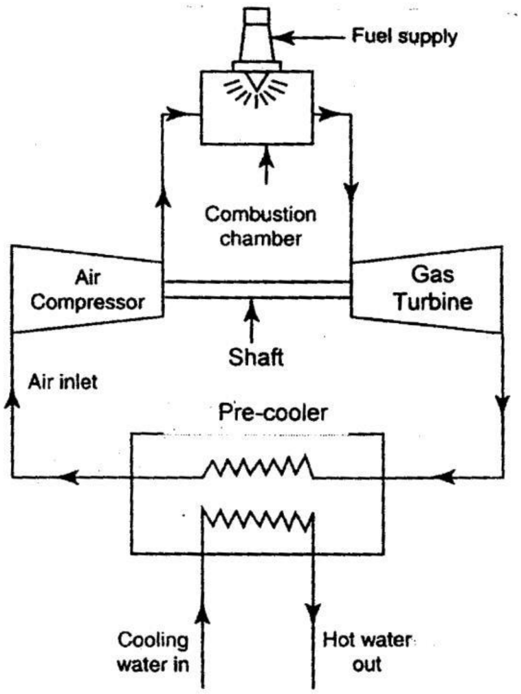


output from the unit, the turbine must develop more gross work output than the work required to drive the compressor and to overcome mechanical losses in the drive.

Working of Closed Cycle Gas Turbine

It consists of compressor, combustion chamber, gas turbine and pre cooler. The schematic diagram of a closed cycle gas turbine plant is shown in fig. 4.20.

In a closed cycle gas turbine, the air is compressed in air compressor isentropically to a required pressure and then passed through a combustion chamber where fuel injects to the air and ignited. The high temperature air from combustion chamber expands through a gas turbine where the heat energy is converted into mechanical energy. Then the exhaust gas from the gas turbine is passed through a pre-cooler where it is cooled at constant pressure with the help of circulating water to its original pressure. Then the same air is passed through the compressor again and again.



It is thus obvious, in a closed cycle gas turbine, the same air is continuously circulated repeatedly throughout the system.

Comparison of Open and Closed Cycle Gas Turbines

Sl. No	Open cycle gas turbine	Closed cycle gas turbine
	Advantages	Disadvantages
1.	No pre-cooler is required because of burned gas from gas turbine exhausted to atmosphere.	Separate pre-cooler arrangement is necessary.
2.	For the same power developed, the size and weight of the open cycle gas turbine unit are less.	The size and weight are more.
3.	Initial cost and maintenance cost of the plant are less	Initial cost and maintenance cost are more.
4.	Combustion efficiency is more.	Combustion efficiency is less.
5.	Coolant is not required, therefore, it is used for moving vehicle such as air craft, jet propulsion etc.	Coolant is required for pre-cooler, therefore, it is used for stationary applications such as power generation etc.
6.	The response to load variation is greater than closed cycle gas turbine.	The response to load variation is less.
Sl. No	Open cycle gas turbine	Closed cycle gas turbine
	Advantages	Disadvantages

1.	Part load efficiency decreases rapidly as the considerable % age of power developed by the turbine is used to drive the compressor	Efficiency is same throughout the cycle.
2.	Turbine blades are fouled by the combustion products.	The turbine blades do not wear away, since the combustion is external.
3.	Starting of the plant is difficult	Starting of the plant is easy.
4.	As direct heating is used in open cycle plant, high quality fuels are required.	Low quantity fuels can be used since the combustion is external.
5.	Thermal stresses are high.	Thermal stresses are low.
6.	Frequent internal cleaning of the system is necessary.	No need for internal cleaning.

Brayton Cycle or Joule Cycle

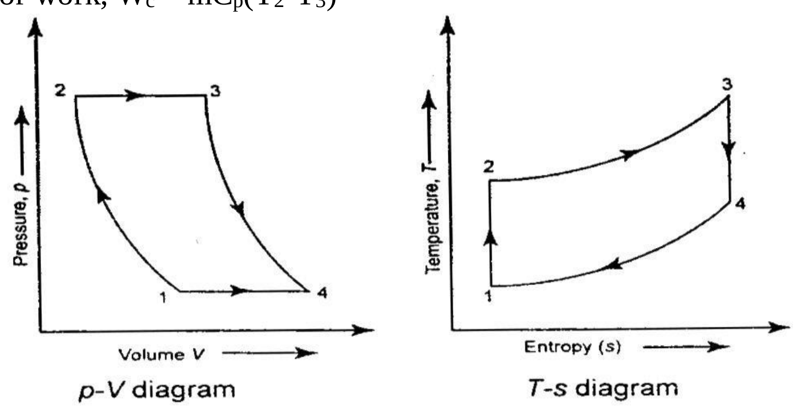
The Brayton cycle is the theoretical cycle for gas turbines. It consists of two reversible adiabatic processes and two constant pressure processes. This cycle is, therefore, also called *constant pressure cycle*.

The p-V and T-s diagram for this cycle is shown in fig..

Process 1-2:

The air is compressed in the compressor isentropically from p_1 to p_2. During this process, the pressure increases from p_1 to p_2 and temperature increases from T_1 to T_2. But, the volume reduces from V_1 to V_2.

Compressor work, $W_c = mC_p(T_2\text{-}T_3)$



Process 2-3:

The compressed air is passed through combustion chamber where fuel injected and burned at constant pressure p_2 and temperature increases from $T_2$to T_3.

Heat added, Qs = m x $C_p(T_3\text{-}T_2`)$

Process 3-4:

The air is then returned to its original position after passing through cooler where it cools at constant pressure process.

Turbine work, $W_T = mC_p(T_3-T_4)$

Process 4-1:

The air is then returned to its original position after passing through cooler where it cools at constant pressure process.

Heat rejected, $Q_R = mxC_p(T_4-T_1)$

$$Efficiency,\ \eta_{Brayton} = \frac{W}{Qs} = \frac{Qs - QR}{Qs}$$

$$= \frac{mCp(T3-T2) - mCp(T4-T1)}{mCp(T3-T2)}$$

$$= 1 - \frac{(T4-T1)}{(T3-T2)}$$

The efficiency equation can be simplified in terms of compression ratio (r) and pressure ratio (Rp)

Compression ratio, $r = \frac{V1}{V2} = \frac{V4}{V3}$ or $r = \frac{v1}{v2} = \frac{v4}{v3}$

Pressure ratio, $R_P = \frac{P_2}{P_1} = \frac{P_3}{P_4}$

Consider process 1 -2 : isentropic compression

$$\frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = (r)^{\gamma-1}$$

$$T_2 = T_1 (r)^{\gamma-1}$$

Also,

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

$$T_2 = T_1 . (R_p)^{\frac{\gamma-1}{\gamma}}$$

Consider process 3- 4 : isentropic expansion

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = (r)^{\gamma-1}$$

$$T_3 = T_4 (r)^{\gamma-1}$$

Also,

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_3 = T_4 (R_p)^{\frac{\gamma-1}{\gamma}}$$

Substituting T2 and T3 values in efficiency equation.

$\eta_{Brayton}$ in terms of pressure ratio

$$\eta = 1 - \frac{T_4 - T_1}{T_4 (R_p)^{\frac{\gamma-1}{\gamma}} - T_1 (R_p)^{\frac{\gamma-1}{\gamma}}}$$

$$\boxed{\eta_{Brayton} = 1 - \frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}}}}$$

$\eta_{Brayton}$ in terms of compression ratio

$$\eta_{Brayton} = 1 - \frac{T_4 - T_1}{T_4 (r)^{\gamma-1} - T_1 (r)^{\gamma-1}}$$

$$= 1 - \frac{T_4 - T_1}{(r)^{\gamma-1} (T_4 - T_1)}$$

$$\boxed{\eta_{Brayton} = 1 - \frac{1}{(r)^{\gamma-1}}}$$

For the same compression ratio, efficiency of brayton cycle is equal to Otto Cycle efficiency.

Work Ratio:

The term work ratio is useful parameter for power plants cycles. It is defined as the ratio of network transfer in a cycle to the positive work transfer or turbine work in the cycle.

$$\text{Work ratio} = \frac{\text{Net work transfer}}{\text{Positive work transfer}}$$

$$= \frac{mC_p (T_3 - T_4) - mC_p (T_2 - T_1)}{mC_p (T_3 - T_4)} = 1 - \frac{T_2 - T_1}{T_3 - T_4}$$

$$= 1 - \frac{T_1 (R_p)^{\frac{\gamma-1}{\gamma}} - T_1}{T_3 - \frac{T_3}{(R_p)^{\frac{\gamma-1}{\gamma}}}} = 1 - \frac{T_1 \left[(R_p)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{T_3 \left[1 - \frac{1}{(R_p)^{\frac{\gamma-1}{\gamma}}} \right]}$$

$$\boxed{\text{Work ratio} = \frac{T_1}{T_3} (R_p)^{\frac{\gamma-1}{\gamma}}}$$

It can be seen from the above equation that the work ratio depends not only on the pressure ratio but also on the ratio of the minimum and maximum temperature. For a given inlet temperature, T_1, the maximum temperature, T_3 must be made as high as possible for getting high work ratio,

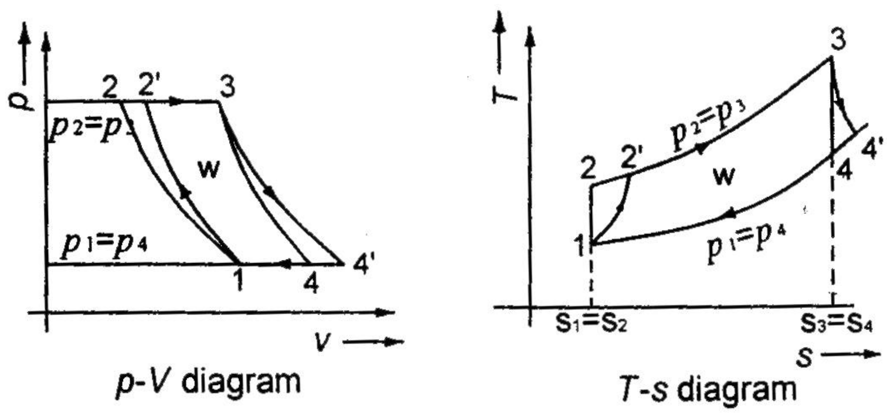
$$\eta_{Brayton} = 1 - \frac{T_4 - T_1}{T_4 (r)^{\gamma-1} - T_1 (r)^{\gamma-1}}$$

$$= 1 - \frac{T_4 - T_1}{(r)^{\gamma-1} (T_4 - T_1)}$$

$$\boxed{\eta_{Brayton} = 1 - \frac{1}{(r)^{\gamma-1}}}$$

For the same compression ratio, efficiency of brayton cycle is equal to Otto Cycle efficiency.

ACTUAL BRAYTON CYCLE



In Ideal cycle, compression and expansion process are reversible adiabatic. But in actual practice, it is not possible to achieve reversible process because of friction and unaccounted heat loses in turbine and compressor. Therefore, an actual gas turbine plant differs from the ideal one. The actual *p* – V and *T* – *s* diagram is shown in fig4.22.

In the above diagram, the ideal process is represented by 1-2-3-4 lines, and the actual process is represented by 11-2`-3-4` lines.

Work required by compressor, Wc = m x Cp (T_2` - T_1).

Work done by the turbine, W_γ = m x Cp ($T_3 – T_4$`)

Net work available,

$W = W_\gamma – Wc$

= ($T_3 – T_4$`) - ($T_2$` - T_1)

Net heat supplied, Qs = m x C_p(T_3-T_2`)

Isentropic efficiency of the compressor, $\eta_c = \dfrac{T_2 - T_1}{T_2` - T_1}$

Isentropic efficiency of the turbine, $\eta_\gamma = \dfrac{T_3 - T_4}{T_3 - T_4`}$

The net output of the cycle is reduced by the amount [(h_4` - $h_4$) + ($h_2$` - h_2)], and the heat supplied is reduced by the amount (h_2` - h_2). Therefore, the efficiency of the cycle is less than that of the ideal cycle.

Thermal efficiency for actual cycle,

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

Qptimum pressure ratio of the Brayton cycle (Rp) $_{opt}$ **:**

The pressure ratio at which the work capacity is maximum known as optimum pressure ratio, *(Rp)* $_{opt}$. When $T_2 = \sqrt{T_1 \, x \, T_3}$ we can obtain the optimum pressure ratio of the cycle.

We know that, $\left(\frac{p_2}{p_1}\right) = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$

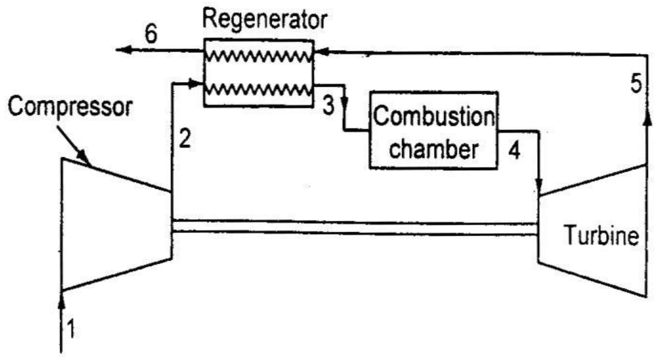
$$(R_p)_{opt} = \left[\frac{(T_1 \times T_3)^{\frac{1}{2}}}{T_1}\right]^{\frac{\gamma}{\gamma-1}}$$

$$\boxed{(R_p)_{opt} = \left[\frac{T_3}{T_1}\right]^{\frac{1}{2} \times \frac{\gamma}{\gamma-1}}}$$

The optimum pressure can also be obtained by differentiating network output with respect output with respect to the pressure ratio and putting the derivative equal to zero.

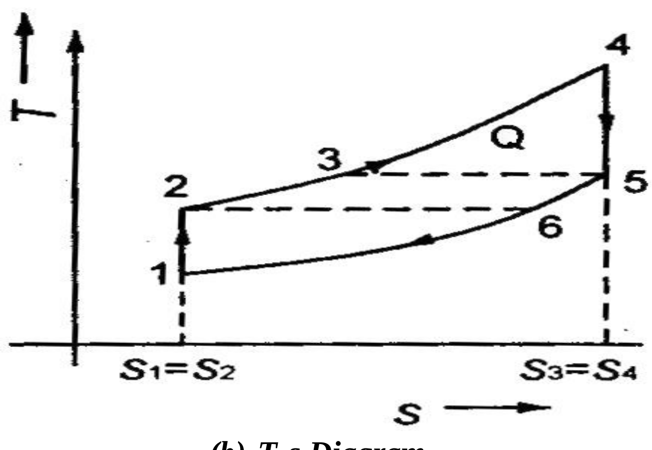
BRAYTON CYCLE WITH REGENERATION

The temperature of the exhaust gases of the turbine is higher than the temperature of the air after compression. If the heat energy is used to heat the air after compression in the heat exchanger called *"regeneration"*. It will reduce the energy requirement from the fuel thereby increasing the efficiency of the cycle. Fig (a) shows the single stage regenerative gas turbine cycle and fig (b) is the corresponding cycle represented on T-s diagram.



(a) Brayton cycle with regenerator

Air is drawn from the atmosphere into the compressor and is compressed isentropically to state 2. It is then heated at constant pressure in the regenerator to state3 by the exhaust gases from the turbine. Since the temperature of the air is increased before it reaches the combustion chamber, less amount of fuel will be required to attain designed turbine inlet temperature of the products of combustion.



(b) T-s Diagram

After combustion at constant pressure in the combustion chamber, the gas enters the turbine at state 4 and expands to 5. If then enters the regenerator as stated earlier, where it gives up a portion of its heat energy to the compressed air from the compressor and leaves the regenerator at state 6.

In an ideal regenerative cycle, the temperature of the air leaving the regenerator to combustion chamber is equal to the temperature of exhaust gases leaving the turbine. i.e., $T_3 = T_5$.

But in actual cycle, the temperature of the air leaving the regenerator is less than T_5. i.e., $T_3 < T_5$. The effectiveness of the regenerator is given by the ratio of the actual temperature rise to the maximum possible rise.

Effectiveness, $\epsilon = \frac{T_3 - T_2}{T_5 - T_6} = \frac{T_3 - T_2}{T_5 - T_2}$

For regenerative cycle, for unit mass flow rate

Head supplied, $Q_S = C_p (T_4 - T_3)$

(For process 2-3, heat is supplied by regenerator)

Head rejected, $Q_R = C_p (T_6 - T_1)$

(For process 5-6, heat is rejected by regenerator)

Turbine work, $W_\gamma = C_p (T_4 - T_5)$

Compressor work, $W_c = C_p (T_2 - T_1)$

Efficiency, $\eta = 1 - \frac{Q_R}{Q_S} = 1 - \frac{T_6 - 1}{T_4 - T_3}$

For ideal cycle $T_3 = T_5$, $T_6 = T_2$

$$\because \eta = 1 - \frac{T_2 - T_1}{T_4 - T_5} = 1 - \frac{T_1\left(\frac{T_2}{T_1} - 1\right)}{T_4\left(1 - \frac{T_5}{T_4}\right)}$$

We know that, $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$ and

$$\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} \qquad \left(\begin{matrix} \therefore p_5 = p_1 \\ p_4 = p_3 = p_2 \end{matrix}\right)$$

$$\eta = 1 - \frac{T_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{T_4\left[1 - \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$= 1 - \frac{T_1}{T_4}\frac{\left(p_2^{\frac{\gamma-1}{\gamma}} - p_1^{\frac{\gamma-1}{\gamma}}\right) \Big/ p_1^{\frac{\gamma-1}{\gamma}}}{\left(p_2^{\frac{\gamma-1}{\gamma}} - p_1^{\frac{\gamma-1}{\gamma}}\right) \Big/ p_2^{\frac{\gamma-1}{\gamma}}}$$

Efficiency of the regenerative Brayton cycle,

$$\eta = 1 - \frac{T_1}{T_4}\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\boxed{\eta = 1 - \frac{T_1}{T_4}\left(R_p\right)^{\frac{\gamma-1}{\gamma}}}$$

From the above formula, it is obvious that efficiency of the regenerative Brayton Cycle depends not only on the pressure ratio but also on the ratio of the two extreme temperatures.

Brayton Cycle With Reheater

As stated earlier, the work output can be increased by multistage expansion with reheating between the stages. Fig.4.25 (a) shows the ideal Brayton cycle with reheating and Fig. 4.25 (b) shows the p – V and T-s Diagrams for the same.

The air is first compressed in the compressor, passed into the heating chamber, and then to the first turbine. The air is once again passed into the heating chamber called reheater and then to the second turbine. The area under the p-V diagram is increased by the amount 4\`-4-5-6-4\`. Therefore the network is increased. In fig.4.25 (b), the ideal cycle without reheater is shown by the process 1-2-3-4\`-1, and the cycle with reheater is shown by 1-2-3-4-5-6-1.

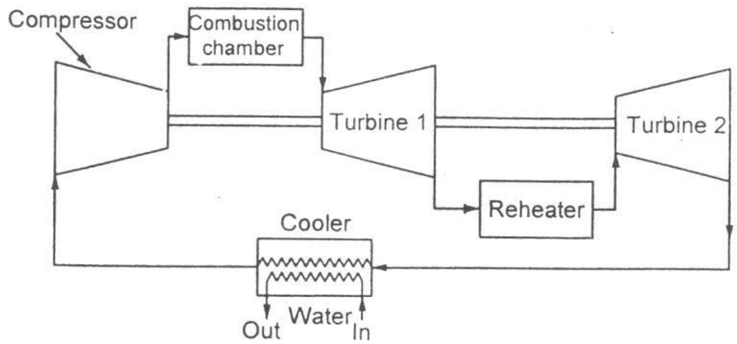


Fig. 4.25(a) Brayton cycle with reheater

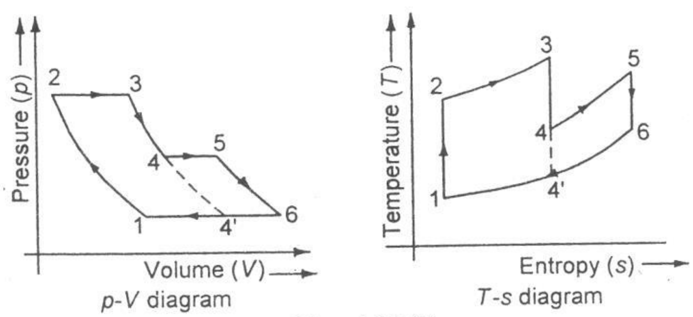


Fig. 4.25(b)

Work done required by the compressor per kg of air

$$W_c = C_p (T_2 - T_1)$$

Work done by two turbines per kg of air

$$W_\gamma = C_p (T_3 - T_4) + C_p (T_5 - T_6)$$

Network, $W = W_\gamma - W_c$

Note:

For obtaining maximum work $\frac{p_3}{p_4} = \frac{p_5}{p_6}$

$$p_4 = p_5 = \sqrt{p_3 \times p_6} = \sqrt{p_1 \times p_2} \quad \left(\because p_1 = p_6 \text{ and } p_2 = p_3 \right)$$

Brayton cycle with Inter Cooling

The thermal efficiency of the brayton cycle may further be increased by providing multistage compression with intercooler between the compressors and multistage expansion with reheater between the turbines. The work required during multistage compression with intercoolers is less than the single stage compression. Similarly, the work output from the turbine is increased by multistage expansion with reheating. As a result, the net work output from the plant increased. Fig.4.24, (a) Shows an ideal gas turbine plant operated by Brayton Cycle with two-stage compression.

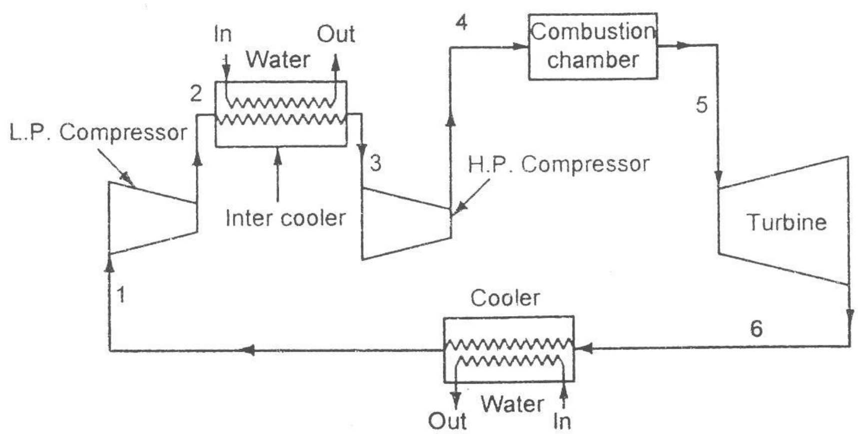


Fig. 4.24.(a) Brayton cycle with inter cooler

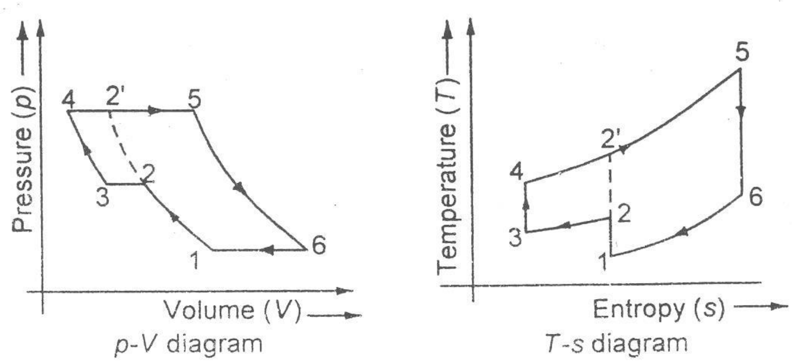


Fig. 4.24(b)

Fig.4.24 (b) shows the p-V and T-s diagram of the multistage compression Brayton cycle with intercooler.

Initially, the air is compressed in the low pressure compressor (L.P. Compressor) and it is passed to an intercooler with reduces the temperature of the air to its original temperature at constant pressure. After that, the compressed air is again compressed in the high-pressure compressor (H.P. Compressor) Then the compressed air is passed through the heating chamber where heat is added to the air. Now, the air is expanded through the turbine. Finally, the air is cooled in the cooling chamber to its original temperature.

In fig.4.24 (b) the ideal cycle without inter cooling is represented by 1-2`-5-6-1 and the cycle with intercooler is represented by 1-2-3-4-5-6-1. The area under the p-V diagram is increased by the amount 2-3-4-2`-2; therefore, the net work output is increased.

Work done by the turbine per kg of air, $W_\gamma = Cp\ (T_5 - T_6)$

Work required by the two compressors per kg of air

$$W_c = Cp\ (T_2 - T_1) + Cp\ (T_4 - T_3)$$

Network, $W = W_\gamma - W_c$

Note:

For perfect inter cooling $T_1 = T_3$ and $T_2 - T_4$

The intermediate pressure for perfect inter cooling is

$$p_3 = p_2 = \sqrt{p_1\ x\ p_4} = \sqrt{p_5 x\ p_6}$$

Brayton Cycle with Inter Cooling, Reheating and Regeneration

The previously stated three methods for improving thermal efficiency of the cycle are combined together for getting maximum efficiency. Fig.4.26 (a) shows the ideal Brayton cycle with inter cooling, reheating and regeneration and fig 4.26 (b) shows the same processes in T-s Diagram.

Work required by the compressor

$$W_c = Cp\ (T_2 - T_1) + Cp\ (T_4 - T_3)$$

Work done by turbines

$$W_\gamma = Cp\ (T_6 - T_7) + Cp\ (T_8 - T_9)$$

Network, $W = W_T - W_c$

Heat supplied externally to the cycle

$$Q_s = Cp\ (T_6 - T_5) + Cp\ (T_8 - T_7)$$

Heat rejected, $Q_R = Cp\ (T_{10} - T_1) + Cp\ (T_2 - T_3)$

Thermal efficiency of the cycle,

$$\eta = 1 - \frac{Q_R}{Q_S} = 1 - \frac{(T_6 - T_5) + (T_8 - T_7)}{(T_{10} - T_1) + (T_2 - T_3)}$$

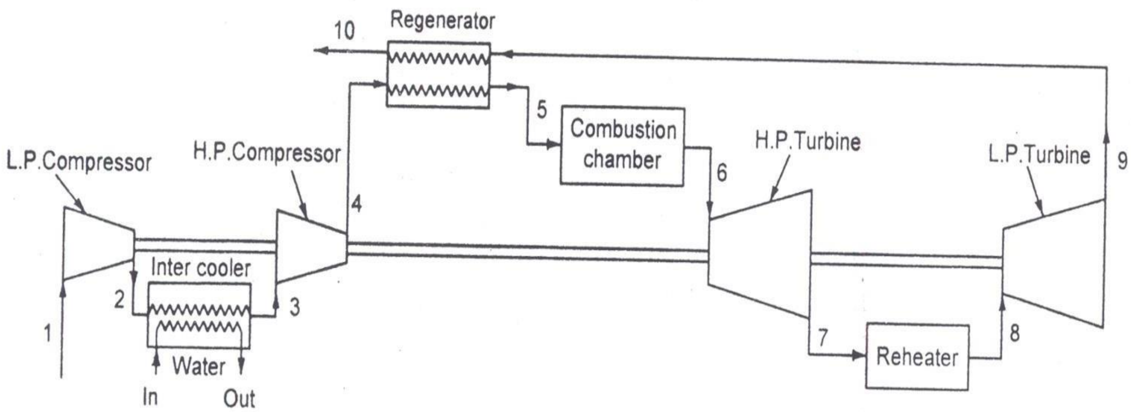


Fig. 4.26(a). Brayton cycle with inter cooler, reheater and regerneration

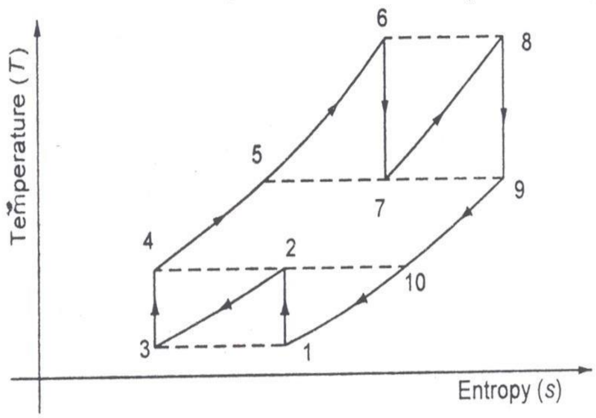


Fig. 4.26(b). T-s diagram

Nuclear Fuels

There are many metals such as Uranium, Thorium and Plutonium used to produce nuclear energy. Among those, Uranium is most important nuclear fuel. It exists in three different forms in nature having mass numbers 234,235 and 238. The average percentage in the earth is as follows:

$$_{92}U^{238} = 99.28\%;\ _{92}U^{235} = 0.714\%;\ _{92}U^{234} = 6.006\%$$

Among the above, U^{235} is called as primary fuel. It is naturally available up to 0.7% in the Uranium ore. It is more unstable and is capable of sustaining chain reaction.

U^{235} and PU^{239} are known as secondary fuels. They are produced artificially from Th^{232} and U^{238} respectively.

It is estimated that almost all the resources of Uranium are situated in U.S.A. (33%), South Africa (20%), Australia (20%) and Canada (20%). The most economical and low cost Uranium is available in Australia. In India, a large amount of thorium is available.

Some of the properties required by the Uranium fuel are as follows:

1. Undergo fission process.
2. High tensile strength to prevent the buckling of fuel element and to bear thermal stresses.
3. High radiation stability to resist nuclear radiation against buckling.
4. High conductivity to transfer the large amount of heat released and to reduce high thermal stresses.
5. Better machine ability with higher ductility.
6. Better corrosion resistance.

There are two kinds of nuclear fuels available depending on the method of releasing energy.

i. Fissile fuels
ii. Fertile fuels

1. Fissile fuels:

These fuels undergo fission process. When unstable heavy nuclear is bombarded with neutrons, it splits into two fragments of approximately equal mass. A large amount of heat is released during this fission process. The fissile materials are used as fuel in nuclear power plant. There are three basic fissionable materials available. They are U^{235}, PU^{239} and U^{233}

2. **Fertile fuels:**

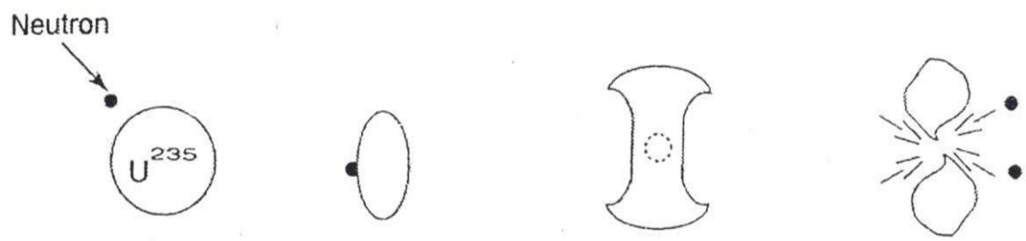
Some materials are not fissionable by themselves. Yet, they can be converted into fissionable materials. They are called as *fertile fuels*. These materials absorb neutron and undergo spontaneous change to produce fissionable materials. Only U^{235} is available in nature. U^{235} and PU^{239} are produced artificially. U^{233} is produced by nuclear reaction of thorium element. PU^{239} is produced by neutron irradiation of U^{238}. These PU^{239} and U^{233} can be fissioned by neutrons. U^{238} and Th^{232} are known as *fertile fuels*.

Nuclear Fission

Nuclear fission is the process of splitting of nucleus into two almost equal fragments accompanied by release of heat.

In other words, it is the process of splitting of unstable heavy nucleus into two fragments of approximately equal mass when bombarded with neutrons.

The fission fragments formed due to fission are the isotopes. The nuclear binding energy per fragment is more than that of heavy nuclei. Thus, there is a considerable release of energy during the process. This process is accompanied by the emission of neutrons and gamma rays.



The fission phenomenon is explained with the fig. 3.2. fig. (a) refers the pre-fission stage. Neutron reaches the U^{235} nucleus. Fig. (b) refers the collision of neutron with nucleus and slightly distorted stage. In Fig. (c), the neutron is absorbed by the nucleus and the nucleus is in the excited state. At this stage, it attains the shape of a dumb-bell. Fig. (d) refers the post fission stage. The nucleus is split into two fragments. Two free neutrons are ejected with high velocity.

The above process is possible only if the nucleus is excited to the sufficient energy and attains the stage (c). The excitation energy required to split the nucleus is called *"Critical energy"*. The critical energy should be more than the neutrons binding energy.

During the fission process, a large amount of energy is released and the fission fragments are associated with high velocities. These fragments collide with other nuclei in the mass and are stopped. The associated velocity energy is converted into heat which is a large amount of energy obtained from the fission. One neutron obtained from fission interacts with another U^{235} nucleus and thus undergoes fission process. Thus the process is self-sustaining.

To sustain the fission process, the following requirements must be fulfilled.

(i) The neutrons emitted in fission must have adequate energy to cause fission of other nuclei.

(ii) The number of neutrons produced must be able not only to sustain the fission process but also to increase the rate of fission.

(iii) The fission process must liberate the energy.

(iv) It must be possible to control the rate of energy liberation.

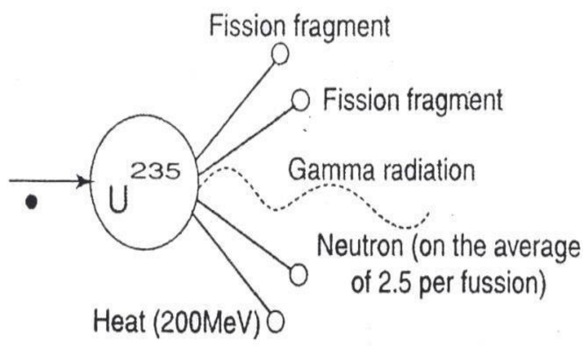


Fig. 3.3. represents the fission of Uranium 235. When a neutron is captured by a nucleus of an atom of U-235, U236 isotope forms. This is highly unstable type of isotopic. Uranium perhaps one millionth of a second. It splits roughly into two equal parts and liberates a total energy of 200*MeV*.

The products formed include the fission fragments, neutrons and gamma rays. The fission products absorb most of the total energy released by the fission as kinetic energy which is converted into heat as the fragment collide when a neutron causes fission of $U^{235,}$ a typical reaction produces barium, krypton, two or three neutrons and release of energy due to loss of mass. This process is shown in fig3.3.

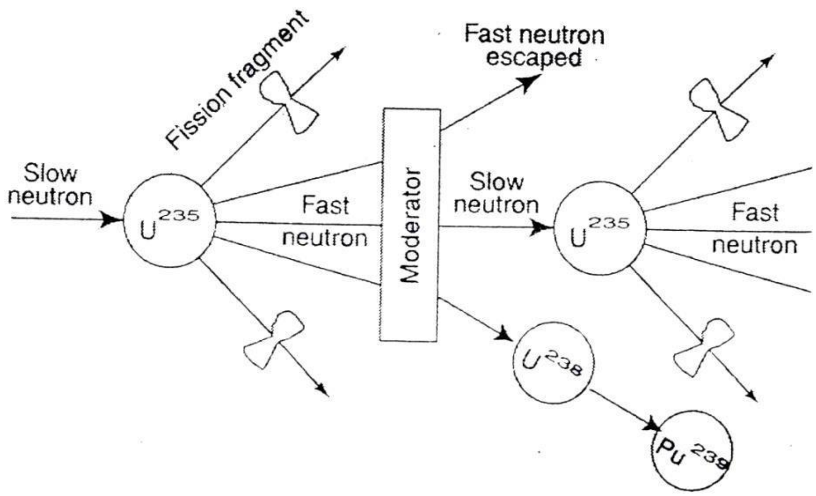
The immediate products of a fission reaction, such as Ba^{137} and Kr^{97} are called fission fragments. Both the products are called *fission products.*

Chain Reaction

During fission process, neutron is absorbed by the nucleus of atom of U^{235} and splits up into two fragments of approximately equal size. Also about 2.5 neutrons are released and a large amount of energy is produced. The neutrons produced move with very high velocity (1.5 x 10^7 *m/s*) and fission other nuclei of U^{235}. Thus, fission process and release of neutrons take place continuously throughout the remaining material. This self-sustaining reaction is known as chain reaction.

Definition:

This chain reaction is the process in which the number of neutrons keeps on multiplying rapidly during the fission till whole of the fissionable material is disintegrated.



The chain reaction will become self-sustaining or self-propagating only. At least one fission neutron becomes available for causing fission of another nucleus.

This condition can be conveniently expressed in the form of *multiplication factor or reproduction factor* of the system.

$$K = \frac{\text{Number neutrons in any particular generation}}{\text{Number neutrons in the preceding generation}}$$

For sustaining chain reaction, K should be greater than 1 and if K is less than 1, chain reaction cannot be maintained.

There are two reasons why not all the fission neutrons cause further fission.

1. Absorption of some neutrons cause further fission products, non-fissionable nuclei in the fuel, structural material, moderator and so on.
2. Leakage of neutrons escaping from the core.

For example, about 2.5 neutrons are released in fission of each nuclei of U^{235}. Out of these, one neutron is used to sustain the chain reaction. 0.9 neutrons are absorbed by U^{238} and become fissionable material Pu^{239}. The remaining 0.6 neutrons are partly absorbed by control rod material, coolant, moderator, and partly escape from the reactor.

Nuclear Fusion

Nuclear fusion is the process of combining of fusing two higher nuclei into a stable and heavier nuclide. In this process also, large amount of energy is release because mass of the product nucleus is very less when compared to mass of the two nuclei which are fussed.

Difference between nuclear fission and nuclear fusion

S. No	Nuclear fission	Nuclear fusion
1.	It is the process of breaking a heavy nucleus with some projectiles into two or more light fragments with liberation of a large amount of energy.	It is a process of fusing two light nuclei into single nucleus with the liberation of a large amount of heat.
2.	This process results in the emission of radioactive rays.	This process does not emit any king of radioactive rays.
3.	This process takes place spontaneously at ordinary temperature.	This process takes place at very high temperature (nearly at about > 10^5K).
4.	The mass number and atomic number of the daughter elements (new elements) are considerably lower than that of the parent nucleus.	The mass number and atomic number of the product are higher than that of the starting elements.
5.	This process gives rise to chain reaction.	This process does not give rise to chain reaction.
6.	During nuclear fission, neutrons are emitted.	During nuclear fusion, protons are emitted.
7.	Nuclear fission can be performed under controlled conditions.	Nuclear fusion cannot be performed under controlled conditions.

Main Components of a Nuclear Power Plant

The main components of nuclear power plant are

- Nuclear reactor.
- Heat exchange or steam generator.
- Steam turbine.
- Condenser.
- Electric generator.

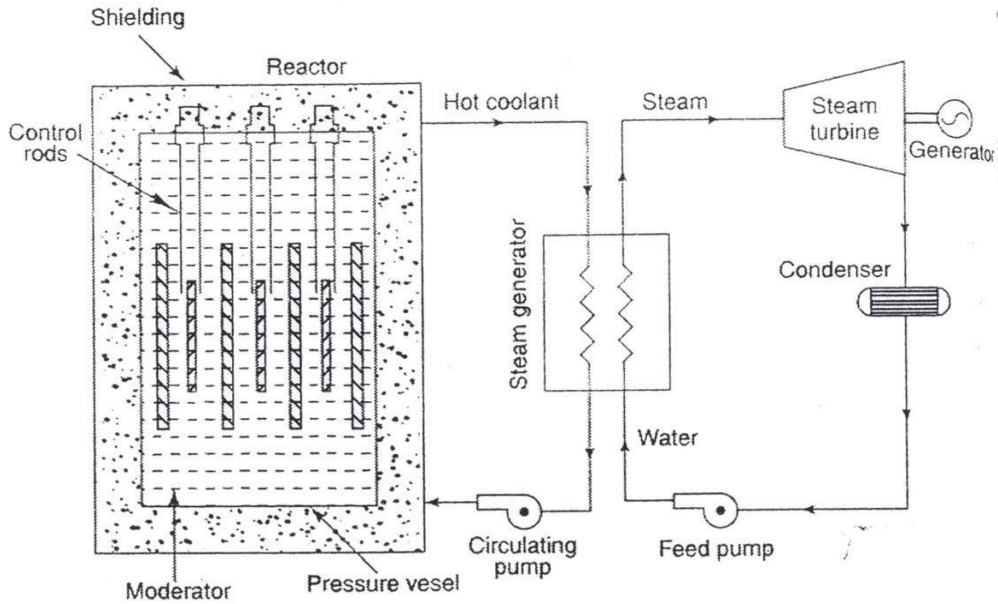


Fig 3.5 shows a schematic diagram of nuclear power plant. In nuclear power plants, the reactor function is similar to the furnace of steam power plant. It contains pressure vessel, fuel rods, moderator, shielding as shown in fig. 3.5. There are various types of reactor used in practice which will be discussed later. The fuel elements are inserted in the reactor core. The control rods are introduced and positioned in the core to control the chain reaction. Heavy water reactor acts as a moderator as well as the coolant.

The heat librated in the reactor as a result of nuclear fission of the fuel is taken up by the coolant circulating through the reactor core. Hot coolant coming out of the reactor core is then circulated through the tubes of steam generator to generate the steam. The water coming out of the heat exchanger is circulated by the pump to maintain the pressure in the circuit in the range of 100 to 130*bar*.

The steam so produced expands in the steam turbine for producing work. Steam coming out of the turbine flows to the condenser for condensation. The steam turbine in turn runs an electric generator thereby producing electrical energy.

Main Components of a Nuclear Reactor

A nuclear reactor is similar to the furnace of a steam power plant or combustion chamber of a gas turbine plant. In this nuclear reactor, heat is produced due to nuclear fission chain reaction. Fig. 3.6. shows the various components of a nuclear reactor.

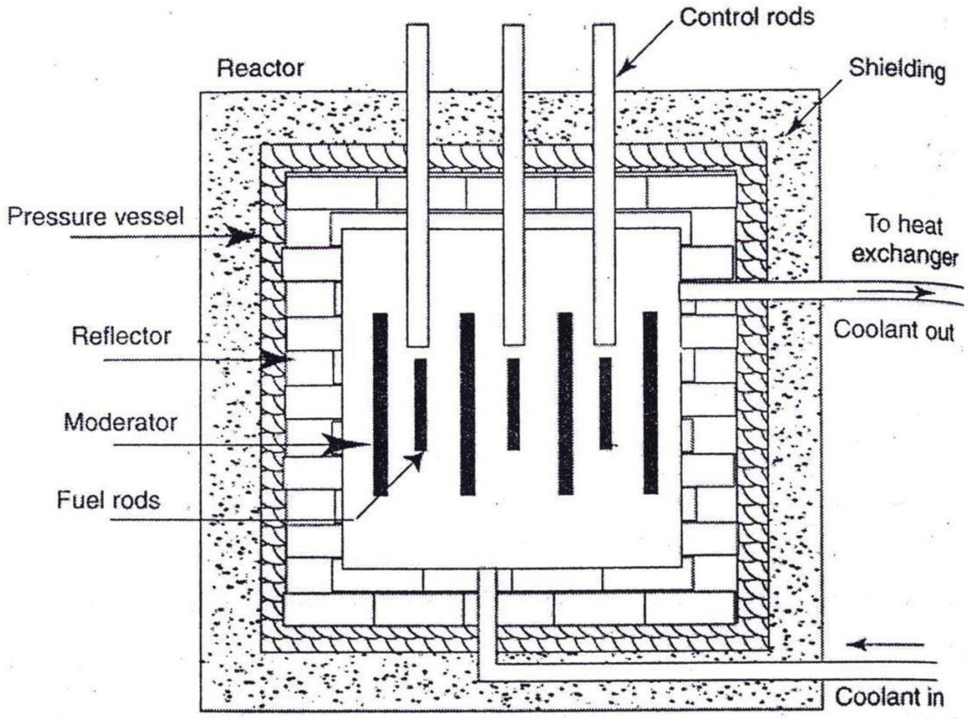
The nuclear reactor consists of the following principle parts:

(i) Reactor core
(ii) Moderator

(iii) Control rods
(iv) Reflector
(v) Cooling system
(vi) Reactor Vessel
(vii) Biological shielding

1. **Reactor core:**

It consists of nuclear fuel, the neutron moderator and space for the coolant. The nuclear fuel is an element or isotope whose nuclear undergo nuclear fission by nuclear bombardment and produces a fission chain reaction. Nuclear fuel may be one or all of the following U^{235}, U^{235} and $P\ U^{239}$. Reactor core generally has a shape approximately a right circular cylinder with diameters ranging from 0.5m to 15m.



The fuel elements are made of plates or rods of Uranium metal. These plates are usually clad in a thin sheet of stainless steel, Zirconium or Aluminum to provide corrosion resistance. The fuel is shaped and located in such a way that heat produced within the reactor is uniform. Adequate arrangements should be made for fuel supply, charging or discharging and storing of the fuel.

2. **Moderator:**

The process of slow down the neutrons from high velocity without capturing them is known as *moderation*. Moderator is a material which is used to slow down the neutrons from high velocities without capturing them. The fast moving neutrons are far less effective in causing the fission and try to escape from the reactor. Thus, the speed of the fast moving neutron is reduced by introducing moderator. Heavy water (D_2O), Water (H_2O), Beryllium (Be), Graphite (C) and Helium (He) gas are commonly used moderators.

A good moderator should possess the following properties:

- High thermal conductivity
- High slowing down power
- Low parasite captures
- Lighter
- High resistance to corrosion
- Stability under heat and radiation
- Abundance in pure form
- High meeting point for solids and low melting point for liquids.

The moderator is characterized by *moderating* ratio which is the ratio of moderating power to the macroscopic neutron capture coefficient. If the moderating ratio is high, the given substance is more suitable for slowing down the neutrons.

3. **Control rods:**

The function of control rod is:

- To control the rate of fission.
- To start the nuclear chain reaction when reactor is started from cold.
- To shut down the reactor under emergency condition.
- To maintain the chain reactor at a steady state.
- To prevent the melting of fuel rods.

Boron, Cadmium and Hafnium are mostly used as control rods. These control rods are used to absorb the neutrons thereby reducing the chain reaction. The control rods must be able to absorb excess neutrons.The position of these rods is regulated by electronic or electro-mechanical device. Control rods should possess the following properties:

- Good stability under heat and radiation
- Adequate heat transfer properties
- Better corrosion resistance
- Sufficient cross-sectional are for the absorption of neutrons.

4. **Reflector:**

Reflector material is placed round the core to reflect back some of the neutrons that leak out from the surface of the core. The reflected neutrons cause more fission and improve the neutrons economy of the reactor. Reflector is generally made of the same material as the moderators. Water, carbon, graphite, beryllium are generally used as reflectors.

5. **Cooling system:**

The coolants are used to carry away heat produced inside the reactor to the heat exchanger. From the heat exchanger, heat is transferred to another working medium for further utilization of power generation.

The desirable properties for a reactor coolant are:

- Low melting point
- High boiling point
- Low viscosity
- Non-corrosiveness
- Non-toxicity
- Low parasite capture
- High chemical and radiation stability
- High specific heat
- High density

The various fluids are used as coolant like water (light water or heavy water), gases (helium, CO_2, hydrogen or air), liquid metals such as sodium and organic liquids.

6. **Reactor vessel:**

The reactor vessel encloses the reactor core, moderator, reflector, shield and control rods. It is a string walled container to withstand high pressure. At the top of the vessel, holes are provided to insert control rods. At the bottom of the vessel, the reactor core is placed.

7. **Biological shielding:**

Shielding is necessary to protect the walls of the reactor vessel from radiation damage and also protect the operating personnel from exposure to radiation. Thick layers of lead concrete or steel are provided all around the reactor. These layers absorb the gamma rays, neutrons etc.

A good shielding material should have the following properties.

- It should absorb α, β and γ radiations efficiently.
- It should have uniform density.
- It should not be decomposed by radiation.
- It should be fire resistant

Types of Reactors

The nuclear reactors are classified according to the following characteristics.

(i) According to the neutrons energy.

a. Fast reactors – Fast fission is caused by high-energy neutrons.
b. Intermediate or epithermal.
c. Low energy or Thermal reactors – Fission is due to slow moving neutrons

(ii) According to the fuel used

a. Natural fuel reactor – Natural Uranium is used as fuel.
b. Enriched Uranium reactor – Uranium used in this reactor contains 5 to 10% of U^{235}.

(iii) According to the type of coolant used

a. Water cooled reactors – Ordinary of heavy water is used as coolants.
b. Gas cooled reactors – CO_2, He, N2, air etc. are used as coolants.
c. Liquid metal cooled reactors – Liquid metals such as sodium, bismuth and lead are used as coolants.

(iv) According to the type of moderators used

a. Graphic moderator reactor
b. Beryllium moderator rector
c. Water moderator reactor

(v) According to the construction of core

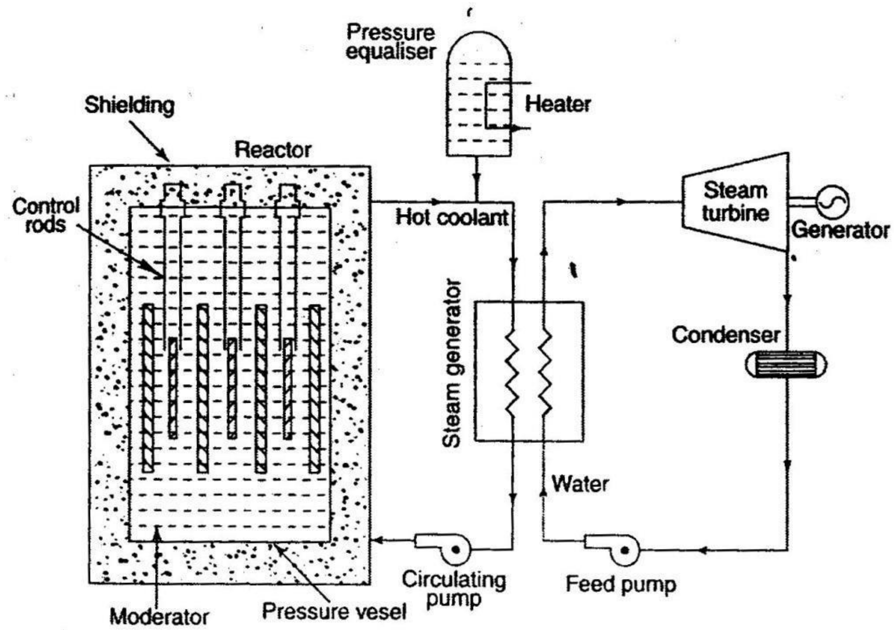
a. Cubical core reactor
b. Cylindrical core reactor
c. Spherical core reactor
d. Annulus core rector
e. Slab core reactor

Factors control the selection of a particular type of a reactor:

1. Neutrons energy
2. Type of fuel
3. Type of coolant
4. Type of moderators
5. Construction of core

Pressurised water reactor (PWR):

A pressurized water reactor is a light water cooled and moderated reactor having an unusual core design using both natural and highly enriched fuel. The nuclear power plant using a prescribed water reactor is shown in fig. 3.7.



The main components of the reactor are

(i) Reactor
(ii) Pressuriser
(iii) Heat exchanger
(iv) Coolant pump

The components of the secondary circuit of pressurized water plant are similar to those in a normal steam station (ie. Steam turbine, condenser, feed pump, and heat exchanger)

The coolant in the primary circuit is pumped to the reactor core. The coolant absorbs heat energy which is liberated during nuclear fission in the reactor core. The hot coolant passes through the heat exchanger where the coolant transfers heat energy to the feed water and steam is generated. The water from the heat exchanger is again circulated by the coolant pump. The water becomes radioactive in passing through the reactors. Therefore, the entire primary circuit including heat exchanger must be shielded to protect the operating personnel. The steam in the turbine is not radioactive and need not be shielded.

The pressure in the primary circuit should be high so that the boiling of water takes place at high pressure. This enables water to carry more heat from the reactor. The pressurising tank keeps the water at about 14MN/m^2 so that it will not boil. Electric heating- coil in the pressuriser boils the water to form the steam which is collected in the dome as shown if fig. 3.7 as more steam is forced into the dome by boiling, its pressure rises and pressurises the entire circuit. To reduce the pressure, water spray is used to condense the steam.

A pressurised water reactor can produce only saturated steam. If there is a need of superheated steam, separate furnace should be provided.

Advantages:

1. Water which is cheaply available in plenty is used for coolant, moderator and reflector.
2. The reactor is compact and high power density (65kN/*litre)*.
3. Number of control required is less.
4. Easily available natural uranium is used as fuel.
5. Steam is not contaminated by radiation. Hence, maintenance of turbine, feed heaters and condenser is normal.
6. This reactor allows to reduce the fuel cost extracting more energy per unit weight of fuel.

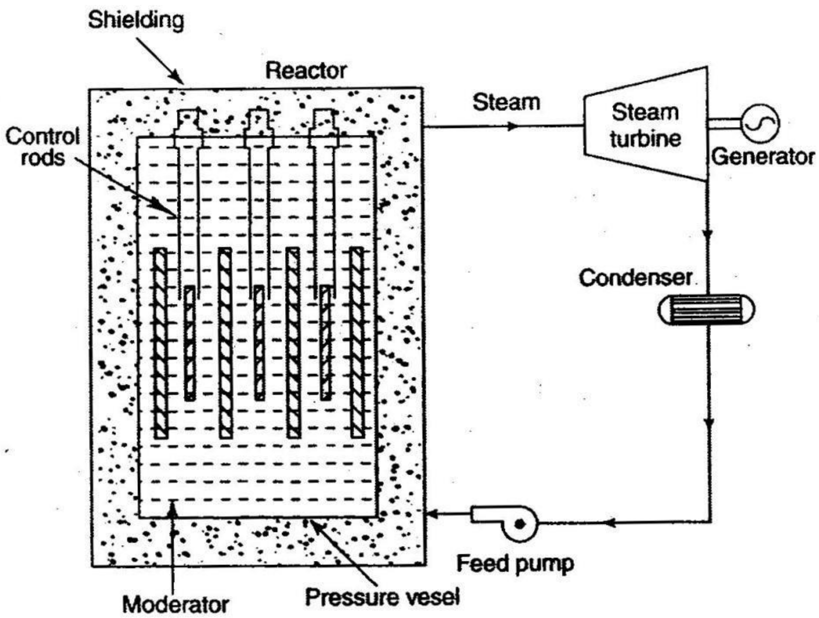
Disadvantages:

1. High pressure requires stronger reactor vessel and hence capital cost is high.
2. Thermal efficiency of the plant is low since low pressure is maintained in secondary circuit.
3. Fuel element fabrication is expensive.
4. Reprocessing of fuel is difficult since, it is affected by radiation.
5. It is necessary to shutdown the reactor for fuel charging which required a couple of month time.
6. Uneven heating is caused when gamma radiation pass through the pressure vessel. Hence, thermal stresses involved make difficulty in design.
7. Low volume ratio of moderator to fuel makes fuel element design and insertion of control rods difficult.
8. The corrosion problems are more severe as the pressure is high.

Boiling water reactor (BWR):

The arrangement of boiling water reactor is simple when compared to the pressurized water reactor. The nuclear power plant using boiling water reactor as shown in fig 3.8. In this type of reactor also, enriched uranium is used as a fuel and water is used as moderator, coolant and reflector in PWR. Only difference between PWR and BWR is that in a B.W.R, the steam is generated in the reactor itself of a separate steam generator.

Water enters the reactor at the bottom. This water is heated by the heat released due to this fission of fuel and gets converted into steam. The steam which leaves from the top of the reactor is passed through the turbine and expanded.



Exhaust steam from the turbine passes through the condenser and condensed. The condensed water is again recirculated again by using feed pump. India's first nuclear power plant at Tarapur has two B.W.R.S of 200*MV* capacity each.

Advantages:

1. The reactor vessel is much lighter than PWR since the pressure inside the reactor is small.
2. There is no heat exchanger, pressuiser and circulation pump. This reduces cost of the plant.
3. Thermal efficiency of BWR plant is more (30%) than PWR plant (20%).
4. The metal temperature remains low for given output condition.
5. BWR is a self controlled reactor as the reactivity is automatically reduced, if the vapour is not dense to moderate the neutrons effectively.
6. A BWR is more stable than PWR and much stable than any other type of reactor.

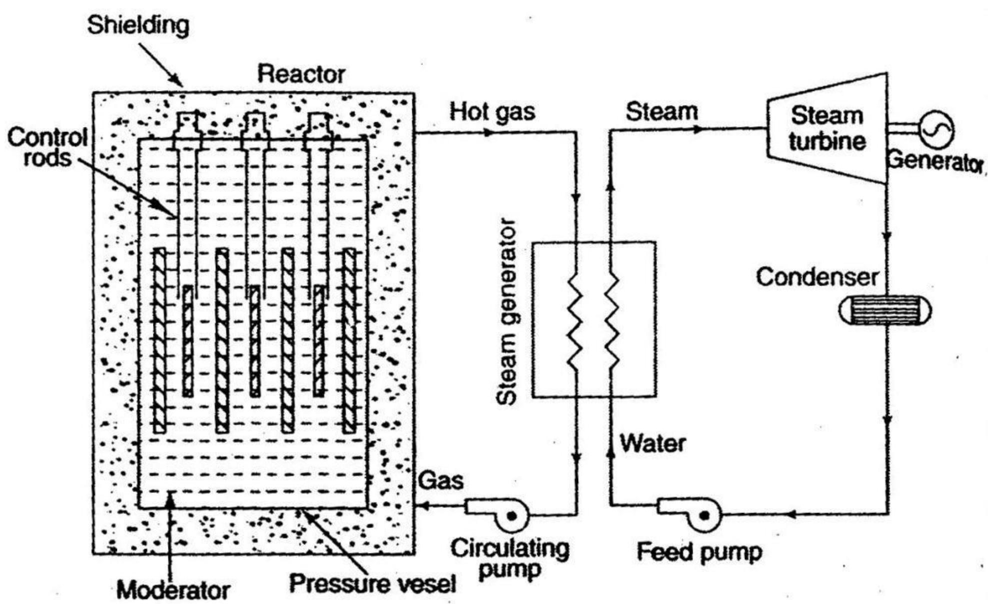
Disadvantages:

1. The steam entering the turbine is slightly radioactive. Hence, shielding of turbine and piping are needed.
2. Wastage of steam resulting in lowering of thermal efficiency on part load operation.
3. Lower power density (33.6kW/*litre)* and large in size.
4. Power demand fluctuation cannot be met.

3. Gas cooled reactor (GCR):

In this reactor, carbon dioxide gas is used to carry away the hear produced due to nuclear fission in the reactor. The first gas cooled rector with CO_2 gas as coolant moderator were developed in Britain during 1956-69. The fuel was natural Uranium, clad with an alloy of magnesium called Magnox. The gas is maintained at a pressure of about 16*bar*.

Various types of GCR have been developed. England developing an advanced gas cooled reactor (AGR system) and Germany and the USA developing helium cooled, graphite moderated systems. Gas enters the reactor at the bottom. This gas is heated by the heat released due to the fission of fuel and leaves the reactor at the top and flows to heat exchanger. In the heat exchanger, hot gas transfers its heat to water which gets converted into steam. The gas is recirculated with the help of gas blowers.



This steam passes through the turbine and expanded to get mechanical work. Exhaust steam from the turbine is condensed with the help of condenser.

Advantages:

1. Fuel processing is simpler than any other reactors.
2. No corrosion problem.
3. The Uranium carbide and graphite are able to resist high temperatures and hence, the problem of limiting the fuel element temperature is not as series as in other reactors.
4. It gives better neutrons economy due to low parasite absorption.
5. Graphic remains stable under irradiation at high temperatures.
6. There is no possibility of explosion in reactor since, the use of CO_2 as coolant completely eliminates this problem.

Disadvantages:

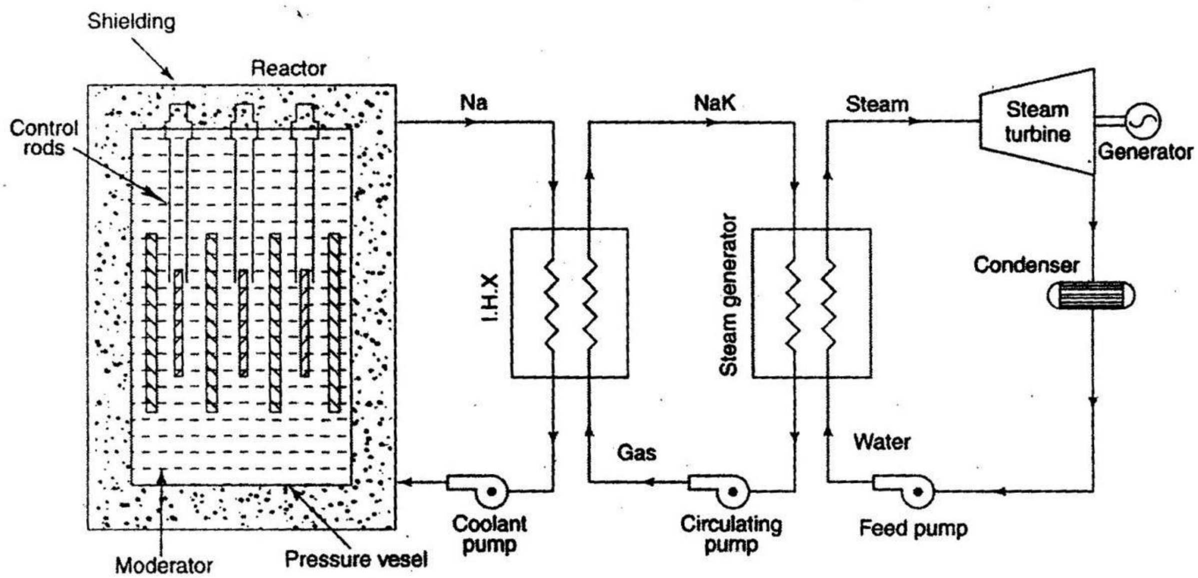
1. Fuel loading is more elaborated and costly.
2. The cost of heavy water (D_2O) is high (Rs. 500 per kg).

3. Power density is very low (9.7kW/litre) and hence, large vessel is required.
4. Large amount of fuel loading is initially required since, the critical mass is high.
5. Very high standard design, manufacture inspection and maintenance are required.
6. Leakage of gas is a major problem, if helium is used instead of CO_2.
7. More power is required for circulation of coolant when compared to water-cooled reactors.

Fast breeder reactor (FBR):

In fast breeder reactors, enriched Uranium (U^{235}) or Plutonium is kept in the casing without using moderator, The casing is surrounded by a thick blanket of fertile Uranium (U^{238}). This is known as *breeding material.* Fig. 3.10. shows a schematic diagram of a fast breeder reactor. Fast moving neutrons are liberated due to fission of enriched uranium (U^{235}). The ejected excess neutrons are absorbed by the fertile Uranium (U^{238}) which is converted into fissionable material (PU^{239}). The fissionable material ($P\ U^{239}$) is capable of sustaining chain reaction.

The reactor employs two liquid metal coolant circuits as shown in fig. 3.10. Liquid sodium (Na) is used as primary coolant. Sodium potassium (NaK) alloy is used as secondary coolant.



There are two heat exchangers used in this power plant. One is intermediate heat exchanger (IHE) and other is steam generator. The intermediate heat exchanger is used to transfer heat from primary coolant (Na) to secondary coolant (Na K). The feed water is heated in the steam generator by the hot secondary coolant. The steam produced in the steam generator is then utilized for power generation.

Advantages:

1. No moderator is required.
2. High breeding is possible
3. It gives high power density than any other reactor.
4. High efficiency in the order of 40% can be obtained.
5. Better fuel utilization.
6. Absorption of neutrons is low.

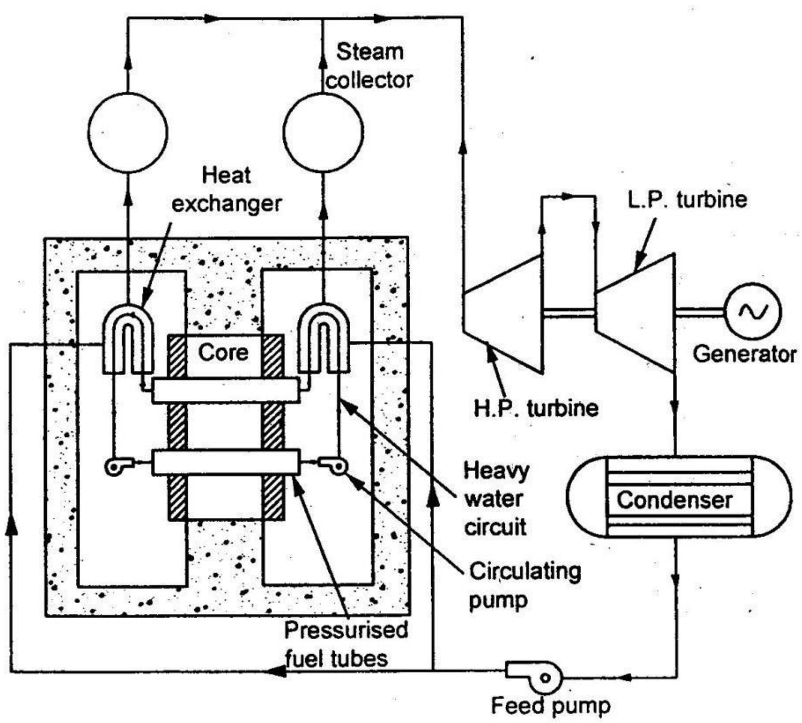
Disadvantages:

1. It requires highly enriched fuel.
2. Special coolants are required to carry out the large quantity of heat from the reactor core.
3. Handling of sodium is a major problem because it becomes hot and radioactive.
4. Specific power of reactor is less.
5. Safety must be provided against melt-down.
6. Neutron flux is high at the center of the core.

Heavy water cooled and moderated type reactor (or) CANDU (Canadian-deuterium-uranium) reactor:

This type of reactor was designed and developed in Canada. In this reactor, heavy water (99.8% deuterium oxide D2O) is used as moderator and coolant as well as the neutron reflector. These reactors are more economical to those countries which do not produce enriched Uranium as very costly. Natural Uranium (0.7% U^{235}) is used as fuel in this reactor. The arrangement of CANDU reactor power plant is shown in fig 3.11.

The coolant (heavy water) is passed through the pressurised fuel tubes and heated up by nuclear fission. This hot coolant is passed through the heat exchanger where the heat is transferred to the feed water and steam is produced. By varying the moderator level, the reactor can be easily controlled and hence, control rods are not necessary. In this reactor, steam is generated at a temperature of about 265°C.



The reactor vessel and the steam generator system are enclosed by a concrete containment structure. For rapid shutdown purposes, the moderator can be dumped through a very large area into a tank provided below the reactor.

Advantages:

1. There is no need of enriched fuel.
2. Cost of the reactor is less for the construction of lighter reactor vessel to withstand low pressure.
3. There are no control rods required.
4. Construction period of this plant is shorter.
5. Heavy water is used as a moderator which increases its effectiveness and provides low fuel consumption.

Disadvantages:

1. Heavy water is costly.
2. Leakage of water is a major problem.
3. Low power density (9.7kW/Litre)

Very high standards are required for the design, manufacture and inspection

NUCLEAR POWER PLANT

Introduction:

Now-a-days, large amount of coal and petroleum products are being used to produce energy. After few years, these sources will be unable to meet the demands of increasingly power hungry world. In addition, the problems associated with environmental pollution, mine safety, fuel transportation and so on are much higher in these power plants. Thus, there is a tendency to seek alternative sources of energy.

The nuclear chain reaction and nuclear explosion were predicated in 1939 by German scientists. This invention has given great confidence of producing nuclear energy from nuclear fission of materials like Uranium (U), Plutonium (Pu), etc. The energy from nuclear fission of these materials is used to heat water to generate steam and subsequently electrical energy. It has been found that one kg of Uranium can produce energy equivalent to 4500 tons of high grade coal or 1700 tons of oil. This shows that nuclear energy can be successfully employed for producing low cost energy in large quantity.

The total amount of nuclear fuels such as Uranium and thorium in the earth's crust is estimated approximately 1012 tonnes. A nuclear power reactor provides about 15% of world's electrical power requirement. The first nuclear fission reactor in the world was installed at University of Chicago in December 1942 for research purpose. In India, the first research nuclear reactor installed at Trambay in 1956. More than 600 Nuclear power plants were commissioned in the world with total of 500000MW capacity. The world's first nuclear power plant was commissioned in 1954 in U.S.S.R. In India, the first nuclear power plant was commissioned at Tarapur.

Advantages of Nuclear power plants:

- No atmospheric pollution by combustion products.
- Space requirement is less when compared to other conventional power plants are of equal size.
- Environmental pollution is less as compared to fossil fuel power plants.
- It is well suited to meet large power demands. They give better performance at high load factors (80 to 90%).
- Increased reliability of operation.
- Fuel transportation cost isles and large storage facilities are not needed since nuclear fuel has very high energy density.
- Nuclear power plants are not affected by adverse weather conditions.
- The expenditure on metal structure, piping, storage mechanisms are much lower for a nuclear power plants than a coal burning power plants.
- Water requirement is very less.

Disadvantages of nuclear power plants:

- High initial cost and complexity of nuclear fuel cycle is beyond the reach of poor developing countries.
- Nuclear power plants are not well suited for varying load conditions.
- The danger of radioactivity always persists in the nuclear stations.
- Danger of nuclear explosion in the reactor due to failure of controls.
- Maintenance cost is very high.
- Disposal nuclear radioactive waste is major problem in nuclear power plants. If they are not disposed carefully, it may have bad effect on the health of workers.
- These power plants require highly trained personnel to operate nuclear reactors.

LAYOUT OF NUCLEAR POWER PLANT

Introduction:

The nuclear power plants are now comparable to or even lower than the unit cost in coal fired power plants. Nuclear power utilization can help to save a considerable amount of fossils fuels which can be used in other areas. The heat produced due to fission of U and Pu is used to heat water to generate steam which is used for running turbo generator.

One kilogram of U can produce as much energy as possible by burning 4500 tonnes of high-grade coal.

Main components of a Nuclear Power Plant:

1. **Fuel:**

   The fuel which is used in the nuclear reactors are U^{235}, pU^{239} and U^{233}.

2. **Nuclear reactor:**

   It consists of reactor cone, reflector, shield etc. It may be regarded as a substitute for the boiler fire box of a steam power plant. During the fission process, the large amount of heat is liberated by U235. This large amount of heat is absorbed by the coolant and it is circulated through the core.

   The various types of reactors used in nuclear power plant is

   1. Boiling water reactor
   2. Pressurised water reactor
   3. Heavy Water-cooled reactor.

3. **Steam generator:**

It is fed with feed water and the feed water is converted into steam by the heat of the hot coolant. The coolant is used to transfer the heat from the reactor core to the steam generator.

4. **Moderator:**

It is used to reduce the Kinetic energy of fast neutrons into slow neutrons and to increase the probability of chain reaction.

5. **Reflector:**

It is used in the reactor to conscience the neutrons in order to r educe the consumption of fissile material.

6. **Turbine:**

The steam produced by the steam generator is passed to the turbine and it is connected to the generator.

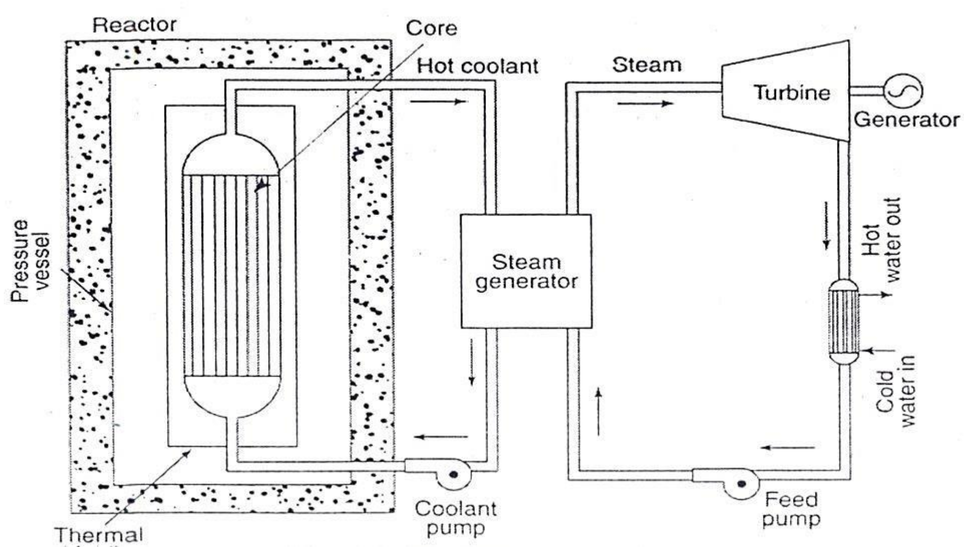
7. **Control rods:**

It is used to control the nuclear chain reaction and functions of the nuclear reactor.

8. **Coolant pump and feed pump:**

It is used to maintain the flow of coolant and feed water in the power plant. The ordinary water or heavy water is common coolant.

9. **Shielding:**



The reactor is a source of intense radioactivity. These radiations are very harmful and shielding is provided to absorb the radioactive rays. A thick concrete shielding and pressure vessel are provided to prevent the radiations escaped to atmosphere.

The hot coolant goes to the steam generator where the feed water is absorbed the heat from the coolant and converted into steam. This steam is used to run the steam turbine and it is connected to the steam generator. The used steamed is condensed and it is reused in the boiler. The mechanical energy of the steam turbine is converted into electrical energy by an electric generator.

Advantages of nuclear power plant:

1. Space requirement of a nuclear power plant is less.
2. It is easily adopted where water and coal resources are not available.
3. There is increased reliability of operation.
4. It is not affected by adverse weather conditions.
5. It does not require large quantity of water.
6. Nuclear power plant consumes very small quantity of fuel.
7. Nuclear power plants are well suited to meet large power demands.
8. Space for fuel storage is not needed.
9. No ash handling.

Disadvantages:

1. It is not suitable for variable load conditions.
2. Radioactive wastes may affect the health of workers and other population.
3. It requires high initial cost.
4. It requires well-trained personnel.

LAYOUT OF GAS TURBINE POWER PLANT

The gas turbine power plant has relatively low cost and can be quickly put into commission. Gas turbine installations require only a fraction of water used by their steam turbine counter-parts. The size of gas turbine plants used varies from $10MW$ to $50MW$ and the thermal efficiency of about 22% to 25%. It is very much useful in peak load. The gas turbine plant requires less space only.

Elements of a Gas Turbine Plant

The gas turbine plant consists of

1. Compressor
2. Intercooler
3. Regenerator
4. Combustion chamber
5. Gas turbine
6. Reheating unit.

1. Compressor:

In gas turbine plant, the axial and centrifugal flow compressors are used. In most of the gas turbine power plant, two compressors are used. One is low-pressure compressor and the other is high-pressure compressor.

In low-pressure compressor, the atmospheric air is drawn into the compressor through the filter. The major part of the power developed by the turbine (about 66%) is used to run the compressor.

This low-pressure air goes to the high-pressure compressor through the intercooler. Then the high-pressure air goes into the regenerator.

2. Intercooler:

The intercooler is used to reduce the work of the compressor and it is place in between the high pressure and low-pressure compressor. Intercoolers are generally used when the pressure ratio is very high. The energy required to compress the air is proportional to the air temperature at inlet. The cooling of compressed air in intercooler is generally done by water.

3. Regenerator:

Regenerators are used to preheat the air which is entering into the combustion chamber to reduce the fuel consumption and to increase the efficiency. This is done by the heat of the hot exhaust gases coming out of the turbine.

4. Combustion chamber:

Hot air from regenerator flows to the combustion chambers and the fuel like coal, natural gas or kerosene are injected into the combustion chamber. After the fuel injection, the combustion takes place. These high-pressure, high- temperature products of combustion are passed through the turbine.

5. **Gas turbine:**

Two types of gas turbines are used in gas turbine plant.

1. High pressure turbine.
2. Low pressure turbine.

The combustion products from the combustion chamber are first expanded in high-pressure turbine and then it expands in low-pressure turbine. Due to the expansion in the gas turbine, the heat is converted into mechanical work. The gas turbine classification is based on the cycle of operation as follows.

i. Open cycle gas turbine:

In open cycle gas turbine plants, the air (or) gases coming out from the gas turbine is exhausted to the atmosphere.

ii. Closed cycle gas turbine:

In closed cycle gas turbine plants, the air (or) gases coming out form the gas turbine plant is cooled in the cooler and it is again re-circulated. The working fluid is continuously used in the system without change of phase.

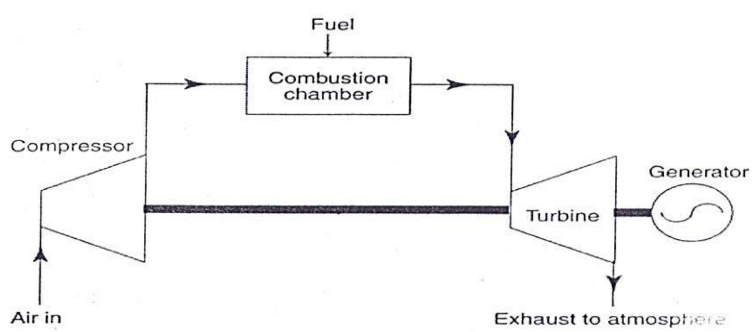


Fig. 1.9. Open cycle gas turbine power plant

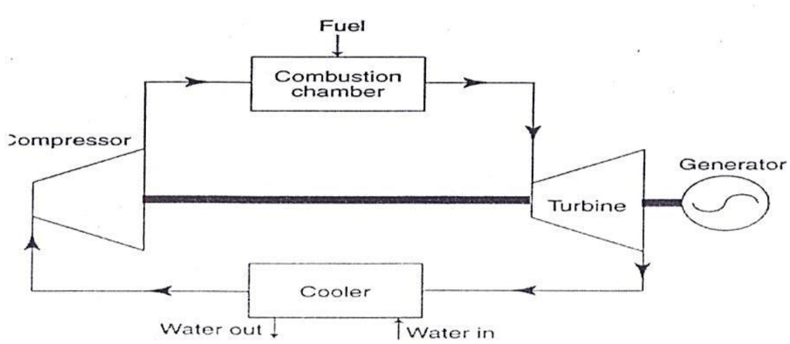
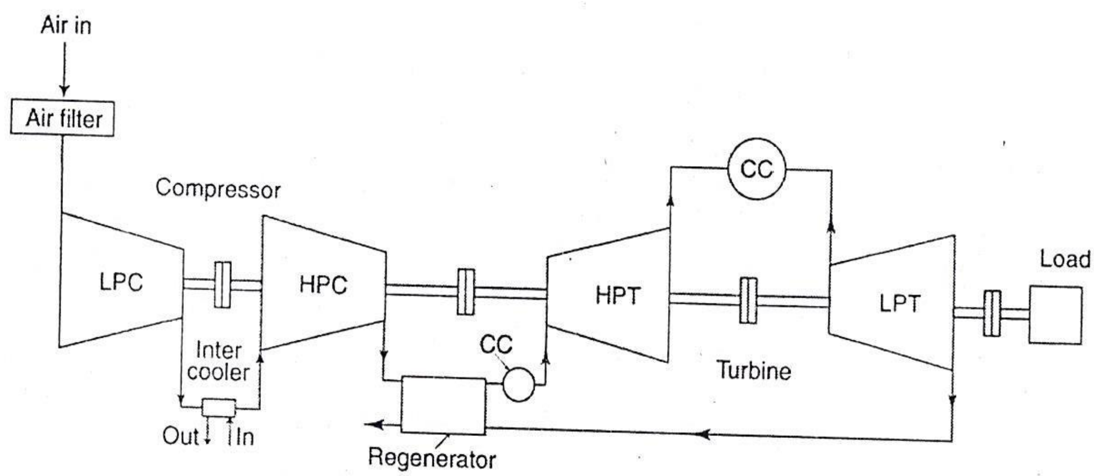


Fig. 1.10. Closed cycle gas turbine power plant

6. **Reheating unit:**

In this unit, the additional fuel is added to the exhaust gases coming out form the high pressure turbine, and the reheated combustion products goes into the low pressure turbine.

rking of Gas Turbine Plant



The working of gas turbine plant is shown in fig 1.11. The atmosphere air is drawn into the low-pressure compressor through the air filter and it is compressed.

The compressed low-pressure air goes into the high pressure compressor through the inter cooler. Here, the heat of the compressed air is removed. Then the high-pressure compressed air goes into the combustion chamber through the regenerator. In the combustion chamber, the fuel is added to the compressed air and the combustion of the fuel takes place.

The product of the combustion goes into the high-pressure turbine. The exhaust of the high pressure turbine goes to another combustion chamber and the additional fuel is added and it goes to the low pressure turbine.

After the expansion in the low-pressure turbine, the exhaust is used to heat the high-pressure air coming to the combustion chamber through the regenerator. After that, the exhaust goes to the atmosphere.

Advantages of gas turbine plant:

1. Smaller in size and weight as compared to an equivalent steam power plant.
2. Natural gas is a very suitable fuel.
3. The gas turbine plants are subjected to less vibration.
4. The initial cost is lower than an equivalent steam plant.
5. The installation and maintenance costs are less than thermal plants.
6. There are no standby losses in gas turbine plants.
7. It requires less water as compared to a steam plant.
8. Any quantity of fuels can be used in gas turbine plants.
9. It can be started quickly.
10. The exhaust of the gas turbine is free from smoke.
11. Gas turbines can be built relatively quicker and requires less space.

Disadvantages:

1. Part load efficiency is poor.
2. The unit is operated at high temperature and pressure, so special metals are required to maintain the unit.
3. Major part of work, (about 66%) developed in the turbine is used to drive the compressor.
4. The devices that are operated at high temperature are complicated.

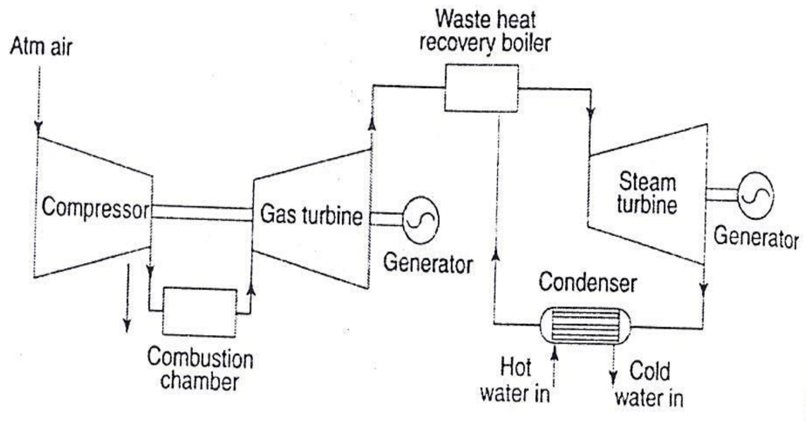
COMBINED POWER CYCLES

Introduction:

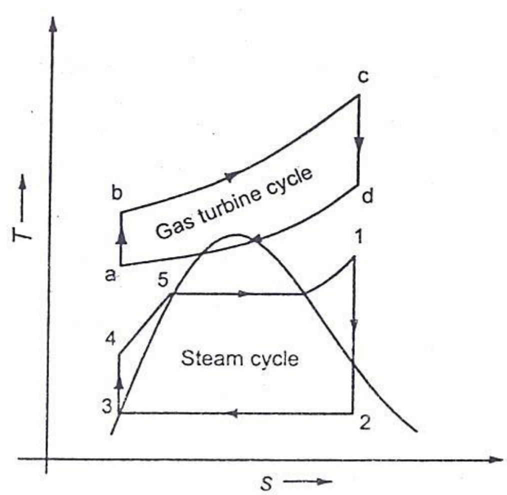
The maximum steam temperature in a power cycle exceeds 600°C, but the pulverized coal furnace temperature is about 1300°C. So, there is a lot of energy wasted in the power plant. To increase the efficiency and reduce the fuel, the combined power cycles are introduced by superposing a high temperature power plant as a topping unit to the steam plant. The combined plants may be of the following types:

1. Gas turbine-steam turbine power plant
2. Thermionic-steam power plant
3. Thermo electric-steam power plant
4. M.H.D-steam power plant.
5. Nuclear-steam combined power plant.
6. MHD-gas turbine power plant.

Gas turbine-steam turbine plant:



It is the combination of simple gas turbine power plant and steam power plant. The two cycles of Gas turbine Steam turbine power plant are connected in series, the topping cycle on Brayton cycle and the bottoming one operating on Rankine cycle.



In the gas turbine unit, the heat from the exhausted gas turbine is recovered by a heat recovery boiler and the steam is produced by using this heat in the boiler and it goes to the steam turbine. Here, two generators are used to produce the power.

One generator is connected to the gas turbine unit and the other generator is connected to the steam turbine unit. So, the overall heat rejection will be reduced. As a result of this, the overall efficiency will increase. It is given by

$$\eta = \eta_1 + \eta_2 - \eta_1 \eta_2$$

Where η_1 and η_2 are the thermal efficiencies of the Brayton cycle and the steam cycle respectively. The achievable overall efficiency may be in the range of 40 – 45%.

Advantages of Combined Cycles

1. Low environment effect.
2. Small amount of water required.
3. Low investment cost.
4. The efficiency of combined cycle plant is more than the open cycle power plant.
5. When compared with ordinary steam plants, these plants produce less smoke.
6. Simplicity of operation.
7. Great operating flexibility.
8. It gives high ratio of power output to fuel.

COMPARISON OF VARIOUS POWER PLANTS

1. Thermal power plant Vs Hydro-plant:

Sl. No.	Thermal power plant	Hydro power plant
1.	Initial cost is low.	Initial cost is high.
2.	Located near to load center.	Not like that
3.	Transmission losses are less.	Transmission losses are high .
4.	Power production is not dependent on nature's mercy.	It is only dependent on nature's mercy.
5.	Construction time is less	Initial construction requires long time.
6.	Power generation cost is high	Power generation cost is less.
7.	Air pollution is more.	No air pollution.
8.	Fuel transportation is difficult.	No fuel transportation.
9.	Life of the plant is less.	Life of the plant is high.
10.	Efficiency of the plant is less.	Efficiency of the plant is high.
11.	Not suitable for peak load plant.	It is suitable.

2. Steam power plant Vs Nuclear power plant:

Sl. No.	Steam power plant	Nuclear power plant
1.	It is not suitable where water and coal resources are not available.	No such constraints.
2.	Fuel storage space is required.	No fuel storage space.
3.	Requirement of workmen is very high.	Can be managed with very less number of workmen.
4.	Capital cost is high.	Capital cost is less when size of plant is increased.
5.	No radioactive material.	Radioactive wastes.
6.	Space requirement is high.	Space requirement is less.
7.	Steam power plants are affected by weather conditions.	It will not be affected by adverse weather conditions.
8.	It requires large quantity of water.	It does not require large quantity of water.
9.	Large quantity of fuel is required.	Less quantity of fuel required.
10.	Maintenance cost is less.	Maintenance cost is high.
11.	Operating cost is high.	Operating cost is less.
12.	Steam power plant efficiency = 20 to 30%.	Nuclear power plant η = 30 to 32%.

3. Diesel power plant Vs Gas turbine power plant:

Sl. No.	Diesel power plant	Gas turbine power plant
1.	The efficiency of the diesel power plantis about 35 to 42%.	The efficiency of the simple gas turbinepower plant is 20 to 25%.
2.	Only particular fuel should be used.	The fuel of different qualities can be used in this plant.
3.	The work output is high.	The network output is less.
4.	It is not require special metals.	The unit is operated at high temperature and pressure so special metals are required.
5.	Cost of the plant is less	Gas turbine cost is high.
6.	Limited plant capacity.	Capacity of the plant is higher than dieselpower plant.
7.	Not suitable for continuous over loads.	It can be work on over loads.
8.	Lubrication cost is high	No lubrication cost is less.
9.	No ash-handling problem.	It has ash handling.
10.	Life of the plant is less.	Life of the plant is high when compared todiesel power plant.

Waste Disposal and Safety

Introduction:

Nuclear power is classified as clean energy source because of absence of noxious combustion products and a supply of fuel which will last for centuries when breeder reactors become operational. The nuclear power generation poses mainly two problems as follow:

(i) The management of radioactive waste, and
(ii) The danger passed in case of accident is very high and long standing.

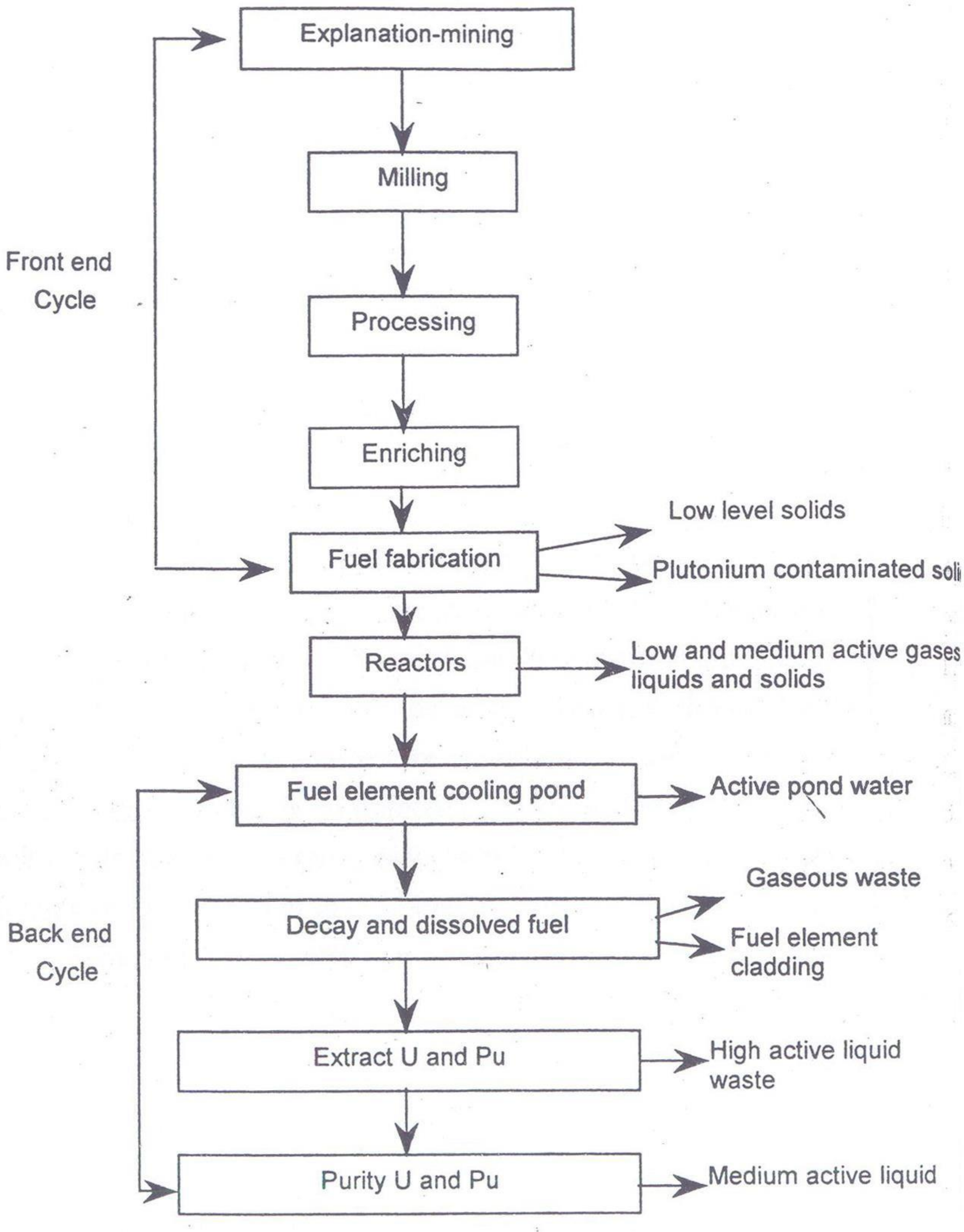
The radioactive emission during the operation of the power plant is negligible but the emission intensity is very high which comes out from the wastes. They emit large quantities of γ-rays which is very danger or for living matters. It is estimated that the radioactive waste coming out of 400MV power plant would be equal to 100 tons of radium daily. This much of radioactive waste disposed to the atmosphere would kill all the living organisms within the area of about 100 square kilometers. Therefore, safe disposal of nuclear waste is a major problem, and of course, very essential too. There are number of methods developed for the last 25 years to dispose off the different types of nuclear waste safety.

Wastes from fuel cycle:

Most nuclear power plants in operation or under construction in the world today are using, ordinary water cooled and moderated reactors such as pressurized-water reactor (PWR) and the boiling water reactor (BWR). Almost all current water reactors use slightly enriched Uranium dioxides fuel. A fuel has to go through the following cycle:

(i) Back end cycle that includes pre-reactor preparation
(ii) In-reactor use
(iii) Front end cycle that includes post reactor management

A typical fuel cycle with its waste coming out at different stages in shown in fig.3.13



Types of nuclear wastes:

The nuclear wastes are classified as follows:

(i) On the basis of half life
  (a) Fission products
  (b) Actirides
  (c) The neutron activation products
(ii) On the basis of the intensity of radiation
  (a) Low level waste
  (b) Medium level waste
  (c) High level waste

1. Fission products:

The wastes produced from reactor operations include fission products and Plutonium. The half-lives of most of the fission products are 30 years or less. But their toxic lifetime is of the order of 500 to 1000 years. Most of the fission products are initially radioactive and decay with the emission of β and γ-rays.

2. Actirides:

Actirides are produced in nuclear reactors as a result of neutron capture by Uranium. The most important is Plutonium. The other Actirides are Neptunium, Americium and Curium. The Actirides decay mainly by emission of α-particles until a stable isotope of load is formed. α-particles can be easily stopped and hence, Actirides do not require thick shielding. However, α-particles are very energetic and toxic if inhaled as dusts.

3. Neutron activation products:

These are produced when fast neutrons are absorbed by structural materials in the reactors as coolant, fuel cladding, etc. These products decay with the emission of β and γ radiations.

4. Low level wastes:

Low level wastes contain less than 10 nanocuries per gram of transuranium contaminants and that have low but potentially hazardous concentration of radioactive materials. Low level wastes are produced in almost all activities (such as power generation, medical, industrial, etc.) that involve radioactive materials. They require little or no shielding, and are usually disposed off in liquid form shallow land burial.

5. Medium level wastes:

Medium level wastes contain more than 10 nanocuries but less than 100 nanocuries per *gram* of transuranium contaminants. These wastes are mainly contaminated with neutron activation product isotopes.

6. High level wastes:

The high level wastes contain more than 100 nanocuries per *gram* of transuranium contaminants. These are generated in the reprocessing of spent fuel. The spent fuel is withdrawn from the reactor and placed in a water pond. The heat is removed in the water pond and shorter lived radianuclides decay. The pond wastes are continually treated to remove activity due to release of fuel from defective cladding. The spent fuel is then transferred to the reprocessing plant where cladding that contains the fuel is removed and the fuel is dissolved in nitric acid. The U^{235} and Pu^{239} are then removed laving 99% non-volatile fission products behind in solutions known as *"highly active liquid waste".*

Effects of high-level wastes:

It is important to study the effects of high level wastes to biological systems. The principle effect is the destruction of body cells in the vicinity of the irradiated region due to interaction of the radiation and the tissue. There are the following three ways through which the interaction between radiation and tissue is manifested.

1. **Ionization:**

The formation of ion-pair in tissue requires 32.5eV of energy. When a single 1Mev β-particle is stopped by tissue about 3100 ion-pairs are formed. If $1cm^2$ area of tissue surface is subjected to a beam of β-particles/cm^2/sec, about $31x10^6$ ion-pairs are formed in each second. This absorption results in complete damage of tissues in the body of man or beast or bird.

2. **Displacement:**

If the energy of the impinging particle is sufficient high, an atom in the tissue is displaced from its normal lattice position with possible adverse effects. Neutron and γ-radiation result in atomic displacement.

3. **Absorption:**

Absorption of neutron by a tissue nucleus results in forming a radioactive nucleus and changes the chemical nature of the nucleus. This casus malfunctioning of the tissue cell and cell damage causes severe biological effects including genetic modifications.

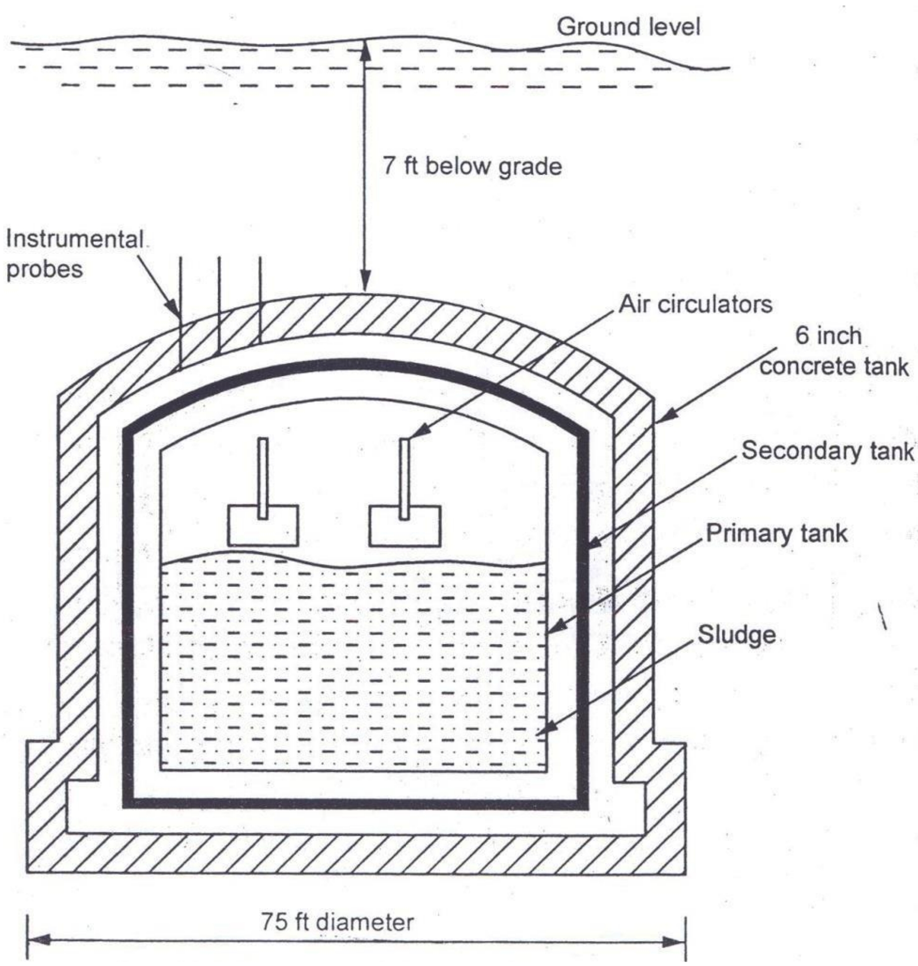
Nuclear waste disposal:

Many ends of radioactive wastes such as gaseous, liquid and solid are formed in the various phases of nuclear fuel cycle. These wastes must be disposed off in such a manner that there is no harm to human, animal or plant life. Solids of low and medium level wastes are buried at depths of few meters at carefully selected sites. Gaseous wastes are discharged to the atmosphere through high stacks. Liquids having low or medium level of radioactivity are given preliminary treatment to remove most of the activity in the form of solid precipitate and then discharged in dry wells or deep pits.

Different methods for various nuclear wastes disposed are discussed below:

1. **Disposal of level solid waste:**

Low level solid waste requires little or no shielding. It is usually disposed off by keeping it in a steel or concrete tank. These tanks are buried either few meters below the soil or kept at the bed of the Ocean. This is shown is fig.3.14.



2. **Disposal of medium level solid waste:**

Medium level wastes are mainly contaminated with neutron activation product isotopes. They are in corporate into cement cylinders and cement in non-combustible and provide shielding against external exposure. Cement is also having the ability of resistance to reach by ground water.

3. **Disposal of high level wastes:**

Spent fuel from the nuclear reactor can either be stored directly or reprocessed. The storage system avoids the coasts and hazards associated with a reprocessing plant. The second method, reprocessing, utilizes the unused uranium, converted Plutonium and other radioisotopes for the use in wide variety of services, such as isotope generators, medicine, agriculture, and Industry.

Reprocessing of spent fuel is done by dissolving it in nitric acid then removing the converted Plutonium and unspent uranium by solvent extraction. The remaining solution contains more than 99.99% of the non-volatile fission products plus some constituents of the cladding of the fuel elements, traces of plutonium, uranium.

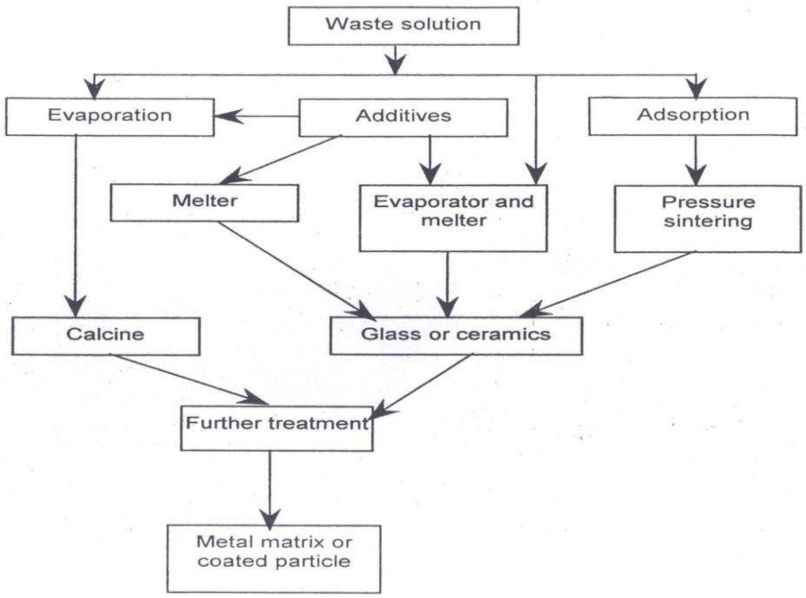
The remaining solution constituents the high level wastes. It usually concentrated by evaporation and then stored as an aqueous nitric acid solution, usually in high integrity stainless steel tanks. However, permanent storage in liquid form requires continuous supervision and tank replacement over an indefinite period of time.

The conversion of the liquid wastes to a solid form is very important. This avoids leakages, requires less supervision, and is more suitable for final disposal. Advanced process is currently being developed. This solid product should maintain its mechanical strength. Ideally, it should have a low leak rate.

Glasses and ceramics are now considered to be most suitable forms for this final disposal. This involves evaporation and de-nitration (or calcinations) to form a granular or solid calcine. This is considered an interim product, since it does not meet all the above requirements. It is treated further by being mixed additives and is then melted to form glasses or ceramics.

A second process involves mixing the additives with the original waste solution, evaporating, de-nitrating and melting this mixture to form glasses or ceramics.

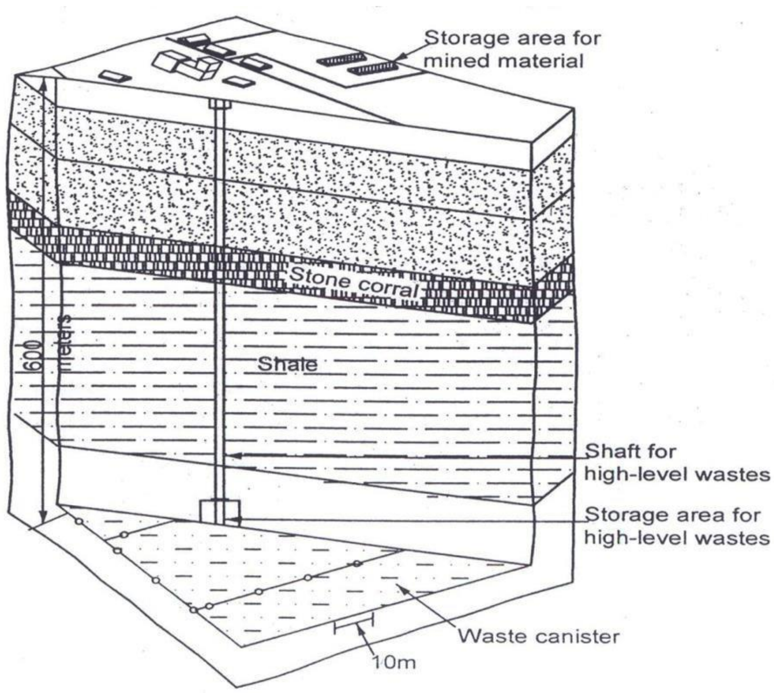
A third process uses an adsorption process and treatment at high temperature to produce the ceramics.



Most solidification plants produce off gases-of steam and oxides of nitrogen that usually contain some fine particulate carryover and volatile radio-nuclides. These gases must be treated. All processes involve high temperature as well as high levels of radioactivity.

1. **Underground disposal of high level waste:**

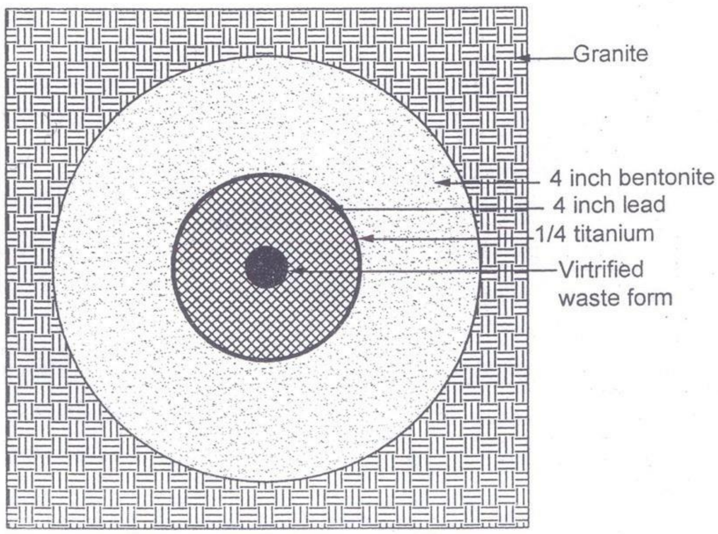
The final disposal of the wastes with or without the above treatments is also of major concern. Many countries are undertaking activities involving underground disposal in deep geological formation.



These activities include the investigation of suitable sites and suitable methods of storage in these sites.

The main objectives are the protection of present and future populations from potential hazards. The suitable sites must be free of flowing ground wastes, but the storage vessels must demonstrate reliability even in flowing condition.

A cavity is excavated 511*m* depth in salt mine and the cylinders are stored in this cavity. It has a special advantage that the salt is strong absorber of radioactive emissions and has good thermal conducting which helps to keep the temperature within acceptable limit.



The solidified waste is placed in canisters which are stored in holes in rock salt with a spacing of about 10m to allow for the efficient dissipation of energy without exceeding permissible temperature limits of either the canisters of the salt. It is estimated that each canister will require about 100m^2 of salt for cooling.

The cross-section of a canister of Swedish design for the disposal in granite. It shows vitrified waste surrounded by 4 inch of lead, 0.25 inch of titanium, 4 inch of bentonite (an absorptive and colloidal clay mineral) and finally, granite.

4. Nuclear waste disposal in India:

Nuclear waste disposed from various power plants in India is to be permanently buried at a site in Rajasthan. The Atomic Energy Board has identified 100km^2 area there. The vault is dug out in granite rocks 100m below the ground. These vaults will hold all wastes from India's nuclear power plants. The radioactive waste is first embedded in tough, boro-silicate vitrified glass. Each glass block is enclosed by stainless steel box and two such sides and stakes in the vault. The vitrified glass blocks in which the radioactive wastes are held must be stored in waste for at least 25 years before final burial. One such facility is operating at Tarapur.

5. **Waste disposal in Ocean:**

The countries situating near the sea are considering the ocean floor as a safe place for the permanent nuclear waste disposal. The floors of the deep ocean provide safe and potential waste disposal sites for solidified high level waste. It should be taken are that the fish and sea wilds are not affected by the disposal of nuclear wastes. The following points should be considered for selecting sea site.

(i) Waste container design and their thermal conductive and corrosive properties.
(ii) Water flow current and sea bed properties.
(iii) Water flow pattern at the site and the sea for predicting the movement and dilution of the dissolved species.
(iv) Chemical and thermal properties of the sediments and underlying rocks concerning absorption and migration of long lived nuclides must be known.

The various countries like USA, Canada and Japan are using this system of disposal.

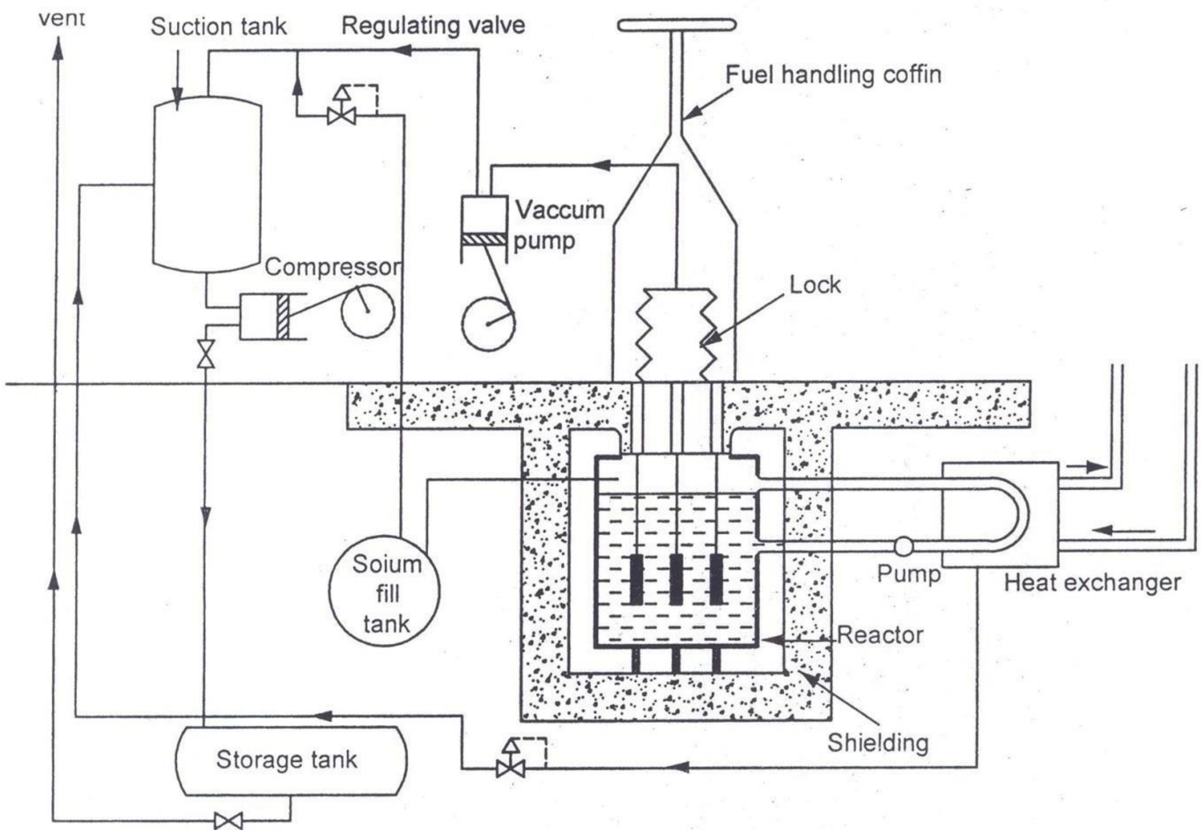
Nuclear waste disposal in Ocean can be considered safe, it wastes are kept in intermediate storage. They decay to a sufficiency low level. The corrosion resistant containers can be kept on the sea floor, if they lost for 300 years or more. This provides sufficient time for the fission products to decay.

6. **Nuclear waste gas disposal:**

The various gases such as Krypton, iodine, CO_2, tritium and strontium are released during the nuclear fuel consumption. When these gases are disposed into atmosphere, it creates lots of problems to mankind. Gases like iodine and strontium are strong radioactive gases which are absorbed by the plants and enter into human body through the food.

Cesium is absorbed by muscle and strontium in bones and paralyses the health. For removing Krypton and iodine gases coming out from spent fuel, various methods are developed. Methods for removing tritium and CO_2 are also being developed. Krypton is removed by cryogenic treatment and packed in gas cylinders under high pressure. Another advanced method is also developed for storing the recovered krypton in a sodalite Zeolite matrix at atmospheric pressure. Iodine can be removed from off-gases by caustic scrubbing or HNO_3 scrubbing processes for separating and concentrating tritium are based on voloxidation, pyro-chemical processing and isotropic enrichment.

Processes for removing radioactive CO_2 by caustic scrubbing and adsorption on molecular sieves are also developed.



The radioactive gases collected and stored in the tank buried in the ground and disposed off to the atmosphere when radioactivity level comes down sufficiently. The gaseous wastes problem arises from the possibility of ruptures in the fuel element cladding. This might release gaseous fission primary sodium tank consists of radioactive detector sensor which senses the radioactivity. If excess radioactivity is detected, this gas will be pumped into radioactive storage tank. It will also activate the values to shut the gas stream being vented into a compressor suction tank. From the suction tank, the compressor forces this gas into a storage tank where it can undergo radioactive decay. The tank capacity may be from $150m^3$ at $7bar$. When the radioactivity in the tank comes sufficiently low, this gas may be bled from the storage tanks and discharged out through the vent line.

UNIT-V

ECONOMICS OF POWER PLANTS

Important Terms and Definitions

1. Connected load:

It is the combined continuous rating of all the receiving apparatus on consumer's premises. If a consumer has connections for 3 lamps of 40 watts each, and power point of 500W for refrigerator and T.V. consuming 60W, then the total connected load of the consumer = 3 x 40 + 500 + 60 = 680W.

2. Demand:

It is the load that is drawn from the source of supply at the receiving terminals averaged over a suitable and specified internal of time.

3. Maximum demand:

It is the maximum load which is used by a consumer at any time. It is determined by measurement, according to specifications over a prescribed interval of time. It can be less than or equal to connected load. But generally, the actual maximum demand is less than the connected load because all the loads never run in full load at the same time.

4. Demand factor:

It is the ratio of actual maximum demand of the system to the total connected demand of the syste.

$$\text{Demand factor} = \frac{Actual\ maximum\ demand}{Total\ Connected\ demand}$$

5. Load factor:

It is the ratio of average load over a given time interval to the peak load during the same time interval.

$$\text{Load Factor} = \frac{Average\ load\ over\ a\ given\ time\ interval}{Peak\ load\ during\ the\ same\ time\ interval}$$

Load factor is always less than unity. It plays an important part on the cost of power generation per unit. The higher the load factor, the lesser will be the cost of power generation per unit for the same maximum demand.

6. Capacity factor or plant capacity factor:

It is the ratio of actual energy produced in kilowatt hours (kWhr) to the maximum possible energy that could have been produced during the same period.

$$\text{Capacity factor} = \frac{Actual\ energy\ produced\ in\ kWHr}{Rated\ capacity\ of\ \text{the}\ plant} = \frac{E}{C\ x\ t}$$

$$\text{Capacity factor} = \frac{Average\ \ load}{Rated\ capacity\ of\ \text{the}\ plant}$$

Where, E Energy produced in kWhr

C Capacity of the plant in kW

t Total number of hours in given period.

If the rated capacity of the plant is equal to the peak load, then the load factor and capacity factor will be nemerically equal.

7. Utilisation factor:

It is the ratio of maximum load to the rated capacity of the plant.

$$\text{Utilisation factor} = \frac{Maximum\ \ load}{Rated\ capacity\ of\ \text{the}\ plant}$$

8. Reserve factor:

It is the ratio of load factor to capacity factor.

$$\text{Reserve factor} = \frac{Load\ \ factor}{Capacity\ factor}$$

9. Diversity factor:

It is defined as the ratio of sum of individual maximum demand to the actual peak load of the system.

$$\text{Diversity factor} = \frac{Sum\ of\ individual\ maximum\ demand}{Actual\ peak\ load\ of\ \text{the}\ system}$$

10. Plant use factor:

It is the ratio of energy produced in a given time to the maximum possible energy that could have been produced during the same period of operation.

$$\text{Plant use factor} = \frac{Actual\ energy\ produced\ in\ given\ time\ period}{Maximum\ possible\ energy\ produced\ by\ \text{the}\ plant}$$

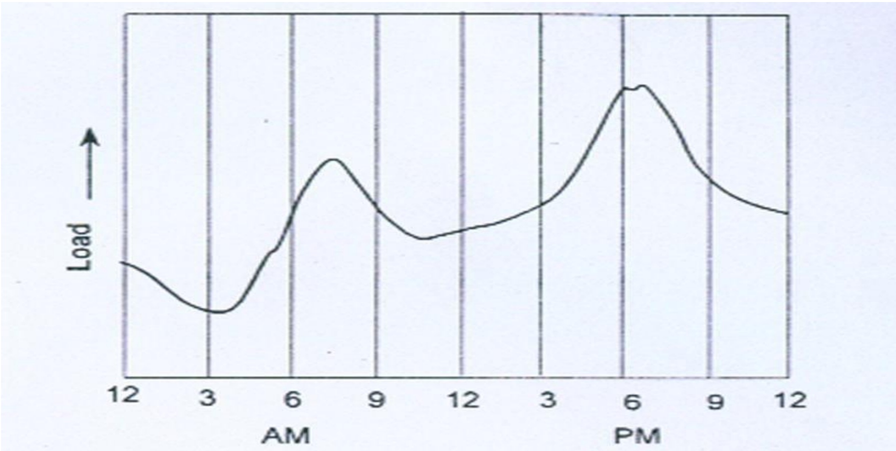
$$= \frac{E}{c\ x\ t_1}$$

Where, t_1 actual number of hours when the plant has been in operation.

11. Load curve:

It is a graphical representation which shows the power demands for every instant during a certain time period. It is drawn between load in kW and time in hours. If it is plotted for 1 hour, it is called hourly load curve and if the time is considered is of 24 hours then it is called daily load curve. When it is plotted for one year (8760 hours), then it is called annual load curve.

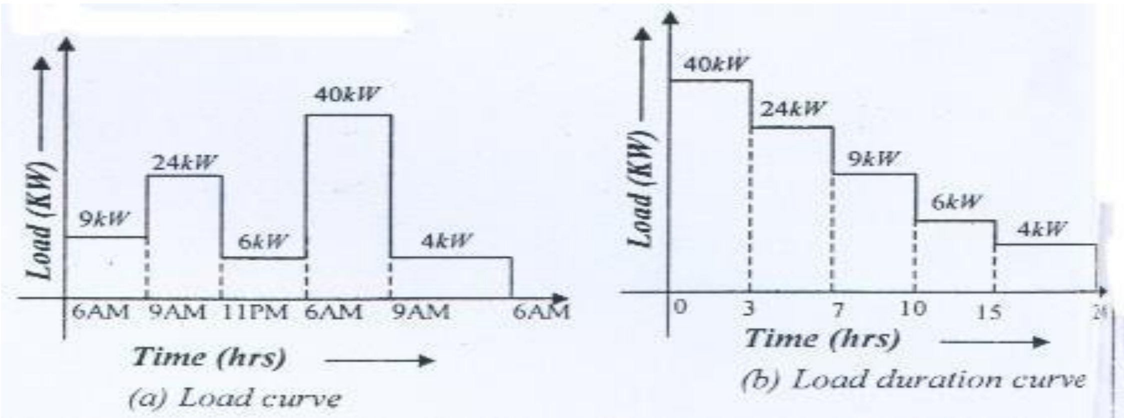
The area under the load curve represents the energy generated in the priod considered. If we divide the area under the curve by the total number of hours, then it will give the average load on the power station. The peak load indicated by the load curve represents the maximum demand of the power station.



Load curve

This curve gives full information about the incoming load and helps to decide the installed capacity of the power station. It is also useful to decide the economical sizes of various generating units.

12. Load duration curve:



Load duration curve

This curve represents the re-arrangement of all the load elements of load curve in

A typical daily load curve for a power station is shown in fig. It may be observed that the maximum load on power station is 40kW from 6 to 9P.M. Similarly, other loads of the load curve are plotted in decreasing order in the fig (b). This curve is called load duration curve.

It is observed that the area under both the curves is equal and represents the total energy delivered by generation station. Load duration curve gives a clear analysis about generation power economically.

Types of loads:

The various types for loads are described below:

(i) **Residential load:** This type of load includes domestic lights, power needed for domestic appliances such as radios, television, electric cookers, water heaters, refrigerators, grinders etc.

(ii) **Commercial load:** It includes lighting for shops, advertisements and electric appliances used in shops, hotels and restaurants etc.

(iii) **Industrial load:** It consists of load demand of various industries.

(iv) **Municipal load:** It consists of power required for street, lights, water supply and drainage purposes.

(v) **Irrigation load:** It includes electrical power required for pumps to supply water to fields.

(vi) **Traction load:** It consists of power required for tram cars, trolley, buses and railways.

13. Dump power:

This term is used in hydroelectric power plants. It shows the power in excess of the load requirements.

14. Firm power:

It is the power which should always be available even under emergency conditions,

15. Prime power:

The power which may be mechanical, hydraulic or thermal that are always available for conversion into electric power.

16. Base load and peak load power plants

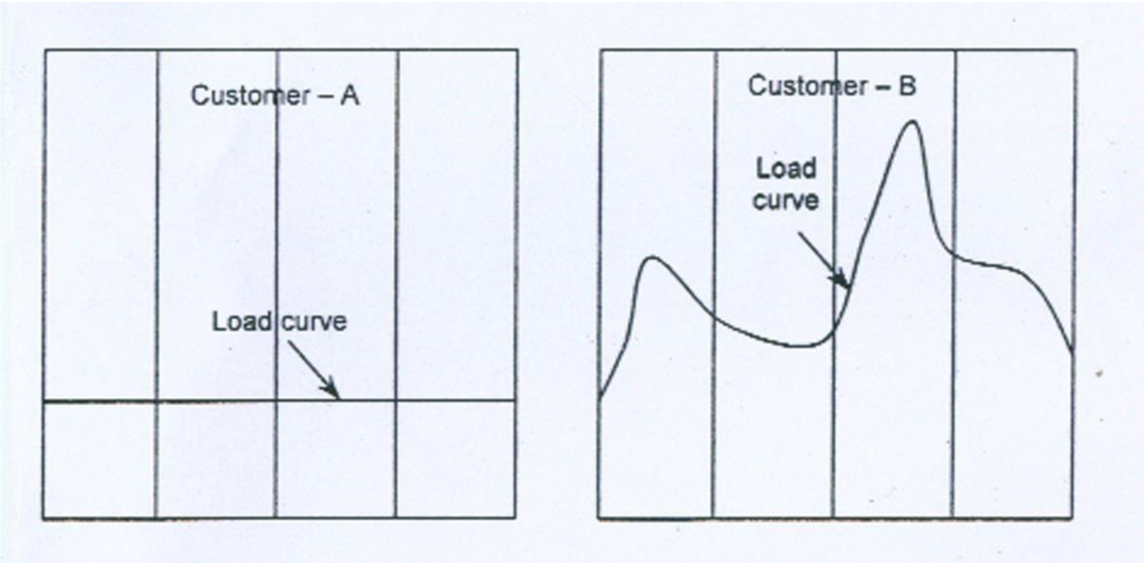
The base load is the load below which the demand never falls and is supplied 100% of the time. The power plants used to supply base loads are called *base load power plants.* The base load power plants are loaded heavily. Operating cost of such plants is very important. A high capital cost is permissible, if low operating costs can be maintained. Hydro and nuclear power plants are usually classified as base load power plants.

The peak load is the load which occurs at the top portion of the load curve. The power plants which are used to supply peak loads are called as *peak load power plants.* The peaking load occurs for about 15% of the time. The peak load power plants are of smaller capacity, run for a shorter period in the year and work at low load factors. Peak load power plants should be capable of quick starting. Since peaking load plants are used only for a small fraction of time, the fuel cost is not of major importance. Minimum capital cost should be the criterion. Diesel power plants are usually classified as peak load power plants.

ACTUAL LOAD CURVES

Load curve is a graphical representation which shows the power demands for every instant during certain time period. By drawing these load curves, the peak load can be identified and hence the capacity of power plant can be judged.

Fig. shows two load curves in which the energy consumed by the customer is same but the way adopted to use is different. The design of any power plant is bases on the way that the customer adopted to use energy. The customer X and Y consume same amount of energy but the nature of consumption is different.



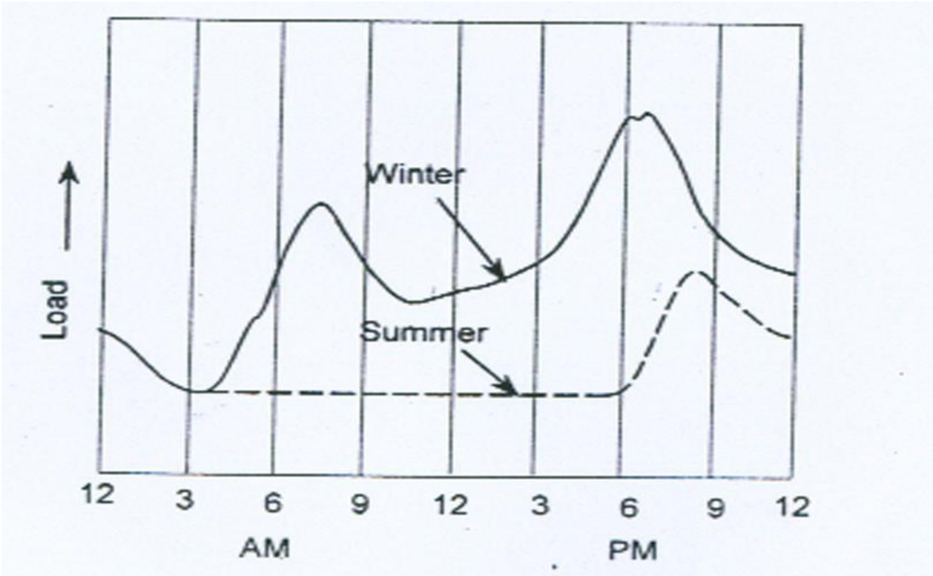
Constant and variable demand load curve

In fig, the peak load is far greater than the first. Therefore, the generating capacity of the plant required to supply the load of Y is greater than the capacity required to supply the load of X. The plant designed for customer Y is not only bigger in size but it also runes underload conditions for the majority of the period. Therefore, the cost of energy supplied to Y may be more than the cost of energy supplied to X even the total energy consumed by both customers is same.

As explained earlier, the different types of loads for different types of customers are explained below:

1. Residential load curve:

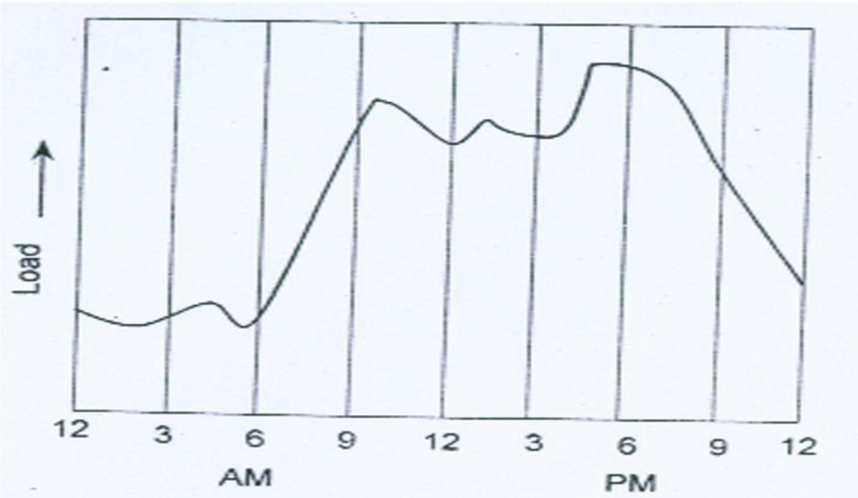
Fig. shows as typical residential load curve. During the early morning hours (6A.M. to 9A.M.), the energy is required for light, fans, refrigerators, water heaters. After the breakfast (at 9A.M.), the demand decreases and fairly remains constant till about 4 P.M. After 4 P.M, the demand is beginning to increase and attains its peak at 6P.M. The peak load remains almost constant up to 8P.M, after that it decreases rapidly and attains minimum at 12P.M, the foresaid statements are applicable for summer season.



Residential load curve

But during winter season, the load remains constant during day time ad will be minimum. After 5P.M. the load rapidly approaches its peak. The high demand occurs at about 8P.M.

2. Commercial load curves:



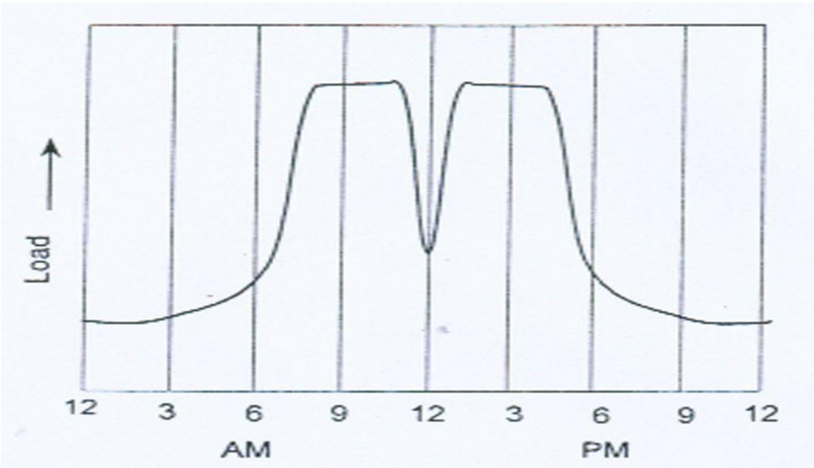
Commercial loads of shops, offices and hospitals

Fig. shows a typical load curve for commercial usage like shops, office, restaurants etc. The lighting in shops and office starts at 6A.M. for cleaning and sweeping and them it reaches peak at 10A.M. It remains constant more or less during 10A.M. to 4P.M. It increases further during

4 to 7P.M. as more lights are required. Then, the load rapidly falls during 7P.M. to 12P.M. as the offices remain closed.

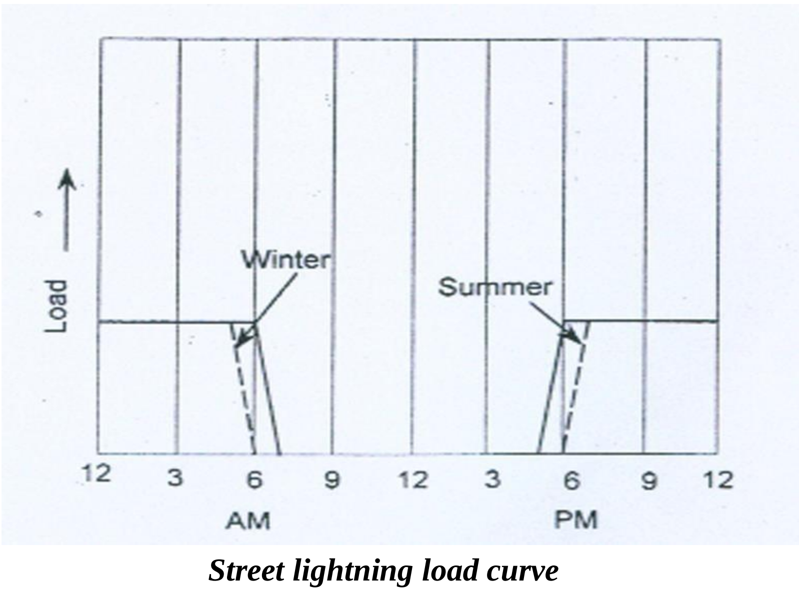
3. Industrial load curve:

Fig. shows a typical load curve for industrial community of on shift basis. In early morning from 5A.M. to 8A.M, the energy demand increases as some for the machinery starts for warming prior to operation. The entire industry starts running and energy demand remains constant from 8A.M. to shortly before noon. There is a heavy fall in energy demand during 12 to 1P.M. due to lunch hours. By 2P.M. again, the load attains the same level as at 8A.M, Shortly before 5P.M, the load starts to drop as the shift of work ends. By 6P.M. most of the machines are shut down and load gradually decreases to minimum until 10A.M. Then the minimum demand continues till the start of next working day.



Industrial load curve for one shift

4. Street lighting load curve:

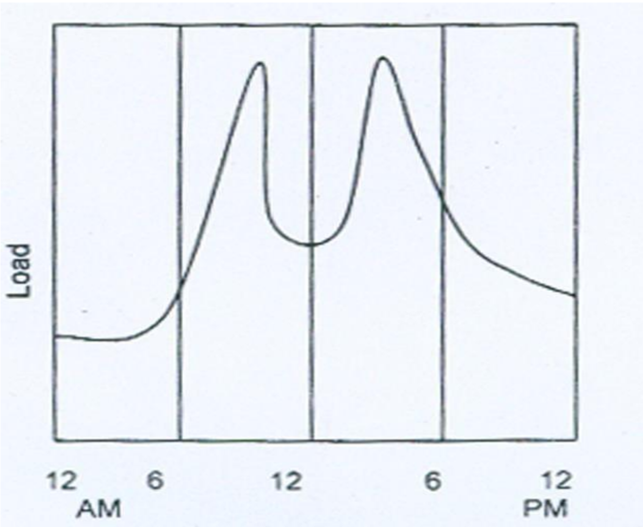


Street lightning load curve

Fig. shows a typical local curve for street lighting. Street lighting is the only form of load that does not exhibit peak demands. Normally, all streetlights are simultaneously made 'On' at 6P.M. and are turned 'Off' at 6A.M. The load demand remains more or less constant during these hours.

5. Urban traction load curve:

Fig. shows a typical load curve for urban traction. During midnight hours from 12P.M. to 5A.M, the demand tapers off as the service reaches its minimum level. As the early factory workers start for their work, the required train services increases rapidly and consequent load continuously rise as the factory workers are followed by office workers, school children, college students and early shoppers. The peak load reaches about at 9.30A.M. After 10P.M., the load rapidly diminishes as some of the trains return to the yards.



Urban load curve

The minimum load is reached at noon hours and then rises continuously until the evening rush hours. The load again reaches its peak at 5P.M. when most of the workers go back to their homes. The load after 6P.M. falls rapidly.

VARIABLE LOAD OPERATINGS

The variable load operation problem affects power plant design and operation as well as the cost of generation. The necessity of supplying a variable load influences the characteristics and the method of using the power plant equipment. The generation of power must be regulated according to the demand. For that purpose governing is necessary to achieve it. Quick response to varying load is another important requirement of the power plant.

A carful study of the load duration curve helps to decide the capacity of the base load plant and also of the peak load plant. The base load plant should be run at high load factor. The peak load plant should be of smaller capacity to reduce the cost of generation. It could be a gasturbine unit, pumped hydro-system, compressed air energy storage system or a diesel engine depending on the size and scope of availability.

If a whole load is to be supplied by the same power plant, the generation and prime mover must be able to take varying load as quick as possible without variation of the voltage or frequency of the system. When the load on the generator increases, it will show down the rotor and prime mover and therefore, it reduces the frequency. When the speed of the prime mover decreases, the governor must act. It is the function of the governor to control the supply of fuel to prime mover according to the load. It should be enough to bring the speed back to normal and pick up the load. Frequency stabilizers are used to maintain the frequency constant which may change due to response of the equipment.

In case of thermal power plant, the raw material used are fuel air, and water to produce variable power. According to the requirement, the raw materials are supplied correspondingly with an increase in load on the plant, the governor admits more steam and maintains the turbine speed up to certain point, the governor responds rapidly with change in load but beyond this point changes are not so rapid. Because of fluctuating steam demand, it becomes very difficult to secure good combustion and steady steam pressure. Therefore, the design of thermal plants for variable loads is always more difficult than diesel or hydroelectric power plants and it is always desirable to allow the thermal plant to operate as base load plant.

Economic load sharing between base load plant and peak load plant is desirable. Steam power plant, and nuclear power plant are preferred as base load plants whereas diesel power plant and hydro power plant can be used as peak load plant. Hydro power plant with larger water storage can also be used as base load plant.

COST OF ELECTRICAL ENERGY

A power plant should provide a reliable supply of electricity at minimum cost to the customer. The cost of the electricity is determined by the following costs:

FIXED COST OR CAPITAL COST

It is the cost required for installation of complete power plant. This cost includes the cost of land, buildings, equipments, transmission and distribution lines, cost of planning and designing the plant and many others. It also consists of interest, taxes, depreciation, insurance etc.

1. Land, building and equipment cost:

The cost of land and building does not change much with different types of power plants but the equipment cost changes considerably. The cost of building can b reduced by eliminating the superstructure on the boiler house and turbine house. To reduce the cost of equipment, unit system may be adopted, reduced by simplifying the piping system and elimination of duplicate system such steam headers and boiler feed heaters.

The cost of the equipment or the plant investment cost is usually expressed on the basis of *kW* capacity installed. The per *kW* capacity may not vary for various thermal power plant where as for hydro electric power plant, it changes a lot because the cost of hydroelectric power plant depends on the availability of foundation, types of dam available head and spillways used.

2. Interest:

The money needed for investment in an enterprise may be obtained as loans, through bonds and shares. Interest is the difference between money borrowed and money returned. The rate of interest may be simple rate expressed as % per annum or may be compounded. A suitable rate of interest must be considered on the capital invested.

3. Depreciation cost:

It is the amount to be se aside per year from income to meet the depreciation caused by the age of service, wear and tear of machinery. It also covers the decrease in value of equipment due to obsolescence.

The power plant and equipment in the plant will have a certain period of useful life. After years of use, the equipment loses its efficiency or becomes absolute and needs replacement. Sometimes, Equipment may have to be changed even when fairly new, if more efficient equipment has come into the market. Some money is put aside annually to enable this to be done when necessary. This is known as *depreciation fund.*

The following methods are generally used to calculate the depreciation cost:

(i) Straight line method.

(ii) Sinking fund method.

(iii) Diminishing value method.

(i) Straight line method:

It is the simplest and commonly used method. It is based on the assumption that depreciation occurs uniformly for every year according to a straight-line law. They money saver neglects any interest.

According to this method, annual amount to be set aside is calculated by the following expression.

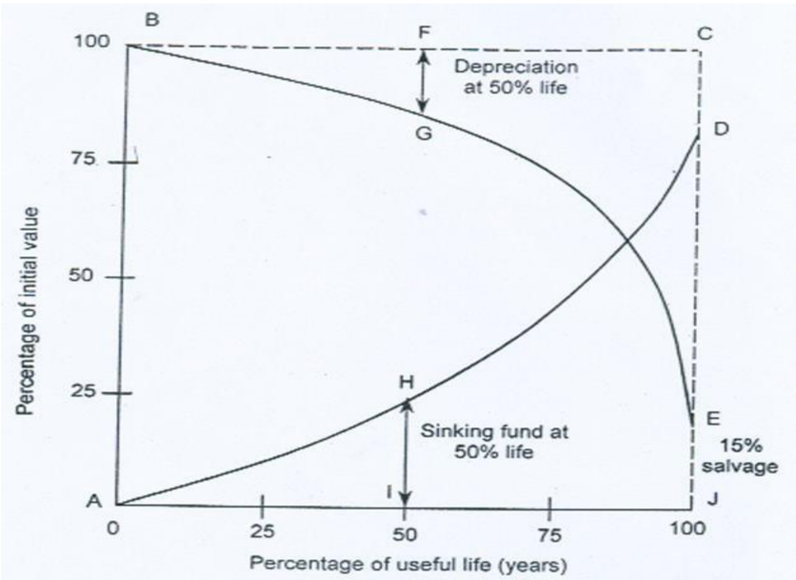
$$A = \frac{P - S}{n}$$

Where, P = Capital cost of the equipment.

S = Salvage value at the end of plant life.

n = Life of plant in years.

The straight line method is represented by the fig.



(ii) Sinking fund method:

In this method, a sum of money is set aside every year for *N* years and invested to earn compound interest. This method is bases 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. Let *A* is the annual deposit and '*I*' is the interest compounded annually when the deposit is invested

Then amount set aside at the end of first year = A

Amount at the end of second year = A + interest on A

$= A + Ai = A\,(1 + i)$

Amount at the end of third year = $A(1 + i)$ + interest on $A\,(1 + i)$

$= A(1 + i) + A(1 + i)$

$= A(1 + i)^2$

Similarly, at the end of 1th year = $A(1 + i)^{n-1}$

Total amount accumulated in N years (say x) = Sum of the amounts accumulated in n years

$$X = A + A\,(1 + i) + A\,(1 + i)^2 + \ldots + A\,(1 + i)^{n-1}$$

$$= A\left[1 + (1+i) + (1+i)^2 + \ldots + (1+i)^{n-1}\right] \quad \text{---------- (i)}$$

Multiplying the above equation (i) by $(1 + i)$, we get

$$= (1+i)x = A\left[(1+i) + (1+i)^2 + \ldots + (1+i)^n\right] \quad \text{---------- (ii)}$$

Subtracting equation (i) from (ii), we get

$$xi = A\left[(1+i)^n - 1\right]$$

$$x = A\left[\frac{(1+i)^n - 1}{i}\right]$$

Where x is the sum of amounts saved together with interest earnings

Therefore, x = (P – S)

Where, P = Capital cost of the equipment

S = Salvage value at the end of Nth year

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

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

(iii) **Diminishing value method:**

In this method, the amount set aside per year decreases as the life of the plant increases. The following example gives clear idea of this method.

Say the equipment cost as Rs. 40000. The amount set aside is 10% of the initial cost at the beginning of the year and 10% is the remaining cost with every successive year. Therefore,

The amount set aside during first year

$$= 40000 - \frac{10}{100} x 40000 = Rs.36000.Balance$$

The amount set aside during 2nd year

$$= 36000 - \frac{10}{100} x 36000 = Rs.32400.Balance$$

The next installment during third year

$$= 32400 - \frac{10}{100} x 32400 = Rs.29160.Balance$$

The main disadvantage of this method is that it requires heavy investments in the early years when the maintenance charges are minimum and it goes on decreasing as the time passes but the maintenance charges increase.

4. Insurance:

Now-a-days, insurance plays a vital role in the country. It becomes necessary to insure the costly equipments especially for the \fire or accident risks. A fixed sum is set aside per year as insurance charges. The annual premium may be 2 to 3% of the equipment cost but the annual installment is quite heavy when the capital cost of the equipment is high.

5. Management cost:

This cost includes the salary of the management employees working in the plant. This must be paid whether the plant is working or not. Therefore, this cost is included in the fixed cost.

OPERATING COSTS

The operational cost includes the cost of fuel, cost of lubricating oil, greases, cooling water, cost of maintenance and repairs, operating labour cost, supervision cost and taxes. This cost varies with amount of electrical energy produced.

1. Cost of fuel:

The fuel consumption depends on the amount of electrical energy produced. As load on the prime movers increases, the fuel consumption will increase and so does the cost. The efficiency of the prime mover is the highest at the rated load. At lower loads, the efficiency decreases and so, the fuel consumption will increase. The selection of the fuel and the maximum economy in its use are, therefore, very important consideration in thermal plant design. The cost of fuel includes not only its price but also its transportation and handling costs also. The cost of fuel depends on the calorific value and availability.

2. Lubrication 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 the power plant as the efficiency of the power plant decreases with the age.

3. Cost of maintenance and repairs:

In order to avoid breakdowns, maintenance is necessary. It includes periodic cleaning, adjustments and overhauling of equipments. The material used for maintenance is also charged under this head.

It is necessary to repair when the plant breakdown or steps due to faults in mechanism. The repairs may be major or minor and are charged to the depreciation fund of the equipment. This cost is higher for thermal power plants than hydro power plants.

4. Cost of operating labour:

This includes the salary of the operating labour working in the plant. Maximum labours are needed in a thermal power plant using coal as a fuel. A hydro power plant or a diesel power plant of same capacity requires a lesser number of labours. In automated power plant, labour cost is reduced to a great extent.

5. Cost of supervision:

In includes the salary of the supervising staff. A good supervision reduces the breakdowns and extends the plant life. The supervising staff includes the superintendent, chief engineer, engineers, store incharges, purchase officers etc.

6. Taxes:

The various taxes are included in this head. These are income tax, sales tax, provisional tax, commercial tax etc.

The total cost of energy produced is the sum of fixed charges and operating charges.

Total cost = Fixed costs + Operating costs.

ECONOMIC LOAD SHARING BETWEEN POWER PLANTS

Different power plants such as hydro, thermal, nuclear, gas turbine, MHD etc are operated combinedly to give greater reliability and maximum economic benefits. When the number of stations works in combination with each other to supply the power to the consumers, the system is known as *interconnected system.*

In an interconnected system, the major problem is division of load among the power plants. The load distribution among the power plants depends upon the operating characteristics of the power plant. The distribution of load amount the power plant in an interconnected system is done in such a way that the overall economy is achieved.

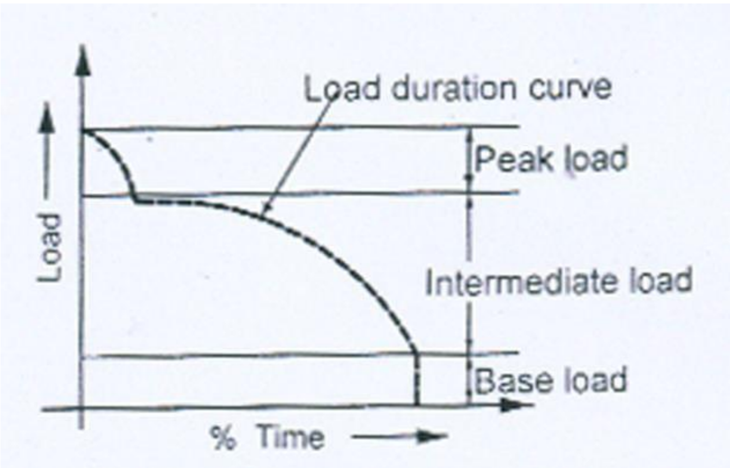


Fig.shown as load duration curve. The whole area under the load curve is divided into three parts as base load, intermediate load and peak load. It is not economical to design a power plant to load to the maximum peak load as it works in under-load condition for the most of time. In order to achieve maximum possible is the loading of the most efficient power station in the order of merit of low fuel cost. It is made possible by establishing central control room which can control number of power plants simultaneously in the grid system. This also saves the fuel consumption per kW of power generation. In addition to the saving in fuel consumption, there is also saving due to reduced spare capacity required and also due to the employment of large size units.

Base load station takes up the load on the lower region of the load curve. This station is highly efficient and operates on three shift basis throughout the year. The fixed cost of these plants is high. Capacity factor is the index of the return on the capital investment on the plant. Continuous operation of base load plant at high load factor improves the capacity factor and this makes operation of the base load plant an economic proposition. Hydro and nuclear power plants are usually classified as base load plants.

Intermediate stations operate on two or single shift basis. The capital cost of such plant is lower and fuel cost is higher than base load plants. Thermal stations fall under this category.

Peak load plants operate only when required for short times under the upper part of the load curve. Plant capacity factor is low as it is operating for short duration. Fuel is very high but total capital cost is less. Diesel and gas turbine plants are classified under this category.

For a known load duration curve, the economic load sharing between base load and peak load plants operating in parallel can be found as follows.

Let the operating costs are known and these are given by

$$C_2 = A_2(P - P_b) + B_2(N - N_P)$$

The cost of the system C is given by

$$C = C_1 + C_2 = (A_1 P_b + B_1 N_p) + \left[A_2 (P - P_b) + B_2 (N - N_p)\right]$$

The minimum total cost can be obtained when

$$\frac{dc}{dP_b} = 0$$

$$\therefore (A_1 - A_2) + (B_1 - B_2)\frac{dN_b}{dP_b} = 0$$

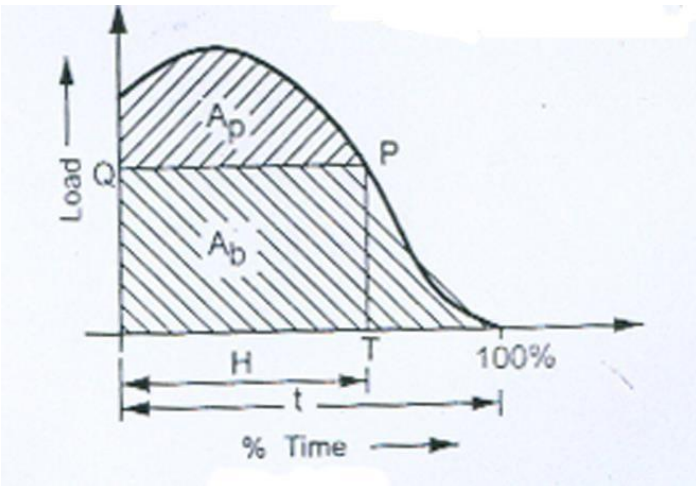
$$\therefore \frac{dN_b}{dP_b} = \left(\frac{A_1 - A_2}{B_1 - B_2}\right) hrs$$

Thus for economic load sharing, the area under the load curve is so divided by horizontal line that its magnitude is given by

$$H = \frac{A_1 - A_2}{B_2 - B_1} hrs$$

The indicates that for economic load sharing, peak load plant should work for H hrs per years. The value of H should be always higher.

$$\therefore A_1 > A_2 \text{ and } B_2 > B_1$$



A_1 is higher and B_1 is lower for base load plant as compared to peak load plant. Mark the point T on the x-axis of load curve for the distance of H hrs in percentage $\left(\frac{H}{8760} x100\right)$. Draw the vertical line through T which meets the load curve at point P.

Draw the horizontal line PQ as shown in fig. Now, the area A_p above the line PQ gives the energy generated by peak load plant and area below it gives the energy generated by the base load plant. The scale taken for drawing load curve is 1cm = x % along time axis, and 1cm = y in kW along the load axis.

$$\therefore 1cm^2 = (x\%)xy$$

100% = 8760 hrs

$$1cm^2 = \left(\frac{x}{100} x8760\right) xy \quad \text{in kWh}$$

If areas A_b and A_p in cm^2 are known, then

$$N_b = A_b \, x \left(\frac{x}{100} x8760\right) xy \quad \text{in } kWh \text{ -------- for base load plant}$$

$$N_p = A_p \, x \left(\frac{x}{100} x8760\right) xy \quad \text{in } kWh \text{ -------- for peak load plant}$$

Thus, the load sharing between the two power plants can be achieved and this results in overall efficiency of operation.

ENERGY RATES

The rate of energy sold to the consumers depends upon the type of consumers such as domestic, commercial and Industrial. The rate of energy also depends upon the total energy consumed and the load factor of the consumer.

The rate of energy is decided in such a way that the following items must cover within the energy rate:

(i) Recovery of capital cost invested for the generating power plant.

(ii) Recovery of the running costs such as operating cost, maintenance cost, metering the equipment cost, billing cost etc.

(iii) Minimum profit on the invested capital, since the power plant is considered as the profitable business for the government.

Determination of cost of each item mentioned here is simple but the allocation of theses items among various classes of consumers are rather difficult. This repairs considerable engineering judgment.

The general energy rate or tariff can be given by the following equation:

$$E = Ax+By+C$$

Where

E = Total amount of bill for the period considered

A = Rate per kW of maximum demand

x = Maximum demand in *kW*

B = Energy rate per *kW-hr*

Y = Energy consumed in *kW-hr* during the period considered

C = Constant amount charged to the consumer during each bill period. This charge is independent of demand or total energy.

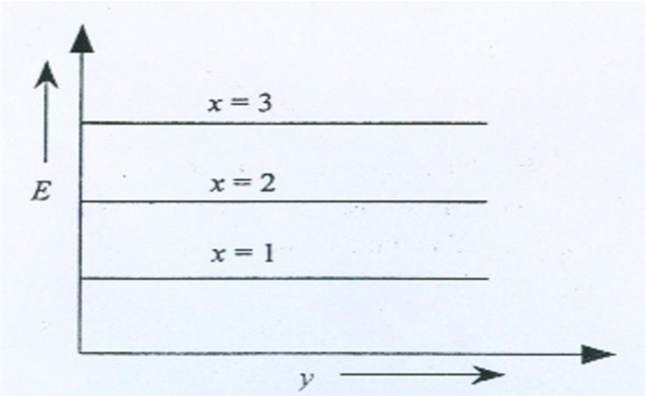
TYPES OF TARIFFS

The various forms used for changing the consumers as per their energy consumed and maximum demand are discussed below.

1. Flat demand rate:

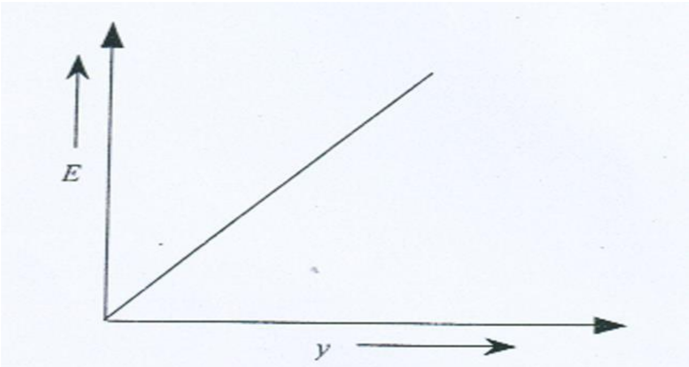
In this type of charging, the charging depends only on the connected load and fixed number of hours of used per month or year. This can be given by the following equation

$$E = Ax$$



Flat demand rate

The notations are taken as discussed above. This rate expresses the charge per unit of demand (*kW*) of the consumer. Here no metering equipments and manpower are required for charging. In this system, the consumer can theoretically use any a mount of energy upto that consumer by all connected loads. The unit energy cost decreases progressively with an increases energy usage. The variation in total cost and unit cost are shown in fig.



Straight meter rate

This type of charging depends upon the amount of total energy consumed by the consumer. The bill charge is directly proportional to the energy consumed by the consumer. This can be represented by the following equation.

$$E = By$$

The major drawbacks of this system are:

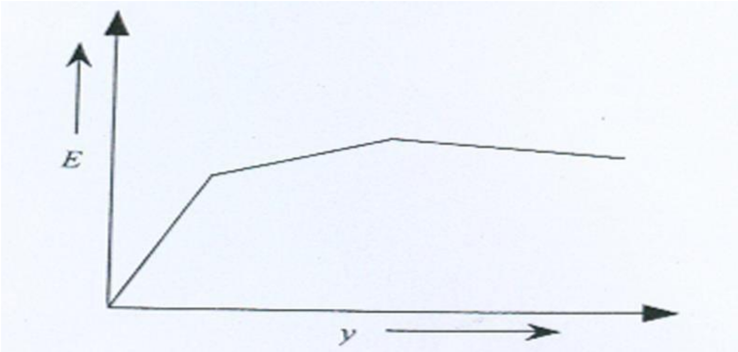
(a) In this type of system, the consumer using no energy will not pay any mount although he has incurred some expenses to the power station.

(b) The rate of energy is fixed, therefore this method of charging does not encourage the consumer to use more power.

The variation in total cost and unit consumed are shown in fig.

3. Block-meter rate:

In previous straight line meter rate, the unit charge is same for all magnitudes of energy consumption. The increases consumption spreads the item of fixed charge over a greater number of units of energy.



Block meter rate

Therefore, the price of energy should decrease with an increase in consumption. The block meter rate is used to overcome this difficulty. This method of charging is represented by the equation.

$$E = B_1 y_1 + B_2 y_2 + B_2 y_3 + ...$$

Where

$B_3 < B_2 < B_1$ and

$y_1 + y_2 + y_3 + ... = y$ (total energy consumption

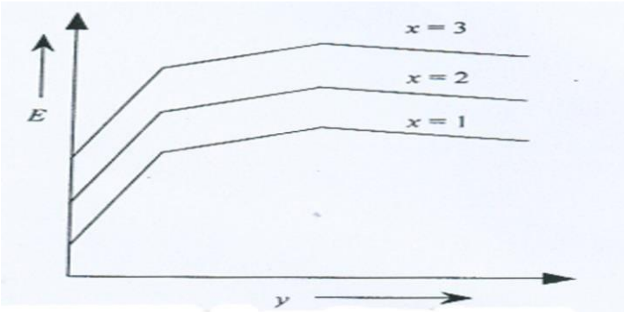
The level of $y_1, y_2, y_3, ...$is decided by the government to recover the capital cost. In is system, the rate of unit charge decrease with increase in consumption of energy as shown in fig

4. Hopkinson demand rate of Two-part tariff:

This method of charging depends upon the maximum demand and energy consumption. This method is proposed by Dr. John Hopknson in 1982.

This method of charging is represented by the equation

$$E = A+By$$



Hopkinson method of charging

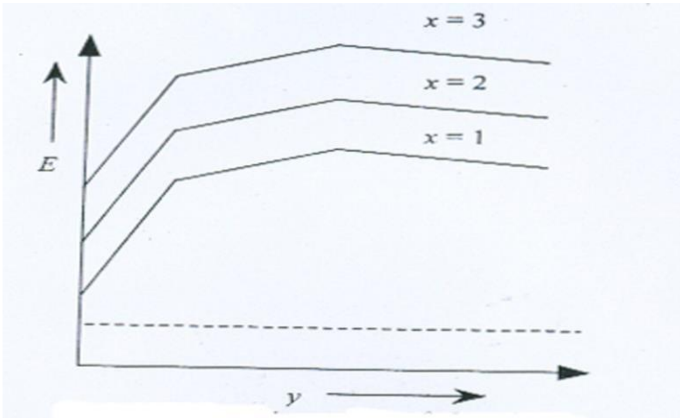
In this method, two meters are required to record the maximum demand and the energy consumption of the consumer. This method is generally used for the industrial consumers. The variation in total cost with respect to the total energy consumption taking x as parameter is shown in fig.

5. Doherty rate or three part tariff:

This method is proposed by Henry L. Doherty. In this method of charging, the consumer 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 etc.

This method of charging is expressed by the equation.

$$x = Ax+By+C$$

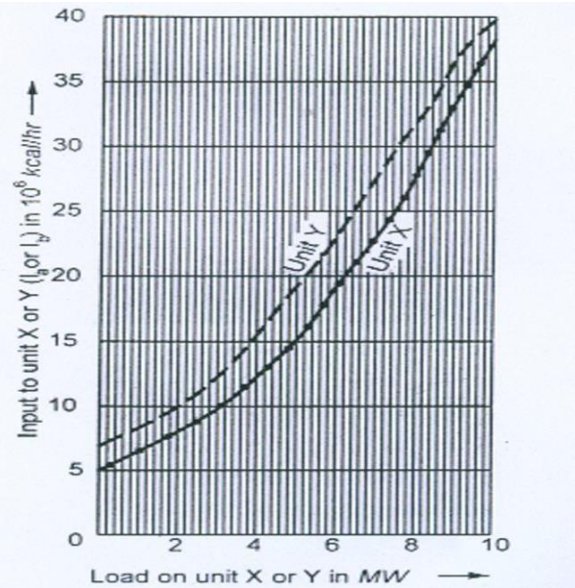


Doherty method of charging

This method of charging is most commonly used in Tamilnadu and all over India. In this method, the customers are discouraged to use more power when the generating capacity is less than the actual demand. For example, for the first 50*kW-hr* units the charging rate is fexed as, says Rs. 2.5/*kW-hr* and if it exceeds than this charge is rapidly increased as Rs. 3.5/*kW-hr* for next 100 *kW-hr* unit (i.e from 51*kW-hr* to 150*kW-hr*). This method is unfair to the customer, but very common in India and many developing nations.

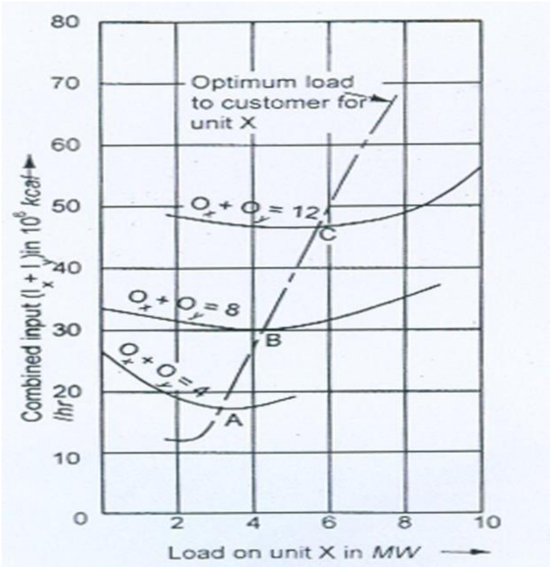
ECONOMICS OF LOAD SHARING BETWEEN GENERATORS

During design of power plants, prime importance is given to the economics of load sharing. Engineers are designing the power plant components such as boilers, heat turbines, heat exchangers, condensers, and generators etc for getting the highest thermal efficiency of the plant, various methods have been developed for economic operation of the power plant under varying load conditions. Transmission loss is also minimized by introducing the successful design of transmission lines. The main problem for the electrical power engineers is the economic load sharing of the output of the generators. The proper sharing of load between two generators tog give maximum overall efficiency is the major problem in load distribution amount generators.



Input – output curves of unit X and Y

This input-output carries for two generators within a power plant which are operating in parallel and supply a common load is shown in fig. From the fig, it is evident that the generator X is more efficient than Y throughout its load range as the output of X is more than output of Y for the same input. Therefore, the engineers may think that they can load generator X first to its full capacity and then for generator Y for the remaining load. But it is not proper distribution as the overall efficiency of the system would not be highest with the distribution of loads as mentioned above. Therefore, it is essential to find out load distribution between generators to give the highest efficiency for the system.



Variation of combined input with varying load sharing between X and Y

This problem can be resolved by plotting the sum of the inputs of X and Y against the load X for a given constant load on the two limits. It is shown in fig.

Say total load is 4*MW*. If the load on X = 0 and on Y = 4*MW*, then the load on X+Y = 4*MW*. The required input for X and Y can be calculated from fig. if the load on X = 1 and on Y 3*MW* then again the combined load supplied by X+Y = 4*MW* and the corresponding required input for this load division can also be calculated from fig. different outputs of X as shown in fig. Such different curves for different constant value of (O_x + O_y) can also be drawn using the same procedure as described above. In the curves drawn, it is clear that one point on the curve the combined input is minimum for a given total load. Corresponding to this point (A) of minimum input to the system for the required output, we can find out the load on generator X. the load on generator Y is the difference of load sharing, highest efficiency can be achieved.

This method is useful only for the system having two generators. If the number of generators supplying the load is more than two, this method becomes cumbersome process.

The condition of minimum input for any combined constant output is

$$\frac{d(I_x + I_y)}{dO_x} = 0$$

$$\therefore \frac{dI_x}{dO_x} + \frac{dI_y}{dC_x} = 0$$

$$\frac{dI_x}{dO_x} = -\frac{dI_y}{dO_x} \qquad \text{------------ (1)}$$

But $\frac{dI_y}{dO_x} = \frac{dI_y}{dO_y} \cdot \frac{dO_y}{dO_x}$ ------------ (2)

But $O_y = O_c - O_x$

Where, $O_c = O_x + O_y$ Combined output of X and Y

$$\frac{dO_y}{dO_x} = \frac{dO_c}{dO_x} \cdot \frac{dO_x}{dO_x}$$

Where O_c= constant

$$\therefore \frac{dO_y}{dO_x} = -1$$

Substituting this value in equation (2)

$$\frac{dI_y}{dO_x} = -\frac{dI_y}{dO_y} \qquad \text{-------------- (3)}$$

This is the condition for the maximum input for the combined constant output. If there are n units, supplying a constant load, then the required condition for the minimum input or maximum system efficiency is

$$\frac{dI_1}{dO_1} = \frac{dI_2}{dO_2} = \frac{dI_3}{dO_3} = \text{...........} = \frac{dI_n}{dO_n}$$