TUTORIAL - 8

Energy Conservation and Energy Management in Power Plant

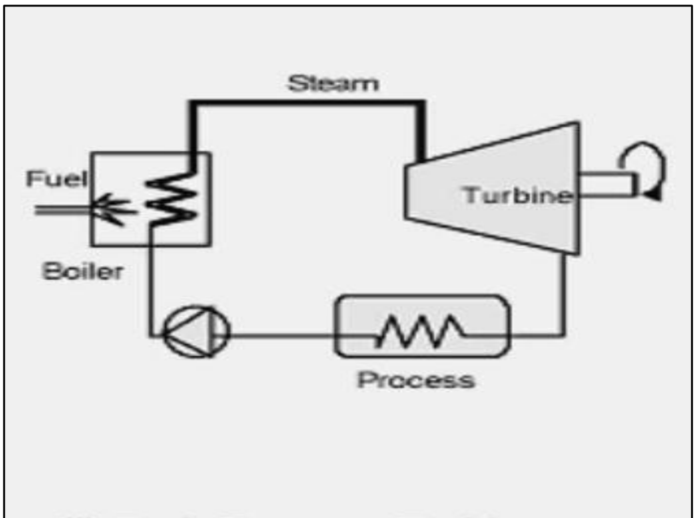
1. What is the function of ‘back pressure steam turbine’?

A back pressure turbine, also known as a "non-condensing turbine" is typically found in industries requiring "process steam" and include facilities such as; cogeneration / CHP systems, district energy systems, paper and pulp plants, refineries and oil and natural gas facilities where there are large amounts of low pressure process steam available.

- A turbine-generator can often produce enough electricity to justify the capital cost of purchasing the higher-pressure boiler and the turbine-generator.
- Since boiler fuel usage per unit of steam production increases with boiler pressure, facilities often install boilers that produce steam at the lowest pressure consistent with end use and distribution requirements.
- In the backpressure turbine configuration, the turbine does not consume steam. Instead, it simply reduces the pressure and energy content of steam that is subsequently exhausted into the process header. In essence, the turbo generator serves the same steam function as a pressure reduction valve (PRV)—it reduces steam pressure—but uses the pressure drop to produce highly valued electricity in addition to the low-pressure steam. Shaft power is produced when a nozzle directs jets of high-pressure steam against the blades of the turbine’s rotor. The rotor is attached to a shaft that is coupled to an electrical generator.
- Within the industrial applications for power and energy generation, process steam is used in a number of areas. Most commonly, process steam is distributed within an industrial facility in the form of "saturated steam". Saturated steam occurs at pressures pre- determined by the required saturation temperature, which in turn is based on the total overall highest required temperature for the facility.
- This steam is either directly supplied by a boiler or by cogeneration (also referred to as "CHP," "CHP systems" or "combined heat and power" utilizing one or more steam turbines. In this case, the boiler supplies the steam turbine and the steam is taken from the exhaust of a back-pressure turbine.
- Back-pressure turbines expand high-pressure steam through a turbine. The output steam is exhausted at a relatively low pressure suitable for onsite heat requirements. It is possible to release the steam at various points through the turbine allowing access to more than one grade of heat; the extraction of steam from the turbine will result in a decrease in power across the blades. Backpressure steam turbines have traditionally been the most popular generation technology for CHP.

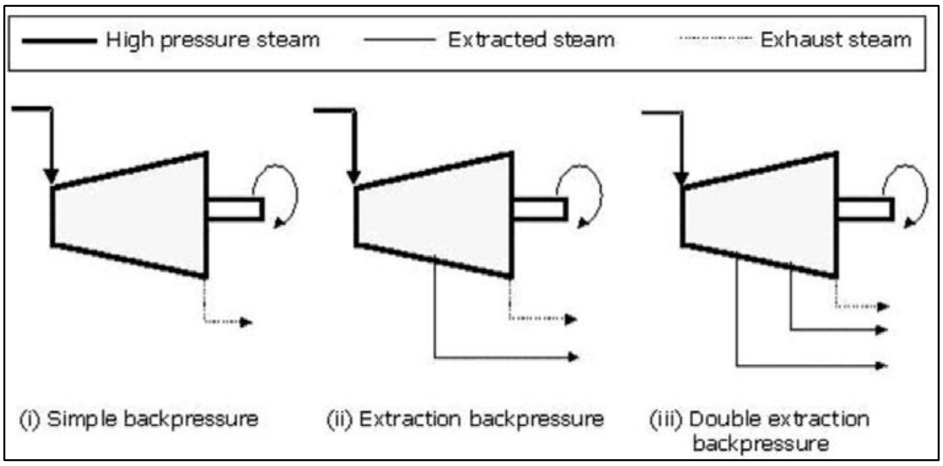
2. Explain working of Back pressure steam turbine.

- Steam turbines are the most commonly used for cogeneration applications.
- In the steam turbines, the incoming high pressure steam is expanded to a lower pressure level, converting the thermal energy of high pressure steam to kinetic energy through nozzles and then to mechanical power through rotating blades.



(i) Back-Pressure Turbine

- In this type steam enters the turbine chamber at high pressure and expands to low or medium pressure.
- Enthalpy difference is used to generate power/work.
- Depending on the pressure (or temperature) levels at which process steam is required, backpressure steam turbines can have different configurations as shown in below figure



- In extraction and double extraction backpressure turbines, some amount of steam is extracted from the turbine after being extracted from the turbine after being expanded to a certain pressure level.
- The extracted steam meets the heat demands at pressure levels higher than the exhaust pressure of the steam turbine.
- The efficiency of backpressure steam turbine cogeneration system is highest. In cases where 100 percent backpressure exhaust steam is used, the only inefficiencies are gear drive and electric generator losses, and the inefficiency of steam generation.
- Therefore with an efficient boiler, the overall thermal efficiency of the system could reach as much as 90%.

3. What are the advantages of Diesel Generator set for power generation?

- ✓ Low installation cost and operating cost
- ✓ Short delivery periods and installation period
- ✓ Higher efficiency (as high as 43 – 45%)
- ✓ More efficient plant performance under part loads
- ✓ Suitable for different types of fuels such as low sulphur heavy stock and heady fuel oil in case of large capacities
- ✓ Minimum cooling water requirements
- ✓ Adopted with air cooled heat exchanger in areas where water is not available
- ✓ Short startup time
- ✓ Easily available in the market
- ✓ Portable
- ✓ Least inflammable
- ✓ Easy maintenance

4. What are the advantages of Hydro Power Plant?

Fundamentals of power plant

- Power plant is assembly of systems or subsystems to generate electricity, i.e, to produce power with economy and requirements.
- So the power produced must be 1. Economically useful. 2. Environmental friendly to society
- Therefore, power plant can be defined as: "a machine or assembly of equipment that generate and deliver a flow of mechanical or electrical energy. or, power plant may also be defined as: The engineering and technology required for the production of central station electric power

There are different power plant as follow:

1. **Steam power plant:** Steam power plants use fuels such as petroleum, coal, or biomass are burned to heat water to create steam, the pressure of the steam spins a turbine turning the copper wire inside the generator.
2. **Gas turbine plant:** Gas power plants uses fuels that are burned to create hot gases to spin the turbine.
3. **Combined cycle plant:** The combined-cycle unit combines the Rankine (steam turbine) and Brayton (gas turbine) thermodynamic cycles by using heat recovery boilers to capture the energy in the gas turbine exhaust gases for steam production to supply a steam turbine
4. **Hydro-electric plant:** Hydroelectric plant use falling (or flowing) water to spin the turbine blades. Water flowing in high altitude rivers is stored in a man- made reservoir as shown in the figure. The kinetic energy of the flowing water is transformed into potential energy as the water level rises. This water is carried through pipes to the turbine situated at the bottom of the dam.
5. **Nuclear power plant:** Nuclear power plants use nuclear fission to turn water into steam. This drives the steam turbine, which spins a generator to produce power.
6. **Wind turbine plant:** Wind power plants use the wind to push against the turbine blades, spinning the copper wires inside the generator to create an electric current

Working cycles related to power plant

- Steam power plant ->Rankin cycle

- Gas turbine-> Brayton cycle
- I C Engines-> Otto –diesel –dual cycles

➢ Advantages and Disadvantages of Hydropower

Hydropower offers advantages over other energy sources but faces unique environmental challenges.

Advantages:

- Hydropower is clean energy
- Hydropower is a fueled by water, so it's a clean fuel source. Hydropower doesn't pollute the air like power plants that burn fossil fuels, such as coal or natural gas.
- Hydropower is a domestic source of energy, produced in the United States.
- Hydropower relies on the water cycle, which is driven by the sun, thus it's a renewable power source.
- Hydropower is generally available as needed; Engineers can control the flow of water through the turbines to produce electricity on demand.
- Hydropower plants provide benefits in addition to clean electricity. Impoundment hydropower creates reservoirs that offer a variety of recreational opportunities, notably fishing, swimming, and boating. Most hydropower installations are required to provide some public access to the reservoir to allow the public to take advantage of these opportunities. Other benefits may include water supply and flood control.
- Hydropower is one of the best generating options. In fact, a complete life-cycle assessment shows that its greenhouse gas (GHG) emissions are very low.
- For instance, a hydropower plant with a reservoir in a northern area emits 10 grams of carbon dioxide (CO2) per kilowatt-hour produced, the same quantity as wind power. Solar power, generated via photovoltaic panels, emits four times more GHGs, and a coal-fired power plant produces 100 times more GHG emissions than a hydropower plant.

Disadvantages:

- Fish populations can be impacted if fish cannot migrate upstream past impoundment dams to spawning grounds or if they cannot migrate downstream to the ocean. Upstream fish passage can be aided using fish ladders or elevators, or by trapping and hauling the fish upstream by truck. Downstream fish passage is aided by diverting fish from turbine intakes using screens or racks or even underwater lights and sounds, and by maintaining a minimum spill flow past the turbine.
- Hydropower can impact water quality and flow. Hydropower plants can cause low dissolved oxygen levels in the water, a problem that is harmful to riparian (riverbank) habitats and is addressed using various aeration techniques, which oxygenate the water. Maintaining minimum flows of water downstream of a hydropower installation is also critical for the survival of riparian habitats.
- Hydropower plants can be impacted by drought. When water is not available, the hydropower plants can't produce electricity.
- New hydropower facilities impact the local environment and may compete with other uses for the land. Those alternative uses may be more highly valued than electricity generation. Humans, flora, and fauna may lose their natural habitat. Local cultures and historical sites may be impinged upon. Some older hydropower facilities may have historic value, so renovations of these facilities must also be sensitive to such preservation concerns and to impacts on plant and animal life.

5. Explain pass out steam turbine.

In certain applications simple steam turbines are unable to meet specific requirement. Back pressure turbine, pass out or extraction turbine and mixed pressure turbines are such special purpose turbine whose details are given ahead.

Pass Out or Extraction Turbine:

Pass out turbine refers to the steam turbine having provision for extraction of steam during expansion. Such provision is required because in combination heat and power requirement the steam available from back pressure turbine may be more than required one or the power produced may be less than the required value. Pass out turbine has arrangement for continuous extraction of a part of steam at the desired pressure for process heating and left out steam goes into low pressure section of turbine through a pressure control valve. In the low pressure section of turbine control mechanism is provided so that the speed of turbine and pressure of steam extraction remains constant irrespective of the variations in power produced and process heating.

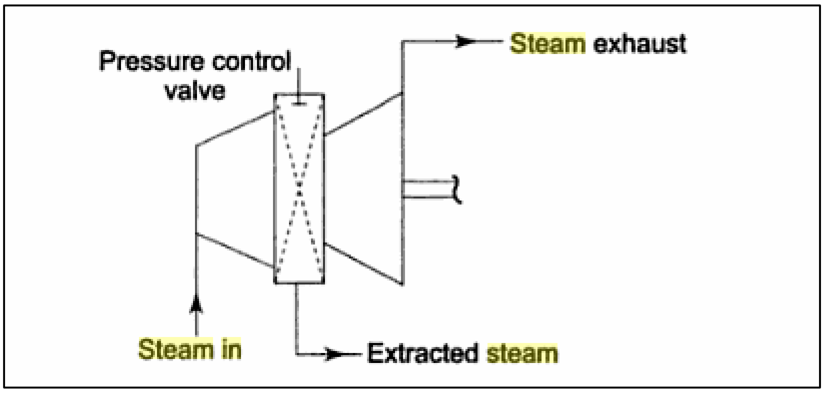


Figure: Pass Out Turbine

The pass out turbines have to operate under widely varying load so its efficiency is quite poor. For facilitating the operation of pass out turbine from no extraction to full steam extraction conditions, nozzle control governing or throttle control governing are used.

A pass out turbine for the campus would bleed steam at 7 bar to the heating system, however converting the heating system to MTHW operation would improve the turbine performance even further as the HP turbine stage would expand the full steam mass flow to a lower bleed pressure.

The pass out turbine also allows much greater flexibility in matching the turbine heat and work outputs to the work/heat ratio of the load. The range of work/heat ratios that can be covered without importing or exporting heat or power for the campus. While the need to match turbine characteristics to load is important, attempting to neither import or export heat or power may not be the overall most efficient use of the plant or fuel. As the electrical output is the most valuable, maximizing this output (rather than losing potential work in incompletely expanded steam) and selling extra electricity is 44 more efficient than operating at a lower efficiency for the sake of achieving a close match of loads to turbine output.

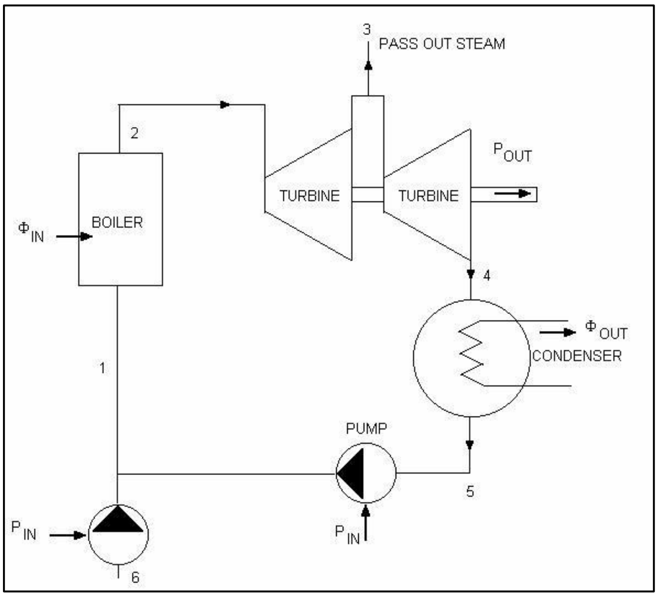
Theoretical turbine electrical efficiency curves and pass out bleed steam rates are superimposed and show the improved work efficiency of the second stage condensing turbine, and the wide range of work / heat ratios the pass out turbine can accommodate.

In realizing this performance model on the CHP analysis spreadsheet, the pass out bleed steam flow is determined from the campus heat load, and simultaneous electrical load from the campus electrical load. The following relationship for turbine steam consumption is based on linear equations relating steam consumption to pass out steam flow and electrical load.

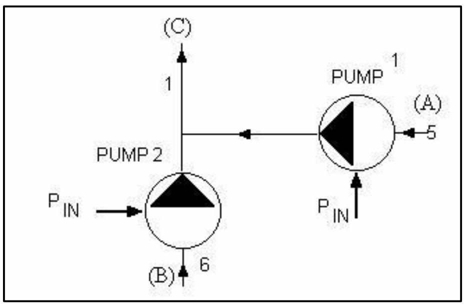
Qin =1.12 + (Qout * 0.684) + (Wout * 2.433) MW

This equation is the turbine efficiency function used in the CHP analysis spreadsheet to determine the thermodynamic performance of the pass out turbine CHP plant. Economic analysis of the CHP plant is based on the results of the thermodynamic performance of the turbine, and the same economic factors as used for the back pressure turbine. In many cases a turbine manufacturer I s –back pressure turbines will be pass out turbines with blanked off pass out steam bleed points.

The circuit of a simple pass-out turbine plant is shown below. Steam is extracted between stages of the turbine for process use. The steam removed must be replaced by make-up water at point 6.



In order to solve problems you need to study the energy balance at the feed pumps more closely so that the enthalpy at inlet to the boiler can be determined. Consider the pumps on their own, as below.



The balance of power is as follows.

$P_1 + P_2$ = increase in enthalpy per second. $= m_C h_C - m_A h_A - m_B h_B$

- **Pass out Condensing Turbines:**

The pass-out condensing turbine is preferred when some process steam is required at a relatively low pressure. Such turbines can often have a large operating envelope within which the demands for electricity generation and process steam can be balanced.

6. Discuss different methods used to improve the performance of Thermal Power Plants. <u>OR</u> State and explain various efficiency improvement methods used in thermal power plant.

Improving the efficiency of thermal power production can solve the energy crisis to a great extent till other sources are developed to their full potential.

- **Thermal Power Plant**

  - Converts energy stored in fuels into shaft work or the electricity.
  - The Working fluid water is in liquid phase or vapor phase during the cycle.
  - Water follows B-T-C-P (B-Boiler; T-Turbine; C-Condenser; P-Pump) path of the cycle.
  - Cyclic Process.

$$\sum_{\text{cycle}} Q_{\text{net}} = \sum_{\text{cycle}} W_{\text{net}}$$

or,

$$Q_1 - Q_2 = W_T - W_P$$

where

Q_1 = heat transferred to the working fluid, kJ/kg

Q_2 = heat rejected from the working fluid, kJ/kg

W_T = work transferred from the working fluid, kJ/kg

W_P = work transferred into the working fluid, kJ/kg

The efficiency of the vapour power cycle would thus be

$$\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

- **Rankine Cycle**

Steady Flow Energy Equation

- Boiler h4 + Q1= h1 ;Q1= h1-h4
- Turbine h1= WT + h2 ; WT= h1-h2
- Condenser h2= Q2+ h3 ; Q2= h2-h3
- Pump h3+ Wp = h4 ; Wp = h4-h3
- hi is the specific enthalpy at state i.

- In carnot cycle, Non-practical cycle giving maximum thermal efficiency

$$\eta_{max} = 1 - \frac{T_2}{T_1} = \eta_{Carnot}$$

- **Efficiency of thermal power plant is improved by:**

1) Increasing mean temperature of heat addition
2) Increasing superheat
3) Increasing inlet pressure
4) Decrease of condenser pressure
5) Reheating of steam
6) Regenerative feed water heating
7) Number of extraction stages-Carnotisation of Rankine cycle
8) Gas-Turbine-Steam-Turbine Plants
9) Use Solar and geo-thermal plants as alternatives
10) Need of urgent development of other sources of energy

- **Mean Temperature**

- Carnot Cycle superimposed on Rankine Cycle
- Writing the equations

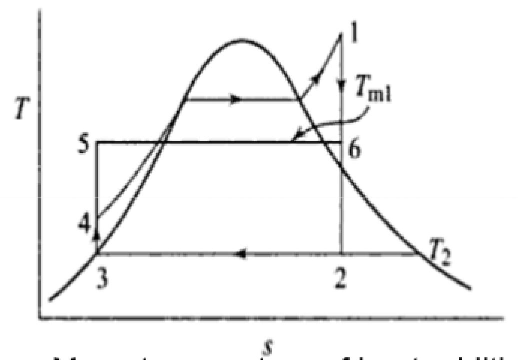
$$Q_1 = h_1 - h_4 = T_{m1}(s_1 - s_4)$$

$$T_{m1} = \text{mean temperature of heat addition} = \frac{h_1 - h_4}{s_1 - s_4}$$

$$\text{Since } Q_2 = \text{heat rejected} = h_2 - h_3 = T_2(s_1 - s_4),$$

$$\eta_{Rankine} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(s_1 - s_4)}{T_{m_1}(s_1 - s_4)} = 1 - \frac{T_2}{T_{m_1}}$$

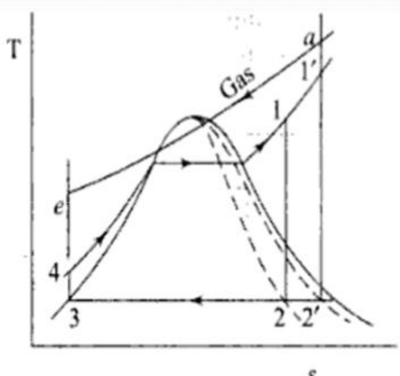
- The higher the mean temperature of heat addition, the higher will be the cycle efficiency.



Mean temperature of heat addition

- Efficiency in Steam Power Plant: **ηrankine= fn (Tm1)**

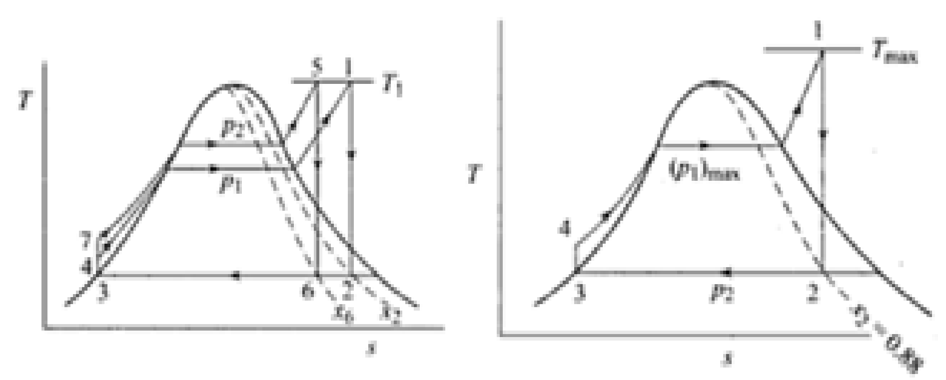
- **Effect of Superheat**



Effect of superheat

- Increasing the initial temperature at constant pressure changes the state from 1 to 1’
- Tm increases for 4-1’ than 4-1 which increases the efficiency of which increases the efficiency of Rankine Cycle
- The expansion line of steam in the turbine shifts to the right increasing Tm. Life of Turbine increased due to reduced wetness of steam
- Maximum temperature limited

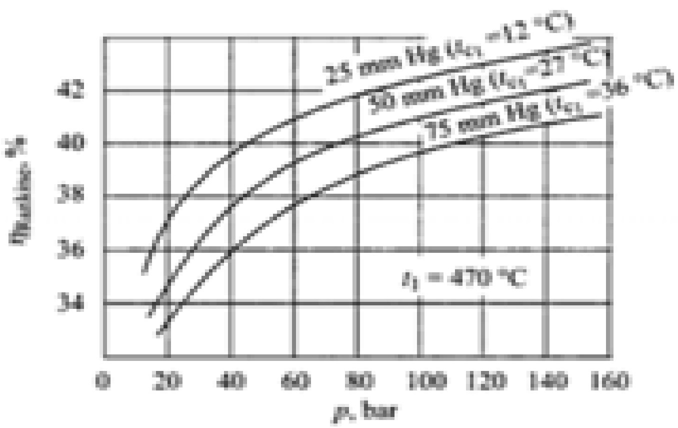
- **Effect of Inlet Pressure**



- Metallurgical Limit p2 > p1

- Tm in 7-5 is greater than 4-1
- Expansion line of the steam shifts to the left
- To prevent excessive erosion in the turbine blades, moisture content at the turbine exhaust < 12 %
- Maximum steam pressure gets fixed

➢ **Variation of steam condition**



Effect of inlet steam pressure (p) and condenser pressure on efficiency

- Improvement in cycle efficiency with the decrease of condenser pressure
- Lower cooling water temperature (tc1) gives lower condenser pressure.
- Prabal Goyal Thermodynamics of Thermal Power Generation15 IIT Delhi gives lower condenser pressure.
- Efficiency of steam power plant more in cold region than warm regions.
- Increasing the inlet steam pressure improves efficiency but maximum pressure constrained due to finite material properties of boilers and turbines.

➢ **Other efficiencies along with thermodynamic efficiency**

- Auxiliaries in the plant like conveyors, pumps, crushers and fans

$$\eta_{aux} = \frac{\text{net power transmitted by the generator}}{\text{gross power produced by the plant}}$$

Therefore, the overall efficiency of the plant is the product of five component efficiencies as given by

$$\eta_{overall} = \eta_{boiler} \times \eta_{cycle} \times \eta_{turbine(mech)} \times \eta_{generator} \times \eta_{aux}$$

For a modern power plant, the typical values are

$$\eta_{boiler} = 0.92,\ \eta_{cycle} = 0.44,\ \eta_{turbine(mech)} = 0.95,\ \eta_{generator} = 0.93,$$
$$\eta_{aux} = 0.95,\ \eta_{overall} = 0.92 \times 0.44 \times 0.95 \times 0.93 \times 0.95 = 0.34$$

- Thermal power generation-not very efficient

- Gas turbine cycles, Simple open cycle Brayton cycle Gas turbine - Thermal efficiency. Actual Brayton cycle - its thermal efficiency. Cycle air rate, work ratio optimum pressure ratio. Means of improving the efficiency and specific output. Gas turbine with

  1. Reheat
  2. Inter-cooling
  3. Regeneration

- Effect of these on efficiency effect of operating variables on thermal efficiency, air rate and work ratio, water injection.

The thermal efficiency and specific work output (W_{net}) of simple cycle are low. The thermal efficiency can be improved either by increasing the specific work output or by reducing the heat supplied. The specific work output is a difference between work developed by turbine (W_T) and work required to drive the compressor. Any method of increasing W_T and reducing W_C will result in increase in specific work output. For steady flow compression or expansion the work done is given by $\int -vdp$, where v is specific volume. Therefore the specific volume of working fluid should be as high as possible for work developing machine like turbine and should be as low as possible for work absorbing machine like compressor. The specific volume is proportional to temperature at given pressure ($pv = mRT$). Hence the gas is to be admitted at high temperature in turbine. This is achieved by process called as reheating. The gas must be admitted at low temperature in compressor. This is done by process called as intercooling. Thus intercooling and reheating will improve the specific work output. But the method of intercooling and reheating increase the heat supplied to the cycle. The increase in heat supplied due to these methods is more than the corresponding improvement in specific output. Hence intercooling and reheating individually or together results in decrease in thermal efficiency.

From the above discussion it is clear that in order to reap the benefit of increase in specific output due to intercooling and reheating another method of decreasing heat supplied should be used so that thermal efficiency is also improved. One method of doing this is to recover heat from exhaust gases which is called as regeneration.

Thus it is clear from above discussion that regeneration alone improves thermal efficiency but is has no effect on specific work output. Intercooling and reheating improves the specific work output but decreases the thermal efficiency. But intercooling, reheating and regeneration together will result in improvement of both specific work output and thermal efficiency.

These methods i.e. intercooling, reheating and regeneration are discussed in the succeeding articles.

1 Intercooling

As discussed earlier about half the power developed by the turbine is consumed by compressor. The work required by the compressor can be reduced by compressing the air in stage and incorporating an intercooler between the stages. The turbine plant with two stage compression is shown in Fig. (a) and its T-S representation is shown in Fig. (b).

Similar analysis holds true for actual cycle. If $\eta_{HPT} = \eta_{LPT}$, then for maximum power output the pressure ratio in HP turbine and LP turbine should be same.

$$\frac{P_3}{P_4} = \frac{P_5}{P_6} \quad \text{But } P_4 = P_5 = P_i$$

Where P_i is intermediate at which reheating is carried in reheater.

$$\therefore \quad \frac{P_3}{P_i} = \frac{P_i}{P_6} \Rightarrow \boxed{P_i = \sqrt{P_3 P_6}}$$

This equation of P_i need improvement if $\eta_{HPT} \neq \eta_{LPT}$ and if reheating is not perfect.

When $T_3 = T_5$, reheating is called as perfect reheating.

Heat supplied without reheating.

$$Q_s = C_p(T_3 - T_2)$$

Heat supplied with reheating.

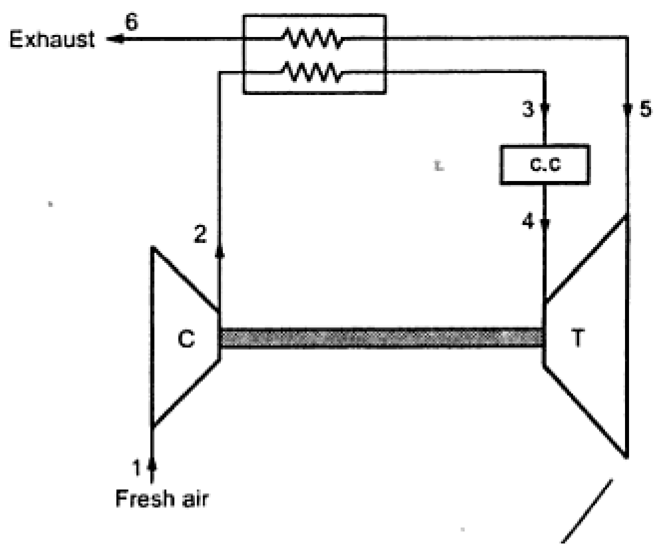
$$Q_s = C_p(T_3 - T_5) + C_P(T_5 - T_4')$$

Thus it is clear that heat supplied with reheating is more than that without reheating. Hence though net work is increased by reheating, the heat supplied is also increased and the net effect can be to reduce thermal efficiency. Also for reheating the A : F ratio must be high, so that after combustion in combustion chamber excess air is available for combustion in reheater by injecting fuel in it.

The use of reheater is not economically justified for more than two to three stages.

3 Regeneration

Since exhaust gases leaving the turbine are at very high temperature as compared to ambient, they carry considerable amount of heat with them. Large portion of this heat can be recovered by using a heat exchanger which uses this heat for increasing the temperature of gases entering the combustion chamber. This will reduce the quantity of heat supplied. This heat exchanger is called as regenerator and the process is reffered as regeneration. The net result is saving in fuel cost for same output. Fig. shows a gas turbine plant with a regenerator and its T-S representation.



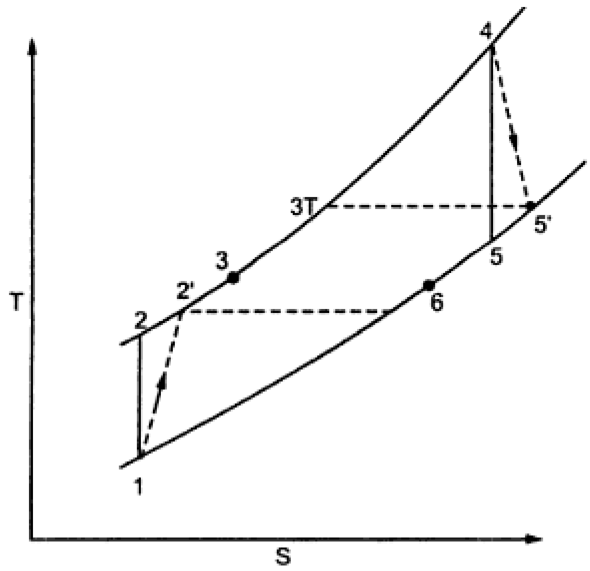


Fig. Gas Turbine with regenerator and TS diagram

Processes are similar to the processes as explained in actual cycle except with a difference that the temperature of air entering the combustion chamber is increased from T_2' to T_3 due to regeneration and the temperature of exhaust gases decreases from T_5' to T_6. The theoretical possible limit of heating of air leaving the compressor due to regeneration is shown by point '3T' at which $T_3 = T_5'$ i.e. temperature of exhaust gases leaving the turbine. This thing will happen when the heat exchanger is infinetely large. But this is not actually possible and this fact will be taken into account by effectiveness of heat exchanger or regenerator ϵ.

$$\epsilon = \frac{\text{Actual temperature rise}}{\text{Theoretical maximum possible temperature rise}}$$

$$\boxed{\epsilon = \frac{T_3 - T_2'}{T_5' - T_2'}}$$

It can be seen that heat supplied to cycle without regeneration is

$$Q_s = C_p(T_4 - T_2')$$

And with regeneration

$$Q_s = C_p(T_4 - T_3)$$

It is obvious from T-S diagram that quantity of heat supplied with regeneration is less than that without regeneration as $(T_4 - T_2') > (T_4 - T_3)$. But there is no effect of regeneration of turbine work and compressor work. Hence regneration has no effect on specific work output W_{net}. But it will result in increase in thermal efficiency. A regenerator is widely used in large gas turbine units.

If the thermal efficiency is plotted for various pressure ratios and minimum to maximum temperature ratios the trend of variation will be as shown in Fig.

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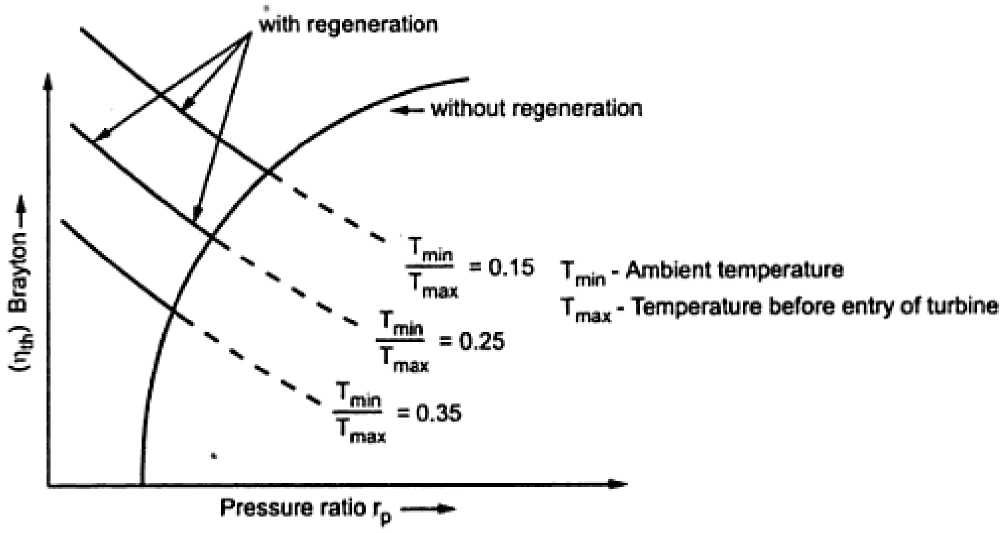

Fig. Thermal effieiency of ideal Brayton cycle with and without regeneration

It is clear from the figure that regeneration is most effective at lower pressure ratio and low minimum (ambient) to maximum (turbine inlet) temperature ratios.

So it is clear from previous discussion that regeneration is effective when temperature at inlet to turbine is maximum, which will result in higher temperature of exhaust. The temeprature of exhaust is higher if reheating is used. Thus regeneration will be beneficial when reheating is used. Also by using regeneration loss in thermal efficiency due to intercooling can be recovered. Fig. (a) shows such a plant with regeneration, reheating and intercooling and it is represented on T-S diagram in Fig. (b).

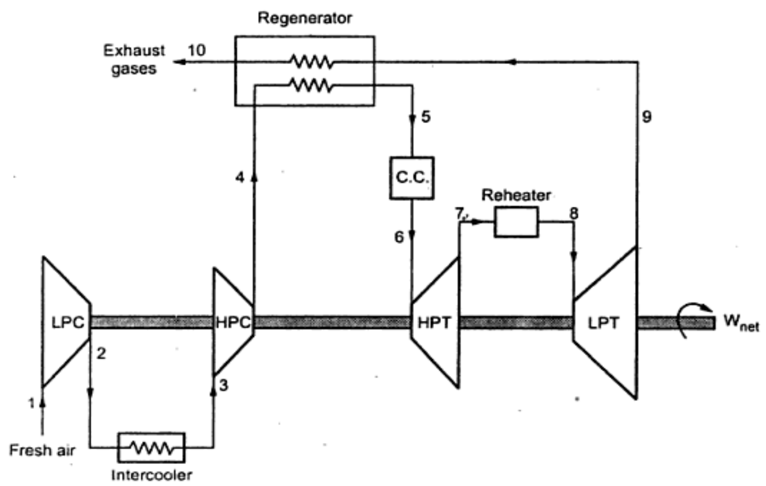

Fig. (a) A gas turbine plant with 2-stage compression with intercooling, 2-stage expansion with reheating and regeneration

- Combine Cycle of Cogeneration is already discussed in previous tutorials.

Thermal Power Plant Performance Measures

The thermal performance indicator is used to monitor thermal power station units' efficiency. It is an indication of the thermal units' success in meeting thermal design capabilities and enables comparison among similar units.

Thermal performance indicator = $\frac{\text{gross design heat rate}}{\text{adusted actual gross heat rate}}$ **x100**

This indicator is used to evaluate operating parameter deviation from the design values and take appropriate corrective action where necessary.

The following indicators are used to evaluate station performance on daily, monthly, quarterly and annually basis. These indicators can be calculated for the unit or Station basis.

Plant Availability

Availability = $\frac{\text{operating}}{\text{total hours for period under riview}}$

Plant load factor

Plant load factor= $\frac{\text{energy generated}}{\text{MCR X hours in period}}$ **x100**

- **Planned outage rate**

  %planned outage rate= $\frac{\text{outage}}{\text{hours in period under riviev}}$ **x 100**

- **Forced outage rate**

  %forced outage rate = x $\frac{\text{outage}}{\text{hours in period under riview}}$ **100**

- **Reliability**

  It is an indication of how well maintenance management programmes are being executed

  %reliability = 100% - forced outage rate

- **Thermal efficiency**

It is an indication of how well the plant is being operated as compared to the design characteristics.

Thermal efficiency ή = $\frac{\text{energy generated x time}}{\text{MC x CV}}$ **x100**

Where: MC – quantity of coal consumed
CV- calorific value of coal

- **Overall unit efficiency**

ή= ήBoiler x ήTurb x ήGen x ήwrks

Where:
$ή_{Boiler}$ – boiler efficiency $ή_{Turb}$ - turbine efficiency

$ή_{Gen}$ – generator efficiency $ή_{wrks}$ – works efficiency

- **Operational Efficiency**

Operational efficiency is the ratio of the total electricity produced by the plant during a period of time compared to the total potential electricity that could have been produced if the plant operated at 100 percent in the period.

Operational efficiency = $\frac{E}{E_{100\%}}$ **x 100 ………..Eqn 8**

Where:
E = energy output from the power plant in the period (kWh)
$E_{100\%}$ = potential energy output from the power plant operated at 100% in the period (kWh)

- **Economic Efficiency**

Economic efficiency is the ratio between productions costs, including fuel, labour, materials and services, and energy output from the power plant for a period of time.

Economic efficiency= $\frac{\text{production costs for a period}}{\text{energy output from the power plant in the period (kWh)}}$

7. Explain fluidized bed combustion (F.B.C.) and discuss importance of air fuel ratio.

Fluidized bed combustion (**FBC**) is a combustion technology used to burn solid fuels. In its most basic form, fuel particles are suspended in a hot, bubbling of ash and other particulate materials (sand, limestone etc.) through which jets of air are blown to provide the oxygen required for combustion. The resultant fast and intimate mixing of gas and solids promotes rapid heat transfer and chemical reactions within the bed. FBC plants are capable of burning a variety of low-grade solid fuels, including most types of coal and woody biomass, at high efficiency and without the necessity for expensive fuel preparation (e.g., pulverising). In addition, for any given thermal duty, FBCs are smaller than the equivalent conventional furnace, so may offer significant advantages over the latter in terms of cost and flexibility.

FBC reduces the amount of sulfur emitted in the form of SO_x emissions. Limestone is used to precipitate out sulfate during combustion, which also allows more efficient heat transfer from the boiler to the apparatus used to capture the heat energy (usually water tubes). The heateiety dprecipitate coming in direct contact with the tubes(heating by conduction) increases the efficiency. Since this allows coal plants to burn at cooler temperatures, less NO_x is also emitted. However, burning at low temperatures also causes increased polycyclic aromatic hydrocarbon emissions. FBC boilers can burn fuels other than coal, and the lower temperatures of combustion (800 °C / 1500 °F) have other added benefits as well.

- **Types**

FBC systems fit into essentially two major groups, atmospheric systems (FBC) and pressurized systems (PFBC), and two minor subgroups, bubbling (BFB) and circulating fluidized bed (CFB).

1. FBC

Atmospheric fluidized beds use limestone or dolomite to capture sulfur released by the combustion of coal. Jets of air suspend the mixture of sorbent and burning coal during combustion, converting the mixture into a suspension of red-hot particles that flow like a fluid. These boilers operate at atmospheric pressure.

2. PFBC

The first-generation PFBC system also uses a sorbent and jets of air to suspend the mixture of sorbent and burning coal during combustion. However, these systems operate at elevated pressures and produce a high-pressure gas stream at temperatures that can drive a gas turbine. Steam generated from the heat in the fluidized bed is sent to a steam turbine, creating a highly efficient combined cycle system.

3. Advanced PFBC

A 1½ generation PFBC system increases the gas turbine firing temperature by using natural gas in addition to the vitiated air from the PFB combustor. This mixture is burned in a topping combustor to provide higher inlet temperatures for greater combined cycle efficiency. However, this uses natural gas, usually a higher priced fuel than coal.

APFBC: In more advanced second-generation PFBC systems, a pressurized carbonizer is incorporated to process the feed coal into fuel gas and char. The PFBC burns the char to produce steam and to heat combustion air for the gas turbine. The fuel gas from the carbonizer burns in a topping combustor linked to a gas turbine, heating the gases to the combustion turbine's rated firing temperature. Heat is recovered from the gas turbine exhaust in order to produce steam, which is used to drive a conventional steam turbine, resulting in a higher overall efficiency for the combined cycle power output. These systems are also called APFBC, or advanced circulating pressurized fluidized-bed combustion combined cycle systems. An APFBC system is entirely coal-fueled.

GFBCC: Gasification fluidized-bed combustion combined cycle systems, GFBCC, have a pressurized circulating fluidized-bed (PCFB) partial gasifier feeding fuel syngas to the gas turbine topping combustor. The gas turbine exhaust supplies combustion air for the atmospheric circulating fluidized-bed combustor that burns the char from the PCFB partial gasifier.

CHIPPS: A CHIPPS system is similar, but uses a furnace instead of an atmospheric fluidized-bed combustor. It also has gas turbine air preheater tubes to increase gas turbine cycle efficiency. CHIPPS stands for combustion-based high performance power system.

8. Explain with neat sketch various methods used for combustion of pulverized coal.

The first commercial application of pulverized coal firing for steam generation was made in early 1920s. Since then it has become almost universal in central utility stations using coal as fuel. Coal is first ground to dust like size and powdered coal is then carried in a stream of air to be through burners into the furnace. As the entering coal particles get heated in high temperature flames in the furnace, the volatile matter is distilled off and this reduces the coal particles to minute sponge-like masses of fixed carbon and ash. The volatile gases mix with the oxygen of the air, get ignited and burn quickly. Oxygen of the hot air reacts with the carbon particles, which is stripped off by turbulent mixing of these particles and air, high temperature, and adequate time to complete combustion reactions. The ash resulting from combustion (i) partly falls to the furnace bottom and (ii) the rest is carried in gas stream as fly ash to flue-gas outlet, or (iii) is deposited on the boiler heating surface. Modern central station boiler furnace has water-cooled walls that from part of the heat-absorbing surfaces in stream generation.

- To burn pulverized coal successfully, the **following two conditions must be satisfied**:

1. Large quantities of very fine particles of coal, usually those that would pass a 200-mesh sieve must exist to ensure ready ignition because of their large surface-to-volume ratio.
2. Minimum quantity of coarser particles should be present since these coarser particles because slagging and reduce combustion efficiency.

A typically screen analysis of a high volatile bituminous coal sample, pulverized to 80%200 (0.074mm opening),

99.5%-50 mesh

96.5%-100 mesh

80%-200 mesh

This is not a satisfactory grind because of the high percentage retained on the 50 mesh, even though the surface area remains the same. Thus classification plays a major role in matching the particles size to the reactivity of the fuel.

Greater surface area per unit mass of coal allows faster combustion reactions because more carbon becomes exposed to heat and oxygen. This reduces the excess air needed to complete combustion. This also reduces the dry exhaust loss through chimney and raises the stream generator efficiency. However, the extra cost of the pulverizing equipment and grinding energy partly offset these advantages.

- **Advantages of Pulverized coal firing**

1. Low excess air requirement.

2. Less fan power.

3. Ability to use highly preheated air reducing exhaust losses.

4. Higher boiler efficiency.

5. Ability to burn a wide variety of coals.

6. Fast response to load changes.

7. Ease of burning alternately with, or in combination with gas and oil.

8. Ability to release large amounts of heat enabling it to generate about 2000 t/h of stream or more in one boiler.

9. Ability to use fly ash for making bricks etc.

10. Less pressure losses and draught need.

- **Disadvantages**

1. Added investment in coal preparation unit.

2. Added power needed for pulverizing coal.

3. Investment needed to improve fly ash before ID fan.

4. Large volume of furnace needed to permit desired heat release and to withstand high gas temperature.

However, the advantages far outweigh the disadvantaged in large utility central stations, and the net gain has led to the wide use of pulverized coal firing in such systems.

In modern plants the hot air for drying coal in the pulverized is supplied from the forced draught fan and the air preheater, as shown schematically in fig 1. Most of the air (about 70%) leaving the air preheater goes directly to the burner wind box on the boiler and is known as secondary air. The remaining air, called the primary air, is used to dry the coal in the pulverizer and convey the powdered coal from the pulverizer to the burners (or storage bins). Burners make the mixing of coal, primary air, and secondary air.

In some instances, the temperature of the air preheater is not high enough to dry the coal properly. Then, a primary air heater using steam coils may be used to raise the air temperature, or very hot flue gases from the stream generator may be mixed with air to raise its temperature. The flue gases must be taken from a point of stream generator where the concentration of CO2 is low and must be well diluted with air in the mixing chamber. Otherwise, the presence of the CO2 will be detrimental to the combustion process.

An advantage of coal pulverizers over stokers is the ability of pulverizers to use hot air at the temperature ranging from $260\,℃$ to $420\,℃, depending\ on\ the\ kind\ of\ coal$.These high air temperatures promote good combustion and permit lower flue gas exit temperatures.

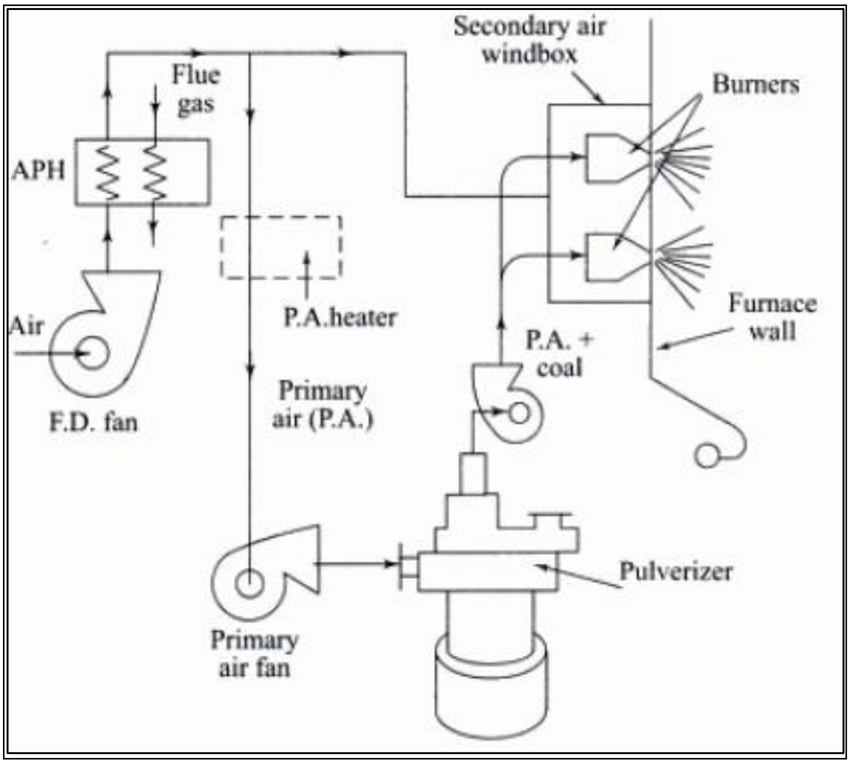

Figure: Primary and secondary air in a pulverizer coal firing system

In order to maintain the desired air temperature leaving the pulverizer with variation on coal moisture and verifying air temperature with boiler load (Table 1), tempering air from the boiler room or forced-draught fan exit is mixed with primary air at the pulverizer inlet to maintain the necessary outlet temperature. Again, if the temperature of the hot primary air is very high then in addition to moisture, some volatile matter may also be distilled off from the coal releasing heat, which may lead to fire hazard in a cumulative effect. Tempering air may be used to offset this tendency.

System	Storage (°C)	Direct (°C)	Semidirect (°C)
1. High-rank high-volatile bituminous	54	77	77
2. Low-rank high volatile bituminous	54	71	71
3. High-rank low volatile bituminous	57	82	82
4. Lignite	43	43-60	49-60
5. Anthracite	93	95	95

Table: Allowable pulverizer outlet temperatures

9. Explain fluidized bed combustion and discuss its advantages.

Fluidized bed combustion (FBC) makes use of a fluidized bed of inert particles, by the burning of fuel, usually (but certainly not exclusively) solid fuel e.g. coal, within the fluidized solids. The fluidized solids dissipate and distribute the heat from the burning fuel particles such that the fluidized particles are virtually at a uniform temperature, vertically and horizontally, everywhere within the bed. A typical fluidized combustion bed temperature is 850-900ºC. This uniformity usefully enables the combustion temperature to be confidently measured and controlled, such that some of the worst effects of conventional 'grate' combustion can be avoided. The fluidized bed also provides a high heat transfer rate to cooling surfaces e.g. boiler tubes, immersed within it. This provides means to reduce the size, and potentially the cost, of heat transfer equipment that uses solid fuel as its heat source. There are also potential environmental benefits from the use of FBC.

- **Advantages:**

1. **High Efficiency**

   FBC boilers can burn fuel with a combustion efficiency of over 95% irrespective of ash content. FBC boilers can operate with overall efficiency of 84% (plus or minus 2%).

2. **Reduction in Boiler Size**

   High heat transfer rate over a small heat transfer area immersed in the bed result in overall size reduction of the boiler.

3. **Fuel Flexibility**

   FBC boilers can be operated efficiently with a variety of fuels. Even fuels like flotation slimes, washer rejects, agro waste can be burnt efficiently. These can be fed either independently or in combination with coal into the same furnace.

4. **Ability to Burn Low Grade Fuel**

   FBC boilers would give the rated output even with inferior quality fuel. The boilers can fire coals with ash content as high as 62% and having calorific value as low as 2,500 kCal/kg. Even carbon content of only 1% by weight can sustain the fluidised bed combustion.

5. **Ability to Burn Fines**

   Coal containing fines below 6 mm can be burnt efficiently in FBC boiler, which is very difficult to achieve in conventional firing system.

6. **Pollution Control**

   SO_2 formation can be greatly minimised by addition of limestone or dolomite for high sulphur coals. 3% limestone is required for every 1% sulphur in the coal feed. Low combustion temperature eliminates NO_x formation.

7. **Low Corrosion and Erosion**

The corrosion and erosion effects are less due to lower combustion temperature, softness of ash and low particle velocity (of the order of 1 m/sec).

8. Easier Ash Removal – No Clinker Formation

Since the temperature of the furnace is in the range of 750 – 900 °C in FBC boilers, even coal of low ash fusion temperature can be burnt without clinker formation. Ash removal is easier as the ash flows like liquid from the combustion chamber. Hence less manpower is required for ash handling.

9. Less Excess Air – Higher CO2 in Flue Gas

The CO2 in the flue gases will be of the order of 14 – 15% at full load. Hence, the FBC- boiler can operate at low excess air - only 20 - 25%.

10. Simple Operation, Quick Start-Up

High turbulence of the bed facilitates quick start up and shut down. Full automation of startup and operation using reliable equipment is possible.

11. Fast Response to Load Fluctuations

Inherent high thermal storage characteristics can easily absorb fluctuation in fuel feed rates. Response to changing load is comparable to that of oil fired boilers.

12. No Slagging in the Furnace–No Soot Blowing

In FBC boilers, volatilization of alkali components in ash does not take place and the ash is non sticky. This means that there is no slagging or soot blowing.

13. 13 Provisions of Automatic Coal and Ash Handling System

Automatic systems for coal and ash handling can be incorporated, making the plant easy to operate comparable to oil or gas fired installation.

14. 14 Provision of Automatic Ignition System

Control systems using micro-processors and automatic ignition equipment give excellent control with minimum manual supervision.

15. High Reliability

The absence of moving parts in the combustion zone results in a high degree of reliability and low maintenance costs.

16. Reduced Maintenance

Routine overhauls are infrequent and high efficiency is maintained for long periods.

17. Quick Responses to Changing Demand

A fluidised bed combustor can respond to changing heat demands more easily than stoker fired systems. This makes it very suitable for applications such as thermal fluid heaters, which require rapid responses.

18. 18 High Efficiency of Power Generation

By operating the fluidised bed at elevated pressure, it can be used to generate hot pressurized gases to power a gas turbine. This can be combined with a conventional steam turbine

10.With neat sketch explain working of "Cyclone Burner".

Developed in the early 1942 by Babcock & Wilcox to take advantage of coal grades not suitable for pulverized coal combustion, cyclone furnaces feed coal in a spiral manner into a combustion chamber for maximum combustion efficiency.

During coal combustion in a furnace, volatile components burn without much difficulty. Fuel carbon "char" particles (heavier, less volatile coal constituents) require much higher temperatures and a continuing supply of oxygen. Cyclone furnaces are able to provide a thorough mixing of coal particles and air with sufficient turbulence to provide fresh air to surfaces of the coal particles.

Cyclone furnaces were originally designed to take advantage of four things

1. Lower fuel preparation time and costs
2. Smaller more compact furnaces
3. Less fly ash and convective pass slagging
4. Flexibility in fuel types

➢ **Operation**

A cyclone furnace consists of a horizontal cylindrical barrel attached through the side of a boiler furnace. The cyclone barrel is constructed with water cooled, tangential oriented, tube construction. Inside the cyclone barrel are short, densely spaced, pin studs welded to the outside of the tubes. The studs are coated with a refractory material, usually silica or aluminum based, that allows the cyclone to operate at a high enough temperature to keep the slag in a molten state and allow removal through the tap.

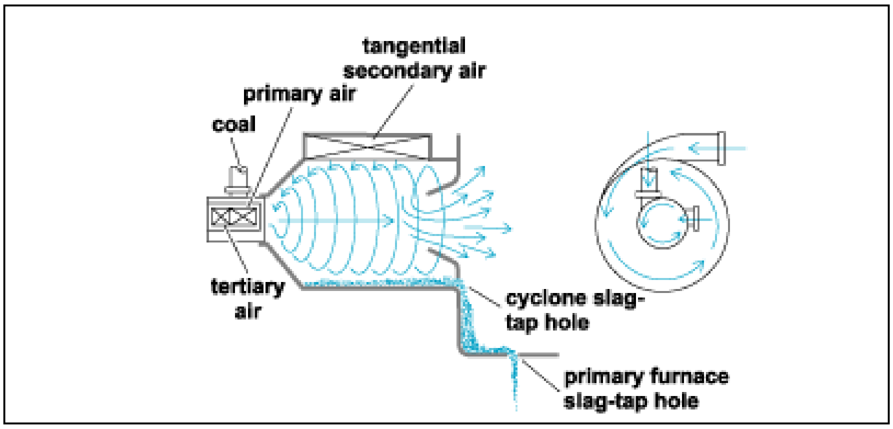

Figure: Cyclone Burner

Crushed coal and a small amount of primary air enter from the front of the cyclone into the burner. In the main cyclone burner, secondary air is introduced tangentially, causing a circulating gas flow pattern. The products, flue gas and un-combusted fuel, then leave the burner and pass over the boiler tubes. Tertiary air is then released further downstream to complete combustion of the remaining fuel, greatly reducing NOx formation. A layer of molten slag coats the burner and flows through traps at the bottom of the burners, reducing the amount of slag that would otherwise form on the boiler tubes.

Cyclone Furnaces can handle a wide range of fuels. Low volatile bituminous coals, lignite coal, mineral rich anthracitic coal, wood chips, petroleum coke, and old tires can and have all been used in cyclones.

A water-cooled horizontal cylinder in which fuel (coal, gas, or oil) is fired and heat is released at extremely high rates. When firing coal, the crushed coal is introduced tangentially into the burner at the front end of the cyclone (see illustration). About 15% of the combustion air is used as primary and tertiary air to impart a whirling motion to the particles of coal. The whirling, or centrifugal, action on the fuel is further increased by the tangential admission of high-velocity secondary air into the cyclone.

The products of combustion are discharged through a water-cooled reentrant throat at the rear of the cyclone into the boiler furnace. Essentially, the fundamental difference between cyclone furnaces and pulverized coal–fired furnaces is the manner in which combustion takes place. In pulverized coal–fired furnaces, particles of coal move along with the gas stream; consequently, relatively large furnaces are required to complete the combustion of the suspended fuel. With cyclonic firing, the coal is held in the cyclone and the air is passed over the fuel. Thus, large quantities of fuel can be fired and combustion completed in a relatively small volume, and the boiler furnace is used to cool the products of combustion. See also Boiler; Steam-generating furnace; Steam-generating unit.