used efficiently.

4. Coals with high ash content and low calorific value can also be used in FBC boilers.
5. The pollution caused by FBC system is less. SO_2 formation by the burning of high sulphur content coals is reduced because of the addition of limestone or dolomite. Also, the low combustion temperature eliminates the formation of NO_x.
6. The erosion and corrosion of the system are reduced because of lower combustion temperature, softness of ash and low velocity of particles.
7. The CO_2 content in the flue gas is of the order of 14 to 15% at the full load capacity.
8. High turbulence in the boiler bed facilitates quick start and shut down.
9. Inherent high thermal storage characteristics provide fast response to load fluctuations.
10. There is no slagging or soot blowing and the removal of ash is easy.
11. Routine maintenance is reduced and high efficiency is maintained for long periods.

Retrofitting of FBC systems. Retrofitting fluidized bed combustion systems to conventional boilers is possible. Conversion of a conventional coal fired boiler system to a fluidized bed combustion system can be executed without effecting major changes and has been done in India also. The important factors which should be considered in retrofitting a FBC system are :

1. Water and steam circulation
2. Clearance between furnace bottom and grate
3. Type of particulate control device
4. Availability of space

But before adopting the conversion, the cost-benefit analysis should be done. Oil fired boilers can also be converted into a coal fired fluidized bed combustion system.

8.6. TYPES OF FLUIDIZED BED COMBUSTION BOILERS

There are three basic types of fluidized bed combustion boilers :

1. Atmospheric Classic Fluidized Bed Combustion System (AFBC)
2. Circulating (fast) Fluidized Bed Combustion System (CFBC)
3. Pressurized Fluidized Bed Combustion System (PFBC).

8.6.1. Atmospheric classic fluidized bed combustion system. Fig. 8.4 shows an atmospheric fluidized bed combustion system. Such boilers are also called *bubbling bed boilers*. Coal is crushed to a size of 1 to 10 mm depending on the grade of coal and the type of fuel feed system. Because of the low combustion temperature, inferior grade coal can also be used. Usually two methods are adopted for feeding of fuel. The crushed coal is pneumatically transported from feed hopper to the combustor through a feed pipe. This method is known as *under-bed pneumatic feeding*. In the other method known as *over-bed feeding*, coal is crushed into sizes of 6 to 10 mm and is delivered to a spreader with the help of a conveyor. The spreader uniformly distributes the coal over the bed surface. In over-bed feeding system coal of larger sizes are used and the need of transport line is eliminated.

An air distributor, made up of perforated metal plate, forms the floor of the furnace. The atmospheric air is delivered at some pressure and acts both as the fluidization air and combustion air. The function of air distributor is to introduce the fluidizing air evenly through out the whole cross section of the bed. It keeps the solid particles moving on constantly and prevents the formation of defluidizing zones in the bed. The atmospheric air is preheated by the exhaust flue gases before admitting into the bed. The rate at which the air is blown through the bed decides the quantity of fuel that can be reacted. Normally the velocity of fluidizing air is kept in the range of 1.2 to 3.7 m/sec. The distributor plate is protected from the high temperature of the furnace by providing a refractory lining, a static layer of bed material or water cooled tubes.

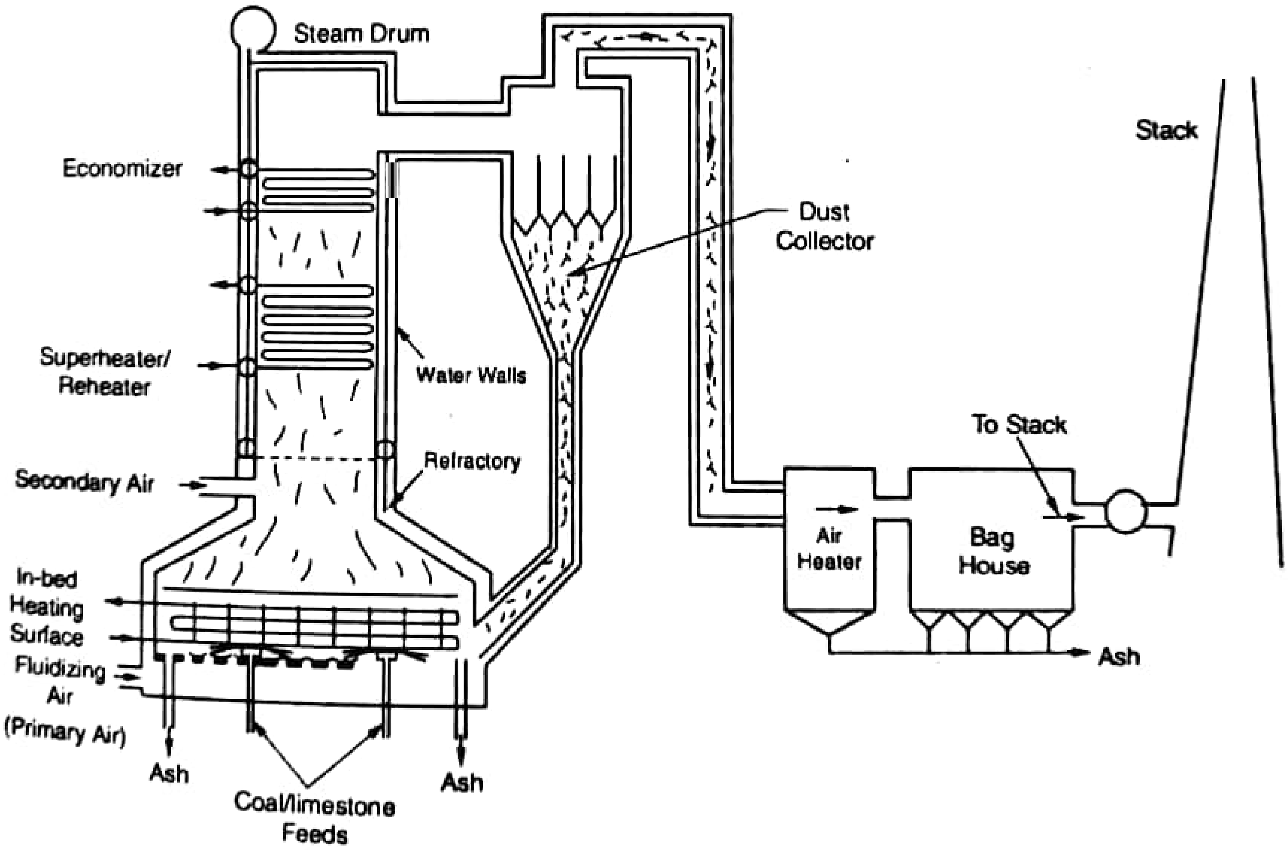

Fig. 8.4. Atmospheric fluidized bed combustion system.

Sand, ash, crushed refractory or limestone are generally used as the material for the bed. The bed is usually 0.9 to 1.5 m deep. The two bed types used are shallow bed and deep bed. The difference between the two beds is their height. A shallow bed has a lower bed resistance and therefore lower pressure drop. The pressure drop is more in case of deep bed and thus, the fan power requirement is more. Very little material leaves the bubbling bed therefore very little amount of solids needs to be recycled. Generally, all the AFBC boilers use *in-bed heat transfer* process. In this process, the heat is transferred between the bed material and an immersed surface. The immersed surface could be a bundle of evaporator tubes or coils. Extracting heat from the bed maintains the bed temperature. From the pressure drop considerations, a horizontal orientation heat exchanger in a shallow bed is more useful than a heat exchanger of vertical bundle in a deep bed. The heat transfer in the bed depends on the bed pressure, bed temperature, air velocity, particle size, and the design of heat exchanger and air distributor. The combustion gases pass over the superheater, the economizer, the dust collector and the air pre-heater before leaving to stack.

In the fluidized bed combustion boilers, nearly 30 to 40% of the total ash is the *bottom ash*. The bottom ash, also called as *bed ash*, is removed by continuous over flow and also by intermittent flow from the bottom. The continuous flow is required to maintain the bed height whereas the intermittent flow is needed to remove oversize particles. Bed height is maintained and oversize particles are removed to avoid accumulation and subsequent defluidization. The balance 60 to 70% of the total ash is the *fly ash*. The amount of fly ash is more in a FBC boiler as compared to conventional boilers because of elutriation of particles at high velocities. The fly ash carried away by the flue gas is initially removed in the convection section and then from the bottom of air preheater. Finally, a major portion of the fly ash is removed in the dust collectors. The common types of dust collectors used are cyclone collector, bagfilters, electrostatic precipitators etc.

The volumetric heat release rates are 10 to 15 times higher and the surface heat transfer rates are 2 to 3 times higher than a conventional boiler. This makes an AFBC boiler more compact than a conventional boiler. Atmospheric fluidized bed combustion system is characterized by narrow temperature range (800°C to 900°C). If the temperature exceeds 950°C, there is a chance of clinker formation and if it falls below 800°C, there is loss of combustion efficiency. Similarly, the temperature should be in the range of 800°C to 850°C, for efficient sulphur retention. In the AFBC System, since most of the sulphur is retained in the bed by the use of limestone (as bed material) the formation of H_2SO_4 acid is less and the gases can be cooled to a lower temperature before leaving to the stack.

8.6.2. Circulating fluidized bed combustion system (CFBC). Circulating or Fast Fluidized Bed Combustion (CFBC) technology has been developed from bubbling bed combustion and said to be the second generation fluidized bed boiler. Some of the drawbacks associated with bubbling bed combustion have been rectified in this system. A CFBC system could be a good choice if the capacity of boiler is large or medium, sulphur and NO_x control are important and low grade fuel is to be used.

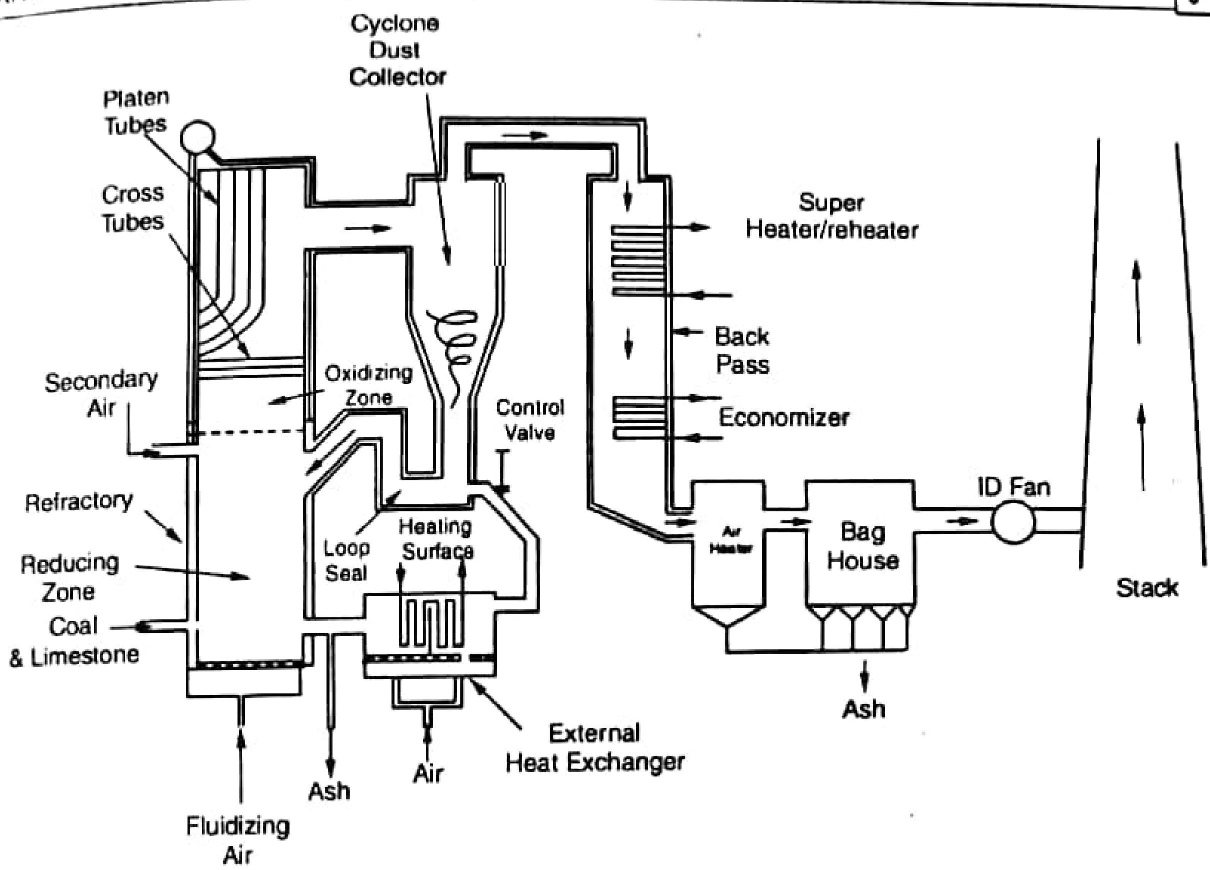

Fig. 8.5. Schematic diagram of CFBC system.

Fig. 8.5 shows the schematic diagram of CFBC boiler. A CFBC boiler is divided into two sections. The first section consists of furnace or fast fluidized bed, cyclone dust collector, solid recycle device or loop seal, and external heat exchanger. All these components from a closed loop. The second section is the back-pass, where the remaining heat from the flue gas is absorbed by the reheater, superheater, economizer, and air preheater just the same way as in conventional boilers. Crushed coal in the sizes of 6 to 12 mm along with limestone is injected into the furnace. A stream of upward flowing air, called the primary combustion air, enters the bottom of the furnace through an air distributor or grate and the particles are suspended in the stream. This upward flowing air is 60 to 70% of the total air and the balance of the combustion air, known as secondary air, is injected from some height to complete the combustion. The fluidizing velocity for the circulating bed is in the range of 4 to 9 m/sec.

The bed temperature is nearly uniform in the range of 800 to 900°C. There are no tubes immersed in the bed for steam generation, in fact the furnace enclosure is generally made of water tubes. A fraction of the generated heat is absorbed by these water tubes. Fine particles are elutriated out of the furnace along with flue gas. Relatively coarse particles of sorbent (limestone or dolomite) and unburned char are captured in the cyclone dust collector and are recycled back to the furnace. Finer solid residues such as ash and spent sorbents generated during combustion and desulphurization escape through the cyclones, but are collected by a bag-house or electrostatic precipitator. In some CFBC systems, as the one shown in Fig. 8.5 may have external heat exchangers with heat transfer surfaces immersed in it. A part of the hot solids recycling between the cyclone and the furnace is diverted through the external heat exchanger for heat removal. The circulating bed is designed to move a lot more solids out of the furnace. A high air velocity along with intense gas-solid mixing promotes high heat release and heat dispersion in the bed. High heat release rate per unit of furnace area results in less floor area and small furnace cross section. The circulating particles provide efficient heat transfer to the furnace walls and longer residence time. Longer residence time permits the use of limestone ($CaCO_3$) and dolomite ($MgCO_3$) as the two main sorbents used for the absorption of SO_2. Limestone is decomposed, reacts and the $CaSO_4$ thus formed retains the sulphur in the bed (in solid form). Therefore, the combustion efficiency and SO_2 retention are increased. The combustion controlling factors are temperature, residence time and turbulence. Taller furnace used in large units offers better space utilization, and greater fuel particle and sorbent residence time. Because of the low combustion temperature and staged distribution of combustion air, the NO_x emission in CFBC system is low (50 to 150 ppm).

Advantages. The advantages of CFBC system can be summarized as :

1. Fuel particles constitute less than 1 to 3% by weight. This allows an excellent mixing of particles and gas.
2. A wide variety of fuel can be used and that too without the support of an auxiliary fuel.
3. Superior mixing, large reaction space and long residence time gives high combustion efficiency and high sulphur retention (upto 90%).
4. High processing capacity due to high gas velocity.
5. High heat release rate per unit of furnace area results in small furnace cross section.
6. The temperature is practically constant through out the process because of high turbulence and solid circulation.
7. Minimum NO_x formation because of low combustion temperature and staged distribution of combustion air.
8. A relatively high fluidizing gas velocity and staged combustion air admission permits a CFB boiler to respond quickly to load changes.
9. CFBC boilers are normally more economical than the AFBC boilers for applications having hourly steam requirement of more than 75 to 100 T.

Disadvantages. The major disadvantages of CFBC system are :

1. CFBC system requires huge mechanical cyclones to seize and recycle the large amount of bed material. This necessitates a taller boiler.
2. Gradual wearing down of particles and erosion of reactor walls.

8.6.3. Pressurized fluidized bed combustion. Pressurized Fluidized Bed Combustion (PFBC) system uses a special pressurized fluidized bed and is suitable for applications requiring large scale coal burning. If a coal fired fluidized bed combustor is operated at elevated pressure, the products of combustion can be expanded in a gas turbine to produce electricity. The use of high pressure increases the amount of combustion and therefore, the boiler size can be significantly reduced. Pressurized fluidized bed combustion system has the potential to operate a coal fired gas turbine and can also be used in conjunction with a steam power plant. By combining the output of both gas and steam turbines, the efficiency of electricity generation is 5 to 8% more than the conventional method. One of the first PFBC plants with an electrical output of 80 MW was installed at Vartan in Sweden in the year 1991.

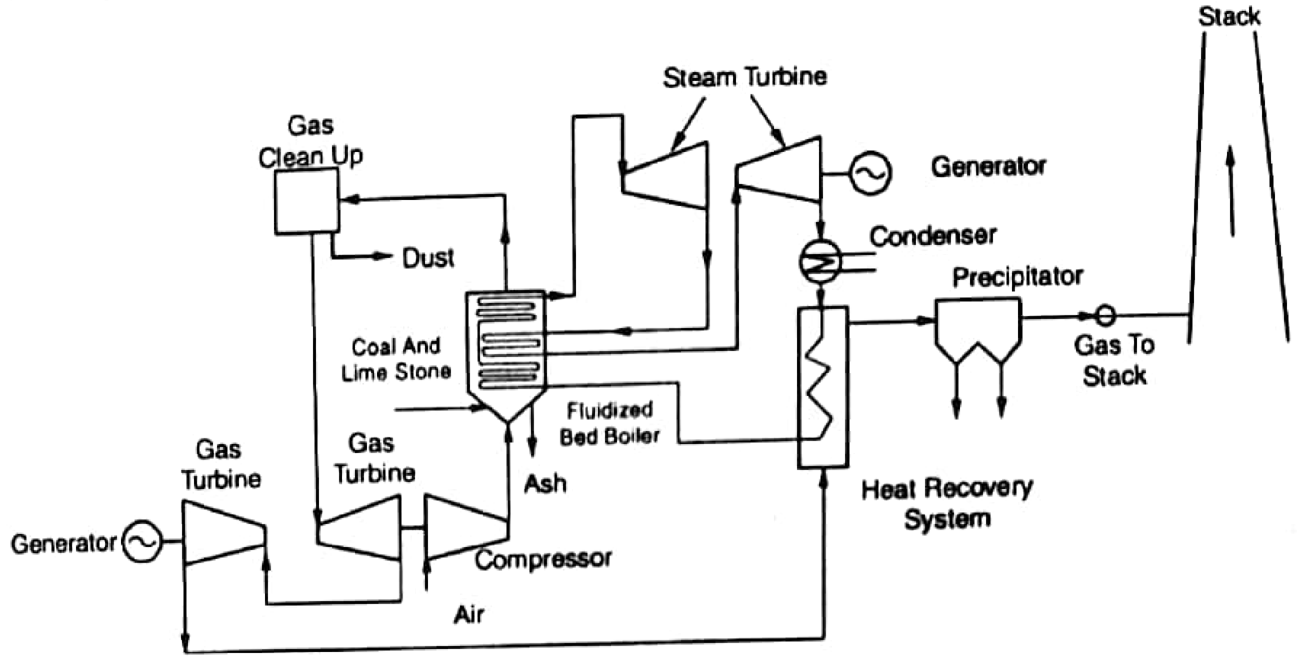

Fig. 8.6. Simplified diagram of PFBC plant.

Fig. 8.6 shows a schematic diagram of a system using a pressurized fluidized bed combustor (PFBC). Coal and lime stone are supplied to the pressurized combustor. The limestone, used as the bed material, absorbs sulphur. Desulphurization of the flue gas takes place along with combustion. The combustion products leaving the combustor are made to pass through a hot gas cleaning system comprising of cyclones and ceramic filters before entering the gas turbine. Cleaning of combustion gases reduce the erosion and corrosion of the turbine. After being de-dusted in cyclones and filters, these high pressure flue gases expands in the gas turbine, generating electricity. The exhaust gas from the gas turbine, at about atmospheric pressure, flows through the catalyst reduction and stack gas cooler before leaving to the atmosphere.In the catalyst reduction NO_x is removed. Cooling tubes immersed in the fluidized bed are used to generate steam which drives a steam turbine. The condensate from the steam turbine is pre-heated with the help of waste heat from gas turbine exhaust. This pre-heated condensate is used as feed water for steam generation.

In PFBC system, the bed vessel is operated at pressure of 10 to 16 bar*. The use of high pressure increases the amount of combustion and causes high heat flux through the in-bed tubes. This increases the gas density and reduces the bed area for a particular heat release. Therefore, the boiler size can be reduced to a considerable extent. Power plant

* 1 bar = 1.019 kg/cm²

using PFBC are smaller in size than FBC and conventional steam and combined cycle plants. For example, the diameter and height of a typical 250 MW PFBC boiler is 40 feet and 100 feet respectively which is just half of a conventional pulverized fuel boiler of the same capacity. The use of this technology is dependent on compatibility of the hot gas clean up system with gas turbine inlet temperature and maximum particulate size. About 80% power is contributed by steam turbine and the remaining 20% by the gas turbine. The temperature in the PFBC is limited to about 850°C because this is the most encouraging temperature for sulphur retention and is below the ash fusion temperature of coal.

The simplified diagram for a 350 MW PFBC plant in operation in Japan is shown in Fig. 8.7. To further improve the overall cycle efficiency, partial or mild gasification of coal is done. Mild gasification is a devolatilation process which produces a series of alternate fuels by composing coal into simpler components at relatively mild temperature and pressure. This is known as the second generation of PFBC systems. By partial gasification and by combusting the char in a fluidized bed combustor, an optimum can be achieved between the gasifier and the combustor sizing as well as the steam and gas turbines. Also, the advantages of higher gas turbine inlet temperature can be utilized.

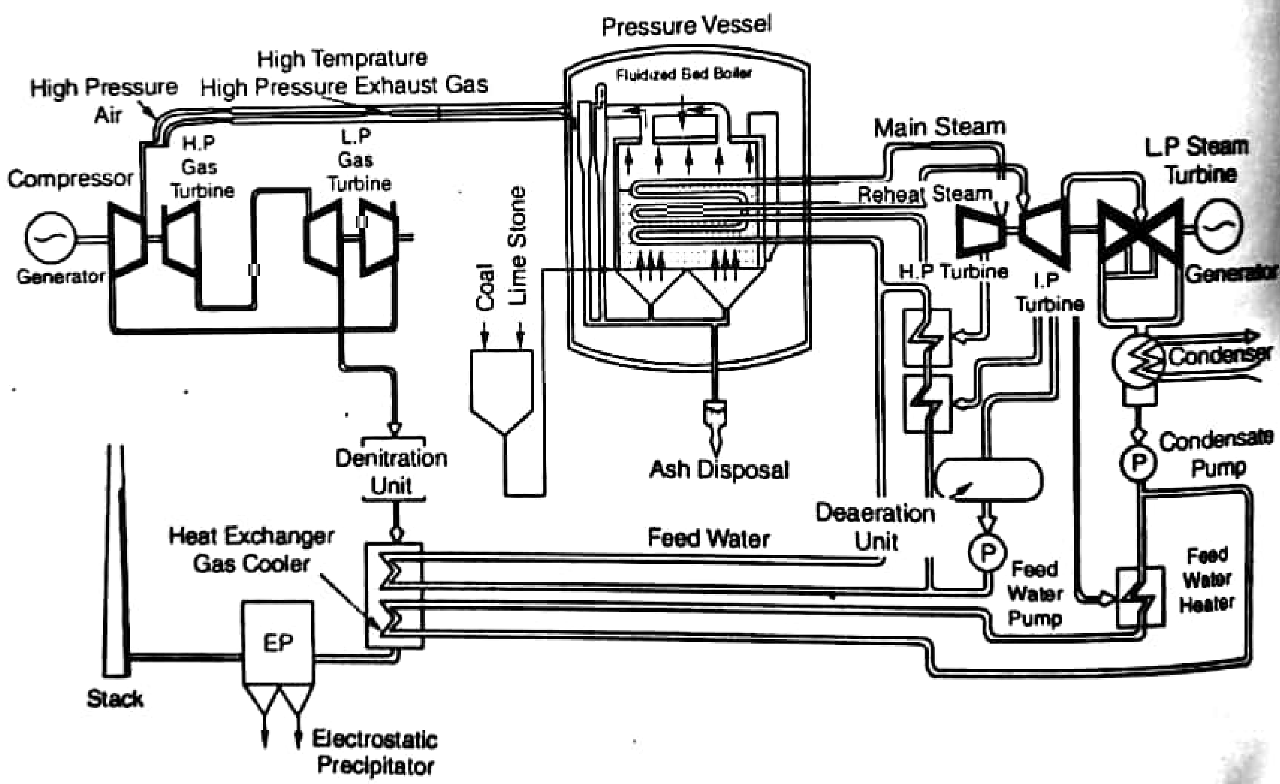

Fig. 8.7. A 350 MW PFBC power plant.

SOLVED QUESTIONS

Q. 1. ***Write a short note on clean coal technologies.*** [*RGPV Bhopal, Dec., 2008*]

OR

What are clean coal technologies ? Enlist the advantages of employing clean coal technologies in power generation. [*RGPV Bhopal, Dec., 2007*]