Coal Firing:
Coal Firing & its techniques
In olden days adopting old design of small package boilers, hand firing was done. Even not very long ago, locomotive engines were deployed for hauling of train compartments, wherein only hand feeding of coal used to be done. Gradually such manual handling of coal has been dispensed with and modern mechanical coal firing techniques have been developed. Modern techniques of coal firing system consist of different designs such as automatic Stoker firing, Pulverized fuel firing, Fluidized bed combustion etc.

Advantages of mechanical coal firing appliances (techniques) over hand firing:
Mechanical coal firing appliances are much superior to hand firing, as it is fired by machine. The inherent superiority of mechanical stoker is that, coal is fired continuously with fire doors closed, which is not possible in case of hand firing. In case of mechanical firing, smoke nuisance is abated, excess air is reduced, there is no disturbance of fuel bed, ash is cleaned automatically, variation in steam demand could be easily adjusted by increasing or decreasing the firing rates and duties of boiler. In adopting mechanized fuel firing combustion is made perfect and the combustion efficiency is improved. Due to improved combustion unburned in flue gas is reduced to bare minimum. This can be seen from the percentage of CO₂ which otherwise in manual firing methods used to be at least 3% to 4% is less. Due to efficient combustion, saving of precious fuel is achieved to the extent of about 10 to 15%, since the boiler performance and efficiency has shown remarkable increase by 5 to 7%. Let us now study various modern mechanised methods adopted in coal firing system.

Stoker firing system:
Different types of stokers are,
a) Chain grate stoker
b) Multiple retort stoker
c) Spreader stoker
d) Low ram cooking stoker
e) Sprinkler stokers
f) Under feed stokers
g) Pulsating stoker

Stoker-fired systems account for approximately 90 percent of coal-fired water tube boilers. All the above Stoker firing systems can be divided into three groups: Underfeed stokers; Overfeed stokers; and Spreader stokers. These systems differ in how fuel is supplied to either a moving or stationary grate for burning. One important similarity among all stokers is that all design types use underfire air to combust the coal on the grate, combined with one or more levels of overfire air introduced above the grate. This helps to ensure complete combustion of volatiles
and low combustion emissions. Many stokers also utilize fly ash re-injection to minimize the unburned carbon content in the fly ash. Underfeed stokers were once the primary stoker type used in industrial and utility steam generation, but the high costs of maintenance and the slow response of these units to varying loads have made them less competitive in the present market. Spreader stokers, however, are extremely popular in industry today, due in part to their wide fuel capability.

In general, stoker coal is fed crushed with a nominal size of less than two inches. Overfeed and spreader stokers can be used to burn almost any type of coal or solid fuel, including wood, wood waste, and bagasse. Coking bituminous coals, however, are not used in overfeed stokers to avoid matting and restricting the airflow through the grate. Coking has little effect on the performance of spreader stokers. Most packaged stoker units designed for coal firing are of less than 100 million Btu/hr capacity. Larger units are typically field-erected.

**Chain Grate Stokers:**

It will be of interest first, however, to consider something of the history of the chain grate stoker in the boilers. Mechanical stokers were introduced about the year 1820; following upon an insistence on pollution control problems and to find a solution for smoke nuisance. Later, John Juckes patented a chain grate stoker on the lines of the machine now familiar in so many boiler houses and when Babcock and Wilcox developed their water tube boiler, they coupled with it the development of this chain grate stoker.

On a typical chain grate stoker the links of the chain are made of a good grade cast iron and are narrow and deep in order to give the smallest possible amount of heat absorbing surface. This is done, of course, so that the links shall remain cool in service. The links are supported and kept in position by fixed bulb bars, so that no driving strains are taken by the links themselves. Air spaces between the links are kept as fine as possible to avoid riddling and to give good air distribution. As the links pass over the rear of the grate they drop with a definite movement to shake fine ash free of the air spaces.

![Clinker Dams](image1)

![Ash Dumping Plate](image2)

![Rear Sprockets](image3)

**Fig. 1**
Cast iron bars known as clinker dams, remove the heavy clinker and ash from the grate as the links scrape past the noses of these dams (see Fig. 1). The clinker then drops into a pit for periodic removal by means of deashing doors of dumping plates, which are operated by a lever from outside the boiler. These doors seal off air from the atmosphere when in the normal closed position to avoid cold air being drawn into the back of the furnace. Separate hoppers are provided under the grate for riddling and for fine ash.

The bulb bars carrying the links are bolted to an under-carriage chain, which runs on rollers on both the service and return runs in order to reduce friction and so keep down the driving force required.

The drive is from a shaft at the front, which has a number of sprocket wheels to engage with the carrier chain. At the rear end, the carrier chain is guided by another set of sprockets, each of which is mounted on a short shaft running in heavy bearings. The driving shaft is turned slowly and continuously by an electric motor through a gearbox giving a choice of perhaps eight speeds. A rheostat on the motor starter can sometimes carry out further speed control.

The space between the top and the underside of the chain is divided into compartments across the grate, and air is admitted to each compartment by a damper, which can be regulated as required. A coal hopper is fitted at the front of the grate and feeds coal to the grate in a steady flow. The thickness of the layer of coal carried forward into the fire is regulated by an adjustable plate usually known as guillotine or fire door.

The operation of the chain grate stoker is a fairly simple matter. As mentioned earlier, the thickness of the fuel bed is controlled by the guillotine fire door or regulating shutter, while the length of the fire is controlled largely by the speed of the grate and also to some extent by the distribution of primary air. Thickness of fire and speed of grate should be adjusted together to give the best results. As much as possible of the grate area should be used but the ash passing over the clinker dams should be completely dead. In the second type, the grate surface is made up of a series of louvers in place of the grate links. Apart from these features the stoker is broadly similar to that already described and the remarks on operation apply equally.

The best coal for chain grate use is one having a fairly good volatile content and a low caking index, that is to say, one which will not “cauliflower” on the grate. A certain percentage of ash is necessary in order to protect the grate from radiant heat in the furnace. Higher caking coals can be burned however and wetting such coals helps to produce satisfactory fires because wetting results in making the fire uniformly porous. Grates such as these can be used for boilers up to 250,000 pounds of steam per hour, but for large boilers, other methods of firing have to be used and the most important of these today is pulverized fuel firing.

Multiple Retort Stoker (Taylor Stoker Type):
This grate consists of alternate troughs or retorts and banks of tuyere plates, which are the real, grate surface. The retorts are rectangular in shape and gradually reduce in depth from front to rear of the grate. This means that the volume of each
retort gradually becomes less and less and as the coal passes down, it is forced to spill over the tuyeres or grate surface where it can burn. The surface of the grate lies at an angle of twenty-five degrees to the horizontal, this being the angle at which the fullest use can be made of the force of gravity to aid the passage of the fuel bed down the grate without causing it to slide. The retorts are placed at regular intervals across the width of the grate and their sides form the supports for the grate surface. This grate surface consists of a number of overlapping plates called tuyeres arranged in banks between each pair of retorts. Banks of half tuyeres are ribbed to form air passages and this breaks the forced draught supply into a large number of small jets.

The coal hopper is fitted across the front of the stoker and primary rams, which are circular plungers of cast iron 23 cm in diameter, move to and fro taking charges of coal from the hopper, each ram forcing its charge through an entrance throat into the upper end of a retort.

The travel of the rams is fixed at 23 cm and therefore the amount of coal delivered at each stoke cannot be varied by the operator. Theoretically the force of the primary ram should be effective down the entire length of the retort, but in practice further rams, commonly called pushers, are fitted in each retort to assist the passage of the fuel bed. The number of tuyeres making up each bank and the
number of pushers fitted depends upon the length of the grate required just as the number of retorts and tuyeres banks depends upon the width of grate required. Each pusher can be said to feed a number of tuyeres with coal from the retort on the forward stroke and the length of this stroke can be varied from outside the boiler by adding or removing U-shaped washers or different thickness to the driving rod of the pusher. The primary rams are driven by connecting rods from crankshafts, and in turn move bell cranks to which are attached the driving rods of the pusher. The crankshafts vary in number according to the width of grate and are connected together by two speed gearboxes driven by an electric motor. The speed of the rams and pushers can be varied by a rheostat on the starter of the driving motor in addition to the two speeds of the gearboxes. By reason of the shape of the retort from front to rear, the coal in it is in the form of a wedge, and it is the action of this wedge of coal being forced down the retort which moves the coal down the grate and also upwards to the grate surface. When the fire reaches the rear of the grate the retort has practically no depth and very little coal remains. The coke and ash at this point goes forward to an extension grate consisting usually of fixed cast iron bars with a few moving bars which have a variable rise and fall to agitate the residue of the fire and so complete the burning off. The clinker and ash then move off into an ash pit fitted with crushing rollers to break up the large clinker before it falls into the ashing sluice or the storage hopper. For this grate, coal with a medium or high caking index is necessary for good operation and anthracites can be burned with good results. With bituminous coals, up to 30 percent coke breeze can be added if well mixed.

The speed of the rams alone varies the amount of coal delivered to the grate, but the length of stroke given to each pusher is important in keeping an even fuel bed. In practice the top pushers have the longest stoke and the travel of each succeeding pusher is decreased. The length of travel of the bottom pusher and the level of ash in the ash pit must be regulated together to bring the clinker out of the fire continuously and yet not allow the fire to thin out too much at the rear end. The ash pit is sealed against the entry of cold air by the hot ash in it and this is another reason for the careful regulations of the height of ash in the pit.

**Spreader Stokers:**
The Spreader Stoker is a method of overfeed firing which carries out mechanically what the human stoker does in hand firing a grate. It has been more widely in the U.S.A. than in this country. During World War II however, when lower grades of coal had to be burned, much trouble was experienced in power stations with stoker-fired boilers due to boiler fouling. With pulverized fuel, boiler fouling was not found to be such a problem, and it was thought that the spreader stoker also might offer this advantage with the added attraction of having only to crush the coal instead of powdering it. Consequently, eight spreader stockers were ordered in 1945 for Kearsley Power Station and the first of these went into service in 1949.
The operation of the stoker is as follows :-
The fuel is delivered evenly over the breadth and length of the furnace where it ignites and burns rapidly. The ash forms a protective layer on the grate surface.
which is in the form of a chain grate moving slowly to the front of the furnace to discharge ash. Air from the forced draught fan passes up through the grate and cools the ash as well as keeping the grate at a safe temperature. There are no air compartments and the front end of the grate is provided with air seals as shown in the General view in Fig. 3.

Fig. 3

One very essential point is that the furnace be correctly designed for this type of firing, a high combustion chamber being necessary. To some extent the spreader stoker suffers the same limitations as to the size of boiler possible, which are found with chain grate stokers however, and no very great extension of their use can be foreseen.

**Cyclone Furnace:**
In direct contrast to the spreader stoker the cyclone furnace aims at bringing all the ash from the coal, to a fluid State, and it is continuously run off and quenched. This is done to prevent grits from passing through the boiler thereby avoiding losses due to unburned carbon in grits and keeping the boiler free from fouling. This type of furnace has been developed and tried in the U.S.A. and in view of the experience
there, the then Central Electricity Authority decided to install a trial unit in this
country.
As with the spreader stoker crushed coal is used but the size is regulated to not
more than 5 mm. the primary hot air is added at this stage and the air pressure
carries the coal into the furnace. We will discuss about the cyclone furnace in
further detail in the furnace section.

**Pulverized Coal Firing:**
In most of the large power plants, where fuel is coal, pulverized coal is extensively
used in pulverized fuel firing coal is finely powdered in grinding mills before firing
it through burners and thus presence of fines in coal supplied cause no problems.
According to load conditions of boiler, fuel air ratio is required to be maintained.
Due to firing coal in pulverized form as the fuel is burnt in suspension, ash in
coal becomes air borne and is discharged with the waste gases. Therefore efficient
grit arresters including electrostatic precipitators are requested to be installed
to prevent fine particulate matter (fly ash) polluting the atmosphere. In this
firing as the coal is reduced almost to the consistency of a fluid, correct quantity
of air has to be supplied for the ignition into the furnace, so that the
distillation of volatile and their combustion is practically instantaneous. In
pulverized firing much less excess air say slightly above theoretical value is
sufficient for good combustion. Adequate drying of pulverized coal should be done
as the moisture content of fuel causes problems and higher free moisture in
pulverized coals may cause difficulty in its transmission. Drying system is generally
incorporated in grinding mills.

When coal is pulverized it is ground to a flour-like fineness and injected into the
combustion chamber in a finely divided state together with the primary air. In a
pulverized fuel furnace the hydrocarbons and the carbon burn at practically the
same time.
This method of burning coal has distinct advantages:
a) The quantity of excess air can be controlled and kept down to a small
   percentage, thus producing high combustion temperature and high efficiency.
b) The lower grades of coal can be burned more efficiently than by most other
   firing methods.
c) The boiler is ‘flexible’, i.e. the rate of firing can be quickly changed to meet
   varying loads.
d) There is no known limit to size, P.F. boilers with an evaporation of 560-700
   Kg/sec are now in service.
e) The P.F. boiler will burn a wider variety of coals with less trouble than with
   other methods.

Almost any dry coal, whether high or low in volatile or ash content can be burnt but
the most suitable coal for this use contains 25% volatile and has not more than
medium caking power. Coals of lower volatile content are more difficult to burn,
and require a larger combustion space to burn them completely. These are usually
burned in the “U” flame type of furnace which maintains a high temperature
immediately after the burner mouth by the use of refractory lining of that part of the furnace.

The degree of fineness of P.F. is measured by passing it through a sieve. The size of the sieve is specified under British Standard Specification (usually abbreviated to B.S.S.). The sieve mesh is measured in small fractions of one inch. For example a 100 B.S.S. sieve will have square holes, the length of each being 152 \( \mu \text{m} \) and the area of each hole is 0.232 \( \text{mm}^2 \) and in a 200 B.S.S. sieve the length of the side of the holes will be 76 \( \mu \text{m} \); the area of each hole being (76 \( \mu \text{m} \)) or 0.057 \( \text{mm}^2 \).

Success in burning depends on uniformity of fineness, particularly in the case of anthracite. The normal degree of fineness required lies between 70 – 80% through a B.S.S. 200 mesh sieve and perhaps up to 85% in the case of anthracite.

The fuel/air mixture from the mill to the combustion chamber is usually at a temperature of about 66°C (150°F). At temperatures higher than this there is a danger of pre-ignition in the fuel pipeline. If this pre-ignition occurs both the mill and the pipeline may be damaged. Also there is a tendency for some types of fuel to coke at the burner tips, distorting the flame and lowering the efficiency.

If the fuel/air temperature is too low the moisture in the coal, instead of being vaporized and flowing to the combustion chamber with the ground coal, is likely to collect in the mill or fuel/air pipeline causing a partial fuel blockage and erratic fuel flow. This may cause flame instability or complete loss of ignition. Complete choking of mills has been known to occur due to wet coal plus low inlet air temperature. Hot air reduces the moisture content of the fuel/air mixture to about 2%. Primary air temperatures required for modern mills are in the region of 95°C to 205°C.

**Types of Pulverised Fuel Furnaces:**

There are three main types of furnace:

- a) Dry bottom furnace
- b) Wet bottom or slag tap furnace
- c) Cyclone fired furnace

We will discuss in more detail about the above in the furnace section of this chapter.

**Detailed methods of firing can be divided into:**

- a) horizontal firing
- b) vertical firing
- c) tangential firing
- d) opposed wall firing

**Horizontal firing:**

The majority of horizontally fired boilers use what is generally termed the short flame turbulent burner. Other burners used are the rotary burner and intervene burner. The short flame turbulent burner is ideally suited for bituminous coals.

**Vertical firing:**
Low volatile coals should be fired in a vertical direction. As low volatile coals burn with a long flame, turbulence of a type produced by the circular burner is not required. Intimate mixing of the coal and air is obtained by dividing the secondary air and the coal into alternate streams or by admitting the coal in a thin stream surrounded by secondary air. The majority of the air is provided in the burner, the remainder, known as tertiary air, is introduced progressively through the front wall at right angles to the flame path. The flame length can be controlled by varying the secondary air.

**Tangential firing:**
Tangential firing was developed in Britain and is employed in I.C.L. boilers. It depends on the maintenance of a turbulent zone in the centre of the furnace by directing a non-turbulent flame horizontally from each corner of the furnace towards an imaginary circle of which the flame path is tangent. An important development of tangential firing was the use of tilting burners by which steam temperature can be controlled over a wide range of load and operating conditions. By tilting the fuel and air stream downwards, greater heat absorption by the furnace is produced. The reverse effect is obtained by tilting the burner upwards. The fig. 4 shows the control of maximum heat release zone position by tilting burners.

![Fig. 4](image)

**Opposed wall firing:**
Opposed firing has been used in a few boilers, and it is fitted as Drax, where there is ample distance between burner walls for efficient combustion from all burners.

**Advantages of tangential firing:**
When a stream of pulverized coal & air is thrown into a furnace, turbulence takes
place accelerating the combustion reactions. If a number of parallel streams are introduced, it results in stream lined flow. In tangential firing, the projected jet of one burner strikes another and another turbulent zone is created. Therefore in such set up, all four corners of the furnace burners are fitted which are directly tangentially at the center. Thus the stream of fuel and the air from each burner impinges on each other creating intensive turbulence so vital for good combustion. Such action gives a rotary motion to the flame which extends out filling the furnace which results in small flame length, so degree temperature although heat liberation is high. Because instead of absorption only radiation, large quantity of convection effect of the flame sweeps the heating surface.

**Fluidized Bed Combustion:**
Fluidized Bed Combustion (FBC) is a proven and tested technology for burning any grade of coal or agro waste eliminating the operational problems caused by high ash and sulphur contents. Much high quantity of coal could be consumed than other types of fuel firing systems. Fluctuations of load could be controlled with ease due to high thermal strong characteristics 80% or even more efficiency could be achieved by optimum operation practice. In this, the grate is covered with a layer of granular material either lime, limestone and crushed coal is mixed in and air is forced through the mixture causing it to bubble. Here the mixture burns at about half the temperature as in other burners, which appears like boiling liquid and hence the name Fluidized Bed. At such low temperatures lumps of ash is not formed and sulphur is absorbed by limestone and low grade coal containing high sulphur contents could be burned without the risk of pollution.
More of the fluidised combustion will be dealt with further in later part of this section.

**Flame Monitoring Equipment:**
There is a risk of spontaneous combustion of unburned pulverized fuel in a hot combustion chamber following failure of the flame and serious furnace explosions have occurred in the past. Therefore, a detection system capable of monitoring the furnace conditions continuously required.
The following systems are in the process of development:
- a) flame rod system
- b) photo-electric cells
- c) ultra-violet scanners
- d) acoustic methods
- e) television scanning

The flame rod system operates by utilizing the conductivity of the flame to complete an electrical detecting circuit. An electrode rod is placed in the flame and forms an electrical circuit consisting of the power supply, the flame rod, the flame and burner carrier tube. This type, is only suitable for sufficiently ionisable flames, i.e., gas flames.
Photo-electric cells are of several types such as, photo emission cells, vacuum cells, gas filled cells, photo conductive cells. These devices are generally responsive to
luminous flux and the last type, photo conductive cell, has an advantage as it is responsive to infra-red plus visible radiation. Since there are no flames without infra-red radiation this cell may be universally applicable to gas, fuel oil and pulverized coal. By means of a special electronic circuit these infra-red detectors can be made sensitive to only the flicker frequency band characteristic of the actual flame flicker. In this way the steady radiation from hot refractory is not detected. The photo-electric devices have a disadvantage that they do not possess the property of discrimination between several burners of a multi-burner furnace. The ultra-violet detector is a more recent development, the theory being that certain oxygen-hydrogen radicals which exist in the early stage of the combustion process are the source of the ultra-violet radiation. This explains the fact that ultra-violet radiation can be detected in flames only when the fuel contains hydrogen and that outside the primary combustion zone the ultra-violet radiation is very low. (Fig. 5). This last characteristic makes these cells ideally suited for the monitoring of multiple burner boilers as the discrimination ability of the detector is high. An acoustic device has been developed which monitors the sound of the burner flame relying on the fact that a healthy burner emits a particular sound and that variations from this sound are indicative of abnormal conditions. With this system also, discrimination between various burners on a multi-burner installation can be a problem. The use of closed circuit television to observe the furnace condition is another method of flame monitoring. The very high temperatures encountered in a modern furnace are an obvious problem in designing this type of monitor.

![Coal Pulverisers](image)

**Coal Pulverisers:**
Pulverised fuel firing is a method whereby the crushed coal, generally reduced to a fineness such that 70-80% passes through a 200 mesh sieve is carried forward by air through pipes directly to burners or storage bins from where it is passed to burners. When discharged into combustion chamber, the mixture of air and coal ignites and burns in suspension.
The economic motives for the introduction and development of pulverised fuel firing are:

a) Efficient utilization of cheaper low grade coals.
b) Flexibility in firing with ability to meet fluctuating loads.
c) Elimination of banking losses.
d) Better reaction to automatic control.
e) Ability to use high combustion air temperature increasing the overall efficiency of boiler.
f) High availability.
g) The only disadvantage is that the initial cost of equipment for preparation of pulverised coal will be high.

Types Of Pulverisers (Depending on speed):
Milling plant may be divided into three main types depending on speed of the pulveriser-low, medium and high speed each having its own advantages and drawbacks.

Low speed mill:
These are commonly known as tube ball mills and operate at approximately 17 to 20 rev/min. in most cases under suction although pressurized version is also in operation.
Such low speed is essential with this type of mill as otherwise the balls will be held along the rotating surface due to centrifugal force and no milling can take place.
Major advantage of the mill is that the wearable part which needs replacement between annual overhauls is only the ball and this can be done when mill is in operation. Hence availability of each mill can reach 100% of the boiler availability. However the gear box and main bearing failure may reduce the availability. The main disadvantage is that the power consumed per ton of coal pulverised is nearly twice that of the economic mills such as bowl mills. In addition to this the power consumption is practically constant whatever may be the load at which mill is operated thus calling for operation at or near full load to achieve economy in operating cost.
Spare mill for maintenance purpose is not necessary due to high availability. Even though this mill requires higher floor area, foundation and initial cost of the equipment it is preferred by some customers because of high reliability coupled with low maintenance.

Example of Low Speed Pulveriser
The tube ball mill:
Fig. 6 consists of a large round shell or tube mounted on hollow trunions through which the carrying air enters and leaves. The tube contains a charge of steel balls about 50 mm diameter and as the whole mill revolves, the balls grind the coal by their tumbling motion inside the tube. Air carries the ground coal to a classifier and coarse material is returned again to the inlet. The speed of this mill is low, about 15 to 25 revolutions per minute, and maintenance is low, but it takes up a lot of space, is very noisy in use and the power consumption in KWh per ton is very high especially
at partial loads. An advantage is the reserve capacity of this mill in the event of a coal feed stoppage.

Medium speed mills:
This is normally of vertical spindle design and operate between 30 to 100 rpm. Combustion engineering’s bowl mill B & W’s ball and race mill and other designs are available in the market. These are suitable for both pressurized and suction operation. These are most economic mills with regard to operating cost since comparatively small mass is being rotated at moderate speed. Replace of wearable parts in between annual overhauls is essential but facilitated by the design of mill and availability of spare mill for each boiler. The mills of varying capacities from 1 to 100 T/hr and even more have been designed and in operation. Power consumption varies with loading on mill which offers maximum efficiency when used in direct firing. In addition to the saving in operating cost, it requires less space, less initial foundation cost, thus the mill is seen increasingly used throughout the world.

Example of medium Speed Mills
The Raymond Bowl:
This mill is a medium speed mill with a grinding unit consisting of a fixed ring or bowl having vertical grinding faces and within these faces, a number of arms hanging vertically and each carrying a grinding roller. The arms hang from a frame on a rotating pedestal and, as this speeds round at form 80 to 110 revolutions per minute, the arms are swung outwards until the rollers are in contact with the vertical faces of the fixed ring or bowl.
Coal is ground in this way, and air entering the mill base carries it up to the separating chamber at the top of the mill. The raw coal from the mill base is brought to the grinding unit by means of ploughs which rotate with the centre driving shaft. Fig. 7 shows the bowl mill.

Many of the Generating Board’s pulverized fuel mills in smaller stations are of the Lopulco type shown in Fig. 8 and Fig. 9 and this is a development of the Raymond Bowl mill.

The bowl has been modified to form a flat circular surface and this ring rotates against two rollers which are coupled together by a tensioning spring.

Coal is passed on to the grinding table and is crushed as it passes under the rollers; air fed in at the base is drawn up through the mill, possibly assisted by an exhauster fan, carrying the finely crushed coal with it to pass through a classifier at the top. This classifier may be one of two types, the whizzer type or the cage type.
The finer coal particles are fed to the burners by the exhauster fan and the coarse particles are separated off and returned by gravity to the grinding ring for further treatment. Hence the mill works under suction from the exhauster. Provision is made for drying wet fuels in the mill itself by means of preheated air led into the mill base.

A second type of mill common to the large boilers is the “Ball” type in which the grinding elements are in the form of a large ball-bearing, the top ring of which is stationary and the bottom one revolving. Between the two rings are the grinding balls of forged steel which are rotated by the movement of the bottom ring. Grinding pressure between the balls and rings is set by springs acting on the top ring and these can be adjusted from outside the mill. Coal is fed into the middle of the top ring and is ground to a fine powder as it finds its way between the rotating balls. It then drops over the edge of the bottom ring and is caught up in a current of high speed hot air which sweeps it through a classifier or separator.
This classifier is a runner made up of blades and can be driven separately so that the correct speed to suit conditions can be used. The blades strike the larger particles of coal and are set and shaped in such a way that these particles are thrown back to the centre of burners with the primary hot air. A rotating table type of feeder discharges the raw coal to the centre of the top grinding ring, the feeder being driven by a separate motor having a speed regulator. On modern boilers the ratio of coal to air is kept constant by means of an automatic combustion control system so that a mixture of the right proportions is always delivered to the burners. Changes in the rate of fuel fed to the burners are made simply by adjusting the damper for the supply of hot air to the mill. These features may be applied equally to the Lopulco type mill. Any materials which cannot be ground, such as the hard impurities in the coal which are called pyrites, are dealt with as follows. Below the bottom grinding ring is a device known as the yoke segmental seal ring and this is fitted with ploughs which move the pyrites round to openings in the top bearing plate. From these openings they are discharged into chambers which can be cleaned out when necessary. Fig. 10 shows the paths taken by the coal and air through the mill to the burners. An essential feature of this type of mill, which works under pressure, is the air sealing arrangement within the mill. The air sealing pressure is greater than the mill chamber air pressure and so prevents the crushed fuel from entering such parts as
the driving gear bore. The air seal fans are sometimes inter-locked with the main fans so that if the air seal fans trip, the main fans also stop.

**High speed mill**
This mill is directly coupled to the motor thus eliminating speed reduction gears essential for other type. This is run at 500 to 1000 rpm depending upon design. Beater mill, impact mill, fan mill etc. are of this design.
This mill offers compact design, less initial cost and floor area. But the operating cost and maintenance cost is very high. Because of fast wear of hammer due to high speed replacing of hammers once a week or even earlier may be warranted where abrasive coal is used. High level of maintenance work involved in addition to operation and maintenance cost, practically eliminated this mill for higher capacity boilers.

**Example of High Speed Mills**
**The Impact Mill:**
It is a high speed machine which reduces the coal either by means of fixed and moving pegs, or by means of swinging hammers, in the swinging hammer type a number of beater plates are mounted on a horizontal shaft and the swinging hammers are loosely held between the plates. A casing, which is lined, encloses the machine and forms an air chamber where the fine coal can be picked up by the incoming air and carried out through the top of the mill to a classifier chamber. The speed of the main shaft is very high but the mill is fairly quiet in use. Maintenance is rather high however, and, due to the high speed, tramp iron and hard foreign matter can do much harm. Also the high speed prevents large units of this type being made. Fig. 11 shows an impact mill.
It would be true to say that the grinding mill is the heart of the pulverized fuel system and a knowledge of its construction and working is of paramount importance. A brief survey of some of the types of mill used will be of interest, before passing on to a study of the two main types of mill in present day practice.

Definitions:

**Automatic Control:**
Either complete automatic boiler control initiated by steam pressure or automatic draught control initiated by pressure in the boiler combustion chamber.

**Bin and Feeder System:**
A system of pulverizing plant which includes the use of receptacles for the storage of pulverized fuel.

**Classifier:**
A fixed or rotating device regulating the degree of fineness of grinding.

**Dampers:**
Includes butterfly dampers, rubber seated valves, dust tight valves, gate valves or other suitable type of shut-off device.

**Ignition Flame:**
The flame form an ignition torch used for lighting up the pulverized fuel.

**Coal Mills:**
Includes attritors, bowl mills, ball mills, tube mills, roller mills and similar types of pulverizing equipment.

**Unit System:**
A combination of boiler and pulverizing plant which does not include any storage capacity for the pulverized fuel.
Firing with Oil Fuel:

Fuel Oil Systems:
Fuel oil system consists of fuel oil storage tanks, piping system, oil pump, oil meters, oil heaters, oil strainers and burners. From fuel storage tanks, oil is transferred by pump to a service tank which is placed at an elevation. From service tank oil is discharged to meters and then to oil heaters, strainers and finally to burner manifold. An oil burning installation is shown in fig. 12.

The calorific value of oil fuel is higher than coal because:

a. Oil contains very little ash or water.
b. It contains a higher proportion of hydrogen which has a higher calorific value than carbon. (CV of Hydrogen is 145,000 KJ/kg. and Carbon 33,800 KJ/kg).

There is a marked similarity between the principles used to burn oil and to burn P.F. although the methods used are dissimilar. The essential factor in both forms of firing is to break the fuel into fine particles. This breaking down of oil is called ‘atomising’. If atomisation is to be efficient the viscosity must be low. Lowering the viscosity is carried out by heating the oil before pumping it to the burner.

Fuel oil is required to be heated before it is led to the burner to maintain its viscosity to the consistency it could be easily atomized. Therefore if fuel oil is not preheated, bad combustion, poor atomisation, too long a flame, deposition of carbon and smoke occurs and starting of burner is difficult.

Oil heaters are fitted with relief valve, connections for gauges, thermometers and oil drains. Heater drains must be observed to determine the presence of oil due to leakages into steam side. If oil leakage is found, the heater must be stopped for repairs and another one cut into service. Oil heaters must be periodically cleaned.

Oil temperature must be observed if it is within the limits prescribed. Excessive preheating causes cracking and coking of oil preheaters resulting in blocked burners and loss of heat. If higher temperature is maintained, fouling of heater will occur.
and carbon deposits will be formed on the tubes. Therefore it is necessary that oil temperature must be controlled within the specified limits.

Strainers play a pertinent part in fuel oil system. They are fitted for removing solid particles and foreign matter in oil. Strainers must be cleaned at least once in a day or earlier. Pressure gauge connected by a three way valve to each side of a strainer will indicate pressure drop. Unusual pressure drop will indicate fouling of strainers.

Heated oil fuel is continuously circulated through a ring main system and the oil to the pumping and heating units is drawn from the suction main and surplus oil is returned to the storage tank in use, through the return main. The connection between the suction and return mains is made through a pressure regulating valve which maintains a constant pressure in the suction main. The return main is of smaller bore piping and from it there are connections to each storage tank with isolating valves so that the return oil goes to the storage tank in service. The heated oil is discharged from the pumping and heating units through the delivery or hot filters to the individual boiler ring main which feeds the burners. The oil can be recirculated before lighting up to ensure the oil in the individual ring main is at the ignition temperature.

Fuel oil burners atomise oil into fine spray which when mixed with air forms a combustible mixture and when ignited gives out intense heat. Finer the spray more readily the oil will ignite to attain good combustion. Poor atomisation causes heavy carbon deposits.

Problems likely to be encountered, when storing fuel oil are as follows:
Impurities like sludge, water, free carbon, mud, sand, wood splinters, twigs, rust, gasket materials, pump hose shrouds and rags are likely to be found in storage tanks. Such contaminants cause problems when firing fuel oils. Storage tank construction must be strong and oil tight and located at a place where it readily accessible for inspection. Storage tanks may also be calibrated. The slope of the tank should be such that impurities collect near the drain point. Drain cock should be operated before delivery of oil. Storage tanks must be cleaned periodically and the impurities removed. Dipstick should be calibrated for the compartment concerned. Below 25°C furnace oil is not pumpable. Additives may be added to service tanks to absorb water and sludge.

Problems arising prior to burning of oils (pre combustion problems):
Before oil is fired in the boiler it must be preheated to the required temperature, water in oil emulsified, sludge dissipated and dissolved, and acid neutralized, corrosive elements eliminated thus stabilizing the oil fuel. Slagging and corrosion can be abated by use of additives.

The following problems are likely to be encountered in firing fuel oil:

a) When oil is not efficiently filtered oil strainers get plugged and oil heaters fouled.
b) Burner tips get plugged and fouled, which must be cleaned at regular intervals.
c) Flame impingment occurs for which the burner must b properly aligned.
d) Incomplete combustion results when optimum air is not supplied and when modulation of oil and air is not proper.

e) Soot formation takes place if combustion is poor.

f) When flame flutters and goes out and if oil is not smartly cut out flue gas explosion is likely to occur.

g) Slagging on furnace is noticed due to flame impingement, oil is too viscous or too light, high oil pressure, cold furnace and too high steam or air pressure.

h) Slag deposits may accumulate on superheater and reheater derating their performance, and corrosion problems may arise.

i) Built up of deposits on the tubes causes blockage of gas pass due to which impingment of flow of gases on other tubes may overheat them causing rupture.

Ash which is sulphate of alkalis and vanadium pentoxide in fuel oil are likely to cause trouble. Melting points of such compounds are low and form thin coating on tubes.

Post combustion problems:
They consist of high temperature slagging and corrosion of boiler components which are exposed to radiant heat; components subjected to low temperature corrosion, fouling and plugging.

Low temperature corrosion in furnace:

a) Low temperature corrosion could be attributed to sulphur content in fuel, excess air, flame temperature and presence of vanadium oxide precipitated on tubes if the melting point of vanadium pentoxide is reduced in presence of ash and sulphur oxide.

b) Air heaters and economisers operating below dew point cause condensation of sulphuric acid which results in corrosion.

c) Low temperature corrosion could be abated with alkaline additives. Injection of gaseous ammonia also prevents such corrosion.

For efficient utilization of fuel oil the following precautions are necessary:

a) Oil temperature must be maintained at the optimum value. White smoke indicates too high temperature and heavy carbon deposits in the furnace are formed. Black smoke indicates too low temperature.

b) Oil must be efficiently filtered and the filters cleaned periodically.

c) Maintain optimum oil pressure. Black smoke indicates too high or too low pressure.

d) Air supply must be optimum. Excess air cools the furnaces and produces white smoke. Deficient air supply produces black smoke. Preheated air plays a pertinent part not only in oil firing but of all fuels. By preheated air flame temperature is raised, better combustion and heat transfer results, excess air could be reduced and heat covered from flue gas is returned to furnace.

e) Clean the burners at regular intervals.

f) Keep all stand-by filters, pumps, and heaters in clean condition and ready for immediate service.
g) Prevent accumulation of water in storage and service tanks as water never burns.

h) Adjust oil burners to suit the load by altering the sizes of the orifices. Do not shut off burners to accommodate load conditions.

i) If the burner puffs or pulsate the preheating temperature must be decreased.

j) Steam and ventilate a tank before attempting to clean it.

k) Avoid smoke. This indicates mal-operation which affects economy.

l) To prevent fire hazards adopt precautionary measures. Prevent oil leakages and accumulation. Keep supply of sand on hand or fire extinguishers for any eventualities.

Oil Burners:
The oil burners prepare the fuel for combustion in addition to proportioning fuel and air and mixing them. As the fuel oil gets pulverised, its surface area increases manifold and finely dispersed fuel oil particles become intimately mixed with combustion air. Greater the surface area exposed for combustion and better the intermixing with the air, more complete and rapid will be the combustion process.

Two ways (with many variations) are (1) oil may be vaporized or gasified by heating within the burner or (2) oil may be atomized by the burner so vaporization can occur in the combustion space. Vaporizing burners (first group) are limited in range to fuels they can handle and find little use in power plants. If oil is to be vaporized in the combustion space in the instant of time available, it must be broken up into many small particles to expose as much surface as possible to the heat.

Atomization is effected in three basic ways:

(a) **Steam Atomization**: fuel oil, at the exit of the burner, is pulverised by the atomizing action of one or more jets of steam. In steam atomising burner oil is atomized by steam pressure. Steam atomising burners possess the ability to burn almost any fuel oil, of any viscosity, at almost any temperature. For heavy oil, steam atomising is preferred as due to reaction of steam and hydrocarbons containing large number of carbon atoms simpler substances are formed. Also that thermal advantage is obtained as steam reacts to give increased heat by preventing the escape of unconsumed products. Steam consumption for atomising oil is about one to five percent of steam produced.

(b) **Air Atomization**: fuel oil is atomized in the same way as steam atomization-the only difference is that air instead of steam is used as the atomizing agent and the oil is forced under pressure through a nozzle. Oil could be supplied to the burner either by gravity or a pump which serves to carry oil to the burner tips to overcome the resistance and play no part in atomisation. Gear pumps of positive displacement type are used to pump furnace oil. The atomising air is supplied by blowers usually driven by electric motors and the burner could be lighted up any time.

(c) **Mechanical Atomization**: fuel oil is broken down into finely divided minute particles by means of mechanical devices by centrifugal force.
Selection of burners:
Selection of burners depends upon the following factors:
1. Range on which a burner is expected to function over a turn down ratio.
2. Condition of temperature in combustion chamber requiring preheated air.
3. Shape of flame. In wide flame, air could be easily mixed with oil droplets, resulting in good mixture.
4. For small diameter flame if pressure jet burner is used air must be supplied by forced draught to ensure reasonable velocity through the air register.

Classification of burners:
The group classification of burners is based on the dynamics of droplet formation. The following principle types of fuel oil burners have been identified:

a) Horizontal rotary cup
b) Twin fluid atomizer
c) Pressure Jet atomizer

Horizontal rotary cup Burner:
Horizontal rotary cup burner is the simplest oil atomizer in appearance and construction. Its name may be traced to its water-glass or drinking cup appearance, as shown in fig. 13 Below.

The cup is attached to a motor driven by a hollow shaft containing a fuel pipe terminating in the cup in a special orifice or a tip termed a distributor. The other end of the hollow pipe is the oil inlet port. The shaft is driven in the horizontal position by a motor at a speed of 3-5 thousand revolutions per minute. The oil forms a thin film on the inner surface of the spinning cup when the fuel oil is directed onto it. It slides around on itself and starts moving two ways from the starting contact point with the cup. The portion of oil flowing towards the closed end of the cup forms a kind of thin barrier restricting its further movement in that direction. The flow of oil is forced towards the open end by the centrifugal force imparted on it and this process presses the oil against the inner surface of the cup. This results in the motion of the oil out of the open end. The thin oil film cylinder as soon it is
extruded from the spinning cup it gets broken into thousands of small droplets. The thinner wall of the liquid cylinder the more complete its disintegration as it escapes into the stream of the combustion air into a non-variable 180 degree pattern. The cup is griddled by an air nozzle that forms the burner snout. The primary air stream fed through the air inlets is forced out of the air nozzle at a velocity of 10-20 thousand feet per minute depending on the firing rate of the burner. This may correspond to 18 inches or more of water column of pressure at higher firing rates. This envelopes and captures the oil droplets emerging out of the cup.

In spite of this level of pressure supplying combustion air, this can meet only 15% of the total air requirement. The remaining air is taken into the combustion space as secondary air through natural or mechanical draft in most case by passing the rotary burner.

A cylindrical cup generates a longer narrower flame while a conical produces a wider shorter shape of flames. There is some flexibility available in the choice of nozzle-cup combustion for specific burner requirements. This type of burner is best suited for use with heavy oil as compared to light or distillate type oils.

**Advantage:**

i) Good atomisation.

ii) Droplets produced are more uniform in size than those produced by any other methods.

iii) Much less sensitive to viscosity change of fuel oil.

iv) Much less liable to clogging by grit than other mechanical atomizers.

**Disadvantage:**

When the burner is taken shutdown, deposition of carbon particles, due to thermal cracking of fuel oil induced by radiation heat from the hot surroundings, takes place on the rotary cup surface, destroying its smoothness.

**Twin Fluid Atomiser:**

The so called twin fluid atomizers are designed to spray a mixture of oil and steam, the fuel being generally introduced into the high velocity air stream in discrete jets. These are based on the spray nozzles that have emerged as the most popular mechanism of oil droplet preparations.

Fig. 14 below shows such a burner.

![Fig. 14](image)

These customarily operate with oil pressure less than 100 psi and more often less than 30 psi. The air pressure may vary from 3-15 psi in the medium air pressure; it may be 15 psi or more in high air pressure burners. The dry steam pressure may vary
from 25 to 175 psig. In both these versions the high pressure atomizing air remains unaltered with change of load and demands for higher load are met through the regulation of the secondary air. This results in higher efficiency of such system even at lower loads. For the same reason since the atomising air forms only a small part of the total air requirements for combustion, these burners are better suited for generation of higher temperatures in the furnaces through preheating the combustion air. This is achieved by feeding the comparatively colder primary air at 300 °C or so (at which effective oil cracking may take place) through the burner and injecting the heated secondary air directly into the combustion zone may be used in place of compressed air as a better atomising medium.

A typical widely used low pressure burner is shown in the fig. 15 below.

![Fig. 15](image)

Low pressure oil at 8 to 12 psi and compressed air or the atomising air at 24 " WG streams are brought into the atomiser through different routes, made to interact with each other and leave through a common orifice. The amount of aeration in the mixing process is not much although fine oil droplets formation is promoted through colloidal dispersion. Bulk of the oil however is subjected to a centrifugal force in swirl chamber like that in a pressure atomiser. The process of oil spray production depends on the oil-air interaction within the nozzle. Size wise this is bigger for equivalent capacities, its orifice being about 50 times larger. Most of the designs are based on a pipe within a pipe nozzle lines as illustrated in the above figure. The efficiency of these burners sharply gets reduced at low loads. In a self proportioning version there is a provision for regulating oil and air flow through a single lever.

**The Pressure Jet Burner:**
The function of the burner is to split the oil up into a fine spray, or to use a more technical term, to atomise it, as without this treatment the heavy oil would not burn. Fig. 16 shows the construction of a pressure jet oil burner. In the pressure jet type of burner the oil, heated usually to between 121-177˚C (250-350˚F) is forced under pressure through a small hole in the tip of the burner. These tips are discs of metal with a small hole in the centre, and it is usual to have several sets of tips, each set having a different sized hole to suit different grades of oil. The oil pressure at the pump will vary from 0 to 0.31 bar according to the load required from the boiler. Small changes in load can be made by reducing or increasing the oil pressure, but for greater load changes the number of burners in use is varied and if necessary the size of tips used is changed also. For raising steam,
only one or two burners will be used and the number of burners increased to suit as the boiler comes on load.
It is usual to fit a mechanical safety catch on an oil burner so that the burner cannot be withdrawn unless the oil supply valve is shut. Automatic purging by either compressed air or steam is normally fitted to all burners and this prevents the build up of carbon in burners temporarily withdrawn from service due to load changes. Without this purging, the heat radiated from the furnace would carbonize any oil remaining in the burner.

The primary air for combustion is delivered around the burner and is distributed evenly by means of an air cone or ‘register’ set in the housing, while secondary air is delivered direct to the furnace. In front of the air cone is the burner cone or diffuser which is considerably smaller in diameter than the air cone and serves to prevent the forced draught from sweeping directly over the end of the burner nozzle and so chilling the flame in addition to diffusing the oil mist. Adjustable valves are fitted around the air cone and a master air valve is also fitted. For good combustion the flame should always be white and clear and oil pressure and temperature, size of burner tip, and openings of air vanes must all be adjusted to obtain this type of flame.
With oil fuel burning the regulation of oil pressure and temperature are of great importance because too high a pressure will result in too high a rate of oil delivery at the burner nozzle, and too high a temperature may cause the oil to carbonise in the nozzle.
The filters should be changed over as often as necessary, and burner parts kept clean at all times. Cleaning of burners is usually necessary about once in 24 hours of steaming and cleaning is done by soaking in paraffin or some other cleaning medium. The utmost attention to cleanliness of the burners is essential to obtain the best results.
Sonic Burner:
A sonic burner is a modern development in firing oil fuel which is a pressure jet burner with a sonic head attached to which connections are provided in either steam or compressed air. This medium on passing through the sonic head gains high velocity which produces resonance around the burner tip. Thus a powerful sonic energy is created into which a controlled amount of oil is fed.
In such burners oil is divided into very fine particles and combustion is closed to stoichiometric condition.
In such burners better heat transfer, better flame control, high degree of combustion, high operating temperature and high turn down ratio of 1:20 can be obtained. A flame of lower dimension can be produced in such burners and thus combustion chamber volume could be reduced.

Firing of Gas:
Burning of gas is easy and clean. No atomisation is required. Combustion of 1 m\(^3\) of natural gas requires roughly 20 m\(^3\) of hot air. Proper mixing of gas and air can be ensured by introducing the gas into the air flow in the form of thin jets of high penetrability (see fig. 17). Because of good mixing excess air required for the combustion is less.

Combined gas fuel oil burners:
The advantage of combined gas- fuel oil burners is that the change from one fuel to other can be done quite easily. In addition both fuel can be burned under almost optimal condition. The natural gas and fuel oil can be burnt on furnaces of the same design due to the following common combustion characteristics:
1. Both natural gas and fuel oil contain practically no moisture and they give rise to roughly the same volume of combustion products. Thus the blowers of steam boiler run efficiently irrespective of whether fuel oil or natural gas is being burnt in the boiler furnace.
2. Combustion of either fuel takes place in the vapour state and the intensity of burning in either case is determined by the conditions of intermixing. Combustion mechanism is the same.
3. Both the fuels have nearly the same value of highest allowable heat release per unit volume of the furnace. For fuel oil it is 300 kW/m\(^3\) and for natural gas it is 350 kW/m\(^3\). And as such for the same stem output of a boiler, the furnace
dimensions for these two kinds of fuel can be taken to be the same for practical purposes.

4. Both fuels are practically free from ash-formation problem upon combustion. Therefore, clinkering of waterwall tubes does not arise and slag-handling facilities are unnecessary. This is why furnaces for both fuels are designed with a horizontal or slightly inclined bottom.

5. More homogenization of air-fuel mixture is possible as both fuels are in a vapour state prior to ignition. This means virtually complete combustion with less amount of excess air.

6. For both fuels, air can be preheated to the same temperature 250-300ºC (523-573ºK) making it possible to install combined gas-fuel oil burner system.

7. Both fuels produce a relatively short flame core-zone near the burners during intensive burning.

The fig. 18 indicates the various components of s coaxial gas-fuel oil burner with central gas supply.

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<tr>
<td>1</td>
<td>Annular gas channel</td>
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<td>2</td>
<td>Fuel oil burner</td>
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<td>3</td>
<td>Tangential vanes</td>
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<td>4</td>
<td>Air control gate valve</td>
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<td>5</td>
<td>Flame protecting disc of gas head</td>
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<td>6</td>
<td>Air box</td>
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<tr>
<td>7</td>
<td>Air supply to cool the head and disc</td>
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<td>8</td>
<td>Conical port</td>
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<td>9</td>
<td>Igniter channel</td>
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Fig. 18

**Furnace:**

**Introduction:**

Furnace is the primary location of a boiler, where the combustibles of a fuel is burnt in a confined space to generate heat. The heat that is released from the burning fuel is absorbed by the water flowing through the tubes that line the roof and walls of the furnace. The important parts of a furnace are the fire box, tubes, stack and burners.

Furnace is designed for efficient and complete combustion of fuel, minimizing the losses. Major factors that assist for efficient combustion inside a furnace are ‘Time of residence’ (fuel) inside the furnace, ‘Temperature’ inside the furnace and ‘Turbulence’ which causes rapid mixing between fuel and air. Enormous heat is released in burning of fuel and the heat is to be immediately absorbed by the water for conversion to vapour stage. Accordingly the water circulation surrounding the furnace or the combustion region is to be so well arranged, so that efficient transfer
of heat takes place ensuring that the metallurgy of the pressure parts are not getting over heated. Modern boilers are designed with water cooled furnaces, with the construction of water walls on all sides. Panels of slender pipes, connecting two long headers at the top and bottom and forming a closed chamber of four sides of the combustion zone, are arranged as waterwalls, carrying water under circulation. The water carried through these walls instantaneously absorbs the heat generated in the furnace and cools the furnace tube material. Hence such furnaces are termed as water-cooled furnaces.

Different Parts of a Furnace:

**Firebox or combustion chamber:**
Firebox is an enclosed place in which heat is produced. It is made big enough so that all the fuel is completely burned before striking the furnace tubes or going out of the flue gas duct to the stack. The firebox is lined with heat resisting brick or refractory so as to withstand high temperature without melting or splitting. The fire brick and refractory lining also help to confine the heat within the box.

There are two sections in a fire box. They are:

a) **Convection Section,**
   Convention Section is the extension of the fire box where the tubes are heated by the flue gas as it goes from the fire box to the stack.

b) **Radiant Section.**
   In the radiant section of the furnace the fuel is fired by the proximity of the tubes to the flame and also by the heat radiating from the furnace walls.

**Furnace Wall Tubes :**
The water flows through the furnace in wall tubes usually entering bottom of the radiant section where the temperature is the highest and up to the Convective section. Wall tubes make the walls of the furnace, framing into a shape of a furnace.

‘Furnace width’ of a furnace is termed to denote the distance between the side walls of a furnace.

‘Furnace depth’ of a furnace is termed to denote the distance between the front and the rear walls of the furnace.

The wall, which is being faced while standing in front of a furnace, is called the front wall. The wall just opposite is called rear wall. The to the right while facing the front wall is the right side wall and the other to the left is called the left side wall.

**Stack:**
It is the tall and erect structure standing at the back of a boiler, through which the flue gas finally escapes out to atmosphere. It helps to create draft for the products of combustion to flow out from the furnace combustion chamber towards the chimney. The draft at any location in the furnace is the difference between the pressure at that location and the atmospheric pressure on the outside. The cooler outside air is heavier than the hot air inside the stack. The cold air flows in through
the furnace through the air openings. This cool air becomes hot and in turn more cold air enters the furnace. This pushes the hot flue gas through the stack which is lighter. This way the air flow through the furnace becomes continuous. The stack and the connecting duct must be large enough to accommodate large volume of flue gas through the furnace.

**Burners:**
Burners are mechanical devices for mixing controlled amounts of fuel and air to support combustion at the burner tips. These burners are designed to operate on oil, coal or fuel gas. Some of the newer burners are designed for a combination of oil and coal or oil and gas. Furnaces equipped with combination burners can usually be fired entirely on gas or oil or coal. Gas or the fuel oil enters through the center pipe. Air with enough velocity is supplied or sucked in through the opening which has an adjustable damper. The amount of air supplied / sucked in is controlled by this damper called ‘primary air damper. Air supplied / sucked in through primary damper is called primary air. It mixes with air in the mixing chamber on the way to the burner tip. This is typical of pre-mix burner. This intimate mixing improves combustion. All the air that is required for combustion cannot be supplied by the primary air damper. The rest of the air required is supplied / sucked in through the opening at the burner tip, called ‘secondary air damper’, by the draft in the furnace. The additional combustion air supplied through the secondary air dampers for support of combustion just outside the burner is called ‘secondary air’

**Different Type of Furnace:**

**P.F. Fired Dry Bottom Furnaces:**
These are furnaces in which slag is removed in solid state. The temperature of the furnace combustion chamber is invariably well below the ash fusion temperature. Hence the slag formed in the process of combustion falls down, before it can melt and start flowing as liquid (Fig. 19).
The tall rectangular radiant type furnace is the feature of the modern dry bottom Pulverized fuel boilers. Increased height not only facilitates adequate natural circulation but also aids reduction of furnace exit gas temperature hence less soot deposit in superheaters and reheatars. Single furnace or multifurnace with division walls is selected according to the size of the boiler. Multifurnace are necessary for higher capacity boilers to provide sufficient heat transfer surface for the corresponding furnace volume required for combustion.

Dry bottom furnace is selected for coal of non-slagging type (i.e.) fusion temperature of the ash (produced by combustion) will be more than the temperature encountered in the furnace. Normally a maximum of 20% total ash may be collected as slag from bottom of furnace. The rest of ash is carried away along with flue gas and can be separated after boiler. If slagging type coal is used in dry bottom furnace slag will fuse and deposit in the heat transfer surfaces of furnace, superheater and reheater where removal may pose big problems.

Usually these types of furnaces are provided with dry bottom slag hoppers. These hoppers are filled with water and are equipped with mechanism for removal of slag falling into the hopper water bath. Molten slag droplets entering into the hopper water bath are cooled immediately and the slag solidifies, before it is carried to a slag crusher for crushing and disposing off. The water bath also acts as a hydraulic seal preventing the entry of cold atmospheric air from beneath the furnace.

Bottom Hopper, below the furnace, is formed by sloping the front and rear walls, thus the amount of brick work is reduced and hence maintenance is less. By this arrangement, loss of efficiency due to evaporation of water from hopper is also effectively reduced.

Most of the Indian coals contain high amount of silica in the ash and hence ash fusion temperatures are high. Hence dry bottom types are best suited for Indian coals. In addition, loss of efficiency due to sensible heat in the molten ash of wet bottom furnace which increases with ash content also favors use of dry bottom furnace for high ash content coals.

**Slag type or wet bottom furnace:**
These furnaces are designed for removal of slag in molten state (Fig. 20). The temperature of the combustion products in the lower portion of the furnace is should be higher than the slag fluidity. The temperature of the combustion products should reach;

\[ 'T' \text{ gas} > 'T' \text{ ash soft} + (50 \text{ to } 100 \degree C), \]

where the \('T' \text{ gas}\) is the gas temperature of the combustion products’ and \('T' \text{ ash soft}\) is the ash fusion temperature.

Slagging type Furnaces normally are designed with two separate furnace parts. Complete combustion of fuel takes place in the primary furnace and very high rate of heat release is generated. At this portion of the furnace the ash gets fused and the molten slag gets collected in the bottom ash hopper. The hot flue gases are directed into secondary furnace, which is very similar to dry type furnace. The molten slag collected at the bottom of the primary furnace is chilled with addition of water. Then the clinker so formed is crushed to granular form by slag crushers for easy disposal. As the ash had to flow from the primary furnace, coal having low
melting temperature can only be used. To obtain high temperature inside the primary furnace, which will facilitate the easy flow of ash, very small but highly rated design is needed for primary furnace. High temperature refractory material is used inside the primary furnace and hence maintenance is needed.

Fig. 20
Horizontal cyclone type furnace may be more suitable, as primary furnace, where coals with low melting point of ash are burned (Fig. 21). As slag is removed in the furnace itself, the heat transfer surfaces are kept reasonably clean.

Fig. 21

Advantages of slag bottom type furnaces:

a) Heat loss due to unburnt in bottom is reduced to one third for the same fuel, as compared to dry bottom furnace
b) Slag bottom furnaces can be smaller than dry bottom furnace because heat release rate per unit furnace volume is about 20% more than dry bottom type.

c) Furnace bottom of wet bottom furnace is air tight and heat loss due to waste gases is reduced.

d) Slag disposal is less expensive compared to dry bottom slag handling.

Disadvantages of slag bottom type furnace

a) Heat carried by the bottom ash slag is much more, sometimes higher than the heat saved in improvement on unburnt loss

b) Higher yield of Nox due to high flame core temperature.

Oil fired boiler furnace:
Greater emissivity of oil flame results in a high absorption by the furnace wall surface hence higher furnace loading is possible. Normally about 65% of furnace volume is enough for an oil fired boiler compared to the corresponding output PF fired boiler. Oil fired furnace is generally closed at the bottom as there is no need to remove slag as in the case of PF fired boiler. Bottom will have small amount of slope to prevent film boiling in the bottom tubes.

If boiler has to be designed for both PF as well as oil, the furnace has to be designed for coal as otherwise higher heat loading with PF will cause slagging and high furnace exit gas temperature. Superheaters and reheaters may have to be designed for operation of oil in the furnace designed for coal, otherwise superheater outlet temperature may not be obtainable. However ratio of heat transfer between evaporation and superheating can be varied using burner tilting and/or gas recirculation.

Construction of Water Cooled Boiler Furnace:
Furnace wall construction has gone through various stages of development from conventional refractory backed walls to present day fusion welded panels also known as “membrane panels”.

The other well-known construction is “tangent tubes”. In the “tangent tubes” construction (See Fig. 22), the water wall tubes are placed in close pitches such that they practically touch each other.

![Welded Wall arrangement](image1)

![Skin cased (Tangent tube) arrangement](image2)

Fig. 22
Small amount of insulation and boiler casing are slung with the tubes from the building structure. The independently supported casing with its associated heavy buck-stays used in the earlier (refractory type construction) type is thus eliminated. Generally the chosen ratio of front width to furnace depth is 1 : 1.2. These type of tangential tubes construction are the widest in use in high capacity boilers, because the heat generation capacity is very high and also the heat release and distribution is uniform to furnace walls.

In “membrane wall construction” the tubes are placed side by side with a gap of about 12 mm and the tubes are joined by welding a continuous longitudinal strip on both the tubes thus making like a panel at the manufacturer’s works itself. The length and width of panel is limited by transportation consideration only. The panels in turn are welded together at site to form the complete furnace. Thus the total amount of welding work at site is limited to very great extent thus facilitating easy erection and high quality welds.

Air infiltration, which will reduce the efficiency of boiler is greatly reduced by use of these types of construction. Membrane type construction also facilitates use of pressurized firing in furnace, which will eliminate one of the boiler house auxiliary-ID fan.

Provision for free expansion of furnace tubes is vital in all cases and it is normal for tube walls to be entirely suspended from the top of the structural members so that all expansion is taking place in a downward direction. 40 metres high furnace will have roughly 125 mm expansion due to temperature change alone during boiler operation.

The furnace is contained in position and load created by furnace pressure, seismic and wind load is safely transmitted by special supports called buck-stays which is carefully designed such that it does not restrict in any way the free movement required due to temperature change.

Advantages of a water-cooled furnace:

a) In furnace not only combustion but also heat transfer is taking place simultaneously.

b) The maintenance work involved in repairing the fire bricks (which is otherwise necessary) is practically eliminated.

c) Due to heat transfer in the furnace, temperature of the flue gas leaving the furnace is reduced to the acceptable level of the superheating surfaces.

d) Higher heat loading in the furnace is possible as heat is being simultaneously removed by heat transfer, and hence economy in surfacing.

Additional points to be considered while designing water cooled furnaces:

a) The height, size and surface area of furnace water walls are so chosen for a natural circulation boiler, such that adequate water circulation in the furnace tubes is always ensured.

b) Care is taken in deciding the size of furnace and location of burners so that flame does not impinge on any furnace tubes.

c) Care is taken to ensure circulating water is uniformly distributed in all tubes of the water wall and at the same time uniform heat absorption is taking place over the entire heating surface.
d) Shape of furnace to ensure gas path which will ‘fill’ the furnace and hence provide maximum absorption.

e) Care to design required volume of furnace to ensure required velocity of products of combustion, which will ensure sufficient retention time for the coal particles to get ignited and burn completely.

f) Care is taken to see that the furnace is so designed that the ash fusion temperature is not reached inside the furnace and no Slagging take place.

g) Provision for removal of ash (wet or dry) from bottom of furnace in the case of p.f. fired boilers.

Furnace is to be well supported to withstand static load, load due to furnace pressure, wind and seismic load but at the same time allow for free expansion due to temperature change.

**Cyclone Furnace:**
Cyclone furnace firing, developed in the 1940s, represents one of the most significant steps in coal firing since the introduction of pulverised coal firing in the 1920s. It is now widely used to burn poorer grades of coal having high ash and moisture content. Biofuels like rice husks can also be successfully burned in cyclone furnaces for steam generation.

![Cyclone Furnace Diagram](image)

The cyclone is essentially a water-cooled horizontal cylinder (Fig. 23) located outside the main boiler furnace, in which crushed coal (60 mm size or less) is fed and fired with very high rates of heat release. The cyclone is made to a diameter of 1.8-4 m and its length is 1.2-1.3 times its diameter. The crushed coal is fed into the cyclone from the left along with primary air, which is about 20 percent of combustion or secondary air. The coal air mixture is entered tangentially, thus imparting a centrifugal motion to the coal particles. The secondary air is also admitted tangentially at the top of the cyclone at high speed (80-120 m/s) imparting
further centrifugal motion. A small quantity of air, called tertiary air, is admitted at the centre. Combustion of the coal is completed before the resulting hot gases enter the boiler furnace. The whirling motion of coal and air results in large volumetric heat release rates ranging from 4.7 to 8.3 MW/m$^3$ and high combustion temperatures, more than 1650°C. These high temperatures melt the ash into a liquid slag that covers the surface of the furnace bottom, where it is solidified and fragmented for removal.

The main advantage of cyclone firing is the removal of ash, about 60 percent, as molten slag through the slag tank. Thus only 40 percent ash leaves with flue gases, compared with 85 percent ash for dry-bottom pulverised coal furnaces, this reduces erosion and fouling of boiler surfaces as well as the size of dust-removal precipitators or bag houses at boiler exit. Another advantage is that only crushed coal is used and no pulverization equipment is needed and that the boiler size is reduced. The disadvantages are higher forced draught fan pressures and therefore, higher power requirement, and formation of relatively more oxides of nitrogen, Nox, which are air pollutants.
Fluidized Bed Combustion

INTRODUCTION
During the mid to late 1980s, fluidized bed combustion (FBC) rapidly emerged as a viable option to stoker fired and pulverized coal-fueled units for the combustion of solid fuels. Initially used in the chemical and process industries, FBC was applied to the electric utility industry because of its perceived advantages over competing combustion technologies.
Sulfur dioxide emissions could be controlled from FBC units without the use of external scrubbers, and nitrous oxide (NOx.) emissions from FBC units were inherently low. Furthermore, FBC units were touted as being "fuel flexible," with the capability of firing a wide range of solid fuels with varying heating value, ash content, and moisture content. Also, slagging and fouling tendencies were minimized in FBC units because of low combustion temperatures.

Principles of Fluidized Bed Combustion Operation:
A fluidized bed is composed of fuel (coal, coke, biomass, etc.) and bed material (ash, sand, and/or sorbent) contained within an atmospheric or pressurized vessel. The bed becomes fluidized when air or other gas flows upward at a velocity sufficient to expand the bed. The process is illustrated in Figure below.

At low fluidizing velocities (1 to 3 m/s), relatively high solids densities are maintained in the bed and only a small fraction of the solids are entrained from the bed.
A fluidized bed that is operated in this velocity range is referred to as a bubbling fluidized bed (BFB). A schematic of a typical BFB combustor is illustrated in Figure below.
As the fluidizing velocity is increased, smaller particles are entrained in the gas stream and transported out of the bed. The bed surface, well-defined for a BFB combustor, becomes more diffuse and solids densities are reduced in the bed. A fluidized bed that is operated at velocities in the range of 4 to 7 m/s is referred to as a circulating fluidized bed, or CFB. A schematic of a typical CFB combustor is illustrated in Figure below.

Advantages of Fluidized Bed Combustion:
An environmentally attractive feature of FBC is that sulfur dioxide (SOx) can be removed in the combustion process by adding limestone to the fluidized bed, eliminating the need for an external scrubber. The calcium oxide formed from the calcinations of limestone reacts with SO2 to form calcium sulfate, which is removed from the flue gas with a conventional particulate removal device.
In FBC, the combustion temperature is controlled at approximately 1,550 to 1,600° F as compared to approximately 3,000° F for conventional boilers. Combustion at the lower temperature has several benefits. First, the lower temperature minimizes sorbent (typically limestone) requirements because the required Ca/S molar ratio for a given S02 removal efficiency is minimized in this temperature range. Second, 1,550 to 1,600° F is well below the ash fusion temperatures of most fuels so the fuel ash never reaches its melting point.

The slagging and fouling problems that are characteristic of pulverized coal units are significantly reduced, if not eliminated. Finally, the lower temperature reduces NOx emissions. Since combustion temperatures are below ash fusion temperatures, design of an FBC boiler is not as dependent on ash properties as is a conventional boiler. With proper design considerations, a FBC boiler can fire a wider range of fuels with less operating difficulty.

The advantages of FBC in comparison to conventional pulverized coal-fueled units can be summarized as follows:
- S02 can be removed in the combustion process by adding limestone to the fluidized bed, eliminating the need for an external desulfurization process.
- Fluidized bed boilers are inherently fuel flexible and, with proper design provisions, can burn a variety of fuels.
- Combustion in FBC units takes place at temperatures below the ash fusion temperatures of most fuels. Consequently, tendencies for slagging and fouling are reduced with FBC.
- Because of the reduced combustion temperatures, NOx emissions are inherently low.

**Heat Transfer:**
In a BFB unit, combustion heat is absorbed from the gas by heat transfer tubes immersed in the bed and by conventional water wall surface. In-bed tubes can serve as either steam generation surface or superheat surface.

Although an in-bed heat exchanger is a possible source of erosion problems, the close contact with bed materials and excellent mixing provides high heat transfer. Heat transfer in the convection pass is similar to that for a conventional stoker-fired or pulverized coal-fueled steam generator.

In a CFB unit, combustion heat is absorbed from the gas by conventional water wall surface, by platens located in the upper region of the combustor, or by heat transfer surface located in external heat exchangers. The velocity of the solids in a CFB is relatively lower than that of the gas. The high slip velocity (difference between mean gas velocity and the mean solids velocity), in combination with the intense mixing that occurs, results in high heat and mass transfer rates. The high inventory of circulated particles leads to consistently uniform temperatures throughout the combustor and the recycle system, as well as a long solids inventory residence time. The long residence and contact times, increased slip velocities, and intense mixing result in higher heat and mass transfer rates and higher combustion efficiency in a CFB than are available with a BFB.
CFB vs. BFB Technology:
In comparison to BFBs, CFBs offer the following potential advantages:
- Greater fuel throughput per unit of cross-sectional area is possible because of higher combustion air velocities.
- Combustion efficiencies are higher.
- The calcium-to-sulfur ratio is lower for a given SO₂ removal rate.

Categories of Fluidized Bed Combustion:
Two categories of FBC systems are potentially applicable to power generation: atmospheric fluidized bed combustion (AFBC) and pressurized fluidized bed combustion (PFBC). AFBC systems are commercially available and are currently being applied to electric utility applications. In the AFBC option, the fluidized bed is used to generate steam for power production using a conventional Rankine cycle. A block flow diagram for power generation from an AFBC is presented in the Figure below. PFBC is under development, with several large demonstration units in operation or in the planning stage. PFBC units operate at 10 to 15 atmospheres and offer the potential advantages of smaller boilers in comparison to AFBC. The smaller equipment size provides opportunities for modular construction with PFBC units. Removal of particulate matter from the high-temperature, combustor discharge flue gas stream is an integral part of the PFBC process. However, gas cleanup at high temperatures (800 to 900° C, for example) is a technology that is not fully demonstrated. Because of the cleanup and other development issues, the PFBC technology is generally believed to lag the AFBC technology by 5 to 10 years.

ATMOSPHERIC FLUIDIZED BED COMBUSTION
Bubbling Fluidized Bed Combustors:
General Configuration: A typical BFB arrangement is illustrated schematically in Figure below. Fuel and sorbent are introduced either above or below the fluidized bed (Overbed feed is illustrated).
The bed, consisting of about 97% limestone or inert material and 3% burning fuel, is suspended by hot primary air entering the bottom of the combustion chamber. The bed temperature is controlled by heat transfer tubes immersed in the bed and by varying the quantity of coal in the bed. As the coal particle size decreases, as a result of combustion or attrition, the particles are elutriated from the bed and carried out of the combustor. A portion of the particles elutriated from the bed are collected by a cyclone (or multiclone) collector downstream of the convection pass and returned to the bed to improve combustion efficiency. Secondary air can be added above the bed to improve combustion efficiency and to achieve staged combustion, thus lowering NOx emissions. Most of the early BFBs used tubular air heaters to minimize air leakage that could occur as a result of the relatively high primary air pressures required to suspend the bed. Recent designs have included regenerative type air heaters. The TVA 160-MW BFB shown in Figure below shows such an arrangement.

The convection pass can be of the tower design located above the freeboard as illustrated in the figure or of the Back pass type found in a conventional pulverized coal unit. Split back pass arrangements are normally used for reheat control.

**Fuel Feed Systems:**
Two types of fuel feed systems are used with BFB units: over bed feed and under bed feed. With over bed feed, spreader feeders are used to distribute fuel above the bed. Over bed feed is less complex than under bed feed and minimizes the potential for erosion and plugging in the fuel feed system. However, over bed feed has a number of disadvantages. Partial combustion above the bed reduces the opportunity for sulfur capture, and fines in the feed can be entrained from the bed before combustion is complete. Typically, fuel feed size is restricted to 30 mm top size, with a maximum of 20% less than 6 mm. Even with fuel size restrictions and an ash recycle system, combustion efficiencies are lower with over bed feed than with under bed feed, particularly with non reactive fuels. Also, limitations in spreader throwing distances preclude the use of over bed feed for very large units. Under bed
Feed systems typically use pneumatic transport to deliver fuel and limestone to the combustor. The fuel is restricted in top size to 6 mm to 12 mm to facilitate pneumatic conveying and is introduced through nozzles located just above the air distributor. With under bed feed, fines can be fired efficiently, and combustion efficiency and sulfur capture are usually greater than with over bed feed. Potential for pluggage and erosion is increased, however, and multiple feed ports are required. Crusher/dryers are usually required to control fuel top size and moisture content. Fuel moisture content is restricted to about 6% to avoid plugging of pneumatic conveying lines. To achieve good fuel distribution, one feed port is typically required for every 1 to 1.5 m² of bed area. Thus, while under bed feed provides better performance than over bed feed, it is more complex and has the potential for greater maintenance requirements. The advantages and disadvantages of over bed versus under bed feed systems are summarized in Table below.

Table: Advantages and Disadvantages of Over bed and Under bed Feed Systems

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Over bed System</strong></td>
<td>1. Partial combustion above the bed can reduce sulfur capture</td>
</tr>
<tr>
<td>1. Minimizes potential for plugging in the</td>
<td>2. Inadequate mixing of fuel and sorbent for sulfur capture</td>
</tr>
<tr>
<td>fuel feed system</td>
<td>3. Unable to use fines. (Fines tend to be elutriated from the bed, leading</td>
</tr>
<tr>
<td>2. Capable of firing larger sized coal</td>
<td>to excessive carbon losses and poor sulfur capture.)</td>
</tr>
<tr>
<td>3. Fewer feed ports with conventional</td>
<td>1. Large potential for pluggage in feed system</td>
</tr>
<tr>
<td>spreader feeders.</td>
<td>2. Small fuel feed size; more crushing required</td>
</tr>
<tr>
<td><strong>Under bed System</strong></td>
<td>3. Multiple feed ports needed in each section of the bed</td>
</tr>
<tr>
<td>1. Fines can be fired efficiently</td>
<td></td>
</tr>
<tr>
<td>2. More uniform distribution of fuel and</td>
<td></td>
</tr>
<tr>
<td>sorbent</td>
<td></td>
</tr>
<tr>
<td>3. More complete combustion within the bed</td>
<td></td>
</tr>
</tbody>
</table>

**Fuel Requirements:**
A BFB unit can accommodate a variety of fuels, including both low-grade and high sulfur fuels. The size of feed materials depends on the reactivity of the fuel and the type of feed system used. Larger particle sizes can be used for highly reactive fuels such as lignite and some sub bituminous coals. Smaller particle sizes are typically required for less reactive fuels such as anthracite and petroleum coke. As indicated in the previous section, fuel feed top size is restricted to about 30 mm for over bed feed and about 12 mm for under bed feed. High moisture fuels typically can be accommodated by over bed feed systems, while moisture content is restricted to about 6% with under bed feed systems.
Sorbent Requirements: The basic chemical compound used to capture sulfur in the fluidized bed is lime (calcium oxide), which is generally introduced into the system as limestone or dolomite. Once introduced into the bed, limestone is calcined to lime according to the following equation:
\[ \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \]
The resulting lime reacts with \( \text{SO}_2 \) and oxygen to form calcium sulfate as follows:
\[ \text{CaO} + \text{SO}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{CaSO}_4 \]
Dolomite, when introduced into the bed, calcines to form a solid mixture of CaO and MgO. The CaO forms calcium sulfate as does the limestone, but the magnesium oxide is un-reactive.
Sorbent feed particle size affects the process as well as the design of the unit and auxiliary equipment. Stone elutriation, required Ca/S ratio, bed particle size, bed bubble phenomena, and bed voidage are among the major items affected or determined by a given sorbent size and fluidization velocity.
Overall calcium use generally increases, up to a limit, with a decrease in sorbent feed size as a result of the increased surface area for sulfur absorption. With further decrease in sorbent size, the bed removal rate becomes excessive, thereby resulting in poor sorbent use. Sorbent use also depends on the porosity of the particle surface formed during calcination.
Highly porous particles have larger surface areas exposed for the sulfation reaction. If the pores in the particle are too deep, however, they can become plugged by \( \text{CaSO}_4 \), thus stopping the sulfation reaction. The presence of dolomite usually enhances the reactivity of the sorbent. Apparently, porosity is increased by the calcination of \( \text{MgCO}_3 \).
Sorbent use in the sulfation process is difficult to predict. Most manufacturers require test burns with the fuel and sorbent to be used before they will offer guarantees on limestone usage.
Sorbent can be fed into the fluidized bed by mixing the sorbent with the fuel or by using separate feed systems similar to those used for the fuel. Separate feed systems are most often used for fuel and sorbent so that better process control of the Ca/S ratio can be achieved to improve control of \( \text{SO}_2 \) emissions.

Ash Systems:
Solids are removed from the fluidized bed by elutriation and through drain ports located in each compartment of the bed. Solids that are elutriated from the bed and freeboard area of the combustor are captured by a mechanical dust collector (typically a multiclone collector).
To improve combustion efficiency and maintain bed inventories, most of the solids are usually recycled to the combustor. Recycled material can be fed underbed or overbed.
The recycle ratio, defined as the ratio of the recycle mass flow to fuel feed mass flow, usually ranges from 1:1 to 3:1 when firing bituminous coals. Solids passing through the mechanical dust collector are collected by a conventional particulate removal device, such as an electrostatic precipitator or fabric filter.
A bed solids removal system is required to maintain an adequate bed level and inventory of bed material in the fluidized bed. The system also removes tramp
material from the bed. It consists of bed drain lines with drain valves discharging bed material to a water-cooled ash cooler. To reduce carbon losses in the ash removed from the bed, ash classifiers are sometimes used. Fine material separated in the classifiers is returned to the bed, while the coarse materials are discharged to the ash removal system. In determining the required equipment capacities, consideration must be given to the maximum expected drain rates and maximum material discharge temperature.

The ash and other spent solids from a BFB are in a dry form that can be conveyed pneumatically and stored in silos. Disposal will generally be by truck transport to a landfill.

**Heat Transfer:**
Although the overall steam cycle defines the heat that must be absorbed by the steam generating, superheating, and reheating surfaces, BFB manufacturers have some flexibility in the manner in which the heat transfer surfaces are arranged. Some manufacturers do not place the heat transfer surface in the bed, while others place horizontal or sloped tubes in the bed area. In addition, the in bed tubes may be either water or steam cooled. The design for the 160-MW TVA demonstration unit includes a water wall combustor; super heater and steam generation tubes in the bed; and reheat, superheat, and economizer tubes in the convection section. The interrelationship of the cooling media, allowable pressure drops, heat transfer coefficients, bed temperature, fluidizing air velocity, surface requirements, and tube bundle geometry need to be taken into account in the design of the inbed surface arrangement. Steam flow and temperature imbalances should be minimized. In addition, the inbed tube bundle arrangement must effectively use the available bed volume dictated by the bed plan area, bed depth, and clearance requirements.

Heat transfer to surfaces immersed in a fluidized bed occurs by means of gas convection, radiation, and particle convection. The gas convection contribution to the overall heat transfer is small. The radiation contribution is larger, but the overall heat transfer is dominated by particle convection.

**Air Heaters:**
Testing and operation at first-generation BFB facilities revealed that regenerative-type air heaters were not acceptable for fluidized bed service because of excessive air leakage. Higher air-side pressures required by the fluidized bed process dictated the need for tubular air heaters to minimize air in-leakage.

**Fans and Blowers:**
The combustion air systems for BFB boilers and conventional boilers are similar. Conventional design practices are suitable for the FBC air system, including ductwork, fans, and dampers. However, the higher air-side pressures associated with BFBs must be accounted for in the design.

Positive displacement or rotary blowers supply air at higher pressures for pneumatic conveying. Pneumatic conveying is used to convey fuel (underbed feed), limestone, and solid waste products.
Startup Burners:
Startup burners are used to raise the temperature of the bed to the auto-ignition temperature of the fuel being fired. For coal-fired BFBs, the auto-ignition temperature is approximately 650° C. Typically, the startup burners are placed in an air duct leading to the fluidized bed. Bed lances are sometimes used to supplement the heat input of the startup burners. Usually, startup is accomplished by heating one of several compartments in the bed. When ignition is accomplished in the first compartment, other compartments are gradually brought to temperature and placed into operation.

Operating Parameters:
Typical BFB operating parameters are shown in Table below. Bed temperature is normally selected to optimize sulfur removal while achieving acceptable carbon burnout.

<table>
<thead>
<tr>
<th>Bed temperature, °C</th>
<th>850 - 900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficial velocity, m/s</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Bed depth, m</td>
<td>0.6 - 1.8</td>
</tr>
<tr>
<td>Freeboard height, m</td>
<td>2.5 - 6.0</td>
</tr>
<tr>
<td>Coal feed particle size, mm</td>
<td>30 x 0</td>
</tr>
<tr>
<td>Over bed feed</td>
<td>12 x 0</td>
</tr>
<tr>
<td>Under bed feed</td>
<td></td>
</tr>
<tr>
<td>Sorbent feed particle size, mm</td>
<td>3</td>
</tr>
<tr>
<td>Calcium/sulfur ratio</td>
<td>2.5 - 4.0</td>
</tr>
<tr>
<td>SO₂ removal, %</td>
<td>90</td>
</tr>
<tr>
<td>Combustion efficiency, %</td>
<td>90-98</td>
</tr>
<tr>
<td>Recycle ratio</td>
<td>0-5</td>
</tr>
<tr>
<td>Excess air, %</td>
<td>20-35</td>
</tr>
<tr>
<td>NOₓ emissions, ppm</td>
<td>150-350</td>
</tr>
</tbody>
</table>

The optimum bed temperature for sulfur removal is approximately 1,550° F, as indicated in figure below.
If sulfur removal is not a consideration or low-volatile fuels are being fired, higher bed temperatures can be used to increase combustion efficiency. Fluidizing air is required to provide the oxygen for combustion air as well as to lift and expand the bed. The air velocity dictates, to some extent, the height of the overall bed and affects the entrainment of smaller particles in the air leaving the bed. Typically, the fluidizing velocity ranges from 1 to 3 m/s, with 2.5 m/s being most common.

Bed depth and freeboard height (height from the top of the bed to the top of the combustor) are selected to match the fuel and type of feed system. Deeper beds are required when low volatile fuels such as anthracite and petroleum coke are fired, while shallow beds can be used for more reactive fuels such as lignite and sub-bituminous coal. For a reactive fuel, a bed height of 0.6 m in the slumped position is typical, which normally results in an expanded bed height of about 1.2 m. Larger freeboard heights are usually selected for low-volatile fuels or when overbed feed is used. The increased freeboard provides additional residence time to complete the combustion process.

As discussed previously, fuel feed particle size is a function of the type of fuel feed system. In addition, larger fuel particle sizes can be used for reactive fuels, while smaller sizes are necessary when firing less reactive fuels. Care must be taken to minimize the amount of fines in the feed to a BFB, particularly if overbed feed is used. Typically, the amount of fines in the feed is restricted to <25% minus 16-mesh with overbed feed and <20% minus 30-mesh with underbed feed. Sorbent size is selected to maximize sorbent use and prevent excessive elutriation of un-reacted sorbent from the combustor. Ca/S ratios are selected to achieve the
desired removal of S02. The Ca/S ratio required to achieve a given S02 removal depends on the type of fuel feed system used, the reactivity of the sorbent, and the amount of solids recycled to the combustor (recycle ratio). Testing conducted at the TVA 20-MW pilot plant indicated that, with under bed feed, >95% sulfur removal could be achieved at Ca/S ratios ranging from about 2.6 to 3.1 if a recycle ratio of 1.5 was maintained. With over bed feed, sulfur retention was also sensitive to the amount of fines in the feed, but that sulfur retention values of 90% or greater could be achieved at Ca/S ratios ranging from 2.7 to 3.7 and recycle ratios ranging from 0 to 1.5, if the fuel feed contained <7% minus 30-mesh fines. The sulfur retention test results are shown in figure below.

Combustion efficiency in a BFB usually ranges from 90% to 98% and is a function of bed temperature, type of fuel feed, fuel reactivity, bed depth, and recycle ratio. Results of underfeed tests at TVA's 20-MW pilot plant indicated combustion efficiencies ranging from about 90% to 97% for recycle ratios ranging from 0 to 2.0, respectively (Figure below).
Combustion efficiency at TVA's 20-MW pilot plant

Testing at ABB Combustion Engineering's Great Lakes FBC Demonstration Plant indicated that combustion efficiency did not improve significantly when excess air levels were increased above the 10% to 20% level.

The mechanism of NOx formation in a BFB is complicated and depends on the coal de-volitization rate and its volatile content, excess air level, bed temperature, and other factors. Generally, NOx emissions in the range 150 to 350 ppm and lower can be achieved. However, NOx emissions tend to increase as Ca/S levels increase. Thus, reducing SO₂ emissions may result in an increase in NOx emissions.

Control Philosophy:
Two methods are commonly used to control load or steam flow with a BFB. The first involves velocity turndown whereby fuel and airflow are uniformly varied across the entire bed to control steam flow while maintaining bed temperature. The combustor vessel can be designed such that as fuel and airflow are reduced and the bed slumps, the in-bed heat transfer surface is uncovered, thus lowering the rate of heat transfer to steam ing surface in the bed.

The second method of load control involves slumping the bed in separate zones of the combustor. To reduce load, fluidizing air to individual zones or compartments is reduced or isolated, thus slumping the beds in the affected compartments. This allows maintaining bed temperatures in the active compartments at the reduced loads.

In practice, both methods of load control are usually used in conjunction with each other. Overall load turndown to 25% load is usually achievable when both methods of load control are used. Bed temperature control at a given fuel flow is a function of air flow and heat transfer in the bed area.

It is desirable to maintain bed temperatures at near optimum levels over the entire load range to maximize sulfur capture. Although this goal usually is not achievable, a properly designed BFB combustor will allow effective bed temperature control over a wide load range. The designer can use bed zoning, bed slumping, bed inventory, and effective placement of the heat transfer surface to control bed temperatures.
Once the BFB is constructed and placed into operation, airflow is the primary parameter that is varied to control bed temperature. Also, bed inventory can be varied somewhat to provide a secondary level of bed temperature control. Bed inventory is controlled by draining solids from the combustor to maintain a constant pressure differential across the bed.

Steam temperature control in a BFB is similar to that used for a conventional pulverized coal unit. Biasing control dampers in the convection pass are used for primary superheat/reheat steam temperature control. Secondary steam temperature control is achieved with de-superheater sprays.

**Circulating Fluidized Bed Combustors**

**General Configuration:**

A typical CFB arrangement is illustrated schematically in figure below. In a CFB, primary air is introduced into the lower portion of the combustor, where the heavy bed material is fluidized and retained.

The upper portion of the combustor contains the less dense material that is entrained from the bed. Secondary air typically is introduced at higher levels in the combustor to ensure complete combustion and to reduce NOx emissions.

The combustion gas generated in the combustor flows upward with a considerable portion of the solids inventory entrained. These entrained solids are separated from the combustion gas in hot cyclone-type dust collectors or in mechanical particle separators, and are continuously returned to the combustion chamber by a recycle loop.

The combustion chamber of a CFB unit for utility applications generally consists of membrane-type welded water walls to provide most of the evaporative boiler surface. The lower third of the combustor is refractory lined to protect the water walls from erosion in the high-velocity dense bed region.

Several CFB designs offer external heat exchangers, which are unfired dense BFB units that extract heat from the solids collected by the dust collectors before it is
returned to the combustor. The external heat exchangers are used to provide additional evaporative heat transfer surface as well as superheat and reheat surface, depending on the manufacturer's design. The flue gas, after removal of more than 99% of the entrained solids in the cyclone or particle separator, exits the cyclone or separator to a convection pass. The convection pass designs are similar to those used with conventional coal-fueled units, and contain economizer, superheat, and reheat surface as required by the application.

**Fuel Feed Systems:**
Fuel feed in a CFB is usually controlled with gravimetric feeders with rotary lock valves used to isolate the feeders from the combustor. Some CFB manufacturers have designed for negative pressure in the combustor at the fuel feed points and have eliminated the rotary lock valves. Fuel typically flows by gravity into the combustor, with some designs using an air assist in the fuel feed chute. Pneumatic fuel feed systems can also be used, including air swept crushers, and dense phase conveying systems are also available. The number and location of feed points varies with the fuel being fired and with the manufacturer's design. Because of the thorough mixing that occurs in a CFB, typically a relatively few feed points are required in comparison to a BFB with underbed feed. Fuels with low bulk densities require more fuel feed points to physically accommodate the high volume flows. Feed points are usually in the front wall of the combustor or in the seal lines from the cyclone separator to the combustor, or both. High-moisture fuels are usually introduced in the seal lines from the cyclone, where they mix with hot re-circulated solids to accomplish some drying before being introduced into the combustor. From gravimetric feeders, the lignite is conveyed by volumetric feeders to the siphon seal return lines. Reportedly, the TNP unit has achieved full capacity with three of four feed systems in operation. Liquid fuels are usually dispersed in the combustor with bed lances, either stationary or retractable. Because of the short bed residence time with liquid fuels, typically more feed points are required with liquid fuels in comparison to solid fuels.

**Fuel Requirements:**
In comparison to a BFB with under bed feed, fuel preparation requirements for a CFB are typically less severe. A wide variety of fuels can be accommodated, and fines in the fuel can be fired with no difficulty. While they can be fired satisfactorily in a CFB, high-moisture fuels and fuels with a large amount of fines can present severe materials handling difficulties. To prevent plugging, special design measures may be required, including the strategic placement of air blasters and the use of dryers. To achieve acceptable combustion efficiencies, low volatile fuels, such as anthracite, must be crushed to smaller top size than higher volatile fuels. It is not unusual to see sizing specifications of 2 mm or less for low volatile fuels. Larger fuel sizes are acceptable for higher volatile fuels. Lignite is crushed to 10 mm top size prior to introduction into the combustor. Coal is crushed to 6 mm top size.
Sorbent Requirements:
Sorbent requirements for a CFB are similar to those for a BFB. Most manufacturers require test burns with the fuel and sorbent to be used before they will offer guarantees on limestone usage. Typically, limestone is crushed to a top size of 1,000 microns with an average size of 150 microns. Although the sorbent can be introduced into the combustor by mixing with the fuel, the more usual process is to introduce the sorbent into the combustor by separate feed systems. Most systems use day bins for temporary storage of sorbent, followed by rotary airlock feeders that drop the sorbent into pneumatic conveying lines for transport to the combustor. Gravimetric feeders can be used if more accurate control of sorbent feed is desired.

Ash Systems:
Typically, ash is removed in three locations in a CFB installation: the combustor, the backpass or air heater hoppers, and the fly ash particulate removal device. The primary function of the combustor ash removal system is to control bed inventory. Bed material is removed as required to maintain the desired bed pressure drop. A secondary function of the combustor ash system is to remove oversized or tramp material that, if left to accumulate, could restrict airflow and de-fluidize a portion of the bed.

Two primary types of combustor ash removal systems are available for application to CFBs. The first type consists of water-cooled screw conveyors that cool the hot ash leaving the combustor to a temperature that can be accommodated by the ash handling system, similar to that used for BFBs. Usually, one or two bed drains are sufficient for a medium to large CFB. The second type of combustor ash removal system consists of small fluidized bed heat exchangers, called strippers or classifiers, mounted on the sides of the combustor near the combustor floor. Air nozzles are located on the combustor floor to direct solids material to the inlet of the ash classifiers. Air flow is directed through the classifiers at sufficient velocities to fluidize the solids material. Fine materials are returned to the bed, while coarse materials are discharged from the classifiers for disposal. Ash strippers or classifiers typically include cooling coils immersed in the bed to cool the ash and recover heat for the feed heating cycle. An ash stripper design is shown in Figure below.
Ash collected in the economizer, air heater hoppers, and the particulate removal device, such as a fabric filter or electrostatic precipitator, is removed with conventional dry ash removal systems.

Ash handling system capacities should be conservatively sized. The expected ash split between bed ash and fly ash is difficult to predict and the ash content of the fuel can vary significantly. A conservative design criterion for ash handling systems conveying capacity would be 100% of total solids capacity for the bed ash system and 100% of total solids capacity for the fly ash system.

**Ash Recycle System:**
The combustion gas generated in the combustor of a CFB flows upward with a considerable portion of the solids inventory entrained. These entrained solids are separated from the combustion gas and are continuously returned to the combustion chamber by a recycle loop. Most CFBs use one or more hot cyclones to separate solids from the combustion gas. The cyclones are designed to remove all solid particles >100 microns in diameter, which normally results in an overall separation efficiency >99% (Singer 1991). The cyclones are constructed with steel plate lined with one or more layers of refractory.

The hot face of the refractory is a dense erosion-resistant material, while the inner layers are less dense insulating materials.
Cyclones may be un-cooled, water cooled, or steam cooled. Un-cooled cyclones use several layers of refractory with a total thickness in the range of 12 to 16 in. The outside surface temperature of un-cooled cyclones is typically on the order of 120° C. With water or steam cooling, refractory can typically be reduced to a single layer 2 in. thick. Outside surface temperatures of cooled cyclones are nominally 60° C. The cooled cyclones have the advantages of less radiant heat loss, lighter weight, and more rapid startup times. Units with thick cyclone refractory typically require 12 to 16 hours for startup to avoid thermal stresses and spalling of the refractory. With cooled cyclones, startup times usually are not limited by refractory considerations.

Another type of particle separator used on CFBs, a U-beam collector, consists of a series of vertical channels that trap the particles in the flue gas and drop them into a particle storage hopper. Solids collected by cyclone separators or U-beam collectors are returned to the combustor with a solids re-injection device often called a seal pot, L-valve, or J-valve. The solids re-injection device is essentially a non-mechanical loop seal that allows movement of solids against the combustor backpressure. The bottom of the seal is fluidized so that the solids in the seal can seek different levels on each side of the seal corresponding to the differential pressure. Flow of solids through the seal may or may not be controlled by a valve. On units with a fluidized bed heat exchanger (FBHE), a plug valve is typically used to regulate the flow of solids to the FBHE.

**Fluidized Bed Heat Exchangers:**
Several circulating bed designs offer separate FBHEs, which are unfired dense BFBs that extract heat from the solids collected by the cyclone or U-beam dust collectors before it is returned to the combustor. The FBHEs are used as evaporative heat transfer surfaces as well as superheat and reheat surfaces, depending on the manufacturer's design. An FBHE can be designed for total recirculation of solids from the cyclones or U-beam separators, or for partial flow with the remainder of solids returned directly to the combustor. FBHEs use low fluidizing velocities (0.3 to 1.2 m/s), and virtually no combustion occurs in the heat exchanger because of the low carbon content of the solids being circulated. Erosion/corrosion in the heat exchanger is not a significant concern because of the low fluidizing velocities and low levels of combustion. The initial FBHEs were separate stand-alone vessels and were commonly called external heat exchangers. In more recent designs, the FBHEs have been incorporated into the design of the combustor, usually sharing a wall with the combustor. In the integrated FBHE design, the walls of the FBHE are formed by water-cooled membrane panels.

**Heat Transfer:**
The flue gas, after removal of more than 99% of the entrained solids in the cyclone or U-beam particle separator, enters the convection pass. The convection pass designs are similar to those used with conventional coal-fueled units, and contain economizer, superheat, and reheat surface as required by the application.
Depending on the manufacturer's design, the superheat surface is typically located in convection pass and combustion chamber, or the convection pass and external heat exchanger. The location of the superheat surface in a combustion chamber is an area of concern because of the potential for erosion. Designs that offer a combustion chamber superheat surface typically use pendant sections, or wing walls that are located along the combustor walls, or tubes that traverse the combustor and that are protected from erosion.

The reheater surface is typically located in an external heat exchanger, in the convection pass and combustion chamber, or in the convection pass only. The designs that use FBHEs for the reheater surface have several advantages over the other options. The FBHE can be isolated during boiler startup, thus protecting tubes from high temperatures. The FBHE also offers high heat transfer rates, which minimizes surface area requirements, and as previously noted, the erosion of tube surface in an FBHE is not a significant concern. Designs that split the reheater surface between the combustion chamber and convection pass must incorporate some means to protect the combustion chamber reheater surface from high temperatures during startup. The placement of the reheater surface in the combustion chamber also has the disadvantage of possible erosion. Designs that locate all of the reheater surface in the convection pass (similar to a conventional boiler) solve the startup tube protection problem, but the low flue gas temperatures mean a large surface area may be required.

**Refractory:**
Refractory linings are typically used in CFBs to protect metal surfaces from erosion and/or to protect against corrosion in areas of a reducing atmosphere. The most common areas where refractory is used include the lower portion of the combustor; cyclone separators, seal pots, FBHEs, ash coolers, and solids return lines. Multiple layers of refractory are typically used for un-cooled surfaces such as cyclone separators, in which the total thickness can range from 12 to 16 in. Dense erosion-resistant materials are used on the hot face, while lighter weight insulating materials are used on the inner face. The refractory in a CFB can greatly increase the weight of the unit and increase startup times. As indicated previously, units with thick refractory layers can require 12 to 16 hours for startup to avoid thermal stresses and spalling of the refractory. In addition, refractory layers are susceptible to failure and can be a significant maintenance concern during operation. The three basic modes of refractory failure are thermal shock, erosion/abrasion, and corrosion. Once cracks appear in the refractory, foreign material quickly fills the void and accelerates the failure mechanism.

The various CFB manufacturers are striving to improve refractory performance. Water or steam-cooled surfaces significantly reduce the required thickness of refractory and permit shop application of refractory where application can be more strictly controlled. New types of refractory are being developed for application to CFBs and greater quality control is being used in applying the refractory.
Air Heaters:
Due to the high air pressures required in CFBs and the excessive leakage that could consequently occur with conventional regenerative air heaters, low-leakage-type air heaters, such as tubular air heaters and heat pipe air heaters, are used in CFB applications. Generally, separate primary and secondary air heaters are used, and an air heater also can be used for the FBHE fluidizing air.
With tubular air heaters, gas-over-tube/air-through-tube designs are usually used to facilitate cleaning with soot blowers.
Tubular air heaters were used on almost all of the early CFB units. The tubular air heater sizes required with larger units and units that require gas outlet temperatures below 150°C present a problem because of excessive space requirements and pressure drops.
Cold-end protection by means of steam preheating, hot water preheating, or air bypass is usually required for air heaters in CFB applications. There is the potential for reducing or eliminating cold-end protection, since $S_0_2/S_0_3$ levels at the air heater are low (from sorbent addition to the combustor).

Fans and Blowers:
The combustion air system for a CFB is similar to, and provides the same functions as, the air systems on a conventional boiler. Generally, separate centrifugal fans, arranged in parallel, are used for primary and secondary air. A series arrangement can also be used, with the second fan supplying the high-pressure primary air.

Startup Burners:
The startup burner system for a CFB is similar to that for a BFB.

Operating Parameters:
Typical operating parameters for a CFB are shown in Table below. As with BFBs, gas solid temperatures are usually maintained in the range of 850 to 900°C for optimum sulfur capture.

<table>
<thead>
<tr>
<th>Table: Typical CFB Operating Parameters</th>
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<tbody>
<tr>
<td>Bed temperature, °C</td>
</tr>
<tr>
<td>Superficial velocity, m/s</td>
</tr>
<tr>
<td>Coal feed particle size, mm.</td>
</tr>
<tr>
<td>Sorbent feed particle size, microns</td>
</tr>
<tr>
<td>Recycle ratio</td>
</tr>
<tr>
<td>Calcium/sulfur ratio</td>
</tr>
<tr>
<td>$S_0_2$ removal, %</td>
</tr>
<tr>
<td>Combustion efficiency, %</td>
</tr>
<tr>
<td>NOx emissions, ppm</td>
</tr>
</tbody>
</table>

Higher bed temperatures are used if sulfur capture is not a concern or if low-volatile fuels are being fired. The higher bed temperatures increase carbon burnout, but generally lead to higher NOx emissions.
Typical superficial gas velocities in the combustor are much higher for CFBs compared to BFBs. Selection of the design velocity is usually a compromise between heat transfer rates, erosion, and turndown. Velocities at the higher end of the range promote good heat transfer and provide for large turndown ratios, but significantly increase the potential for erosion. Low velocities minimize the potential for erosion, but heat transfer and turndown suffer.

As indicated previously, fuel feed size is dictated by the type of fuel being fired. The smaller feed sizes are used when firing low-volatile, high-ash fuels, while the larger fuel feed sizes are used when firing reactive fuels. In comparison to BFBs, the fuel feed size for CFBs typically is much smaller.

Sorbent feed size in a CFB is about 1,000 microns. The management of both fuel and sorbent feed size is important to overall CFB performance. Particle sizes that are too large will lead to excessive bed pressure drops and carbon losses when bed material is drained from the combustor. Particles that are too fine will be carried through the cyclone separator.

As with BFBs, the Ca/S ratios are selected to achieve the desired sulfur removal. The results of performance testing at the Nucla CFB are summarized in Figure below.

The correlation shown is for a combustor temperature of 800 to 850° C and indicates that a Ca/S ratio of 1.5 is required for 70% SO₂ removal, and a Ca/S ratio of 4.0 is required for 95% SO₂ removal. The results reported indicate that SO₂ removal is quite temperature sensitive. At a bed temperature of 900° C, a Ca/S ratio of about 2.7 was required to achieve 70% SO₂ removal at Nucla.

Combustion efficiencies are typically quite good in a CFB. Results of testing at the Nucla Station indicated that combustion efficiency varied over a narrow range of 97.6% and 98.9% for loads ranging from 55 to 110 MW. No significant variation in
combustion efficiency was noted when bed temperature, primary/secondary air distribution, excess air, and coal feed configuration were varied.

Control Philosophy:
Turndown from full load operating conditions on a CFB is initiated by reducing fuel and air flow to the combustor. Initially, both fuel and air flow can be reduced and, thus, combustion temperatures can be maintained at full load values. When the load is reduced to a certain point, however, it is necessary to hold air flow constant to provide for adequate combustor performance and to prevent severe temperature mal-distributions in the combustor.
At loads below this point, combustor temperature drops. When the combustor temperature falls to a pre-selected value, startup burners must be placed in operation. If the CFB is provided with a FBHE, turndown is achieved by first reducing solids flow to the FBHE. Since operation of the combustor is not initially impacted, combustor temperatures remain at optimum values. At reduced loads, solid flow to the FBHE is stopped. At loads below this point, fuel and air flow to the combustor must be decreased as discussed previously. One of the primary advantages of a FBHE, therefore, is that optimum combustor temperatures can be maintained over a wider load range than for CFBs that do not have a FBHE.
As with BFBs, bed temperature control is maintained by varying airflow. Also, bed inventory is maintained by draining solids from the combustor to maintain a constant pressure differential across the bed. Steam temperature control in a CFB is similar to that used for a BFB or for a conventional pulverized coal unit.
Q. What causes heavy black smoke when fuel oil is burnt?

A. The main causes which tend to heavy black smoke are
   i) If the fuel oil is not properly prepared i.e. temperature and viscosity of fuel oil is not as per the requirement,
   ii) Guns are not in clean condition,
   iii) Air supplied is insufficient and
   iv) Atomization in fuel oil is poor.

Q. What is the effect of moisture and sediments in oil burning?

A. The moisture in fuel oil when burnt is converted into steam, which then carry the heat to the chimney & is a direct loss to boiler. Also too large moisture content sometimes result in lowering of the burning temperature, improper combustion, choking of burner tips and erosion & corrosion of boiler parts like Air preheater, ID fan, chimney internal, ducts etc. Sediments in fuel oil are nothing but incombustible which lowers the calorific value of fuel, choke burners & form slag & deposits on the outer surfaces of the various tubes thereby lowering the heat transfer.

Q. In pulverized coal firing, which principal pulverizers are used?

A. The types of pulverizers commonly used are ball, bowl, impact, ring roll & ball race types.

Q. What is the function of a fuel oil burner?

A. Fuel oil burners atomize oil into fine spray which when mixed with air forms a combustible mixture and when ignited produces intense heat. Finer the spray, more readily the oil will ignite to attain good combustion. Poor atomization causes heavy carbon deposits.

Q. What is turn-down ratio?

A. Turn down ratio is the ratio of maximum to minimum load in a burner. Thus, it is the ability of a burner to produce good combustion even at low loads. If a turndown ratio is of 3:1, it means that even at 33% of the maximum rating, atomization of oil will be efficient.
Q. What are the causes of flame impingement in oil firing? Is it harmful?

A. Flame impingement occurs when
   1) The burner is not correctly centered
   2) The burner tip gets partially choked
   3) Atomized oil strike the furnace plate
   4) Improper combustion takes place due to faulty design of a burner installation.
   Flame impingement is very much harmful to boiler components. It causes local overheating of the metal as water circulation is not fast enough to keep the temperature of the metal within the safe limits. Flame impingement on water tubes may cause bulging and subsequent rapture.

Q. Why coke deposits are formed in oil fired furnace?

A. When oil droplets as a result of poor atomizing, delayed combustion etc., hit colder surfaces, the conversion process gets retarded and oil coke deposits are formed.

Q. When a boiler is switched over from fuel oil to natural gas firing, heat absorption in the furnace space decreases. Why?

A. Flames produced by natural gas have lower emissivity than those produced by fuel oil upon combustion. Since the mode of heat transfer within the furnace space is of radiative type, decrease in flame emissivity results in lowering of the heat absorption rate.

Q. What do we mean by fuel bed firing on stoker fired steam generator?

A. In fuel bed firing, fuel is pushed, dropped, or thrown on a grate in a high temperature region within the furnace. Air flows upward the grate and through the fuel bed that forms on it. The green coal is heated, volatile matter distills off and coke is left on the grate. As the coke burn to a mixture of carbon dioxide and carbon monoxide, ash remains. The volatile matter of the coal and the carbon monoxide from the coke, burn over the fuel bed with air that has come up through it. Usually, secondary air is admitted to the furnace over the grate. Thus anywhere from 40 to 60% of the coal’s heat is liberated over the fuel bed. So burning of gases is a big part of the job even with fuel-bed firing.
EXAMLES FOR PRACTICE

Q.1 What is meant by boiler purging?

Q.2 What are the advantages of using pulverized fuel?

Q.3 What is the advantage of a tilting burner with pulverized fuel?

Q.4 What is the purpose of a classifier in a P.F. mill?

Q.5 What are pre-combustion problems before oil is fired?

Q.6 Before turning a boiler, which items should be checked?

Q.7 What conditions are necessary to cause thermal explosions? Name the common type of furnace explosion.

Q.8 What is fluidized bed combustion? State its advantages.

Q.9 Name the different types of stokers used in boiler furnace and explain any one of them