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TYPES OF BOILERS

In simple a boiler may be defined as a closed vessel in which steam is produced from water by combustion of fuel.

The steam generated is employed for the following purposes :

- For generating power in steam engines or steam turbines,
- In the textile industries for sizing and bleaching etc. and many other industries like
- sugar mills; chemical industries.
- For heating the buildings in cold weather and for producing hot water for hot water supply.

The primary requirements of steam generators or boilers are :

- The water must be contained safely.
- The steam must be safely delivered in desired condition.

REQUIREMENT OF A BOILER

A good boiler should possess the following qualities:

- It should be able to generate steam at the required pressure and quantity with minimum fuel consumption.
- Its initial cost, installation, maintenance, and operational cost should be as low as possible.
- It should occupy a small floor area and should be light in weight.
- It should be able to meet the fluctuating demands of steam without fluctuations in steam pressure.
- All parts of the boiler should be easily accessible for cleaning, inspection, and maintenance.
- It should have minimum joints to avoid leakage of steam.
- Its erection time should be reasonable with minimum labour.
- The velocities of water and flue gas should be high for better heat transfer with minimum pressure drop through the system.
- There should be no deposition of mud and foreign materials inside the surface and soot deposits on the outside surface of heat-transferring parts.
- The boiler should conform to safety precautions as laid down in the Boiler Regulations.

FACTORS AFFECTING BOILER SELECTION

The factors affecting boiler selection are as follows:

- Power to be generated, that is, steam to be raised per hour
- Working pressure
- Initial capital investment
- Facilities available for erection
- Availability of floor area
- Location of power house
- Availability of fuel and water
- Probable load factor
- Operating and maintenance cost
- Accessibility for inspection, cleaning, and maintenance

HORIZONTAL, VERTICAL OR INCLINED

If the axis of the boiler is horizontal, the boiler is called as horizontal, if the axis is vertical, it is called *vertical boiler* and if the axis is inclined it is known as inclined boiler. The parts of a horizontal boiler can be inspected and repaired easily but it occupies more space. The vertical boiler occupies less floor area.

FIRE TUBE AND WATER TUBE

In the **fire tube boilers**, the hot gases are inside the tubes and the water surrounds the tubes. Examples: *Cochran, Lancashire and Locomotive boilers*.

In the **water tube boilers**, the water is inside the tubes and hot gases surround them. Examples: Babcock and Wilcox, Stirling, Yarrow boiler etc.

EXTERNALLY FIRED AND INTERNALLY FIRED

The boiler is known as externally fired if the fire is outside the shell. Examples: Babcock and Wilcox boiler, Stirling boiler etc.

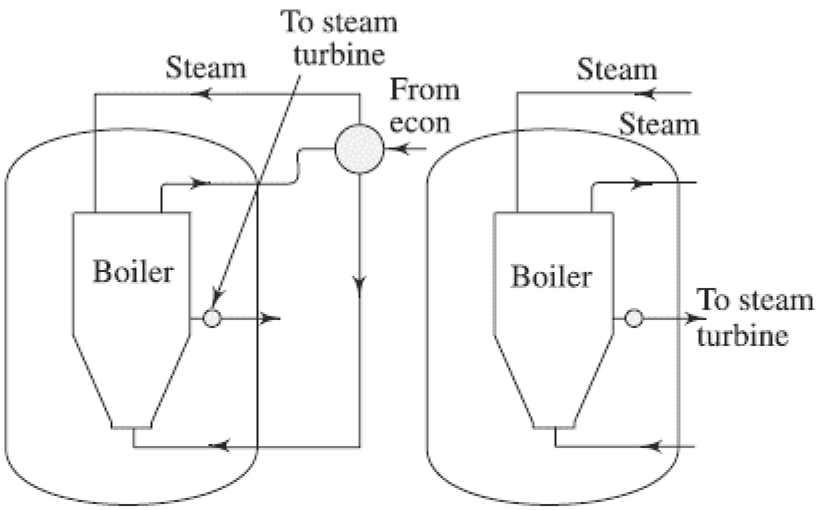
In case of internally fired boilers, the furnace is located inside the boiler shell. Examples: Cochran, Lancashire boiler etc.

FORCED CIRCULATION AND NATURAL CIRCULATION

Forced Circulation Boiler. In forced circulation type of boilers, the circulation of water is done by a forced pump. Examples: Velox, Lamont, Benson boiler etc.

Natural Circulation Boiler. This is caused by density difference. In natural circulation type of boilers, circulation of water in the boiler takes place due to natural convention currents produced by the application of heat. Examples: Lancashire, Babcock and Wilcox boiler etc.

Following figure shows this circulation system.



Natural Circulation boiler **Forced circulation boiler**

Advantages of forced circulation boiler

- The evaporator tubes may be built in any orientation. Natural circulation requires vertical piping whereas the forced circulation ensures flow in any direction.
- The walls of the tube may be built smaller due to the greater tolerance of higher pressure losses.
- The general forced circulation boiler has a low circulation ratio of range between three and ten. The circulation ratio is how much steam is produced per how much feed was put in. Natural circulation boilers have a huge range of circulation ratios all the way from five to one hundred.

Limitations of Forced Circulation over Natural Circulation

- higher costs
- reduced reliability, and
- increased energy consumption

HIGH PRESSURE AND LOW PRESSURE BOILERS

The boilers which produce steam at pressures of 80 bar and above are called **high pressure boilers**. Examples : Babcock and Wilcox, Velox, Lamont, Benson boilers.

The boilers which produce steam at pressure below 80 bar are called **low pressure boilers**. Examples: Cochran, Cornish, Lancashire and Locomotive boilers.

STATIONARY AND PORTABLE

Primarily, the boilers are classified as either stationary (land) or mobile (marine and locomotive).

- Stationary boilers are used for power plant-steam, for central station utility power plants, for plant process steam etc.
- Mobile boilers or portable boilers include locomotive type, and other small units for temporary use at sites (just as in small coal-field pits).

SINGLE TUBE AND MULTI-TUBE BOILERS

The fire tube boilers are classified as single tube and multi-tube boilers, depending upon whether the fire tube is one or more than one. The examples of the former type are cornish, simple vertical boiler and rest of the boilers are multi-tube boilers.

WASTE HEAT RECOVERY BOILER (WHRB)

Waste heat recovery boilers are used to utilize the heat energy from the system which would otherwise go waste. Mass of hot gas and its temperature are the main factors that decide the design of a waste heat recovery boiler.

In sponge iron kilns, lot of hot gas is produced. This hot gas is utilised in the boiler for steam generation. The hot gas contains significant amount of abrasive dust. These dust particles may damage the boiler tube due to erosion. Erosion problem is minimised by lowering the gas velocity. By providing abrupt change in the direction of flue gas flow, dust particles settle down and are removed by suitable ash handling system. Lot of hot gas escapes from cement kiln preheater and cooler. By installing WHRB in these areas, steam can be generated.

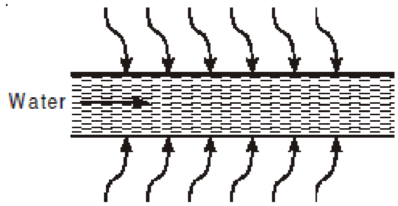
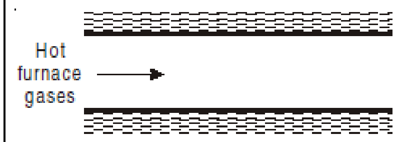
Hot exhaust gas from gas turbine is used in the waste heat recovery boilers for steam generation. The steam is used to drive steam turbine. This arrangement is called combined cycle. In some chemical processes, heat is produced due to exothermic reaction. For example,

$$N_2 + 3H_2 \rightarrow 2NH_3 + 22 \text{ kcal of heat}$$

$$2SO_2 + O_2 \rightarrow 2SO_3 + 45 \text{ kcal of heat.}$$

COMPARISON BETWEEN FIRE-TUBE AND WATER-TUBE BOILERS

S. No.	Particular	Fire-tube boilers	Water-tube boilers
1.	Position of water and hot gases	Hot gases inside the tubes and water outside the tubes.	Water inside the tubes and hot gases outside the tubes.
2.	Mode of firing	Generally internally fired.	Externally fired.
3.	Operating pressure	Operating pressure limited to 16 bar.	Can work under as high pressure as 100 bar.
4.	Rate of steam production	Lower	Higher.
6.	Suitability	Not suitable for large power plants.	Suitable for large power plants.
6.	Risk on bursting	Involves lesser risk on explosion due to lower pressure.	Involves more risk on bursting due to high pressure.
7.	Floor area	For a given power it occupies more floor area.	For a given power it occupies less floor-area.
8	Construction	Difficult	Simple
9	Transportation	Difficult	SIMPLE
10.	Shell diameter	Large for same power	Small for same power
11	Chances of explosion	Less	More
12.	Treatment of water	Not so necessary	More necessary
13.	Accessibility of various parts	Various parts not so easily accessible for cleaning, repair and inspection.	Various parts are more accessible.
14.	Requirement of skill	Require less skill for efficient and economic working.	Require more skill and careful attention.

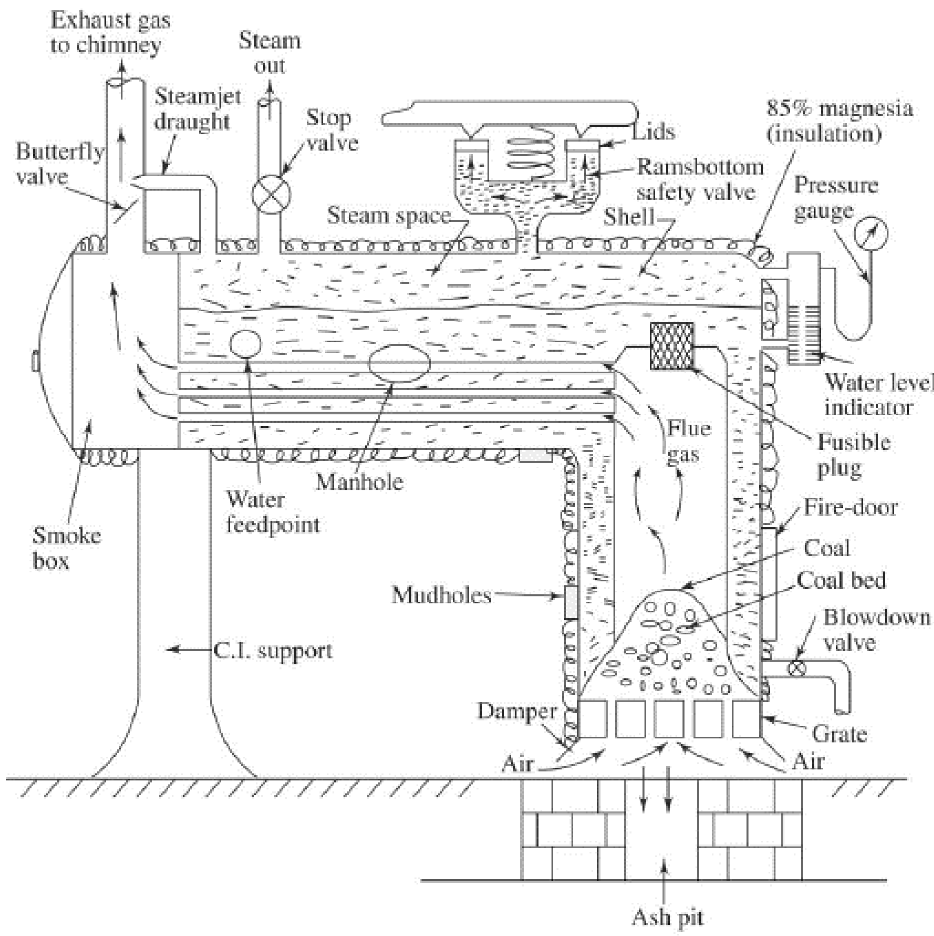
15.			

FIRETUBE BOILERS

A fire-tube boiler is so named because the products of combustion pass through its tubes or flues, which are surrounded by water. They may be either:

- Externally fired (e.g. locomotive type boilers, Lancashire boilers, horizontal return tubular (HRT) boiler etc.), or
- Internally fired (e.g. Scotch-marine boilers, package boilers, etc.).

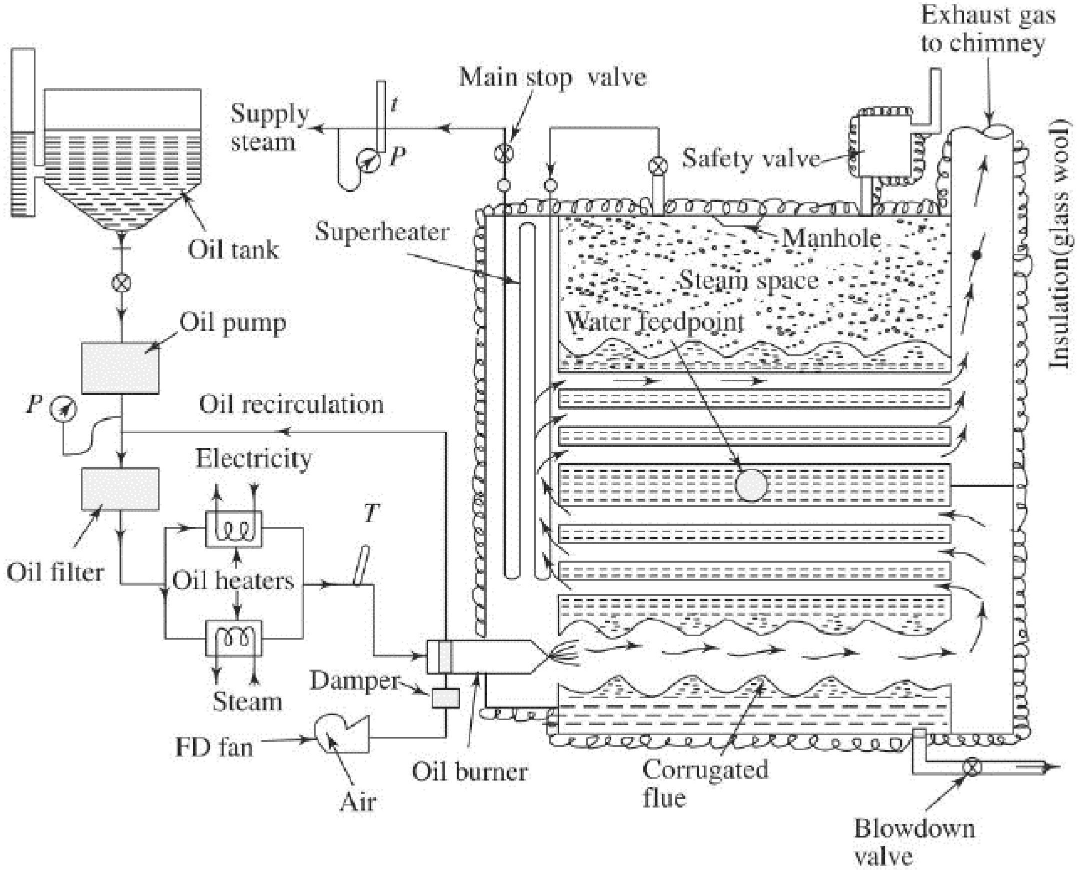
Following figure shows a typical externally **fired fire-tube boiler** in which the *furnace is outside the boiler shell*. Coal is entered manually by shovels on to the grate by opening the fire-door. The products of combustion flow through the tubes which are immersed in the shell containing water. A fusible plug made up of a low melting point alloy (lead-based) is installed on the roof of the crown in the furnace. If the water-level in the shell falls below a certain level, the *fusible plug melts* due to overheating and water pours down through the hole formed and puts out the fire.



There is a *spring-loaded safety-valve* provided to keep the boiler pressure within the safety limit. The spring is set in such a way that the upward thrust of steam against the lid is balanced by the downward thrust of the spring. If the operating steam pressure exceeds this value, the upward thrust of steam will then be greater than the downward spring thrust and the difference will force open the lid upward, as a result of which steam will be released with a hissing sound, the steam pressure inside the shell will 20 down till the lid is forced down to be back on its seat.

As the hot flue gases flow through the tubes, heat is transferred from gas to water all along the length. The gas is cooled and the water is heated till there is nucleate boiling around the tubes and steam is formed. Steam is taken out at the required rate by opening the main stop valve. Auxiliary' steam may also be taken to operate a steam jet water injector to feed water into the shell. The shell is insulated all around by asbestos and 85% magnesia to reduce heat loss to the surroundings. Air flow from below the grate is regulated by operating dampers according to the requirement of combustion. An elliptic manhole is provided for a man to go in to do cleaning or repair as the need arises.

An **oil-fired pressurized package type boiler** is shown below. It is an internally fired fire-tube boiler, since the furnace is within the cylindrical shell. Oil is filtered, adequately heated either by electricity or steam, and is then fed through the burner. Air is supplied by an FD fan. Excess oil is returned to the main feedline. Combustion occurs in a horizontal corrugated flue, and the combustion gases flow through the tubes in two passes till they are let out through a chimney to atmosphere.



The **package-type boiler** has certain inherent advantages:

- It is highly compact. A large surface area of heat transfer is provided in a small volume. The furnace volume is less since it is pressurized.
- No ID fan is required. A short chimney is provided just for disposal of flue gases.
- The entire unit is mostly fabricated in the factory itself. It is transported to the site and installed there with relative ease.
- It occupies less space.
- It is easy to operate. Because of these advantages, package boilers were favoured in process industries. But the paucity of oil supply has reduced its demand giving way to the use of fluidized bed boilers mostly based on coal.

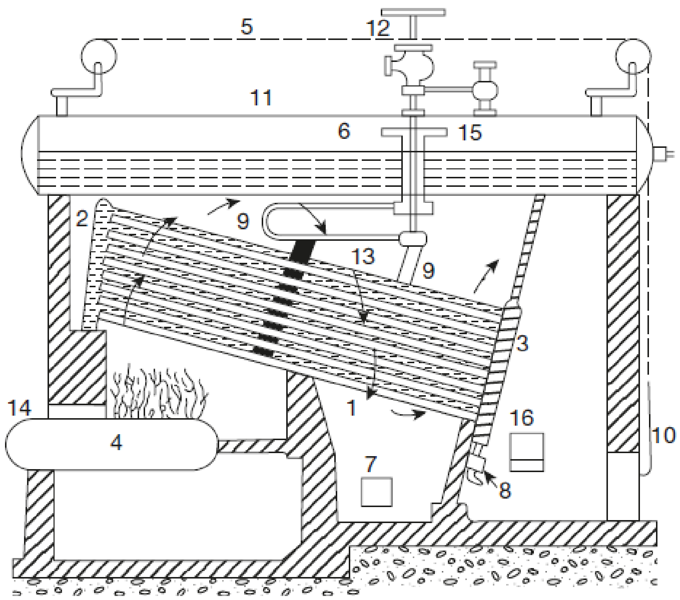
WATER TUBE BOILERS

For pressures above 10 bar and capacities in excess of 7000 kg of steam per hour, the water tube boiler is used almost exclusively.

Babcock and Wilcox Boiler

Following figure shows a stationary type Babcock and Wilcox boiler. It consists of a large number of parallel tubes inclined at an angle which varies from 5° to 15° to the horizontal which connect the uptake header with the *downtake* header. These are connected to the shell having a substantial quantity of water in it.

1. Water tubes
2. Uptake header
3. Downtake header
4. Grate
5. Damper chain
6. Steam pipe
7. Soot doors
8. Mud box
9. Baffles
10. Damper
11. Shell
12. Stop valve
13. Superheater tubes
14. Fire hole
15. Tube
16. Side flue



The *uptake header* is connected to the shell, through a short tube, whereas a long tube is employed to connect the downtake header with the shell.

The coal is fed through the fire hole on to the chain grate stoker. The velocity of the chain is adjusted so as to ensure complete combustion of coal by the time it reaches the other end of the grate. The flue gases first rise up, move down, and rise up again due to the presence of the *baffles*.

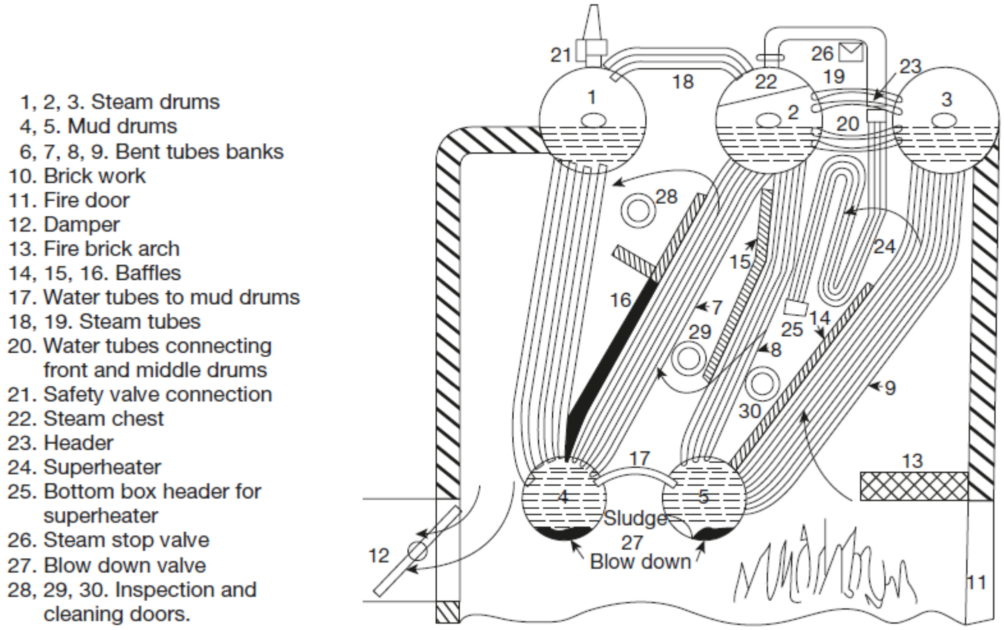
The *hot water and steam moisture* rise up through the uptake header into the boiler shell, where steam separates from water and collects in the steam space.

The *cold water* flows down into the tubes through the downtake header. Hence, a continuous circulation of water is maintained by the convection currents set up.

A set of *superheater* tubes is provided to superheat steam which enters these tubes from the steam space in the boiler shell. The superheated steam can be taken out to the *steam stop valve*, through the steam pipe. The lower part of the downtake header has a *mud box* attached to it to collect the sediments. The *damper chain* controls the quantity of air flowing through the boiler. Two *soot doors* are provided for internal cleaning of boiler.

Stirling Boiler

Following figure shows the Stirling boiler, which comes in a water tube type in which *three steam drums* are connected together by the *banks of bent water tubes*.



These tubes stand nearly in a vertical position near the rear end while they slope steeply over the fire at the front end. The *baffles* deflect the products of combustion from the furnace over the banks of tubes into the *mud drum*. The steam generated collects in the steam spaces of the three drums. The steam can be raised at a working pressure of 60 bar with the temperature as high as 450°C. An evaporation capacity of 50,000 kg/h has been achieved with a Stirling boiler.

REVOSTEAM COIL TYPE BOILER

Revosteam, Coil Type Boiler, is a unique water tube coil type boiler in which water flows inside the tube.

It uses the "**Reverse Flow**" combustion concept, which is unique in the industry. When flue gas reaches the bottom of the shell, it flows in the opposite direction. This flue gas flow improves combustion efficiency while also allowing for a high rate of heat transfer to the adjacent water coil.

- Revosteam is a truly Non-IBR boiler.
- It is coil type, water-tube design boiler.

- Instant Steam generator.
- The water flows inside the coil and the flame is on outside it, providing heat to produce steam.
- REVOSTEAM is a fully automatic boiler and it switches on and off automatically depending upon a preset steam pressure controlled through a pressure switch
- Water feeding is also automatic
- Forced circulation, water tube design and REVERSE FLOW combustion enable the boiler to produce steam at full working pressure with in 3-5 minutes from cold start

Construction

A Water tube Coil type boiler comprises of a **jacketed MS shell** housing a **helical coil**.

The combustion air is forced through the jacketed shell by means of a **centrifugal blower** thereby getting preheated

The **flame** travels downwards inside the coil and the **flue gases** reverse upwards thereby giving two passes in the radiant zone ensuring complete combustion and higher heat flux.

The **third pass** of the flue gases is in the convective zone between the coil and the inner shell.

Flue gases then travel to the Economizer forming the **fourth pass**.

Advantages

- Fully Automatic unit
- Unique four pass design
- High efficiency and low running cost
- Minimum site-work, low installation costs
- Instant streaming within 5 minutes of cold start
- Built-in economiser increases the operating efficiency
- Fail-safe design and dependable operating instruments
- Qualified attendant not required
- Multipass design with economiser
- Easy access for inspection and cleaning
- Large tube diameter ensure longer coil life Pre-heated air gives excellent combustion
- Truly Non -IBR design-outside the purview of IBR

HIGH PRESSURE BOILERS

In all modern power plants, boilers raising steam at pressures greater than 100 bar are universally used. These are called high pressure boilers.

They offer the following advantages:

- The efficiency and the capacity of the plant can be increased as reduced quantity of steam is required for the same power generation if high pressure steam is used.
- The forced circulation of water through the boiler tubes provides freedom in the arrangement of furnace and water walls in addition to the reduction in the heat exchange area.
- The tendency of scale formation is reduced due to high velocity of water.
- The danger of overheating is reduced as all the parts are uniformly heated.
- The differential expansion is reduced due to uniform temperature and this reduces the possibility of gas and air leakages.

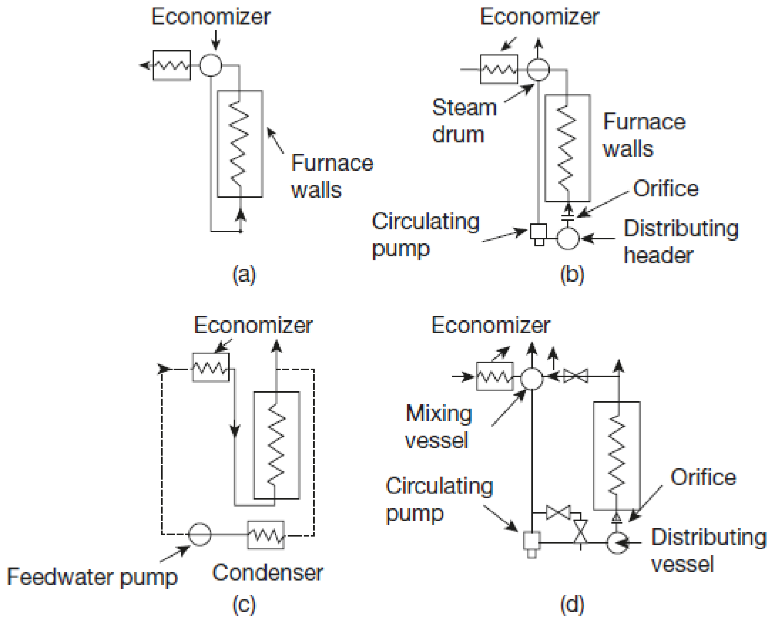
Boiler Circulation

Before discussing about various types of high pressure boilers, let us understand about boiler circulation.

There are four types of boiler circulation as follows.

- **Natural circulation:** Water circulates naturally in a boiler when its density in one part of the circuit is less than that in another part at the same level. The boiler drums, tubes, and water wall make up the multi-passage circuit. During steam formation in a simple drum, the water near the sides of the drum gets heated and forms steam bubbles, lowering its density. The water in the drum centre being heavier displaces the lighter water-bubble mix and, in turn, gets heated up. This sets up a constant circulation that releases steam into the upper drum region.
  Similarly, in a water tube circuit, the water from the drum flows through the downcomer tube to the bottom of the heated riser. Heat forms steam bubbles in water passing through the riser, lowering the density of the mixture. The heavier downcomer water displaces the riser mixer to establish continuous flow. The force of gravity to produce flow in a natural circulation comes from the difference between the densities of the fluids in the downcomer and riser portions of the circuit. The natural circulation is depicted in Fig. (a).
- **Forced circulation:** Forced circulation in various circuits of boiler units is produced by mechanical pumps as depicted in Fig. (b).
- **Once-through forced circulation:** This type of circulation, as depicted in Fig. (c), receives water from the feed supply, pumping it to the inlet of heat-absorbing circuit. Fluid heating and steam generation take place along the length of the circuit until evaporation is completed. Further process through the heated circuits results in superheating the vapour.
- **Once-through with recirculation (forced):** The 'recirculating' forced-circulating type unit has water supplied to the heat absorbing circuits through a separate circulating

pump. The water pumped is considerably in excess of steam produced and requires a steam-and-water drum for steam generation. This type of system is depicted in Fig. (d).



Advantages of Forced Circulation Boilers

The advantages of forced circulation boilers are as follows:

- Smaller bore and therefore, lighter tubes
- Absence from scaling troubles due to high circulation velocity
- Lighter for a given output
- Steam can be raised quickly and load fluctuations met rapidly
- Uniform heating of all parts eliminates the danger of overheating
- Greater flexibility in layout of boiler parts
- Boiler can be operated at desired conditions
- Boiler can be started rapidly

LaMont Boiler

The feed water from hot well is supplied to a storage and separating drum (boiler) through the economizer. Most of the sensible heat is supplied to the feed water passing through the economizer. A pump circulates the water at a rate 8 to 10 times the mass of steam evaporated. This water is circulated through the evaporator tubes and the part of the vapour is separated in the separator drum. The large quantity of water circulated (10 times that of evaporation) prevents the tubes from being overheated.

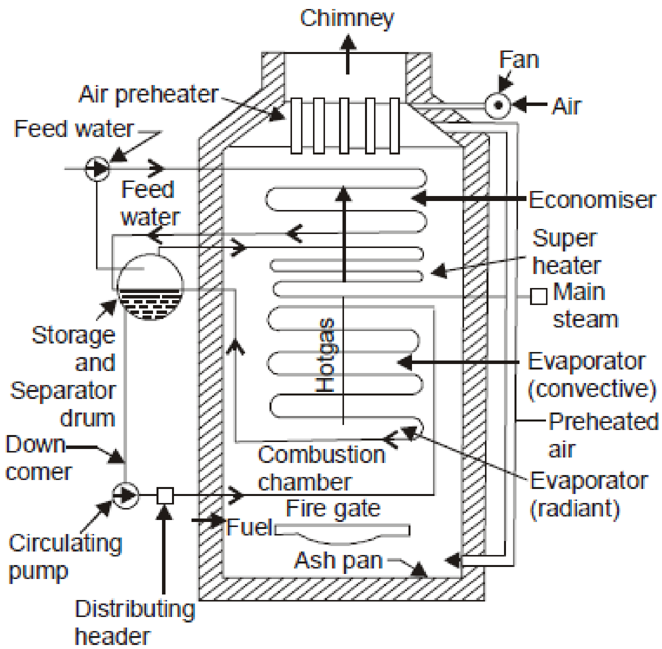
The centrifugal pump delivers the water to the headers at a pressure of 2.5 bar above the drum pressure. The distribution headers distribute the water through the nozzle into the evaporator.

The steam separated in the boiler is further passed through the super-heater.

To secure a uniform flow of feed water through each of the parallel boiler circuits a choke is fitted entrance to each circuit.

These boilers have been built to generate 45 to 50 tonnes of superheated steam at a pressure of 120 bar and temperature of 500°C. Recently forced circulation has been introduced in large capacity power.

Following figure shows a LaMont steam boiler.



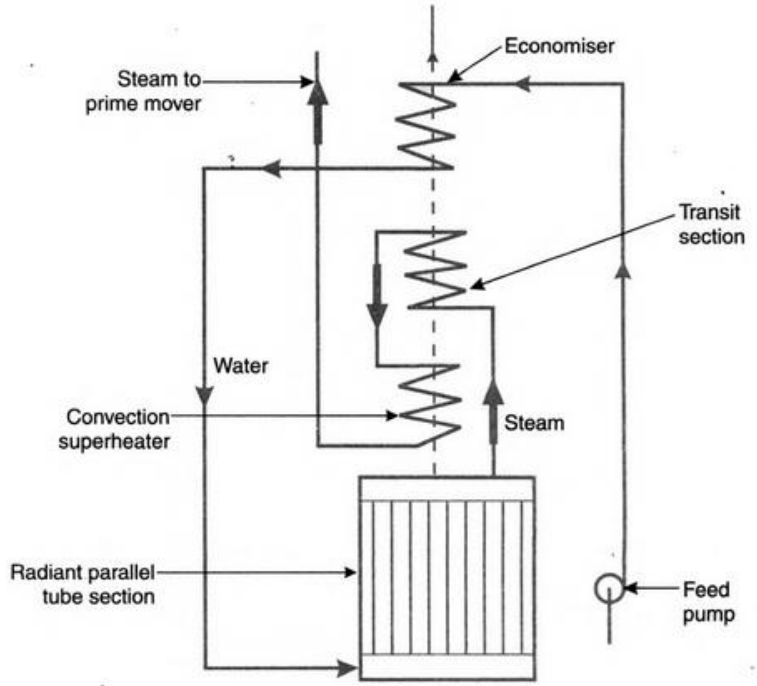
LaMont Boiler

Benson Boiler

In the LaMont boiler, the main difficulty experienced is the formation and attachment of bubbles on the inner surfaces of the heating tubes. The attached bubbles to the tube surfaces reduce the heat flow and steam generation as it offers high thermal resistance than water film. Benson in 1922 argued that if the boiler pressure was raised to critical pressure (225 atm.), the steam and water have the same density and therefore, the danger of bubble formation can be easily eliminated The first high pressure Benson boiler was put into operation in 1927 in West Germany.

This boiler too makes use of forced circulation and uses oil as fuel. It chief novel principle is that it eliminates the latent heat of water by first compressing the feed to a pressure of 235 bar, it is then above the critical pressure and its latent heat is zero.

Following figure shows a schematic diagram of a Benson boiler.



Benson Boiler

This boiler does not use any drum. The feed water after circulation through the economic tubes flows through the radiant parallel tube section to evaporate partly. The steam water mixture produced then moves to the transit section where this mixture is converted into steam. The steam is now passed through the convection superheater and finally supplied to the prime mover.

Boilers having as high as 650°C temperature of steam had been put into service. The maximum working pressure obtained so far from commercial Benson boiler is 500 atm. The Benson boilers of 150 tonnes/h generating capacity are in use.

Advantages of a Benson Boiler

The Benson boiler possesses the following advantages :

- It can be erected in a comparatively smaller floor area.
- The total weight of a Benson boiler is 20% less than other boilers, since there are no drums. This also reduces the cost of the boiler.
- It can be started very quickly because of welded joints.

- Natural convection boilers require expansion joints but these are not required for Benson boiler as the pipes are welded.
- The furnace walls of the boiler can be more efficiently protected by using smaller diameter and closed pitched tubes.
- The transfer of parts of the boiler is easy as no drums are required and majority of the parts are carried to the site without pre-assembly.
- It can be operated most economically by varying the temperature and pressure at partial loads and overloads. The desired temperature can also be maintained constant at any pressure.
- The blow-down losses of the boiler are hardly 4% of natural circulation boiler of the same capacity.
- Explosion hazards are not severe as it consists of only tubes of small diameter and has very little storage capacity.
- The superheater in a Benson boiler is an integral part of forced circulation system, therefore no special starting arrangement for superheater is required.

Super Critical Boilers

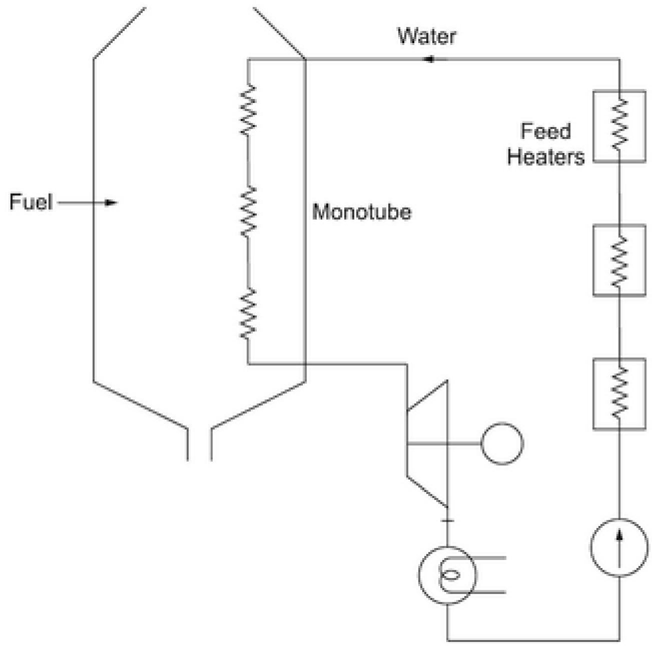
A large number of steam generating plants are designed between working ranges of 125 atm. and 510°C to 300 atm. and 660^{0}C ; these are basically characterised as *sub-critical* and *super-critical.*

Usually a *sub-critical boiler* consists of three distinct section as preheater (economiser), evaporator and superheater.

A *super-critical boiler* requires only preheater and superheater.

The constructional layout of both the above types of boilers is, however, practically identical.

These days it has become a rule to use super-critical boilers above 300 MW capacity units.



Super critical boiler

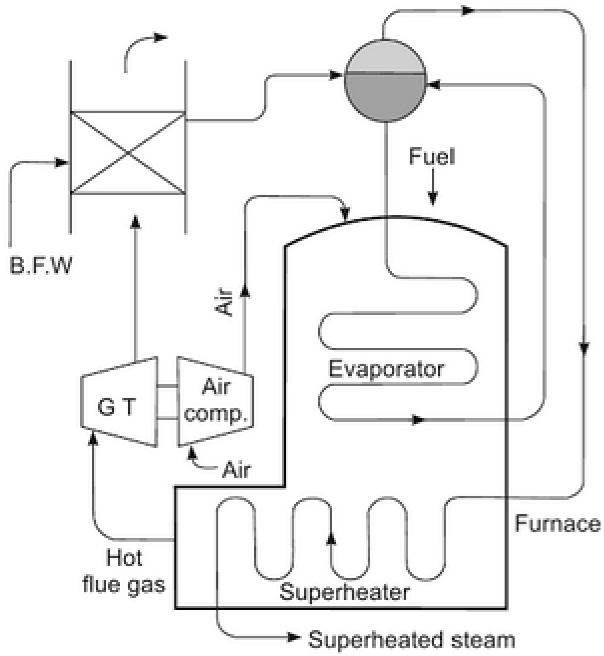
The super-critical boilers claim the following advantages over critical type :

- Large heat transfer rates.
- Owing to less heat capacity of the generator the pressure level is more stable and therefore gives better response.
- Because of absence of two phase mixture the problems of erosion and corrosion are minimised.
- More adaptable to load fluctuations (because of great ease of operation, simplicity and flexibility).
- The turbo-generators connected to super-critical boilers can generate peak loads by changing the pressure of operation.
- Higher thermal efficiency.

Presently, 246 atm. and 538^{0}C are used for unit size above 500 MW capacity plants.

Supercharged Boiler

In a supercharged boiler, the combustion is carried out under pressure in the combustion chamber by supplying the *compressed* air. The exhaust gases from the combustion chamber are used to run the gas turbine as they are exhausted to high pressure. The gas turbine runs the air compressor to supply the compressed air to the combustion chamber.



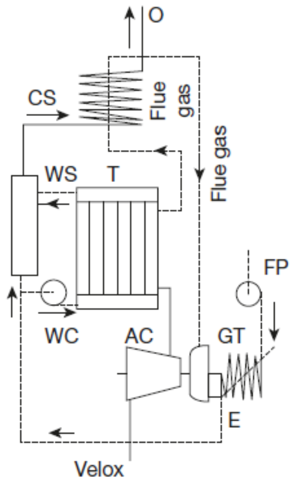
Supercharged Boiler

Advantages:

- Owing to very high overall heat transfer co-efficient the heat transfer surface required is hardly 20 to 25% of the heat transfer surface of a conventional boiler.
- The part of the gas turbine output can be used to drive other auxiliaries.
- Small heat storage capacity of the boiler plant gives better response to control.
- Rapid start of the boiler is possible.
- Comparatively less number of operators are required.

Velox Boiler

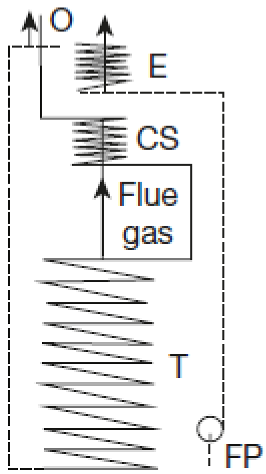
The arrangement of a Velox boiler is shown in following figure.



The pressurised combustion chamber (furnace) of this boiler uses low excess air and has high heat transfer rates. The air for the furnace is supplied by the air compressor. After heating water and steam, the combustion gases pass through a gas turbine to atmosphere. This gas turbine drives the axial flow compressor that raises incoming combustion air from atmosphere to the furnace pressure. The other important components are feed pump, economiser, steam separating section, water circulating pump, and convective superheater. This boiler is built for pressure ranging from 70-80 bar and 500°C.

Once-through Boiler

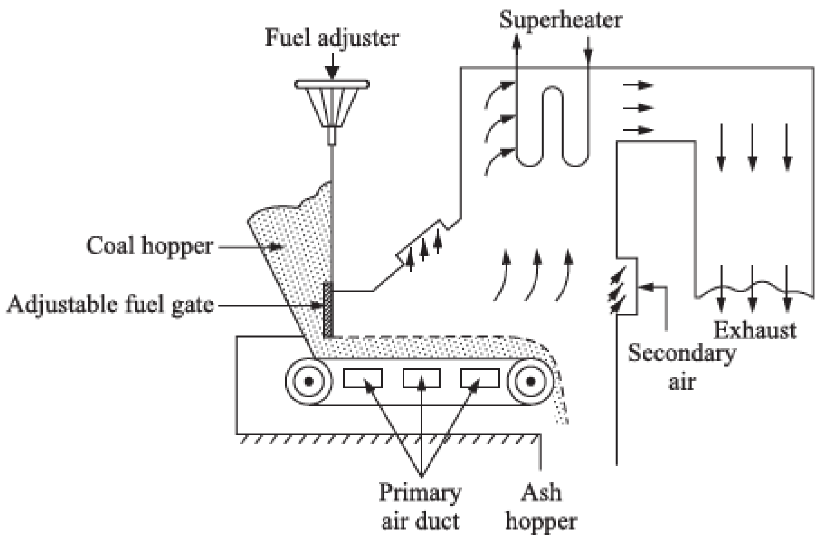
The arrangement of this boiler is shown in following figure.



It has inclined coils arranged in a spiral. Forty coils are paralleled around the furnace. Steam generated in the headers flows into headers and then to the convective superheater. Other essential components are the feed pump and economiser.

TRAVELLING GRATE FIRED BOILER

In traveling grate-fired boiler, coal is fed onto the grate which moves at the bottom portion of the furnace. The moving grate is having suitable openings to admit combustion air from the bottom of the grate. This air cools down the grate as well as ash and is used as primary air for the burning of coal.



Chain grate and **bar grate** are similar to each other except in the construction of the grate. In chain grate, cast iron links are connected in series by pins to form a chain. In bar grate, cast iron surfaces are mounted on bars. These bars are mounted on drive chain. In both the cases, the chain is driven by two sprocket wheels. One of the sprockets, mostly at the front of the furnace is driven by a variable speed drive.

The depth of coal on the grate is varied with the help of an adjustable gate. The speed of the grate can also be adjusted. The coal is fed from the furnace front end and ash is collected from the rear end of the grate.

Primary air from FD fan is supplied through air ducts under the grate. Secondary air is supplied above the grate for complete combustion of coal.

SPREADER STROKE FIRED BOILER

In spreader stoker-fired boiler, coal is fed with the help of a rotating feeding device called feeder or spreader. It is a rotating drum having large number of blades mounted on it. When the spreader rotates, it throws coal into the furnace. Some portion of coal, particularly fine particles, burns in suspension and remaining large size coal falls to the stationary or moving grate where it burns. The stationary grate is moved periodically to remove ash from the grate. Primary air is supplied to the furnace through the openings of the grate. Secondary air is supplied through nozzles. Depending upon the load on the boiler, spreader speed is adjusted.

FLUIDIZED BED COMBUSTION (FBC) BOILER

Fluidisation bed combustion is a method of burning solid fuel in winch the fuel is continually fed into a *hot fluidised bed of inert bed material*. Inert fluidised bed is heated to the ignition temperatures of fuel and the fuel is supplied continuously into the bed. The fuel burns rapidly and bed attains a uniform temperature. Combustion takes place at about 850 °C to 950 °C. This lower combustion temperature is due to effective extraction of heat from the bed through in-bed heat transfer tubes and water-cooled, fin-welded membrane wall. As this temperature is much lower than ash fusion temperature, *melting of ash and associated problems are avoided*. Also, volume of fuel in the bed at any time is less. So, *high ash content fuel can be used in this boiler*. Small amount of dolomite or limestone is fed into the bed which minimises formation of **sulphur dioxide gas (SO_2)**. Another merit of this boiler is the minimum production of **NO_x** in the boiler, as combustion temperature is less.

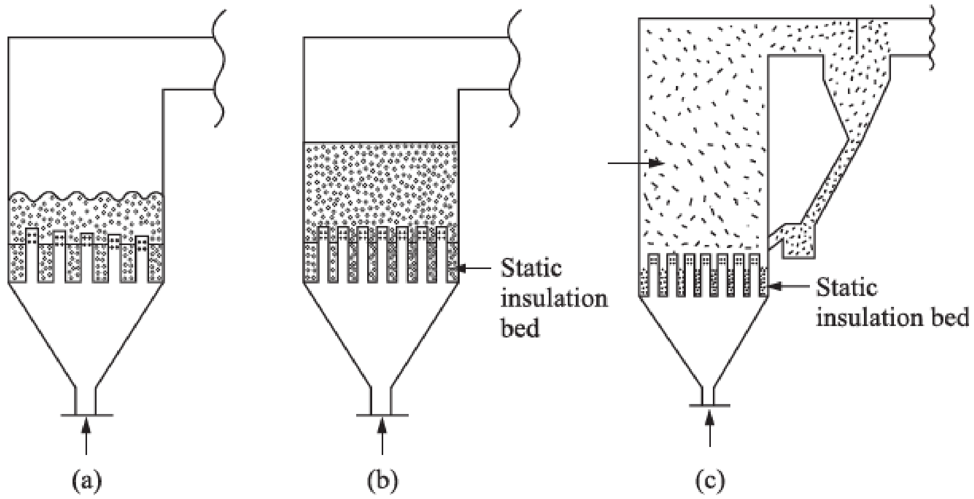
FBC has following advantages

- FBC boiler can bum fuel with higher combustion efficiency.
- Size of the boiler is smaller as compared to the conventional stoker-fired or pulverised boiler. FBC boiler can be operated efficiently with a variety of fuels.
- Coal can be fed either independently or in combination with other solid fuels into the same furnace. Even fuels like washery rejects, biomass solid waste can be burnt efficiently. Inferior quality fuel can be used in this boiler. The boilers can fire coals with ash contents as high as 62% and having calorific value as low as 2500 kcal/kg.
- Coal containing fines below 6 mm can be burnt efficiently in FBC boiler.
- SO_X formation can be minimised by addition of limestone or dolomite for high sulphur coals. Low combustion temperature eliminates NO_X formation.

Mechanism of Fluidisation

Fluidisation or suspension is a process in which small solid granular particles are suspended in a vertical rising current of air. When air is introduced through the bottom of a bed of finely divided solid granular particles, it moves upwards through the bed via the empty spaces between the particles. At low air velocity, the bed remains in a fixed state. When velocity increases, the bed gets expanded in volume, as the particles move away from each other. When velocity is increases further, it reaches a critical value at which the particles become suspended.

At this critical value, the bed is said to be fluidised and it behaves as a fluid. Bed of granular particles is converted from a static solid-like state to a dynamic fluid-like state. By further increasing air velocity, bulk density of the bed continues to decrease and the bed material blows away. So, air velocity is maintained between minimum fluidisation velocity and particle entrainment velocity. Air velocity is around 1.5 m/s such that the bed particles do not leave bed and are carried out. This ensures stable operation of the bed and avoids particle entrainment in the gas stream. Higher air velocity of around 4 m/s is used in case of CFBC boiler where the bed is expanded to top of the furnace. Fixed bed, fluidised bed and extended fluidising bed (circulating fluidised bed) are shown below.



(a) Fixed bed low-velocity air; (b) Fluidised bed air velocity 1.5 m/s and (c) Extended circulating fluidising bed air velocity 4 m/s.

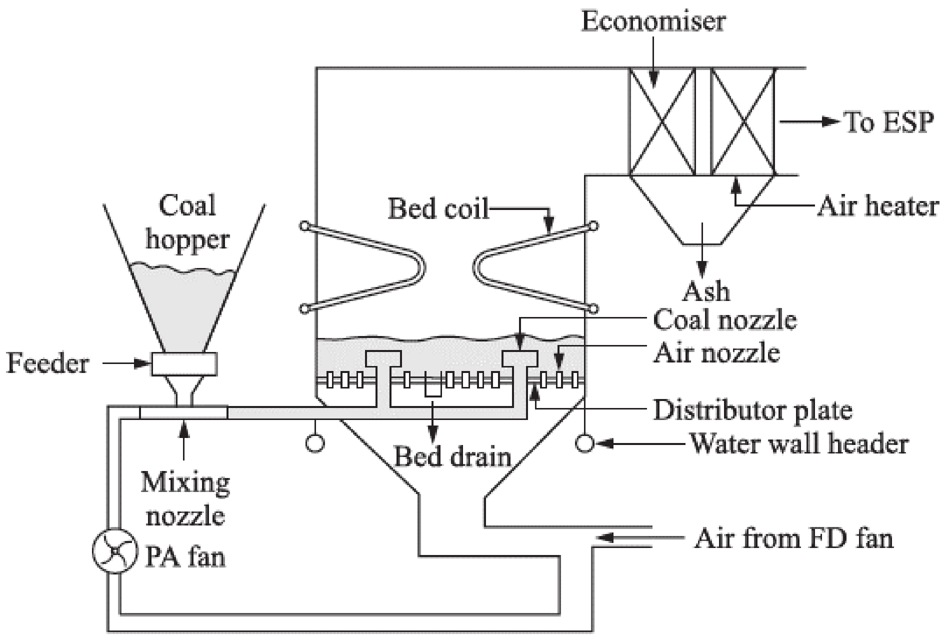
Types of FBC Boilers

- Atmospheric fluidised bed combustion (AFBC) boiler
- Circulating fluidised bed combustion (CFBC) boiler
- Bubbling fluidised bed combustion (BFBC) boiler

Atmospheric Fluidised Bed Combustion (AFBC) Boiler

AFBC boiler mainly comprises of the following systems:

- Air distributor
- Fluidised bed
- Fuel feeding system
- In-bed heat transfer surface
- Ash handling system



FD fan supplies the required fluidisation air for the boiler. This Air is heated at **air heater** and is distributed to compartmentalised **airbox**. The main function of air **distributor** is to introduce the fluidising air evenly throughout the bed cross section for keeping the solid particles in fluidised condition and prevent any defluidisation zone within the bed. Air is supplied from airbox which is placed just below the distributor plate. Air from FD fan is supplied to the airbox.

Major portion of the **fluidised bed** volume contains inert bed material. Bed material is obtained from crushed **refractory bricks** or sieved ash. Initial bed height is maintained up to 250 mm to 300 mm. Out of this bed height, around 100 mm bed does not participate in fluidisation. This layer is called as **static bed layer**. This static layer of bed material **protects the distributor plate** from high temperature of the furnace. 150 mm to 200 mm bed (above air nozzle level) is available for fluidisation. During operation 200 mm to 300 mm bed height is maintained (excluding 100 mm static bed height). During fluidisation, bed expands up to 1500 mm. Bed tubes are immersed in this expanded bed to maintain the required bed temperature.

Operating bed height which is equal to the pressure drop across bed can be calculated as the difference of the two pressure drops (without bed and with bed) at a particular air flow.

Let air flow be 200 mm (without bed and with bed)

Airbox pressure without bed be 200 mmwc

Airbox pressure with operating bed be 450 mmwc

Furnace pressure at both the conditions be 5 mmwc

Then, bed height = (450 + 5) – (200 + 5) = 250 mmwc or 250 mm (as bulk density of bed material is 1000 kg/m^3).

Total bed of larger size boiler is divided into compartments. Each compartment is having independent coal feeding system with its own airbox and air nozzles for fluidisation.

Depending upon the load on the boiler, some compartments are taken out of service. This procedure is called **compartment slumping**. To maintain the temperature of the slumped compartment, fluidising air is charged to that compartment. This is called **bed mixing**.

Crushed coal of size 6–8 mm is stored in the coal bunker nearer to the boiler. This coal is introduced into the fluidising bed as per the requirement through coal feeders. **Underbed** pneumatic feeding and **overbed** feeding methods are adopted in AFBC boiler. During starting, oil or gas burners are used to heat the bed material initially.

In **underbed pneumatic feeding** fuel from the bunker is fed pneumatically into the bed through a rotary feeder and a mixing nozzle located below the bunker.

In **over-bed feeding** crushed coal from the coal bunker is conveyed to the spreader by a screw conveyor.

The temperature of fluidising bed is maintained at around **900 °C**. The bed temperature is maintained by transferring the heat of bed to the **feedwater** quickly. For this, **bed tubes** are placed inside the fluidising bed in which the boiler water flows.

Normally, **inferior quality coal** is used in the AFBC boiler. Ash and shale percentage is more in this type of coal. After complete combustion of the fuel in the bed, larger size ash particles remain in the bed. Accumulation of this ash increases the bed height and affects the fluidisation. This ash is called as **bed ash** or **bottom ash**. Increase in pressure drop across the bed indicates the bed height. To maintain the bed height, bed ash overflow arrangement is provided so that excess bed ash overflows to a separate compartment where it is cooled and drained out.

The amount of **fly ash** generated in AFBC boiler is more due to the escape of particles. Fly ash carried away by the flue gas is removed at the following stages:

- Convection zone
- Bottom of air preheater
- Bottom of economiser
- Electrostatic precipitators (ESP)

Circulating Fluidised Bed (CFBC) Boiler

CFBC technology was developed to burn difficult fuel and used for small capacity industrial boilers. Now, this technology is used successfully to install higher capacity power boilers for power generation. CFBC boiler is still in developing stage and is considered a better option of power generation in future due to several benefits such as improved efficiency, reduced emission, high fuel flexibility, ease of co-firing, lower costs and possibility of subcritical, supercritical and ultrasupercritical parameters.

Like AFBC, CFBC boiler utilises fluidised bed principle. But here, *fluidisation velocity is kept more* (4–5 m/s). So, the fluidised bed is extended throughout the furnace. Crushed fuel is injected into this fluidised bed and combustion takes place. As the velocity is more, so the bed particles, along with some non-combustion particles, move out of the furnace with flue gas. Heavier particles of flue gas are separated in a solid separator and circulated back into the furnace. Due to circulation of hot particles, efficient heat transfer is possible. Unburnt loss is minimum in CFBC boiler, as unburnt particles are recirculated into the furnace, hence provides more time for complete combustion. Residence time is more in CFBC boiler due to taller furnace design. Hence, combustion is efficient and suitable for staged combustion to minimise NOx formation. No bed coils are immersed in the bed for steam generation. Hence, erosion of bed tubes is avoided, resulting in more reliable operation.

Some **merits** of CFBC boiler are listed below:

- Higher degree of fuel flexibility
- High combustion efficiency
- Low NOx emissions
- Good turn down ratio
- No need of in-bed tubes, which are subject to erosion
- Smaller combustor cross section
- Fewer fuel feed points
- Elimination of slagging
- High availability
- Easy to operate and maintain

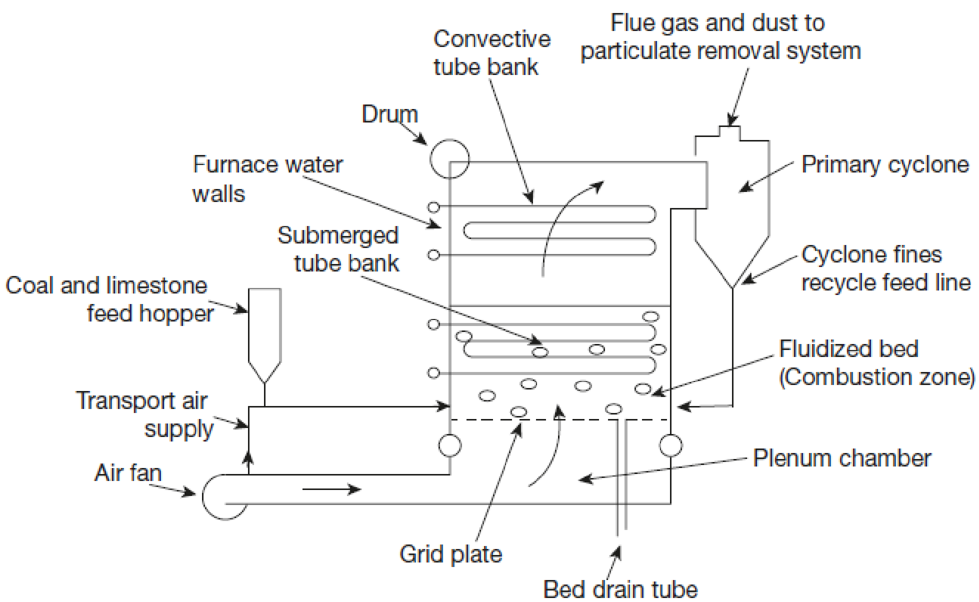
Difference between AFBC and CFBC

	AFBC	CFBC
Wind box pressure	600-700 mmwc	1000-1200 mmwc
Combustion	Mostly in bed	Combination of bed and suspension combustion
Ash Recirculation	No recirculation. But facility can be provided	100% of ash carried by FG can be recycled back to furnace.
Combustion efficiency	Good	Better

Unburnt	Higher	Lower
Bed temperature	Lower	Higher
Air distribution	Primary/Secondary = 80/20	Primary/Secondary = 60/40
Fuel feeding	Underfeed or overfeed	overfeed
Furnace size	Smaller	Bigger
Air velocity	1.8 - 3.5 m/s	10-12 m/s

Bubbling Fluidised Bed Boiler (BFBB)

A schematic diagram of BFBB is shown below. In this boiler, crushed coal (6−20 mm) is injected into the fluidised bed of limestone just above an air-distribution grid at the bottom of the bed.



The air flows upwards through the grid from the air plenum into the bed, where combustion of coal occurs. The products of combustion leaving the bed contain a large proportion of unburnt carbon particles which are collected in cyclone separator and fed back to the bed. The boiler water tubes are located in the furnace.

Since most of the sulphur in coal is retained in the bed by the bed material used (limestone), the gases can be cooled to a lower temperature before leaving the stack with less formation of acid (H_2SO_4). As a result of low combustion temperatures (800−900°C), inferior grades of coal can be used without slagging problem and there is less formation of NO_x. Cheaper alloy materials can also be used, resulting in economy of construction.

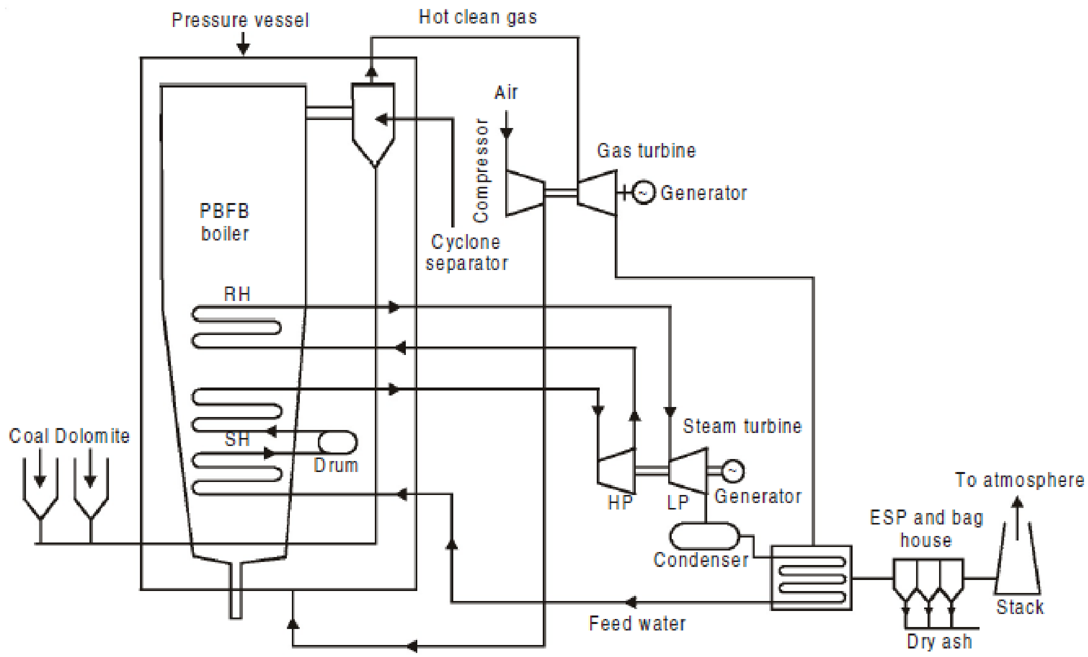
The volumetric heat release rates are 10 to 15 times higher and the surface heat transfer rates are 2 to 3 times higher than a conventional boiler. This makes the boiler more compact.

Advantages of BFBB

- The unit size and hence capital cost are reduced due to better heat transfer.
- It can respond rapidly to changes in load demand.
- Low combustion temperatures (800−950°C) restricts the formation of NOx pollutants.
- Fouling and corrosion of tubes is reduced considerably due to low combustion temperatures.
- Cost of coal to fine grind is reduced as it is not essential to grind the coal very fine.
- Low grade fuels and high-sulphur coal be used.
- Fossil and waste fuels can be used.
- Combustion temperature can be controlled accurately.

Pressurized Bubbling Fluidized Bed Combustion (PBFB or PFBC)

The pressurized bubbling fluidized bed (PBFB) technology utilizes a bubbling fluidized bed boiler operating at 1.2—1.6 MPa inside a pressure vessel in conjunction with a gas turbine combined cycle.



Combustion air is compressed in a twin-shaft, intercooled GT-driven-air-compressor and flows to the PBFB combustor. Coal is fed as coal-water paste to the combustors. A part of the combustion-heat is used to generate steam in the inbed heat transfer surface. The steam then flows to the steam turbine which generates approximately 80% of the plant power output.

Advantages of pressurized FBC system over atmospheric FBC system are given below:

- It allows increased coal loading per m^2 in the combustion chamber since the burning rate of fuel is higher.
- It required reduced air velocity.
- NOx, emissions are reduced.
- It has improved overall thermal efficiency of the plant.
- The overall size of the plant is considerably reduced, hence the overall cost of the plant.
- Better desulphurisation is accomplished.

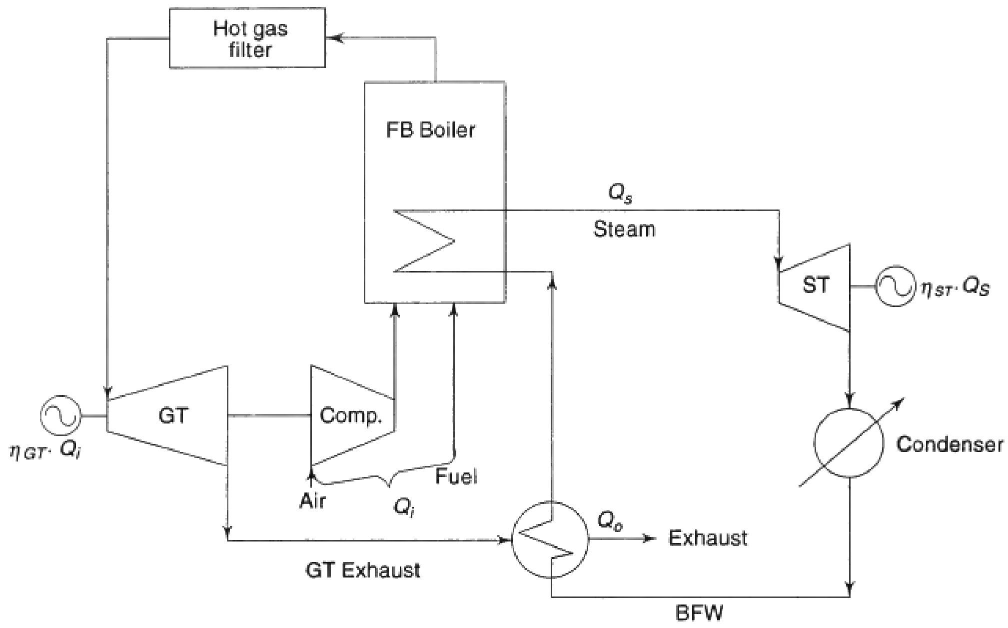
Example (Haryana BOE 2019, 10 marks)

Show that the combined cycle efficiency of PFBC is always greater than the equivalent steam cycle plant efficiency.

Solution

PFBC system operates with steam and gas turbines in tandem. Since some portion of the input energy is extracted by the GT at a higher temperature than that recovered by the ST, the overall efficiency |of the combined cycle is about 40-41% compared to about 38% for a basic steam cycle.

Consider the simplified diagram of supercharged PFBC system.



Overall energy balance yields

$$Q_i = Q_s + x.\eta_{GT} Q_i + Q_0 \quad (1)$$

Power generated by ST

$$p_{ST} = \eta_{ST} Q_s \tag{2}$$

Power generated by GT

$$p_{GT} = x\eta_{GT} Q_i \tag{3}$$

Efficiency of the combined cycle

$$\eta_{cc} = \frac{p_{ST} + p_{GT}}{Q_i} \tag{4}$$

Boiler efficiency

$$\eta_b = \frac{Q_i - Q_0}{Q_i} \tag{5}$$

Plant efficiency

$$\eta_p = \eta_b \eta_{ST} \tag{6}$$

where

Q_i = total thermal input, W

Q_0 = heat rejection to the atmosphere, W

Q_s = heat absorbed by steam, W

From equation (4)

$$\eta_{cc} = \frac{p_{ST}}{Q_i} + \frac{p_{GT}}{Q_i} = \eta_{ST}.\frac{Q_s}{Q_i} + \frac{x.\eta_{GT}.Q_i}{Q_i}$$

$$= \eta_{ST}.\frac{Q_i - x\eta_{GT}.Q_i - Q_o}{Q_i} + x.\eta_{GT}$$

$$= \eta_{ST}\left(1 - x\eta_{GT} - \frac{Q_o}{Q_i}\right) + x\eta_{GT}$$

$$= \eta_{ST}(\eta_b - x\eta_{GT}) + x.\eta_{GT}$$

$$= \eta_p + x.\eta_{GT}(1 - \eta_{ST})$$

Since x, η_{GT} and (1 - η_{ST}) are always positive, the combined cycle efficiency is always greater than the equivalent steam cycle plant efficiency, η_p.

$$= \eta_{ST} \frac{Q_i - x \cdot \eta_{GT} \cdot Q_i - Q_o}{Q_i} + x \cdot \eta_{GT} \quad \text{Eqn. 1}$$

$$= \eta_{ST} \left(1 - x \cdot \eta_{GT} - \frac{Q_o}{Q_i}\right) + x \cdot \eta_{GT}$$

$$= \eta_{ST} (\eta_b - x \cdot \eta_{GT}) + x \cdot \eta_{GT} \quad \text{Eqn. 5}$$

$$= \eta_p + x \cdot \eta_{GT} (1 - \eta_{ST}) \quad \text{Eqn. 6}$$

SUPER CRITICAL BOILERS

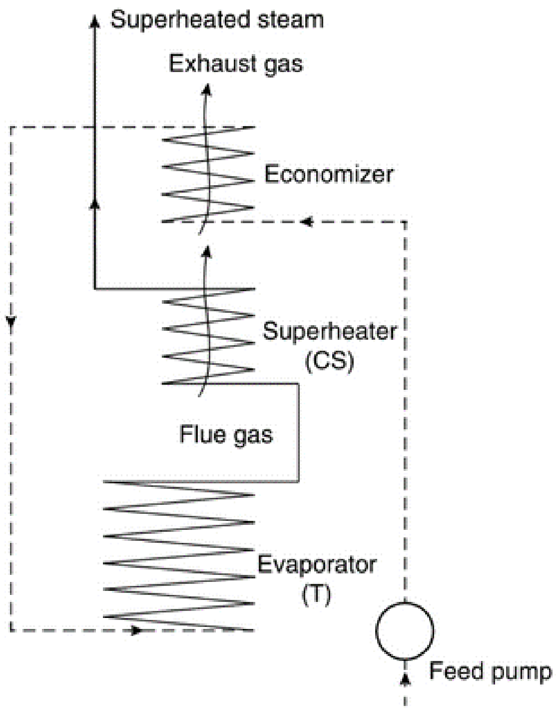
A large number of steam generating plants are designed between working ranges of 125 atm. and 510°C to 300 atm. and 660^{0}C ; these are basically characterised as *sub-critical* and *super-critical.*

Usually a sub-critical boiler consists of three distinct section as preheater (economiser), evaporator and superheater.

A super-critical boiler requires only preheater and superheater.

The constructional layout of both the above types of boilers is, however, practically identical.

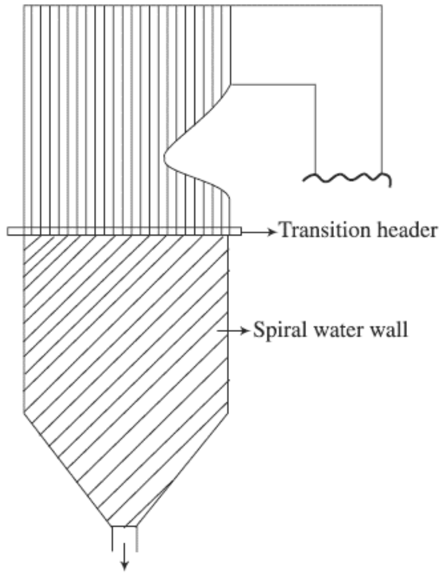
These days it has become a rule to use super-critical boilers above 300 MW capacity units.



Super critical boiler

The boiler consists of inclined evaporator coils (T) arranged in a spiral. Forty such coils are paralleled around the furnace. Steam generated in the evaporators flows into the headers and then to the convection superheater (CS). The superheated steam is utilized for power generation.

In a **conventional vertical wall design**, the riser or wall tubes in the central region are exposed to the highest heat flux, while the tubes in the corner region receive less heat. The steam temperature in the middle tubes are higher than those in the comer tubes. This *unequal temperature difference* can cause severe thermal stress on the tubes. To avoid this, **spiral membrane wall design** is adopted for supercritical boilers.



The temperature profiles of wall tubes of vertical type and the spiral type are shown in figure. In the spiral design, the lower portion of the furnace is arranged in a spiral configuration such that the steam circulates in tubes around the boiler as it travels up the furnace.

An **intermediate header** is used to make the furnace wall vertical at the upper region of the furnace. As the furnace wall tubes are at an angle, the spiral tubes are not self-supporting. The supporting load is transferred to the upper section vertical tubes.

The **economizer** is positioned at the lower uncooled casing section of the parallel pass **heat recovery area** (HRA).

Feedwater after economizer passes through **evaporator**, where entire water is converted into steam with small superheat.

Steam from the evaporation circuit passes through **in-line steam/water separator** to get final superheated steam.

Reheat steam obtained from HP turbine is first heated in **primary reheater** placed at HRA. The steam then passes thorough final reheater tubes to achieve the final reheat steam temperature.

The super-critical boilers claim the following advantages over subcritical type :

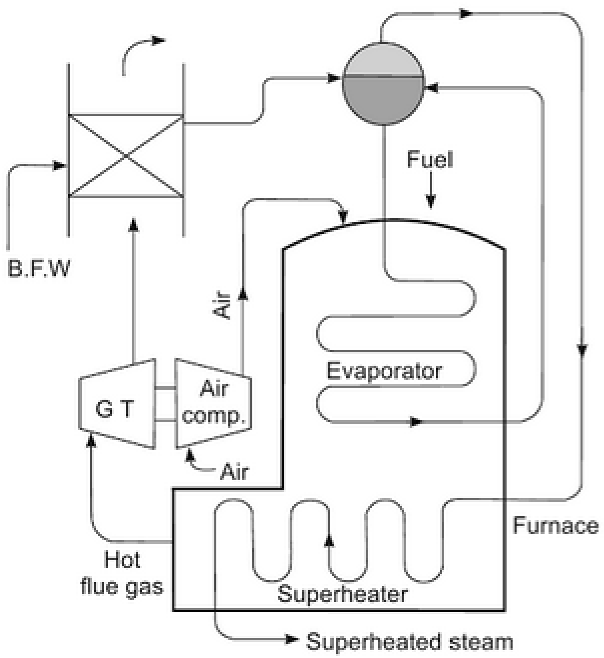
- Large heat transfer rates.
- Owing to less heat capacity of the generator the pressure level is more stable and therefore gives better response.
- Because of absence of two phase mixture the problems of erosion and corrosion are minimised.

- More adaptable to load fluctuations (because of great ease of operation, simplicity and flexibility).
- The turbo-generators connected to super-critical boilers can generate peak loads by changing the pressure of operation.
- Higher thermal efficiency.

Presently, 246 atm. and 538^{0}C are used for unit size above 500 MW capacity plants.

SUPERCHARGED BOILER

In a supercharged boiler, the combustion is carried out under pressure in the combustion chamber by supplying the *compressed* air. The exhaust gases from the combustion chamber are used to run the gas turbine as they are exhausted to high pressure. The gas turbine runs the air compressor to supply the compressed air to the combustion chamber.



Supercharged Boiler

Advantages:

- Owing to very high overall heat transfer co-efficient the heat transfer surface required is hardly 20 to 25% of the heat transfer surface of a conventional boiler.
- The part of the gas turbine output can be used to drive other auxiliaries.
- Small heat storage capacity of the boiler plant gives better response to control.
- Rapid start of the boiler is possible.
- Comparatively less number of operators are required.

QUESTIONS FROM BOE EXAMS

Write a short note on Circulating Fluidized Bed Combustion (CBB 2021, 5 marks).

Answer: Described in this module.

What are the advantages of water tube boiler over fire tube boiler? (CBB 2021)

Answer: Described in this module.

What are the comparative advantages and disadvantages of fire tube and water tube Boilers? (Maharashtra BOE 2023, 4 marks)

Answer: Described in this module.

Explain Fluidized bed combustion. What is the difference between AFBC & CFBC Boiler? (Maharashtra BOE 2025, 5 marks)

Answer: Described in this module.

Discuss operational problems of spent wash fired boiler in sugar industry. (Maharashtra BOE 2025, 5 marks)

Answer:

- **Solids Content & Concentration:** Spent wash requires high solids content (around 60%) for combustion, which is energy-intensive and can damage boiler components, notes a study on CABI Digital Library.
- **Sticky Nature:** Spent wash's sticky nature can lead to fouling in the boiler and ash handling systems, hindering efficiency and increasing maintenance needs, according to a study on CABI Digital Library.
- **Fouling & Corrosion:** High ash fusion temperatures, chlorides, calcium oxide, and sulphates can contribute to fouling and corrosion of boiler tubes, reducing heat transfer and potentially requiring premature replacement, according to a study by Boiler World Update.
- **Calorific Value:** The low calorific value of spent wash can affect boiler efficiency and necessitate adjustments to operating parameters, notes a study by Boiler World Update.
- **Flue Gas Corrosivity:** Flue gases from spent wash fired boilers are highly corrosive, potentially causing damage to boiler components and necessitating proper handling and control,

Why spiral wall design is adopted in super critical boiler? Why transition header is required in this case? (Maharashtra BOE 2025, 4 marks)

Answer: Described in this module.

Explain the difference between sub-critical and super-critical boilers. (Maharashtra BOE 2025, 5 marks)

Answer: Described in this module.

What are the methods to improve Efficiency of Bagasse fired Water Tube Boiler? (Maharashtra BOE 2025, 5 marks)

Answer: Improving the efficiency of a bagasse-fired water tube boiler involves optimizing combustion, heat transfer, and operational practices while minimizing losses. Below are key methods to enhance efficiency:

- **Maintain Proper Air-Fuel Ratio:** Use excess air control (typically 20-30% for bagasse) to ensure complete combustion without excessive heat loss. Install oxygen sensors for real-time monitoring.
- **Improve Bagasse Quality:** Ensure consistent moisture content (ideally 45-50%) by proper drying or storage. High moisture reduces calorific value and efficiency.
- **Install Economizers:** Recover heat from flue gases to preheat feedwater, improving efficiency by 3-5%.
- **Use Air Preheaters:** Heat combustion air with flue gas heat, increasing combustion efficiency.
- **Install Superheaters:** Increase steam temperature for higher energy output, improving cycle efficiency.
- **Control Flue Gas Temperature:** Keep flue gas exit temperature as low as possible (around 150-180°C) without causing corrosion, using heat recovery systems.
- **Integrate Co-Generation:** Use excess steam for power generation or process heating, maximizing overall plant efficiency.

Write short notes on Natural and Forced circulation of Boiler. (Maharashtra BOE 2023, 2 marks)

Answer: Described in this module.

What are the advantages and limitations of forced circulation over natural circulation. (Haryana BOE 2019, 2 marks)

Answer: Described in this module.

List down in details Major advantages of FBC Boiler System. (Gujarat BOE 2024, 5 marks)

Answer: Described in this module.

What is Clinker? Why clinker is formed during AFBC start up? (Gujarat BOE 2024, 5 marks)

Answer: Clinker is a solidified mass of fused ash.

When commercial size grades of coal or other inert-containing solid fuels are fired in FB combustors, there is a gradual accumulation of oversize inerts in the bed. Most of the coal-inerts tied to the ash are of relatively low density causing the ash particles to diffuse throughout the bed, thereby increasing the mean particle size. This has the effect of increasing the minimum fluidizing velocity and therefore, for a given operating velocity, less gas will pass through the bed as bubbles, reducing the intensity of turbulence.

If the accumulated mass of oversize inerts exceeds 20%, the reduced mixing rate will give rise to lateral temperature gradients, eventually leading to clinker formation around the fuel feed points. When this might occur, it is imperative to provide a bed-regrading system permitting periodic withdrawal of the bed material, separating the oversize by screening and returning the correct size to the bed.

What is revosteam (water tube coil type) boiler? Tell its three advantages. (Jharkhand BOE 2024, 6 marks)

Answer: Described in this module.

Describe various types of high-pressure boilers used in practice. (Assam BOE 2022, 5 marks)

Answer: Described in this module.

Make a neat sketch of Benson boiler with showing its main parts. What are its main five advantages? (Gujarat BOE 2024, Assam BOE 2022, 5 marks)

Answer: Described in this module.

Explain the unique features of high pressure boilers. (Kerala BOE 2023, 5 marks)

Answer: Advantages are described in this module.

Enumerate the factors that should be considered while selecting a boiler. Explain the unique features of high pressure boilers. (Kerala BOE 2023, 5 marks)

Answer: Described in this module.

Modem high-pressure naval steam boilers are designed with all tubes bent to an arc of a circle. What are the advantages of this design? (Haryana BOE 2019, 2 marks)

Answer:

- Bent tubes allowed for better heat transfer
- Much refractory was eliminated
- The tubes could form flue gas baffles

Difference between the following in brief: Steam boiler and Steam generator (Jharkhand BOE 2021, 1.5 marks)

Answer: A steam boiler consists of the *containing vessel and convection heating surfaces* only, whereas a *steam generator covers the whole unit*, encompassing water wall tubes, superheaters, air heaters and economizers.

What is PFBC in the context of steam generator? (Haryana BOE 2019, 1 mark)

Answer: Described in this module.

What are the common failure modes in the flue-gas-heated waste-heat boiler. (Haryana BOE 2019, 2 marks)

Answer: HEX tubes are a crucial component of any waste heat boiler, but they are often exposed to demanding operation settings, including high temperature, high pressure, corrosive flue gas, alkaline fly ash and so on. Accordingly, HEX tubes of a waste heat boiler frequently encounter severe failures; the typical failure causes found in WHBs being categorised into the following classes:

- defects of the material
- high-temperature corrosion
- stress corrosion cracking and
- dew point corrosion

What factors are responsible for the lower projected cost of PCFB as against PBFB? (Haryana BOE 2019, 2 marks)

Answer: PCFB (Pressurized Circulating Fluidized Bed) boilers are generally considered cheaper than PBFB (Pressurized Bubbling Fluidized Bed) boilers due to a combination of factors including simpler design, lower material handling complexity, and potentially higher exit gas temperatures.

Show that the combined cycle efficiency of PFBC is always greater than the equivalent steam cycle plant efficiency. (Haryana BOE 2019, 10 marks)

Answer: Explained in this module.

Draw a neat diagram of straight-tube water tube boilers have straight, inclined tubes to aid in water circulation. (Assam BOE 2023)

Answer: Described in this module.

What are the benefits a CFBC boiler offers? (Assam BOE 2022, 2 marks)

Answer: Described in this module.

Explain briefly the methods used to control SOx and NOx in FBC boilers. (Assam BOE 2022, 5 marks)

Answer: If a fuel contains more sulphur content, a limestone particle bed is used to control SOX and NOX formation.

What is the difference between vibrating grate stoker and retort stoker? (Assam BOE 2023, 3 marks)

Answer: Described in this module.