CHAPTER FOUR:

Steam Boiler

4.1 Boiler Design and Construction

Boiler: A boiler is a closed vessel in which water is heated, steam is generated, superheated or any combination thereof under pressure or vacuum by the direct application of heat from combustible fuels or electricity. The steam produced is used for: [function of boiler]

(*i*) Producing mechanical work by expanding it in steam engine or steam turbine.
(*ii*) Heating the residential and industrial buildings
(*iii*) Performing certain processes in the sugar mills, chemical and textile industries.

Usually boilers are coal or oil fired. A boiler should fulfill the following requirements

(*i*) **Safety.** The boiler should be safe under operating conditions.
(*ii*) **Accessibility.** The various parts of the boiler should be accessible for repair and maintenance.
(*iii*) **Capacity.** The boiler should be capable of supplying steam according to the requirements.
(*iv*) **Efficiency.** To permit efficient operation, the boiler should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.
(*v*) It should be simple in construction and its maintenance cost should be low.
(*vi*) Its initial cost should be low.
(*vii*) The boiler should have no joints exposed to flames.
(*viii*) The boiler should be capable of quick starting and loading.

The performance of a boiler may be measured in terms of its evaporative capacity also called power of a boiler. It is defined as the amount of water evaporated or steam produced in kg per hour. It may also be expressed in kg per kg of fuel burnt or kg/hr/m2 of heating surface.

4.1.1 Boiler Classifications

Boilers are classified by their pressure capacity, their design type and by their use.

High & Low Pressure Boilers –

The **M.A.W.P** or Maximum Allowable Working Pressure is the highest amount of pressure that the vessel is designed to withstand. Pressure is measured in terms of pounds per square inch or **psi**. **Psig** (gauge) indicates gauge pressure, which ignores the atmospheric pressure. **Psia** (absolute) is the sum of gauge pressure plus the atmospheric pressure at that location, which varies based on altitude. A **compound gauge** measures indicates pressure and vacuum.

• **Low-pressure boilers** are designed to withstand a maximum of 15 psig steam or a M.A.W.P. 160 psig water.

The boilers can be classified according to the following criteria.

According to flow of water and hot gases.
1. Water tube.
2. Fire tube.

In water tube boilers, water circulates through the tubes and hot products of combustion flow over these tubes. In fire tube boiler the hot products of combustion pass through the tubes, which are surrounded, by water. Fire tube boilers have low initial cost, and are more compacts. But they are more likely to explosion, water volume is large and due to poor circulation they cannot meet quickly the change in steam demand. For the same output the outer shell of fire tube boilers is much larger than the shell of water-tube boiler. Water tube boilers require less weight of metal for a given size, are less liable to explosion, produce higher pressure, are accessible and can response quickly to change in steam demand. Tubes and drums of water-tube boilers are smaller than that of fire-tube boilers and due to smaller size of drum higher pressure can be used easily. Water-tube boilers require lesser floor space. The efficiency of water-tube boilers is more.

According to position of furnace.
(*i*) Internally fired (*ii*) Externally fired

In internally fired boilers the grate combustion chamber are enclosed within the boiler shell. Whereas in case of extremely fired boilers and furnace and grate are separated from the boiler shell.

According to the position of principle axis.
(*i*) Vertical (*ii*) Horizontal (*iii*) Inclined.

According to application.
(*i*) Stationary, (*ii*) Mobile, (Marine, Locomotive).

According to the circulating water.
(*i*) Natural circulation (*ii*) Forced circulation.

According to steam pressure.
(*i*) Low pressure (*ii*) Medium pressure (*iii*) Higher pressure

Water tube boilers are classified as follows.
1. Horizontal straight tube boilers
(*a*) Longitudinal drum (*b*) Cross-drum.
2. Bent tube boilers
(*a*) Two drum (*b*) Three drum
(*c*) Low head three drum (*d*) four drum.
3. Cyclone fired boilers

Various advantages of water tube boilers are as follows.
(*i*) High pressure of the order of 140 kg/cm2 can be obtained.
(*ii*) Heating surface is large. Therefore steam can be generated easily.
(*iii*) Large heating surface can be obtained by use of large number of tubes.
(*iv*) Because of high movement of water in the tubes the rate of heat transfer becomes large resulting into a greater efficiency.

Fire tube boilers are classified as follows.
1. External furnace:
(*i*) Horizontal return tubular
(*ii*) Short fire box
(*iii*) Compact.
2. Internal furnace:
(*i*) Horizontal tubular

(*a*) Short fire box (*b*) Locomotive (*c*) Compact (*d*) Scotch.
(*ii*) Vertical tubular.
(*a*) Straight vertical shell, vertical tube
(*b*) Cochran (vertical shell) horizontal tube.
Various advantages of fire tube boilers are as follows.
(*i*) Low cost
(*ii*) Fluctuations of steam demand can be met easily
(*iii*) It is compact in size.

4.1.2 Fire-Tube Boiler

This boiler consists of a cylindrical shell with its crown having a spherical shape. The furnace is also hemispherical in shape. The grate is also placed at the bottom of the furnace and the ash-pit is located below the grate. The coal is fed into the grate through the fire door and ash formed is collected in the ash-pit located just below the grate and it is removed manually. The furnace and the combustion chamber are connected through a pipe. The back of the combustion chamber is lined with firebricks. The hot gases from the combustion chamber flow through the nest of horizontal fire tubes (generally 6.25 cm in external diameter and 165 to 170 in number). The passing through the fire tubes transfers a large portion of the heat to the water by convection. The flue gases coming out of fire tubes are finally discharged to the atmosphere through chimney (Fig.1&2). The spherical top and spherical shape of firebox are the special features of this boiler. These shapes require least material for the volume. The hemi spherical crown of the boiler shell gives maximum strength to withstand the pressure of the steam inside the boiler. The hemi-spherical crown of the fire box is advantageous for resisting intense heat. This shape is also advantageous for the absorption of the radiant heat from the furnace.
Coal or oil can be used as fuel in this boiler. If oil is used as fuel, no grate is provided but the bottom of the furnace is lined with firebricks. Oil burners are fitted at a suitable location below the fire door. A manhole near the top of the crown of shell is provided for cleaning. In addition to this, a number of hand-holes are provided around the outer shell for cleaning purposes. The smoke box is provided with doors for cleaning of the interior of the fire tubes.
The airflow through the grate is caused by means of the draught produced by the chimney. A damper is placed inside the chimney (not shown) to control the discharge of hot gases from the chimney and thereby the supply of air to the grate is controlled. The chimney may also be provided with a steam nozzle (not shown; to discharge the flue gases faster through the chimney. The steam to the nozzle is supplied from the boiler. The outstanding features of this boiler are listed below:
1. It is very compact and requires minimum floor area.
2. Any type of fuel can be used with this boiler.
3. It is well suited for small capacity requirements.
4. It gives about 70% thermal efficiency with coal firing and about 75% with oil firing.
5. The ratio of grate area to the heating surface area varies from 10: 1 to 25: 1.

It is provided with all required mountings. The function of each is briefly described below:
1. Pressure Gauge. This indicates the pressure of the steam in the boiler.

2. Water Level Indicator. This indicates the water level in the boiler, the water level in the boiler should not fall below a particular level otherwise the boiler will be overheated and the tubes may burn out.

3. Safety Valve. The function of the safety valve is to prevent the increase of steam pressure in the holler above its design pressure. When the pressure increases above design pressure, the valve opens and discharges the steam to the atmosphere. When this pressure falls just below design pressure, the valve closes automatically. Usually the valve is spring controlled.

4. Fusible Plug. If the water level in the boiler falls below a predetermined level, the boiler shell and tubes will be overheated. And if it is continued, the tubes may burn, as the water cover will be removed. It can he prevented by stopping the burning of fuel on the grate. When the temperature of the shell increases above a particular level, the fusible plug, which is mounted over the grate as shown in the Fig. 1, melts and forms an opening. The high-pressure steam pushes the remaining water through this hole on the grate and the fire is *extinguished.*

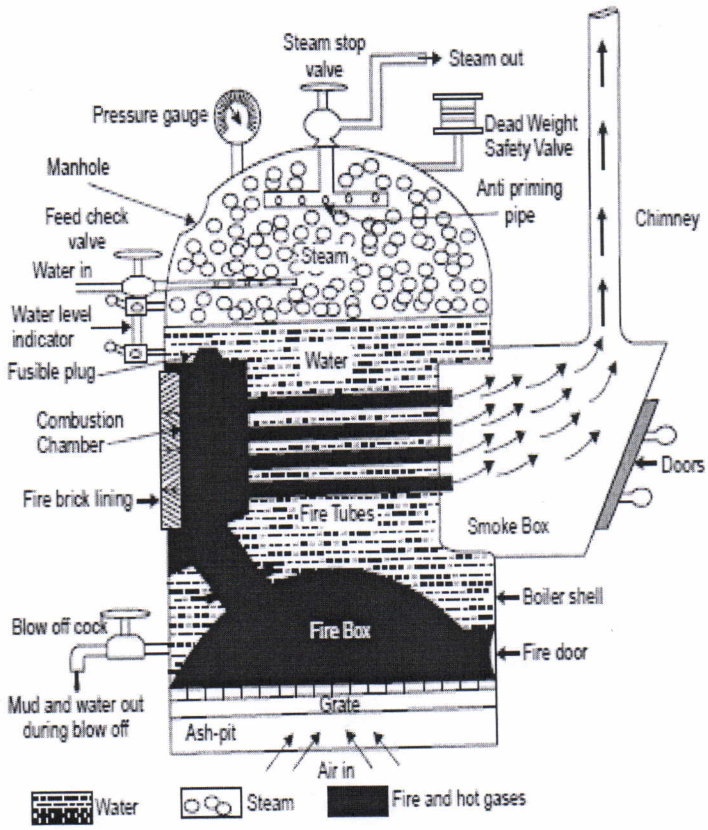

Fig. (1) Fire-tube boiler with accessories

5. Blow-off Cock. The water supplied to the boiler always contains impurities like mud, sand and, salt Due to heating, these are deposited at the bottom of the boiler, and if they are not removed, they are accumulated at the bottom of the boiler and reduce its capacity and heat transfer rates. Also the salt content will goes on increasing due to evaporation of water. These deposited salts are removed with the help of blow off cock. The blow-off cock is located at the bottom of the boiler as shown in the figure and is operated only when the boiler is running. When the blow-off cock is opened during the running of the boiler, the high-pressure steam pushes the water and the collected material at the bottom is blown out. Blowing some water out also reduces the concentration of the salt. The blow-off cock is operated after every 5 to 6 hours of working for few minutes. This keeps the boiler clean.

6. Steam Stop Valve. It regulates the flow of steam supply outside. The steam from the boiler first enters into an ant-priming pipe where most of the water particles associated with steam is removed.

7. Feed Check Valve. The high pressure feed water is supplied to the boiler through this valve.

This valve opens towards the boiler only and feeds the water to the boiler. If the feed water pressure is less than the boiler steam pressure then this valve remains closed and prevents the back flow of steam through the valve.

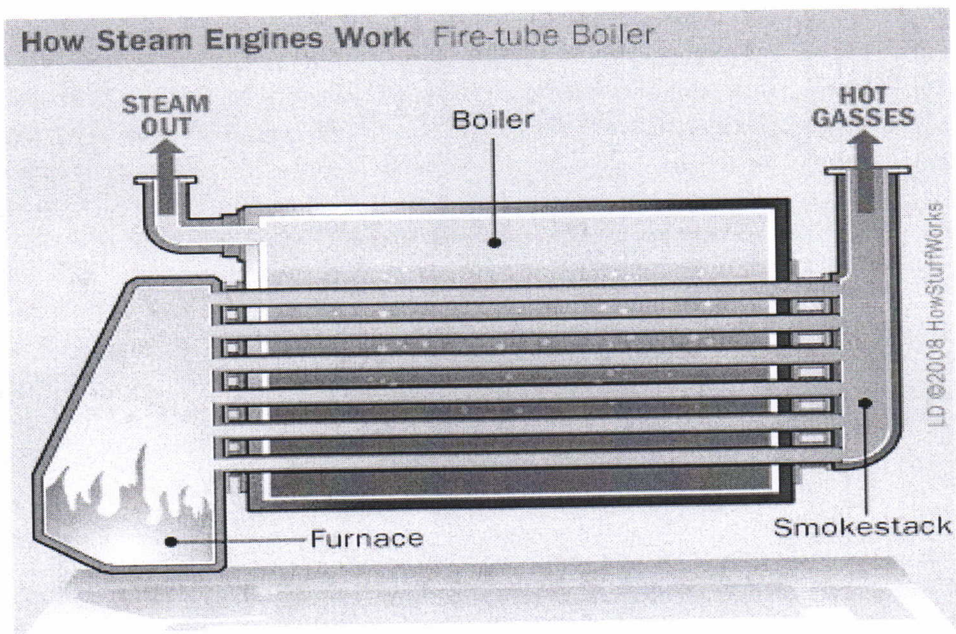

Fig. (2) Shape of fire-tube

4.1.3 Water-tube boilers

• **Water-tube boilers** have water running through the tubes and fire or gases of combustion surrounding the tubes. The water tubes are connected into a steam drum at the top and a mud drum at the bottom. The fire is in the **Combustion chamber**. The boiler design can also be identified by the shape of the tube configuration, with the common types being called A, O, and D style boilers. The **cast iron sectional boiler** is neither fire tube nor water tube though it has some operating characteristics of a water tube boiler. The water is inside the sections and the fire is outside the sections. Cast iron sectionals used for steam heating may have distinct operating problems that are not typically found in other boiler types, such as the intolerance for poor water chemistry.

• A boiler may be classified as either a **steam boiler** or **hot water boiler**. The vessels are the same and the **boiler trim** (controls & piping) determine the use of the vessel. A steam boiler must maintain a water level covering the top of the heating (tube) surfaces while leaving room for steam production. A hot water boiler is completely full of water over the top of the boiler into the expansion tank.

INDUSTRIAL Water Tube BOILERS

The boilers are generally required in power station, chemical industries, paper industries, pharmaceutical industries and many others. Efficiency, reliability and cost are major factors in the design of industrial boilers similar to central stations. Boiler's capacity varies from 100 to 400 tons of steam per hour. Industrial companies in foreign countries with large steam demands have considerable interest in cogeneration, the simultaneous production of steam and electricity because of federal legislation. High temperature and high pressure boilers 550°C and up to critical pressure) are now-a-days used even though high pressure and temperature are rarely, needed to. Process requirement but they are used to generate electricity to surging prices of the oil, most of the industrial boilers are designed to use wood, municipal - pulverized coal, industrial solid waste and refinery gas few industrial boilers which are in common use are discussed below.

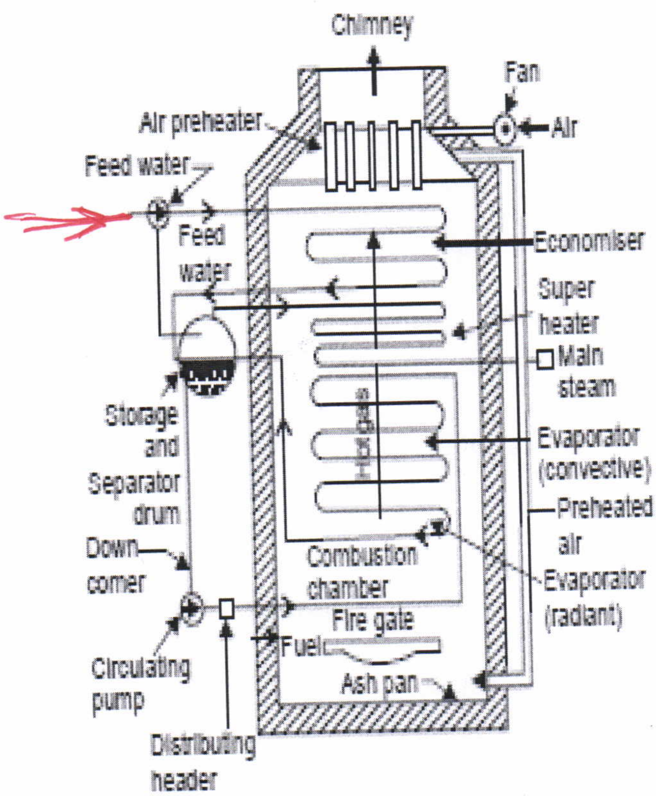

Fig.3 simple water-tube boiler layout

MERITS AND DEMERITS OF WATER TUBE BOILERS OVER FIRE TUBE BOILERS MERITS

1. Generation of steam is much quicker due to small ratio of water content to steam content. This also helps in reaching the steaming temperature in short time.
2. Its evaporative capacity is considerably larger and the steam pressure range is also high-200 bar.
3. Heating surfaces are more effective as the hot gases travel at right angles to the direction of water flow.
4. The combustion efficiency is higher because complete combustion of fuel is possible as the combustion space is much larger.
5. The thermal stresses in the boiler parts are less as different parts of the boiler remain at uniform temperature due to quick circulation of water.
6. The boiler can be easily transported and erected as its different parts can be separated.
7. Damage due to the bursting of water tube is less serious. Therefore, water tube boilers are sometimes called safety boilers.
8. All parts of the water tube boilers are easily accessible for cleaning, inspecting and repairing.
9. The water tube boiler's furnace area can be easily altered to meet the fuel requirements

Demerits:

1. It is less suitable for impure and sedimentary water, as a small deposit of scale may cause the overheating and bursting of tube. Therefore, use of pure feed water is essential.
2. They require careful attention. The maintenance costs are higher.
3. Failure in feed water supply even for short period is liable to make the boiler over-heated.

Boiler Lay-up

Any extended period of time (summer) during which a boiler(s) is idle and is not expected to operate. Lockout/Tag out boiler(s) and shut-off gas supply.

A non-operational steam boiler should be filled to the top with chemically treated feed water or condensate to minimize corrosion during lay-up. Inactive heating systems, along with boilers, in vacated buildings, should be drained due to danger of freezing.

Boiler Pass. The path of travel of the combustion gases through the full length of boiler including the initial pass in the primary combustion zone. A boiler may have as many as four passes.

Boiler Programmer. A boiler programmer is the mastermind that controls the firing cycle of a boiler. It performs two functions. (1) Senses the presence of a flame during pilot and main flame and (2) programs the operation of a burner system so that motors, blowers, ignition and fuel valves are energized only when they are needed, and then in proper sequence. **Note:** Not all boilers have programmers.

Boiler System: A system comprised of the boiler(s), its controls, safety devices, interconnecting piping, vessels, valves, fittings and pumps.

Breeching. A duct for the transport of the products of combustion between the boilers and the stack.
Forced-Draft Fan. A fan, in boilers with power burners that supplies air for combustion of fuel as well as draft.
Furnace. An enclosed space provided for the combustion of fuel.
Gage Glass. The transparent part of a water gage assembly connected directly or through a water column to the boiler, below and above the waterline, to indicate the water level in a steam boiler.
Induced-Draft Fan. A fan, generally mounted on horizontal breeching, which pulls the flue gases out of some boilers, with atmospheric burners, into the stack.
Limit Control. A device, with a manual reset, which shuts down the burner when operating limits are surpassed.
Low Water Fuel Cut-Off. (LWC) A device, most often float-operated, which shuts down the fuel burner when the water level in the boiler drops below its operating level. Two low water fuel cutoffs are required on steam boilers. The primary LWC has a combination condensate feed pump control and an auxiliary control that automatically cuts off the fuel supply if the proper water level is not being maintained. The secondary LWC is set one inch lower than the primary and it causes a safety shutdown, requiring manual reset. **Note:** Even though most hot water heating boilers have a LWC, by code one is required only on boilers with capacities of 400,000 Btu/hr or greater.
Makeup Water. Water introduced into the boiler, from outside the boiler system, to replace that lost (leaks) or removed from the system.
Manhole. The opening in a pressure vessel of sufficient size to permit a man to enter.
Operating Control. A device which automatically controls the operation of a fuel burner to maintain the desired temperature or pressure.
pH. A logarithmic scale used to measure the degree of acidity or alkalinity of a solution. The scale runs from 1 (strong acid) to 14 (strong alkali) with 7 (distilled water) as the neutral point.
Power Burners. Power burners are designated to operate with a furnace pressure higher than atmospheric and are equipped with sufficient blower capacity to force products of combustion through the boiler without the help of natural or induced draft.
Pigtail Loop. Each pressure control device on steam boilers should have a pigtail loop, which acts as a steam trap, installed between the controller, and the boiler. This prevents the controller's diaphragm or bellows from seeing any steam, thus preventing damage to it.
Safety Relief Valve. An automatic pressure-relieving device required by code to be used on hot water heating boilers that is actuated by the pressure generated within the boiler. Valves of this type are spring loaded without full-opening action and have a factory set nonadjustable pressure setting. A safety relief valve set pressure must be equal to or less than boiler Maximum Allowable Working Pressure (MAWP) and its relieving capacity must be equal to or greater than boiler output.
Shell. The cylindrical portion of a pressure vessel.
Tube sheet. The end plates with holes, in some boilers, that connects the ends of fire tubes.
Water tube. A tube(s), in a boiler, having the water and steam on the inside and heat applied to the outside.
Water Softener. Equipment used to remove the hardness from boiler feed water. A sodium zeolite water softener uses an ion exchange process to remove calcium and

magnesium ions from water and replaces them with sodium. A brine solution and resin beads are part of the system which most water softeners use.

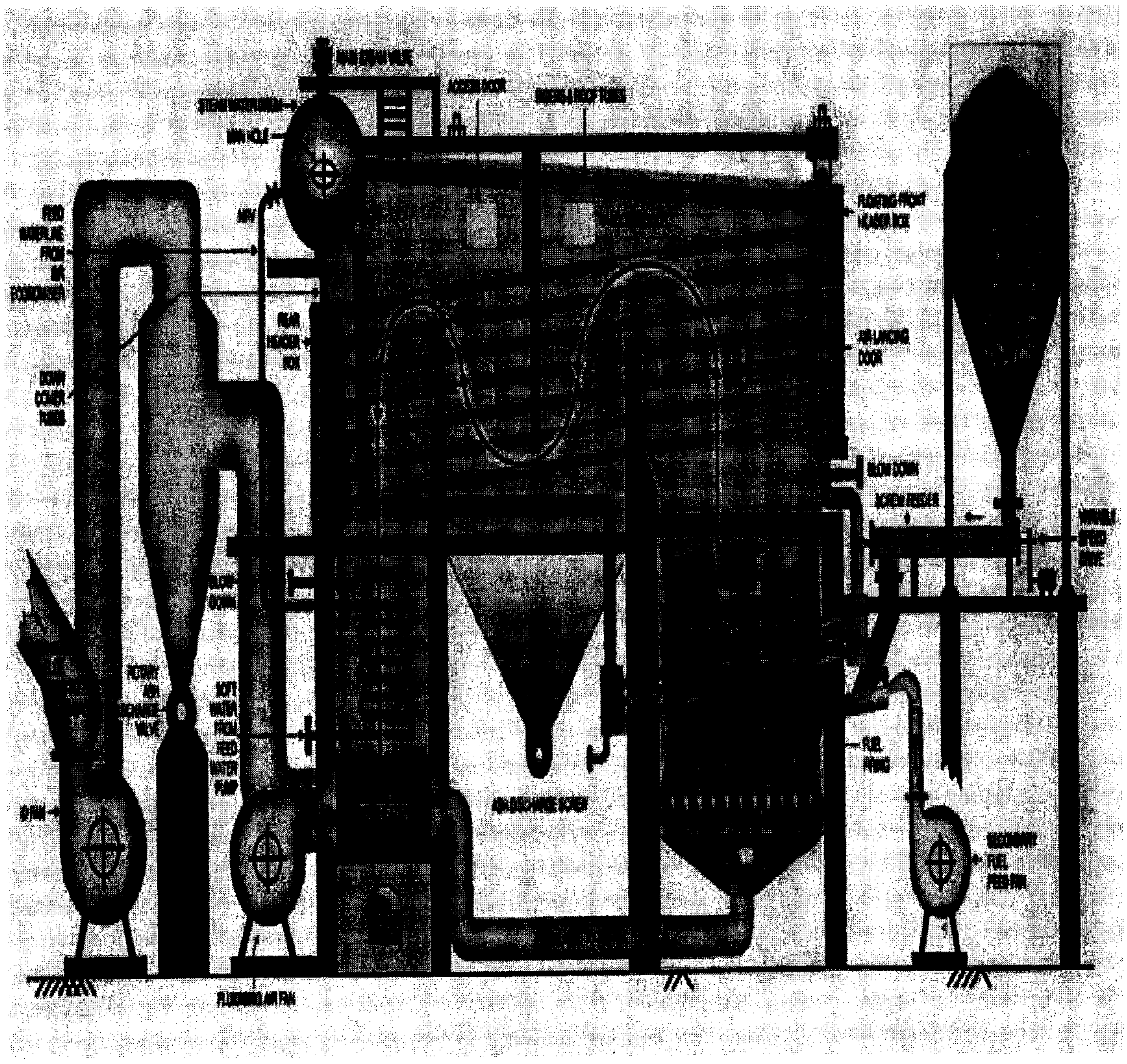

Fig.(4) HP Steam Boiler

4.2 REQUIREMENTS OF A GOOD BOILER

A good boiler must possess the following qualities:

1. The boiler should be capable to generate steam at the required pressure and quantity as quickly as possible with minimum fuel consumption.
2. The initial cost, installation cost and the maintenance cost should be as low as possible.
3. The boiler should be light in weight, and should occupy small floor area.

4. The boiler must be able to meet the fluctuating demands without pressure fluctuations.
5. All the parts of the boiler should be easily approachable for cleaning and inspection.
6. The boiler should have a minimum of joints to avoid leaks which may occur due to expansion and contraction.
7. The boiler should be erected at site within a reasonable time and with minimum labor.
8. The water and flue gas velocities should be high for high heat transfer rates with minimum pressure drop through the system.
9. There should be no deposition of mud and foreign materials on the inside surface and soot deposition on the outer surface of the heat transferring parts.
10. The boiler should conform to the safety regulations as laid down in the *Boiler Act.*

4.2.1 HIGH PRESSURE BOILERS

In all modern power plants, high pressure boilers (> 100 bar) are universally used as they offer the following advantages. In order to obtain efficient operation and high capacity, forced circulation of water through boiler tubes is found helpful.
I. 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.
2. The forced circulation of water through boiler tubes provides freedom in the arrangement of furnace and water walls, in addition to the reduction in the heat exchange area.
3. The tendency of scale formation is reduced due to high velocity of water.
4. The danger of overheating is reduced as all the parts are uniformly heated.
5. The differential expansion is reduced due to uniform temperature and this reduces the possibility of gas and air leakages.

4-3

Boiler Calculations

a) Heat transfer required to form steam

$$Q_B = \dot{m}_s (h_2 - h_1) \text{ KJ},$$

h_2: specific enthalpy of steam formed
h_1: sp. enthalpy of liquid of feed water

b) Energy required from fuel

$$= \dot{m}_f * C.V \quad \text{KJ}$$

$\dot{m}_f$: mass of fuel used (kg)
C.V: Calorific value of fuel KJ/kg

c) Boiler thermal efficiency

$$\eta_{th} = \frac{\text{Energy to steam}}{\text{Energy from fuel}}$$

$$\eta_B = \frac{\dot{m}_s (h_2 - h_1)}{\dot{m}_f * C.V} \times 100\%$$

d) Equivalent evaporation of boiler

- The specific enthalpy of evaporation of water to vapour from and at 100°C is (2256.9) KJ/kg

∴ The equivalent evaporation of a boiler from and at 100°C $= \dfrac{m_s (h_2 - h_1)}{2256.9}$ (kg)

Ex: 4.1 : A boiler generates 5000 kg of steam/h at 1.8 MPa. The steam temp. is 325°C and the feed water temp. is 49°C. The efficiency of the boiler plant is 80% when using oil of C.V of 45500 KJ/kg. The steam generated is supplied to a turbine which develops 500 KW and exhaust at 0.18 MN/m², the dryness fraction of the steam being 0.98. Estimate the mass of oil used per hour and the fraction of the enthalpy drop through the turbine which is converted into useful work.

If the turbine exhaust is used for process steam heating find the heat transfer available per kg of exhaust steam above 49.4°C.

Solution:

sp. enthalpy of steam generated $h_2 = 3087.6 \frac{KJ}{Kg}$ at 1.8 MPa, 325°C

" " of feed water at 49.4°c $(h_1) = 206.9$ KJ/kg.

energy to form steam $(Q_B) = \dot{m}_s(h_2 - h_1)$

$= 5000(3087.6 - 206.9)$, and this is 80% of the energy from fuel.

$\therefore$ the energy from fuel/h $= \dfrac{5000 \times 2880.7}{0.8}$

$\therefore \eta_B = \dfrac{m_s \times \Delta h}{\dot{m}_f \times C.V}$ $\therefore \dot{m}_f = \dfrac{5000 \times 2880.7}{0.8 \times 45500}$

$\therefore \dot{m}_f = 395$ Kg/hr

Specific heat for exhaust steam $= h_f + x h_{fg}$

$$= 490.7 + 0.98 * 2210.8 = 2655.7 \text{ KJ/kg}$$

$\therefore$ Specific enthalpy drop in turbine $= 3087.6 - 2655.7$

$$= 431.9 \text{ KJ/kg}$$

Enthalpy drop in turbine $= \dot{m}_s \times \Delta h = \frac{5000}{3600} * 431.9$ KJ/s

Energy out-put from turbine $= 500 \text{ kW} = 500$ KJ/S

$\therefore$ fraction of enthalpy drop converted into useful work

$$= \frac{500}{\frac{5000}{3600} \times 431.9} = 0.834$$

The heat transfer available in exhaust steam above $49.4°$

$$= 2655.7 - 206.9 = 2448.8 \text{ KJ/kg.}$$

Ex: 4.2: A boiler plant supplies 5400 kg of steam/h at 750 kN/m² and 0.98 dry from feed water at 41.5 °C, when using 670 kg of coal/h having a C.V of 31000 KJ/kg.

Determine;

a) i) the efficiency of the boiler
ii) the equivalent of evaporation from and 100 °C

b) find the saving in coal/h if by fitting an economizer it is estimated that the feed water could be raised to 100 °C assuming i) other conditions unaltered
ii) the efficiency of the boiler increase by 5%.

Solution

Steam raised / kg of coal $= \frac{5400}{670} = 8.06 \doteq \frac{\dot{m}_s}{\dot{m}_f}$

Specific enthalpy of steam raised,

$h_2 = h_f + x_2 h_{fg} = 709.3 + 0.98 \times 2085.3 = 2719.3 \text{ kJ/kg}$

Specific enthalpy of water $= 173.9$ kJ/kg

i) $\eta_B = \frac{\dot{m}_s}{\dot{m}_f} \frac{(h_2 - h_1)}{C.V} = 8.06 \frac{(2719.3 - 173.9)}{31000} \times 100\% = \cancel{66\%}$ 66.3%

ii) Equivalent evaporation from and at 100°C

$= \frac{8.06 \times 2545.4}{2256.9} = 9.12$ kg / kg of coal.

b) sp. enthalpy of water at 100°C $= 419.1$ kJ/kg

Energy to steam under new conditions,

$= 2719.3 - 419.1 = 2300.2$ kJ/kg

energy to steam / h $= 2300.2 \times 5400$

$\therefore$ i) $\eta_B = \frac{\dot{m}_s}{\dot{m}_f} \cdot \frac{\Delta h}{C.V}$; $0.663 = \frac{5400 \times 2300.2}{\dot{m}_f \times 31000}$

$\Rightarrow \therefore \dot{m}_f = 605$ kg/hr

$\therefore$ Saving $= 670 - 605 = 65$ kg/hr

ii) with new boiler efficiency $= 66.2 + 5 = 71.2\%$

$\therefore \eta_B = 0.712 = \frac{5400 \times 2300.2}{\dot{m}_f \times 31000}$

$\Rightarrow \dot{m}_f = 562$ kg/h

$\therefore$ Saving in coal / hr $= 670 - 562 = 108$ kg