12
Draught System

12.1. INTRODUCTION

The draught is one of the most essential systems of thermal power plant. The purpose of draught is to supply required quantity of air for combustion and remove the burnt products from the system. To move the air through the fuel bed and to produce a flow of hot gases through the boiler, economizer, preheater and chimney require a difference of pressure equal to that necessary to accelerate the burnt gases to their final velocity and to overcome the pressure losses equivalent to pressure head. This difference of pressure required to maintain the constant flow of air and to discharge the gases through the chimney to atmosphere is known as draught.

Draught can be obtained by use of chimney, fan, steam or air jet or combination of these. When the draught is produced with the help of chimney only, it is known as *Natural Draught* and when the draught is produced by any other means except chimney it is known as artificial draught.

12.2. LOSSES IN THE AIR-GAS LOOP SYSTEM AND ITS MEASUREMENT

The total draught required to produce the current of air and to discharge the hot gases to the atmosphere is the arithmetic sum of all draught losses in the series circuit.

The total draught losses in the air and gas loop system are given by

$$h_t = h_v + h_b + h_e + h_d.$$

where h_t = Total draught loss in cm of water

h_v = Velocity head in cm. of water head (velocity of gas exits from chimney)

h_b = Fuel bed resistance equivalent to cm of water head.

h_e = Head loss in the equipments.

h_d = Head loss in ducts and chimney.

The details of each loss are given below :

1. Fuel Bed Resistance (h_b). The fuel bed resistance depends on fuel size, bed thickness and combustion rate. The effect of combustion rate on resistance for different types of stokers is shown in Fig. 12.1. The resistance of the spreader stoker is not shown in figure because much of the coal is burned in suspension. The draught resistance of spreader stoker may be taken as 6 cm of water head.

2. Head Loss in Equipments (h_e). The manufacturers generally supply data for equipment resistance like air heater, economiser, boiler passes, superheaters, etc.

A survey of test data indicates that the draught losses follow a parabolic law. The data given by the

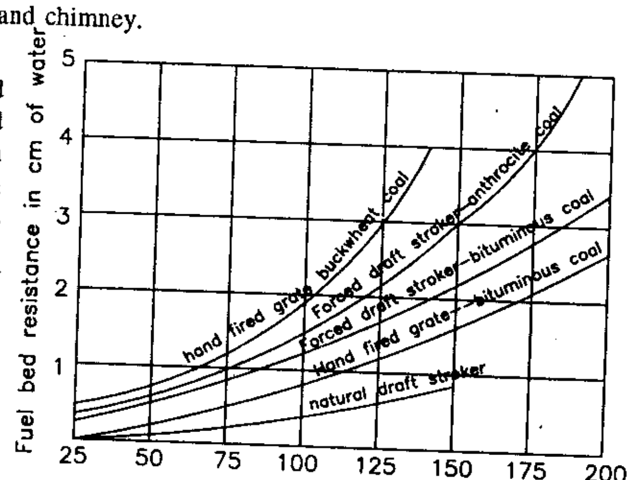


Fig. 12.1. Draft loss through fuel bed.

manufacturers is customarily guaranteed at one rating of the complete unit, therefore the loss at another rating can be calculated by using the following equation :

$$h_{e2} = h_{e1}\left(\frac{m_{s2}}{m_{s1}}\right)^{1.8 \text{ to } 2.0}$$

where h_e is the draught loss at the steam generating rate of m_s.

The draught losses through the boiler setting are accountable for the gases sweeping over the steam generating tubes, superheater elements and several reversals that must be made at the end of each pass. The draught loss varies as the square of velocity of gas flow or square of the ratio of boiler rating.

3. Velocity Head Loss (h_v). The velocity head loss is always equal to $V^2/2g$ where V is the velocity at the exit of the chimney. The draught system is designed to give minimum $V^2/2g$ loss but it must be sufficient to diffuse and mix with the surrounding atmospheric air. Its value also depends upon the natural air velocity at chimney height. Higher velocity head is required if the natural air velocity is higher. No general data can be given for such loss. It is decided as per the site of the power plant, air temperature and natural air flow condition. To know the velocity head, a velocity versus, velocity head in cm of water is shown in Fig. 12.2.

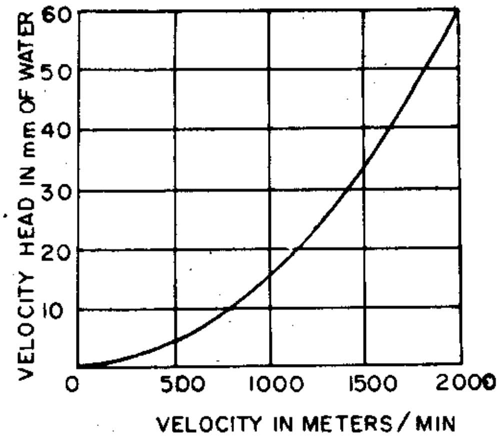


Fig. 12.2. Velocity head in mm of water versus velocity in metres per minute at atmospheric conditions.

4. Head Loss in Ducts and Chimney (h_d). The draught loss due to friction in air and gas ducts and chimney is given by Fanning equation as

$$h_d = f.\frac{L}{4R_h}\left(\frac{V^2}{2g}\right) \text{ in metres of fluid flowing}$$

where R_h is hydraulic radius (cross-sectional area/wetted perimeter) and 'f' is the friction factor of the duct through which air or gas flows. The value of f depends upon the smoothness of the duct and Reynold number of the fluid flowing. The values of 'f' may be taken as 0.005 for steel and 0.007 for masonry and concrete when air is flowing and 0.014 when gas is flowing either through steel or masonry or concrete duct. This is because, in case of gas ducts and chimneys, there is not so much difference on account of the tendency of both brick and steel surfaces to soot up to approximately the same conditions.

To find out the losses in bends, elbows and valves, the losses are generally given in terms of equivalent duct length and the same equation as given above can be used for finding the pressure losses. The pressure loss in gas duct and air duct should be calculated separately as the value 'f' is different.

Measurement of Draught. The draught losses in different parts of the boiler plant are measured in mm of water with the help of manometers. This pressure may be above atmospheric pressure or below atmospheric pressure. For very accurate measurement, the inclined type manometer is used.

The typical draught at different points of the boiler plant measured by U-tube manometer is shown in Fig. 12.3.

The measurement of draught serves not only to find out the resistance to the air and gas flow but it also indicates the rate of flow.

12.3. NATURAL DRAUGHT AND DESIGN OF CHIMNEY

The natural draught is obtained with the use of tall chimney which may be sufficient or insufficient to overcome the losses in the system. Its usefulness depends upon the capacity of the plant, equipments included in the plant and duct work. This system of producing the draught is useful for small capacity boilers and it does not play much important role in the present high capacity thermal power plants.

A chimney is a vertical tubuler structure of masonry ; brick, steel or reinforced concrete built for the purpose of enclosing a column of hot gases to produce the draught and discharge the gases high enough which will prevent an air-pollution. The draught produced by the chimney is due to the temperature difference of hot gases in the chimney and cold air outside the chimney.

Consider the height of the chimney above the grate level is 'H' as shown in Fig. 12.4. The pressure acting on the grate from the chimney side

$$p_1 = p_a + w_g H.$$

and the pressure acting on the grate from atmospheric side

$$p_2 = p_a + w_a H.$$

where p_a is the atmospheric pressure and w_a and w_g are the weight densities of atmospheric air and hot gases passing through the chimney.

The gas density varies along the height of the chimney as part of the heat is lost by the gas to the chimney. Therefore the average density of gas should be taken for calculation.

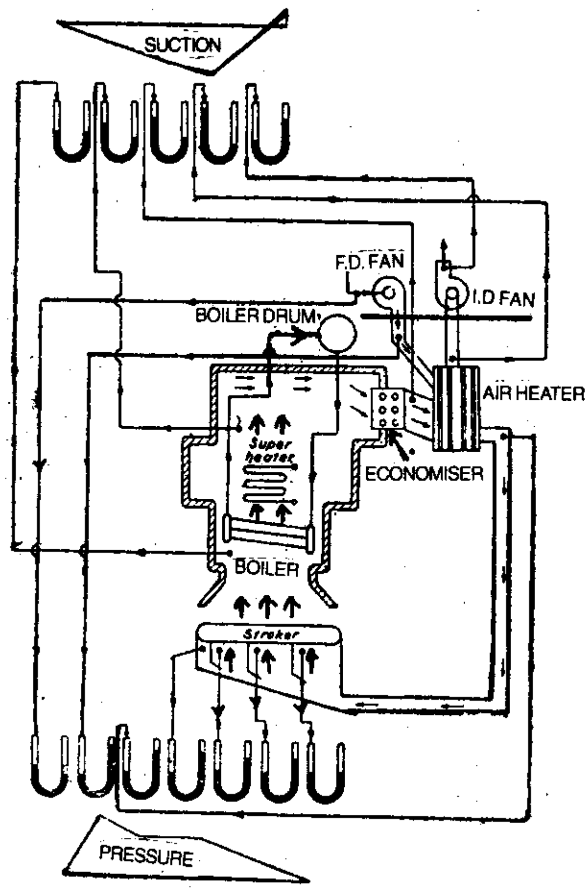


Fig. 12.3.

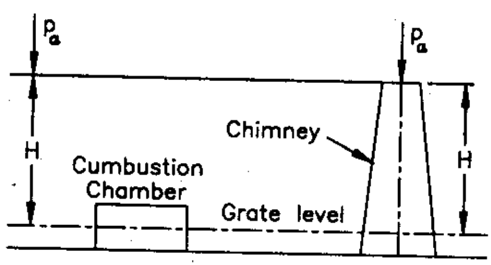


Fig. 12.4.

The net acting pressure on the grate of the combustion chamber due to the pressure exerted by gas column and air column is given by

$$p = p_2 - p_1 \text{ as } w_a > w_g.$$

$$= (p_a + w_a H) - (p_a + w_g H) = H(w_a - w_g) \text{ kgf/cm}^2 \ldots \quad (12.1)$$

This difference of pressure is responsible for causing the flow of air through the combustion chamber and gases through the chimney and is known as static draught.

The acting pressure can be increased either by increasing the height of the chimney or reducing the density of hot gases (allowing the hot gases to go out of boiler at higher temperature). This acting pressure is always small and generally measured in terms of mm of water with the help of water manometer.

The acting pressure in terms of water head is given by

$$\frac{h_w}{1000} \times w_w = H(w_a - w_g) \qquad \text{...(12.2)}$$

where h_w is the equivalent water head in mm and w_w is weight density of water.

$$\therefore \quad \frac{h_w}{1000} \times \rho_w g = H(\rho_a - \rho_g) \cdot g \qquad \text{...(12.3)}$$

where ρ represents the mass density.

$$\therefore \quad \frac{h_w}{1000} \times 1000 = H(\rho_a - \rho_g).$$

$$\therefore \quad h_w = H(\rho_a - \rho_g) \text{ mm of water head.} \qquad (12.4)$$

In an ordinary chimney this pressure difference lies between 10 to 12 mm of water head.

The condition for the maximum discharge through the chimney is given by

$$\frac{T_g}{T_a} = 2\left(\frac{m_a + 1}{m_a}\right) \qquad \text{...(12.5)}$$

and the draught in mm of water for maximum discharge is given by

$$h_w = \frac{176.5H}{T_a} \qquad \text{...(12.6)}$$

where T_a and T_g are the air and gas temperatures and m_a is the mass of air supplied per kg of coal burnt in the combustion chamber.

The maximum mass flow for the above condition through the chimney is given by

$$m_g = \frac{A \cdot p_g}{R_g} \sqrt{2gH} \cdot \frac{m_a}{m_a + 1} \cdot \frac{1}{2T_a} \qquad \text{...(12.7)}$$

where A is the cross-sectional area of the chimney at bottom and p_g and R_g are the pressure and gas constant for the hot gases flowing through the chimney.

Advantages and Limitations of Chimney Draught

Advantages :

(1) It does not require any external power for producing the draught.

(2) The capital investment is less than the capital investment required for artificial draught. The maintenance cost is nil as there is no mechanical part.

(3) Chimney keeps the flue gases at a high place in the atmosphere which prevents the contamination of atmosphere in a crowded locality and maintains the cleanliness.

(4) It has long life.

Limitations :

(1) The maximum pressure available for producing natural draught by chimney is hardly 10 to 20 mm of water under the normal atmospheric and flue gas temperatures.

(2) It is clear from the equation 12.6 that the available draught decreases with increase in outside air temperature and for producing sufficient draught, the flue gases have to be discharged at comparatively high temperatures resulting in the loss of overall plant efficiency.

(3) The design of the power plant should be made to utilise the maximum heat energy from the burned gases. This is generally done by extracting the heat from flue gases in the economiser, superheater, and air preheater. This is not possible with natural draught because if the temperature of the flue gases is decreased, the effective draught is reduced further effecting the generating capacity.

(4) As there is no through mixing of air and fuel in the combustion chamber due to low velocity of air therefore combustion is very poor. This increases the specific fuel consumption.

(5) The chimney has no flexibility to create more draught under peak load conditions because the draught available is constant for a particular height of chimney and the draught can be increased by allowing the flue gases to leave the combustion chamber at higher temperatures. This reduces the overall efficiency of the plant.

(6) Nearly 20% heat released by the fuel is lost to the flue gases.

The chimney draught is only used for very small boilers. Nowadays the chimney is never used for creating draught in thermal power plants as it has no flexibility, the total draught produced is insufficient for high generating capacity and it reduces the overall efficiency of the plant. The chimney is used in all power plants only to discharge the flue gases high in the atmosphere to maintain the cleanliness of the surrounding atmospheric air.

12.4. ARTIFICIAL DRAUGHT (FORCED AND INDUCED DRAUGHTS)

It has been seen that the draught produced by chimney is affected by the atmospheric conditions. It has no flexibility, poor efficiency and tall chimney is required. In most of the modern power plants, the draught used must be independent of atmospheric condition, and it must have greater flexibility (control) to take the fluctuating loads on the plant.

Today's large steam power plants requiring 20 thousand tons of steam per hour would be impossible to run without the aid of draft fans. A chimney of any reasonable height would be incapable of developing enough draft to move the tremendous volume of air and gases (400×10^3 cu-m to 800×10^3 cu-m per minute). The further advantage of fans is to reduce the height of the chimney needed.

The draught required in actual power plant is sufficiently high (300 mm of water) and to meet high draught requirements, some other system must be used, known as artificial draught. The artificial draught is more economical when the required draught is above 40 mm of water. The artificial draught is produced by a fan and it is known as fan (mechanical) draught. Mechanical draught is preferred for central power stations.

12.5. FORCED DRAUGHT

In a forced draught system, a blower is installed near the base of the boiler and air is forced to pass through the furnace, flues, economiser, air-preheater and to the stack. This draught system is known as positive draught system or forced draught system because the pressure of air throughout the system is above atmospheric pressure and air is forced to flow through the system. The arrangement of the system is shown in Fig. 12.5.

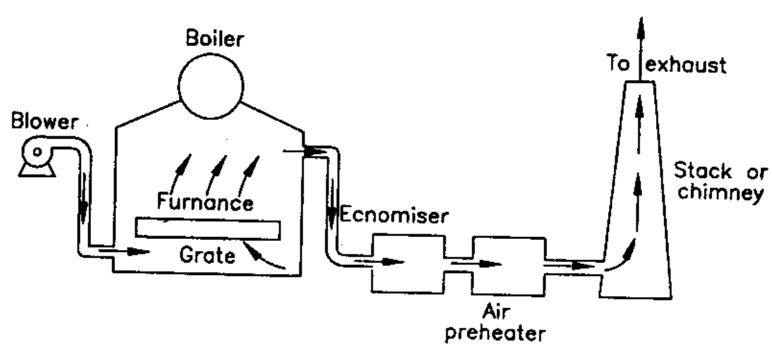


Fig. 12.5. Forced draught.

A stack or chimney is also used in this system as shown in figure but its function is to discharge gases high in the atmosphere to prevent the contamination. It is not much significant for producing draught therefore height of the chimney may not be very much.

12.6. INDUCED DRAUGHT

In this system, the blower is located near the base of the chimney instead of near the grate. The air is sucked in the system by reducing the pressure through the system below atmosphere. The induced draught fan sucks the burned gases from the furnace and the pressure inside the furnace is reduced below atmosphere and induces the atmospheric air to flow through the furnace. The action of the induced draught is similar to the action of the chimney. The draught produced is independent of the temperature of the hot gases therefore the gases may be discharged as cold as possible after recovering as much heat as possible in air-preheater and economiser.

This draught is used generally when economiser and air-preheater are incorporated in the system. The fan should be located at such a place that the temperature of the gas handled by the fan is lowest. The chimney is also used in this system and its function is similar as mentioned in forced draught but total draught produced in induced draught system is the sum of the draughts produced by the fan and chimney. The arrangement of the system is shown in Fig. 12.6.

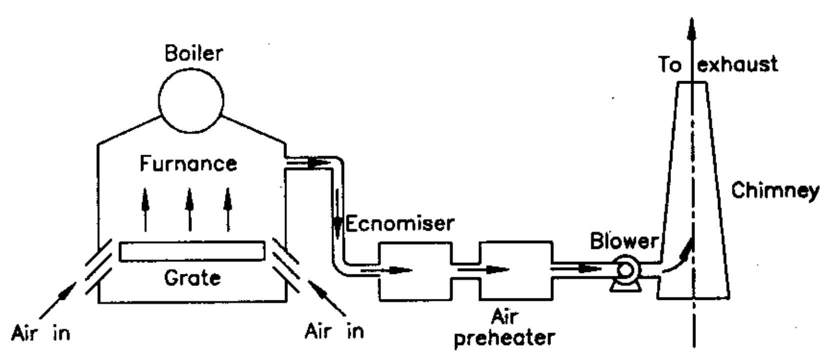


Fig. 12.6. Induced draught.

12.7. COMPARISON OF FORCED AND INDUCED DRAUGHTS

The advantages of the forced draught over the induced draught are listed below :

1. The size and power required by the induced draught fan is more than the forced draught because the induced draught fan handles more gases (air and fuel) and at elevated temperature. The volume of the gas handled by induced draught fan is much larger than the volume handled by forced draught fan due to high temperature of the gases, therefore the size of induced draught fan is 1.3 times the size of forced draught fan.

2. Water cooled bearings are required for induced draught fan to withstand the high temperatures of the flue gases.

3. There is no chance of air leakage in the furnace with forced draught as the pressure inside the furnace is above atmospheric pressure. There is continuous leakage of air in the furnace with induced draught as the pressure inside the furnace is less than the atmospheric pressure. This dilutes the combustion.

4. The flow of air through the grate and furnace is more uniform and it penetrates better into the fire bed when forced draught is used. The better penetration of air through the fuel bed and uniform flow improves the rate of burning.

5. When the doors are opened for firing in case of induced draught fan, there will be rush of cold air into the furnace and this reduces the draught through the system and reduces the heat transmission efficiency of the surfaces.

12.8. BALANCED DRAUGHT

It is always preferable to use a combination of forced draught and induced draught instead of forced or induced draught alone.

If the forced draught is used alone, then the furnace cannot be opened either for firing or inspection because the high pressure air inside the furnace will try to blow out suddenly and there is every chance of blowing out the fire completely and furnace stops.

If the induced draught is used alone, then also furnace cannot be opened either for firing or inspection because the cold air will try to rush into the furnace as the pressure inside the furnace is below atmospheric pressure. This reduces the effective draught and dilutes the combustion.

To overcome both the difficulties mentioned above either using forced draught or induced draught alone, a balanced draught is always preferred. The balanced draught is a combination of forced and induced draught. The forced draught overcomes the resistance of the fuel bed therefore sufficient air is supplied to the fuel bed for proper and complete combustion. The induced draught fan removes the gases from the furnace maintaining the pressure in the furnace just below atmosphere. This helps to prevent the blow-off of flames when the doors are opened as the leakage of air is inwards.

The arrangement of the balanced draught is shown in Fig. 12.7 (*a*) and pressure distribution through the system is shown in Fig. 12.7 (*b*). It is obvious from Fig. 12.7 (*b*) that the pressure inside the furnace is near atmospheric therefore there is no danger of blowout of flames or there is no danger of inrushing the air into the furnace when the doors are opened for inspection.

The pressure of air below the grate is above atmosphere and it helps for proper and uniform combustion. The pressure of air above the grate is below atmosphere and it helps to remove the exhaust gases as quick as possible from the combustion zone.

Advantages of mechanical draught over natural draught. The artificial mechanical draught is better in control and more economical than natural draught. The advantages of mechanical draught over natural draught are listed below :

1. The rate of combustion is high as the available draught is more. The better distribution and mixing of air with fuel is possible therefore the quantity of air required per kg of fuel is less. This further reduces the mass of the flue gases formed and heat carried by exhaust gases.

2. The air flow can be regulated according to the requirement by changing the draught pressure.

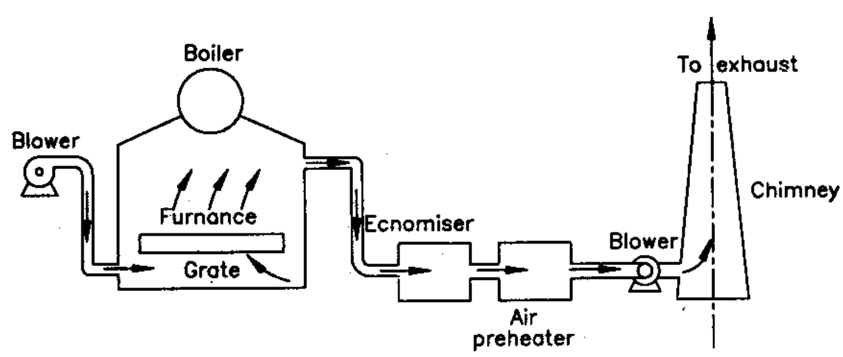


Fig. 12.7. (*a*) Balanced draught.

3. The mechanical draught is independent of the atmospheric temperature whereas the chimney draught is seriously affected by the atmospheric temperature.

4. Low grade fuel can be used in combustion chamber as the intensity of artificial draught is high.

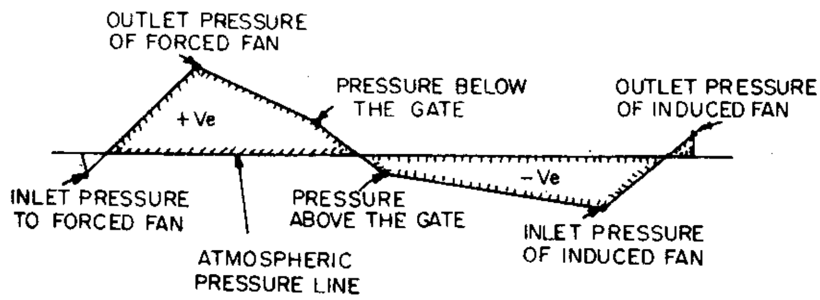


Fig. 12.7. (*b*) Pressure distribution through the system when the balanced draught is used.

5. The chimney draught is produced at the cost of thermal efficiency of the plant because it is necessary to exhaust the gases at high temperature to produce the draught. In mechanical draught, the exhaust gases can be cooled to lowest possible temperature before exhaust and improves the overall thermal efficiency of the plant.

6. The height of the chimney used in mechanical draught can be reduced sufficiently as the function of the chimney is only to exhaust the gases high in the atmosphere to prevent the contamination.

7. The efficiency of the artificial draught is nearly 7% whereas the efficiency of the chimney draught is hardly 1%.

8. The fuel consumption per kW due to artificial draught is 15% less than the natural draught.

9. The fuel burning capacity of the grate is 200 to 300 kg/m^2 in area of the grate per hour with mechanical draught whereas it is hardly 50 kg/m^2-hr with natural draught.

10. It prevents the formation of smoke as complete combustion is possible even with less excess air.

The major disadvantage of the artificial draught is the high capital cost required and high running and maintenance costs of the fans used.

12.9. POWER REQUIREMENT FOR DRAUGHT FANS

The draught produced by the fan is h_w mm of water and the volume discharged is V_a then work done by the gas is given by

$$= h_w \left(\frac{\text{kgf}}{m^2}\right) \times V_a(\text{m}^3) = h_w V_a \text{ kgf-m}$$

$$\therefore \quad \text{H.P. of the fan} = \frac{h_w . V_a}{4500}$$

Considering the transmission efficiency between the prime-mover and fan and mechanical efficiency of the fan as η

$$\text{B.H.P. (of prime-mover)} = \frac{h_w V_a}{4500.\eta}$$

(*a*) B.H.P. of the prime-mover required to run the forced draught fan is calculated as follows :

m_a = air supplied per kg of fuel,

W = coal burned per minute.

$\therefore$ Mass of air supplied per minute = $W.m_a$

$\therefore$ Volume of air supplied per minute = Mass/density = $\dfrac{W.m_a}{\rho_a}$

Substituting the value of ρ_a in the above equation,

V_{af} (volume delivered by forced draught fan per minute)

$$= W.m_a\left(\frac{1}{1.293}\times\frac{T_a}{273}\right)$$

∴ B.H.P. (of the prime-mover)

$$= \frac{h_w}{4500\times\eta}\times\frac{W.m_a}{1}\left(\frac{1}{1.293}\cdot\frac{T_a}{273}\right) \quad ...(12.8)$$

(*b*) B.H.P. of the prime-mover required to run the induced draught fan is calculated as follows.

h_w = the draught produced in mm of water same as forced draught fan.

m_a = It is the mass of air supplied/min.

W = It is the kg of coal burned/min.

Mass of gas handled by the fan/min $= W(m_a + 1)$

Volume of gas handled by the fan/min. $= \dfrac{W(m_a+1)}{\rho_g}$.

Volume delivery by the induced draught fan is given by

$$\therefore \quad V_{ai} = \frac{W(m_a+1)}{1}\cdot\frac{1}{1.293}\times\frac{T_g}{273}\cdot\frac{m_a}{(m_a+1)}$$

$$= \frac{W.m_a}{1.293}\left(\frac{T_g}{273}\right)$$

∴ B.H.P. of the prime-mover running the I.D. Fan

$$= \frac{V_{ai}\times h_w}{4500\times\eta} = \frac{W.m_a}{1.293}\left(\frac{T_g}{273}\right)\frac{h_w}{4500\times\eta} \quad ...(12.9)$$

If W, m_a, h_w and η are same for F.D. and I.D. Fans, then from the equations 12.8 and 12.9, we get,

$$\frac{\text{B.H.P. of prime-mover running F.D. Fan}}{\text{B.H.P. of prime-mover running I.D. Fan}} = \frac{T_a}{T_g} \quad ...(12.10)$$

Generally T_g is equivalent to 1.5 T_a ; therefore I.D. fan requires nearly 50% more power than the F.D. fan to develop the same draught.

12.10. FAN DRIVES AND CONTROL

In most of the power plants, the load changes and therefore the quantity of air supplied to the combustion chamber must be controlled according to the requirements.

The flow and pressure relation of the boiler system in which the air is supplied by the fan is called the system resistance characteristic. The pressure (resistance) along the boiler system consists of the pressure losses in ducts, fitting, filters, fuel bed, air-preheater, economiser and many others. The total resistance of all these equipments also increases with an increase in velocity and quantity of air passing through the system as per the law given below :

$$h_t = KQ^2$$

The resistance curve for the boiler can be drawn with respect to flow quantity as shown in Fig. 12.8. For a particular boiler system, there is only one resistance curve and fan delivering variable quantity of air must operate along the same resistance curve.

To supply the variable quantity of air as per the demand (as per the load on plant), the following methods are used :

1. Damper control. 2. Speed control.

Damper control. The fan is operating at a speed N_1 r.p.m. and delivering air through a system whose resistance is changing along the resistance curve R_1, and say point '*a*' is the point of operation at full load condition. The total static pressure (resistance) developed by the fan and required B.H.P. can be calculated from the fan characteristics as shown in Fig. 12.9. If the load on the power plant is decreased then it is necessary to reduce the supply of air quantity say from Q_a to Q_b as shown in Fig. 12.8.

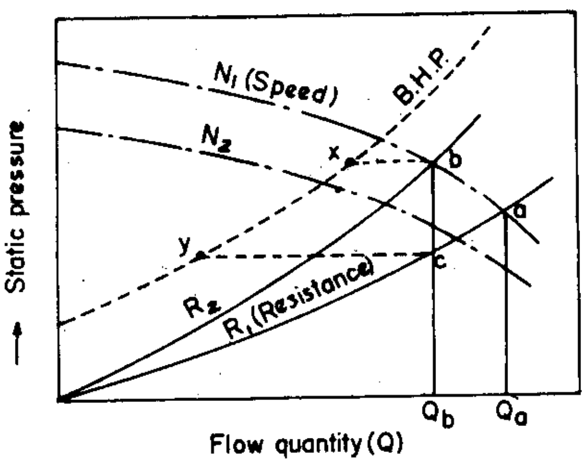


Fig. 12.8.

By increasing the resistance of the system (by partly closing the dampers), the flow quantity can be reduced. The partly closing dampers establish a new resistance curve R_2 which intersects the fan characteristic at point '*b*' which is the desired value. The corresponding values of required B.H.P. and static pressure developed by the fan can be determined from Fig. 12.9.

Speed Control. The flow quantity of air can also be reduced by reducing the speed of the fan from N_1 to N_2 which changes the fan characteristics and permits the operation of the original resistance curve. Under this condition, the operating point will be '*c*'. The corresponding value of required B.H.P. and static pressure developed can also be determined from Fig. 12.9.

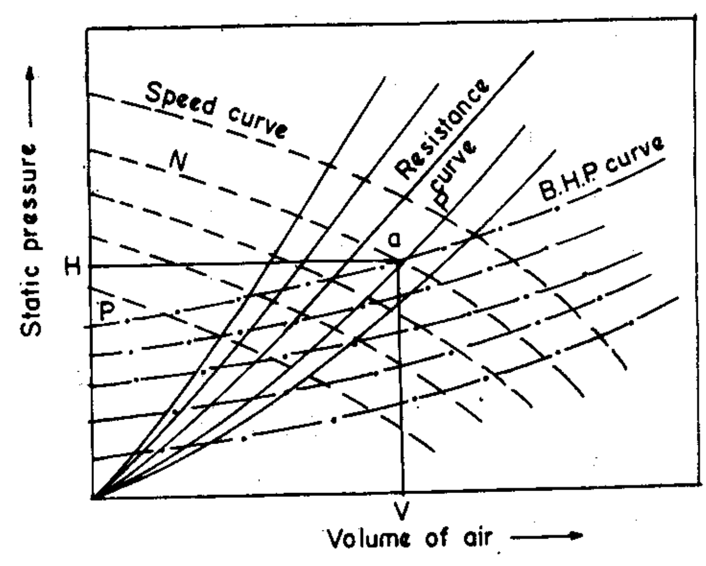


Fig. 12.9. Grab Bucket.

It is obvious from Fig. 12.9 that the power requirement at the point '*c*' is less than that at the point '*b*'.

This indicates that the speed reduction to control the air flow is more economical method than changing the system resistance with the help of dampers. Therefore, it is always desirable to keep the system resistance as minimum as possible and volume adjustments should be made by varying the fan speed for economical operation.

Speed control with slip ring motors or multiple winding induction motors is expensive, therefore the speed control system is seldom used. Most of the plants use inlet louvers or discharge dampers to control the flow with constant speed motor. Some engineers prefer to use constant speed motors but vary fan rotor speed by variable ratio hydraulic or magnetic couplings. The constant speed motor used varies from 1200 to 1300 r.p.m. for F.D. fan drives and 720 to 1200 r.p.m. for ID fan drives.

12.11. DESIGN AND CONSTRUCTION OF CHIMNEY

In modern power plants, the purpose of the chimney is to emit the exhaust gases sufficiently high to avoid the nuisance to the surrounding people. The general practice is to construct the chimney which is 2.5 to 3 times of height of power plant or more.

The main loads acting on the chimney are its own load and wind pressure and it must be designed to withstand these loads for its structural stability. The dead weight of the chimney is treated as a single vertical force acting through the mass centre and wind pressure, as a concentrated horizontal force acting through the centroid of the vertical projected area. Experimental data has shown that the wind pressure on a cylinder is approximately 2/3 of that on a plane surface of the same projected area and shape. Normally, the wind pressure of 150 kgf/m^2 is taken for the design of chimney.

To the layman, chimney building means merely erecting a long tube to carry exhaust gases out of site. In fact this is surprisingly difficult to achieve successfully and involves a wide variety of skills.

(1) **Steel chimneys.** Steel chimneys are generally used for short exhaust stacks where draft is created by fan. Such chimneys are lined with bricks to increase the life. Short stacks are generally made of steel as a matter of economy. Such chimneys can also be erected within a short period as compared with other types. Self-supporting steel stacks located on the roof of power house must be enclosed carefully and sufficient structural steel bracing used to carry the loads into the building columns. Steel chimneys are generally built in welded sections and erected in the field by riveting or welding horizontal joints.

Due to lower capital cost of the steel chimney, power industry tended to favour steel chimney and in the 1950's the number of steel chimneys built increased considerably. The use of oil in the power industry produced a serious problem namely acid condensation due to its sulphur content and severe attack took place upon the inside surface of brick, concrete and steel chimneys. The introduction of insulation of steel chimneys by aluminium cladding in 1958 to minimise corrosion was the first significant development in the history of steel chimneys.

The 'Smog' of 1951 followed by the Clean Air Act of 1956 brought about a revolution in chimney design. Basically, the act greatly increased chimney height and exit velocity of the flue gases. Making chimneys taller was fairly simple but in addition the flue gases had to be at a given minimum exit velocity on maximum load. It was found that if several boilers were connected to a common chimney when on partial load, the flue gas pressure was less than the weight of air in the chimney and 'cold air inversion' took place. Attempts were made to overcome this by the introduction of truncated cones on the top of the chimneys, but often this caused unaccepted back pressure when all boilers were on full load, thus the design of chimneys again reverted to the one boiler, one chimney pattern.

Tall, slim chimneys produce both aesthetic and structural problems. A number of tall, slim steel chimneys grouped together was not aesthetically pleasing, especially if guy ropes were used and it was not structurally viable to build tall slim chimneys of brick or concrete. Thus the steel multiflue chimney was evolved in the mid-1960's, another significant step in chimney design. The design life of a multiflue steel chimney is in the region of 20-30 years. The chimney of 244 m height at Grain Power Station is the best example of multiflue type chimney.

The increased use of gas turbine as a power source has demonstrated the advantage of using steel chimneys as opposed to other forms of construction. A gas turbine can reach full load in about a minute and in consequence, the chimney has to withstand the thermal shock brought about by an increase in temperature of 450-500°C during that period. The thin wall and high coefficient of expansion of steel can successfully accept such a load. Two 60 m high chimneys used at Leicester gas tubine power station is a good example.

The steel chimney is now established as economical and efficient but its vulnerability to oscillation and corrosion and its low resistance to heat transfer created certain difficulties. The main source of corrosion is the presence of SO_2 in the gases. When combined with the O_2 and water vapour, it produces the highly corrosive H_2SO_4. As efficient combustion requires excess air, and plant efficiency requires low gas temperature, SO_2 and its problems will be with us until low cost sulphur free fuels are available for commercial use. Sulphur free natural gas is not the complete solution, as it produces considerable amounts of moisture due to its high hydrocarbon content.

(2) **Site Constructed Chimneys.** Site built chimneys of brick or concrete, whether with mineral or steel liners, remain the only structurally sound alternative for very tall chimneys necessary for power stations or where the life of the chimney must be long, 30 years or more.

Brick chimneys were constructed of common bricks earlier. But nowadays perforated radial bricks are adopted as it gives best results. The perforations aid structural stability and its heat insulating properties of the dead air spaces formed are of advantageous in gaining maximum draft performance of the chimney. Further, the compressive strength of the masonry is greatly increased by the mortar and, therefore, the crushing strength of perforated radial brick exceeds many times the safe design value required in practice. Brick chimneys are rarely used presently for high capacity power generating systems as brick construction being very slow and very expensive.

Reinforced concrete is the most common material used for tall chimney's construction by means of pre-cast sections and was commonly employed but currently is less popular due to various structural difficulties and are usually limited now to chimneys of around 80 m high. The method used now is 'Jump Forming' where the shuttering apparatus is moved up the stack in steps or 'Slip Forming' where shuttering is gradually moved up with continuous concrete pouring. The latter presents more engineering problem and is favoured for fast jobs, building five metres a day being possible, against the usual 10 metres a week with jumps shuttering. Linings are often favoured for very tall structures. Concrete is not suitable due to its high thermal inertia, leading to cracking under thermal stress and subsequent splitting due to acid or water ingress. The market for site built chimneys has been gradually encroached upon the steel chimney due to the cost factor but still concrete chimneys are favoured where life of the chimney is most important. The 259 m reinforced concrete main chimney at Yorkshire power station is the largest chimney ever built in the world.

(3) **Plastic Chimneys and Liners.** There are few companies in U.S.A. offering chimneys in glass fibre reinforced plastic but this method of construction has suffered a certain recession since the late sixties when it became very popular for a short while. Unfortunately plastic chimneys stood up less well to the gas temperatures than had originally been expected and there are numerous examples of this type of flue catching fire or disintegrating. However, there is no doubt that where a low stress, low temperature chimney is required for highly corrosive effluents, the glass reinforced plastic type has a vital part to play. However, as boilers become increasingly more efficient and so exhaust lower temperature gases, and as manufacturing costs for strong high temperature plastics fall, there is no reason why they should not have a substantial future. The flue of 139 m high chimney at Albright and Wilson Whitehaven (U.S.A.) works is constructed from glass fibre reinforced polyester.

The question presently posed is what is the future of chimney ? Will chimneys disappear from the landscape ? Chimneys owe their existence to the fossil fuels, but these will not last for ever. By the year 2000 the sources of power will either have to be nuclear, coal or one of the 'fringe' sources, *i.e.*, hydroelectric, solar, tidal or wave power, all of which except the first will require vast capital sums spent on the development and even then, at the best, will only produce a small percentage of the world power requirement. Nuclear power is fast developing, but not with the speed that was originally forecast and environmentalists are constantly warning of the health hazards. This means that coal will still remain a major source of energy and recoverable world coal reserves should last a further one or two hundred years. Thus it would appear that chimneys will be with us for at least a couple of centuries.

EXERCISES

12.1. What do you understand by a word 'Draught' ? How the draughts are classified ?

12.2. Prove that the draught produced in mm of water head by a chimney is given by

$$h_w = 353\, H \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a + 1} \right) \right]$$

Further prove that the discharge will be maximum for the given height of the chimney when

$$\frac{T_a}{T_g} = 2 \left(\frac{m_a + 1}{m_a} \right).$$

12.3. What are the limitations of chimney draught ?

12.4. Explain the principle used in forced and induced draught. Why balanced draught is preferred over forced or induced draught ?

12.5. Discuss the merits and demerits of forced draught over induced draught.

12.6. What are the different losses which are generally taken into account in designing the draught system ?

12.7. Find out the expression for fan power and compare the powers required for F.D. fan and I.D. fan if the air supplied is same in both cases.

12.8. What are the different centrifugal fans used for draft system ? Why the backward blade fan is preferred for F.D. fan and forward blade fan for I.D. fan ?

12.9. What different methods of control are used to control the air supply under variable load conditions ? Why the speed control is more economical than damper control ? The damper control is preferred over speed control even if it is more costly. Why ?

12.10. The draught produced by a forced draught fan is sufficient to overcome the total frictional losses of the system 20 mm of water head and to impart the velocity of 10 m/sec to the flue gases passing through the chimney. The amount of coal burned per hour is 12,000 kg and air supplied is 12 kg per kg of coal burned. Assuming the atmospheric pressure of 1.03 kgf/cm^2 and temperature of 300°K and mechanical efficiency of 80%, find the power required of a prime mover to run the fan assuming the mechanical efficiency of 80%.

(*b*) If the same draught is produced by using I.D. fan and allowing the flue gases to exhaust at 120°C, find the power of the prime mover required assuming the same mechanical efficiency.

Take R = 29.3 kg-m/kgK for air as well as for gas.

12.11. 1500 cu-m of flue gases per minute are discharged by an I.D. fan through a chimney of diameter of 2 m at 130°C. The total losses in the system are equivalent to 12 cm of water head. Find the power of the motor driving the fan assuming the mechanical efficiency of 85%.

Take R = 30 kg-m/kg-K for gases and atmospheric pressure = 1.03 bar.

12.12. A draught of 5 cm of water column is produced by using I.D. fan. The temperatures of the flue gases and ambient air are 202°C and 37°C respectively. The consumption of coal is 1600 kg/hr and A : F, ratio used is 15 : 1. Assuming the mechanical and transmission efficiencies 85%, 88%, find the power of the prime mover required to run the fan. If the I.D. fan is replaced by F.D. fan assuming other data same, find the percentage reduction in the H.P. of the prime mover required to run the fan.

12.13. Why steel chimneys are more preferred in Gas Turbine power plant than any other chimney ?

12.14. Why the height of the chimney and the gas exit velocity are important in chimney design ? Why multiflue chimneys are preferred over single unit chimney ?

12.15. Discuss the important points in selecting steel or concrete chimney for a thermal power plant. Give your preference with reason and an example of an Indian power plant.

□□□

13
High Pressure Boilers

13.1. INTRODUCTION

The demand for the higher power outputs from the boiler and associated plant has increased in the last ten years. It is a common practice to use high pressure and temperature steam in power plants to increase the efficiency of the plant and to reduce the cost of electricity production. In the last 10 years, the operating pressures and temperatures of boilers have risen, and this has been possible because of developments of materials. For the given steam conditions and boiler size, there is not much variation in efficiency between different types and the widest scope left to the designer only in increasing plant economy by making use of high temperature flue gases.

When steam is needed at pressures, 30 bar, and individual boilers are required to raise less than about 30 tons of steam per hour, shell boilers are considerably cheaper than water tube boiler, and are equally satisfactory in all other respects. Above these limits, shell boilers (generally factory built) are difficult to transport if not impossible. There are no such limits to water tube boilers. These can be site-erected from easily transportable parts, and moreover the pressure parts are of smaller diameter and therefore can be thinner. The geometry can be varied to suit a wide range of situations, and furnace is not limited to cylindrical form. Therefore, water tube boilers are generally preferred for high pressure and high output whereas shell boilers for low pressure and low output.

The modern high pressure boilers used for power generation are for steam capacities 30 to 650 tons/hr and above with a pressure up to 160 bar and maximum steam temperature of about 540°C. One of the largest boiler plants in the world is in U.K. used in the Central Electricity Generation Board. This boiler was disigned for 1700 tons of steam generation per hour at a pressure of 160 bar and a temperature of 560°C with one reheat to 560°C burning 220 tons of coal per hour.

The unique features of the high pressure boilers are discussed below :

1. Method of Water Circulation. The water circulation through the boiler may be natural circulation due to density difference or by force circulation. In all modern high pressure boiler plants, the water circulation is maintained with the help of pump which forces the water through the boiler plant. The use of natural circulation is limited to the sub-critical boilers due to its limitations.

The natural water circulation is shown in Fig. 13.1. The force causing the flow of water through the tube is approximately given by

$$F = (\omega_c H_1 - \omega_h H_2)$$

where ω_c and ω_h are the densities of cold water and hot water and steam mixture.

As $$H_1 \simeq H_2 = H$$

$$F = (\omega_c - \omega_h)\, H$$

As the water rises up, the part of the water converts into steam and is separated in the drum. The percentage of steam separated in the drum is known as "Top Dryness' and the reciprocal of this is called Circulation Ratio.

With an increase in pressure in the boiler, the pres[illegible] difference (force) causing the natural flow of water decreases and this becomes zero at the critical p[illegible] of steam (225 bar), because, the density of water and steam is same. Thus the natural circulation ceases. Therefore, the use of natural circulation is limited to subcritical boilers as mentioned earlier up to 140 bar boiler pressure and use of force circulation becomes imperative for critical and super critical boilers.

Further, to increase the rate of heat transfer (steam generation) in boilers, it is more simpler to use high water velocities rather than high gas velocities, because a smaller quantity of fluid is dealt with and a considerable increase in pressure can be more easily produced than gas.

Hence, the tubes of smaller diameters may be used for a boiler of a given output.

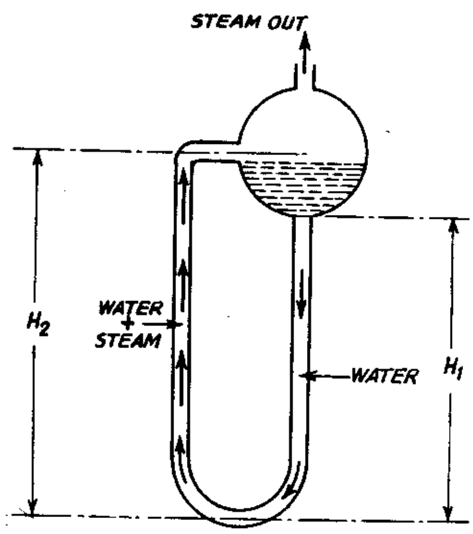


Fig. 13.1. Natural circulation of water.

2. Type of Tubing. In most of the high pressure boilers, the water circulated through the tubes and their external surfaces is exposed to the flue gases. In water tube boilers, if the flow takes place through one continuous tube, the large pressure drop takes place due to friction. This is considerably reduced by arranging the flow to pass through parallel system of tubing. In most of the cases, several sets of tubing are used. This type of arrangement helps to reduce the pressure loss, and better control over the quality of the steam.

3. Improved Method of Heating. The heat transfer can be increased by using improved methods of heating as mentioned below :

(*a*) The saving of latent heat by evaporation of water above critical pressure of the steam.

(*b*) The heating of water can be made by mixing the super-heated steam. The mixing phenomenon gives highest heat transfer coefficient.

(*c*) The overall heat transfer coefficient can be increased by increasing the water velocity inside the tube and increasing the gas velocity above sonic velocity.

The above-mentioned methods of improved heat transfer are used in different types of boilers.

13.2. ADVANTAGES OF HIGH PRESSURE BOILERS

The different advantages of high pressure boilers are listed below :

1. The tendency of scale formation is eliminated due to high velocity of water through the tubes.

2. Light weight tubes with better heating surface arrangement can be used. The space required is also less. The cost of foundation, the time of erection and cost are reduced due to less weight of the tubes used.

3. Due to use of forced circulation, there is more freedom in the arrangement of furnace, tubes and boiler components.

4. All the parts are uniformly heated, therefore the danger of overheating is reduced and thermal stress problem is simplified.

5. The differential expansion is reduced due to uniform temperature and this reduces the possibility of gas and air leakages.

6. The components can be arranged horizontally as high head required for natural circulation is eliminated using forced circulation. There is a greater flexibility in the components arrangement.

7. The steam can be raised quickly to meet the variable load requirements without the use of complicated control devices.

8. The efficiency of plant is increased upto 40 to 42% by using high pressure and high temperature steam. This is illustrated in Fig. 13.2.

9. A very rapid start from cold is possible if an external supply of power is available. Hence the boiler can be used for carrying peak loads or standby purposes with hydraulic station.

13.3. LA MONT BOILER

A forced circulation boiler was first introduced in 1925 by La Mont. This is generally used in Europe and America.

The arrangement of water circulation and different components is shown in Fig. 13.3.

The feed water from hot well is supplied to a storage and separating drum (boiler) through the economiser. The most of the sensible heat is supplied to the feed water passing through the economiser. A centrifugal pump circulates the water equal to 8 to 10 times the weight of steam evaporated. This water is circulated through the evaporator tubes and the part of the water evaporated is separated in the separator drum. The large quantity of water circulated (10 times of evaporation) prevents the tubes from being overheated.

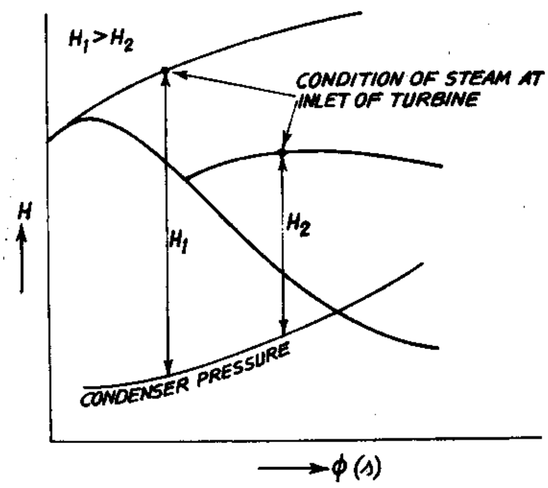


Fig. 13.2. More work output per kg with higher pressure and higher temperature steam for same condenser pressure.

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

The steam separated in the boiler is further passed through the superheater as shown in Fig. 13.3 and finally supplied to the prime mover.

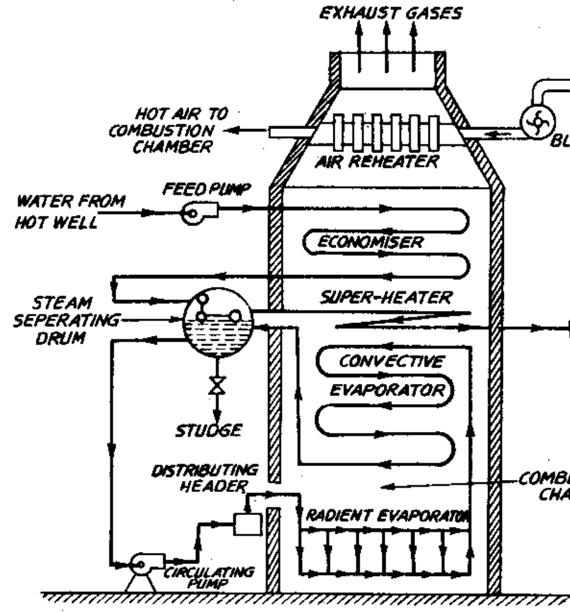


Fig. 13.3. La Mont Boiler.

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

These boilers have been built to generate 45 to 50 tons of superheated steam at a pressure of 120 bar. and at a temperature of 500°C.

13.4. BENSON BOILER

The main difficulty experienced in the La Mont boiler is the formation and attachment of bubbles on the inner surfaces of the heating tubes. The attached bubbles to the tube surfaces reduced 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 bar), the steam and water have the same density and therefore the danger of bubble formation can be easily eliminated. The technical development at that time did not allow to build turbines for such high pressures. The first high pressure Benson boiler was put into operation in 1927 by Siemens Schuckert Merke—West Germany, the well-known pioneers in the field of steam power machines.

The arrangement of the boiler components is shown in Fig. 13.4. The water as passed through the economiser into the radiant evaporator is shown in figure where majority of the water is converted into steam. The remaining water is evaporated in the final evaporator absorbing the heat from hot gases by convection. The saturated high pressure steam (at 225 bar) is further passed through the super-heater as shown in figure.

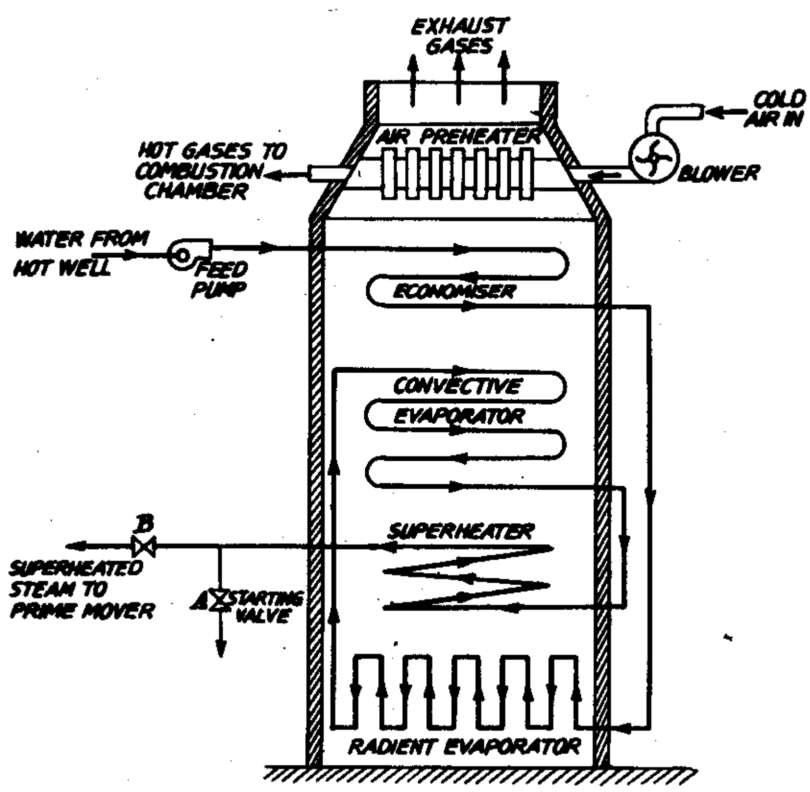


Fig. 13.4. Benson Boiler.

Major difficulty of salt deposition was experienced in the transformation zone when all remaining water converted into steam.

To avoid this difficulty, the boiler (final evaporator) is normally flashed out after every 4000 working hours to remove the salt.

The development of Benson boiler was very slow initially up to 1934. After realization of its importance, several boilers were built and the post-war era gave special impetus to its development. Now it has become customary in Germany to instal Benson boilers in power stations. Boiler having as high as 650°C temperature of steam had been put in service. The maximum working pressure obtained so far from commercial Benson boiler is 500 bar. The Benson boilers of 150 tonnes/hr. generating capacity are in use.

Advantages. 1. As there are no drums, the total weight of Benson boiler is 20% less than other boilers. This also reduces the cost of boiler.

2. Natural circulation boilers require expansion joints but these are not required for Benson as the pipes are welded. The erection of Benson boiler is easier and quicker as all the parts are welded at sites and workshop job of tube expansion is altogether avoided.

3. The transfer of Benson's parts is easy as no drums are required and majority of the parts are carried to the site without pre-assembly.

4. The Benson boiler can be erected in a comparatively smaller floor area. The space problem does not control the size of Benson boiler used.

5. The furnace walls of the boiler can be more efficiently protected by using smaller diameter and closed pitched tubes.

6. The superheater in the Benson boiler is an integral part of forced circulation system, therefore no special starting arrangement for superheater is required.

7. The Benson boiler can be started very quickly because of welded joints.

8. The Benson boiler can be operated most economically by varying the temperature and pressure at partial loads and over loads. The desired temperature can also be maintained constant at any pressure.

9. Sudden fall of demand creates circulation problems due to bubble formation in the natural circulation boiler which never occurs in Benson boiler. This feature of insensitiveness to load fluctuations makes it more suitable for grid power station as it has better adaptive capacity to meet sudden load fluctuations.

10. The flow-down losses of Benson boiler are hardly 4% of natural circulation boilers of same capacity.

11. Explosion hazards are not all severe as it consists of only tubes of small diameter and has very little storage capacity compared to drum type boiler.

During starting, the water is passed through the economiser, evaporator, superheater and back to the feed line via starting valve *A*. During starting the valve *B* is closed. As the steam generation starts and it becomes superheated, the valve *A* is closed and the valve *B* is opened.

During starting, first circulating pumps are started and then the burners are started to avoid the overheating of evaporator and superheater tubes.

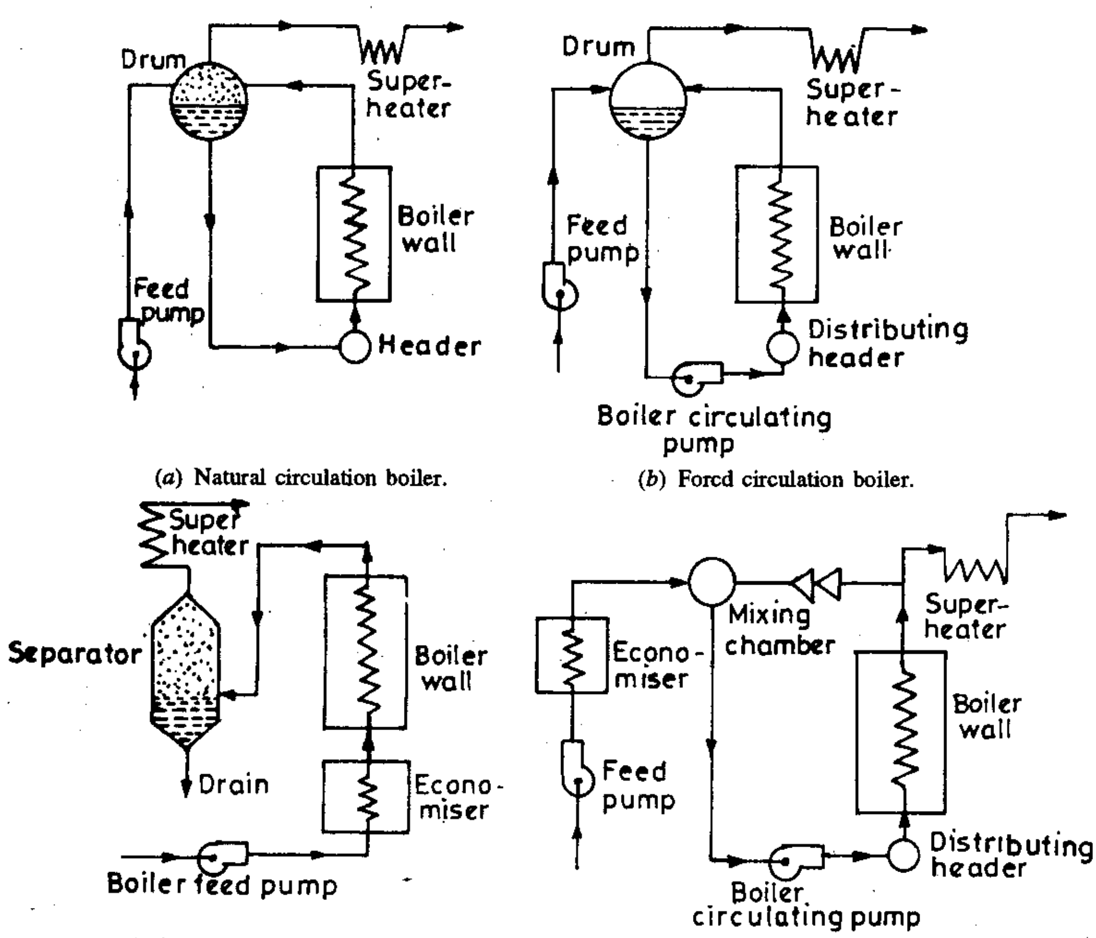
Once Through Boilers for Future Units in India. At the end of VII plan (1987 – 92), the total thermal generation capacity was 42344 MW which is to be increased to 83600 to 118600 MW by the end of 2005. For addition of a massive thermal generation capacity of 41000 MW to 76000 MW in 15-years, a raise in the unit capacity from present 200/500 MW to 500/800 MW seems essential. A mix of 200, 500 and 800 MW needs to be planned for IX and X plans. By the end of VIII plan, our grid sizes would have grown to accept 800 MW units. Major capacity additions in IX plan will have to be done by 500 MW units but in X plan, the major capacity additions will have to be done by 800 MW units.

The costs of construction and fuel are sharply increasing and it is imperative to the designers to economise on the installation cost and to increase fuel efficiency in the new stations by using modern sophisticated technology. Higher size units with higher steam parameters seem a natural choice for economical installation and operation of thermal power plants. The 800 MW units would be designed on supercritical steam pressure with a drumless boiler on once through principle.

Outstanding Feature of Once Through Boiler. With increasing pressure of steam, the differential between the specific weight of saturated water in down-comers and specific weight of steam-water mixture in furnace wall tubes (which causes natural circulation in boiler) goes on decreasing. Sluggish circulation causes *film boiling*. In film boiling, the tube metal remains in contact with steam bubbles which provides high thermal resistance for heat flow and therefore tube metal sharply deteriorates due to high metal temperature leading to boiler tube failures.

For pressures above 180 bar with natural circulation Fig. 13.5 (*a*), it is not possible to prevent "*film boiling*" in the upper furnace tubes. Therefore, generally, above 150 bar pressure, controlled circulation in water walls is used by providing boiler circulating pump between down-comers and lower water distributing heaters and the water walls. In controlled circulation boilers, it is possible to utilize high steam pressure upto 200 bar but beyond this, there is a reduction in the effectiveness of Boiler Drum in separating the saturated steam from water. Therefore, beyond 200 bar, a drumless boiler is envisaged. A separator vessel is utilized to separate out salts from steam water mixture in sub-critical range (< 225.65 bar) but in supercritical range (> 225.65 bar), the separator vessel cannot function and only *once through* (monotube) is adopted. Various manufacturers have adopted different techniques.

Sulzers Brothers Ltd. has adopted separator vessel in their design Fig. 13.5 (*c*) with sub-critical pressures and there are no boiler circulating pumps. The once through circulating is provided by feed pump.



(*a*) Natural circulation boiler. (*b*) Forcd circulation boiler.

(*c*) Once through or Monotype boiler (*d*) Combined circulatry boiler

Fig. 13.5.

M/s Combustion Engineering Co. have adopted a *"Mixing vessel"* which provides suction to boiler circulating pumps at sub-critical pressures, provides suction to boiler circulating pumps and inlet saturated steam to superheater and serves as a receiving header for steam-water mixture from evaporator suction as shown in Fig. 13.5 (*d*). The boiler circulating pumps are required to function in the start-up or low pressure conditions but when the pressure goes above critical pressure then these are stopped and once through circulation is provided by boiler feed pump. This is called a *combined circulation boiler.*

Economy of Once Through Boiler. Advancing the steam parameters results in better efficiency, higher utilization of steam (less specific steam consumption) and small volumetric steam flows in boiler. These effects are shown in Tables 13.1, 13.2 and 13.3.

Table 13.1. Steam Condition and Thermal Efficiency

Unit capacity (MW)	*Steam pressure (bar)*	*Steam Temp./Reheat Temp. (°C)*	*Boiler Capacity (tonne/hr)*	*Efficiency at Generator Terminals (%)*
125	127	538/538	420 – 435	35.5 – 37.5
250	176	565/565	820	38.95
250	306	600/565	788	40.05
350	169	566/566	1157	39.80
500	246	538/538	1770	40.00
600	246	538/566	1900	40.3
700	246	538/538	2500	40.3

Table 13.2. Increase in Theoretical Turbine Output Per Unit of Mass Flow of Steam With Steam Parameters

Steam pressure (bar)	*Steam Temp. (°C)*	*Reheat steam Temp. Temp (°C)*	*Theoretical turbine output per unit mass flow of steam (% variation)*
85	500	—	Base (100)
100	550	—	107
100	600	—	112
100	550	550	131.7
100	600	600	139.6
160	550	—	108.6
160	600	—	115
160	550	550	134.5
160	600	600	143
350	650	665	160

Table 13.3. Variation of Overall Efficiency with Steam Parameters

Steam pressure (bar)	*Steam Temp. (°C)*	*Reheat steam Temp. (°C)*	*Increase in overall efficiency (% variation)*
85	500	—	Base (100)
160	600	—	107.3
160	600	550	120
300	650	565	120
300	600	550	128.5
350	600	550	133.3
350	650	565	135.5

The major difficulties which are to be faced by the designers are :

(1) The purity of feed water and make-up water becomes more and more important with an increase in pressure of the boiler. The importance of purity increases many folds because of elimination of boiler drum in supercritical boilers and even the separator vessel becomes ineffective. Volatile internal treatment for boiler with Hydrazine and NH_3 is to be used and no solid chemicals are to be used for internal cleaning.

(2) The main limitation in the design of high pressure, high temperature boiler is the availability of suitable materials. The temperature limit of ferritic materials is 580°C and as such authentic steels are to be used for parts where metal temperature exceeds this limit. Therefore, the adoption of once through boilers requires easy availability of suitable materials within the country.

Advantages of Once Through Boilers for Large Thermal Units. (1) There is no higher limit for the higher steam pressure and therefore highest pressure can be used to achieve high thermal efficiency.

(2) Full steam temperature can be maintained over a wider load range in once through design.

(3) Elimination of heavy walled drum decreases the metallurgical sensitivity of boiler against pressure changes.

(4) Faster start-up and cooling down of the boiler is possible.

(5) Variable pressure operation can easily be adopted for better performance at part load operation.

(6) It is free from any circulation disturbance due to rapid pressure fluctuations.

(7) Once through circuit permits greater freedom in arrangement and location of heating surfaces.

(8) Its size is smaller and weighs less than natural circulation boiler. The ratios are :

Boiler room floor space – 60%, Boiler room volume space – 58%, Boiler foundation cost – 65%.

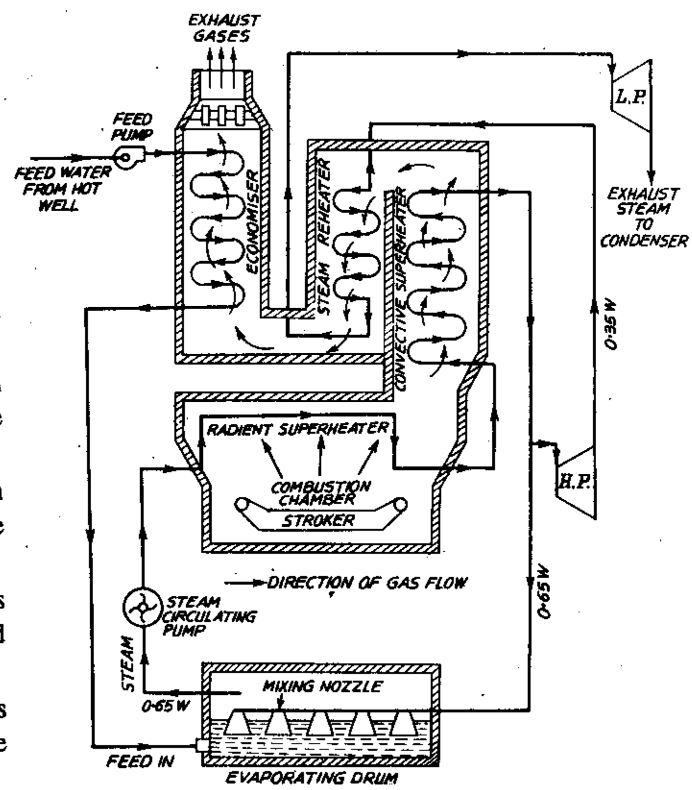


Fig. 13.6. Loeffler Boiler.

(9) Steam temperature can be easily controlled during start-up and shut-down in accordance with predetermined characteristics which is very advantageous for simultaneous start-up of boiler and turbine.

13.5. LOEFFLER BOILER

The major difficulty experienced in La Mont boiler is the deposition of salt and sediment on the inner surfaces of the water tubes. The deposition reduced the heat transfer and ultimately the generating capacity.

This further increased the danger of overheating the tubes due to salt deposition as it has high thermal resistance.

This difficulty was solved in Loeffler Boiler by preventing the flow of water into the boiler tubes. Most of the steam is generated outside from the feedwater using part of the superheated steam coming out from the boiler. The arrangement of the different components, and water and steam circulations are shown in Fig. 13.6.

The pressure feed pump draws the water through the economiser and delivers it into the evaporator drum as shown in figure. About 65% of the steam coming out of superheater is passed through the evaporator drum in order to evaporate the feed water coming from èconomiser.

The steam circulating pump draws the saturated steam from the evaporator drum and is passed through the radiant superheater and then convective superheater. About 35% of the steam coming out from the superheater is supplied to the H.P. steam turbine. The steam coming out from H.P. turbine is passed through reheater before supplying to L.P. turbine as shown in figure.

The amount of steam generated in the evaporator drum is equal to the steam tapped (65%) from the superheater. The nozzles which distribute the superheated steam throughout the water into the evaporater drum are of special design and avoid priming and noise.

This boiler can carry higher salt concentration than any other type and is more compact than indirectly heated boilers having natural circulation. These qualities fit it for land or sea transport power generation.

Loeffler boilers with generating capacity of 100 tonnes/hr and operating at 140 bar are already commissioned.

13.6. SCHMIDT-HARTMANN BOILER

The arrangement of the boiler components is shown in Fig. 13.7. The operation of the boiler is similar to an electric transformer. Two pressures are used to effect an intercharge of energy.

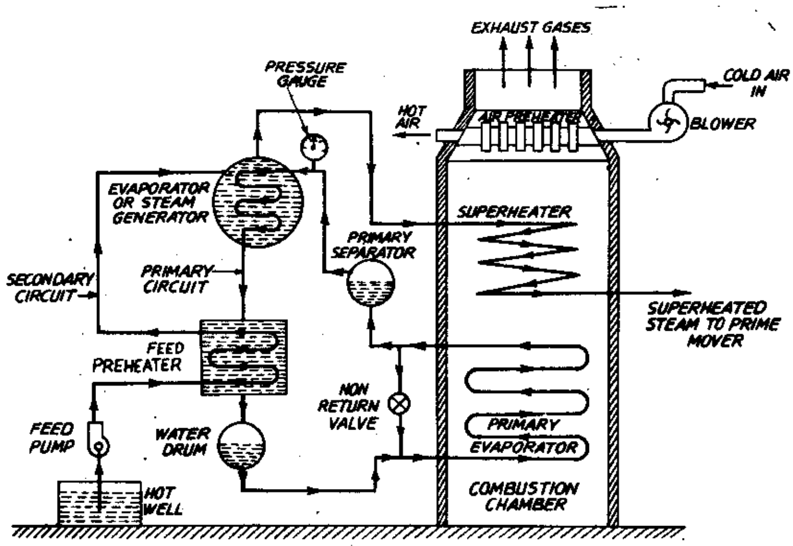


Fig. 13.7.

In the primary circuit, the steam at 100 bar is produced from distilled water. The generated steam is passed through a submerged heating coil which is located in an evaporater drum as shown in figure. The high pressure steam in this coil possesses sufficient thermal potential and steam at 60 bar with a heat transfer rate of 10,000 kJ/m^2-hr°C is generated in the evaporator drum.

The steam produced in the evaporator drum from impure water is further passed through the superheater and then supplied to the prime-mover. The high pressure condensate formed in the submerged heating coil is circulated through a low pressure feed heater on its way to raise the feed water temperature to its saturation temperature. Therefore, only latent heat is supplied in the evaporator drum.

Natural circulation is used in the primary circuit and this is sufficient to effect the desired rate of heat transfer and to overcome the thermo-siphon head of about 2 m to 10 m.

In normal circumstances, the replenishment of distilled water in the primary circuit is not required as every care is taken in design and construction to prevent the leakage. But as a safeguard against leakage, a pressure gauge and safety valve are fitted in the circuit.

Advantages. 1. There is a rare chance of overheating or burning the highly heated components of the primary circuit as there is no chance of interruption to the circulation either by rust or any other material. The highly heated parts run very safely throughout the life of the boiler.

2. The salt deposited in the evaporator drum due to the circulation of impure water can be easily brushed off just by removing the submerged coil from the drum or by blowing off the water.

3. The wide fluctuations of load are easily taken by this boiler without undue priming or abnormal increase in the primary pressure due to high thermal and water capacity of the boiler.

4. The absence of water risers in the drum, and moderate temperature difference across the heating coil allows evaporation to proceed without priming.

13.7. VELOX-BOILER

Now, it is known fact that when the gas velocity exceeds the sound-velocity, the heat is transferred from the gas at a much higher rate than rates achieved with sub-sonic flow. The advantage of this theory is taken to effect the large heat transfer from a smaller surface area in this boiler.

The arrangement of the components of this boiler is shown in Fig. 13.8. Air is compressed to 2.5 bar with the help of a compressor run by gas turbine before supplying to the combustion chamber to get the supersonic velocity of the gases passing through the combustion chamber and gas tubes and high heat release

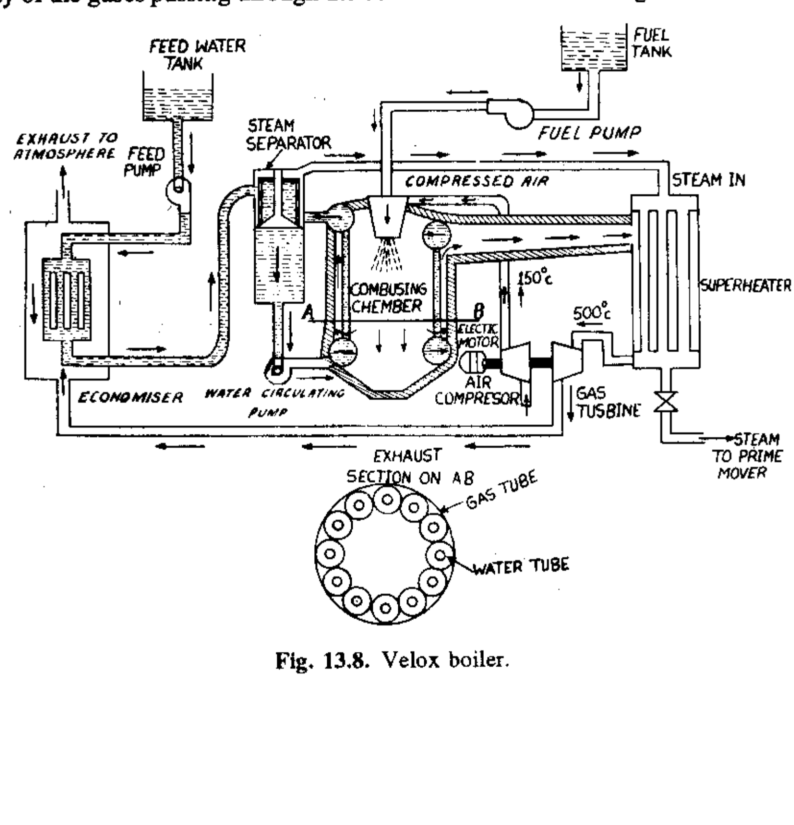


Fig. 13.8. Velox boiler.

rates (35 to 45 million kJ per m^3). The burned gases in the combustion chamber are passed through the annulus of the tubes as shown in figure. The heat is transferred from gases to water while passing through the annulus to generate the steam. The mixture of water and steam thus formed then passes into a separator which is so designed that the mixture enters with a spiral flow. The centrifugal force thus produced causes the heavier water particles to be thrown outward on the walls. This effect separates the steam from water. The separated steam is further passed to superheater and then supplied to the prime-mover. The water removed from steam in the separator is again passed into the water tubes with the help of a pump.

The gases coming out from the annulus at the top are further passed over the superheater where its heat is used for superheating the steam. The gases coming out of superheater are used to run a gas turbine as they carry sufficient kinetic energy. The power output of the gas turbine is used to run the air-compressor. The exhaust gases coming out from the gas turbine are passed through the economiser to utilise the remaining heat of the gases. The extra power required to run the compressor is supplied with the help of electric motor. Feed water of 10 to 20 times the weight of steam generated is circulated through the tubes with the help of water circulating pump. This prevents the overheating of metal walls.

The size of the Velox boiler is limited to 100 tons per hour because 400 kW is required to run the air compressor at this output. The power developed by the gas turbine is not sufficient to run the compressor and therefore some power from external source must be supplied as mentioned above.

Advantages. (1) Very high combustion rates are possible as 35 to 45 million kJ per cu.m. of combustion chamber volume.

(2) Low excess air is required as the pressurised air is used and the problem of draught is simplified.

(3) It is very compact generating unit and has greater flexibility.

(4) It can be quickly started even though the separator has a storage capacity of about 10% of the maximum hourly output.

13.8. SUPER-CRITICAL BOILERS

The increasing fuel costs with decreasing fuel quality have constantly persuaded power engineers to search for more economical methods of power generation. The most recent method to produce economical thermal power is by the use of super-critical steam cycle.

Between the working ranges of 125 bar and 510°C to 300 bar and 600°C, large number of steam generating units are designed which are basically characterised as sub-critical and super-critical. Usually a sub-critical boiler consists of three distinct sections as preheater (economiser), evaporator and superheater and in case of super-critical boiler, the only preheater and superheater are required. The constructural layouts of both types of boilers are otherwise practically identical.

With the recent experiences gained in design and construction of super-critical boilers, it has become a rule to use super-critical boilers above 300 MW capacity units.

The advantages of supercritical boilers over critical type are listed below :

(1) The heat transfer rates are considerably large compared with sub-critical boilers. The steam side heat transfer coefficient for sub-critical is 165000 kJ/m^2-hr°C when the steam pressure and temperature are 180 bar and 538°C whereas the steam side heat transfer, coefficient for super-critical boiler is 2,20,000 kJ/m^2 hr-°C when the steam is generated at 240°C.

(2) The pressure level is more stable due to less heat capacity of the generator and therefore gives better response.

(3) Higher thermal efficiency (40 to 42%) of power station can be achieved with the use of super-critical steam.

(4) The problems of erosion and corrosion are minimised in super-criticial boilers as two phase mixture does not exist.

(5) The turbo generators connected to super-critical boilers can generate peak loads by changing the pressure of operation.

(6) There is a great ease of operation and their comparative simplicity and flexibility make them adaptable to load fluctuations.

Although, thermodynamically higher steam temperature and pressure are always desirable but the trend is halted due to availability of material and difficulties experienced in the turbine and condenser operations due to large volumes.

Presently, 246 bar and 538°C are used for unit sizes above 500 MW capacity plants.

13.9. 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 gas turbine as they are exhausted at high pressure. The gas turbine runs the air compressor to supply the compressed air to the combustion chamber.

The arrangement of the different components of a supercharged boiler is shown in Fig. 13.9. The gases coming out from the combustion chamber are passed through the gas turbine and the hot exhaust gases from gas turbine are further used to preheat the feed water. The pressure to the gas side is 5 bar and pressure to the steam side of 200 bar are generally preferred.

The advantages of supercharged boilers claimed over other boilers are listed below :

1. The heat transfer surface required is hardly 30 to 25% of the heat transfer surface of a conventional boiler due to very high overall heat transfer coefficient.

2. Rapid start of the boiler is possible due to reduced quantity of the whole boiler structure materials (steel, brick and refractories). A supercharged boiler of 150 tons/hr. generating capacity can be brought to full steam pressure within 25 minutes.

3. Small heat storage capacity of the boiler plant gives better response to the control.

4. The part of the gas turbine output can be used to drive other auxiliaries.

5. The number of operators required is less than the conventional boiler plant.

The only disadvantage of this type of boiler is tightness of high pressure gas passage is essential.

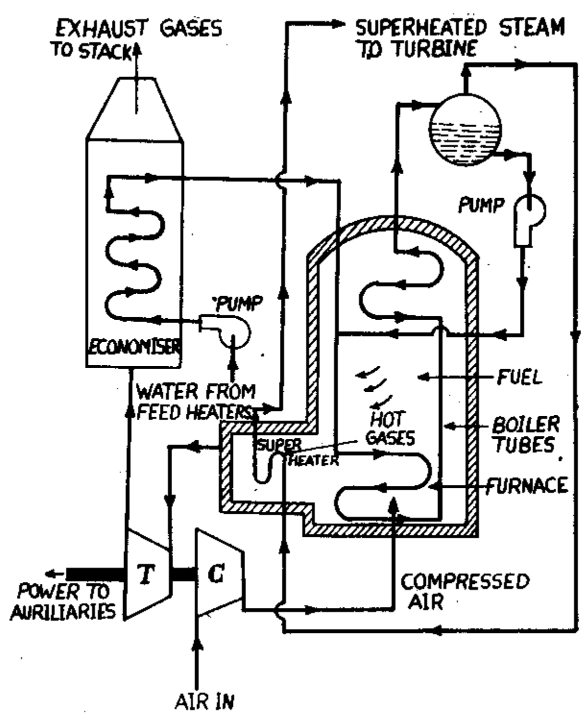


Fig. 13.9. Supercharged Boiler.

13.10. FLASH STEAM GENERATOR

Special form of water tube boiler is the flash steam generator. This is basically a helix tube fired by down jet combustion of gas or oil. The advantages are very rapid response (full steam production within about five minutes) and output ranges up to an evaporation rate of about 1 kg/sec with operating steam pressure ranging from 3 to 70 bar. Water is pumped into the helix and at the exit 90% of it is in the form of steam, the remaining water fraction being collected in a separator. The combustion efficiency is about 80% on oil, and 73% on gas. The tube helix principle, which eliminates the need for a water space, gives an extremely high heat output in a small area. The largest model ever used produces 0.18 kg/m^2-sec. (or about 420 kW/m^2). This boiler is more suitable when the plant is designed to take peak loads.

13.11. WASTE HEAT BOILER

The early use of waste heat boilers was confined to the iron and steel industry, and gas industry also used them extensively. Hundreds of waste heat boilers were used successfully in past. Modern steel making methods are less amenable to waste heat boilers than open hearth furnaces. On the other hand, steel reheating furnaces can successfully operate with waste heat boilers. The ships operated by diesel engines exhaust at quite low temperature, about 320 to 350°C. The quantity of gases thus exhausted, about 100,000 kg/hr. is ample at this temperature to raise all the steam needed to serve the ship.

Pollution of land, rivers and atmosphere is the threat to the survival of physical life and must be stopped.

The discharge of human sewage to rivers and the sea can no longer be tolerated. There are no adequate landfill sites for the disposal of these wastes. These factors have combined to create the need for a new technology – that of waste disposal. In case of municipal and industrial wastes, incineration is the process used, that is mostly exothermic. In chemical complexes, waste heat recovery is a common place. In the above cases, waste heat boilers can be effectively used to recover much of the heat otherwise lost.

Before selecting the waste heat boiler, it is necessary to know the mass flow available and its temperature in addition to the chemical and physical active substance (SO_2, abrasive dust) carried by waste hot gases.

The economic use of boiler depends upon the mass flow and its temperature.

Problems with Waste Heat Boilers. (1) Control. The steam demand will not always match the heat supply to the boiler, and it will be necessary to divert gases to atmosphere to prevent safety value. The required hot gas dampers can be heavy and expensive, both in first cost and maintenance.

(2) Fouling. The adherence of solid substances to the heating surfaces will cause a reduction in heat transfer and an increase in draught loss. It is indicated that the adherence of deposits is largely the result of condensation of low melting point alkali sulphates which then act as the bonding agent for larger particles.

(3) Corrosion. Sulphur burns to SO_2 and also SO_3. The latter reacts with water vapour to form H_2SO_4 which will condense on surfaces below the acid dew point (120-150°C). Corrosion will be catastrophic if the surface temperatures are below the H_2SO_4 dew point (50-70°C) and such temperature must be avoided.

(4) Erosion. Parts of boilers can become eroded by the action of abrasive dusts. Ceramic or metal tube end protections should be fitted to avoid erosion.

Supplementary Firing. In some cases, it becomes necessary to augment the heat output from a waste heat boiler to meet the demand of required steam. The methods used are listed below :

(1) The waste heat boiler may be constructed with furnace to contain an oil or gas burner and add the products of combustion to those from the process where waste heat is recovered and pass them through the same connection again.

(2) If the waste products of combustion are rich in oxygen and are clean and free from pulsation, they will support combustion of another fuel in an 'in duct' burner. Such an application is for gas turbine exhaust.

Ministry of Non-conventional Energy has requested State Electricity Boards (SEBs) to pay higher tariff for electricity generated from agro and urban wastes. This is because, the power generation from wastes is costly and risky but would help to eliminate accumulation of urban and solid agro wastes which is a major

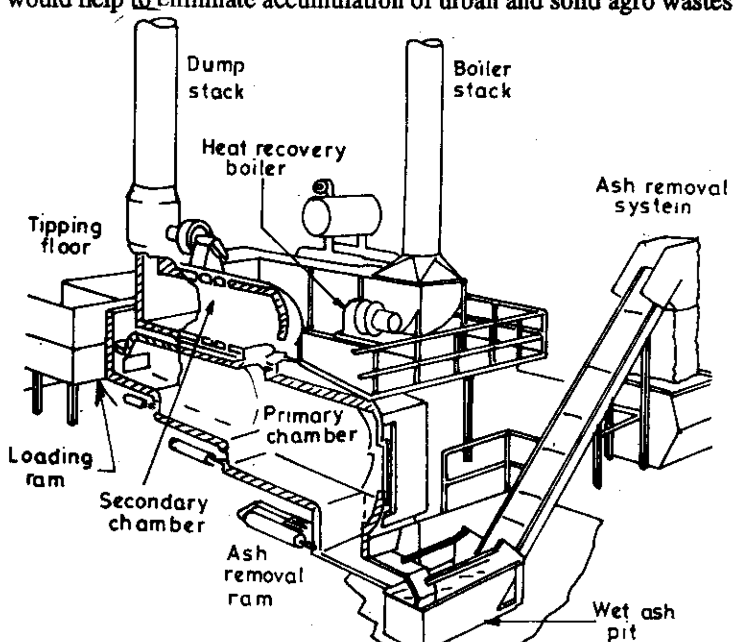


Fig. 13.10. Modular incinerator is equipped with dual combustion chambers to ensure efficient burning of solid wastes and dust.

health hazard. The secretary of non-conventional energy (Mr. Prabhakar) stated in Aug. 1975 that with the support and encouragement given by the Govt. the electricity generation from waste is likely to go up to 800 – 1000 MW in coming five years. The Minister of Non-conventional Energy Sources (Mr. Krishna Kumar) stated that this ministry has embarked upon an ambitious programme to set up about 2000 agro-based power plants in each Taluk, using agro and urban wastes.

Different Types of Waste-Heat Boilers

(1) Dual Combustion Chamber. Solid wastes are most commonly burned in dual chamber as shown in Fig. 13.10. A ram type feeder injects the waste into primary combustion chamber where the material is reduced to inert ash weighing approximately 5% of the initial charge. Entrained particulates and gases pass into the secondary combustion chamber where they are burned.

Either batch or continuous waste-feeding system is used in this boiler. Residual ash is removed manually from batch units and automatically from continuous models. Automatic ash removal system consists of a conveyor that moves the ash along the combustion chamber floor and discharges it from the unit.

(2) Liquid Waste Incinerators. It has a simpler unit as shown in Fig. 13.11. It is simpler than solid-

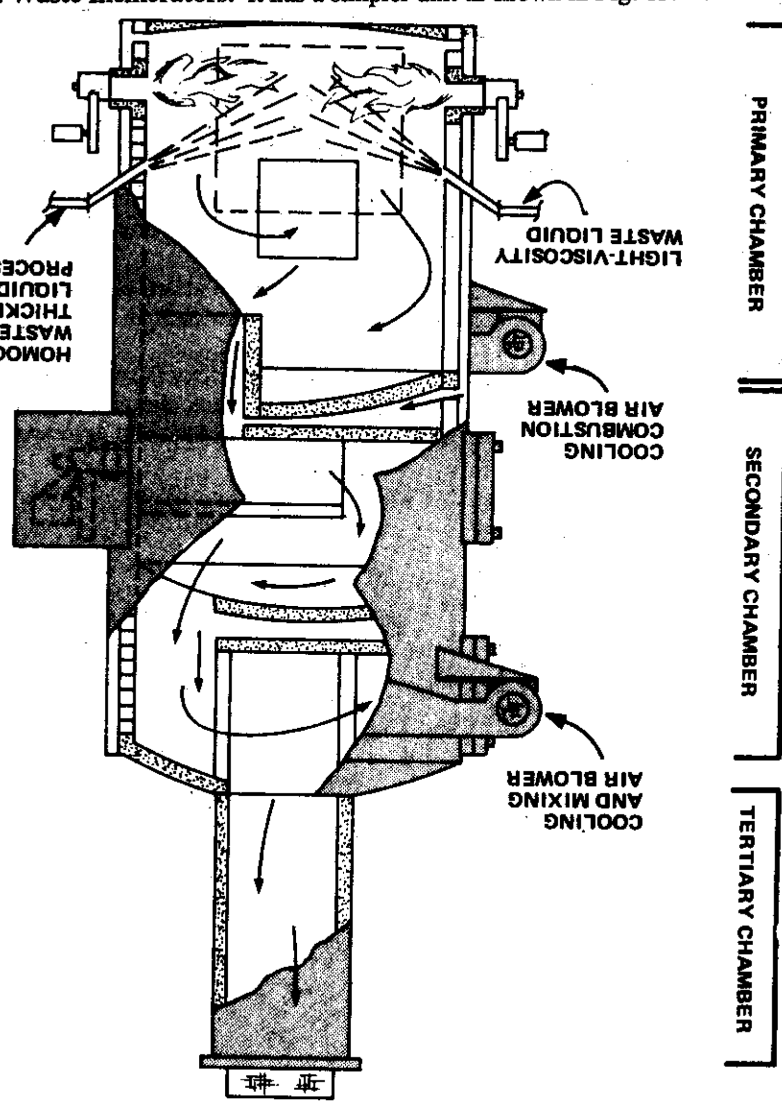


Fig. 13.11. Liquid-waste and sludge incinerator uses atomizing nozzles to inject waste into primary combustion chamber.

waste units because the liquids can be handled relatively easily and have a low ash content and relatively consistent heat content. Atomizing nozzles are used to inject the waste liquid into the combustion chamber. Accurate control of temperature and mixing is required to ensure complete combustion.

(3) Rotary Kilns. Mixtures of solid and liquid waste can be burned in rotary kilns as shown in Fig. 13.12. The tumbling action in rotary units permits more waste to be exposed to the combustion process than in stationary units. Solid and liquid waste mixtures are fed concurrently into rotary units, but individually into modular units. In modular unit, solids are fed into primary combustion chamber, while the liquids are injected on top of the solid.

Burning rates of this unit range from 5 to 50 tons of solid per day. Approximately 6 to 60 million kJ/hr are released when mixture of solid and liquid is burned. Heat may be recovered to generate steam in heat exchanger located in the way of hot-gas discharge. The heat exchanger must be capable of resisting abrasion and corrosion, especially when exposed to high chlorine or sulphur concentrations.

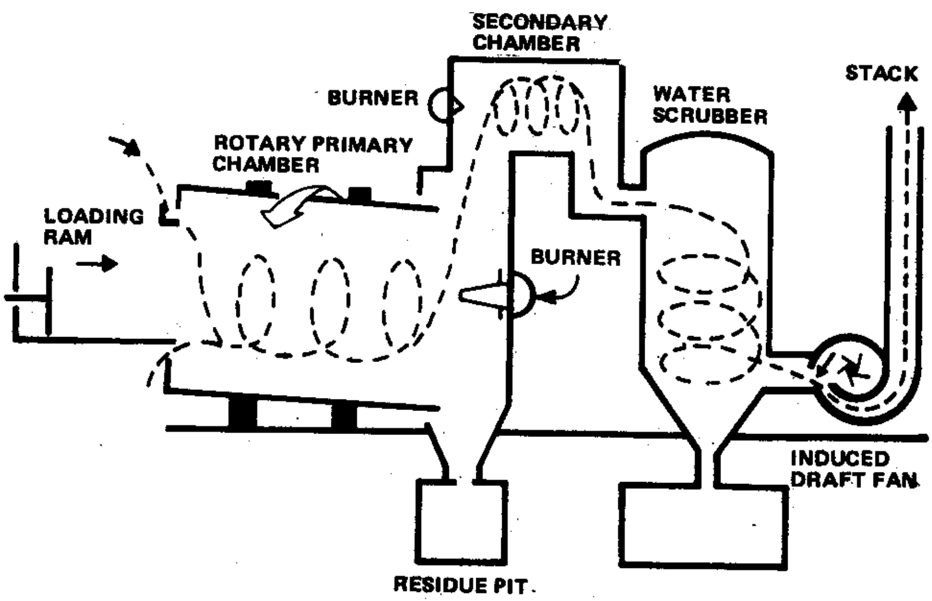


Fig. 13.12. Rotary kiln can burn mixtures of solid and liquid wastes, is fitted with scrubber to prevent air pollution.

Waste composition, generation rate and plant energy demand determine the size of the waste heat boiler as well as the type of boiler. The quantity and composition of the waste to be burned must be identified. Volume and make-up usually vary from day-to-day, so the burning system must be able to perform efficiently at maximum and minimum feed load.

(4) Waste as a Supplementary Fuel for Existing Plant. Sewage sludge cakes can be used with the existing plant as supplementary fuel using coal or oil as basic fuel. The difficulties which are to be considered are :

(*i*) How much sludge could be burned with oil or coal ?

(*ii*) What would be the effect of such fuel mixtures on the combustion, corrosion, slagging, capacity and efficiency of the existing plant ?

To examine the possibilities of sludge-cake combustion, Public Service Electric Co. had conducted experiments using a sludge whose properties are listed below by burning in two 300 MW boilers using coal (1 – 1.5% sulphur) and oil (0.3% sulphur).

Table 13.4. Comparison of sludge with coal, oil, and refuse-derived fuel

	HHV, kJ/kg	*% Ash*	*Ash fusion temp., F*[1]	*% S*	*% Chlorides*	*Ultimate analysis, %*			
						C	*H*	*N*	*O*
Eco-Fuel II per AD Little, Inc.	7800	9.4	– –	0.1 – 0.6	0.1 – 0.7	41.6 – 47.3	5.5 – 6.3	0.6 – 1.5	33.9 – 38.6
Typical sludge cake, dried	8738	26.22	2130–2305[2]	0.43	0.88	44.68	6.31	1.33	19.70
Coal	12,685	8.85	– –	1.26	– –	79.49	4.81	1.4	1.26
Oil	19,308	0.01	– –	0.29	– –	86.91	12.47	0.014	0.106
Typical sludge with 50% water	4355	13.07	– –	0.21	– –	22.27	3.14	1.33	9.82

[1]Range is initial deformation [2]. Mixed with coal ash.

In comparing the operation of a boiler when burning two different types of fuels, it can be assumed (*i*) constant fuel mass input (*ii*) constant fuel heat input and (*iii*) constant boiler output.

Considering constant fuel heat input, the total mass input rate of the fuel will be increased by a factor (C.V. of primary fuel/C.V. of mixture). The allowable percentage sludge in the fuel mixture may be calculated from mass balances. They depend on allowable particulate emission standard and relative magnitudes of sewage plant output and boiler-fuel input. Fig. 13.13 shows the allowable sludge fuel against precipitator efficiency for coal and oil.

Moisture in the sludge will also have some effect on boiler cold-end corrosion. Sludge contains less sulphur than coal or oil, therefore, any increase in stack gas DPT would be due to sludges water content. For 20% sludge input, exhaust gas DPT increases by 3 to 4°C. Increasing exhaust gas temperature by this amount to avoid condensation increases exhaust losses by 0.1 to 0.2%. But if dried sludge is used, there is no change in DPT of the exhaust gases. High temperature corrosion depends on percentage sodium in ash. Sodium content being lower in sludge, there is no danger of high temperature corrosion by burning the sludge-cake mixture.

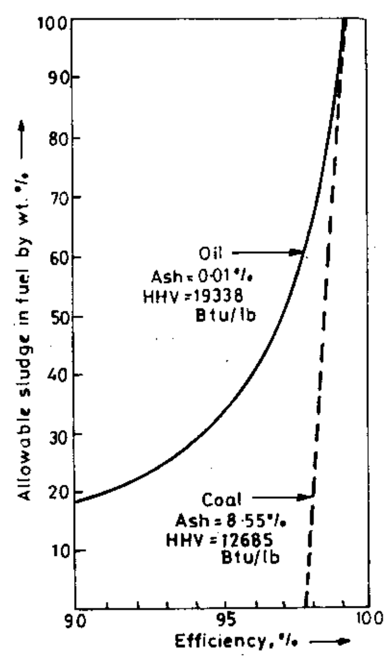


Fig. 13.13. Electrostatic precipitator collection efficiency, % Graph shows sludge percentage permitted to meet the required standard.

Till ash fusion temperature is not above 1260°C, there is no ash flow problem. The ash fusion temperature of the sludge ash is below 1260°C, there is no ash flow problem when sludge is used as fuel with coal or oil. There is also no problem concerning ash disposal when sludge is used as part-fuel.

The ash-resistivity measurements made of the sludge-cake ash were in the range of 2.3×10^{11} to 3.2×10^{11} Ω-cm. The electrostatic precipitators are designed for removal of coal ash when its resistivity is 5×10^{10} Ω-cm. The effect of sludge moisture and sodium content would improve precipitator performance by acting as conditioning agents.

Sulphur emissions would not appear to be a problem when burning a sludge-coal or sludge-oil mixture as sludge has lower sulphur content than the coal. On mass basis, at 50% water content in the sludge, it has lower sulphur content than the oil. On kJ basis, its sulphur content is somewhat higher, but 20% sludge and 80% oil would result in SO_2 emission of only 0.35 kg/million kJ which is far below the emission standard imposed by the Govt.

13.12. LOCATION OF HEATING SURFACES IN WATER TUBE BOILERS

A high pressure boiler is not a simple assembly of certain components like burners, superheaters, air heaters and others. The functions of these components are inter-related. The quality of coal used and the operating conditions have great influence on the selection of these components and more than that they influence the philosophy of the general design.

The location of the heat transfer surface (evaporator, super-heater and reheater) in a boiler is very important and it depends upon the required duty from the boiler. The most commonly used furnace layout for pulverised fuel boilers is shown in Fig. 13.14. In the zone-I, heat transfer is predominantly by radiation as the flame in this zone is diffused yellow-flame which radiates much more than the premixed blue flame. As the burned gases move upward and secondary air is added, the effect of radiation is reduced and convection becomes predominant as the flame (hot gases) changes from diffused to premixed. The space marked by (R + C) receives heat by convection as well as radiation provided suitable heat transfer surface is introduced into the path. The heat transfer in the Zones II and III takes place mainly by convection. Zone II is identified as high temperature and Zone III as low temperature zone.

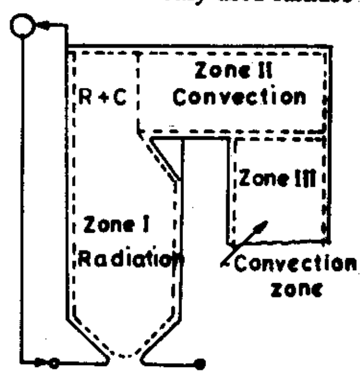


Fig. 13.14.

It is essential to provide an opportunity to fuel and air to come in intimate contact for a longer time to achieve the complete combustion. This opportunity decreases as the reaction proceeds towards the completion. Therefore, it is always essential to supply excess air to ensure complete combustion. The boiler efficiency decreases with an increase in excess air. The demand for excess air is considerably reduced in pulverised fuel firing system by creating a turbulence to air which increases the surface contact between fuel and air.

Hot turbulent air coupled with low excess air produced a very high flame temperature. At this temperature, ash always remains in molten condition. Metal surface temperatures of all heat transfer surfaces (as they carry water or steam) are less than the ash fusion temperature (AFT). In order to avoid the solidification of molten ash on the metal surfaces, the use of convection heat transfer should be avoided as long as the gas temperatures are higher than AFT. Till then the heat transfer must be by radiation only as in Zone I. The exit gas temperature has a profound bearing on the safe and economical operation of the boiler. The exit gas temperature should be as high as possible to provide a high temperature potential for the heat transfer surfaces located in these Zones (Zones II and III), but at the same time, it should be lower than AFT to avoid slag deposition. About 50% of the total heat generated is absorbed in the radiation zone. This value increases with fall in AFT or fall in excess air supply. Therefore, the maintenance problem becomes more severe if low AFT coal is used in a furnace designed for high AFT coal. In order to have a smaller furnace, it is necessary to have a lowest possible tube metal surface temperature. The evaporators always offer lower metal surface temperatures relative to superheats and, therefore, the evaporator is most suitable component to be located in Zone I (Radiant Zone).

The gas temperature is fairly high in Zone II and main mode of heat transfer is convection. Therefore, the slagging problem in this zone should not be neglected. Sometimes locating *panels and **platens before Zone II, brings down the gas temperature to a safer level. These panels and platens can be evaporator or superheater.

*Panels are the heat transfer surfaces at a considerably greater distance from each other. Therefore, they permit large radiant heat absorption.

**Platens are heat transfer surfaces which are closer to each other and heat absorption in platens take place by convection and radiation simultaneously.

Superheater elements are more expensive than evaporator because of their high metal surface temperature. It is desirable to locate the superheater surfaces in this region to reduce its total surface area requirement. Therefore, Zone II (high temperature convection zone) is highly preferable to locate the superheater.

The gas temperature in Zone III is relatively low so the cost of the superheater increases if located in this zone. Even though, some part of the superheater can be located at the beginning of this zone if the sufficient space is not available in Zone II. The Zone III is more appropriate and economical for locating the heat recovery units like economiser and preheater.

The required superheat temperature in a power plant increases with an increase in operating pressure. Usually beyond 100 bar, reheat becomes essential. The total amount of heat generated in the furnace is distributed among evaporator, superheater, reheater, economiser and preheater and their percentages depend upon the working condition (part or full load) of the plant and the highest operating pressure used.

The percentages distributed among different heat components as per the highest pressure used in the plant are listed in Table 13.5.

Table 13.5

Pressure (bar)	*Temperature °C*	*Approximate % of total energy needed for*			
		Evaporator	*Superheater*	*Reheater*	*Economiser & Preheater*
60	480	64	24	–	12
85	510	62.1	28	–	9.9
125	540	55.5	28.3	13.5	2.7
165	570	48.7	34.4	13.3	3.6

It can be seen from the above table that the major parameters which influence the orientation of heat transfer surfaces are pressure and temperature. In order to justify the above statement, features of four representative boilers used in different power plants in India are discussed here. The particulars of the boilers are listed in Table 13.6.

Table 13.6

Name of Power Plant	*Pressure kgf/cm²*	*Temperature °C*	*Steam Generating rate tons/hr.*	*Electrical output in MW*
Bokaro (two-boilers)	60	490	150	50
Ramagundam	90	520	310	66
Chandrapura	135	540	480	140
Trombay	175	570	520	150

It will be seen from Table 13.5 and Table 13.6, the pressures and temperatures are nearly same. The arrangement of the components of the boilers in above-mentioned power plants is shown in Fig. 13.15.

(*a*) **Bokaro-Thermal Plant Boiler.** The operating conditions are just similar to the data given at No. 1 of Table 13.5. The evaporator takes nearly 64% generated energy whereas superheater takes only 24%. Therefore, the entire furnace (E_1) is water cooled and remaining part of the evaporator (E_2) is located in the latter part of Zone II. Two drum arrangement is conventional for these operating conditions. The two drum arrangement can be replaced by panels and platens but this arrangement can lead to lower gas temperatures, at Zone II which may be highly undesirable for superheater. The superheater in this plant is totally a convective heat transfer type.

(*b*) **Ramagundam Thermal Plant Boiler.** The arrangement of this boiler surface is similar to Bokaro except the evaporator duty is slightly reduced. The low temperature section of supeheater (S_1) is introduced as widely spaced platens and the final stage of the superheater (S_2) is kept away from the flame.

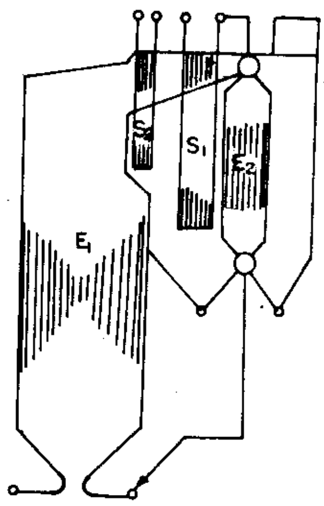


Fig. 13.15. (a) Bokaro.

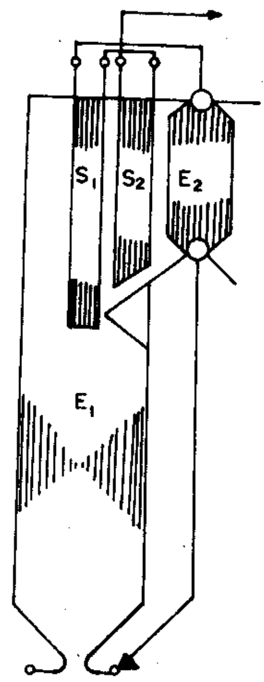


Fig. 13.15. (b) Ramagundam.

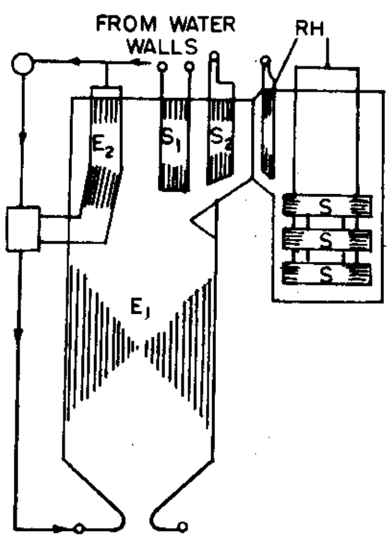


Fig. 13.15. (c) Chandrapura.

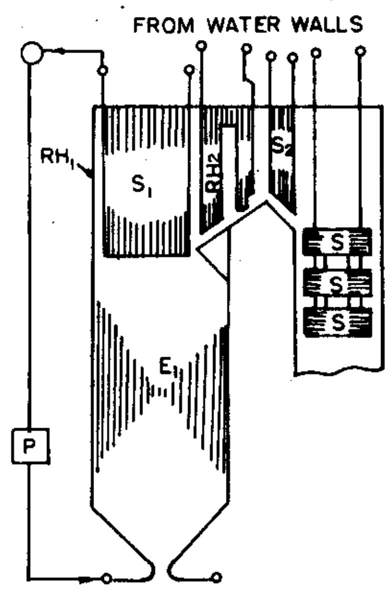


Fig. 13.15. (d) Trombay.

(*c*) **Chandrapura Power Station Boiler.** The operating pressure and temperature range in this unit is significantly high, therefore, the reheat of the steam is essential. As evaporator duty is considerably reduced (9%), it is not necessary to locate the evaporator in zone II as was needed for Bokaro and Ramagundam. Therefore, furnace walls are totally covered by evaporator (E_1) and a small portion (E_2) is located as radiant platens near the upper front wall. The Zone II is totally occupied by superheater and reheater surfaces. The part of the superheater (S_1) is platen. The reheater (RH) is in the form of platen and panel. The bulk of the superheater (BS) is located in Zone III (rear pass). It is interesting to note that the space occupied by two drum arrangement in Bokaro and Ramagundum plants is used by the superheater.

(*d*) **Trombay Power Station Boiler.** In the boiler of this plant, the evaporator duty is still decreased compared to Chandrapura and superheater and reheater duty has increased as the operating pressure and temperature are still higher. All the superheater and reheater elements cannot be located in Zone II and Zone III as the duty on these elements is increased and the space available in Zone II and III will not be sufficient. As well as all the available energy in the Zone I is not needed for evaporator. Therefore, some of the superheater elements must be located in Zone I. E is the evaporator located in the furnace wall. Widely spaced panels (S_1) and platens (S_2) are superheater elements. The reheater (RH_2) is located in between the superheater S_1 and S_2 in the form of platens. The upper front wall of the evaporator is used as reheater (RH_1) where the heat transfer mainly takes place by radiation. The rear pass or Zone III consists of horizontal banks of superheater elements (S).

It is more interesting to note that superheater elements have entered in zone I in a big way.

In super-critical boilers, double reheat is essential and in order to make high temperature zones available for superheater and reheater elements, the transition Zone (where water suddenly changes to steam at critical point) is generally shifted to the cooler sections of the boiler to accommodate superheater and reheater in hotter Zone II. The water steam circuit described earlier of Benson boiler corresponds to this arrangement.

The distribution of the heat transfer surface is also influenced by AFT, method of controlling the superheater temperature, gas recirculation in addition to the highest pressure and temperature of the steam used in the cycle as discussed earlier. Lower AFT coals require large radiant surface and superheater can be placed in the form of platens, whereas pendant type (partly by radiation and partly by convention) are more suitable with high AFT coals. An excellent control over superheat temperature can be achieved with the help of tilting burners at high operating pressures. This is achieved by changing the furnace heat absorption. The gas recirculation method plays more important role at still higher operating pressures. As the fraction of recirculated gas increases at a given steaming rate, the furnace heat absorption in Zone I decreases and available energy for Zone II also decreases. This technique preliminary used as control on superheat temperature and now has become a powerful tool in the hands of the designers to design the different heat transfer surfaces and locate their positions according to operating conditions.

13.13. FURNACE WALL DESIGN

The aim of the furnace design is to make arrangement for maximum heat release from the fuel within the combustion chamber and arrangement of sufficient heat absorbing surfaces so as to abstract the liberated heat of the fuel to the fullest extent.

The furnace is a confined space in which the fuel is burnt to liberate heat energy. Therefore, it must have suitable enclosure for burning the fuel, an arrangement for regulating the flue gases, heat absorbing surfaces and an arrangement for the disposal of residue, if any. The furnace design mostly depends upon type of fuel used, method of firing, characteristics of ash produced, evaporative capacity required and nature of load on power plant.

There are mainly three types of furnace walls used in furnace construction :

1. Refractory Walls. Solid refractory walls are used for low capacity boilers. This arrangement consists of a single section of homogeneous refractory. The materials commonly used for refractories are fire clay, silicon carbide, magnesite, and magnesia. The refractory materials can withstand high temperatures.

2. Hollow air-cooled refractory walls. In this construction, a hollow space is provided between refractory section and water casing and air is circulated through this hollow space. The circulation of air keeps the refractory walls cool. The hot air coming out of hollow space is used in the furnace.

Water Walls. In all modern high capacity boilers, the water walls are commonly used. In this arrangement, the whole combustion region is surrounded by tubes through which water flows. These tubes are backed by refractory walls. This type of water wall construction protects the refractory walls from erosion.

The water-walls are composed of a plain or finned tubes and are arranged side by side and connected at the ends to upper and lower headers of the boiler water circulation system. The furnace refractory walls are cooled totally or partially as shown in Fig. 13.16 (*a*), (*b*) and (*c*).

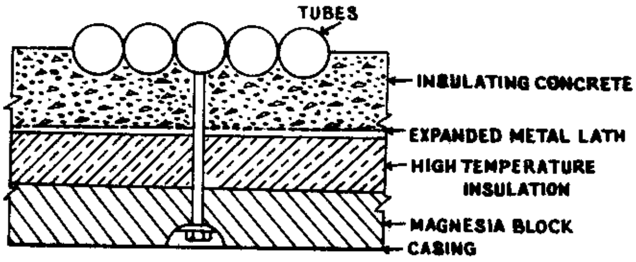


Fig. 13.16. (*a*) Touching tubes arrangement.

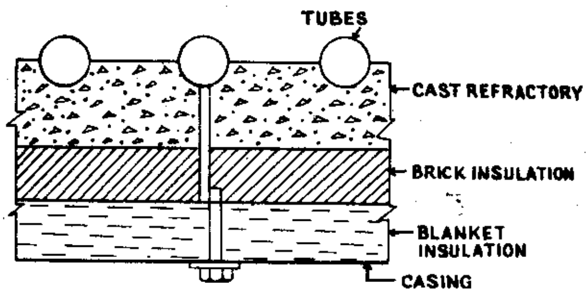


Fig. 13.16. (*b*) Half-radiant tubes cast in refractory.

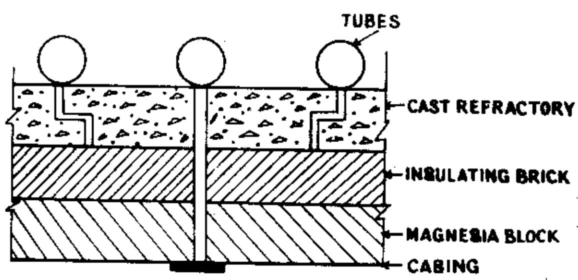


Fig. 13.16. (*c*) Tangent tubes arrangement.

The advantages of the water-wall construction over other constructions are listed below :

(1) These walls provide the protection to the refractory walls and prevent from erosion and extend the life of the furnace.

(2) The evaporation capacity of this arrangement is very high as radiant heat is directly given to the water through these tubes.

(3) Very high heat transfer rates (8×10^5 kJ/m^2-hr) are achieved with this arrangement of water circulation.

(4) With water-walls, the boiler rating is as high as 450% whereas with refractory walls it is hardly 200%.

(5) This arrangement reduces the furnace volume due to high heat transfer capacity.

(6) This arrangement is mostly suitable for pulverised fuel firing system.

13.14. TYPES OF FURNACES

1. Pulverised Fuel Dry Bottom Furnace. A tall, rectangular radiant type furnace is a common feature of a modern dry bottom pulverised fuel boilers. The purpose of increasing the height of the boiler is to lower the gas temperature at the furnace outlet and thereby reduce slagging high temperature deposits in the superheater zone. In the latest designs, the furnace walls are fully cooled by base tubes. Refractory covered tube walls have been abandoned except where low volatile coals are to be burned because it becomes necessary to reduce the cooling rate in the burner zone to maintain satisfactory ignition and burning.

The hot gases are passed through an arched baffle screening before passing the gases over convection type superheater. This induces the turbulence to the gases and even up the temperature and further increases the heat transfer rate in the convection zone.

The heat rating of such furnaces falls in the region of 600×10^3 to 800×10^3 kJ/m^2-hr.

2. Stag Type Furnace. In this type of furnace, the heat release rate is of the order of 16×10^6 kJ/m^3-hr. in the primary zone of the furnace and then the gases pass into the secondary furnace and to the outlet after passing through the convection section.

Molten slag is formed in the primary zone as heat release rates are very high. The slag formed is collected in the bottom hopper where it is chilled and breaks up into a granular form. The horizontal cyclone furnace is of this type and extensively used in USA and Germany. Such types of furnaces are not used in India anywhere. This type of furnace is characterised by a small, high temperature, highly rated primary zone into which fuel and air are introduced tangentially at a very high velocity. It is necessary to maintain high temperature for ash slagging purposes and simultaneously protect the tube-walls from overheating by providing a covering with chrome-ore.

Slag may freeze when boiler is working under low load condition unless ash fusion temperature of coal is very low. But experience has shown that the coal having slagging ash fusion factor higher than 75 can be used in slagging furnaces without any danger of freezing. The slagging ash fusion factor which is mostly dependent on the silica content is defined as

$$F_a = \frac{SiO_2}{(SiO_2 + Fe_2O_3 + MgO + CaO)} \times 100$$

3. Oil fired Furnaces. High rating of the furnace wall is possible for oil fired furnaces as flame formed by oil has high emissivity which results in a high absorption by the furnace walls. It is possible to adopt a furnace having a volume of 60% of heat required for pulverised fuel furnace for the same output.

As outstanding feature of this furnace is that special provision need not be made for ash collection at the bottom of the furnace.

Many times it becomes necessary to use coal or oil as a fuel for the furnaces, under these circumstances, it becomes necessary to design the furnace to burn the coal and not for oil. Because the adoption of the smaller furnace suitable for oil firing would result in highly rated furnace when burning coal with the consequent risk of furnace slagging. Boilers for King north power plant of 500 MW capacity are of this type.

A converse phenomenon was observed when number of coal fired boilers were converted to oil fired boilers during 1960-70 in USA. The original furnace was too large for oil firing and was unable to achieve final steam temperature because of low heat content of the gases at the furnace exit. This problem was solved by adding refractoy belt into the furnace to reduce furnace absorption, an introduction of false furnace floor to reduce the size of the furnace or by adding extra surfaces in the superheater region in the connection zone.

13.15. DESIGN CONSIDERATIONS FOR MODERN BOILERS

The factors which are responsible for the efficient design of boiler are discussed below :

1. Furnace Design. In recent years, manufacturers have designed utility boilers mere conservatively to improve availability. This is very essential in the furnace which must be sufficiently large to complete combustion of fuel and contain enough heat transfer surface in suitable arrangement, to prevent excessive slagging on the water walls and tubes. In addition to this, its design must ensure a uniform flow of flue gas with a flat temperature profile at the furnace outlet to prevent fouling and problems related to high metal temperature in the convection part of the boiler.

Depending on the slagging tendency (depends upon % ash and its fusion temperature) in the boiler, the heat input/m^2 is reduced considerably in the present design. The present trend of loading the furnace is 48 to 58 million kJ/m^2-hr. instead of 60 to 68 million kJ/m^2-hr. used earlier. To avoid the formation of NO_x and slag, heat release rate in the burner zone is also reduced by 30 to 45%.

2. Convection Pass Designs. If the convection zone is properly designed as per fuel specification, an inadequate furnace can create problems on convection section by slagging. Once the slag is formed on convection section, gas temperature in that section increases and slagging progresses further and it becomes more difficult to control. Excessive soot blowing is used to relieve the problem, it may cause erosion of the tubes which will decrease reliability. Therefore, selection of a furnace exit gas temperature is an extremely important factor in convection pass performance.

3. Flue Gas Velocity. The erosion of the convection pass tubes is proportional to the amount of ash carried by the gas but it is an exponential function of gas velocity. Even with relatively low gas velocities, harmful tube erosion can occur if localized high concentration of flyash is allowed to develop.

Earlier, the gas velocity used in pulverised coal fired boilers was 23 to 24.5 m/sec which is reduced to 20 m/sec with the past experience of erosion. In cases where ash is high and abrasive, velocity of 15 m/sec or less may be recommended. Additionally, erosion shields are also used.

4. Water Circulation. Earlier forced circulation was favoured over natural circulation for boilers operating at high pressures (150 bar) to avoid the burn-up of tubes. But development of internally ribbed tubes have solved the problem of burn-up under high heat load conditions. The ribbed tubes have provided a greater margin of safety even with natural circulation in high heat absorption area. Internal ribbing creates a centrifugal action that forces water towards the tube surface and prevents the formation of a steam film. The pressure drop with ribbed fins is slightly higher than smooth tubes and they have only marginal effect on flow circulation rates.

5. Furnace Membrane. The construction of water wall is changed in last few years. Some manufacturers have increased both diameter and tube spacing. 68 mm diameter tube with 80 mm centre to centre distance are adopted instead of 93 mm diameter tube with 100 mm centre-to-centre distance. Since furnace size remains the same for a given rating, less steel is consumed by using larger tubes and wider spacing, reducing capital ; shipping, construction and erection costs.

Heavy tube wastages are experienced at steam temperatures 570°C and above. Thus higher efficiencies offered by high temperature cycles will not come within reach until economic materials capable of withstanding the severe service conditions of coal fired boilers are developed. The metal oxide scales formed on the internal surfaces of superheater and reheater at such high temperatures remained a principle source of solid particles carried by steam into the turbine which further erode the turbine blades rapidly. Therefore new alloys must be found out to face this difficulty.

Coal Characteristics and Selection of Coal-Fired Boilers. Coal, unlike oil or natural gas, varies widely in its composition and characteristics. Therefore, before sizing the coal-fired boilers, the fuel (coal and its characteristics) must be specified.

The ultimate analysis of the coal helps to calculate the heating value of the coal and to make combustion calculations and predict boiler performance. Whereas, the proximate analysis of the coal describes its probable behaviour in the furnace. The volatile matter, moisture, ash and fixed carbon are determined by proximate analysis. The ash characteristics further decide the performance of the boiler when boiler operating is predetermined.

(*i*) **Volatile Matter (VM).** The percentage of VM provides ignition rate information. The VM content decides the burning profile which decides the rank of coal as shown in Fig. 13.17.

Low ranked coals such as sub-bituminous and lignite, generally have high VM contents consequently, they burn faster than higher ranked coals as bituminous coals. A low rank coal with high moisture must remain in the hot zone of the furnace for longer time for complete combustion. Therefore, larger furnaces are required for low rank with high moisture coals. More moisture in the coal lowers its C.V. and more fuel is needed.

(*ii*) **Ash Content and its Composition.** Ash analysis decides the rate of ash deposition on the heat transfer surfaces and nature of ash decides the rate of slagging and corrosion of heat transfer surfaces. The ash analysis is used to design the furnace with right shape, to burn the fuel completely and cool the gases sufficiently so that convection passes can be kept relatively free from ash deposition by soot blowing.

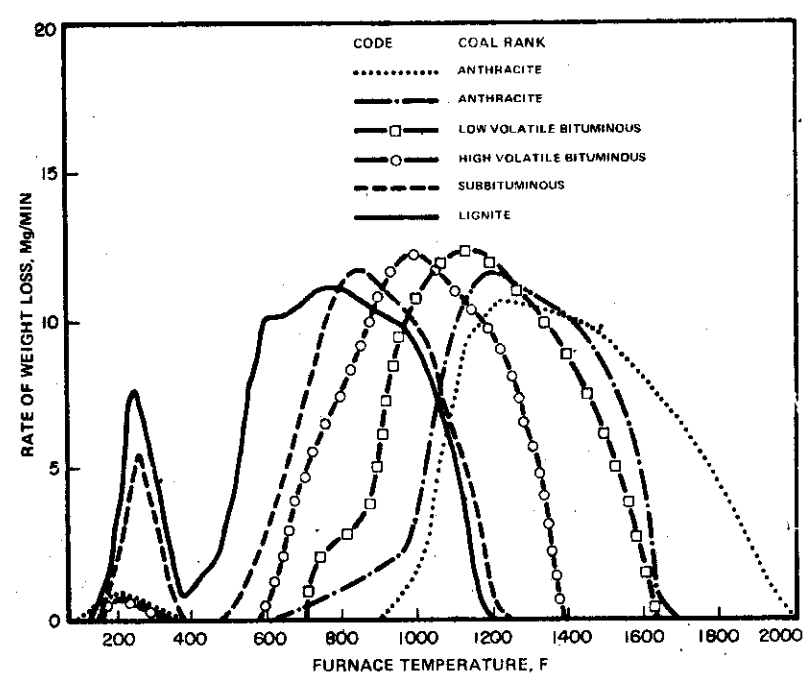


Fig. 13.17. Curves indicate the burning profiles for different coal ranks. Lower ranked coals, such as western subbituminous and lignite, burn faster than higher-ranked, low-volatile eastern bituminous coals. Because of its high moisture content, a low ranked western coal must remain in the furnace's hot zone longer for complete combustion. Consequently, larger furnaces are required for western coals.

(*a*) **Slagging and Fouling.** The mineral matters released from the coal burning in the furnace may (*i*) remain solid and pass through the boiler as flyash (*ii*) melt and become a liquid which may stick to the furnace heat transfer surfaces (*iii*) volatize and condense on convective superheater.

The chemical reactions formed at the elevated temperature between different constituents of the ash decide the nature of compounds formed. Chemical interaction of ash constituents often results in eutectic melting temperature lower than those of individual components which is responsible for ash deposition on boiler and superheater surfaces.

When the gas temperature is too high, the ash remains in molten stage and becomes sticky. The deposits on upper surface of boiler and convective zone become excessive and shutdowr of the boiler is required as plugging cannot be controlled.

Slagging results in dense and insulating deposits of molten ash on surfaces exposed to radiant heat. Slagging is a key factor in determining the number of soot blowers and their location in the furnace. For effective operation, soot blowers must be located in the molten-ash *plastic* region (viscosity of 250 to 10,000 poise) of the furnace. Below 250 poise, the slag is liquid and above 10,000 poise, it is considered solid.

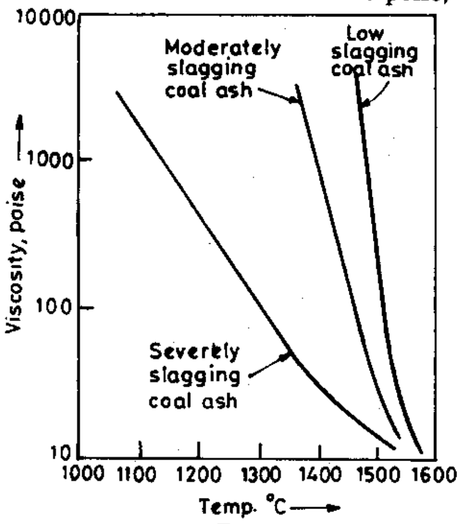


Fig. 13.18.

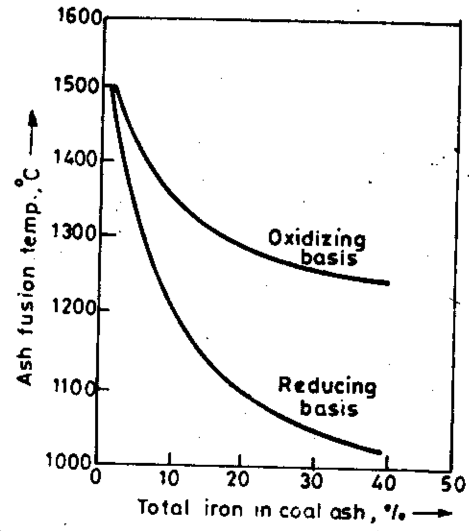


Fig. 13.19.

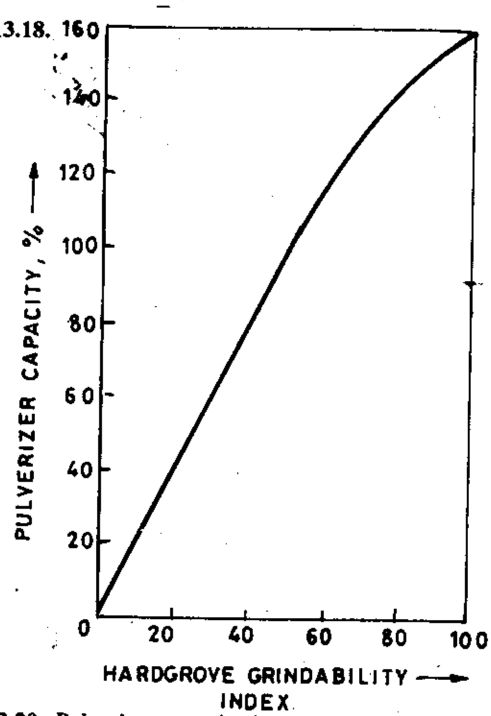


Fig. 13.20. Pulverizer capacity increases with a coal's Hardgrove grindability index. For example, a pulverizer operating at 100 percent capacity with coal having a grindability index of 50 can attain about 115 percent of rated capacity if coal with a Hardgrove grindability of 60 is substituted.

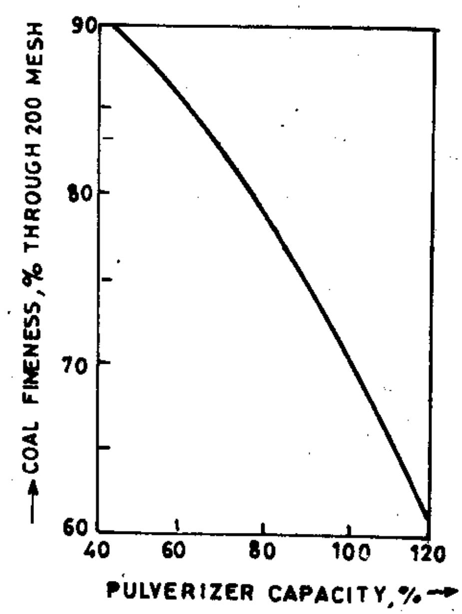


Fig. 13.21. Pulverizer capacity varies inversely with the required coal fineness. For example, a pulverizer operating at 100 percent of capacity with 70 percent fineness attains less than 80 percent efficiency if the fineness increases to 80 percent. Also, the finer the coal must be, the more energy that is required to pulverize it.

Lignite type coal has high or severe slagging potential. Most such fuels have low fusion temperatures and the viscosity temperature relationship as shown in Fig. 13.18. indicates that a greater portion of the slag's plastic zone is in the temperature range below 1200°C. Therefore, larger furnaces and more number of soot blowers are required.

(*b*) **Ash Indexes.** Fouling Index characteristics can be statistically related. Bituminous coal ash indexes have been developed with corresponding slagging and fouling classifications of low, medium, high and severe.

The slagging index for bituminous ash coals uses the ratio of basic ash to acidic ash constituents. The amount of sulphur in coal is a factor in establishing the index because half of the sulphur is ferrous sulphide. When the coal burns, the sulphur is liberated as sulfur dioxide and the iron is oxidized to ferric oxide or ferrous oxide, depending on furnace temperature. In reducing atmosphere, more ferrous oxide is generated than normal, lowering the melting temperature. Iron and its compounds, which are principal components of bituminous ash, have dominant influence on the behavior of this ash in the furnace. Fig. 13.19 shows the effect of iron on the ash fusion temperature. As the iron content increases, the difference between the ash fusion temperature under oxidizing and reducing furnace conditions increases rapidly.

Statistical methods used in developing slagging indexes for bituminous coals are not applicable for developing indexes for lignite ash. Boiler designers usually rely on the slag viscosity characteristics of lignite ash to predict slagging tendency in the furnace. A slagging index based on ash fusion temperature is sufficiently accurate with lignite ash coals.

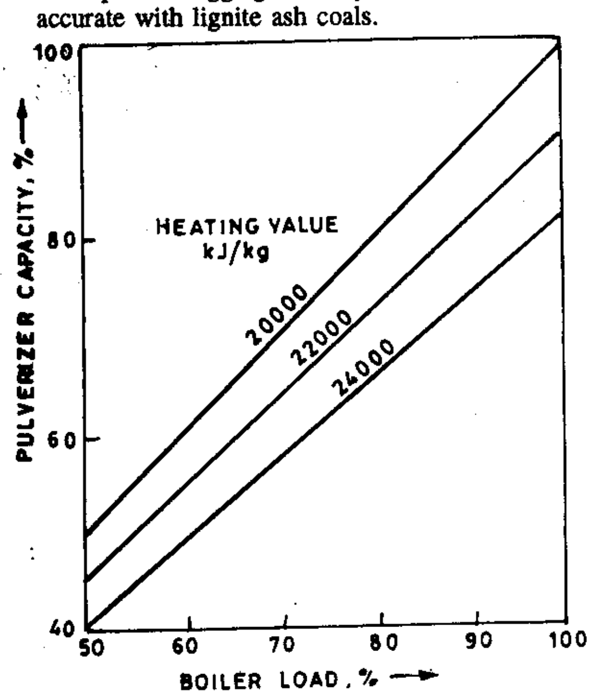


Fig. 13.22. A coal's heating value does not alter pulverizer capacity, but it does affect the amount of fuel required to provide a given boiler load. The higher the heating value is, the less coal that is required and the smaller the pulverizer that is needed.

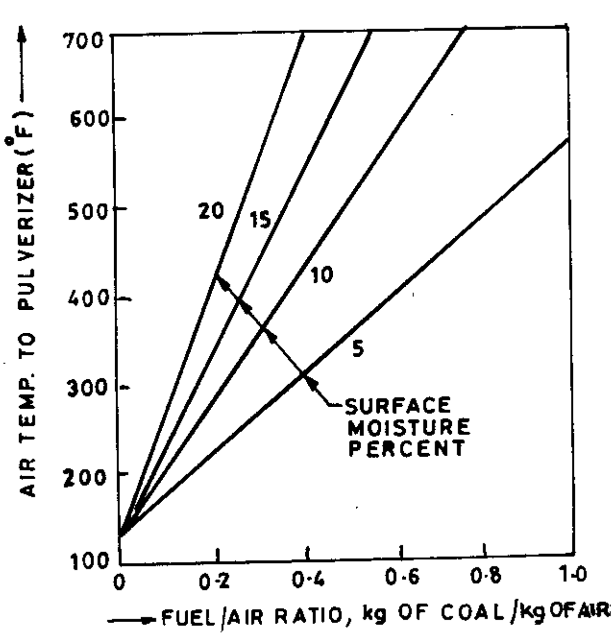


Fig. 13.23. Surface moisture must be evaporated while coal is being ground in the pulverizer. Air temperatures up to 700°F are required for coal with a high moisture content.

13.16. CORROSION AND DEPOSITION IN BOILERS AND ITS PREVENTION

Proper selection of tube material for fossil fired boilers is very essential for its safety and performance. High pressures and temperatures, corrosion, erosion and stress, all must be accommodated in the boiler tubes. In addition to this, operating procedures and maintenance also have impact on tube performance. It is also necessary to keep the tubes clean internally and externally free of deposits that could impair heat transfer and lead to corrosion, ultimately causing tube failures.

Carbon steels and ferritic alloys with small percentages of chromium (5-10%) are used for furnace walls and economisers. Carbon steels can also be used for superheater and reheater tubes provided the temperature of the steam does not exceed 500°C. Alloy-steels are recommended when steam temperature exceeds 500°C. Carbon-molybdenum steel is used at the inlet section and ferritic alloy steel with high percentage of chromium is used for downstream section of superheater. Stainless steel and high chromium steels are recommended for hotter sections (560-600°C).

Composite tubes are used when coal-ash attack is severe. A composite tube consists of an outer layer of 50% Cr, 15% Ni steel, metallurgically bonded to inner layer of Alloy 800 H. The outer layer is almost immune to coal-ash attack due to very high percentage of chromium.

Corrosion damage is always experienced inside tubes of the boiler, economiser and superheater when water chemistry is not maintained within limit as recommended by the boiler manufacturers.

To avoid the corrosion, one should understand the importance of maintaining the iron oxide coating on the internal surfaces of the boiler tubes. An iron oxide Fe_3O_4 (magnetic), a normal corrosion product that forms on steel, is protective to corrosion caused by boiler water. Once it is formed, further inside corrosion of the tubes stops. But if it is destroyed, corrosion will resume until conditions favourable to oxide formation are re-established in the system.

A few important phenomena which contribute to corrosion and possible methods to avoid them are discussed below :

(A) Water Side Problems

1. Hydrogen Induced Brittle Fracture. This occurs when boiler water pH is too low. In this fracture phenomena, H_2 atoms are produced between the deposits and tube surface and react with cementite (hard iron compound) at the grain boundaries of the tube materials to form methane gas. Overheating is not required for this reaction to occur. The formed methane gas removes carbon from metal, weakening it by creating fissures in its grain structure. This type of damage is common where condenser leakage occurs in units cooled by sea water.

2. Bulk Deposit Corrosion. It is generally caused by the concentration of soluble corrosive compounds, as alkalies (sodium hydroxide). Due to capillary action of the porous deposit formed on the surface of tubes, the alkaline liquid is drawn towards the tube surface and then it attacks on the metal and metal is eaten. The term *Caustic Gauging* is used for such type of corrosion and tube failures.

3. Corrosion Fatigue. Materials that undergo cyclic strain may suffer fatigue failure. The strain can be mechanical (vibration) or thermal (corrosion). Both accelerate the tube failure and failure may occur at lower strain in a corrosive environment. This is generally caused by a combination of high heat flux and water side deposits.

The reason for the above-mentioned failure is, corrosion product on the surface cracks and acts as wedges during boiler cool-down, causing the cracks to extend. Corrosion attacks the newly exposed surface when the boiler is fired next time, forming still deeper wedges in the next cooling phase.

4. Stress Corrosion Cracking. The superheater elements containing residual stress are susceptible to cracking in high temperature water containing chloride or hydroxide compounds and O_2. Though such conditions are relatively uncommon, they do occur.

5. Oxidation. It is a natural phenomenon in the water side when ferritic alloy steels are used at temperatures 480°C and above. All materials commonly used in high temperature superheater and reheater are subject to oxidation, although at different rates. When the oxide scale on the inner surface of the tubes becomes sufficient thick, the differential expansion between the oxides and the parent metal results in spalling of the oxide from the metal surface – a process called exfoliation. The loose flakes are hard and brittle and generally range from 1 mm to 5 mm in size. The loose scale can clog the tubes at bends, causing their failure by overheating and can damage nozzles and turbine blades along the flow path of the steam.

(B) Fireside Side Problems

Major corrosion problems in coal fired boilers are caused by coal ash. The fire side deposits are classified as fouling and slagging.

Slagging is the depostion of non-combustible molten or fused particles on furnace-tube surfaces. It is generally associated with radiant surfaces in a furnace but slagging also occurs on the superheater or re-heater tubes when molten ash is carried with the hot flowing gases.

On the other hand, fouling is the condensation of combustible constituents, such as sodium sulphate, in areas where temperature is such that, the constituents remain in liquid state. The combustibles, flyash and flue gases react chemically to form the deposits. These are generally found on convection section of the boiler.

Slagging and fouling on the heat transfer surfaces retard heat flow and therefore they should be cleaned periodically to maintain the efficiency. This is generally done by soot blowers, but when this is not totally effective, water washing during outages is used.

Certain coals produce liquid ash compounds which are very corrosive to all conventional boiler materials. The corrosion generally depends on ash properties, rate of ash deposition, tube surface temperature and chromium percentage in the tube material. If high temperature corrosion occurs inspite of design efforts, then the problem can be solved by using one of the following methods :

(1) Replacing the damaged tubes with tubes containing high chromium content.

(2) Using the fuel having more favourable characteristics.

(3) Provide stainless steel tube shields at the cost of reduced efficiency.

Low temperature corrosion generally occurs over economiser, air-preheater and stack surfaces which is discussed in more details in the next chapter.

Erosion is another *menace* faced by the boiler tubes. It is generally caused by an excessive amount of abrasive ash in the coal. This is generally caused in the lo ; temperature section of the superheater. Deflection baffles help to reduce this type of erosion. Another factor is the high gas velocity and flue gas dust loading which are taken into account at the time of designing the boiler.

13.17. EFFECTS OF INDIAN COALS ON BOILER PERFORMANCE

It is always essential to design the boiler to suit a particular type of coal so that outages should be minimum. But it is never assured that the same type of the coal will be supplied to the boiler throughout the plant life. Therefore, it is necessary to design the boiler to suit a coal having properties in a particular range.

Frequent failures and shutdowns of boilers in thermal power plants are the most reported reasons for power shortages. It is always difficult to locate the faulty area, *i.e.* maintenance, or generation or supply of coal.

The inlet temperature of steam to the turbine is one of the most important factor for better performance of the coal. This temperature is limited by the strength and corrosion resistance of the tube material which is exposed to the high temperature gases outside and to high pressure water and steam on the inside. Fossil fuel used for the generation of steam is burnt directly in the furnace of the boiler. The main objectional product of combustion is ash. In suspension firing, the ash particles are carried out of the furnace by flue gases while a part of it settles or adheres to the boiler surface. The settled material on tubes is removed by cleaning. But if the burning temperature is high, the retained ash melts and drains continuously from the furnace. Some of the melted ash forms deposits on the furnace walls and may deposit on the tubes in gas path. These deposits may lead to corrosion of the tube surface. It has been noticed that if the ash deposit on the heat absorbing surface is not cleaned regularly, shutdown of the boiler is essential. Ash deposits in coal fired boilers depend on boiler design, operating parameters and coal ash characteristics.

A few coal and ash characteristics responsible for slagging are discussed below :

(1) Type of Ash Deposits. Coal ash is carried by the flue gases to exhaust in the form of fly-ash. This fly-ash when passing through various sections of the boiler is subjected to chemical reactions and it is deposited on the tube surfaces. These deposits are divided into three types :

(*a*) **Fused Slag Deposits.** These deposits form on furnace walls exposed to radiant heat and superheaters. The slag deposits are associated with molten or sticky particles. Deposits formed outside slag-zone are removed by soot blowers. The deposits formed on water cooled walls vary in appearance and chemical composition which is dependent on coal composition and temperature adjacent to the tubes. As the thickness of deposit increases, the surface exposed to flue gases becomes plastic and removal of this plastic layer is very difficult, as soot blower fails to penetrate this plastic shell. The nature and amount of deposits formed on tubes depends upon ash characteristics, firing method and furnace temperature.

(*b*) **High Temperature Bonded Deposits.** The formation of such deposits takes place on convective heat surfaces which run at fairly high temperature. They are very troublesome because they often obstruct gas passages and are very difficult to remove with conventional cleaning equipments.

(*c*) **Low Temperature Deposits.** These deposits generally occur in air-preheater and economiser and are usually associated with condensation of acid on the heat transfer surfaces. This can be avoided by keeping the heat-transfer surfaces well above the acid dew point temperature of the gas at the cost of low boiler efficiency.

(2) Ash Slagging Parameters. The parameters which are responsible for slagging and fouling are listed below :

(*a*) Ash fusing temperature.

(*b*) Viscosity temperature relationship.

(*c*) Alkali percentage in ash.

(*d*) Base-acid ratio.

Base-Acid Ratio. The constituents of coal-ash can be classified as basic (Fe_2O_3, CaO, MgO, Na_2O and K_2O) and acidic (SiO_2, Al_2O_3 and TiO_3). The viscosity of the slag (indirectly its deposition tendency) is dependent on percentage amounts of basic and acidic constituents. The viscosity of slag decreases as base-to-acid ratio increases to one. This ratio is given by

$$\frac{B}{A} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

This ratio also decides the ash fusing temperature.

The details of the main Indian coals and ash are listed in the table given below. It can be concluded from this, the base-to-acid ratio of all coals except from Assam is less than 0.2 and therefore ash fusion temperature is high. The silica ratio is higher than 0.8 in all coals except in Assam coals. The presence of silica increases ash viscosity and provides easy removal method. The fouling index is below 0.2 except in Assam coal. Therefore Indian coals have very low slagging and fouling tendency except for Assam coal.

Table 13.7. Coal-Ash Analysis of Indian Coals

Indian Coal Field	*Coal Analysis (%)*		*Ash Analysis (%)*								*Ash Fusion Temp. (°C)*		*Slagging Parameters*			
	S	*Ash*	SiO_2	Fe_2O_3	TiO_3	Al_2O_3	*CaO*	*MgO*	Na_2O	K_2O	*Deformation Temp.*	*Flue gas Temp.*	*Base-Acid Ratio*	*Slagging Index**	*Fouling Index***	*Silica ratio****
BCCL-Mines Bihar	0.32	33	58	6.8	2.3	27	1.4	1.6	0.6	1.2	1150	—	0.132	0.04	0.08	0.855
NCL-Mines U.P.	0.27	37.3	58.9	11.8	2.24	22.8	2.9	—	0.13	1.14	1258	1600	0.19	0.05	0.024	0.80
WCL-Mines Maharashtra	2.1	33.3	58.1	6.2	1.72	27.7	1.4	2.2	—	2.13	1159	1420	0.137	0.288	—	0.847
Assam	1.4	8.3	51.1	21.9	0.68	17.0	2.75	2.17	4.28	—	—	—	0.451	0.63	--	0.656

$$\text{*Slagging Index} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} \times \%\ Na_2O \text{ in ash}$$

$$\text{**Fouling Index} = \frac{FeO_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_3} \times \%\ Na_2O \text{ in ash}$$

$$\text{***Silica Ratio} = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO}$$

The boiler performance using Indian coals as fuel is listed below. Most of the boilers are not using soot blowers as they do not face any problem from ash. Some of them use soot blowing once a day only to remove fly ash. Therefore, ash and its effects are not responsible for the outages of the boiler. It may be because of faulty design of the boiler components.

Table 13.8. Ash Deposit Pattern in Boilers of Four Thermal Power Plants

Power Station	*Cleaning Details*	*Ash Deposit Pattern*
Station-A 140 MW Station-A 120 MW	Soot blowers not used. Soot blowers not used.	No ash formation. No ash formation.
Station-B 60 MW Station-B 110 MW	Soot blowing is done in furnace in all 3 shifts and superheater after 3 days. Soot blowing is done in furnace once a day.	Heavy slagging ash deposition on superheater. Ash deposition lies in tolerance level.
Station-C 110 MW Station-C 50 MW	Convection zone once a day. Soot blowers are used in all 3 shifts.	No objectionable deposits. Heavy slagging in superheater.
Station-D 4 × 120 MW	Soot blowers are used in water wall but not with superheater.	No formation of ash is observed any-where.

13.18. CAUSES OF BOILER TUBE FAILURES AND PREVENTION

In modern power plants, the outages of boilers due to tube leakages vary from 10 to 15% of the total outages. With the introduction of 200 and 500 MW capacity boilers, this problem will aggravate further if not combated in the initial stages.

The basic causes of the tube failures are corrosion, stress cracking, thermal fracture, stress rupture and creep distortion.

Control of the water and/or steam environment inside economiser, boiler, superheater and reheater tubes is a pre-requisite for trouble-free performance of a fossil-fired steam generator. When the water and steam chemistry are not maintained within limits recommended by the boiler manufacturer, corrosion or corrosion-related damage may occur in water wall and economizer tubes. And overheating damage may occur in these tubes as well as in superheater and reheater tubes, if poor water treatment and improper boiler operation permit deposits to build up in them.

The overheating of the boiler tubes is the main cause of their failure.

1. Corrosion

The iron reacts with O_2 in presence of water to form iron oxides and hydroxides and the reaction rate depends upon the temperature level.

Internal corrosion of boiler tubes is a major cause of forced outages. It is revealed that about 20% of the boilers operating above 120 bar faced corrosion problems. One of the first things, the operating staff must understand an importance of maintaining the iron oxide coating on the internal surfaces of boiler tubes. This oxide (Fe_3O_4), a normal corrosion product that forms on steel exposed to boiler water, is protective. Once it is formed, corrosion of steel stops. But if it is damaged, corrosion will resume until conditions favourable to oxide formation are re-established in the system.

Fig. 13.24 shows the relative corrosion rate of carbon steel as acid and alkaline concentrations in the boiler water increase. In the pH range from low-acid to low-alkaline, the oxides on boiler tubes are fully protective. When the pH is excessively high or low, the protective oxide is consumed by the corrosive action of acid or alkaline salts in the water. Corrosion rates under these conditions accelerate with increasing concentration. Thus, the primary purpose of a boiler-water treatment is to maintain a low concentration of potentially corrosive salts so the oxide coating remains intact. The iron and copper corrosion can be reduced by maintaining water pH value between 8 and 10. Corrosion starts below 6 pH. At pH 4, the corrosion rate is 25 times of normal and at 3.2 pH, the corrosion rate is 100 times of normal.

Two widely used boiler-water treatments are available to protect steam generator tubes against corrosion are volatile and phosphate controls.

Volatile Control. In this method, volatile neutralizing amine (NH_3) is used to maintain pH that will not disrupt the protective coating on the boiler tubes. The advantage of this system is that it does not contribute additional dissolved solids to the boiler water and minimizes the solid carried in the superheater by the steam. The major disadventage is, it does not provide any protection against contaminants, such as salts carried into the boiler by condenser cooling water leakage.

Phosphate Treatment. It maintains pH in proper alkaline range to protect the preventive layer and it reacts with salt contaminants to prevent the formation of free NaOH or acidic compounds. Phosphate was chosen for this purpose because it is able to react with these contaminants and it does not become corrosive when concentrated.

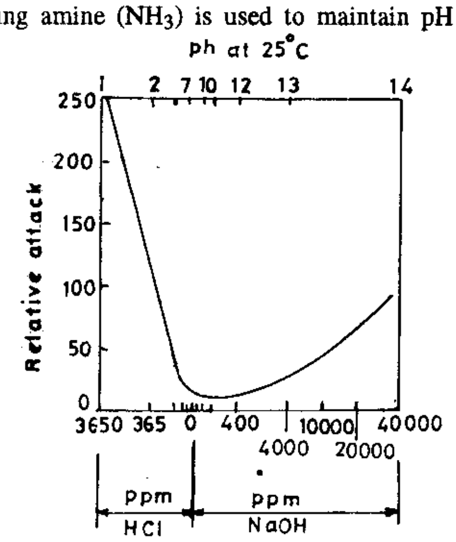


Fig. 13.24.

Another cause of overheating is the scaling of the tubes. The major source of scaling is not corrosion but dissolved solids in the boiler water, like carbonates, bicarbonates and sulphates of calcium, magnesium and sodium. The scaling in the boiler tubes leads to severe overheating and also pitting of the tubes which are mainly responsible for tubes failure.

The effect of scaling on the reduction of heat transfer is shown in Fig. 13.25 for different sludges. The method commonly used to reduce deposits is described below.

Solubilizing Treatment. Hardness ions remain in soluble form rather than forming precipitators, therefore the potentials for agglomeration and sludge binding are greatly reduced.

Solubilizing antiscalants may be sub-classified into two categories, those which react stoichiometrically with feedwater impurities to change their chemical structure and those which alter the action of the impurities. The stoichiometric reactants are known as *chelants.*

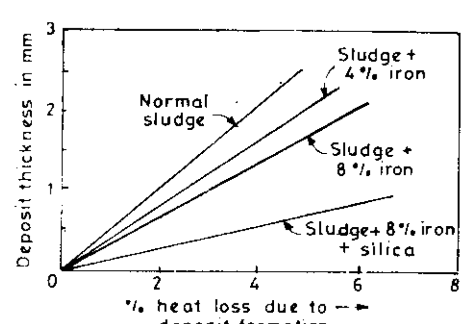


Fig. 13.25.

Two most common chelants used in boiler water treatment are sodium salts of ethylene diaminetetroacetic acid (EDTA) and nitrilotriacetic acid (NTA). These compounds react in a mole to mole ratio with divalent and trivalent cations to form soluble heat stable complexes. Calcium ions in the feedwater and boiler water are tied up by the chelant and are prevented from combining with carbonate, sulphate and silicate anions to form scale. Properly applied chelants effectively prevent calcium related deposit problems.

Magnesium ions present a more difficult problem for a chelant program. In feed water with pH 7 to 8.5 both EDTA and NTA chelate prevent it from causing preboiler deposits. However, magnesium chelation in the boiler is seldom complete because at the higher boiler water pH, there are strong competing reactions from hydroxide and silica for the magnesium. Even when utilizing a chelant program, some precipitation of magnesium hydroxide (brucite) occurs. A polymeric or natural organic sludge conditioner may be incorporated into a chelant program to help disperse magnesium sludges.

The chelant's ability to prevent iron related deposition is of great importance because of the higher feedwater iron concentrations currently found. Much of the improvement results over phosphate program because there is less sludge available for iron binding. Chelants are limited in their ability to form complex iron deposits in boilers with a high hydroxide concentration. Although both EDTA & NTA have relatively strong affinities for ferric iron (Fe^{+3}), the great insolubility of ferric hydroxide presents a competitive reaction that the chelant cannot overcome. Ferrous iron (Fe^{+2}) while not forming as stable a chelant complex is the ferric form, can be more readily chelated because of the greater solubility of ferrous hydroxide, which makes more ferrous ions available for the chelation reaction.

A major disadvantage of the use of chelant is the control required for its effectiveness. A low residual of free chelant must be kept in the boiler because of its cost and potential corrosiveness of high chelant concentrations. Low residual level makes a chelant program highly sensitive to upset in feed water quality. For example, if a 10 ppm NTA residual is maintained in the boiler, it can be completely exhausted by 4 ppm calcium hardness. If the boiler is operating at 20 cycles of concentration, a slippage of 0.2 ppm of calcium into feedwater consumes the entire residual and creates a condition in which calcium scale can rapidly form.

The outer surfaces of the tubes are subjected to ash corrosion when the temperature range is between 540 to 710°C. Alkali sulphates, which are formed at high temperature in vapour form, deposit on the tube surfaces and corrosion starts. This type of corrosion thins out the tube walls to such an extent that metal ruptures under the working pressure.

2. Erosion

The outer surface erosion of the water tubes is caused by an abrasive action of ash particles in the gases. Erosion is enhanced by high flue gas velocities. Erosion creates spots, wall thinning and finally tube failure.

The erosion of the inner surface of the tubes is caused by cavitation when the gas filled bubbles collapse, a cavitation occurs in that region and causes heavy erosion.

The water side corrosion is controlled by removing dissolved solids, O_2 and controlling pH value of feed water.

Fire side corrosion cannot be totally eliminated but it can be minimised by purging the gases periodically and controlling the excess air supplied to the combustion chamber. Additives are also used to control the fire side corrosion and fouling. Fly ash erosion also cannot be eliminated but can be reduced by baffles and tube shields can be welded in the maximum affected zones to minimise the failure.

Quality of Feed Water Required in Modern Boiler

Conductivity ——	0.3 μΩ/cm
Hydrazine ——	0.01 – 0.02 ppm
pH value ——	8.8 – 9.2
O_2 ——	< 0.007 ppm
Iron ——	< 0.01 ppm
Cu ——	< 0.005 ppm
Ni ——	< 0.005 ppm
CO_2 ——	Nil
Silica ——	0.02 ppm

EXERCISES

1. List out the major advantages of high pressure boilers in modern thermal power plants.
2. Draw a neat line diagram of Benson Boiler and discuss its relative merits and demerits.
3. Draw a neat diagram of a Volex Boiler and discuss its merits and demerits with Benson Boiler.
4. What do you understand by supercharged boiler ? Explain its working with a neat diagram. What are its advantages over conventional boilers ?
5. What are the major zones of Boiler ? What are the considerations in locating the Superheater and Economiser ?
6. What are the basic differences between the panels and platens ? Illustrate their locations giving some examples of Indian boilers with figures.
7. What are the different types of walls used in the furnace of modern boiler ? Discuss their relative advantages and disadvantages.
8. What factors are mainly considered in the design of a boiler used in power plant ? Discuss the significance of each with details.
9. What are the main problems encountered to the water side of the boiler tubes ? How these are solved in practice ?
10. What is the difference in fouling and slagging and what are their effects on the boiler performance ? How these problems are solved in practice ? What measures are taken if there is excessive slagging at the time of running the boiler ?

□□□

14
Boiler Accessories

14.1. INTRODUCTION

An huge quantity of fuel is used in thermal power plant and very large quantity of heat is carried by the exhaust gases. The heat carried by the exhaust gases per hour from 100 MW plant is of the order of 300×10^6 kJ as 25% heat remains in the exhaust gases. This loss can be halved by installing an economiser in the flue gases. In the present age of costly fuel, it has become necessary to conserve the fuel by utilizing the wasted energy to the atmosphere. This is done in all modern power plants by incorporating economiser and air preheater. By increasing the temperature of feed water passing through the economiser using waste heat of gas, the quantity of heat given per kg of steam generated in the boiler is reduced. Similarly the temperature of the air is also increased by passing through the air preheater using remaining waste energy of the gases. The preheated air increases the combustion efficiency in the furnace and reduces the fuel loss. In both equipments, the quantity of fuel is reduced by extracting the heat from the exhaust gases.

The common equipments used in thermal power plants to increase the thermal efficiency are economisers, and air pre-heaters. The heat carried with the flue gases is partly recovered in air pre-heaters and economisers and reduces the fuel supplied to the boiler. The preheating of air with the gases increases the combustion efficiency and reduces the fuel consumption. The erosion loss due to condensation in the later stage of turbine (efficiency loss also) is also partly reduced by increasing the temperature of steam above saturation. The adoption of these devices as far as economical justification is concerned depends upon the capacity of the plant. Practically all large capacity power plants can justify the installation of heat reclaiming devices from flue gases.

The adoption of one or both equipments (economiser and air preheater) depends upon the economical justification. It is also equally essential to maintain the performance of these equipments by preventing corrosion and fouling from inside and outside, otherwise the gain from these equipments reduces rapidly with respect to time. The corrosion is generally prevented by using proper materials for the equipments and controlling the flue gas temperature to avoid the condensation of corrosive gases carried by the exhaust gases.

14.2. ECONOMISERS

The economiser is a feed water heater deriving heat from the flue gases discharged from the boiler. The justifiable cost for economiser depends on the total gain in efficiency. In turn, this depends on the gas temperature out of the boiler and feed water temperature to the boiler. Regenerative cycle inherently gives high feed water temperature, therefore the adoption of economiser must be studied very carefully. A typical return bend type economiser is shown in Fig. 14.1.

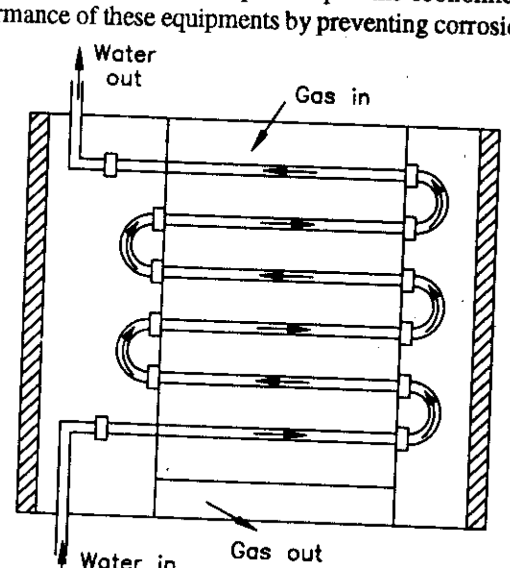


Fig. 14.1. Return bend economiser.

A boiler producing between 10 to 100 tons of steam per hour and operating at 30% or more load should be evaluated for possible retrofitting with an economiser. The cost benefits depend upon the boiler size, type of fuel used and exhaust gas temperature. It has been estimated that about 1% of fuel costs can be saved for every 6°C rise in the temperature of the boiler feed water. Saving upto maximum 20% can be achieved by incorporating economiser where boiler operates very efficiently as shown in Fig. 14.2.

When more heat is available, that can be used in increasing the sensible heat of the feed water or pass it through an air heater. However, in most economisers, the feed water is not heated higher than to within 25°C of the temperature corresponding to the saturation temperature of steam in the boiler thus preventing steam formations in the economiser.

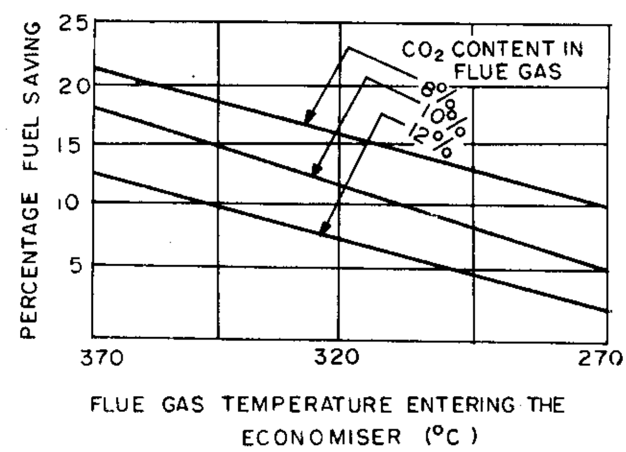
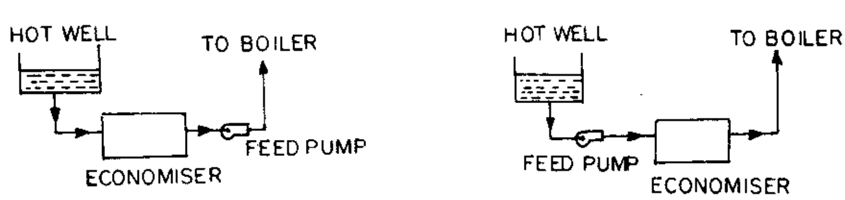


Fig. 14.2. Flue gas temperature entering the economiser (°C) on full saving.

A water temperature of 85°C in the hot well is the maximum at which the feed pump works satisfactorily, as there is a slight negative pressure on the suction side of the pump. At temperatures over 85°C, steam bubbles begin to form and the boiler feed pump will not be able to pump steam and water and flow stops. Therefore, the feed water is pumped through and heated in the economiser. Since it is on the pressure side of the pump, the water can be heated to a much higher temperature than the hot well temperature. The maximum temperature to which the water can be heated in the economiser is 25°C below steam forming temperature in the boiler. The following table gives the maximum temperatures for varying pressures and the possible fuel savings for different hot well temperatures.

Pressure and Saturation temp. in the boiler		*Max economiser outlet temp.*	*Percentage fuel saving using economiser with different hot well temp.*		
kg_f/cm^2	°C	°C	45°C	65°C	85°C
8	174.5	149.5	17	14	10
13	194.1	169	20	17	14
18	208.8	183	23	19	16

The correct position of the economiser is shown in Fig. 14.3.



(*a*) Wrong position of economiser. (*b*) Correct position of economiser.

Fig. 14.3.

Design Requirements for an Economiser. The design requirements must statisfy the following conditions :

* The heat transfer surface should be minimum.
* It must be able to extract maximum possible heat from exhaust gases.

* The height of the tube banks should be minimum so the cleaning on load can be done effectively.
* The gas side pressure loss should be minimum to reduce the running expenses of I.D. fans.
* There must be uniform water flow to avoid the steam formation in the economiser. The pressure loss of water side must be also minimum to reduce the running expenses of the pump.
* There must be ample allowance for expansion under all operating conditions without setting up excessive stresses in any of the components.
* It must fit dimensionally with the preceding unit, usually the primary superheater.
* There must be connection from steam and water drum to the economiser inlet header, to permit the free circulation of water around the economiser to prevent the overheating and boiling during the period when there is no feed-flow during early pressure rising stages.

Types of Economisers. Basically there are two types of economisers as discussed below :

(1) Plain Tube Type Economiser. Plain tube types are generally used in Lancashire boiler working under natural draught. The tubes are made of cast iron to resist corrosive action of the flue gases and their ends are pressed into top and bottom headers.

An economiser consists of a group of these cast iron tubes located in the main flue between the boiler and the chimney. The waste flue gases flow outside the economiser tubes and heat is transferred to the feed water flowing inside the tubes. The external surfaces of the tubes are continuously cleaned by soot scrapers moving up and down. High efficiency of the economiser can be maintained by preventing soot deposition which is a bad conductor of heat.

(2) Gilled Tube Type Economiser. A reduction in economiser size together with increase in heat transmission can be obtained by casting rectangular gills on the bare tube walls. Cast-iron gilled tube economisers can be used upto 50 bar working pressure and such economisers are indigenously available. At higher pressures (> 50 bar), steel tubes are used instead of cast-iron but cast iron gilled sleeves are shrunk to them.

Economisers also may have bare or finned tubes. Bare tubes are specified for dirty fuels but the use of finned tubes in high fouling fuel applications has increased significantly over the past few years.

The choice of finned tubes for an application depends on cost, reliability of the bond between fin and tube, temperature and material limitations and extent of corrosion and fouling as well as on heat transfer and pressure drop requirements.

A wide variety of materials is available for finned tube construction. The choice for each depends on corrosion problems. Finned tubes are constructed from carbon steels, stainless steels and high grade corrosion resistant alloys. 150 to 200 fins per metre are commonly used on the economiser tubes used in clean fuel applications. 80 fins/metre are used when dry solid fuels are used and 120 fins/metre are used when oil fuels are used. When high fouling fuels are used, ample clearance is left between fins, mainly to avoid the bridging effects caused by soot deposits.

Fin thickness ranges from 0.5 mm to 5 mm. Thick fins offer greater heat transfer efficiency than thin fins and reduce total heat transfer surface requirements. In addition to this, thicker fins have greater resistance to gas side erosion and lower fin tip temperature. This is very important in material selection. For example, an extra thick carbon steel fins may eliminate the need for a higher cost alloy fins.

Corrosion of Economiser and its Prevention. The corrosion and its prevention are very important for safe and efficient working of the economiser. Internal and external corrosion are the primary enemies of an economiser and dissolved O_2 and CO_2 are the major culprits.

A properly designed deaerator, combined with water treatment plant, virtually eliminates internal corrosion in the economiser tubes. Deaeration removes 95% dissolved O_2 and CO_2 from the feed water. Vigorous steam scrubbing with chemical assist should follow deaeration to ensure complete O_2 removal and corrosion control.

CO_2 forms carbonic acid (H_2CO_3) when it dissolves in water. This compound is unstable and ionizes into H_2 ion (H^+) and bicarbonate radical (HCO_3^-). The HCO_3^- further ionizes to form the H^+ ion and carbonate ion (CO_3^-). The H_2CO_3 is the only one that exerts gas pressure, therefore, CO_2 must be removed by deaeration at low pH levels.

NH_3 gas forms NH_4OH (ammonium hydroxide) upon dissolving in water. NH_4OH ionizes to form NH_4^+ and OH^- ions. Therefore NH_4OH is responsible for exerting gas pressure and it must be removed by deaeration at higher pH.

The pH value of water passing through economiser should be maintained between 8 and 9 to reduce its effect of acid. CO_2 removal is achieved at low pH and NH_3 removal is achieved at high pH, therefore complete degasification of flow containing combination of two is very difficult to achieve through deaeration alone.

An O_2 scavenger, such as hydrazine sodium sulphite, is used to provide total protection against inside pitting of the tubes.

External corrosion of the economiser tubes is very serious when high sulphur content wet fuels are used in boiler furnaces as the chances of forming H_2SO_4 are more. External corrosion occurs if water vapour in the flue gases condenses at tube surfaces. Reduced tube surface temperature and presence of SO_2 in exhaust gases amplify the corrosion rate. The corrosion rate is a function of the concentration and strength of H_2SO_4, the length of time acid contacts the metal surfaces and metal used for the tubes.

Sulphurous acid is created when SO_2 is dissolved in free moisture in the flue gas, sulphur trioxide may combine with superheated water vapour to form H_2SO_4 at the acid dew point. This reaction usually occurs between 115°C to 140°C under normal boiler operating conditions. Figure 14.4 presents the useful data for preventing external corrosion. It shows design criteria for minimum recommended feed water temperature and acid dew point for various sulphur percentages. Maintaining feedwater temperature at levels indicated in the figure optimizes the potential for low temperature corrosion attack on economisers, even when high sulphur fuels are used in the thermal plants.

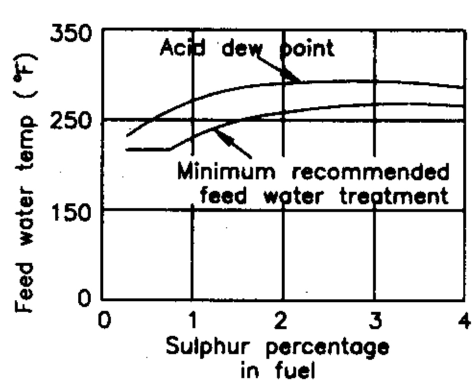


Fig. 14.4. Minimum recommended feedwater temperature for reducing or preventing external corrosion.

The figure also shows that higher the difference between minimum feed water temperature and acid dew point, higher the safety to the economiser but at reduced efficiency.

Figure 14.5 shows minimum safe metal tube temperature for various fuels and sulphur percentages. The rate of acid formation increases with higher amount of excess air and with each degree reduction in the tube surface temperature. Determining the optimum operating point is a delicate issue because every degree rise in feed water temperature affords a greater safety factor against extrnal corrosion, however, economiser efficiency decreases.

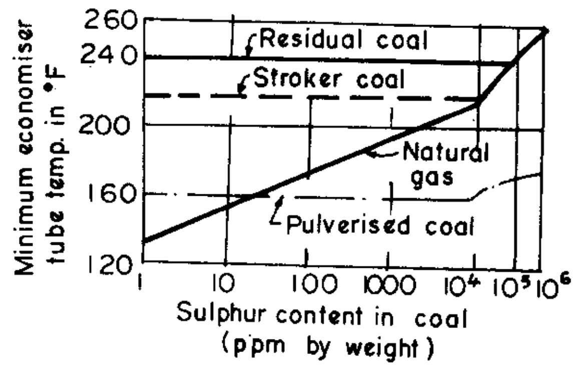


Fig. 14.5. Minimum safe tube temperature for various fuels and sulphur content.

The progressive changes in the operating conditions in the modern power plants have resulted in higher feed water supply temperatures and this has reduced the possibility of cold end corrosion. This fact can dispense the use of costly materials for economiser and therefore economisers with mild steel extended surfaces can be used in the modern power plants. If low sulphur coal is used where chances of carrying sulphur trioxide with the gases are less, the inlet feed water temperature may be much lower provided an adequate margin is held above the acid dew point.

If the low inlet temperature of the feed water is the cause of cold end corrosion, it can be corrected by heating the water with the help of steam from the boiler in the shell and tube heat exchanger. The quantity of steam can be controlled using a thermostatic valve as shown in Fig. 14.6.

Acid corrosion also damages steel stack if the temperature of gas entering the stock falls below its dew point temperature. Proper stack insulation (to prevent the flow of heat from the gases to atmosphere) to keep the wall temperature above the acid dew point is the first step in minimizing the problem. Corrosion resistant materials or high temperature corrosion resistant linings are also used.

Economiser tubes should be designed to withstand maximum attainable flue gas temperatures when dry. This feature, plus an economiser feedwater bypass loop, allows the boiler to operate safely when the economiser is out of service. To maintain the economiser clean, adequately sized access doors should be specified to allow regular inspections, maintenance and repairs.

If it becomes necessary to keep the economiser in non-working conditions (for a month or more) then it is always preferable to keep it dry. For dry storage, the economiser should be drained, cleaned and dried. Hygroscopic deposits should be thoroughly cleaned with a high pressure water spray to prevent fire side corrosion during shut-down.

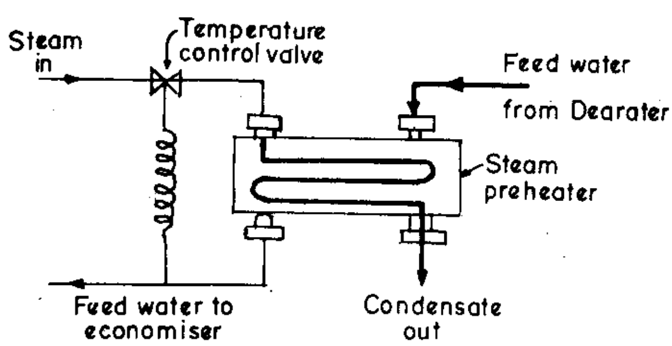


Fig. 14.6. Feedwater preheat system to control cold end corrosion.

If the downtime is small, wet storage is suitable. For wet storage, the economiser should be filled to the normal water level with treated and deaerated feed water. An appropriate dosage of hydrozine and NH_3 and sodium sulphite should be added to the feed water and boiled for one hour before supplying to the economiser.

Other advantages of the Economiser. There are several indirect advantages obtained by installing an economiser with a boiler plant as listed below :

(1) The feeding of the boiler with water at a temperature near the boiling point reduces the temperature differences in the boiler, prevents the formation of stagnation pockets of the cold water and thus reduces greatly the thermal stress created in the pressure parts of the boiler and promotes better internal circulation.

(2) When the feed water is not as pure as it should be, the temporary hardness is deposited on the side inside of the economiser tubes and while this necessitates internal cleaning of the economiser, the evil is not as great as internal cleaning of the boiler.

The temperature experienced in economiser is not as high as in boiler, the salts are deposited as a soft sludge and can be blown down through the economiser through blow-off value instead of forming a hard scale inside of the boiler.

Even where the unwanted hardness is deposited as hard scale on the inside of the economiser tubes, the economiser can be bypassed for internal cleaning without putting the boiler out of operation.

(3) Due to the reduction in the combustion rate of the furnace, the boiler will be more efficient and the actual fuel saving will be greater than the theoretically calculated.

(4) The flow of flue gases over the economiser tubes acts indirectly as a grit arrester and large portion of the soot and fly-ash is deposited on the tubes and scraped off into the soot chamber. This reduces the omission of soot and fly-ash.

14.3. AIR PREHEATERS

The heat carried with the flue gases coming out of economiser is further utilised for preheating the air before supplying to the combustion chamber. It has been found that an increase of 20°C in the air temperature increases the boiler efficiency by 1%.

The air heater is not only considered in terms of boiler efficiency in modern power plants, but also as a necessary equipment for supply of hot air for drying the coal in pulverised fuel systems to facilitate grinding and satisfactory combustion of fuel in the furnace.

The use of preheater is much economical when used with pulverised fuel boilers because the temperature of flue gases going out is sufficiently large and high air temperature (250 to 350°C) is always desirable for better combustion.

Air heaters are usually installed on steam generators that burn solid fuels but rarely on gas or oil fired units. By contrast, economisers are specified for most boilers burning liquid or gas or coal whether or not an air heater is provided.

The principal benefits of preheating the air are (1) improved combustion, (2) successful use of low grade fuel (high ash content) (3) increased thermal efficiency, (4) saving in fuel consumption and (5) increased steam generation capacity (kg/m^2-hr) of the boiler.

The air-preheater must provide reliability of operation, should occupy small space, must be reasonable in first cost and should be easily accessible.

The air-heaters are not essential for the operation of steam-generator but they are used where a study of the costs indicates that some money can be saved or efficient combustion can be obtained by their use. The decision for its adoption can be made when the financial advantage is weighed against the capital and maintenance cost of the heater. The decision cannot be taken so easily as the economic advantages of hot combustion extend to the size of the boiler, the efficiency of combustion, maintenance of furnaces and the saving in heat discharged to the chimney.

The different types of air-heaters which are in use are discussed below :

The air-preheaters are generally divided into two groups as recuperative and regenerative type.

The recuperative heaters continuously transfer the heat from hot gases to cold air. The regenerative heater alternately gets heated and cooled by the hot gases (absorbing heat) and cold air (dissipating heat). Unlike the recuperative type, the regenerative is discontinuous in action and operates on cycle. In rotary regenerative type, the cyclic action applies to the heating and cooling of an individual element of the surface but the flowing stream of air receives heat continuously.

The two recuperative types of heat-exchangers which are commonly used for air-heating are described below :

Tubular Air-heater. A typical arrangement of tubular air-heater is shown in Fig. 14.7. The flue gases flow through the tubes and air is passed over the outer surface of the tubes as shown in figure. The horizontal baffles are provided as shown in figure to increase time of contact which will help for higher heat transfer. In some design, tube-row staggering is used to improve the air-distribution. The steel tubes 3 to 10 m in height and 6 to 8 cm in diameter are commonly used.

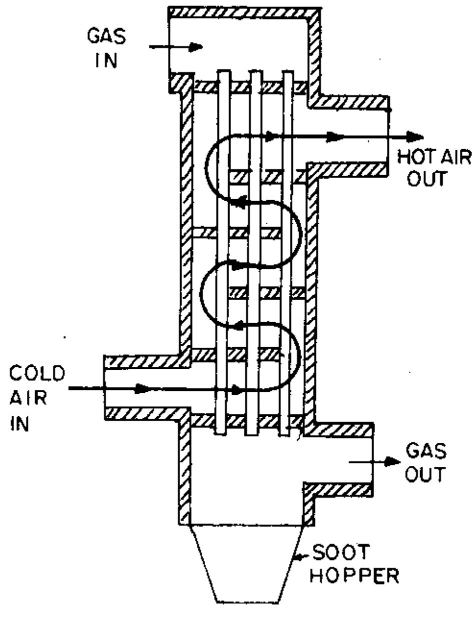


Fig. 14.7. Tubular air-heater.

Plate Type Air-heater. A plate type heater is shown in Fig. 14.8. It consists of rectangular flat plates spaced from 1.5 to 2.5 cm apart leaving alternate air and gas passages. This type of air-heater is not used in modern installations as it is more expensive both as to flat cost and maintenance cost compared with tubular air-heaters.

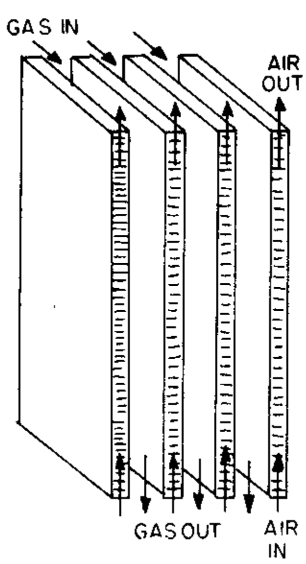


Fig. 14.8. Plate Air-preheater.

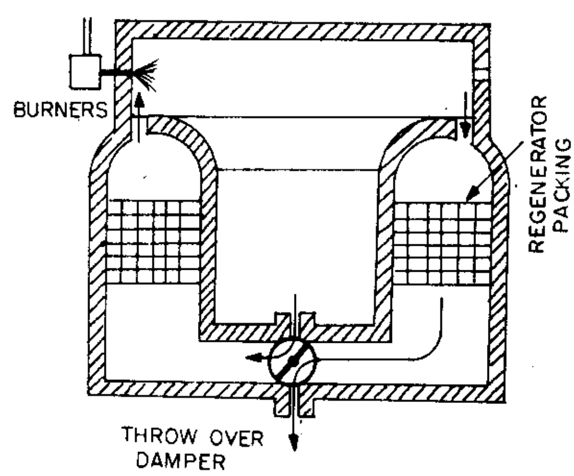


Fig. 14.9. Regenerative heatings.

Regenerative Heat Exchangers. A typical type of stationary regenerative heat exchanger is shown in Fig. 14.9. The transfer of heat from hot gases to cold air is divided into two stages. In the first stage, the heat of the hot gases flowing through the heat-exchanger is transferred to the packing of the heater and it is accumulated in the packing and the hot gases are cooled to sufficiently low temperature before exhaust to atmosphere. This stage is referred to as "Heating period". In the second stage, the cold air is passed through the hot packing where the heat is accumulated and the heat from the packing is transferred to the cold air. This stage is known as "Cooling period".

Two such packings are required in stationary regenerative heater as shown in figure. The period of heating, the period of cooling, the amount of packing required depends upon the mass of gas and air flowing through the packing, the initial and final temperatures of the gases and rise in temperature of the air required.

A rotary type regenerative heat exchanger is described in the chapter of gas turbine power plants so the readers are requested to see the same.

For continuous operation of air-heater, an arrangement must be made to clean the heating surface, particularly gas side. This is done in practice by providing openings for the use of brushes and steam lances or by permanent soot blowers. Hoppers are also provided to accumulate soot at the bottom of the heater.

Acid Corrosion in Air-Heaters and its Prevention. Combustion of sulphur in coal results in the formation of SO_2 and about 3 to 5% of the SO_2 is oxidized to SO_3 depending on O_2 content, moisture and temperature of the flue gas. The SO_2 and SO_3 may then combine with moisture in the flue gas to form sulphurous and sulphuric acids. Sulphurous acid will not form above the dew point temperature and is seldom a problem. However, sulphur trioxide is hygroscopic and absorbs moisture at temperatures well above the dew point, resulting in the formation of a sulphuric acid mist. The temperature at which this acid mist condenses to form sulphuric acid is called acid dew point. The condensed acid causes heavy corrosion of the metal surfaces.

Flue gas from coal fired boilers usually has a water dew point in the range of 95 to 120°F but the acid dew point ranges from 130°F to 400°F, depending on the sulphur content in the fuel. Figure 14.10 shows acid dew point temperature as a function of SO_3 concentration in the flue gas. The wide band shows acid dew point range. High excess air promotes oxidation of SO_2 to SO_3 which raises the acid dew point as well as high moisture content also increases the acid dew point.

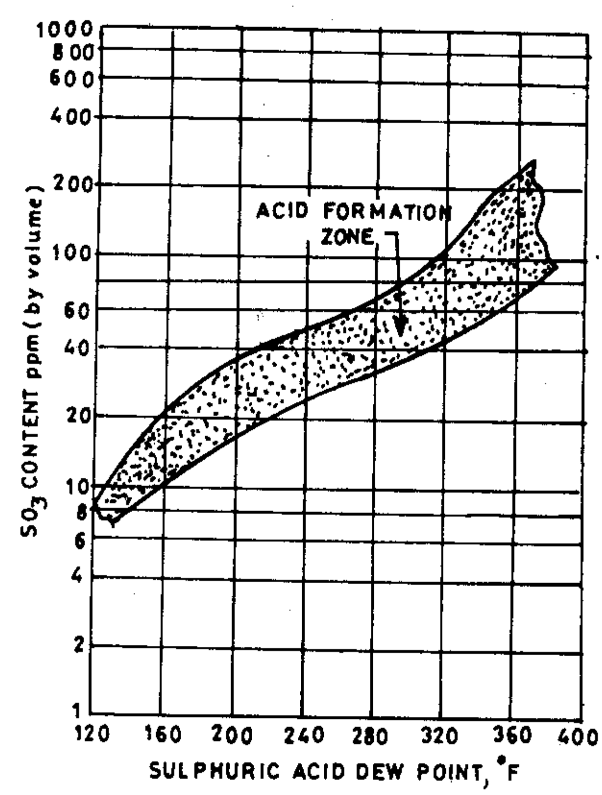


Fig. 14.10. Sulphuric acid dew point as a function of SO_3 content in flue gas, for coal-fired boilers.

To avoid acid condensation and corrosion, air heater manufacturers recommend minimum cold end temperature based on dew point temperature and experience. But uncertainty involved in predicting the acid dew point as it covers a wide band, better protection in coal fired boilers is assured by using acid dew point method (towards minimum) than by accepting manufacturers recommendations for minimum cold air temperatures.

The manufacturers have recommended 155 to 160°F cold end temperatures for tubular air heaters when burning coal containing 1% sulphur. For coals containing 1 to 5% sulphur, recommended minimum cold end temperature lies between 180 to 185°F.

In an existing installation, sometimes it has to use coal containing higher sulphur content. In such case, it may be necessary to remove some heat recovery surface from economiser or air heater to obtain a safe exit gas temperature, which can be determined from Fig. 14.10.

The air-preheater is generally designed on one of the following bases :

(*a*) The lowest metal temperature is always a safe margin above dew point temperature. The temperature limitation imposed causes less percentage of energy recovery but the equipment is safe from corrosion and its capital can be less as carbon steel can be used for the purpose.

(*b*) The maximum possible energy is recovered but materials of construction are selected for resistance to acid corrosion. In this case, operating cost is reduced by saving more fuel but the capital cost is increased.

The choice between two methods will be made on an economic basis as well as safe long working life of the unit.

Corrosion control is of primary concern in air heater design, Corrosion resistant metals or ceramic coated carbon steels are specified in the coldest section of the air heater to prevent the metal corrosion when boiler operates at low load. In cold climates, a steam preheater is often installed ahead of air heater to warm up incoming outside air during the winter as shown in Fig. 14.11. The preheater contributes to high availability by minimizing the possibility of cold end corrosion.

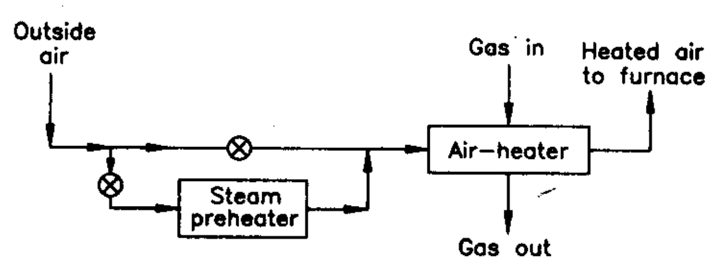


Fig. 14.11. Arrangement of Steam preheater and Air heater.

Low sulphur coals, high burning temperatures, high loads on the boilers and increasing costs of fuel favour the use of economiser and air preheater in the thermal power plants.

In investigating the economics of heat reclaiming equipment for any particular installation, the cost of coal, cost of equipment and local conditions will govern the amount and relative size of economiser and air-heater. In case of economiser, the question as to whether it will be cheaper to preheat the feed water by steam extraction or by flue gas must be considered.

Presently, it is common to install relatively small economiser, large air heater and three to five stages of steam extraction points on the main turbine in modern power plants.

Heat transfer in economisers and air-heaters. In case of economiser and air-preheater, the water or air (which is to be heated) is passed through the tubes whereas the hot flue gases are allowed to pass over the heat transfer surface. This arrangement is preferred as this provides better facilities for tube cleaning which is likely more due to soot formation. The inner surfaces can be cleaned easily in case of economiser just by increasing the water velocity or by adding the chemicals. In case of air-heaters, the inner surfaces are kept clean within a reasonable limit by introducing the filters at the inlet of heat exchanger.

The heat transfer from the hot gas to the heated fluid is given by

$$Q = U\,A\,(\Delta T)_m = m_g\,C_{pg}(T_{h_o} - T_{h_i}) \qquad ...(14.1)$$

where U = Overall heat transfer coefficient

A = Heat transfering area.

$(\Delta T)_m$ = log-mean temperature difference.

It is assumed that the heat lost by hot gases is equal to heat gained by cold fluid and there are no heat losses.

The most effective use of given surface is obtained if the two fluids travel in opposite directions (counter flow). The temperature distributions along the flow paths of fluids are shown in Fig. 14.12.

The $(\Delta T)_m$ for the given temperature distribution as shown in Fig. 14.12, is given by

$$(\Delta T)_m = \frac{\theta_i - \theta_o}{\log_e(\theta_i/\theta_o)} \qquad ...(14.2)$$

where $\theta_i = T_{h_i} - T_{co}$ and $\theta_o = T_{h_o} - T_{c_i}$

The heat transfer for the given surface of heat exchanger and inlet temperatures of hot and cold fluid can be increased by cross flow arrangement instead of counter-flow arrangement. The heat transfer is further increased with the inclusion of baffles.

The log-mean temperature difference for cross-flow with number of baffles used is given by

$$(\Delta T)_m = K.\frac{\theta_i - \theta_o}{\log_e(\theta_i/\theta_o)} \qquad ...(14.3)$$

where K is a multiplication factor whose value depends upon the number of baffles used. The values of K for different arrangements are given in standard text books on "Heat Transfer".

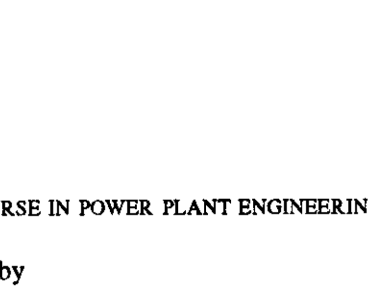


Fig. 14.12.

The overall heat transfer coefficient referred to outer surface of the tube is given by

$$U = \frac{1}{\frac{1}{h_i}.\frac{d_o}{d_i} + \left(\frac{d_o - d_i}{d_o + d_i}\right)\frac{d_o}{K} + \frac{1}{h_o}} \qquad ...(14.4)$$

where d_i and d_o are inside and outside diameters of tube and h_i and h_o are inside and outside heat transfer coefficients and K is conductivity of the tube material.

The values of h_i and h_o can be calculated with the use of following equation

$$^*N_n = 0.023\,(R_e)^{0.8}(P_r)^{0.4} \qquad ...(14.5)$$

In the overall heat transfer coefficient equation, the $\frac{1}{h_i}\,\frac{d_e}{d_i}$, $\left(\frac{d_o - d_i}{d_o + d_i}\right)\frac{d_o}{K}$ and $\frac{1}{h_o}$ represent the resistances of inside fluid, tube material and outside fluid respectively. In case of air-heater, the inner and outer fluid resistances are more or less same but in case of economiser, the inner fluid resistance for heat flow (water resistance) is negligible compared with the heat resistance offered by gas flow. Therefore, the overall heat transfer coefficient cannot be increased just by increasing the velocity of water through the tubes.

*For further details of this equation, the students are advised to see the book on "Heat and Mass Transfer" by the same authors.

For further details of economical velocity through heat-exchangers, the students are advised to see the books on "Heat and Mass Transfer" and "Refrigeration and Air-conditioning" by the same authors.

In addition to the above mentioned resistances, there may be a coating of soot on the outer-surface of the tubes and scale formation on the inner surface of the tubes which further increase the resistance to heat flow. Therefore, in the design a provision for this resistance must be made and to reduce these resistances to minimum, the regular cleaning of inner and outer surfaces is necessary by adding the chemicals in water in case of economiser and by removing the soot with the help of soot blowers.

In economiser and air-preheater, staggered rows of tubes arrangement is preferred over inline arrangement as it gives 20% more heat for the same heat transfer area and for the same inlet temperatures of hot and cold fluids.

Few empirical relations obtained from test results for finding out the overall heat transfer coefficient for economiser and air-preheater are given below :

For economiser

$$U = 10 + 0.0014\,G \quad \text{...(14.6)}$$

$$U = 11 + 0.00095\,G \quad \text{...(14.7)}$$

where G = mass flow in kg/m^2-hr.

For air-heaters

$$U = 2.5 + 0.00045\,G \quad \text{...(14.8)}$$

where G = average gas and air flow in kg/m^2-hr.

The design of regeneration heat exchangers is more complicated and it is not possible to give these details in this book. The interested students are advised to see the book on 'Heat Exchangers' by Keys and London.

Economical Method of Condensing Flue-Gas Water-Vapour. It is absolutely essential to extract maximum heat from exhaust gases for higher thermal efficiency of the plant and economical working. Nearly 13% of boiler fuel heat remains in exhaust gases even if it is cooled in the economiser and preheater. The gases cannot be cooled below 150°C because of danger of acidic condensation of water vapour. Much of this heat can be recovered by condensing water vapour contained in the flue gases and then can be used for (*i*) feed water heating (*ii*) air-preheating or (*iii*) for process hot water.

A typical direct condensing type heat exchanger is shown in Fig. 14.13. Flue gases enter the unit at 150°C or higher, depending on the type of boiler used, passes directly through the cold water stream and then discharged at 40°C to 50°C. The operation is similar to cooling tower working in reverse. Hot gas is cooled and heat recovered is used to provide a hot water source whereas in cooling tower, the air is heated and hot water is cooled.

Since the cooling water extracting the heat is contaminated by the flue gas, a secondary heat exchanger is normally used to transfer the recovered heat to the process fluid.

One big advantage of the direct contact heat exchanger is that there is no resistance to the flow of heat through a separating wall and therefore there is no mechanical complexity for arranging this wall for maximum heat transfer. A wide variety of fluids and solid surfaces can be used under conditions that would cause fouling, corrosion or thermal stresses of conventional heat exchangers. Contact methods used to bring the flue gases and cooling liquids into intimate contact are usually baffle-tray columns, spray chambers or packed columns.

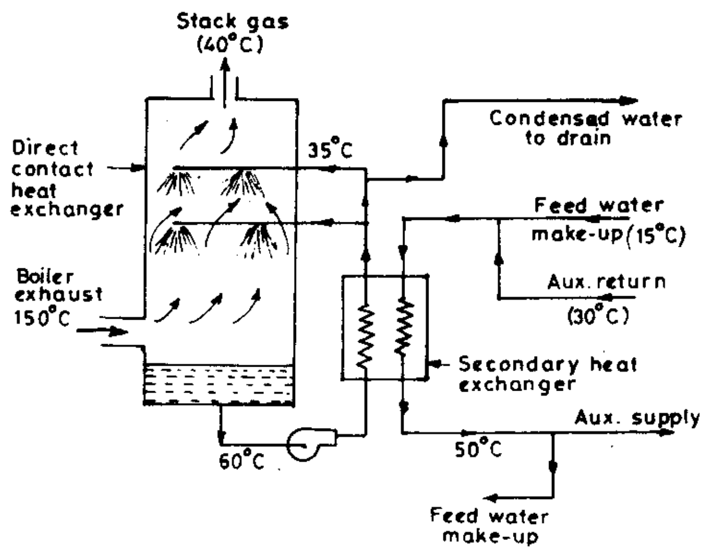


Fig. 14.13. Condensation type heat recovery system.

There is trade off between the heat transfer performance of the equipment used and the gas side pressure drop incurred. Spray chambers have the lowest heat transfer per m^3 volume of the chamber but they have low pressure drop (2.5 mm of H_2O) and can work without any additional fan capacity. A baffle type offers better heat transfer characteristics but has a greater pressure drop than spray type. Additional fan capacity is essential in some cases. The packed tower has the highest heat transfer performance because of large interfacial area but the pressure drop can be as high as 25 cm of H_2O. In addition to this, packing material may foul with ash or soot. The choice of the contacting device is based on the individual needs of the plant, such as hot water temperature, existing fan capacity, available floor space and the retrofit requirements.

Efficiency Gain. Potential efficiency improvement from condensation heat recovery can be visualized from the Figure. If the flue gas is cooled from 150°C to the dew point temperature of 60°C, an efficiency improvement of 3% is possible. Further cooling, resulting in condensation of water vapour, drastically increases heat recovery. At the outlet temperature of 40°C, the efficiency improvement may be as high as 11%. This indicates the importance of achieving flue gas condensation. If the flue gas temperature is reduced in this system from 250°C to 40°C, 15% increase in efficiency can be achieved.

The efficiency gain of a specific installation depends upon

(*i*) Fuel used (H_2 content in fuel).

(*ii*) Flue gas exit temperature from boiler.

(*iii*) Amount of low level heat needed.

(*iv*) Fuel moisture content.

(*v*) Air humidity used for combustion.

Gas fired boilers give higher efficiency other parameters being equal as it contains high percentage of H_2 compared with oil or coal. Installations firing lignite or high moisture content biomass fuels may show additional savings. If combustion air humidity is high, the efficiency improvement from condensation heat recovery may be 1% higher than predicted by the analysis shown here.

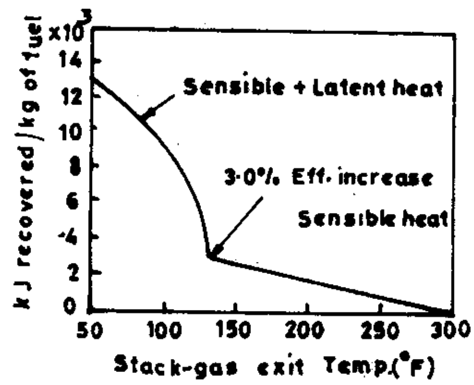


Fig. 14.14. Heat recovery increases dramatically when flue gas is condensed.

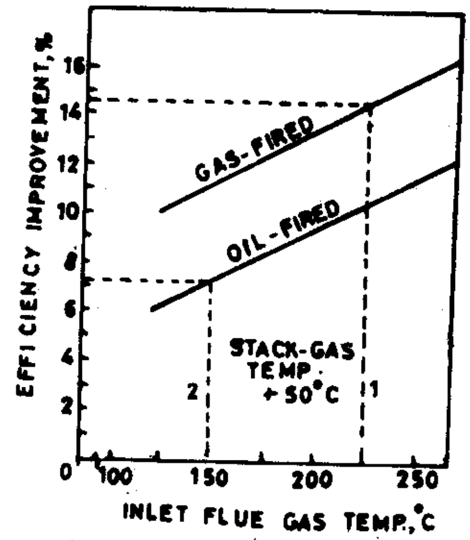


Fig. 14.15. Efficiency increase (right) depends on fuel and on temperature of flue gas.

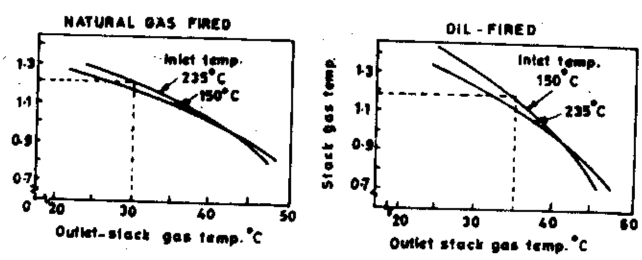


Fig. 14.16. Use these curves to allow for the effect of variations in the exit temperature from recovery unit on efficiency increase possible with heat-recovery unit.

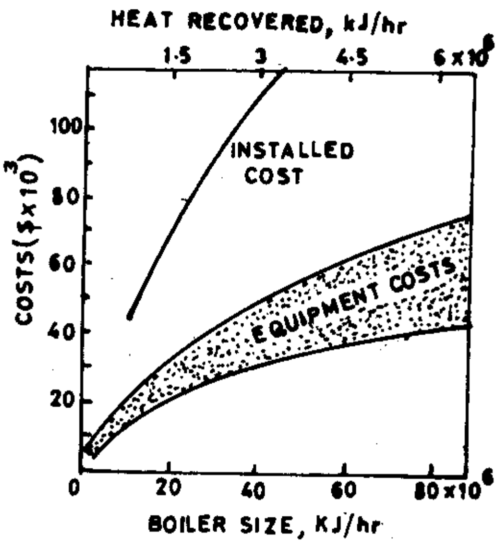


Fig. 14.17. Installation cost of condensation heat-recovery unit may run as high as three times equipment cost.

The efficiency improvement expected in a particular plant can be found from Fig. 14.14 and Fig. 14.15. Fig.14.16 gives the basic efficiency improvement (η_b) for gas and oil at various inlet flue gas temperatures and outlet stack temperature of 40°C. Actual efficiency improvement can be found using a relation

$$\eta_a = F \,.\, \eta_b$$

where F is a factor depending on actual outlet gas temperature. Fig. 14.17 provides the value of F for various outlet gas temperatures for gas and oil as fuels.

Lower η of the oil fired boiler compared with gas fired is because of low H_2 content in fuel. But however, where the cost of oil is higher than natural gas, the economical saving may be greater.

Boiler Make-up-Water Preheat. Make-up water preheat needs depend largely on the amount of condensate that is returned to the boiler. Generally, there is more heat available in the flue gases that can be used to preheat feedwater. If boiler is operating at 100% make-up, only about 60% of the available heat in gas can be transferred to the incoming feed water. This is because of low temperature of the hot water. This limitation can be handled in two ways.

(*a*) Design a heat recovery unit to take a part-stream from the flue gas and then recover as much heat as can be used to heat feedwater.

(*b*) In multiple boiler plants, instal a heat recovery system on one or two boilers only and use it to preheat feed water for all the boilers.

Process Hot Water. In food and textile processes, the hot water needs account for 15% or more of the total boiler load. Any facility with hot water requirements between 10% and 15% of boiler capacity and operating schedule greater than 4000 hrs/year, condensation heat recovery can be considered.

Space Heating. Space heating economics is less favourable than make-up or process hot water, because of the load variation, limited heating season and the difficulty in matching demand and supply schedules.

The cost of buying and installing a condensation heat recovery system is shown in Fig. 14.18. The installation cost is nearly 3 times the equipment cost because of retrofit difficulties involved with an existing installation. Operating costs come mainly from fan and pump power consumption. These generally range from 5% to 10% of the recovered heat. It is estimated that 2 to 3 years are sufficient to recover the total cost of the unit incorporated.

Corrosion in condensing heat recovery unit can be prevented by using 304 or 316 stainless steel or fibreglass reinforced plastic for the tower pump and heat exchanger.

An unique feature of this system is that it recovers energy while reducing emissions. When natural gas is used, a small percentage of NO_x emissions is reduced by condensation of oxides of N_2. SO_2 emissions can be reduced significantly by using an alkaline water spray in a pH range of 6 to 8.

More than 500 such systems are presently operating in Europe with considerable energy saving. A two stage flue gas heat recovery system on a boiler supplying 15 tons of steam per hour used in a chemical plant in West Germany is shown in Fig. 14.18. The flue gas from one boiler is sufficient to provide boiler-feed water preheat to two boilers at a combined rate of 25 tons/hr. The flue gas temperature is reduced from 210°C to 50°C which is sufficient to raise inlet feedwater from 10°C to 70°C. The annual fuel saving (in 1980) of \$ 200 × 10^3 was achieved when natural gas cost was \$ 2.2 per million-kJ. This provided a payback of just one year.

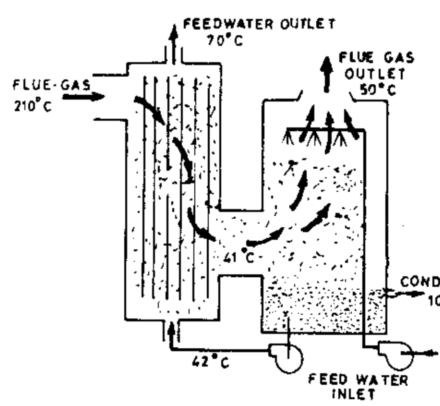


Fig. 14.18.

14.4. SUPERHEATERS

The function of the superheater in the thermal power plant is to remove the last traces of moisture (1 to 2%) from the saturated steam coming out of boiler and to increase its temperature sufficiently above saturation temperature. The super-heating raises overall cycle efficiency as well as avoids too much condensation in the last stages of the turbine (below 12%) whcih avoids the blade erosion.

The heat of combustion gases from furnace is utilised for the removal of moisture from steam and to superheat the steam. Super-heaters usually have several tube circuits in parallel with one or more return bends, connected between headers.

Heat from the hot gases to the vapour in the superheater is transferred at high temperatures. Therefore primary section of superheater is arranged in counterflow and secondary section in parallel flow to reduce the temperature stressing of the tube wall. The metal used for superheat tubes must have high temperature strength, high creep strength and high resistance to oxidation as superheater tubes get rougher service than water walls of the modern boilers. Carbon steels (510°C) and chromium-molybdenum alloys (650°C) are commonly used for superheater tubes.

Considerable ingenuity is necessary to provide superheaters for modern steam power plants. The problem of superheater design and location is complicated by the requirements of increased gas temperatures to provide higher steam temperature. In modern boilers, the temperature of combustion is approaching the fusing temperature of ash in the coal and therefore there is a tendency of the ash to collect in fluid form on the superheater tubes (slagging).

The problem of slagging the superheater is partly eliminated by following methods :

1. Locate the superheater close to the furnace in order to develop the required steam temperature.
2. A bank of screen tubes is located in front of the superheater to limit slag accumulation.
3. Limiting the constant temperature range to 60 to 65% of load rating of the steam generator.
4. With the use of combined convection-radiation superheater.

The steam is superheated by transferring the heat of gases either by convection or by radiation or by combined convection and radiation. Fig. 14.19 shows how steam temperature changes with load for each of these types. The combined type superheater has proved most desirable as it keeps the constant temperature throughout the load range.

The principle of convection superheater is similar to steam generating tubes of the boiler. The hot gases at high temperature sweep over superheater tubes and raise the temperature of steam which magnitude depends upon exit gas temperature leaving the superheater and gas-velocity. The convection superheater may be set as "Interdeck Form" or "Overdeck Form" as shown in Fig. 14.20 (*a*), (*b*), (*c*) and (*d*). The superheater is placed between the water tubes in interdeck arrangement and it is located above the water

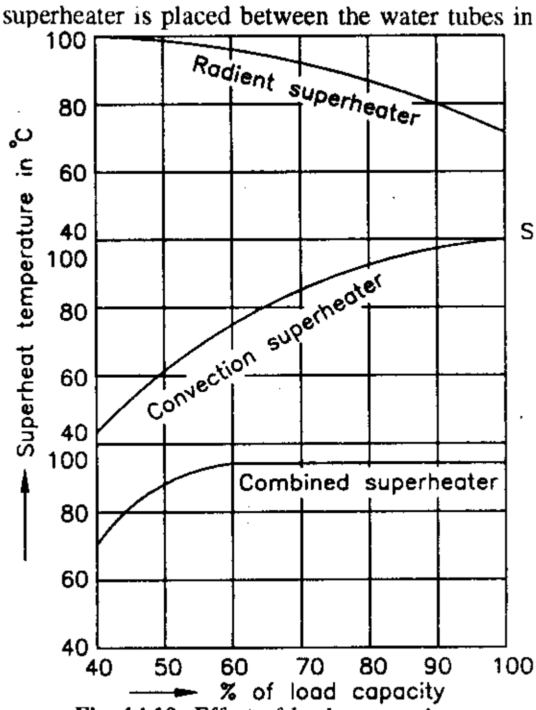


Fig. 14.19. Effect of load on superheater temperature of convection and radiation superheaters.

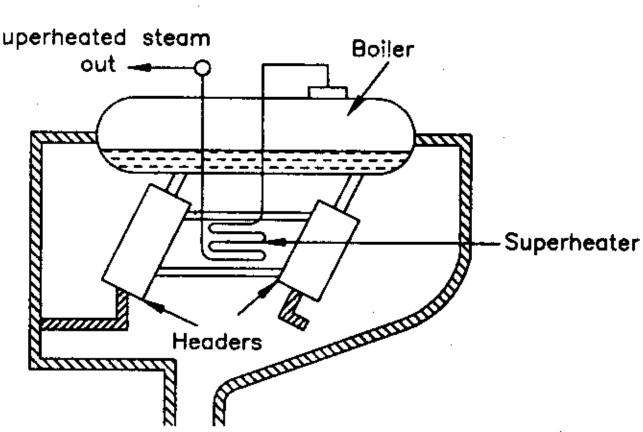


Fig. 14.20 (*a*) Innerdeck superheater.

tubes in case of overdeck type. The detailed description of these is not given as they are not used in present modern steam power plants.

A radiant superheater is located in the furnace wall and absorbs heat from the luminous fuel source just as the furnace wall tubes transmit radiant heat to the saturated water in the wall tubes.

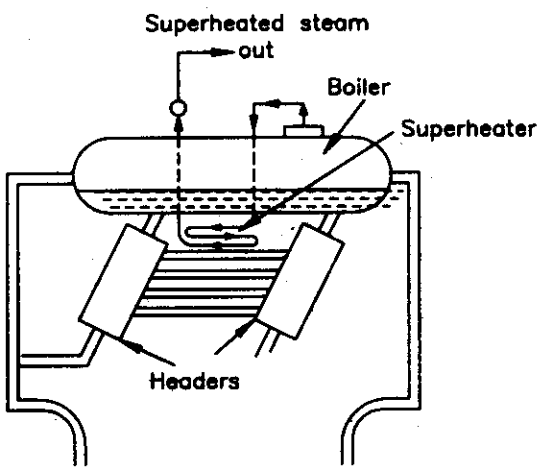


Fig. 14.20 (*b*) **Overdeck superheater.**

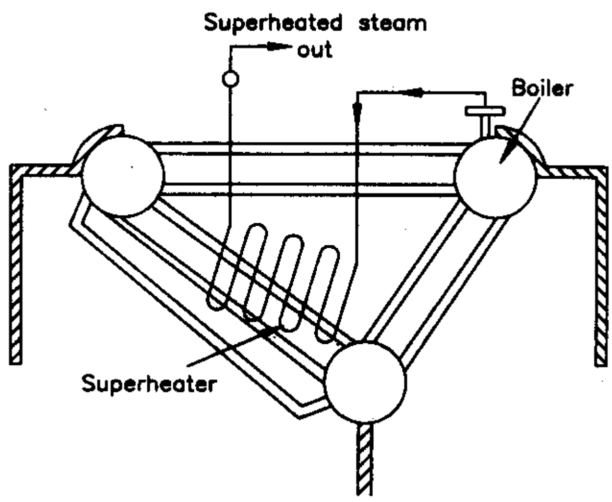


Fig. 14.20 (*c*) **Inner tube superheater.**

The convection part of the superheater is located close to the flow path of the hot gases where temperature exceeds steam temperature.

The material used for superheater tubes should have high temperature strength and high resistance to oxidation and corrosion. Generally, chromium molybdenum alloy is used for superheater tubes used in modern high capacity thermal power plants.

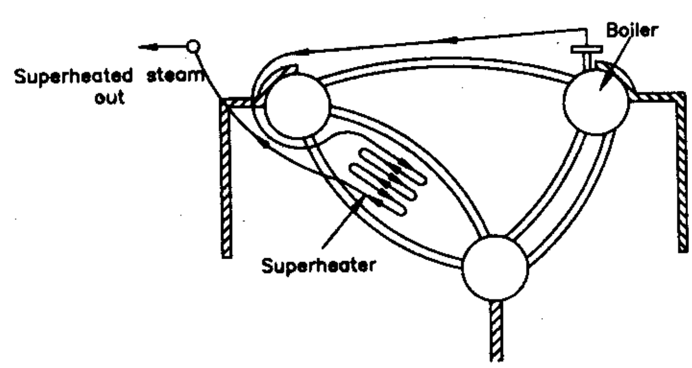


Fig. 14.20 (*d*) **Inner bank superheater.**

Superheat temperature control. Accurate steam temperature control is necessary for avoiding the over stressing of superheater tubes and turbine front stages and to maintain overrall efficiency as high as possible. This can be done by using a combined type superheater as mentioned earlier. One part of the superheater (radiant part) is located in the furnace wall and other part (convection part) in the convection bank.

The common methods used for controlling the superheat temperature of the steam are discussed below :

1. **Bypassing the furnace gas around the superheater.** At lower loads on the power plant, the part of the gases are bypassed with the help of damper as shown in Fig. 14.21 (*a*). Until recently, this method of control was used successfully. But the troubles with satisfactory meterials to withstand erosion and high temperatures in the gas passages have limited the use of damper method of control.

2. **Tilting burners in the furnace.** The temperature of the steam coming out of superheater is controlled by tilting the burners up or down through a range of 30°C as shown in Fig. 14.21 (*b*). By tilting the burner downward in a furnace, much of the heat is given to the water walls by the gas and the gas entering the superheater region is relatively cool. If the burner is turned upward, then the heat given to the boiler water wall is less and hotter gas enters the superheater region to increase the steam temperature.

3. **Auxiliary burners.** The temperature of the steam can be controlled by turning the auxiliary burners in addition to the main burners. The effect of this is similar to tilting burners. The arrangement is shown in Fig. 14.21 (*c*).

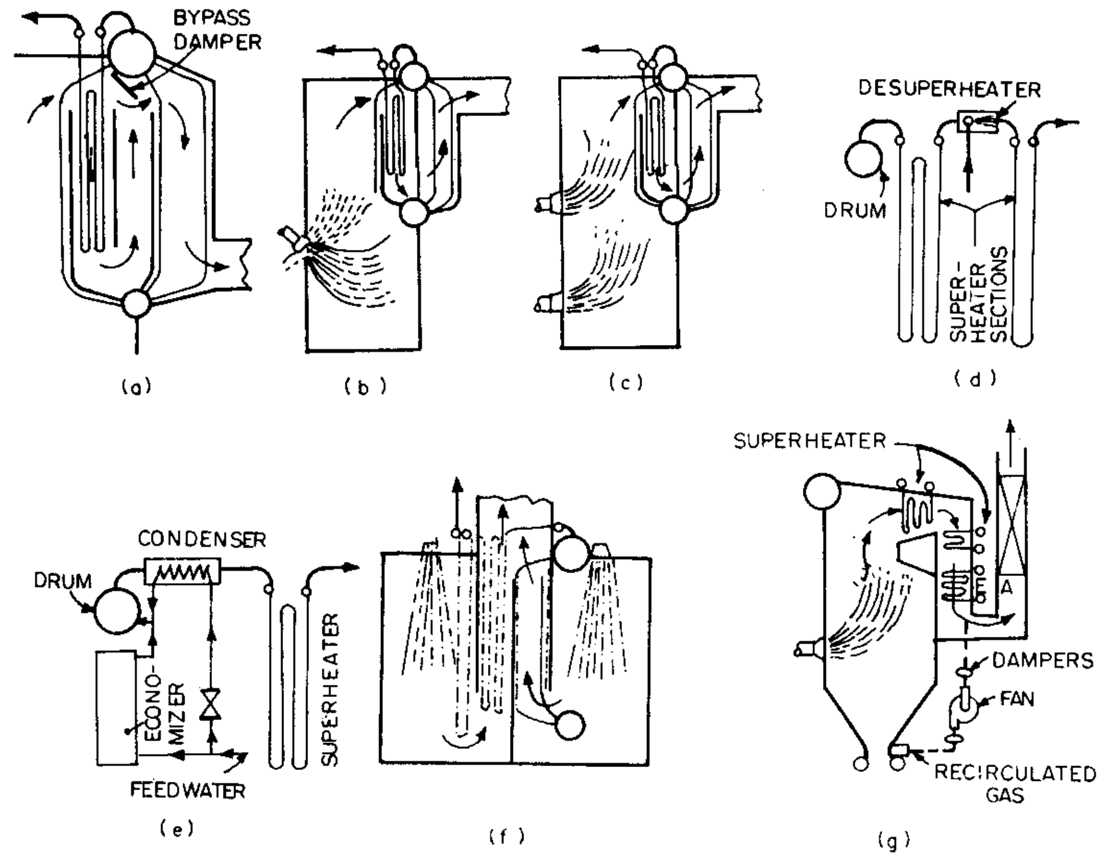


Fig. 14.21. Different arrangements of superheat control.

4. **Desuperheater using water spray.** The temperature of the steam can be controlled by injecting the water either before the superheater or between sections of a superheater as shown in Fig. 14.21 (*d*).

5. **Pre-condensing control.** The temperature of the steam can be controlled by condensing the steam coming out of boiler with a small condenser with the help of feed water as shown in Fig. 14.21 (*e*). Automatic control regulates the amount of feed water by-passed.

6. **Gas recirculation.** The gas coming out of economiser is partly recirculated into the furnace with the help of a fan as shown in Fig. 14.21 (*f*). The recirculated gas acts like excess air and blankets the furnace wall. This reduces the heat absorption by water wall and increases the heat absorption by superheater.

7. **Twin furnace arrangement.** The twin furnace arrangement as shown in Fig. 14.21 (*g*) is an extension of the separately fired superheater. Varying the firing rates between furnaces controls the superheat temperature.

8. **Coil Immersion in the Boiler Drum.** The arrangement of this system is shown in Fig. 14.21 (*h*). A portion of the steam from low temperature section of the superheater is by-passed to a coil immersed in the lower drum of the boiler under the control of a by-pass valve. The latter is actuated by the final temperature of the steam thus making the system automatic. The desuperheated steam in the boiler drum is returned and mixed with the non-desuperheated steam in a junction header and final superheating takes place in the second stage superheater. This method has the advantage that no equipment is exposed to the erosive action of the gases. Another advantage is, there is no overheating of metal at high temperatures. This scheme of temperature control is used by Babcock and Wilcox Company from many years.

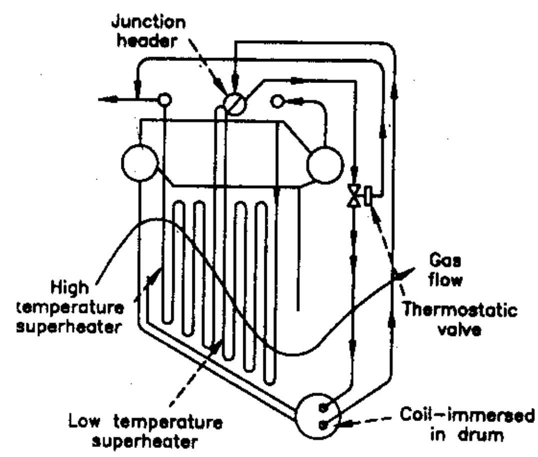


Fig. 14.21. (*h*) Methods for superheat temperature control.

Fouling and corrosion of superheaters. The fouling is a common phenomenon for convection type superheater as they are situated in the flow path of the hot gases. The alkali metals like sodium and potassium in the coal, are volatilised in the combustion process generally when the temperature in the combustion chamber exceeds 1500°C (The temperature of 1500—1650 generally occurs in pulverised fuel boilers) and condenses as sticky substance at temperatures corresponding to those of the superheater tubes. The fly ash particles then adhere and become bonded and finally form a hard mass on the superheater tubes. The layer formed contains the sulphates of sodium and potassium and pyro-sulphates.

The severity of this type of deposit is very much influenced by the presence of alkali chlorides which are most volatile among all compounds of alkalies and they are converted to sulphates by chemical reaction in the presence of SO_2 and O_2. It has been observed that this is not very much serious in pulverised boilers compared with stoker fired boilers. This is because of high ash burden in the pulverised fuel boilers which produce less favourable conditions for bonding process.

Other type of fouling experience is sintered ash deposits which are generally formed at high temperatures. This can be removed by well designed soot-blowers.

Conditions favourable to alkali deposits, combined with high temperatures favourable to sintered ash formation produce most severe superheater fouling. Where conditions are favourable for alkali deposits, the alkali bonded deposits can increase the tube temperature to allow the sintering process to commence. In this way, the fouling increases continuously and keeps the superheater in danger conditions as such fouling cannot be removed easily by soot blowers.

The other factors responsible for the superheater fouling are listed below :

(1) *Sulphur content* of fuel can produce hard acid sulphate type fouling when the coal also contains alkalies.

(2) *High chlorine content* in pulverised coal (> 0.5%) forms severe type of fouling particularly when coal contains less than 14% ash.

(3) *High temperature of the gases* entering into the superheater zone aggravate the severity of trouble with bonded deposits. The temperatures below 1000°C are considered more safe when high chlorine content coals are used.

(4) *High velocity of the gas* also increases the fouling rate because of higher impingement rate of ash and higher tube metal temperature due to increased heat transfer rate at higher velocity.

(5) Fouling by sodium and vanadium even at lower temperature 600°C is experienced when oil is used as fuel instead of coal.

The superheater tubes are subjected to corrosion when they are exposed to oxidising and reducing conditions alternately. This destroys the protective oxide film and exposes the metal surface open to further corrosion. The alkali deposits formed also have corrosion effect on steel depending upon its temperature and composition. Low chromium ferritic steels confer some corrosion resistance but marked resistance is obtained by the use of austenitic alloys.

Heat transfer in superheaters. The required heat transfer surface will depend upon the amount of steam to be superheated, the desired degree of superheat and mean temperature difference between the gases and steam. The gas temperature entering the superheater depends upon the location of the superheater and boiler rating. The following formula approximately gives the area of superheater required.

$$A = \frac{m_s\,(H_o - H_i)}{\left[\dfrac{T_{gi} + T_{go}}{2} - \dfrac{T_{si} + T_{so}}{2}\right] . U} \qquad ...(14.9)$$

where T_{gi} and T_{go} are the gas temperatures at the inlet and outlet of the superheater and T_{si} and T_{so} are the steam temperatures at the inlet and outlet of the superheater. H_i and H_o are the steam enthalpies at the inlet and outlet of the superheater. U is the overall heat transfer coefficient between steam and gas. m_s is the mass of superheated steam. The value of U changes according to the gas flow rate through the superheater.

The heat-transfer to the Radiant superheater is given by Nusselt's formula as given below :

$$Q = 12.9\,\frac{K}{d}\left(\frac{d\,.\,m_s\,.\,C_p}{K}\right)^{0.786} \qquad ...(14.10)$$

where
Q = Bthu/ft²-hr-°F.
K = (Steam conductivity) = 0.0131 Btu/ft-hr-°F.
d = Inside diameter of tubes in inches.
m_s = Mass flow of steam in 1000 lbs/ft²-hr.
C_p = Mean specific heat of steam.

14.5. SOOT BLOWERS

The fuels used in steam power plants create soot and this is deposited on the boiler tubes, economiser tubes and air preheater. The soot deposited on these heat exchangers drastically reduces heat transfer and significantly increases the amount of fuel that must be burned to produce heat equivalent to that generated by clean boiler surface. A reduction in heat transfer efficiency is indicated by an increased flue gas temperature. Therefore, the cleaning of these heat exchanger surfaces during service is very essential. Sootblowers control the build up of soot and ash deposits that create corrosive environment. This is very essential particularly during low load operation when acid dew point of the fuel being fixed could be reached. In addition to this, soot blowing equipment improves heat transfer, controls draft loss and prevents corrosion.

There are mainly two types of soot blowers which are used in the field.

1. Fixed position soot blowers. A fixed position rotating element soot blower is shown in Fig. 14.22. It has nozzles that blow steam or

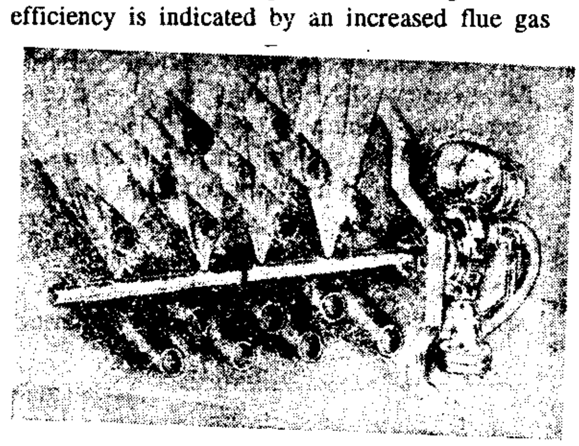


Fig. 14.22.

compressed air in lane or mass patterns depending upon the orientation of the elements as shown in Fig. 14.23.

Lane blowing units position a nozzle in the space between each tube to be cleaned. The element is rotated through a prescribed arc to remove accumulated deposits between the tubes. Mass blowing elements have fewer but larger nozzles and are positioned upto 40—50 cm from the face of the tube banks or where nozzle alignment with the tube lane is not possible.

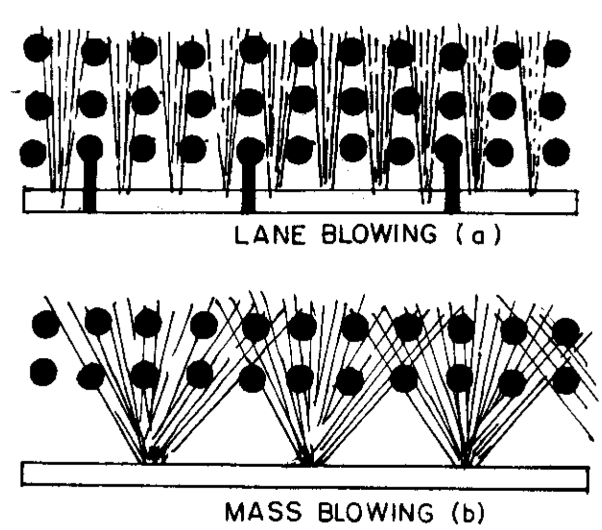


Fig. 14.23.

Typical soot blowing pressures for coal fired boilers are listed below :

Spreader stroker—5 to 7 bar, pulverised coal —5 to 7 bar and underfeed stroker —8 to 10 bar. Higher range is used for steam system.

Oil fired boilers, specially those using fuels with vanadium (150 ppm), require a 10 bar blowing pressure. Soot-blowers are not used for boilers using oil as fuel and when the gas temperature exceeds 950°C because oil ash remains always in a molten state.

Soot blowing in boilers without down stream collection devices usually increases stack emission. This emission increase indicates that the system is accomplishing its purpose.

2. Retractable soot blowers. Retractable soot blowers should be considered when flue gas temperature exceeds 1050°C and when flue gases also contain contaminants harmful to the material of the element. These blowers offer three advantages over fixed position blowers in these instances :

* Retractable soot blowers are installed outside the boiler away from the high temperature gases that would destroy the element of a fixed position blower.
* Retractable blowers concentrate their cleaning energy through a single pair of large nozzles instead of dividing energy along a large number of smaller nozzles. This arrangement provides a 15 : 1 cleaning energy ratio over the fixed position blowers.
* There is no concern for nozzle alignment with boiler tubes as long as sufficient clearance is provided for the retractable blower lance tube to prevent tube erosion.

Use of high ash, heavy slagging fuels has made efficient boiler operation increasingly dependent on the way adopted for maintaining the cleaning equipment. Boiler efficiency and life decrease rapidly as negligent soot blower maintenance practices increase.

If soot and slag are difficult to remove, the pressure of the blowing medium must be higher, more frequent blowing is needed and additional soot blower maintenance is required to prevent breakdown.

3. Soot blower for economiser. The hot gases coming out from an electrostatic precipitator and entering into the economiser also carry soot and this is deposited on the outer surface of the tubes. It is necessary to remove the soot continuously collected over the surface of the tubes. The removing of soot over the economiser tube surfaces is done by automatic mechanical mechanism.

EXERCISES

1. Why economisers are essentially used irrespective of the fuel used in boiler furnace ?
2. Which factors are considered for deciding the size of the economiser ?
3. Economisers are located after feed pump, comment.

4. What are the difficulties experienced in extracting the maximum heat from flue gases in economiser ? What is its limit ?
5. What do you understand by acid corrosion ? What are the cusses and how it is prevented in practice ?
6. Possibility of acid corrosion is more in winter than summer, comment. What is preventive measure for this ?
7. Why the sulphur and moisture content control the heat to be extracted in the economiser ?
8. What is the purpose of air preheater ? Why air preheater is used with only coal burned boiler and not with gas and oil burned boiler ?
9. Sketch different types of air-heaters, mention their field of application and discuss their relative merits and demerits.
10. What are the causes of corrosion in air heaters and how corrosion is prevented in practice ?
11. What is the main purpose of superheater ? What are the advantages of superheated steam ?
12. Draw the line diagrams of inner deck and overdeck type superheaters and discuss their relative advantages.
13. What are the different methods used for controlling superheat of steam ? Explain working of each with neat sketch.
14. What is the necessisty of a soot blower ? Discuss different types of soot blowers used in boiler during operation.
15. Draw a neat diagram of soot-blower mechanism used in economiser for removing the soot and explain its working.

□□□

15

Fluidized Bed Combustion Systems (FBC)

15.1. INTRODUCTION

With the escalating prices of oil and gas during the last decade, the world power industry shattered and there is a common tendency to shift the power industry from oil to coal as coal is abundant compared with oil. With the growing realization that the low sulphur fuel oil and natural gas are not going to be available for electric generation in the near future, the power industry is slowly moving for the old faithful fuel-coal.

Pulverised fuel firing was developed earlier this century and universally used throughout the world till today for power generation. Pulverisation opened a new field of using high ash coals which were not suitable for conventional burning methods.

But the pulverised fuel boilers have some inherent drawbacks as listed below :

* A pulverised fuel fired furnace designed for a particular type of coal cannot be used for burning any other type of coal with the same efficiency and safety.
* The size of the coal used is limited by the furnace temperature and in addition to this, the coal particle size is also governed by the fuel characteristics like volatile matter, ash content, etc. The particle size of the coal used in p.f. furnaces is limited to 70-100 μ. Therefore, large investment is needed for coal preparing equipments and for its maintenance.
* The ignition of the coal particles becomes easy and combustion becomes steady when the temperature in the furnace is of the order of 1650°C. Conisderable difficulty is experienced for maintaining stable combustion at part loads as the temperature drops. This difficulty is generally solved by using auxiliary fuels like furnace oil. The present day boilers work under part load conditions for a considerable period of the day with fuel oil support burners resulting in considerable expenses on fuel oil.
* The high temperature in the furnace creates number of problems like slag formation on superheater, evaporation of alkali metals in ash and its deposition on heat transfer surfaces which is responsible for fouling and corrosion and severe erosion to I.D. fan blades and snapping of wires of electro-static precipitators due to sintering of ash.
* The amount of NO_x formed is considerably large compared with any type of combustion system as the temperature maintained in the furance is considerably high. The removal of SO_2 demands high capital cost equipment.

With the new rules and regulations imposed by the Governments for the air-pollution, the cost of power generation went high as extra equipments are needed to control the pollution to the required level.

Combustion in coal fired boilers usually takes place at 1400°C to 1700°C and excess air needed to insure complete combustion of all the carbon. This combination usually produces undersirable SO_2, NO_x, particulates, and considerable amount of hard ash. At present, the scrubber (wet or dry) is the best available technology for removing SO_2 from flue gases but they are quite expensive which costs 25% of that of the basic plant. In addition, they require a large land area (equivalent to the space occupied by the boiler plant) and constitute a major system that must be maintained and repaired.

At present, the boilers are designed to suit the fuel characteristics. The configuration and size of the boiler furnaces and burners differ considerably depending upon whether the coal is anthracite, bituminous, lignite, oil or gas. Fluidized bed combustion (FBC) can, on the other hand, accept any fuel including low grade coals (even containing 70% ash) oil, gas or municipal waste.

The control of SO_2 and NO_x emissions would be simplified if there was some way to entrap the sulphur during combustion and at the same time, the coal could be burned effectively and efficiently at a temperaute below 1100°C so fixation of atmospheric N_2 would not occur. FBC offers the capability of doing this. Its use in the power generation is recent and coming fast. Its use will solve the power shortage problem in future by allowing to use any type of low grade fuel including even sewage and municipal wastes. FBC presents a practical and economical way to burn coal with minimum SO_2 and NO_x emission.

15.2. PRINCIPLE OF FBC SYSTEM.

When a gas is passed through a packed bed of finely divided solid particles, it experiences a pressure drop across the bed. At low gas velocities, this pressure drop is small and does not disturb the particles. But, if the gas velocity is increased further, a stage is reached when the particles are suspended in the gas stream and the packed bed becomes a fluidised bed. With further increase in gas velocity, the bed becomes turbulent and rapid mixing of particles occures. In general, the behaviour of this mixture of solid particles and gas is like a fluid. Burning of a fuel in such a state is known as fluidised bed combustion.

The arrangement of the FBC system is shown in Fig. 15.1. The fuel and inert material dolomite are fed on a distributor plate and air is supplied from the bottom of the distributor plate. High velocity of air keeps the solid feed material in suspended condition during burning. The generated heat is rapidly transferred to the water passing through the tubes immersed in the bed and generated steam is taken out. During the burning, SO_2 formed is absorbed by the dolomite and prevents its escape with the exhaust gases. The molten slag is tapped from the surface of the bed.

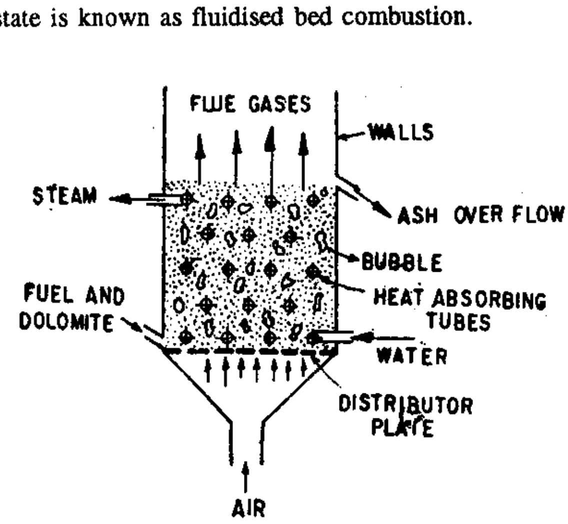


Fig. 15.1. Basic FBC system.

The inert material is used with a primary object of controlling bed temperature and it accounts for 90% of the bed volume. The heat released by the combustion is first used in keeping up the temperature of the inert material and the balance is absorbed by the heat transfer surfaces. It is essential to choose the inert material judiciously as it remains with the fuel in continuous motion and at high temperature (800°C).The inert material should be resistant to heat and disintegration and should have similar density as that of coal. In addition to this, it should not disintegrate coal, the parent material of the bed. Sintered ash, fused alumina, sand, mullite, and zirconia are few suggested inert materials for FBC. However, the proper choice depends on the physical characteristics of coal.

The amount of coal is only a small percentage of bed material (2% only). Since combustion tends to be almost complete while in intimate contact with hot lime stone.

The bed operates at much lower temperature (900°C) but still combustion efficiency remains very high (99.5%) as very high heat transfer rates are maintained over the surface of the tubes. Also the bed coal content is hardly 2 to 3% of bed volume. Thus the presence of even a large amount of ash in coal is no disadvantage. Even the poorest grade coal could be burnt without sacrificing combustion efficiency.

The heat transfer rate to the tube surface is quite high as the system behaves like a violently boiling liquid and nearly 50% of the total heat released in the bed is absorbed by the tubes immersed in the bed leading to considerable reduction in the weight of the material and size of the boiler.

The low and uniform operating temperature of the bed helps to prevent fusion of coal ash and therefore ash produced is soft and less abrasive.

Volatilization of ash constitutes is minimised and corrosion and erosion of submerged tubes are minimised as compared to conventional methods of combustion.

The bed operating temperature of 800—900°C is ideal for sulphur retention. Addition of limestone or dolomite to the bed brings down SO_2 emission level to 15% of that in conventional firing methods. Low NO_x emission is automatically achieved in FBC both due to low bed temperature and low excess air compared to a pulverised fuel furnace.

The cost economics shows that a saving of about 10% in operating cost and 15% in the capital cost could be achieved for a unit rating of 120 MW and it may be still higher for bigger units.

The size of the coal used has pronounced effect on the operation and performance of FBC system. The particle size preferred is 6 to 13 mm but even 50 mm size coal can also be used in this system. But larger size of coals require higher fluidizing velocity which increases pressure drop across the bed. The increase in fluidizing velocity increases ellutriation of carbon thereby increasing carbon back into the FBC but at a high cost of equipments. It is also observed that the heat transfer coefficient decreases with increasing particle size. For a given duty, the decrease in heat transfer coefficients results in increased bed depth to accommodate an increased heat transfer area.

The conventional vertical fluidized bed design discussed previously has three main characteristics.

(1) Horizontal distributer plate (2) Vertical fluidizing airflow and vertical walls.

The conventional FBC has four inherent weaknesses as shown in Fig. 15.2.

(1) Short residence time of fuel in the bed.

(2) Poor lateral mixing of fuel and air.

(3) Elutriation of fine particles.

(4) Ash and heavy incombustibles are difficult to remove.

(1) Short Residence time

The repercussions are listed below :

(*a*) Carbon burn out is not optimum.

(*b*) Reduction of toxic products of combustion is not optimum.

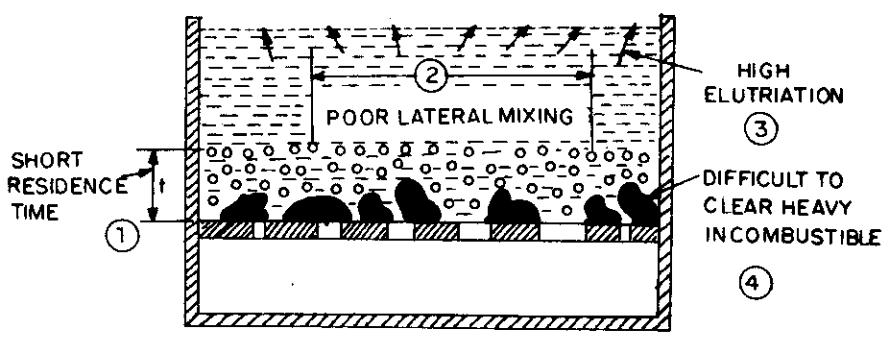


Fig. 15.2.

The consequences are listed below :

(*a*) Lower combustion and thermal efficiency and lower output.

(*b*) Incomplete combustion of toxic gases.

(*c*) More equipments to recapture and recirculate unburned carbon.

(*d*) More secondary air to oxidise CO to CO_2.

(*e*) More sorbent to kill SO_x.

The treatments to overcome the above-mentioned difficulties are listed below :

(*a*) The feed stock should be fine.

(*b*) Lower the bed velocity.

(*c*) Recirculate the unburnt carbon.

(*d*) Supply more sorbent than optimum.

(*e*) Avoid feeding light solids and liquids.

(2) Poor Horizontal Mixing

The repercussions are listed below :

(*a*) Bed fails to mix thoroughly fuel, sorbet and air.

The consequences are listed below :

(*a*) Part of bed is starved of fuel.

(*b*) Other parts of the bed are clinkered.

(*c*) Non-uniform temperature causes problem in control system.

(*d*) Heavy solids sink to bottom and locally block the bed.

(*e*) It creates difficulty in starting the bed from cold.

The treatments to overcome the above-mentioned difficulties are listed below :

(*a*) The fuel should be distributed with more feed points and splitters.

(*b*) Bubble caps are to be introduced to prevent the blockage.

(*c*) Use higher than optimum level of excess air.

(*d*) Use higher than optimum Ca : S ratio.

(*e*) Start up on shallow bed and deepen the bed gradually as temperature rises.

(*f*) Avoid using smoky and smelly fuels as this causes clinkering of the bed.

(3) Elutriation of Fine Particles

The main effect is to carry out unburnt carbon out of in-bed combustion zones.

The consequences are listed below :

(*a*) Lower combustion and thermal efficiencies.

(*b*) Blockage of downstream equipments (in smoke tube boilers).

(*c*) Possibility of fires and downstream explosions.

The treatments to overcome the above-mentioned difficulties are listed below :

(*a*) Add a re-capture and re-circulation chamber.

(*b*) Lower fluidizing velocity.

(*c*) Add higher capacity dust collecting equipments.

(*d*) Increase bed material particle size.

(*e*) Avoid feeding light particles.

(*f*) Add a cyclone in the furnace zone.

(4) Ash Removal Difficulty

The main repercussions are listed below :

(*a*) Heavy incombustibles block the distributor and destroy the fluidized bed.

The consequences are listed below :

(*a*) Loss of full fluidization.

(*b*) Less air distribution hampers proper bubbling.

(*c*) Reduced mixing and therefore thermal output is reduced.

(*d*) Creates cold and hot spots

(*e*) Downtime is more.

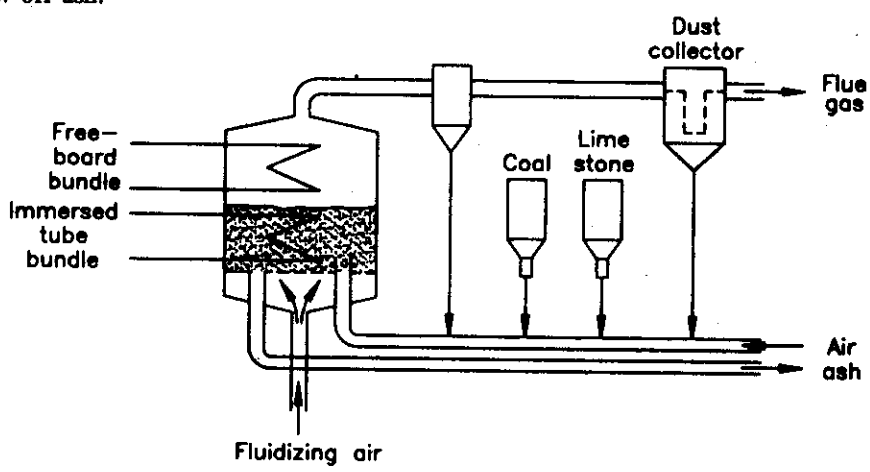
The treatments to overcome the above-mentioned difficulties are listed below :

(*a*) Introduce ash slots.

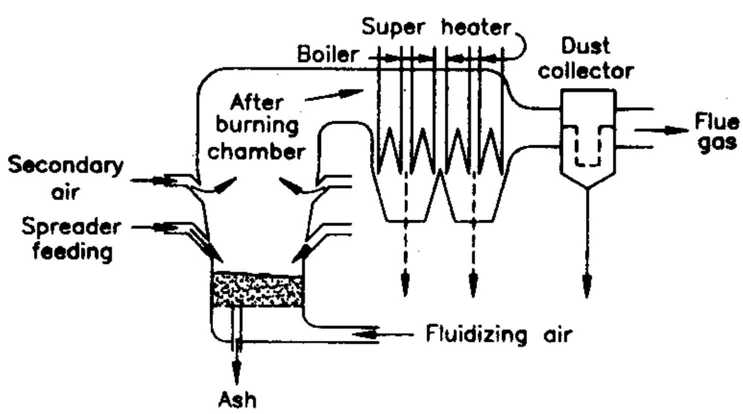
(*b*) Introduce bubble caps.

(*c*) Provide a defluidized layer at bottom of the bed.

(*d*) Blow-off ash.



(*a*) Underfeed system.



(*b*) Overfeed system.

Fig. 15.3. Layout of Classical FBC System.

15.3. TYPES OF FBC

The FBCs are mainly classified into three basic systems which are outlined as given below :

(1) Atmospheric Fluidized Bed Combustor. It is most widely applied and fully developed system at present. The commonly used underfeed and overfeed systems are shown in Figs. 15.3(*a*) and 15.3(*b*).

Underfeed system provides positive load and a compact design but costly in operation. Overfeed system is simple in operation and economical in running but results in smaller output per m^2 area and gives poor desulphurization performance. In this system, the pressure inside the bed is atmospheric.

A group of engineers during 1968-70 was trying to develop a FBC to burn garbage. They found that paper, wood dust, agricultural waste and similar light materials, flew off the bed whilst metals and heavy incombustibles sank to the bottom of the bed to block the distributor.

To overcome these difficulties, they suggested the following modifications in the previous FBC :

(*a*) Bent one of the FBC walls over the bed to contain light particles.

(*b*) Provide sloping distributor plate to give an air-slide effect.

(*c*) Provide non-uniform fluidizing velocities over the bed.

These suggested modifications showed significant improvement and allowed to use light materials as fuels most successfully. Light materials were burned within the bed and heavy incombustibles (ash and metals) gathered at the bottom of the sloping distributor.

The other outstanding features of this arrangement are ash pot at lower end of the distributor plate, secondary air supply over the bed, start-up burner, and arrangement of liquid fuel supply as shown in Fig. 15.4.

The advantages of circulating type FBC are listed below :

(*a*) Increased in bed residence time.

(*b*) High lateral turbulence and so efficient burning.

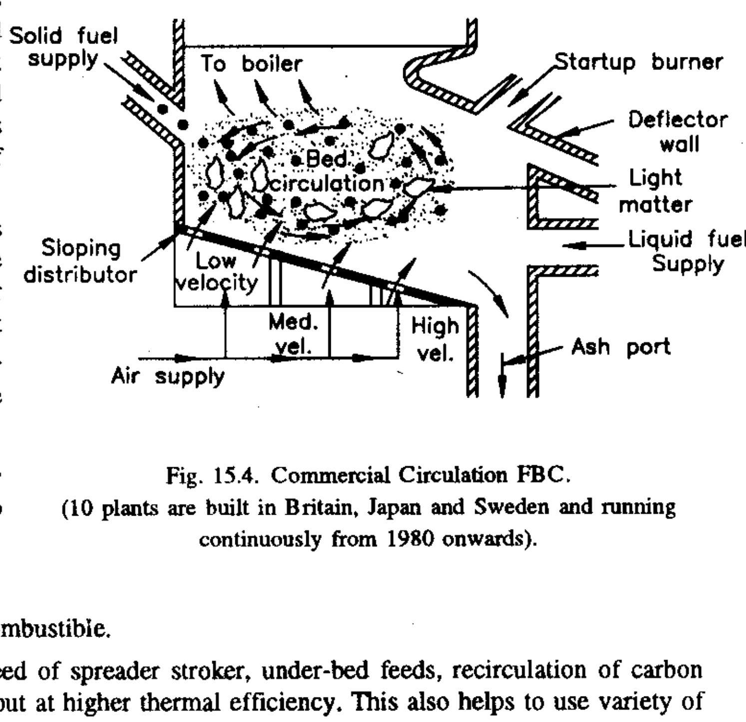


Fig. 15.4. Commercial Circulation FBC.
(10 plants are built in Britain, Japan and Sweden and running continuously from 1980 onwards).

(*c*) Very low elutriation.

(*d*) Easy removal of ash and uncombustible.

These advantages eliminate the need of spreader stroker, under-bed feeds, recirculation of carbon particles, bubble caps and give high output at higher thermal efficiency. This also helps to use variety of fuels without clinkering difficulties.

Extensive burning trials showed that the waste as metals came out in the ash, bright and clean while rubber from tyres burned off without smoke and smell, leaving the type reinforcing metal in the ash. The materials which can be burned are polystyrene, polyamides, tyre rubber, PVC, wax cartons, waste papers, agricultural waste in addition, coals and different forms of oils.

(2) Pressurized FBC-system. This is most modern method used in power industry. The arrangement of the system is shown in Fig. 15.5. In this system, the thermal reactor stress is separated from the presure stress by providing double shell design. The flue gas after passing through dust collector is passed through a gas turbine which can run the compressor to supply pressurised air to FBC for fluidization and combustion. The advantages of pressurised system over atmospheric system are listed below :

* Substantial increase of coal loading (kg/m^2) with simultaneous reduction of air velocity.

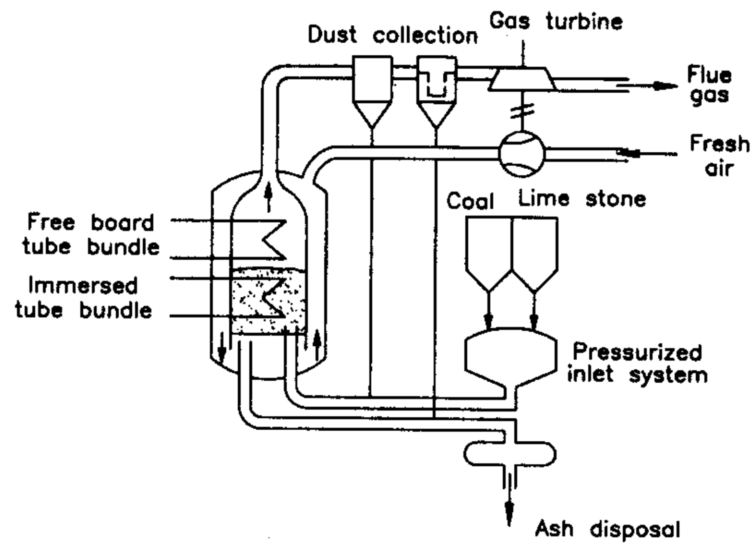


Fig. 15.5. Schematic Layout of Pressurized Fluidized Bed Combustion System.

* Considerable volume reduction of the system as shown in Fig. 15.6.
* High burning rates.
* Improved desulphurization and low NO_x emission.
* Considerable reduction in the cost.

But it is difficult to control and give long life to the plant.

15.4. ARRANGEMENTS OF DIFFERENT FBC PLANTS

The heat generated in FBC can be used for steam generation which can be used in steam power plant or the hot gases from FBC can be directly fed to the gas turbine plant or the heat generated can be simultaneously used to run steam turbine and gas turbine plant.

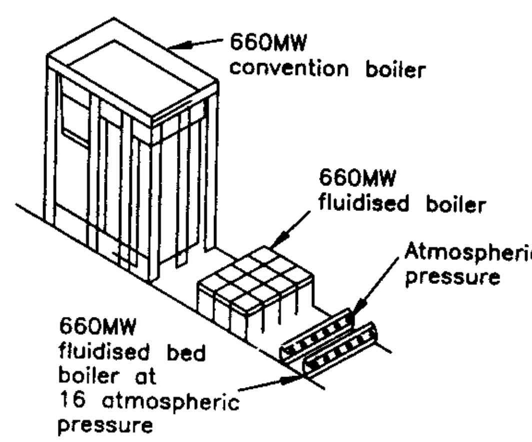


Fig. 15.6. Diagram illustrating effect of fluidised bed combustion on relative boiled volumes.

(A) FBC—With Gas Turbine Plant. Fluidized combustion provides a system which will accept almost any fuel, solid, liquid, and gaseous, provided the fuel can be distributed into the bed satisfactorily. A basic design of a fluidized bed combustion system is illustrated in Fig. 15.7 and 15.8. The combustor vessel contains a bed of granular material, such as coal ash, sand or lime-stone. There will be 200 mineral particles for every particle of fuel. Air from the blower, or compressor is blown through a distribution in the base of the combustor so as to 'fluidize' the particles ; that at such an air velocity, the particles are supported by the gas stream, and are in rapid motion relative to each other. The bed has the appearance of a boiling liquid and shows many fluid-like properties.

As the fuel burns, the heat of burning is carried by the mineral particles as burning particles collide rapidly with the mineral particles. As the air passing through this bed gets heated and hot gas steam is supplied to the gas turbine.

The pressurised fluidized bed combustion system has an added advantage over atmospheric fluidized combustion system as it has more freedom in an electric power producing cycle.

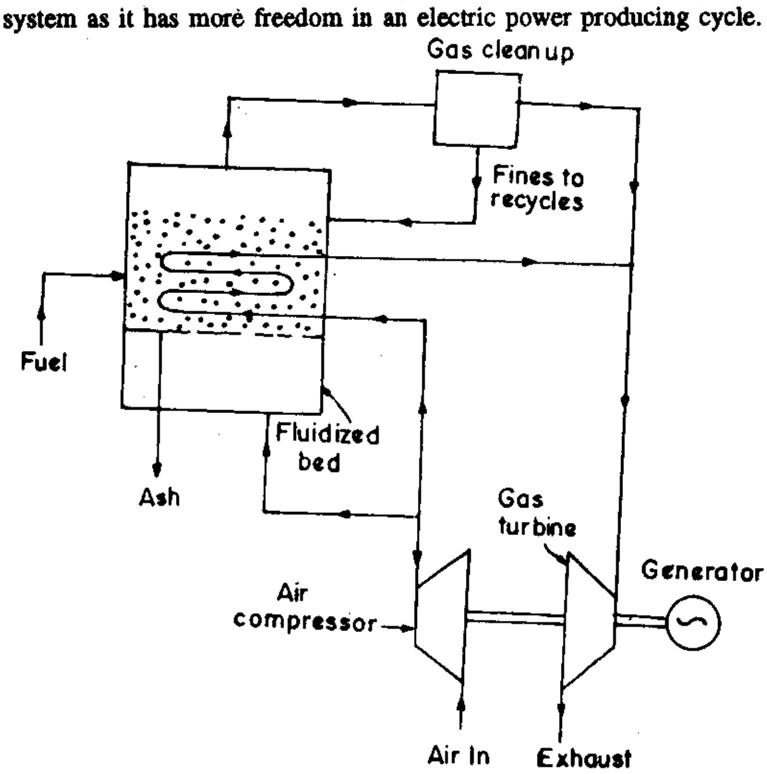


Fig. 15.7. Fluidized Bed with Gas Turbine as power generator.

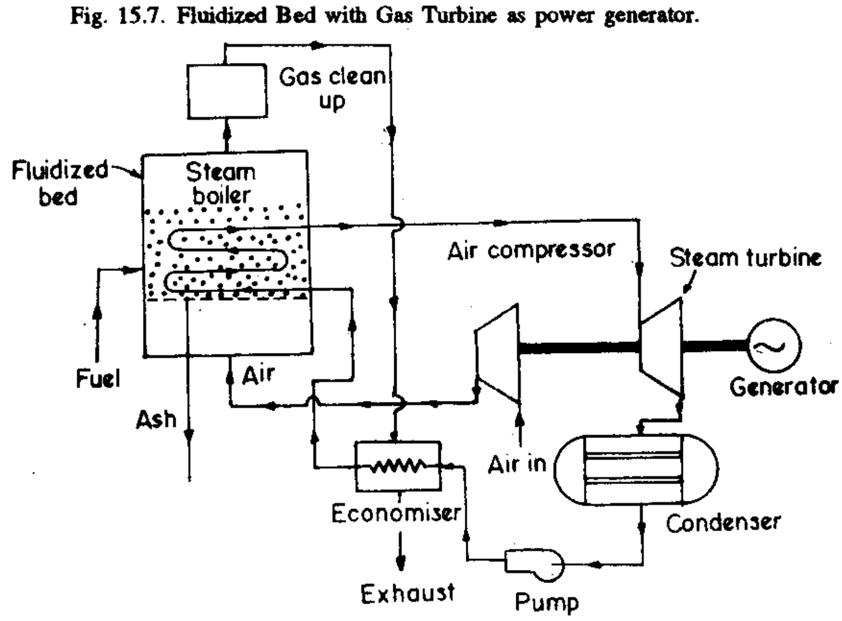


Fig. 15.8. Fluidized bed with steam turbine as power generator.

(B) FBC—With Steam Turbine Plant. In this system, the tubes carrying water are directly immersed in the bed as shown in Fig. 15.8. This provides very compact design of FBC as the heat transfer rate is considerably high. The steam generated is used in conventional steam turbine plant.

(C) FBC—With Steam and Gas Turbine Plants. The basic concept of fluidized combustion is the use of combined steam and gas cycle. A typical cycle is shown in Fig. 15.9. In this system, the pressurised fluid bed is cooled with steam tubes. The steam produced in these cooling tubes is passed through the steam turbine. The exhaust gases coming out from fluidized bed combustor at high pressure and temperature are passed through the gas turbine unit. This arrangement can keep the bed at considerably low temperature and gives higher efficiency.

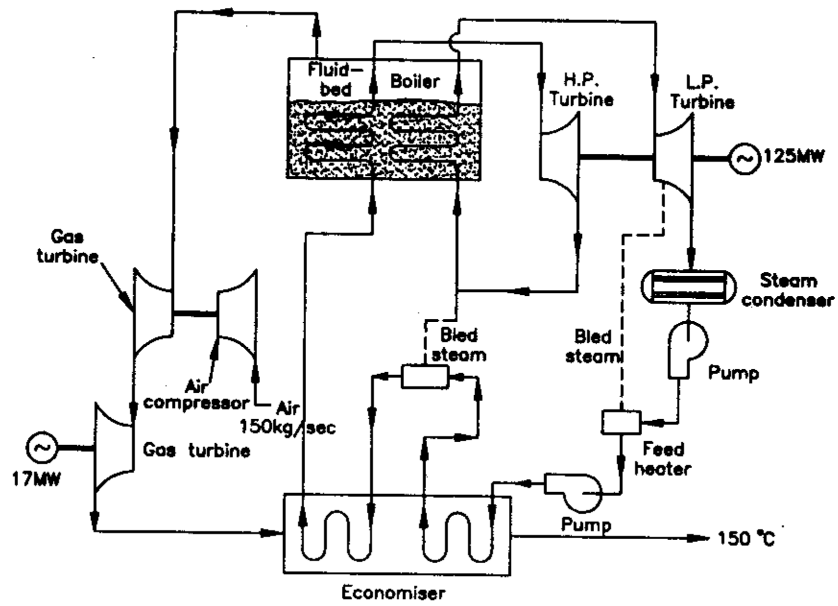


Fig. 15.9. 140 MW Gas-Steam Turbine Fluidized bed system.

The another typical cycle which can be used with fluidised bed is shown in Fig. 15.10. In this system, instead of putting steam tube through the bed to cool it, air can be used. This would give air at about 800°C and this hot air could be put through a closed cycle gas turbine system, giving three sources of electrical output. There would be close loop air cycled gas turbine, an open cycle gas turbine using the exhaust gases from the fluidized bed and a steam turbine cycle using waste heat boilers taking heat from exhausts of two gas turbines, one in open cycle and another in closed cycle.

Control of Atmospheric Pollution. The fluidized bed combustion system is a new technique which can reduce the emission of SO_2 considerably from burning of coal of high sulphur content. This is done by using dolomite or limestone as the bed material.

In the fluidized bed boiler, the limestone particles react with formed SO_2 in the presence of O_2 and forms $CaSO_4$ which can be easily removed from the bottom of the bed being a solid material.

$$2SO_2 + 2CaO + O_2 = 2CaSO_4. \quad ...(1)$$

It is simple to remove sulphur from combustion system as spent additive, along with the ordinary ash discharge ; and since $CaSO_4$ and $MgSO_4$ are non-toxic they can be dumped along with ash without toxic hazards.

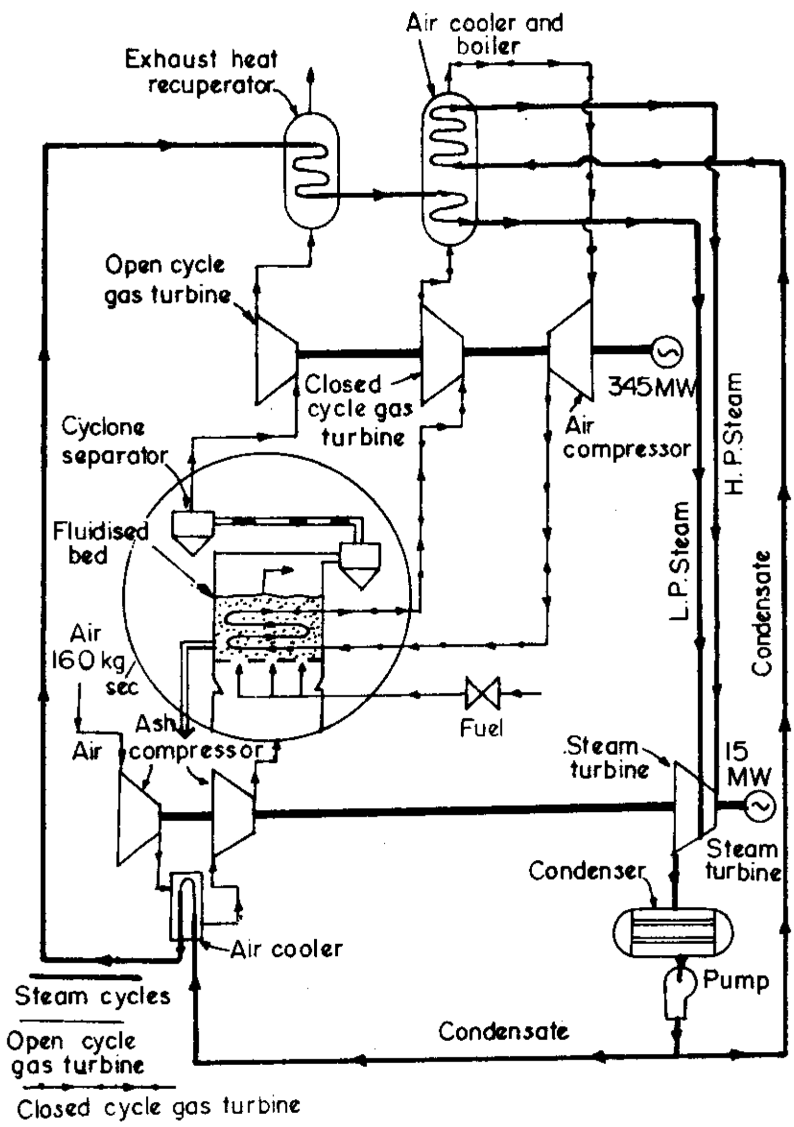


Fig. 15.10. Flow diagram from a proposed 360 MW plant with pressurised fluidised bed air heater.

Reduction in Sulphur emission plotted against Ca/S ratio. Work in UK shows that SO_2 emission can be simply controlled at the limit planned for USA power station in densely populated regions as 100 ppm in chimney gases. It is merely a matter of calcium content of the fluidized bed as shown in Fig. 15.11. The general limit proposed for US power stations in ordinary areas of 700 ppm requires less CaO in the bed.

When used on once through basis, high feed rates of limestone or dolomite to the bed are required if SO_2 removal of 90% is to be achieved. In order to reduce the solid waste disposal burden created by high lime-stone feed rates, a system is now under study in which $CaSO_4$ would be generated back to CaO in a separate fluidized bed reactor by the reaction with a reducing gas at a temperature of about 1100°C.

$$CaSO_4 + CO = CaO + SO_2 + CO_2 \quad ...(2)$$

$$CaSO_4 + H_2 = CaO + SO_2 + H_2O \quad ...(3)$$

The regenerated CaO would be returned to the boiler where it would again react with SO_2 and O_2. SO_2 in the regenerator is at a sufficiently high concentration to be recovered in a by-product sulphur plant. The arrangement of such a plant is shown in Fig. 15.12.

Formation of CaS *via* side reactions is undesirable because large amount of reactants are used and no SO_2 is produced as given by the following reactions :

$$CaSO_4 + 4CO = CaS + 4CO_2 \quad ...(4)$$

$$CaSO_4 + 4H_2 = CaS + 4H_2O \quad ...(5)$$

$CaSO_4$ can also react with CaS as given by the following reaction but this reaction does not occur to a great extent.

$$3CaSO_4 + CaS = 4CaO + 4SO_2 \quad ...(6)$$

The reactions 2, 3 and 6 are favoured by high temperatures whereas 4 and 5 are favoured at lower temperatures. High conversion of $CaSO_4$ to CaO was obtained by adding auxiliary air directly to fluidized bed. This created adjacent reducing and oxidizing zones in the bed which reduces the tendency to form undesired CaS.

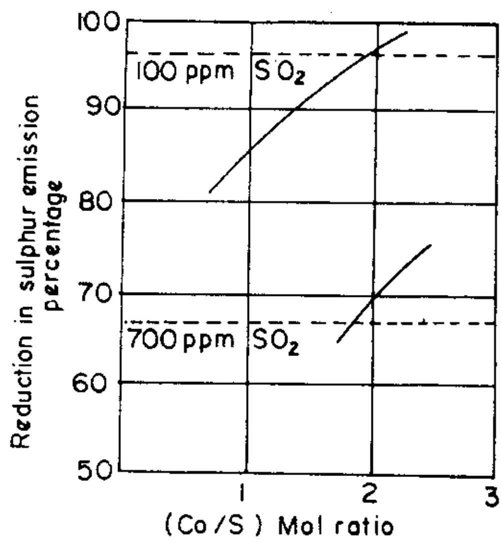


Fig. 15.11. (1) Dolomite and (2) Limestone.

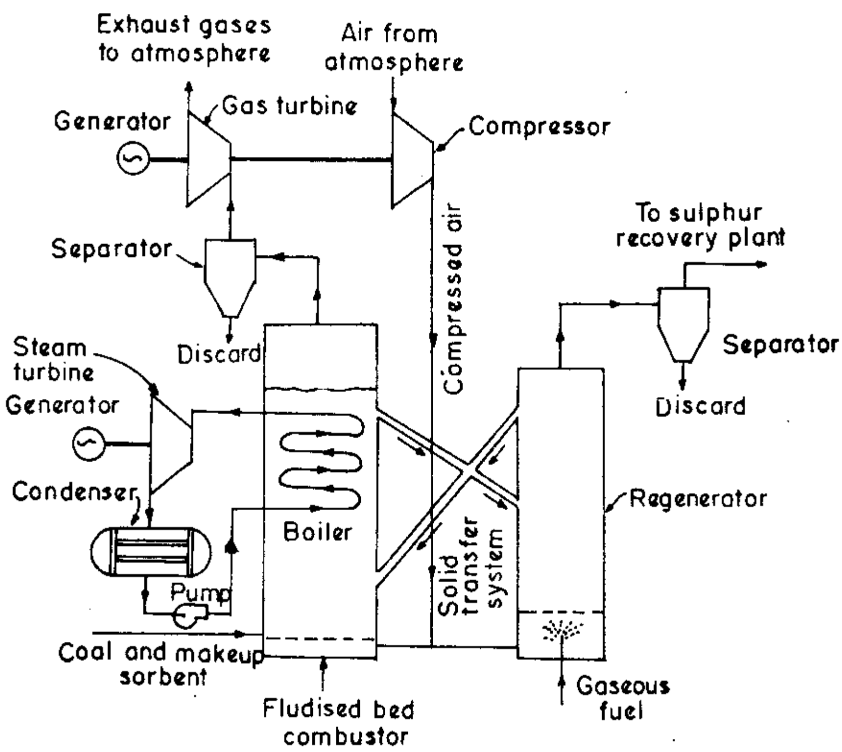


Fig. 15.12. Fluidized bed coal combustion system with SO_2 recovery plant.

The use of fluidized bed with gas turbine plant allows the use of solid fuel and prevents the collapse of gas turbine market due to rising prices and growing scarcity of petroleum products.

The question is going to be asked what economy can be achieved with the use of coal, the most abundant fossil source for future. The question could be positively answered today '*Fluidised Bed*'.

The world's first commercial *fluidized combustion boiler* (FCB) developed at BHEL has been sold to an Indian firm in Madras. FCB can burn a wide variety of low grade coal such as those available in India. The BHEL (Bharat Heavy Electricals Limited) boiler produces 12 tons of steam per hour. Its successful development has attracted the attention of the USA, UK and they have shown interest in joint development programme.

Bharat Heavy Electricals Limited has undertaken a massive programme for the development of both pressurized and atmospheric fluidized bed combustion boilers. The Research and Development wing of BHEL, Hyderabad is presently engaged in the development of FBC system. Engineering development centre, Tiruchirapalli, has an integrated plan for the development of atmospheric fluidized bed combustion boiler.

BHEL has designed and erected two 2 T/hr. fluidized bed boilers, one at CFRI-Dhanbad and other at RRL-Jorhat in co-operation with the national Laboratories. The specific purpose of RRL-Jorhat boiler is to study the combustion characteristics of high sulphur and high ash coal suitable for India, while at CFRI-Dhanbad test boiler was used to generate design data. In addition one 10 T/hr unit has been designed and commissioned at Engineering Development Centre, Tiruchirapalli and this is functioning satisfactorily. Further a 12 T/hr. boiler has been sold to M/s. Tiruchi Distillaries and Chemicals Ltd., Tiruchirapalli.

Rapid strides would be made in coming years to control the pollution from the fuel combustion and maintain the clean atmosphere which is the prime need for human survival.

In all modern thermal plants, the minimum emission of pollutants in the atmosphere and maximum permissible concentration at the ground level can be achieved with the use of high efficiency cleaning equipments and tall stacks. A 400 m stack serving power plant in USA is the tallest stack of date. The tall stacks are effective in lowering the ground level concentrations of pollutants but they do not reduce the amount of pollutants emitted in the atmosphere.

The maximum ground level concentrations of different pollutants emitted by 400 MW plant using coal as fuel are listed in the following table.

Table 15.1. Concentrations of pollutants emitted by 400 MW Plant

Pollutant	*Max concentration (ppm)*	*Pollutant*	*Max. concentration (ppm)*
Aldehydes	1.9×10^{-1}	Carbon monoxide	2.08
Oxides of Nitrogen	79	Hydro carbons	1.47
Oxides of Sulphur	240	Particulate	2.6×10^{-2}

Mento-Park power plant. A gas turbine plant linked to a fluidised bed combustor running on municipal waste and wood scrap from saw mill located at Mento-Park in California is shown in Fig. 15.12. This plant has a capacity of burning 100 tons of waste and scrap per day and generates 1 MW power and it is supplied to a community of about 150,000.

The incoming refuse passes through a shredder and separator where lighter combustible materials—mostly papers and plastics are separated from the heavy metal scrap and glass. The combustible material is then collected in buffer store and further fed to the fluidised bed at the rate demanded by gas turbine.

The fluidised bed used in this plant is steel cylinder 6.7 metre high and 2.9 metre in diameter and lined with firebrick. The bed is of sand-sized material and 60 cm thick. Combustion of refuse takes place at about 780 to 830°C. The burned gases are passed through three stages of separation where all particles above 4μ are removed before entering the power turbine. The life of turbine was estimated to be 20,000 hrs after the measurement of erosion rates. The analised exhaust from the turbine indicates 15 ppm hydrocarbons, 42 ppm carbon monoxide and 20 ppm sulphur dioxide which are far below than the safe accepted levels.

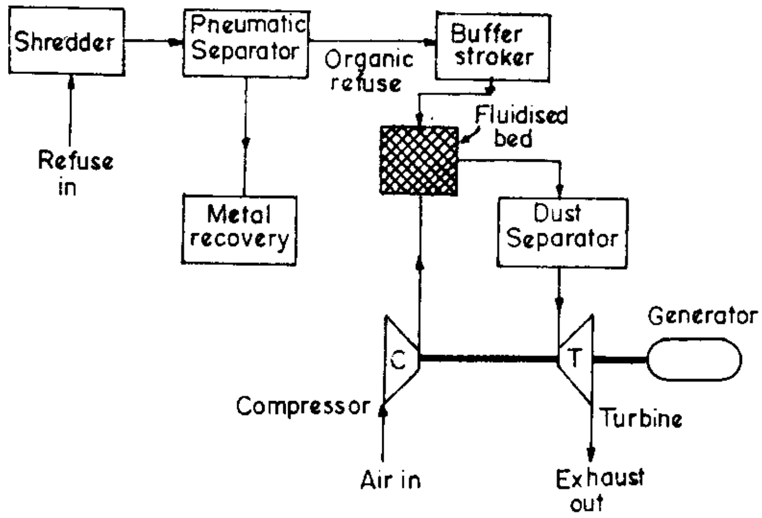


Fig. 15.12. Waste recovery gas turbine plant of 1 MW capacity using fluidised bed.

15.5. FBC—FOR LOW GRADE FUELS

A wide range of waste materials can be burned up in fluidised bed. Although waste materials include sewage sludge, slurries, lignites, municipal and industrial wastes, Municipal wastes carry special interest for power generation using FBC as it solves disposal problem as well as provides additional power.

Municipal refuse is rapidly increasing with the high rate of population growth specially in developing countries like India and Ceylon. It is estimated that a typical urban area in India disposes 0.6 kg/man-day and it is increasing at a rate of 1.3% per year due to the rise in per capita purchase potential. It is also estimated that the waste production will go upto 0.75 kg/man-day in 1995. This is very low compared with developed countries where refuse generation is of the order of 2.5 kg/man-day. But due to high density of population in India, the refuse produced is quite large. (Nearly 3000 tons/day in Bombay).

This refuse is disposed in form of land filling or incineration. The first method is commonly used in India. Landfilling contributes least to air pollution problem but requires large and suitable landsites. Recently, attention has been given in India to incineration as a medium for refuse disposal.

In the incineration process, hydrocarbon compounds of the combustible refuse combine with O_2 of the air to form CO_2 and water and leave the minerals and metals as solid residue. The oxidation releases high energy which can sterilize the residue, destroy odorous compounds and convert the water into vapour which together with CO_2 becomes an acceptable exhaust.

Combustion of municipal refuse produces a significant amount of heat (1 ton refuse = 70 gallons of oil). This heat can be easily recovered in FBC system by the gas which can be further used for power generation.

Figure 15.13 shows a FBC with gas turbine used in USA where municipal waste is used as fuel. It consists of waste processing and handling system, FBC for burning and gas turbine for power generation. The calorific value of Indian waste (1400 – 2200 kJ/kg) is very low compared with developed countries (6000 kJ/kg), therefore self-sustaining combustion reaction can't be maintained in FBC and it will be necessary to use auxiliary fuel.

In comparison with other fluidization bed combustion systems using coal as fuel, the outstanding feature of municipal waste is very high rate of furnace emission which is 5 to 30 kg/ton. In such FBC system, a series of collectors to remove alumina, sand and ash are required in addition to bag houses to reduce the particulate emission.

In addition to power, the materials like metals, glass and ash are recovered in FBC systems. The metals are sold as scrap, glass is sold to glass manufacturer. The ash collected is used for cement production, or stabilizer for road or fill materials.

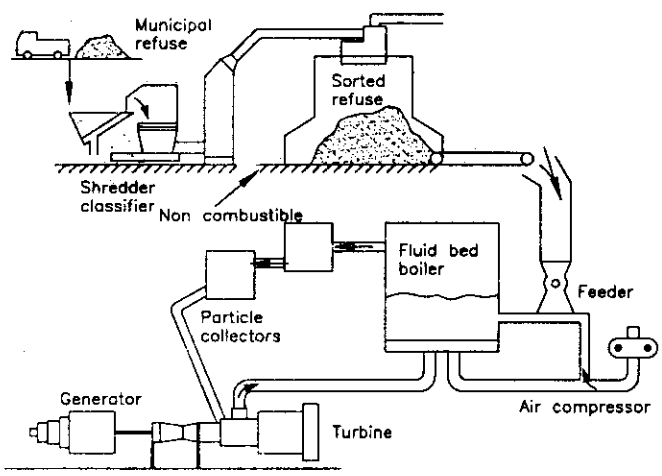


Fig. 15.13.

15.6. CORROSION IN FBC-SYSTEM

The operation of bed at elevated temperature leads to erosion and corrosion of the immersed tubes. More-over, there is higher tendency of erosion due to direct impact of particles. The tubes are covered by smooth and adherent deposits varied in colour from black to red. These deposits mainly consisted of fine particles, 1 to 5 microns in size and 20 to 500 microns in thickeners. The erosion of tubes by impacting of flyash becomes serious at velocities greater than 25 m/s. Thus there is substantial gap between this threshold and maximum fluidization valocities of 3 to 6 m/s which are in current use. The deposits can also absorb most of the kinetic energy of incident particles and reduce their abrasive effect.

The heat transfer tubes operate in FBC under extremely severe conditions. During combustion, atmosphere changes from oxidizing to reducing as gas bubbles, ash particles, burning coal particles imping on the tube surfaces. Overall conditions are likely to cause severe sulphidation and oxidation of tubes. Many alloys perform satisfactory under these conditions because the bed environment is very unique. At any instant, bed contains only 2% fuel and this dilute combustion is mainly responsible for low corrosion rates.

The tube deposits consist of calcium sulphate (mainly), calcium oxide and coal ash. The low bed temperature also does not encourage the formation of alkali-metal vapours. Unlike, the deposits which form on superheater and reheater surfaces in pulverised coal fired boilers, significant amounts of condensed sulphates and chlorides are absent. Generally calcium salts are not regarded as injurious agents of corrosion.

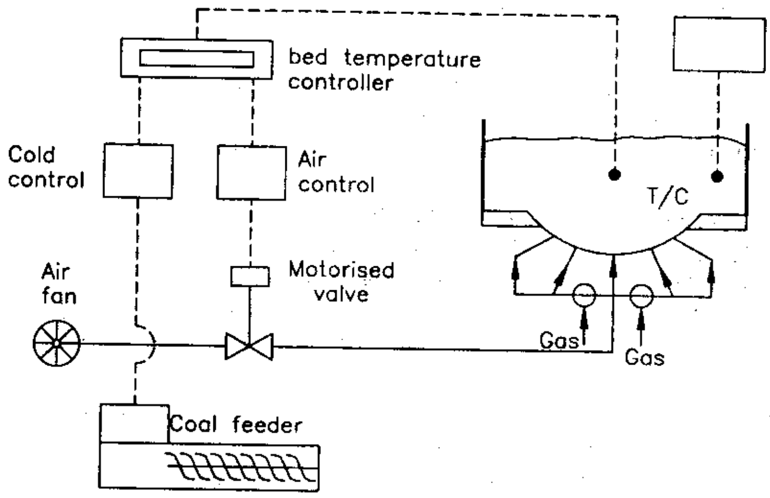
15.7. CONTROL OF FBC-SYSTEM

The heat release rate per unit area of a fluidized bed is linear function of velocity of gas leaving the bed. Higher the velocity, the greater is the heat release. As the velocity is increased, the size of the bed particles must be increased so that particles will not become entrained in the gas but will remain in the bed. Another factor is that the heat transfer rate decreases as particle size increases. Therefore, all the parameters must be properly controlled for the best results.

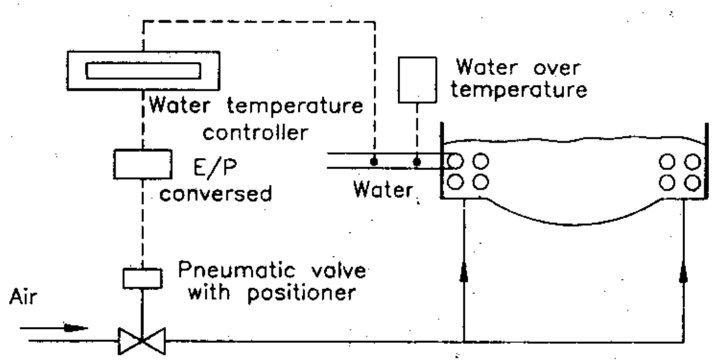
The control system consists of two independent loops as shown in Fig. 15.14.

The combustion bed temperature control consists of a thermocouple in the bed which supplies a signal to a indicating temperature controller which in turn controls a servomotorised value and a variable speed motor controller in parallel. The servo-valve is positioned in the main air supply line to the combustion bed, so controlling the excess air in the bed ensures good efficiency. The motor controller drives the coal feeder, the characteristics of which match the main air valve so that fuel and air supply ratio is kept constant.

The second loop maintains the specified water outlet temperature or steam pressure by controlling the heat input to the primary heating surface in the wings of the combustion. This is achieved by controlling the supply of air to the primary heat transfer zone of the bed. The characteristics of a *shallow bed* are such that one can control the heat transfer to the immersed tubes from maximum down to a negligible quantity by purely varying the fluidization velocity and hence the bed expansion. In case of steam unit, the third is introduced to control the feed water to maintain down water level.



WATER TEMPERATURE CONTROL



FBC BOILER CONTROL SYSTEM

Fig. 15.14.

15.8. STARTING OF FLUID-BED FIRING SYSTEM

Before coal can be fired in a fluid bed, the bed material must be preheated to the ignition temperature of the coal with auxiliary burners.

Two methods are commonly used for this :

1. A few oil or gas burners are lit and directed from above on to the surface of the bed. To ensure that the heat penetrates into the bed, this must be fluidized at regular intervals. The disadvantage of this method is the great amount of auxiliary energy is needed since the heat must penetrate into the bed against the fluidizing motions.

2. The fluidizing air is preheated with oil or gas burners and introduced through the nozzle bottom into the bed at 500°C. When the bed material reaches a certain minimum temperature, gas or light fuel oil lances projecting straight into the bed are ignited and safety burners are fitted above the bed surface. This method assures quick start up and requires little auxiliary energy.

15.9. CONVERSION OF OIL FIRED BOILERS TO FBC SYSTEMS

The oil based power industry is slowly shifting to coal industry and in this transformation, the FBC system plays a vital role. When the oil fired boiler is to be shifted to FBC system, the following modifications are to be made :

(1) **Furnace.** An oil firing furnace is small in volume than coal as larger amount of fuel reaction is available for combustion. The heat release rate of oil fired boiler is 3 times of stoker firing and 5 times of pulverised coal firing. Therefore, the furnace may be suitably enlarged to retain the capacity, incurring high modification cost.

(2) **Combustion system.** In practise, it is found that some excess quantity of air is to be supplied to achieve complete combustion. The forced draft and induced draft fans provided for oil firing may not be able to meet the coal firing needs. A flue gas velocity of 15 m/s or less is recommended in FBC system to avoid erosion and 25 to 35 m/s velocity is adopted in oil fired boilers. The head of the air required in FBC is 80 cm against the head of 20 cm. used in oil fired boiler. Hence the existing forced fan needs replacement..

(3) **Air System.** An air-plenum below distributor plate with suitable connection from FD fan with three to four compartments is provided in FBC system, therefore this special air ducting is to be added.

(4) **Flue Gas System.** The oil fired boiler requires more excess air and velocity of gas is 25 to 30 m/s. Though the fly ash from FBC is soft due to low bed temperature, but high velocity may lead to severe erosion. This can be reduced by changing the gas path suitably.

(4) **Flue Gas System.** The oil fired boiler requires more excess air and velocity of gas is 25 to 30 m/s. Though the fly ash from FBC is soft due to low bed temperature, but high velocity may lead to severe erosion. This can be reduced by changing the gas path suitably.

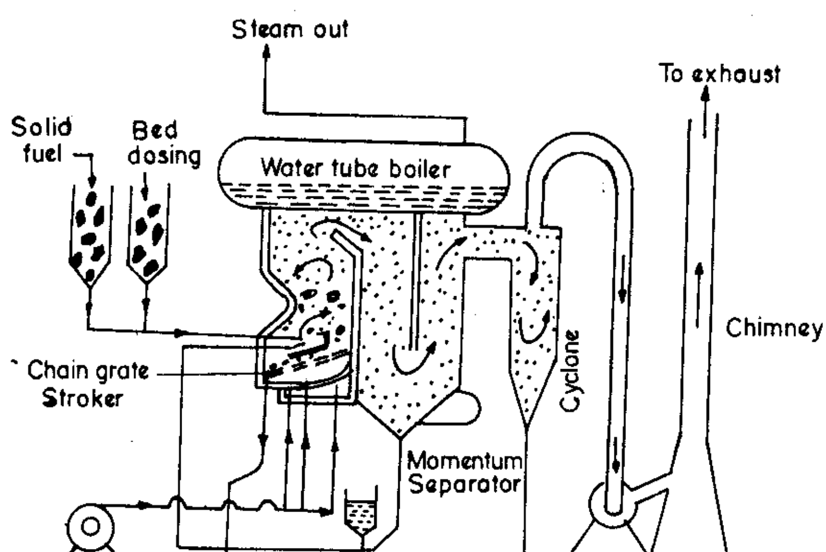


Fig. 15.15. Commercial FBC water tube boiler plant.

(5) **Water Steam Circuit.** The oil flame is at a high temperature, the furnace absorbs 40% or more of the heat output. The low operating temperature in FBC results in low furnace heat absorption. This reduction is more than compensated by the heat absorbed by the immersed tubes in the bed. The low operating

temperature also reduces the heat absorption in the superheater. In such cases, addition of extra surface in the convection pass is needed.

(6) Coal and Ash Handling. In FBC, high ash coals, middling and rejects can be fired by crushing them to 6 mm sizes. To suit this requirement, a crusher and a screen are to be added. Addition of a coal and ash handling system has to be envisaged. Hydraulic system is generally adopted for ash handling.

It is estimated that the difference in operating cost about 12.7 lakhs per MW per year will be sufficient to pay back the capital invested for change over from oil to FBC system.

A typical commercial FBC water tube boiler plant is shown in Fig. 15.15.

15.10. EROSION AND CORROSION AND ITS PRESENTATION IN FBC BOILERS

The principal attraction of FBC is that, a sulphur-avid material such as limestone can be added to capture most of the coal's sulphur content during actual combustion. SO_2 in the gas emission to the atmosphere can be drastically reduced to a tolerable level of 300 – 400 ppm even with high sulphur coals. In addition to this, low bed temperature of 800 to 900°C discourages the release of undesirable NO_x compound. In economic terms, the process offers the advantages of high heat release rates and an outstanding tolerance for difficult fuels of low reactivity such as coal washery slurries, garbage and sewage sludge also.

The tubes in FBC-system are covered by smooth, hard and adherent deposits. The deposits consisted of fine particles, 1 to 5 micron. The deposits attain a steady state thickness. The deposits on tubes in the bed and outside differed in amount and character. A thickness of 2 mm was observed on the underside tubes.

The presence of such deposits has immediate relevance to the question of erosion. In boiler plants, the erosion becomes serious at fly-ash velocities greater than 25 m/sec. Thus there is substantial velocity gap between this threshold and maximum fluidization velocities of 3 to 4 m/sec. It is observed that the deposits layer formed can absorb most of the kinetic energy of incident particles and reduce their abrasive effect. Thus, apart from their tendency to reduce the rate of heat transfer, tube deposits will prevent bed particles from striking the tubes and stop the erosion.

The thin deposit on the in-bed tubes has an important role in the corrosion process. It consists of calcium sulphate (mainly), calcium oxide and coal ash when limestone additives are used. Relatively low bed temperature (800 – 900°C) does not encourage the formation of alkali-metal vapours, accordingly, unlike the deposits which form on superheater and reheater surfaces in pulverised coal-fired boilers. Therefore, significant amounts of condensed sulphates and chlorides are absent. This shift from sodium and potassium sulphates of conventional pulverised boiler deposits to calcium sulphates is intriguing. The calcium salts have not been regarded as dangerous agents of corrosion.

The modification in design and mode in operation can reduce the problem of corrosion. Another way is an absorption or neutralization of corrosive chemical species. Both methods mentioned above are now in use to reduce corrosion. The low bed temperature in FBC system discourages the release of condensable salts and the limestone addition capturing SO_2. The proper selection of blending material like sodium, vanadium and chlorine with fuel is most important for avoiding corrosion action. The detailed chemistry of these processes is out of the scope of this text.

15.11. ADVANTAGES OF FLUIDIZED BED SYSTEMS

(1) The importance of the fluidized bed lies in the fact that it can use solid, liquid or gaseous fuel or mix as well as domestic and industrial waste. Any variety of coal irrespective of rank, ash content, ash fusion temperature, sulphur content can be made use of successfully. Major advantage is the capability of switching from one type of fuel to another, enabling the operator to take advantage of the cheapest fuel available on day-to-day basis. Virtually any type of combustable matter can be burned by adjusting the factors as size, air velocity and rate of feed.

(2) High combustion intensity (kJ/m^2-hr) can be achieved and varied with variation in air pressure supplied to the combustor. A heat rate 3×10^3 kJ/m^2-sec can be achieved even at atmospheric pressure

and a fluidizing velocity of about 3 m/sec. This means that the combustor is much smaller than conventional furnaces. Small combustion chamber cuts the construction time required in addition to its capital cost with which its saves 15 to 20% towards the construction cost. Therefore, it is cheaper in capital and running cost.

(3) Solid mixing is extremely rapid and therefore high heat transfer rates can be obtained to surfaces immersed in the bed, plus a more effective use of tube surface owing to its immersion within the bed. This can lead to a saving of 75% in tube requirements.

(4) Combustion temperature can be controlled accurately and it can be low enough (750°C-900°C) to minimize volatization of ash constituents like alkali metals (that can form deposits upon condensation and can cause corrosion problems in conventional boilers) because the temperature is well below the melting point of most gas-borne solid particles. Also, because ash particles have not been melted, they are soft and non-abrasive, unlike those from previous attempts at solid fuel gas turbine firing, where hard glassy particles erode the turbine blading.

(5) The system can readily be designed for operation at raised combustion pressure, owing to the simplicity of arrangement, small size of the plant and reduced likelihood of corrosion or erosion of gas turbine blades.

(6) The SO_2 formed due to combustion of sulphur can be absorbed in the fluidized bed if some of the mineral particles are $CaCO_3$. A chemical reaction occurs between SO_2 and $CaCO_3$ to form $CaSO_4$. The $CaSO_4$ being solid can be collected with the ash. Thus we can use coals of higher sulphur content even 3.5% which are presently considered unsuitable without the use of flue gas cleaning system. In fluidized bed combustion system, sulphur retention equipment and combustion system are one therefore there is no need to build a separate gas cleaning system which is bigger than boiler plant in some cases. This is major advantage of FBC.

(7) With 2% sulphur coal burned, dolomite feed at a calcium to sulphur mole ratio in the range of 0.5 to 1 was adequate to reduce SO_2 emissions sufficiently, (1.2 lb of SO_2 per million Btu heat input).

(8) Another environmental problem is related to the combustion temperature. Stabilization of combustion at 700-900°C is possible with the use of fluidized bed. This temperature is well below the temperature at which the ash sinters. Therefore, vast bulk of ash can be tapped from the bottom of the bed. Low combustion temperatures also prevent the formation of NO_x. The formation of NO_x is influenced very much by bed temperature and excess air.

(9) As gas velocity increases, the particles are lifted suspending them in a turbulent mass and the floating mass resembles the boiling liquid and give high combustion efficiency 99.9%. One percent increase in efficiency of 30 tons/hr boiler can save around 2 lakh rupees per year.

(10) The combustion in conventional system becomes unstable when the ash exceeds 48% but even 70% ash containing coal can be efficiently burned in FBC.

Flue gases from conventional oil-fired boiler plant contains some 300-500 ppm NO_x and from coal fired plant some 400-800 ppm. By contrast, from fluidized combustion of oil, the NO_x emission remained in the range of 100 ± 120 ppm and with coal under pressure, 120 ± 60 ppm. When burning propane, the NO_x concentrations have been less than 40 ppm. This is comparable with the general limit imposed for US power stations of 700 ppm in ordinary areas and 100 ppm in densely populated areas.

(11) Pulverisation of solid fuel is not necessary with fluidized bed combuster. The maximum size of the coal particle is limited to 6 mm. Most of the research work is done using coal as a fuel as it is available in abundance.

(12) The volatalization of alkali compounds does not occur at bed temperature (800-900°C), so the deposition of the tubes is minimised. Low temperature during combustion reduces the fire side fouling.

(13) The large quantity of bed material acts as a thermal storage which reduces the effect of any fluctuations in fuel feed ratio.

The fluidized bed combustion system is particularly more attractive with high ash fuels (tar sands, oil shales, coal refinery slurry) which can be burned at ease and where there is strict atmospheric pollution legislation.

BHEL Triruchi is undoubted market leader in boiler manufacture in India having supplied equipment that accounts for 65% of the countrys installed power generation capacity.

The company has also acquired and commercialised the technology for manufacture of environment friendly Circulating Fluidised Bed Combustion (CFBC) boilers which are becoming worldwide popular on account of their low emission levels and as their ability to handle a wide range of fuels specially lignite and a low grade coal.

EXERCISES

1. What do you understand by FBC ? Explain its working principle with a neat sketch.
2. Differentiate the constructional features of different FBC with neat sketches and discuss the relative merits and demerits.
3. What are the major advantages of FBC system over the conventional one ?
4. What difficulties are faced when FBC is used for light fuels as municipal and agricultural wastes ?
5. What are the major drawbacks of a conventional FBC system ? What changes are suggested to overcome the same ?
6. Draw a line diagram of FBC system where gas turbine is used as prime mover. What is the main advantage of this system ?
7. Draw a line diagram of FBC system where steam turbine is used as a prime mover and explain its working.
8. Draw a line diagram of FBC system where steam and gas turbines are used as prime movers. What are its advantages over the previous systems.
9. What major factors are responsible for the corrosion of steam tubes in FBC system ? How this problem is solved in practice ?
10. What major changes are required to convert an existing oil fired boiler to FBC system ? Explain in detail giving specific reasons.

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