13

Steam Boilers

13.1. Introduction

A steam generator or boiler is, usually, a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel (solid, liquid or gaseous) to water, and ultimately to generate steam. The steam produced may be supplied :

1. to an external combustion engine, *i.e.* steam engines and turbines,

2. at low pressures for industrial process work in cotton mills, sugar factories, breweries, etc., and

3. for producing hot water, which can be used for heating installations at much lower pressures.

13.2. Important Terms for Steam Boilers

Though there are many terms used in steam boilers, yet the following are important from the subject point of view :

1. *Boiler shell.* It is made up of steel plates bent into cylindrical form and riveted or welded together. The ends of the shell are closed by means of end plates. A boiler shell should have sufficient capacity to contain water and steam.

2. *Combustion chamber.* It is the space, generally below the boiler shell, meant for burning fuel in order to produce steam from the water contained in the shell.

3. *Grate.* It is a platform, in the combustion chamber, upon which fuel (coal or wood) is burnt. The grate, generally, consists of cast iron bars which are spaced apart so that air (required for combustion) can pass through them. The surface area of the grate, over which the fire takes place, is called *grate surface.*

4. *Furnace.* It is the space, above the grate and below the boiler shell, in which the fuel is actually burnt. The furnace is also called *fire box.*

5. *Heating surface.* It is that part of boiler surface, which is exposed to the fire (or hot gases from the fire).

6. *Mountings.* These are the fittings which are mounted on the boiler for its proper functioning. They include water level indicator, pressure gauge, safety valve etc. It may be noted that a boiler cannot function safely without the mountings.

7. *Accessories.* These are the devices, which form an integral part of a boiler, but are not mounted on it. They include superheater, economiser, feed pump etc. It may be noted that the accessories help in controlling and running the boiler efficiently.

13.3. Essentials of a Good Steam Boiler

Following are the important essentials of a good steam boiler :

1. It should produce maximum quantity of steam with the minimum fuel consumption.
2. It should be economical to instal, and should require little attention during operation.
3. It should rapidly meet the fluctuation of load.
4. It should be capable of quick starting.
5. It should be light in weight.
6. It should occupy a small space.
7. The joints should be few and accessible for inspection.
8. The mud and other deposits should not collect on the heating plates.
9. The refractory material should be reduced to a minimum. But it should be sufficient to secure easy ignition, and smokeless combustion of the fuel on reduced load.
10. The tubes should not accumulate soot or water deposits, and should have a reasonable margin of strength to allow for wear or corrosion.
11. The water and flue gas circuits should be designed to allow a maximum fluid velocity without incurring heavy frictional losses.
12. It should comply with safety regulations as laid down in the Boilers Act.

13.4. Selection of a Steam Boiler

The selection of type and size of a steam boiler depends upon the following factors :

1. The power required and the working pressure.
2. The rate at which steam is to be generated.
3. The geographical position of the power house.
4. The fuel and water available.
5. The type of fuel to be used.
6. The probable permanency of the station.
7. The probable load factor.

13.5. Classifications of Steam Boilers

Though there are many classifications of steam boilers, yet the following are important from the subject point of view :

1. *According to the contents in the tube*. The steam boilers, according to the contents in the tube may be classified as :

(*a*) Fire tube or smoke tube boiler, and (*b*) Water tube boiler.

In *fire tube steam boilers*, the flames and hot gases, produced by the combustion of fuel, pass through the tubes (called multi-tubes) which are surrounded by water. The heat is conducted through the walls of the tubes from the hot gases to the surrounding water. Examples of fire tube boilers are : Simple vertical boiler, Cochran boiler, Lancashire boiler, Cornish boiler, Scotch marine boiler, Locomotive boiler, and Velcon boiler.

In *water tube steam boilers*, the water is contained inside the tubes (called water tubes) which are surrounded by flames and hot gases from outside. Examples of water tube boilers are : Babcock and Wilcox boiler, Stirling boiler, La-Mont boiler, Benson boiler, Yarrow boiler and Loeffler boiler.

2. *According to the position of the furnace*. The steam boilers, according to the position of the furnace are classified as :

(*a*) Internally fired boilers, and (*b*) Externally fired boilers.

In *internally fired steam boilers*, the furnace is located inside the boiler shell. Most of the fire tube steam boilers are internally fired.

- In *externally fired steam boilers*, the furnace is arranged underneath in a brick-work setting. Water tube steam boilers are always externally fired.

3. *According to the axis of the shell.* The steam boilers, according to the axis of the shell, may be classified as :

(*a*) Vertical boilers, and (*b*) Horizontal boilers.

In *vertical steam boilers*, the axis of the shell is vertical. Simple vertical boiler and Cochran boiler are vertical boilers.

In *horizontal steam boilers*, the axis of the shell is horizontal. Lancashire boiler, Locomotive boiler and Babcock and Wilcox boiler are horizontal boilers.

4. *According to the number of tubes.* The steam boilers, according to the number of tubes, may be classified as :

(*a*) Single tube boilers, and (*b*) Multitubular boilers.

In *single tube steam boilers*, there is only one fire tube or water tube. Simple vertical boiler and Cornish boiler are single tube boilers.

In *multitubular steam boilers*, there are two or more fire tubes or water tubes. Lancashire boiler, Locomotive boiler, Cochran boiler, Babcock and Wilcox boiler are multitubular boilers.

5. *According to the method of circulation of water and steam.* The steam boilers, according to the method of circulation of water and steam, may be classified as :

(*a*) Natural circulation boilers, and (*b*) Forced circulation boilers.

In *natural circulation steam boilers*, the circulation of water is by natural convection currents, which are set up during the heating of water. In most of the steam boilers, there is a natural circulation of water.

In *forced circulation steam boilers*, there is a forced circulation of water by a centrifugal pump driven by some external power. Use of forced circulation is made in high pressure boilers such as La-Mont boiler, Benson boiler, Loeffler boiler and Velcon boiler.

6. *According to the use.* The steam boilers, according to their use, may be classified as

(*a*) Stationary boilers, and (*b*) Mobile boilers.

The *stationary steam boilers* are used in power plants, and in industrial process work. These are called stationary because they do not move from one place to another.

The *mobile steam boilers* are those which move from one place to another. These boilers are locomotive and marine boilers.

7. *According to the source of heat.* The steam boilers may also be classified according to the source of heat supplied for producing steam. These sources may be the combustion of solid, liquid or gaseous fuel, hot waste gases as by-products of other chemical processes, electrical energy or nuclear energy, etc.

13.6. Simple Vertical Boiler

A simple vertical boiler produces steam at a low pressure and in small quantities. It is, therefore, used for low power generation or at places where the space is limited. The construction of this type of boiler is shown in Fig. 13.1.

It consists of a cylindrical shell surrounding a nearly cylindrical fire box. The fire box is slightly tapered towards the top to allow the ready passage of the steam to the

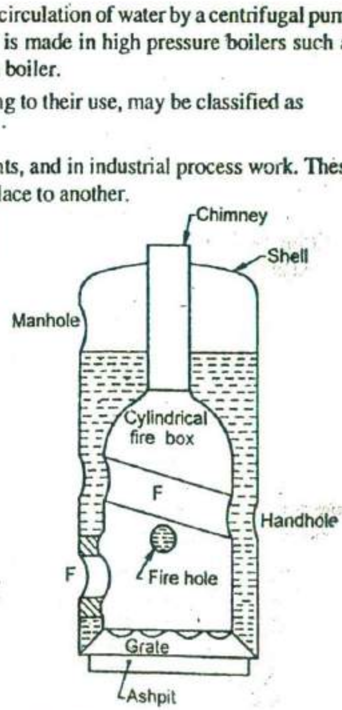

Fig. 13.1. Simple vertical boiler.

surface. At the bottom of the fire box, is a grate. The fire box is fitted with two or more inclined cross tubes *F*, *F*. The inclination is provided to increase the heating surface as well as to improve the circulation of water. An uptake tube passes from the top of the fire box to the chimney. The handholes are provided opposite to the end of each water tube for cleaning deposits. A manhole is provided at the top for a man to enter and clean the boiler. A mudhole is provided at the bottom of the shell to remove the mud, that settles down. The space between the boiler shell and fire box is filled with water to be heated.

13.7. Cochran Boiler or Vertical Multitubular Boiler

There are various designs of vertical multitubular boilers. A Cochran boiler is considered to be one of the most efficient type of such boilers. It is an improved type of simple vertical boiler.

This boiler consists of an external cylindrical shell and a fire box as shown in Fig. 13.2. The shell and fire box are both hemispherical. The hemispherical crown of the boiler shell gives maximum space and strength to withstand the pressure of steam inside the boiler. The hemispherical crown of the fire box is also advantageous for resisting intense heat. The fire box and the combustion chamber is connected through a short pipe. The flue gases from the combustion chamber flow to the smoke box through a number of smoke tubes. These tubes generally have 62.5 mm external diameter and are 165 in number. The gases from the smoke-box pass to the atmosphere through a chimney. The combustion chamber is lined with fire bricks on the shell side. A manhole near the top of the crown on the shell is provided for cleaning.

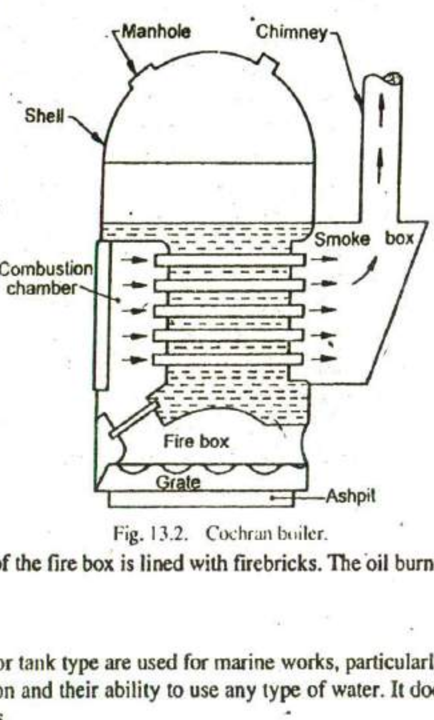

Fig. 13.2. Cochran boiler.

At the bottom of the fire box, there is a grate (in case of coal firing) and the coal is fed through the fire hole. If the boiler is used for oil firing, no grate is provided, but the bottom of the fire box is lined with firebricks. The oil burner is fitted at the fire hole.

13.8. Scotch Marine Boiler

The marine steam boilers of the scotch or tank type are used for marine works, particularly, due to their compactness, efficiency in operation and their ability to use any type of water. It does not require brick work setting and external flues.

It has a drum of diameter from 2.5 to 3.5 metres placed horizontally. These steam boilers may be *single ended* or *double ended*. The length of a single ended steam boiler may be upto 3.5 meters while for double ended upto 6.5 meters. A single ended boiler has one to four furnaces which enter from front end of the boiler. A double ended boiler has furnaces on both of its ends, and may have furnaces from two to four in each end.

A single ended scotch marine steam boiler is fired by four furnaces, as shown in Fig. 13.3. The furnaces are generally corrugated for strength. Each furnace has its own combustion chamber. There are fine flat plates in the combustion chamber, which require staying, *i.e.* the top plate, back plate, two side plates and the tube plate. There are a number of smoke tubes placed horizontally and connect the combustion chamber to chimney. The front and back plates of the shell are strengthened by longitudinal stays.

The combustion chamber walls form the best heating surface. The furnace tubes, smoke tubes and the combustion chamber, all being surrounded by water, give a very large heating surface area in proportion to the cubical size of boiler.. The water circulates around the smoke tubes. The level of water is maintained a little above the combustion chamber. The flue gases, from the combustion chamber, are forwarded by draught through the smoke tubes, and finally up the chimney. The smoke box is provided with a door for cleaning the tubes and smoke box.

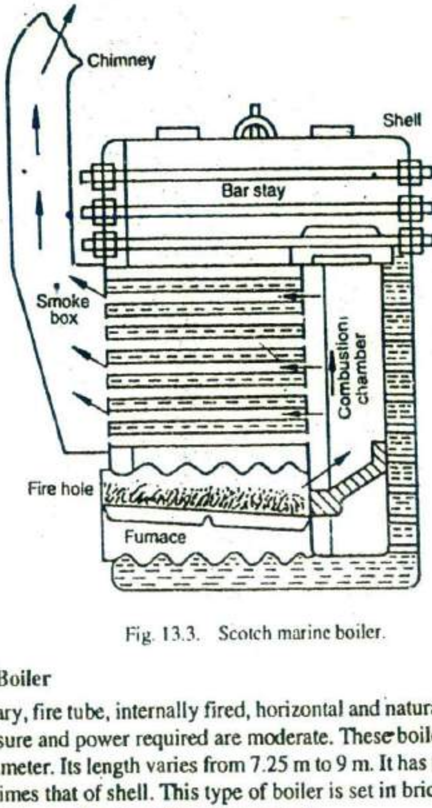

Fig. 13.3. Scotch marine boiler.

13.9. Lancashire Boiler

It is a stationary, fire tube, internally fired, horizontal and natural circulation boiler. It is used where working pressure and power required are moderate. These boilers have a cylindrical shell of 1.75 m to 2.75 m diameter. Its length varies from 7.25 m to 9 m. It has two internal flue tubes having diameter about 0.4 times that of shell. This type of boiler is set in brick work forming external flue so that part of the heating surface is on the external shell.

A Lancashire boiler with brick work setting is shown in Fig. 13.4. This boiler consists of a long cylindrical external shell (1) built of steel plates, in sections riveted together. It has two large internal flue tubes (2). These are reduced in diameter at the back end to provide access to the lower part of the boiler. A fire grate (3) also called furnace, is provided at one end of the flue tubes on which solid fuel is burnt. At the end of the fire grate, there is a brick arch (5) to deflect the flue gases upwards. The hot flue gases, after leaving the internal flue tubes pass down to the bottom tube (6). These flue gases move to the front of the boiler where they divide and flow into the side flue (7). The flue gases then enter the main flue (9), which leads them to chimney.

The damper (8) is fitted at the end of side flues to control the draught (*i.e.* rate of flow of air) and thus regulate the rate of generation of steam. These dampers are operated by chain passing over a pulley on the front of the boiler.

A spring loaded safety valve (10) and a stop valve (11) is mounted as shown in Fig. 13.4. The stop valve supplies steam to the engine as required. A high steam and low water safety valve (12) is also provided.

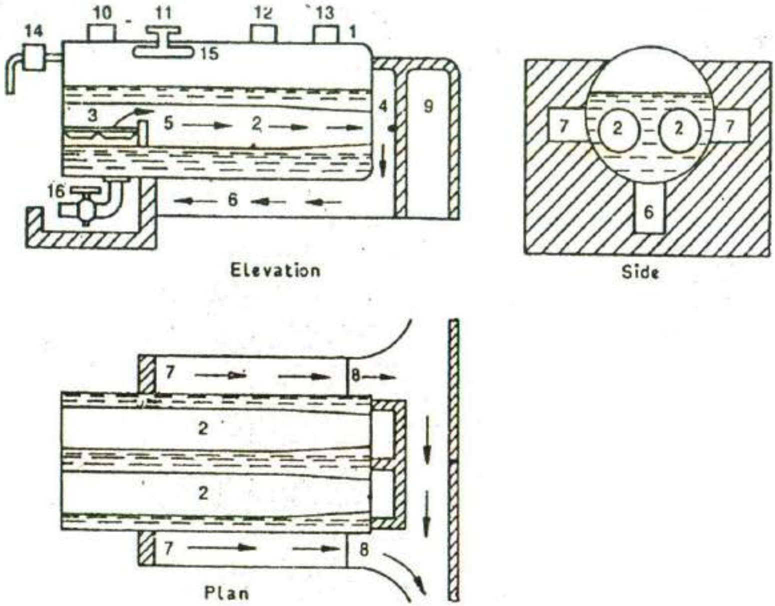

Fig. 13.4. Elevation, side and plan of lancashire boiler.

A perforated feed pipe (14) controlled by a feed valve is used for feeding water uniformly. When the boiler is strongly heated, the steam generated carries a large quantity of water in the steam space, known as *priming*. An antipriming pipe (15) is provided to separate out water as far as possible. The stop valve thus receives dry steam.

A blow-off cock (16) removes mud, etc., that settles down at the bottom of the boiler, by forcing out some of the water. It is also used to empty water in the boiler, whenever required for inspection. Manholes are provided at the top and bottom of the boiler for cleaning and repair purposes.

13.10. Cornish Boiler

It is similar to a Lancashire boiler in all respects, except there is only one flue tube in Cornish boiler instead of two in Lancashire boiler, as shown in Fig. 13.5. The diameter of Cornish boiler is generally 1 m to 2 m and its length varies from 5 m to 7.5 m. The diameter of flue tube may be about 0.6 times that of shell. The capacity and working pressure of a Cornish boiler is low as compared to Lancashire boiler.

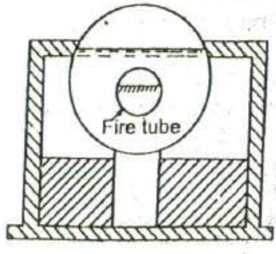

Fig. 13.5. Cornish boiler.

13.11. Locomotive Boiler

It is a multi-tubular, horizontal, internally fired and mobile boiler. The principal feature of this boiler is to produce steam at a very high rate. A modern type of a locomotive boiler is shown in Fig. 13.6.

It consists of a shell or barrel having 1.5 metres diameter and 4 metres in length. The coal is fed into the fire box through the fire door and burns on grate. The flue gases from the grate are deflected by a brick arch, and thus whole of the fire box is properly heated. There are about 157 thin tubes or fire tubes *F* (47.5 mm diameter) and 24 thick or superheated tubes *G* (130 mm diameter). The flue gases after passing through these tubes enter a smoke box. The gases are then lead to atmosphere through a chimney. The barrel contains water around the tubes, which is heated up by the flue gases and gets converted into steam.

A stop valve as regulator is provided inside a cylindrical steam dome. This is operated by a regulator shaft from the engine ro m by a driver. The header is divided into two portions, one is the superheated steam chamber and the other is the saturated steam chamber. The steam pipe leads the steam from the regulator to the saturated steam chamber. It then leads the steam to the superheated tubes, and after passing through these tubes, the steam returns back to the superheated steam chamber. The superheated steam now flows through the steam pipe to the cylinder, one on each side. The draught is due to the exhaust steam from the cylinders, which is discharged through the exhaust pipe. The front door can be opened for cleaning or repairing the smoke box.

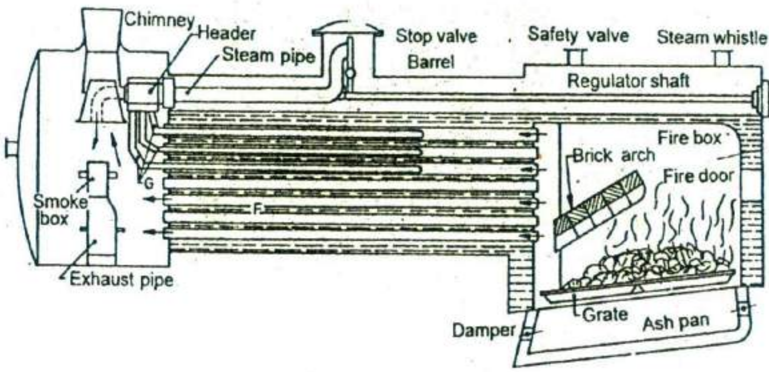

Fig. 13.6. Locomotive boiler.

The safety valves and a steam whistle are provided as shown in Fig. 13.6. The ash from the grate is collected in ash pan and is discharged out from time to time by opening it with the help of dampers operated by rods and levers.

13.12. Babcock and Wilcox Boiler

It is a straight tube, stationary type water tube boiler, as shown in Fig. 13.7. It consists of a steam and water drum (1). It is connected by a short tube with uptake header or riser (2) at the back end.

The water tubes (5) (100 mm diameter) are inclined to the horizontal and connects the uptake header to the downtake header. Each row of the tubes is connected with two headers, and there are plenty of such rows. The headers are curved when viewed in the direction of tubes so that one tube is not in the space of other, and hot gases can pass properly after heating all the tubes. The headers are provided with hand holes in the front of the tubes and are covered with caps (18).

A mud box (6) is provided with each downtake header and the mud, that settles down is removed. There is a slow moving automatic chain grate on which the coal is fed from the hopper (21). A fire bricks baffle causes hot gases to move upwards and downwards and again upwards before leaving the chimney. The dampers (17) are operated by a chain (22) which passes over a pulley to the front of a boiler to regulate the draught.

The boiler is suspended on steel girders, and surrounded on all the four sides by fire brick walls. The doors (4) are provided for a man to enter the boiler for repairing and cleaning. Water circulates from the drum (1) into the header (2) and through the tubes (5) to header (3) and again to the drum. Water continues to circulate like this till it is evaporated. A steam superheater consists of a large number of steel tubes (10) and contains two boxes ; one is superheated steam box (11) and other is saturated steam box (12).

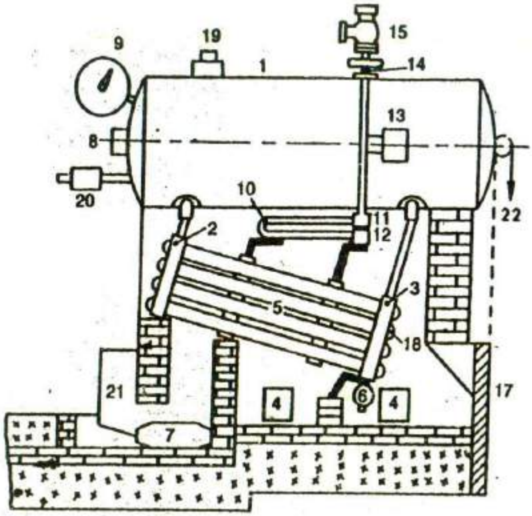

Fig. 13.7. Babcock and Wilcox boiler.

The steam generated above the water level in the drum flows in the dry pipe (13) and through the inlet tubes into the superheated steam box (11). It then passes through the tubes (10) into the saturated steam box (12). The steam, during its passage through tubes (10), gets further heated and becomes superheated. The steam is now taken through the outlet pipe (14) to the stop valve (15).

• The boiler is fitted with usual mountings, such as safety valve (19), feed valve (20), water level indicator (8) and pressure gauge (9).

13.13. La-Mont Boiler

This is a modern high pressure water tube steam boiler working on a forced circulation. The circulation is maintained by a centrifugal pump, driven by a steam turbine, using steam from the boiler. The forced circulation causes the feed water to circulate through the water walls and drums equal to ten times the mass of steam evaporated. This prevents the tubes from being overheated.

A diagrammatic sketch of La-Mont steam boiler is shown in Fig. 13.8. The feed water passes through the economiser to an evaporating drum. It is then drawn to the circulating pump through

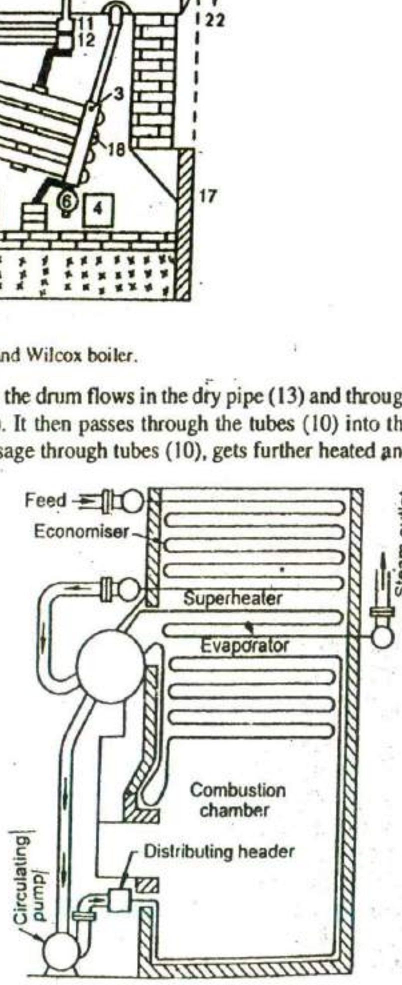

Fig. 13.8. La-Mont boiler.

the tube. The pump delivers the feed to the headers, at a pressure above the drum pressure. The header distributes water through nozzles into the generating tubes acting in parallel. The water and steam from these tubes passes into the drum. The steam in the drum is then drawn through the superheater.

13.14. Loeffler Boiler

This is a water tube boiler using a forced circulation. Its main principle of working is to evaporate the feed water by means of superheated steam from the superheater. The hot gases from the furnace are used for superheating.

A diagrammatic sketch of a Loeffler steam boiler is shown in Fig. 13.9. The feed water from the economiser tubes is forced to mix with the superheated steam in the evaporating drum. The saturated steam, thus formed, is drawn from the evaporating drum by a steam circulating pump. This steam passes through the tubes of the combustion chamber walls and then enters the superheater. From the superheater, about one-third of the superheated steam passes to the turbine and the remaining two-third is used to evaporate the feed water in the evaporating drum.

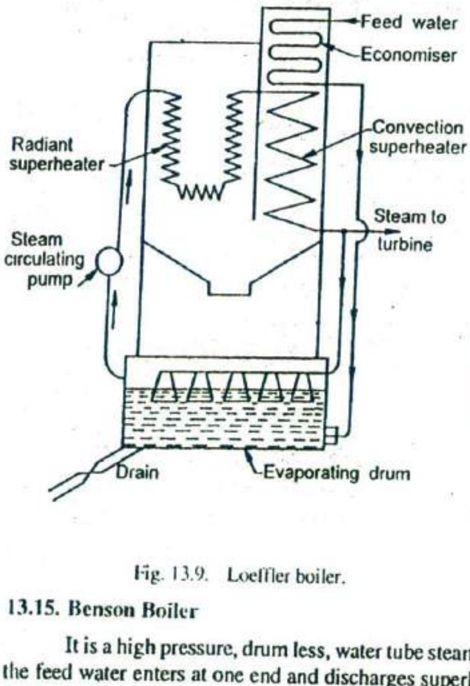

Fig. 13.9. Loeffler boiler.

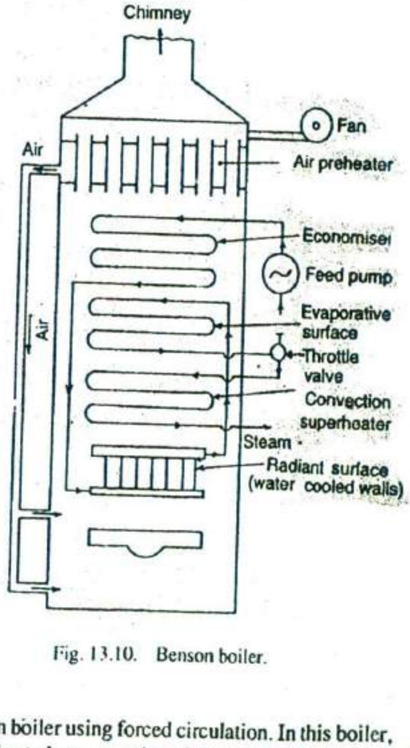

Fig. 13.10. Benson boiler.

13.15. Benson Boiler

It is a high pressure, drum less, water tube steam boiler using forced circulation. In this boiler, the feed water enters at one end and discharges superheated steam at the other end. The feed pump increases the pressure of water to supercritical pressure (*i.e.* above the critical pressure of 225 bar) and thus the water directly transforms into *steam without boiling.

The diagrammatic sketch of a Benson boiler is shown in Fig. 13.10. The feed water passes through the economiser to the water cooled walls of the furnace. The water receives heat by radiation

* We know that at critical pressure, the latent heat of vaporisation is zero. Thus the water transforms into steam without boiling.

and the temperature rises to almost critical temperature. It then enters the evaporator and may get superheated to some degree. Finally, it is passed through the superheater to obtain desired superheated steam.

The Benson boiler is also known as light-weight boiler as there is no large water and steam drum. The thermal efficiency upto 90 percent may be achieved by this boiler. The average operating pressure and capacity of such boilers are 250 bar and 135 tonnes/h. It can be started within 15 minutes.

Following are the advantages of Benson boiler :

1. The initial cost of boiler is low because there is no water and steam drum.
2. Since there is no pressure limit, therefore supercritical pressure may be employed.
3. The high pressure avoids the bubble formation in the tubes which increases heat transfer rate.
4. It is a light-weight boiler.
5. The boiler can be started within 15 minutes.

13.16. Comparison Between Water Tube and Fire Tube Boilers

Following are the few points of comparison between a water tube and a fire tube boiler.

S.No.	*Water tube boiler*	*Fire tube boiler*
1.	The water circulates inside the tubes which are surrounded by hot gases from the furnace.	The hot gases from the furnace pass through the tubes which are surrounded by water.
2.	It generates steam at a higher pressure upto 165 bar.	It can generate steam only upto 24.5 bar.
3.	The rate of generation of steam is high, *i.e.* upto 450 tonnes per hour.	The rate of generation of steam is low, *i.e.* upto 9 tonnes per hour.
4.	For a given power, the floor area required for the generation of steam is less, *i.e.* about 5 m^2 per tonne per hour of steam generation.	The floor area required is more, *i.e.* about 8 m^2 per tonne per hour of steam generation.
5.	Overall efficiency with economiser is upto 90%.	Its overall efficiency is only 75%.
6.	It can be transported and erected easily as its various parts can be separated.	The transportation and erection is difficult.
7.	It is preferred for widely fluctuating loads.	It can also cope reasonably with sudden increase in load but for a shorter period.
8.	The direction of water circulation is well defined.	The water does not circulate in a definite direction.
9.	The operating cost is high.	The operating cost is less.
10.	The bursting chances are more.	The bursting chances are less.
11.	The bursting does not produce any destruction to the whole boiler.	The bursting produces greater risk to the damage of the property.
12.	It is used for large power plants.	It is not suitable for large plants.

QUESTIONS

1. What is a steam boiler ? How they are classified ?
2. Explain the construction and working of a Lancashire boiler with the help of suitable sketches.
3. What is the difference between a Cornish boiler and a Lancashire boiler ?
4. Draw a neat sketch of a Locomotive boiler and label the parts. Explain its working also.
5. Describe with a neat diagram, the construction and working of a Babcock and Wilcox water tube boiler.

6. Explain with a neat sketch the working of a La-Mont boiler.

7. Describe with a neat line sketch of a Benson boiler mentioning its distinguishing features. State the advantages for this type of boilers.

8. What are the differentiating features between a water tube and a fire tube boiler ?

OBJECTIVE TYPE QUESTIONS

1. The water tubes in a simple vertical boiler are
   (*a*) horizontal (*b*) vertical (*c*) inclined
2. Lancashire boiler is a
   (*a*) stationary fire tube boiler (*b*) internally fired boiler
   (*c*) horizontal boiler (*d*) natural circulation boiler
   (*e*) all of the above (*f*) none of the above
3. The diameter of internal flue tubes of a Lancashire boiler is about .... that of its shell.
   (*a*) one-fourth (*b*) one-third (*c*) two-fifth (*d*) one-half
4. Locomotive boiler is a
   (*a*) single tube, horizontal, internally fired and stationary boiler
   (*b*) single tube, vertical, externally fired and stationary boiler
   (*c*) multi-tubular, horizontal, internally fired and mobile boiler
   (*d*) multi-tubular, horizontal, externally fired and stationary boiler
5. Which of the following is a water tube boiler ?
   (*a*) Lancashire boiler (*b*) Babcock and Wilcox boiler
   (*c*) Locomotive boiler (*d*) Cochran boiler
6. In fire tube boilers
   (*a*) water passes through the tubes which are surrounded by flames and hot gases
   (*b*) the flames and hot gases pass through the tubes which are surrounded by water
   (*c*) forced circulation takes place
   (*d*) none of the above
7. Which of the following boiler is best suited to meet the fluctuating demand of steam ?
   (*a*) Locomotive boiler (*b*) Lancashire boiler
   (*c*) Cornish boiler (*d*) Babcock and Wilcox boiler
8. Water tube boilers produce steam at a ...... pressure than that of fire tube boilers.
   (*a*) lower (*b*) higher
9. The locomotive boiler has
   (*a*) 137 fire tubes and 44 superheated tubes
   (*b*) 147 fire tubes and 34 superheated tubes
   (*c*) 157 fire tubes and 24 superheated tubes
   (*d*) 167 fire tubes and 14 superheated tubes
10. La-Mont boiler, is a ..... pressure water tube steam boiler working on forced circulation.
   (*a*) low (*b*) high

ANSWERS

1. (*c*)	2. (*e*)	3. (*c*)	4. (*c*)	5. (*b*)
6. (*b*)	7. (*a*)	8. (*b*)	9. (*c*)	10. (*b*)

14

Boiler Mountings and Accessories

14.1. Introduction

We have already discussed in Art. 13.2 that boiler mountings and accessories are required for the proper and satisfactory functioning of the steam boilers. Now in this chapter, we shall discuss these fittings and appliances which are commonly used these days.

14.2. Boiler Mountings

These are the fittings, which are mounted on the boiler for its proper and safe functioning. Though there are many types of boiler mountings, yet the following are important from the subject point of view :

1. Water level indicator ; 2. Pressure gauge ; 3. Safety valves ; 4. Stop valve ; 5. Blow off cock ; 6. Feed check valve ; and 7. Fusible plug.

14.3. Water Level Indicator

- It is an important fitting, which indicates the water level inside the boiler to an observer. It is a safety device, upon which the correct working of the boiler depends. This fitting may be seen in front of the boiler, and are generally two in number.

A water level indicator, mostly employed in the steam boiler is shown in Fig. 14.1. It consists of three cocks and a glass tube. Steam cock C_1 keeps the glass tube in connection with the steam space. Water cock C_2 puts the glass tube in connection with the water in the boiler. Drain cock C_3 is used at frequent intervals to ascertain that the steam and water cocks are clear.

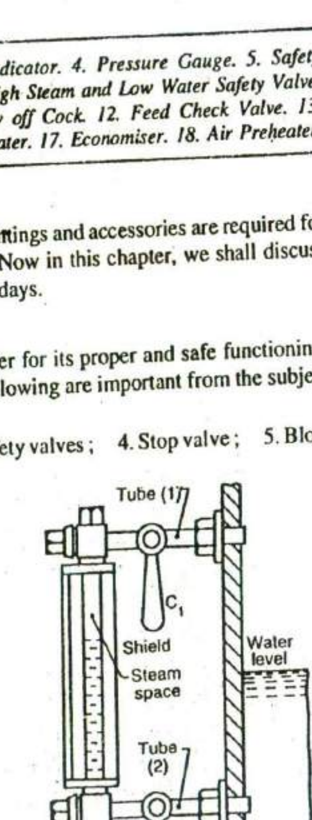

Fig. 14.1. Water level indicator.

In the working of a steam boiler and for the proper functioning of the water level indicator, the steam and water cocks are opened and the drain cock is closed. In this case, the handles are placed in a vertical position as shown in Fig. 14.1. The rectangular passage at the ends of the glass tube contains two balls.

In case the glass tube is broken, the two balls are carried along its passages to the ends of the glass tube. It is thus obvious, that water and steam will not escape out. The glass tube can be easily replaced by closing the steam and water cocks and opening the drain cock.

When the steam boiler is not working, the bolts may be removed for cleaning. The glass tube is kept free from leaking by means of conical ring and the gland nut.

14.4. Pressure Gauge

A pressure gauge is used to measure the pressure of the steam inside the steam boiler. It is fixed in front of the steam boiler. The pressure gauges generally used are of Bourden type.

A Bourden pressure gauge, in its simplest form, consists of an elliptical elastic tube *ABC* bent into an arc of a circle, as shown in Fig. 14.2. This bent up tube is called Bourden's tube.

One end of the tube gauge is fixed and connected to the steam space in the boiler. The other end is connected to a sector through a link. The steam, under pressure, flows into the tube. As a result of this increased pressure, the Bourden's tube tends to straighten itself. Since the tube is encased in a circular curve, therefore it tends to become circular instead of straight. With the help of a simple pinion and sector arrangement, the elastic deformation of the Bourden's tube rotates the pointer. This pointer moves over a calibrated scale, which directly gives the gauge pressure.

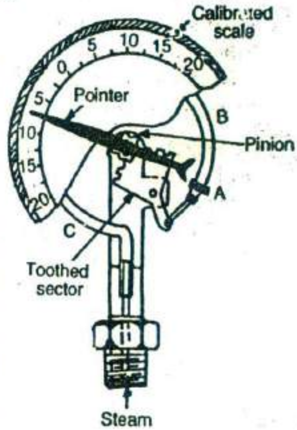

Fig. 14.2. Bourden type pressure gauge.

14.5. Safety Valves

These are the devices attached to the steam chest for preventing explosions due to excessive internal pressure of steam. A steam boiler is, usually, provided with two safety valves. These are directly placed on the boiler. In brief, the function of a safety valve is to blow off the steam when the pressure of steam inside the boiler exceeds the working pressure. The following are the four types of safety valves :

1. Lever safety valve, 2. Dead weight safety valve, 3. High steam and low water safety valve, and 4. Spring loaded safety valve.

It may be noted that the first three types of the safety valves are usually employed with stationary boilers, but the fourth type is mainly used for locomotive and marine boilers.

14.6. Lever Safety Valve

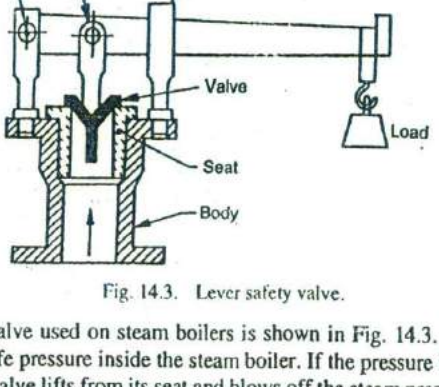

Fig. 14.3. Lever safety valve.

A lever safety valve used on steam boilers is shown in Fig. 14.3. It serves the purpose of maintaining constant safe pressure inside the steam boiler. If the pressure inside the boiler exceeds the designed limit, the valve lifts from its seat and blows off the steam pressure automatically.

A lever safety valve consists of a valve body with a flange fixed to the steam boiler. The bronze valve seat is screwed to the body, and the valve is also made of bronze. It may be noted that by using the valve and seat of the same material, rusting is considerably reduced. The thrust on the valve is transmitted by the strut. The guide keeps the lever in a vertical plane. The load is properly adjusted at the other end of the lever.

When the pressure of steam exceeds the safe limit, the upward thrust of steam raises the valve from its seat. This allows the steam to escape till the pressure falls back to its normal value. The valve then returns back to its original position.

14.7. Dead Weight Safety Valve

A dead weight safety valve, used for stationary boilers, is shown in Fig. 14.4. The valve is made of gun metal, and rests on its gun metal seat. It is fixed to the top of a steel pipe. This pipe is bolted to the mountings block, riveted to the top of the shell. Both the valve and the pipe are covered by a case which contains weights. These weights keep the valve on its seat under normal working pressure. The case hangs freely over the valve to which it is secured by means of a nut.

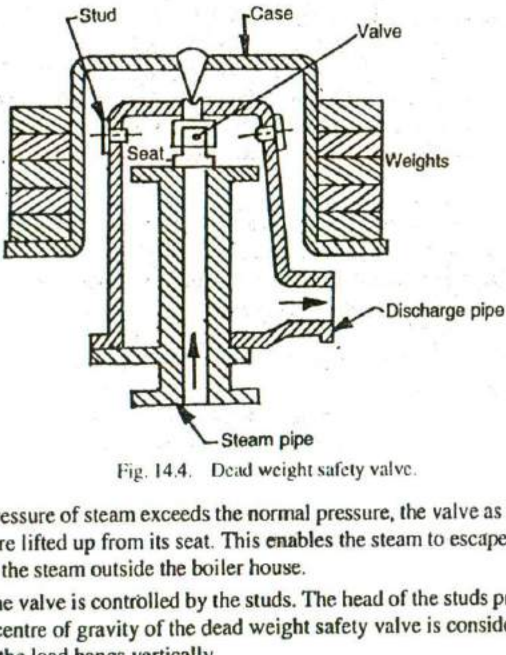

Fig. 14.4. Dead weight safety valve.

When the pressure of steam exceeds the normal pressure, the valve as well as the case (along with the weights) are lifted up from its seat. This enables the steam to escape through the discharge pipe, which carries the steam outside the boiler house.

The lift of the valve is controlled by the studs. The head of the studs projects into the interior of the casing. The centre of gravity of the dead weight safety valve is considerably below the valve which ensures that the load hangs vertically.

The dead weight safety valve has the advantage that it cannot be readily tempered because any added weight must be equal to the total increased pressure of steam on the valve. The only disadvantage of these valves, is the heavy load which these valves carry.

14.8. High Steam Low Water Safety Valve

These valves are placed at the top of Cornish and Lancashire boilers only. It is a combination of two valves, one of which is the lever safety valve which blows off steam when the working pressure of steam exceeds. The second valve operates by blowing off the steam when the water level becomes too low.

A best known combination of high steam low water safety valve is shown in Fig. 14.5. It consists of a main valve (known as lever safety valve) and rests on its seat. In the centre of the main valve, a seat for a hemispherical valve is formed for low water operation. This valve is loaded directly by the dead weights attached to the valve by a long rod. There is a lever *J-K*, which has its fulcrum at *K*. The lever has a weight *E* suspended at the end *K*. When it is fully immersed in water, it is balanced by a weight *F* at the other end *J* of the lever.

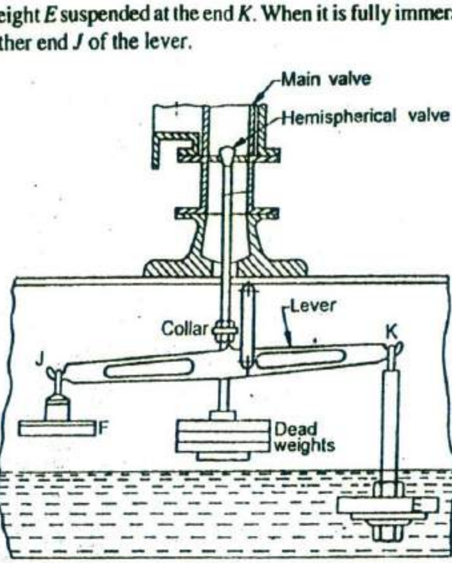

Fig. 14.5. High steam low water safety valve.

When the water level falls, the weight *E* comes out of water and the weight *F* will not be sufficient to balance weight *E*. Therefore weight *E* comes down. There are two projections on the lever to the left of the fulcrum which comes in contact with a collar attached to the rod. When weight *E* comes down, the hemispherical valve is lifted up and the steam escapes with a loud noise, which warns the operator. A drain pipe is provided to carry water, which is deposited in the valve casing.

14.9. Spring Loaded Safety Valve

A spring loaded safety valve is mainly used for locomotives and marine boilers. It is loaded with spring instead of weights. The spring is made of round or square spring steel rod in helical form. The spring may be in tension or compression, as the steam pressure acts along the axis of the spring. In actual practice, the spring is placed in compression.

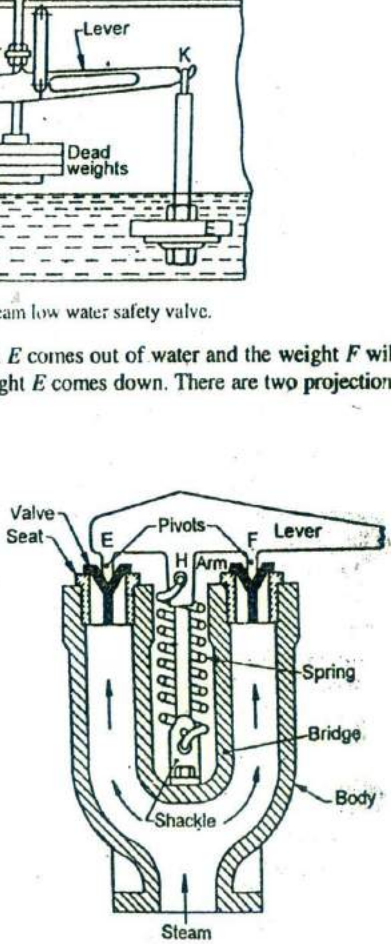

Fig. 14.6. Spring loaded safety valve.

A *Ramsbottom spring loaded safety valve is shown in Fig. 14.6. It is, usually, fitted to locomotives. It consists of a cast iron body connected to the top of a boiler. It has two separate valves of the

* It was introduced by John Ramsbottom of London.

same size. These valves have their seatings in the upper ends of two hollow valve chests. These valve chests are united by a bridge and a base. The base is bolted to a mounting block on the top of a boiler over the fire box.

The valves are held down by means of a spring and a lever. The lever has two pivots at *E* and *F*. The pivot *E* is joined by a pin to the lever, while the pivot *F* is forged on the lever. These pivots rest on the centres of the valves. The upper end of the spring is hooked to the arm *H*, while the lower end to the shackle, which is secured to the bridge by a nut. The spring has two safety links, one behind the other, or one on either side of the lever connected by pins at their ends. The lower pin passes through the shackle while the upper one passes through slot in arm *H* of the lever. The lever has an extension, which projects into the driver's cabin. By pulling or raising the lever, the driver can release the pressure from either valve separately.

14.10. Steam Stop Valve

It is the largest valve on the steam boiler. It is, usually, fitted to the highest part of the shell by means of a flange as shown in Fig. 14.7. The principal functions of a stop valve are :

1. To control the flow of steam from the boiler to the main steam pipe.
2. To shut off the steam completely when required.

The body of the stop valve is made of cast iron or cast steel. The valve, valve seat and the nut through which the valve spindle works, are made of brass or gun metal.

The spindle passes through a gland and stuffing box. The spindle is rotated by means of a hand wheel. The upper portion of the spindle is screwed and made to pass through a nut in a cross head carried by two pillars. The pillars are screwed in the cover of the body as shown in the figure. The boiler pressure acts under the valve, so that the valve must be closed against the pressure. The valve is, generally, fastened to the spindle which lifts it up.

A non-return valve is, sometimes, fitted near the stop valve to prevent the accidental admission of steam from other boilers. This happens when a number of boilers are connected to the same pipe, and when one is empty and under repair.

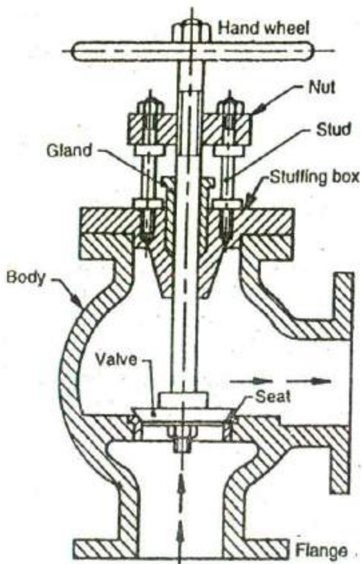

Fig. 14.7. Steam stop valve.

14.11. Blow off Cock

The principal functions of a blow-off cock are :

1. To empty the boiler whenever required.

2. To discharge the mud, scale or sediments which are accumulated at the bottom of the boiler.

The blow-off cock, as shown in Fig. 14.8, is fitted to the bottom of a boiler drum and consists of a conical plug fitted to the body or casing. The casing is packed, with asbestos packing, in grooves round the top and bottom of the plug. The asbestos packing is made tight and plug bears on the packing. It may be noted that the cocks packed in this way keep the grip better under high pressure and easily operated than unpacked.

The shank of plug passes through a gland and stuffing box in the cover. The plug is held down by a yoke and two stud bolts (not shown in the figure). The yoke forms a guard on it. There are two vertical slots on the inside of a guard for the box spanner to be used for operating the cock.

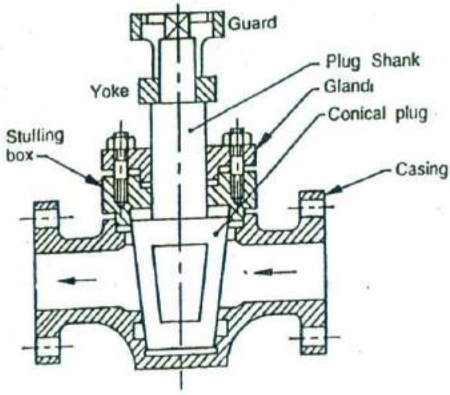

Fig. 14.8. Blow off cock.

14.12. Feed Check Valve

It is a non-return valve, fitted to a screwed spindle to regulate the lift. Its function is to regulate the supply of water, which is pumped into the boiler, by the feed pump. This valve must have its spindle lifted before the pump is started. It is fitted to the shell slightly below the normal water level of the boiler.

A feed check valve for marine boilers is shown in Fig. 14.9. It consists of a valve whose lift is controlled by a spindle and hand wheel. The body of the valve is made of brass casting and except spindle, its every part is made of brass. The spindle is made of muntz metal. A flange is bolted to the end of boiler at a point from which perforated pipe leads the feed water. This pipe distributes the water in the boiler uniformly.

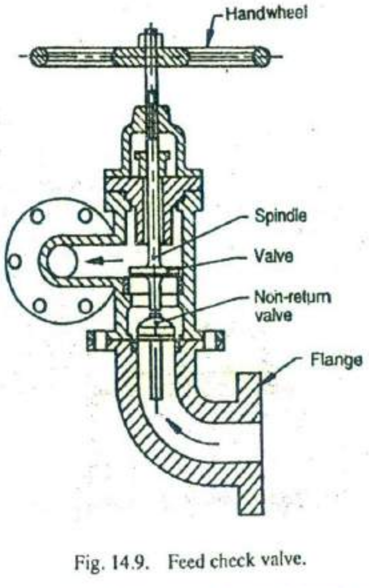

Fig. 14.9. Feed check valve.

14.13. Fusible Plug

It is fitted to the crown plate of the furnace or the fire. Its object is to put off the fire in the furnace of the boiler when the level of water in the boiler falls to an unsafe limit, and thus avoids the explosion which may take place due to overheating of the furnace plate.

A fusible plug consists of a hollow gun metal plug P_1 as shown in Fig. 14.10. It is screwed to the furnace crown. A second hollow gun metal plug P_2 is screwed to the first plug. There is also a third hollow gun metal plug P_3 separated from P_1 by a ring of fusible metal. The inner surface of P_2 and outer surface of P_3 are grooved so that when the fusible metal is poured into the plug, P_2

and P_3 are locked together. A hexagonal flange is provided on plug P_1 to take a spanner for fixing or removing the plug P_1. There is a hexagonal flange on plug P_2 for fixing or removing it. The fusible metal is protected from fire by the flange on the lower end of plug P_2. There is also a contact at the top between P_2 and P_3 so that the fusible metal is completely enclosed. The fusible plugs must be kept in a good condition and replaced annually. A fusible plug must not be refilled with anything except fusible metal.

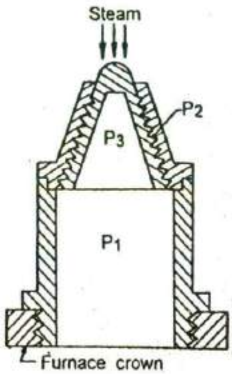

Fig. 14.10. Fusible plug.

14.14. Boiler Accessories

These are the devices which are used as integral parts of a boiler, and help in running efficiently. Though there are many types of boiler accessories, yet the following are important from the subject point of view :

1. Feet pump ; 2. Superheater ; 3. Economiser ; and 4. Air preheater.

Fig. 14.11 shows the schematic diagram of a boiler plant with the above mentioned accessories.

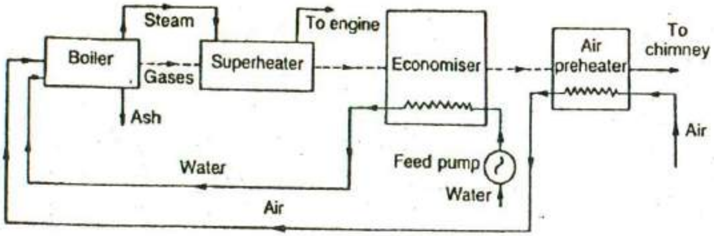

Fig. 14.11. Schematic diagram of a boiler plant.

14.15. Feed Pump

We know that water, in a boiler, is continuously converted into steam, which is used by the engine. Thus we need a feed pump to deliver water to the boiler.

The pressure of steam inside a boiler is high. So the pressure of feed water has to be increased proportionately before it is made to enter the boiler. Generally, the pressure of feed water is 20% more than that in the boiler.

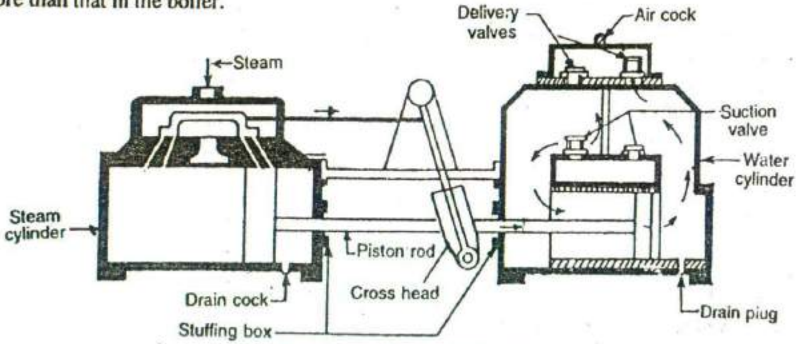

Fig. 14.12. Duplex feed pump.

A feed pump may be of centrifugal type or reciprocating type. But a double acting reciprocating pump is commonly used as a feed pump these days. The reciprocating pumps are run by the steam from the same boiler in which water is to be fed. These pumps may be classified as simplex, duplex and triplex pumps according to the number of pump cylinders. The common type of pump used is a duplex feed pump, as shown in Fig. 14.12. This pump has two sets of suction and delivery valves for forward and backward stroke. The two pumps work alternately so as to ensure continuous supply of feed water.

14.16. Superheater

A superheater is an important device of a steam generating unit. Its purpose is to increase the temperature of saturated steam without raising its pressure. It is generally an integral part of a boiler, and is placed in the path of hot flue gases from the furnace. The heat, given up by these flue gases, is used in superheating the steam. Such superheaters, which are installed within the boiler, are known as integral superheaters.

A Sudgen's superheater commonly employed with Lancashire boilers is shown in Fig. 14.13. It consists of two mild steel boxes or heaters from which hangs a group of solid drawn tubes bent to U-form. The ends of these tubes are expanded into the headers. The tubes are arranged in groups of four and one pair of headers generally carries ten of these groups or forty tubes in all. The outside of the tubes can be cleaned through the space between the headers. This space is closed by covers.

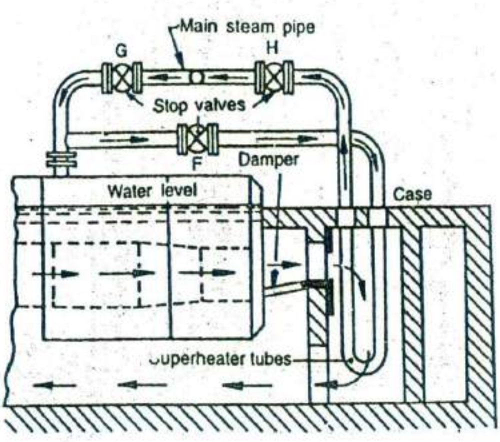

Fig. 14.13. Superheater.

The steam enters at one end of the rear header and leaves at the opposite end of the front header. The overheating of superheater tubes is prevented by the use of a balanced damper which is operated by the handle. The superheater is in action when the damper is in a position as shown in the figure. If the damper is in vertical position, the gases pass directly into the bottom flue without passing over the superheater tubes. In this way, the superheater is out of action. By placing the damper in intermediate position, some of the gases will pass over the superheater tubes and the remainder will pass directly to the bottom flue. It is thus obvious, that required degree of heat for superheating may be obtained by altering the position of the damper.

It may be noted that when the superheater is in action, the stop valves G and H are opened and F is closed. When the steam is taken directly from the boiler, the valves G and H are closed and F is open.

14.17. Economiser

An economiser is a device used to heat feed water by utilising the heat in the exhaust flue gases before leaving through the chimney. As the name indicates, the economiser improves the economy of the steam boiler.

A well known type of economiser is Greens economiser. It is extensively used for stationary boilers, especially those of Lancashire type. It consists of a large number of vertical pipes or tubes placed in an enlargement of the flue gases between the boiler and chimney as shown in Fig. 14.14. These tubes are 2.75 metres long, 114 mm in external diameter and 11.5 mm thick and are made of cast iron.

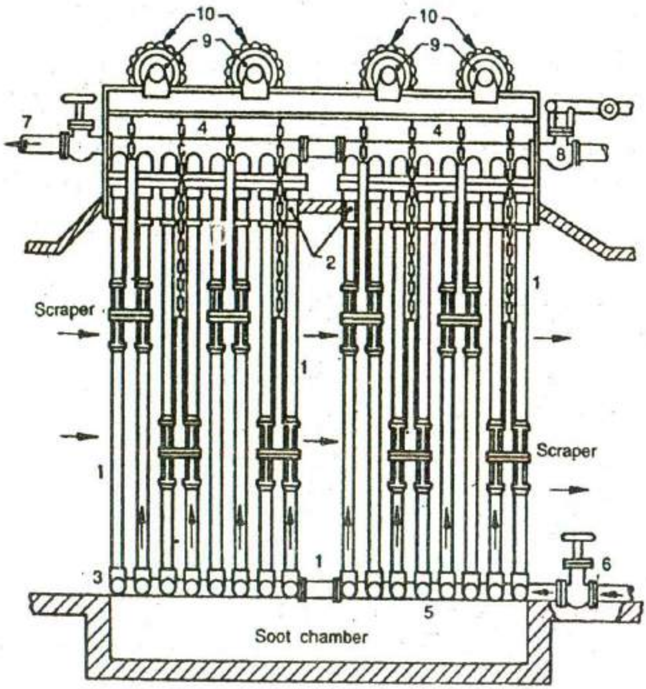

Fig. 14.14. Economiser.

The economiser is built-up of transverse section. Each section consists of generally six or eight vertical tubes (1). These tubes are joined to horizontal pipes or boxes (2) and (3) at the top and bottom respectively. The top boxes (2) of the different sections are connected to the pipe (4), while the bottom boxes are connected to pipe (5). The pipes (4) and (5) are on opposite sides, which are outside the brickwork enclosing the economiser.

The feed water is pumped into the economiser at (6) and enters the pipe (5). It then passes into the bottom boxes (3) and then into the top boxes (2) through the tubes (1). It is now led by the pipe (4) to the pipe (7) and then to the boiler. There is a blow-off cock at the end of the pipe (5) opposite to the feed inlet (6). The purpose of this valve is to remove mud or sediment deposited in the bottom boxes. At the end of pipe (4) (opposite to the feed outlet) there is a safety valve.

It is essential that the vertical tubes may be kept free from deposits of soot, which greatly reduce the efficiency of the economicser. Each tube is provided with scraper for this purpose. The scrapers of two adjoining sections of tubes are grouped together, and coupled by rods and chains to the adjacent group of scrapers. The chain passes over a pulley (9) so that one group of scrapers balance the adjacent group. The pulley (9) of each chain is connected to a worm wheel (10) which is driven by a worm on a longitudinal shaft (not shown in the figure). The scrapers automatically reverse when they reach the top or bottom end of the tubes. These are kept in motion continuously when the economiser is in use. The speed of scraper is about 46 m/h.

It may be noted that the temperature of feed should not be less than about 35° C, otherwise there is a danger of corrosion due to the moisture in the flue gases being deposited in cold tubes. Following are the advantages of using an economiser :-

1. There is about 15 to 20% of coal saving.
2. It increases the steam raising capacity of a boiler because it shortens the time required to convert water into steam.
3. It prevents formation of scale in boiler water tubes, because the scale now forms in the economiser tubes, which can be cleaned easily.
4. Since the feed water entering the boiler is hot, therefore strains due to unequal expansion are minimised.

14.18. Air Preheater

An air preheater is used to recover heat from the exhaust flue gases. It is installed between the economiser and the chimney. The air required for the purpose of combustion is drawn through the air preheater where its temperature is raised. It is then passed through ducts to the furnace. The air is passed through the tubes of the heater internally while the hot flue gases are passed over the outside of the tubes.

The following advantages are obtained by using an air preheater :

1. The preheated air gives higher furnace temperature which results in more heat transfer to the water and thus increases the evaporative capacity per kg of fuel.
2. There is an increase of about 2% in the boiler efficiency for each 35-40° C rise in temperature of air.
3. It results in better combustion with less soot, smoke and ash.
4. It enables a low grade fuel to be burnt with less excess air.

QUESTIONS

1. Describe with a neat sketch, water level indicator for a boiler.
2. Explain how the flow of steam of water is automatically stopped when the glass tube breaks.
3. Why the safety valves are needed in a boiler ? Sketch and describe a Ramsbottom spring loaded safety valve.
4. Differentiate between lever safety valve and dead weight safety valve.
5. What is the purpose of a steam stop valve ? Explain its working.
6. Explain the functions of blow off cock and feed check valve.
7. What is the function of a superheater ? Describe Sugden's superheater.
8. Discuss, briefly, the working of an economiser in a boiler plant giving a neat sketch.
9. Explain why air preheaters are used in a high pressure boiler.

OBJECTIVE TYPE QUESTIONS

1. A device attached to the steam chest for preventing explosions due to excessive internal pressure of steam is called

(a) safety valve (b) water level indicator

(c) pressure gauge (d) fusible plug

2. A safety valve mainly used with locomotive and marine boilers is

(*a*) lever safety valve (*b*) high pressure and low water safety valve

(*c*) dead weight safety valve (*d*) spring loaded safety valve

3. A device used in a boiler to control the flow of steam from the boiler to the main pipe and to shut off the steam completely when required, is known as

(*a*) blow off cock (*b*) fusible plug (*c*) stop valve (*d*) economiser

4. A device used to put off fire in the furnace of the boiler when the level of water in the boiler falls to an unsafe limit, is called

(*a*) blow off cock (*b*) fusible plug (*c*) superheater (*d*) economiser

5. A device used to increase the temperature of saturated steam without raising its pressure, is called

(*a*) blow off cock (*b*) fusible plug (*c*) superheater (*d*) economiser

6. A device used to heat feed water by utilising the heat in the exhaust flue gases before leaving through the chimney, is known as

(*a*) superheater (*b*) economiser (*c*) blow off cock (*d*) stop valve

7. Which of the following are boiler accessories ?

(*a*) safety valve (*b*) pressure gauge (*c*) superheater (*d*) economiser

(*e*) both (*a*) and (*b*) (*f*) both (*c*) and (*d*)

8. An economiser ...... the steam raising capacity of a boiler.

(*a*) increases (*b*) decreases (*c*) has no effect on

9. The pressure of feed water has to be raised before its entry into the boiler. The pressure is raised by a device known as

(*a*) feed check valve (*b*) feed pump (*c*) pressure gauge (*d*) injector

10. An air preheater

(*a*) increases evaporative capacity of the boiler

(*b*) increases the efficiency of the boiler

(*c*) enables low grade fuel to be burnt

(*d*) all of the above

ANSWERS

1. (*a*)	2. (*d*)	3. (*c*)	4. (*b*)	5. (*c*)
6. (*b*)	7. (*f*)	8. (*a*)	9. (*b*)	10. (*d*)

15

Performance of Steam Boilers

1. Introduction. 2. Equivalent Evaporation. 3. Boiler Efficiency. 4. Boiler Trial. 5. Heat Losses in a Boiler. 6. Heat Balance Sheet.

15.1. Introduction

The performance of a steam boiler is measured in terms of its *evaporative capacity. However, the evaporative capacities of two boilers cannot be compared unless both the boilers have the same feed water temperature, working pressure, fuel and the final condition of steam. In actual practice, the feed water temperature and working pressure varies considerably. It is thus obvious, that the comparison of two boilers becomes difficult unless some standard feed temperature and working pressure is adopted.

The feed temperature usually adopted is 100° C and the working pressure as normal atmospheric pressure, *i.e.* 1.013 bar. It is assumed that the boiler is supplied with water at the boiling temperature (100° C) corresponding to the atmospheric pressure.

15.2. Equivalent Evaporation

It is the amount of water evaporated from feed water at 100° C and formed into dry and saturated steam at 100° C at normal atmospheric pressure. It is, usually, written as *"from and at 100°C"*.

As the water is already at the boiling temperature, it requires only latent heat at 1.013 bar to convert it into steam at the temperature (100° C). The value of this latent heat is taken as 2257 kJ/kg. Mathematically,

Equivalent evaporation "from and at 100° C",

$$E = \frac{\text{Total heat required to evaporate feed water}}{2257}$$

Let t_1 = Temperature of feed water in °C,

h_{f1} = Enthalpy or sensible heat of feed water in kJ/kg of steam corresponding to t_1 °C (from steam tables),

h = Enthalpy or total heat of steam in kJ/kg of steam corresponding to a given working pressure (from steam tables),

$= h_f + x\,h_{fg}$ ... (For wet steam)

$= h_f + h_{fg} = h_g$ ... (For dry wet steam)

* The evaporative capacity or power of a boiler is the amount of water evaporated or steam produced in kg/h. It may also be expressed in kg/kg of fuel burnt or kg/h/m² of heating surface.

$= h_g + c_p (t_{sup} - t)$ . . . (For superheated steam)

m_e = Mass of water actually evaporated or steam produced in kg/h or kg/kg of fuel burnt.

We know that heat required to evaporate 1 kg of water

$$= h - h_{f1}$$

$\therefore$ Total heat required to evaporate m_e kg of water

$$= m_e (h - h_{f1})$$

and equivalent evaporation 'from and at 100° C'

$$E = \frac{m_e (h - h_{f1})}{2257}$$

Note : The factor $\frac{h - h_{f1}}{2257}$ is known as factor of evaporation, and is usually denoted by F_e. Its value is always greater than unity for all boilers.

15.3. Boiler Efficiency

It may be defined as the ratio of heat actually used in producing the steam to the heat liberated in the furnace. It is also known as thermal efficiency of the boiler. Mathematically,

Boiler efficiency or thermal efficiency,

$$\eta = \frac{\text{Heat actually used in producing steam}}{\text{Heat liberated in the furnace}} = \frac{m_e (h - h_{f1})}{C}$$

where m_e = Mass of water actually evaporated or actual evaporation in kg / kg of fuel, and

C = Calorific value of fuel in kJ/kg of fuel.

Notes : 1. If m_s = Total mass of water evaporated into steam in kg.

and m_f = Mass of fuel used in kg.

Then $m_e = \frac{m_s}{m_f}$ kg/kg of fuel

and $\eta = \frac{m_s (h - h_{f1})}{m_f \times C}$

2. If a boiler consisting of an economiser and superheater is considered to be a single unit, then the efficiency is termed as overall efficiency of the boiler.

Example 15.1. *A boiler evaporates 3.6 kg of water per kg of coal into dry saturated steam at 10 bar. The temperature of feed water is 32° C. Find the equivalent evaporation "from and at 100° C" as well as the factor of evaporation.*

Solution. Given : m_e = 3.6 kg / kg of coal ; p = 10 bar ; t_1 = 32° C

Equivalent evaporation 'from and at 100° C'

From steam tables, corresponding to a feed water temperature of 32° C, we find that

$$h_{f1} = 134 \text{ kJ/kg}$$

and corresponding to a steam pressure of 10 bar, we find that

$$h = h_g = 2776.2 \text{ kJ/kg}$$ . . . (For dry saturated steam)

We know that equivalent evaporation 'from and at 100° C',

$$E = \frac{m_e (h - h_{f1})}{2257} = \frac{3.6\,(2776.2 - 134)}{2257} = 4.2 \text{ kg / kg of coal} \textbf{ Ans.}$$

Factor of evaporation

We know that factor of evaporation

$$= \frac{h - h_{f1}}{2257} = \frac{2776.2 - 134}{2257} = 1.17 \textbf{ Ans.}$$

Example 15.2. *The following observations were made in a boiler trial :*

Coal used 250 kg of calorific value 29 800 kJ/kg, water evaporated 2000 kg, steam pressure 11.5 bar, dryness fraction of steam 0.95 and feed water temperature 34° C.

Calculate the equivalent evaporation "from and at 100° C" per kg of coal and the efficiency of the boiler.

Solution. Given : $m_f = 250$ kg ; $C = 29\,800$ kJ/kg ; $m_s = 2000$ kg ; $p = 11.5$ bar ; $x = 0.95$; $t_1 = 34°$ C

Equivalent evaporation 'from and at 100° C'

From steam tables, corresponding to a feed water temperature of 34° C, we find that

$$h_{f1} = 142.4 \text{ kJ/kg}$$

and corresponding to a steam pressure of 11.5 bar, we find that

$$h_f = 790 \text{ kJ/kg} ; \; h_{fg} = 1991.4 \text{ kJ/kg}$$

We know that enthalpy or total heat of steam,

$$h = h_f + x\,h_{fg} = 790 + 0.95 \times 1991.4 = 2681.8 \text{ kJ/kg}$$

and mass of water evaporated per kg of coal

$$m_e = m_s / m_f = 2000 / 250 = 8 \text{ kg / kg of coal}$$

∴ Equivalent evaporation 'from and at 100° C'

$$E = \frac{m_e (h - h_{f1})}{2257} = \frac{8\,(2681.8 - 142.4)}{2257} = 0.682 \text{ kg/kg of coal} \textbf{ Ans.}$$

Efficiency of the boiler

We know that efficiency of the boiler,

$$\eta = \frac{m_e (h - h_{f1})}{C} = \frac{8\,(2681.8 - 142.4)}{29\,800} = 0.682 \text{ or } 68.2\,\% \textbf{ Ans.}$$

Example 15.3. *A Lancashire boiler generates 2400 kg of dry steam per hour at a pressure of 11 bar. The grate area is 3 m² and 90 kg of coal is burnt per m² of grate area per hour. The calorific value of the coal is 33 180 kJ/kg and the temperature of feed water is 17.5° C. Determine : 1. Actual evaporation per kg of coal, 2. Equivalent evaporation 'from and at 100° C', and 3. Efficiency of the boiler.*

Solution. Given : $m_s = 2400$ kg/h ; $p = 11$ bar ; Grate area = 3 m² ; Coal burnt = 90 kg/m² /h ; $C = 33\,180$ kJ/kg ; $t_1 = 17.5°$ C

1. *Actual evaporation per kg of coal*

We know that mass of coal burnt per hour,

$$m_f = 90 \times 3 = 270 \text{ kg/h}$$

∴ Actual evaporation per kg of coal,

$$m_e = m_s / m_f = 2400 / 270 = 8.89 \text{ kg / h} \quad \textbf{Ans.}$$

2. *Equivalent evaporation 'from and at 100° C'*

From steam tables, corresponding to a feed water temperature of 17.5° C, we find that

$$h_{f1} = 73.4 \text{ kJ/kg}$$

and corresponding to a steam pressure of 11 bar, we find that

$$h = h_g = 2779.7 \text{ kJ/kg} \qquad \text{. . . (For dry steam)}$$

We know that equivalent evaporation 'from and at 100° C'

$$E = \frac{m_e (h - h_{f1})}{2257} = \frac{8.89 (2779.7 - 73.4)}{2257} = 10.66 \text{ kg/h} \quad \textbf{Ans.}$$

3. *Efficiency of the boiler*

We know that efficiency of the boiler,

$$\eta = \frac{m_e (h - h_{f1})}{C} = \frac{8.89 (2779.7 - 73.4)}{33\,180} = 0.725 \text{ or } 72.5 \% \quad \textbf{Ans.}$$

Example 15.4. *A coal fired boiler plant consumes 400 kg of coal per hour. The boiler evaporates 3200 kg of water at 44.5° C into superheated steam at a pressure of 12 bar and 274.5° C. If the calorific value of fuel is 32 760 kJ/kg of coal, determine : 1. Equivalent evaporation "from and at 100° C," and 2. Thermal efficiency of the boiler.*

Assume specific heat of superheated steam as 2.1 kJ/kg K.

Solution. Given : $m_f = 400$ kg/h ; $m_s = 3200$ kg ; $t_1 = 44.5°$ C ; $p = 12$ bar ; $t_{sup} = 274.5°$ C ; $C = 32\,760$ kJ/kg of coal ; $c_p = 2.1$ kJ/kg K

1. *Equivalent evaporation 'from and at 100° C'*

We know that mass of water evaporated per kg of coal

$$m_e = m_s / m_f = 3200 / 400 = 8 \text{ kg}$$

From steam tables, corresponding to a feed water temperature of 44.5° C, we find that

$$h_{f1} = 186.3 \text{ kJ/kg}$$

and corresponding to a steam pressure of 12 bar, we find that

$$h_g = 2782.7 \text{ kJ/kg} \; ; \text{ and } t = 188° \text{C}$$

We know that enthalpy or total heat required for 1 kg of superheated steam,

$$h_{sup} = h_g + c_p (t_{sup} - t)$$

$$= 2782.7 + 2.1 (274.5 - 188) = 2964.4 \text{ kJ/kg}$$

∴ Equivalent evaporation 'from and at 100° C',

$$E = \frac{m_e (h_{sup} - h_{f1})}{2257} = \frac{8 (2964.4 - 186.3)}{2257} \text{ kg/kg of coal}$$

$$= 9.85 \text{ kg/kg of coal} \quad \textbf{Ans.}$$

2. *Thermal efficiency of the boiler*

We know that thermal efficiency of the boiler,

$$\eta = \frac{m_e (h_{sup} - h_{f1})}{C} = \frac{8 (2964.4 - 186.3)}{32\,760} = 0.678 \text{ or } 67.8 \% \quad \textbf{Ans.}$$

Example 15.5. *The following observations were made on a boiler plant during one hour test :*

Steam pressure = 20 bar ; Steam temperature = 260° C ; Steam generated = 37 500 kg ; Temperature of water entering the economiser = 15° C ; Temperature of water leaving the economiser = 90° C ; Fuel used = 4400 kg ; Energy of combustion of fuel = 30 000 kJ/kg.

Calculate : 1. The equivalent evaporation per kg of fuel ; 2. The thermal efficiency of the plant ; and 3. The percentage heat energy of the fuel energy utilised by the economiser.

Solution. Given : $p = 20$ bar ; $t_{sup} = 260°$ C ; $m_s = 37\ 500$ kg/h ; $t_1 = 15°$ C ; $t_2 = 90°$ C ; $m_f = 4400$ kg/h ; $C = 30\ 000$ kJ/kg

1. Equivalent evaporation per kg of fuel

We know that mass of water actually evaporated,

$$m_e = m_s / m_f = 37\ 500 / 4400 = 8.52 \text{ kg/kg of fuel}$$

From steam tables, corresponding to a feed water temperature of 15° C, we find that

$$h_{f1} = 62.9 \text{ kJ/kg}$$

and corresponding to a steam pressure of 20 bar, we find that

$$h_g = 2797.2 \text{ kJ/kg} ; \text{ and } t = 212.4° \text{C}$$

We know that enthalpy or total heat of 1 kg of superheated steam,

$$h_{sup} = h_g + c_p (t_{sup} - t)$$

$$= 2797.2 + 2.1 (260 - 212.4) = 2897 \text{ kJ/kg}$$

... (Taking $c_p = 2.1$ kJ/kg K)

∴ Equivalent evaporation,

$$E = \frac{m_e (h_{sup} - h_{f1})}{2257} = \frac{8.52 (2897 - 62.9)}{2257} = 10.7 \text{ kg/kg of fuel } \textbf{Ans.}$$

2. Thermal efficiency of the plant

We know that thermal efficiency of the plant,

$$\eta = \frac{m_e (h_{sup} - h_{f1})}{C} = \frac{8.52 (2897 - 62.9)}{30\ 000} = 0.805 \text{ or } 80.5\ \% \textbf{ Ans.}$$

3. Percentage heat energy of the fuel energy utilised by the economiser

From steam tables, corresponding to a temperature of 90° C, we find that

$$h_{f2} = 376.9 \text{ kJ/kg}$$

We know that heat utilised by the economiser per kg of fuel

$$= m_e (h_{f2} - h_{f1}) = 8.52 (376.9 - 62.9) = 2675 \text{ kJ}$$

∴ Percentage of heat utilised by the economiser

$$= \frac{2675}{30\ 000} = 0.089 \text{ or } 8.9\ \% \textbf{ Ans.}$$

Example 15.6. *The following particulars refer to a steam plant consisting of a boiler, economiser and a superheater :*

Steam pressure = 14 bar ; Mass of steam generated = 5000 kg/h ; Mass of coal used = 675 kg/h ; Calorific value of coal = 29 800 kJ/kg of coal ; Temperature of feed water entering the *economiser = 30° C ; Temperature of feed water leaving the economiser = 130° C ; Dryness fraction of steam leaving the boiler = 0.97 ; Temperature of steam leaving the superheater = 320° C.*

Determine : 1. Overall efficiency of the plant, and 2. The percentage of the available heat utilised in the boiler, economiser and superheater respectively.

Solution. Given : $p = 14$ bar ; $m_s = 5000$ kg/h ; $m_f = 675$ kg/h ; $C = 29\,800$ kJ/kg of coal ; $t_1 = 30°$ C ; $t_2 = 130°$ C ; $x = 0.97$; $t_{sup} = 320°$ C

1. *Overall efficiency of the plant*

We know that mass of water actually evaporated per kg of coal,

$$m_e = m_s / m_f = 5000 / 675 = 7.41 \text{ kg}$$

From steam tables, corresponding to a feed water temperature of 30° C, we find that

$$h_{f1} = 125.7 \text{ kJ/kg}$$

and corresponding to a steam pressure of 14 bar, we find that

$$h_f = 830.1 \text{ kJ/kg} ; h_{fg} = 1957.7 \text{ kJ/kg} ; h_g = 2787.8 \text{ kJ/kg} ; \text{and } t = 195° \text{ C}$$

We know that enthalpy or total heat of superheated steam,

$$h_{sup} = h_g + c_p (t_{sup} - t)$$

$$= 2787.8 + 2.1 (320 - 195) = 3050.3 \text{ kJ/kg} \quad \ldots (\text{Taking } c_p = 2.1 \text{ kJ/kg K})$$

∴ Overall efficiency of the plant,

$$\eta = \frac{m_e (h_{sup} - h_{f1})}{C} = \frac{7.41 (3050.3 - 125.7)}{29\,800} = 0.727 \text{ or } 72.7\% \textbf{ Ans.}$$

2. *Percentage of available heat utilised*

Here we shall consider the following three cases :

(*a*) *Considering the boiler*

We know that enthalpy or sensible heat of feed water leaving the economiser or entering the boiler at 130° C (from steam tables),

$$h_{f2} = 546.3 \text{ kJ/kg}$$

Heat utilised in the boiler for 7.41 kg of steam at 14 bar and 0.97 dryness from water at 130° C

$$= m_e [(h_f + x\, h_{fg}) - h_{f2}]$$

$$= 7.41 [(830.1 + 0.97 \times 1957.7) - 546.3] = 16\,174 \text{ kJ}$$

We know that the heat available per kg of coal

$$= 29\,800 \text{ kJ/kg of coal}$$

∴ Percentage of available heat used in boiler

$$= \frac{16\,174}{29\,800} = 0.543 \text{ or } 54.3\% \textbf{ Ans.}$$

(*b*) *Considering the economiser*

We know that heat utilised in the economiser per kg of coal

$$= m_e\, c_p (t_2 - t_1) = 7.41 \times 4.2 (130 - 30) = 3112.2 \text{ kJ}$$

$$\ldots (\because c_p \text{ for water} = 4.2 \text{ kJ/kg K})$$

∴ Percentage of available heat used in the economiser

$$= \frac{3112.2}{29\,800} = 0.104 \text{ or } 10.4\,\% \textbf{ Ans.}$$

(c) Considering the superheater

Heat utilised in the superheater per kg of steam

$$= \text{Total heat of superheated steam} - \text{Total heat of wet steam}$$

$$= [h_g + c_p\,(t_{sup} - t)] - [(h_f + x\,h_{fg})]$$

$$= [2787.8 + 2.1\,(320 - 195)] - [(830.1 + 0.97 \times 1957.7)]$$

$$= 3050.3 - 2729 = 321.3 \text{ kJ}$$

∴ Total heat utilised in the superheater

$$= 7.41 \times 321.3 = 2381 \text{ kJ}$$

and percentage of heat utilised in the superheater

$$= \frac{2381}{29\,800} = 0.08 \text{ or } 8\% \textbf{ Ans.}$$

Note : As a check, the percentage of heat utilised in boiler

$$= 54.3 + 10.4 + 8 = 72.7\,\%$$

which is equal to the overall efficiency of the plant *i.e.* 72.7%.

15.4. Boiler Trial

The main objects of a boiler trial are :

1. To determine the generating capacity of the boiler.
2. To determine the thermal efficiency of the boiler when working at a definite pressure.
3. To prepare heat balance sheet for the boiler.

We have already discussed the first two objects in the previous articles. Now we shall discuss the third object, *i.e.* to prepare heat balance sheet.

15.5. Heat Losses in a Boiler

We know that the efficiency of a boiler is the ratio of heat utilised in producing steam to the heat liberated in the furnace. Also the heat utilised is always less than the heat liberated in the furnace. The difference of heat liberated in the furnace and heat utilised in producing steam is known as ***heat lost in the boiler***. The loss of heat may be divided into various heads, but the following are important from the subject point of view :

1. Heat lost in dry flue gases

Heat lost to dry flue gases per kg of fuel

$$= m_g \times c_{pg}\,(t_g - t_b) \qquad \ldots (i)$$

where m_g = Mass of dry flue gases per kg of fuel,

c_{pg} = Mean specific heat of dry flue gases,

t_g = Temperature of flue gases leaving chimney, and

t_b = Temperature of boiler room.

This loss is maximum in a boiler.

2. Heat lost in moisture present in the fuel

It is assumed that the moisture is converted into superheated steam at atmospheric pressure (1.013 bar).

Heat lost in moisture present in the fuel

$$= m_m (h_{sup} - h_b) = m_m [h_g + c_p (t_g - t) - h_b]$$

$$= m_m [2676 + c_p (t_g - 100) - h_b]$$

... [From steam tables, corresponding to 1.013 bar, $h_g = 2676$ kJ/kg and $t = 100°$ C]

where m_m = Mass of moisture per kg of fuel,

c_p = Mean specific heat of superheated steam in flue gases,

t_g = Temperature of flue gases leaving chimney,

t_b = Temperature of boiler room, and

h_b = Enthalpy or sensible heat of water at boiler room temperature.

3. *Heat lost to steam formed by combustion of hydrogen per kg of fuel*

Let H_2 = Mass of hydrogen present per kg of fuel.

∴ Mass of steam formed

$$= 9 H_2$$

Then the heat lost to steam per kg of fuel

$$= 9H_2 [2676 + c_p (t_g - 100) - h_b]$$

Note : Heat lost to steam and moisture per kg of fuel

$$= (9H_2 + m_m) [2676 + c_p (t_g - 100) - h_b]$$

where m_m is the mass of moisture per kg of fuel.

4. *Heat lost due to unburnt carbon in ash pit*

The heat lost due to unburnt carbon per kg of fuel

$$= m_1 \times C_1$$

where m_1 = Mass of carbon in ash pit per kg of fuel.

C_1 = Calorific value of carbon.

5. *Heat lost due to incomplete combustion of carbon to carbon monoxide (CO)*

This loss, generally, occurs in a boiler due to insufficient air supply.

Heat lost due to incomplete combustion

$$= m_2 \times C_2$$

where m_2 = Mass of carbon monoxide in flue gas per kg of fuel, and

C_2 = Calorific value of carbon monoxide.

6. *Heat lost due to radiation*

There is no direct method for finding the heat lost due to radiation. This loss is calculated by subtracting the heat utilised in raising steam and heat losses from the heat supplied.

15.6. Heat Balance Sheet

A heat balance sheet shows the complete account of heat supplied by 1 kg of dry fuel* and heat consumed. The heat supplied is mainly utilised for raising the steam and the remaining heat is

* It is equal to the calorific value of the fuel.

lost. We know that heat utilised in raising steam per kg of fuel

$$= m_e (h - h_{f1})$$

The heat balance sheet for a boiler trial per kg of fuel is drawn as below :

Heat supplied	*kJ*	*Heat consumed*	*kJ*	*%*
Heat supplied by 1 kg of dry fuel	X	1. Heat utilisied in raising steam	x_1	...
		2. Heat lost in dry flue gases	x_2	...
		3. Heat lost in moisture in fuel	x_3	...
		4. Heat lost to steam by combustion of hydrogen	x_4	...
		5. Heat lost due to unburnt carbon in ash pit	x_5	..
		6. Heat lost due to incomplete combustion	x_6	...
		7. Heat lost due to radiation, etc. (by difference)	$X - (x_1 + x_2 + x_3 + x_4 + x_5 + x_6)$	...
Total	X	Total	X	100%

Example 15.7. *In a boiler, the following observations were made :*

Pressure of steam	= *10 bar*
Steam condensed	= *540 kg/h*
Fuel used	= *65 kg/h*
Moisture in fuel	= *2% by mass*
Mass of dry flue gases	= *9 kg/kg of fuel*
Lower calorific value of fuel	= *32 000 kJ/kg*
Temperature of the flue gases	= *325° C*
Temperature of boiler house	= *28° C*
Feed water temperature	= *50° C*
Mean specific heat of flue gases	= *1 kJ/kg K*
Dryness fraction of steam	= *0.95*

Draw up a heat balance sheet for the boiler.

Solution. Given : $p = 10$ bar ; $m_s = 540$ kg/h ; $m_f = 65$ kg/h ; $m_m = 0.02$ kg/kg of fuel ; $m_g = 9$ kg/kg of fuel ; $C = 32\,000$ kJ/kg ; $t_g = 325°$ C ; $t_b = 28°$ C ; $t_1 = 50°$ C ; $c_{pg} = 1$ kJ/kg K ; $x = 0.95$

First of all, let us find the heat supplied by 1 kg of fuel. Since the moisture in fuel is 0.02 kg, therefore heat supplied by 1 kg of fuel

$$= (1 - 0.02)\, 32\,000 = 31\,360 \text{ kJ} \quad \ldots (i)$$

1. *Heat utilised in raising steam per kg of fuel*

We know that the mass of water actually evaporated per kg of fuel,

$$m_e = m_s / m_f = 540 / 65 = 8.31 \text{ kg}$$

From steam tables, corresponding to a feed water temperature of 50° C, we find that

$$h_{f1} = 209.3 \text{ kJ/kg}$$

and corresponding to a steam pressure of 10 bar, we find that

$$h_f = 762.6 \text{ kJ/kg} ; \; h_{fg} = 2013.6 \text{ kJ/kg}$$

∴ Heat utilised in raising steam per kg of fuel

$$= m_e (h - h_{f1}) = m_e (h_f + x\,h_{fg} - h_{f1})$$

$$= 8.31\,(762.6 + 0.95 \times 2013.6 - 209.3) = 20\,495 \text{ kJ} \quad \ldots (ii)$$

2. *Heat carried away by dry flue gas*

We know that heat carried away by dry flue gas

$$= m_g\, c_{pg}\,(t_g - t_b) = 9 \times 1\,(325 - 28) = 2673 \text{ kJ} \quad \ldots (iii)$$

3. *Heat carried away by moisture in fuel per kg of fuel*

From steam tables, corresponding to a temperature of 28° C, we find that

$$h_b = 117.3 \text{ kJ/kg}$$

We know that heat carried away by moisture in fuel

$$= m_m\,[2676 + c_p\,(t_g - 100) - h_b]$$

$$= 0.02\,[2676 + 2.1\,(325 - 100) - 117.3] = 60.6 \text{ kJ} \quad \ldots (iv)$$

. . . (Taking c_p for superheated steam = 2.1 kJ/kg K)

4. *Heat lost by radiation etc.*

We know that heat lost by radiation etc. (by difference)

$$= 31\,360 - (20\,495 + 2673 + 60.6) = 8131.4 \text{ kJ} \quad \ldots (v)$$

Now complete heat balance sheet per kg of fuel is given below :

Heat supplied	*kJ*	*Heat expenditure*	*kJ*	*%*
Heat supplied by 1 kg of fuel	31 360	1. Heat utilised in raising steam	20 495	65.35
		2. Heat carried away by dry flue gases	2673	8.53
		3. Heat carried away by moisture in fuel	60.6	0.19
		4. Heat lost by radiation etc. (by difference).	8131.4	25.93
Total	31 360	Total	31 360	100

Example 15.8. *The following observations were made during a boiler trial :*

Mass of feed water per hour = 635 kg ; Temperature of feed water = 65° C ; Steam pressure = 10.5 bar ; Oil fired per hour = 52 kg ; Higher calorific value = 44 900 kJ/kg.

Percentage composition of oil by mass, C = 84.75 ; H_2 = 13 ; S = 1.25.

Analysis of dry flue gases by volume, CO_2 = 12.4 ; O_2 = 4.3 ; N_2 = 83.3.

Temperature of gases leaving the boiler = 362° C ; Specific heat of dry flue gases = 1.005 kJ/kg K ; Boiler room temperature = 21° C ; Throttling calorimeter temperature at outlet = 125° C ; Pressure of steam after throttling = 101 mm of mercury ; Barometer reading = 760 mm of Hg ; Heating surface of boiler = 20 m^2 ; Specific heat of superheated steam = 2.1 kJ/kg K ; Partial pressure of steam in flue gases = 0.07 bar.

Draw up a complete heat balance sheet and calculate the boiler efficiency and equivalent evaporation per kg of fuel and per m^2 of heating surface per hour.

Solution. Given : $m_s = 635$ kg/h ; $t_1 = 65°$ C ; $p = 10.5$ bar ; $m_f = 52$ kg/h ; $C = 44\ 900$ kJ/kg ; $t_g = 362°$ C ; $c_{pg} = 1.005$ kJ/kg K ; $t_b = 21°$ C ; $t_{sup} = 125°$ C ; c_p for superheated steam = 2.1 kJ/kg K ; $p_2 = 0.07$ bar

First of all, let us find the dryness fraction of steam before throttling (*i.e.* x).

We know that absolute pressure of steam after throttling

$$= 101 + 760 = 861 \text{ mm of Hg}$$

$$= 861 \times 133.3 = 115\ 000 \text{ N/m}^2 \qquad \ldots (\because 1 \text{ mm of Hg} = 133.3 \text{ N/m}^2)$$

$$= 1.15 \text{ bar} \qquad \ldots (\because 1 \text{ bar} = 10^5 \text{ N/m}^2)$$

From steam tables, corresponding to an initial pressure of 10.5 bar, we find that

$$h_f = 772 \text{ kJ/kg} ; \ h_{fg} = 2006 \text{ kJ/kg}$$

and corresponding to a final pressure of 1.15 bar, we find that

$$h_{g2} = 2681.6 \text{ kJ/kg} ; \ t_2 = 103.6° \text{C}$$

We know that enthalpy or total heat of steam before throttling

= Enthalpy or total heat of steam after throttling

i.e.
$$h_f + x\, h_{fg} = h_{g2} + c_p (t_{sup} - t_2)$$

$$772 + x \times 2006 = 2681.6 + 2.1 (125 - 103.6)$$

$$\therefore \quad x = 0.974$$

In order to draw the heat balance sheet, we shall determine the values of the following heats :

1. *Heat utilised in raising steam per kg of oil*

We know that the mass of water actually evaporated per kg of oil

$$m_e = m_s / m_f = 635/52 = 12.21 \text{ kg}$$

From steam tables, corresponding to a feed water temperature of 65° C, we find that

$$h_{f1} = 272 \text{ kJ/kg}$$

$\therefore$ Heat utilised in raising steam per kg of oil

$$= m_e (h - h_{f1})$$

$$= m_e [(h_f + x\, h_{fg}) - h_{f1}]$$

$$= 12.21 [(772 + 0.974 \times 2006) - 272] = 29\ 960 \text{ kJ} \qquad \ldots (i)$$

2. *Heat carried away by dry flue gases*

First of all, let us find the mass of dry flue gases per kg of fuel (*i.e.* m_g).

The percentage composition of oil by mass is given as :

$$C = 84.75\% = 0.8475 \text{ kg} ; H_2 = 13\% = 0.13 \text{ kg} ; \text{and } N_2 = 1.25\% = 0.0125 \text{ kg}$$

and analysis of dry flue gases by volume is given as :

$$CO_2 = 12.4\% = 0.124 \text{ m}^3 ; O_2 = 4.3\% = 0.043 \text{ m}^3 ; \text{and } N_2 = 83.3\% = 0.833 \text{ m}^3$$

The volumetric analysis of the dry flue gases is converted into mass analysis as given in the following table :

Constituent	Volume in 1 m^3 of the flue gas (a)	Molecular mass (b)	Proportional mass (c) = (a) × (b)	Mass of constituent in kg per kg of flue gas $(d) = \frac{(c)}{\Sigma(c)}$
CO_2	0.124	44	5.456	$\frac{5.456}{30.156} = 0.181$
O_2	0.043	32	1.376	$\frac{1.376}{30.156} = 0.046$
N_2	0.833	28	23.324	$\frac{23.324}{30.156} = 0.773$
Total	1.000		$\Sigma(c) = 30.156$	1.000

We know that mass of carbon in 1 kg of flue gases

$$= \frac{3}{11} CO_2 + \frac{3}{7} CO = \frac{3}{11} CO_2 \qquad \ldots (\because CO = 0)$$

$$= \frac{3}{11} \times 0.181 = 0.0494 \text{ kg}$$

$\therefore$ Mass of dry flue gases per kg of oil burnt,

$$m_g = \frac{\text{Mass of carbon in 1 kg of fuel}}{\text{Mass of carbon in 1 kg of flue gas}}$$

$$= \frac{0.8475}{0.0494} = 17.16 \text{ kg/kg of oil}$$

We know that heat carried away by dry flue gases per kg of oil

$$= m_g \, c_{pg} (t_g - t_b)$$

$$= 17.16 \times 1.005 (362 - 21) = 5880 \text{ kJ} \qquad \ldots (ii)$$

3. *Heat carried away by steam*

Since H_2 is present in the oil, therefore mass of steam formed in the flue gases due to combustion of H_2 is given by

$$m = 9 H_2 = 9 \times 0.13 = 1.17 \text{ kg}$$

From steam tables, corresponding to a partial pressure of steam in the flue gases, *i.e.* 0.07 bar, we find that

$$h_g = 2572.6 \text{ kJ/kg}; \text{ and } t = 39° C$$

and corresponding to a boiler room temperature of 21° C, we find that

$$h_b = 88 \text{ kJ/kg}$$

$\therefore$ Heat carried away by steam in the flue gases per kg of oil

$$= m \, [h_g + c_p (t_g - t) - h_b]$$

$$= 1.17 \, [2572.6 + 2.1 (362 - 39) - 88] = 3700 \text{ kJ} \qquad \ldots (iii)$$

4. *Heat lost by radiation etc.*

We know that heat lost by radiation etc. (by difference)

$$= 44\,900 - (29\,960 + 5880 + 3700) = 5360 \text{ kJ}$$

Now complete heat balance sheet per kg of oil is given below :

Heat supplied	*kJ*		*Heat expenditure*	*kJ*	*%*
Heat supplied by 1 kg of oil	44 900	1.	Heat utilised in raising steam	29 960	66.73
		2.	Heat carried away by dry flue gases	5880	13.10
		3.	Heat carried away by steam	3700	8.24
		4.	Heat lost by radiation etc. (by difference)	5360	11.93
Total	44 900		Total	44 900	100

Boiler efficiency

We know that boiler efficiency,

$$\eta = \frac{m_e(h - h_{f1})}{C} = \frac{29\,960}{44\,900} = 0.6673 \text{ or } 66.73\,\% \text{ Ans.}$$

... [From equation (*i*)]

Equivalent evaporation per kg of fuel

We know that equivalent evaporation per kg of fuel

$$= \frac{m_e(h - h_{f1})}{2257} = \frac{29\,960}{2257} = 13.27 \text{ kg Ans.}$$

Equivalent evaporation per m² per hour

We know that equivalent evaporation per m^2 per hour

$$= \frac{\text{Equivalent evaporation per kg of fuel}}{\text{Heating surface area}} = \frac{13.27}{20} \text{ or } 0.6635 \text{ kg Ans.}$$

EXERCISES

1. A boiler produces 4 kg of steam per kg of coal from feed water at 45° C. The steam pressure is 10.5 bar. If the dryness fraction of steam is 0.98, determine the equivalent evaporation from and at 100° C. **[Ans. 4.52 kg]**

2. A boiler raises 3.7 kg of water per kg of coal from feed water at 54.5° C, to steam at the pressure of 34 bar and temperature of 370° C. Assuming specific heat of superheated steam as 2.6, calculate equivalent evaporation/kg of coal. **[Ans. 4.77 kg]**

3. In a boiler trial, the following observations were recorded :

   Boiler pressure = 10 bar ; Dryness fraction of steam = 0.95 ; Coal consumption = 500 kg/h ; Calorific value of coal = 30 500 kJ/kg ; Feed water temperature = 50° C ; Feed water supplied = 4 tonnes/h.

   Find the evaporation factor and the equivalent evaporation from and at 100° C in kg per kg of coal fired. Take specific heat of feed water as 4.187 kJ/kg K. **[Ans. 1.09 ; 8.72 kg/kg of fuel]**

4. A boiler produces 9000 kg of steam while 1 tonne of coal is burnt. The steam is produced at 10 bar from water at 15° C. The dryness fraction of steam is 0.9. Determine the efficiency of the boiler when the calorific value of the coal is 32 000 kJ/kg. **[Ans. 70.65%]**

5. A boiler delivers steam at 100 bar and 500° C. The feed water inlet temperature is 160° C. The steam is produced at the rate of 100 tonnes/h and the boiler efficiency is 88%. Estimate the fuel burning rate in kg/h, if the calorific value of the fuel is 21 MJ/kg. **[Ans. 14.6 tonnes/h]**

6. In a boiler test, the following observations were made :

Feed water temperature = 12° C ; Pressure of steam = 11 bar ; Dryness fraction of steam = 0.95 ; Mass of coal burnt = 300 kg/h ; Calorific value of coal = 32 000 kJ/kg of coal ; Mass of water supplied to boiler in 7 hrs 14 min = 14 625 kg.

The mass of water in the boiler at the end of the test was less than that at the commencement by 900 kg. Calculate : 1. Actual evaporation per kg of coal ; 2. Equivalent evaporation from and at 100° C per kg of coal ; and 3. Thermal efficiency of the boiler. **[Ans.** 7.15 kg ; 8.33 kg ; 58.75 %**]**

7. A steam plant consisting of a boiler, superheater and economiser has the following particulars :

Steam pressure = 12.6 bar ; Temperature of steam leaving superheater = 245° C ; Fuel used per hour = 1000 kg ; Feed water per hour = 9000 kg ; Temperature of feed water entering the economiser = 40° C ; Temperature of feed water leaving the economiser = 115° C ; Dryness fraction of steam leaving the boiler = 0.9 ; Calorific value of fuel used = 30 240 kJ/kg.

Calculate : 1. Overall efficiency of the plant, and 2. Percentage of heat in fuel used in the boiler, economiser and superheater. **[Ans.** 81.3% ; 62.6% ; 9.37% ; 9.33%**]**

8. The following observations were made during the trial of a boiler plant consisting of a battery of 6 lancashire boilers and an economiser :

Calorific value of coal per kg = 30 MJ/kg ; Mass of feed water per kg of dry coal = 9.1 kg ; Equivalent evaporation from and at 100° C per kg of dry coal = 9.6 kg ; Temperature of feed water to economiser = 12° C ; Temperature of feed water to boiler = 105° C ; Air temperature = 13° C ; Temperature of flue gases entering economiser = 370° C ; Mass of flue gases entering economiser = 18.2 kg/kg of coal ; Mean specific heat of flue gases = 1.005 kJ/kg K.

Find : 1. the efficiency of the boiler alone ; 2. the efficiency of the economiser alone ; and 3. the efficiency of the whole boiler plant. **[Ans.** 72.22% ; 54.43% ; 84.1%**]**

9. The following particulars were recorded during a steam boiler trial :

Pressure of steam = 11 bar ; Mass of feed water = 4600 kg/h ; Temperature of feed water = 75° C ; Dryness fraction of steam = 0.96 ; Coal used = 490 kg/h ; Calorific value of coal = 35 700 kJ/kg ; Moisture in coal = 4% by mass ; Mass of dry flue gases = 18.57 kg/kg of coal ; Temperature of flue gases = 300° C ; Boiler house temperature = 16° C ; Specific heat of flue gases = 0.97 kJ/kg K.

Draw the heat balance sheet of the boiler per kg of coal.

Ans. Heat balance sheet

Heat supplied	*kJ*	*Heat consumed*	*kJ*	*%*
Heat supplied in 1 kg of coal	34 272	1. Heat utilised in raising steam.	22 428	65.44
		2. Heat carried away by dry flue gases.	5116	14.93
		3. Heat lost in moisture.	121	0.35
		4. Heat lost in radiation, etc. (by difference)	6607	19.28
Total	34 272	Total	34 272	100

10. In a boiler trial, the following observations were obtained :

Mass of feed water = 1520 kg/h ; Temperature of feed water = 30° C ; Dryness fraction of steam = 0.95 ; Pressure of steam = 8.5 bar ; Coal burnt/hour = 200 kg ; Calorific value of coal = 27 300 kJ/kg of coal ; Ash and unburnt coal collected = 16 kg/h ; Calorific value of ash and unburnt coal = 3780 kJ/kg ; Mass of flue gases = 17.3 kg/kg of coal ; Temperature of flue gases = 330° C ; Boiler room temperature = 17° C ; Mean specific heat of flue gases = 1 kJ/kg K.

Estimate the thermal efficiency of the boiler and draw the heat balance sheet. **[Ans.** 70.8%**]**

Ans. Heat balance sheet

Heat supplied	*kJ*		*Heat consumed*	*kJ*	%
Heat supplied by 1 kg of coal	27 300	1.	Heat utilised in raising steam	19 329	70.80
		2.	Heat carried away by the flue gases	5415	19.83
		3.	Heat lost in ash and unburnt coal	302	1.11
		4.	Heat lost in radiation, etc. (by difference)	2254	8.26
Total	27 300		Total	27 300	100

QUESTIONS

1. What do you understand by the evaporative capacity of a boiler ?
2. Explain clearly the equivalent evaporation from and at 100° C.
3. Discuss briefly the term boiler efficiency.
4. Enlist the various heat losses in a boiler. Which is the biggest loss ?
5. Draw the heat balance sheet of a boiler.

OBJECTIVE TYPE QUESTIONS

1. The equivalent evaporation is defined as the

   (*a*) ratio of heat actually used in producing the steam to the heat liberated in the furnace

   (*b*) amount of water evaporated or steam produced in kg per kg of fuel burnt.

   (*c*) amount of water evaporated 'from and at 100° C' into dry and saturated steam

   (*d*) none of the above

2. When the enthalpy or total heat of steam is h kJ/kg and the enthalpy or sensible heat of feed water is h_{f1} kJ/kg, then the factor of evapqration is given by

   (*a*) $\frac{h - h_{f1}}{2257}$ (*b*) $\frac{h + h_{f1}}{2257}$ (*c*) $\frac{h \times h_{f1}}{2257}$ (*d*) $\frac{h}{h_{f1} \times 2257}$

3. The amount of water evaporated in kg per kg of fuel burnt is called

   (*a*) equivalent evaporation 'from and at 100° C'

   (*b*) evaporative capacity of a boiler

   (*c*) boiler efficiency

   (*d*) none of the above

4. The ratio of heat actually used in producing the steam to the heat liberated in the furnace is called

   (*a*) equivalent evaporation 'from and at 100° C'

   (*b*) evaporative capacity of a boiler

   (*c*) boiler efficiency

   (*d*) none of the above

5. In a boiler, various heat losses take place. The biggest loss is due to

   (*a*) moisture in fuel (*b*) dry flue gases (*c*) steam formation (*d*) unburnt carbon

ANSWERS

1. (*c*) 2. (*a*) 3. (*b*) 4. (*c*) 5. (*b*)

16

Boiler Draught

1. Introduction. 2. Classification of Draughts. 3. Types of Draughts. 4. Advantages and Disadvantages of Mechanical Draught. 5. Comparison between Forced Draught and Induced Draught. 6. Balanced Draught. 7. Height of Chimney. 8. Condition for Maximum Discharge through the Chimney. 9. Power Required to Drive a Fan. 10. Efficiency of Chimney.

16.1. Introduction

In the last chapters, we have already discussed the formation of steam and combustion of fuels. It may be noted that the rate of steam generation, in a boiler, depends upon the rate at which the fuel is burnt. The rate of fuel burning depends upon the availability of oxygen or in other words availability of fresh air. The fresh air will enter the fuel bed, if the gases of combustion are exhausted from the combustion chamber of the boiler. This is possible only if a difference of pressure is maintained above and below the fire grate. This difference of pressure is known as *draught*.

The main objects of producing draught in a boiler are :

1. To provide an adequate supply of air for the fuel combustion.

2. To exhaust the gases of combustion from the combustion chamber.

3. To discharge these gases to the atmosphere through the chimney.

16.2. Classification of Draughts

In general, the draughts may be classified into the following two types :

1. *Natural draught*. It is the draught produced by a chimney due to the difference of densities between the hot gases inside the chimney and cold atmospheric air outside it.

2. *Artificial draught*. The artificial draught may be a mechanical draught or a steam jet draught. The draught produced by a fan or blower is known as *mechanical* or *fan draught* where as the draught produced by a steam jet is called *steam jet draught*. The artificial draught is provided, when natural draught is not sufficient. It may be induced or forced.

16.3. Types of Draughts

In general, the draughts are of the following three types :

1. *Chimney draught*. The draught produced by means of a chimney alone is known as *chimney draught*. It is a natural draught and has induced effect. Since the atmospheric air (outside the chimney) is heavier than the hot gases (inside the chimney), the outside air will flow through the furnace into the chimney. It will push the hot gases to pass through the chimney. The chimney draught varies with climatic conditions, temperature of furnace gases and height of chimney.

2. *Mechanical or fan draught*. The draught, produced by means of a fan or blower, is known as *mechanical draught* or *fan draught*. The fan used is, generally, of centrifugal type and is driven by an electric motor.

In an *induced fan draught,* a centrifugal fan is placed in the path of the flue gases before they enter the chimney. It draws the flue gases from the surface and forces them up through the chimney. The action of this type of draught is similar to that of the natural draught.

In case of *forced fan draught*, the fan is placed before the grate, and air is forced into the grate through the closed ash pit.

3. *Steam jet draught.* It is a simple and cheap method of producing artificial draught. In a steam jet draught, the exhaust steam, from a non-condensing steam engine, is used for producing draught. It is mostly used in locomotive boilers, where the exhaust steam from the engine cylinder is discharged through a blast pipe placed at the smoke box and below the chimney.

In an *induced steam jet draught*, the steam jet issuing from a nozzle, is placed in the chimney. But in a *forced steam jet draught*, the steam jet issuing from a nozzle is placed in the ash pit under the fire grate of the furnace.

16.4. Advantages and Disadvantages of Mechanical Draught

These days the mechanical draught is widely used in large boiler plants. It has the following advantages and disadvantages over the natural draught.

Advantages

1. It is more economical.
2. It is better in control.
3. The flow of air through the grate and furnace is uniform.
4. It produces more draught.
5. Its rate of combustion is very high.
6. Low grade fuel can be used.
7. The air flow can be regulated according to the changing requirements.
8. It is not affected by the atmospheric temperature.
9. It reduces the amount of smoke.
10. It reduces height of chimney.
11. It increases efficiency of the plant.
12. It reduces the fuel consumption. About 15% of fuel is saved for the same amount of work.

Disadvantages

1. Its initial cost is high.
2. Its running cost is also high.
3. It has increased maintenance cost.

16.5. Comparison between Forced Draught and Induced Draught

The following table gives the comparison between forced draught and induced draught.

S. No.	*Forced draught*	*Induced draught*
1.	The fan is placed before the fire grate.	The fan is placed after the fire grate.
2.	The pressure inside the furnace is above the atmospheric pressure.	The pressure inside the furnace is below the atmospheric pressure.
3.	It forces fresh air into the combustion chamber.	It sucks hot gases from the combustion chamber, and forces them into the chimney.

4.	It requires less power as the fan has to handle cold air only. Moreover, volume of air handled is less because of low temperature of the cold air.	It requires more power as the fan has to handle hot air and flue gases. Moreover, volume of air and gases is more because of high temperature of the air and gases.
5.	The flow of air through grate and furnace is more uniform.	The flow of air through grate and furnace is less uniform.
6.	As the leakages are outward, therefore there is a serious danger of blow out when the fire doors are opened and the fan is working.	As the leakages are inward, therefore there is no danger of blow out. But if the fire doors are opened and the fan is working there will be a heavy air infiltration.

16.6. Balanced Draught

It is an improved type of draught, and is a combination of induced and forced draught. It is produced by running both induced and forced draught fans simultaneously.

16.7. Height of Chimney

We have already discussed that natural draught is produced by means of a chimney. Since the amount of draught depends upon the height of chimney, therefore its height should be such that it can produce a sufficient draught.

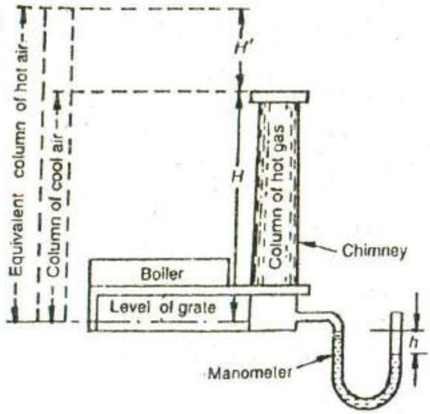

Fig. 16.1 Height of chimney for a given draught.

Let H = Height of chimney above the fire grate in metres.

h = Draught required in terms of mm of water.

T_1 = Absolute temperature of air outside the chimney in K.

T_2 = Absolute temperature of the flue gas inside the chimney in K.

v_1 = Volume of outside air at temperature T_1 in m^3/ kg of fuel.

v_2 = Volume of flue gases inside the chimney at temperature T_2 in m^3/ kg of fuel.

m = Mass of air actually used in kg / kg of fuel.

$\therefore$ $m + 1$ = Mass of flue gases in kg per kg of fuel.

First of all, let us find the volume of outside air per kg of fuel at N.T.P. (*i.e.* at 0° C temperature and 1.013 bar pressure).

Let v_0 = Volume of air at 0° C.

∴ Absolute temperature,

$$T_0 = 0° + 273 = 273\text{ K}$$

Atmospheric pressure,

$$p_0 = 1.013 \text{ bar} = 1.013 \times 10^5 \text{ N/m}^2 \qquad \ldots(\because 1 \text{ bar} = 10^5 \text{ N/m}^2)$$

We know that $p \times v = m\,R\,T$

or $$v_0 = \frac{m\,R\,T_0}{p_0} = \frac{m \times 287 \times 273}{1.013 \times 10^5} = 0.773\,m \text{ m}^3/\text{kg of fuel}$$

$$\ldots(\because \text{For air, } R = 287 \text{ J/kg K})$$

Volume of outside air at T_1 K,

$$v_1 = \frac{v_0 \times T_1}{T_0} \qquad \ldots\left(\because \frac{v_0}{T_0} = \frac{v_1}{T_1}\right)$$

$$= \frac{0.773\,m \times T_1}{273} = \frac{m\,T_1}{353} \text{ m}^3/\text{kg of fuel}$$

Density of outside air at T_1 K,

$$\rho_1 = \frac{m}{\frac{m\,T_1}{353}} = \frac{353}{T_1} \text{ kg/m}^3 \qquad \ldots\left(\because \text{Density} = \frac{\text{Mass}}{\text{Volume}}\right)$$

∴ Pressure due to a similar column of outside (cold) air,

$$p_1 = \text{Density} \times \text{Height} \times g = \rho_1\,H\,g$$

$$= \frac{353}{T_1} \times H \times 9.81 = \frac{3463\,H}{T_1} \text{ N/m}^2$$

According to Avogadro's law, *the flue gas at N.T.P. occupies the same volume as that of air used at N.T.P.*

∴ Volume of flue gases at 0° C

$$= 0.773\,m \text{ m}^3/\text{kg of fuel}$$

and volume of flue gases at T_2 K,

$$v_2 = \frac{m\,T_2}{353} \text{ m}^3/\text{kg of fuel}$$

Density of flue gases at T_2 K,

$$\rho_2 = \frac{m+1}{\frac{m\,T_2}{353}} = \frac{353\,(m+1)}{m\,T_2} \text{ kg/m}^3$$

∴ Pressure due to column of hot gases at the base of chimney,

$$p_2 = \rho_2\,H\,g = \frac{353\,(m+1)\,H \times 9.81}{m\,T_2} = \frac{3463\,(m+1)\,H}{m\,T_2} \text{ N/m}^2$$

We know that the draught pressure is due to the pressure difference between the hot column of gas in the chimney and a similar column of cold air outside the chimney. Therefore draught pressure,

$$p = p_1 - p_2 = \frac{3463\,H}{T_1} - \frac{3463\,(m+1)\,H}{m\,T_2}\ \text{N/m}^2$$

$$= 3463\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right)\text{N/m}^2 \qquad \ldots (i)$$

In actual practice, the draught pressure is expressed in mm of water as indicated by a manometer. Since* $1\ \text{N/m}^2 = 0.101\,937$ mm of water, therefore

$$h = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right)\text{mm of water} \qquad \ldots (ii)$$

Notes : 1. The equations (*i*) and (*ii*) give only the theoretical value of the draught and is known as *static draught*. The actual value of the draught is less than the theoretical value due to the following reasons :

(*a*) The effect of frictional resistance offered to the passage of air through the fire bars, fire flues and chimney is to reduce the draught h.

(*b*) The temperature of flue gases inside the chimney diminishes for every metre of its height.

2. The draught may also be expressed in terms of column of hot gases. If H' is the height in metres of the hot gas column which would produce the draught pressure p, then

$$p = \text{Density} \times H' \times g$$

$$= \frac{353\,(m+1)}{m\,T_2} \times H' \times 9.81 = \frac{3463\,(m+1)}{m\,T_2} \times H'\ \text{N/m}^2$$

Substituting this value in equation (*i*) above,

$$\frac{3463\,(m+1)}{m\,T_2} \times H' = 3463\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right)$$

$$\therefore \qquad H' = H\left[\left(\frac{m}{m+1} \times \frac{T_2}{T_1}\right) - 1\right]\text{metres}$$

3. The velocity of flue gases through the chimney under a static draught of H' metres is given by

$$V = \sqrt{2gH'} = 4.43\sqrt{H'} \qquad \ldots \text{(Neglecting friction)}$$

Example 16.1. *A chimney is 28 m high and the temperature of the hot gases in the chimney is 320° C. The temperature of outside air is 23° C and the furnace is supplied with 15 kg of air per kg of coal burnt. Calculate draught in mm of water.*

Solution. Given : $H = 28$ m ; $T_2 = 320°\text{ C} = 320 + 273 = 593$ K ; $T_1 = 23°\text{ C} = 23 + 273 = 296$ K ; $m = 15$ kg / kg of coal

We know that draught,

$$h = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right) = 353 \times 28\left(\frac{1}{296} - \frac{15+1}{15 \times 593}\right)$$

$$= 15.6 \text{ mm of water } \textbf{Ans.}$$

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* We know that $1\ \text{kg/m}^2 = 1$ mm of water

or $9.81\ \text{N/m}^2 = 1$ mm of water

$$\therefore \qquad 1\ \text{N/m}^2 = \frac{1}{9.81} = 0.101\,937 \text{ mm of water}$$

Example 16.2. *A boiler uses 18 kg air per kg of fuel. Determine the minimum height of chimney required to produce a draught of 25 mm of water. The mean temperature of chimney gases is 315° C and that of outside air 27° C.*

Solution. Given : $m = 18$ kg/kg of fuel ; $h = 25$ mm of water ; $T_2 = 315° \text{C} = 315 + 273 = 588 \text{ K}$; $T_1 = 27° \text{C} = 27 + 273 = 300 \text{ K}$

Let H = Minimum height of chimney required.

We know that draught (h),

$$25 = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right) = 353\,H\left(\frac{1}{300} - \frac{18+1}{18 \times 588}\right) = 0.53\,H$$

$$\therefore \quad H = 47.2 \text{ m} \quad \textbf{Ans.}$$

Example 16.3. *The following data pertain to a steam power plant :*

Height of chimney = 30 m ; Draught produced = 16.5 mm of water gauge ; Temperature of flue gas = 360° C ; Temperature of boiler house = 28° C ; Atmospheric pressure = 1.013 bar.

Determine the quantity of air used per kg of fuel burnt in the boiler.

Solution. Given : $H = 30$ m ; $h = 16.5$ mm of water ; $T_2 = 360° \text{C} = 360 + 273 = 633 \text{ K}$; $T_1 = 28° \text{C} = 28 + 273 = 301 \text{ K}$; $p_0 = 1.013$ bar

Let m = Quantity of air used per kg of fuel.

We know that draught (h),

$$16.5 = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right) = 353 \times 30\left(\frac{1}{301} - \frac{m+1}{m \times 633}\right)$$

$$\frac{m+1}{m \times 633} = \frac{1}{301} - \frac{16.5}{353 \times 30} = 0.001\,76$$

$$m + 1 = 0.001\,76\,(m \times 633) = 1.114\,m$$

$$\therefore \quad m = 8.772 \text{ kg / kg of fuel} \quad \textbf{Ans.}$$

Example 16.4. *A 30 m high chimney is used to discharge hot gases at 297° C to the atmosphere which is at 27° C. Find the mass of air actually used per kg of fuel, if the draught produced is 15 mm of water. If the coal burnt in the combustion chamber contains 80% carbon, 6% moisture and remaining ash, determine the percentage of excess air supplied.*

Solution. Given : $H = 30$ m ; $T_2 = 297° \text{C} = 297 + 273 = 570 \text{ K}$; $T_1 = 27° \text{C} = 27 + 273 = 300 \text{ K}$; $h = 15$ mm of water

Mass of air used per kg of fuel

Let m = Mass of air used per kg of fuel.

We know that draught,

$$h = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{mT_2}\right),$$

$$\therefore \quad 15 = 353 \times 30\left(\frac{1}{300} - \frac{m+1}{m \times 570}\right) = 35.3 - 18.58\left(\frac{m+1}{m}\right)$$

or

$$\frac{m+1}{m} = \frac{35.3 - 15}{18.58} = 1.09$$

$$\therefore \quad m = 11.11 \text{ kg / kg of fuel} \quad \textbf{Ans.}$$

Percentage of excess air supplied

We know that 1 kg of carbon requires 8/3 kg of oxygen or in other words 1 kg of carbon requires

$$\frac{8}{3} \times \frac{100}{23} = 11.6 \text{ kg of air}$$

Since 1 kg of coal contains 0.8 kg of carbon, therefore air required for complete combustion of 0.8 kg of carbon

$$= 0.8 \times 11.6 = 9.28 \text{ kg/kg of fuel}$$

∴ Percentage of excess air supplied

$$= \frac{11.11 - 9.28}{9.28} = 0.197 \quad \text{or} \quad 19.7\ \% \ \textbf{Ans.}$$

Example 16.5. *A boiler is equipped with a chimney of 30 metres height. The flue gases, which pass through the chimney are at temperature of 288° C, whereas the atmospheric temperature is 21° C. If the air flow through the combustion chamber is 18 kg/kg of fuel burnt, find : 1. the theoretical draught produced in mm of water and in height of hot gases column, and 2. velocity of the flue gases passing through the chimney, if 50% of the theoretical draught is lost in friction at the grate and passage.*

Solution. Given : $H = 30$ m ; $T_2 = 288°$ C $= 288 + 273 = 561$ K ; $T_1 = 21°$ C $= 21 + 273 = 294$ K ; $m = 18$ kg/kg of fuel

1. *Theoretical draught produced in mm of water*

We know that theoretical draught produced in mm of water,

$$h = 353\, H \left(\frac{1}{T_1} - \frac{m+1}{m\, T_2} \right) = 353 \times 30 \left(\frac{1}{294} - \frac{18+1}{18 \times 561} \right)$$

$$= 16.1 \text{ mm of water } \textbf{Ans.}$$

Theoretical draught produced in height of hot gases column

We know that theoretical draught produced in height of hot gases column,

$$H' = H \left[\left(\frac{m}{m+1} \times \frac{T_2}{T_1} \right) - 1 \right] = 30 \left[\left(\frac{18}{18+1} \times \frac{561}{294} \right) - 1 \right]$$

$$= 24.2 \text{ m } \textbf{Ans.}$$

2. *Velocity of flue gases passing through the chimney*

Since 50% of the theoretical draught is lost in friction, therefore net draught available,

$$H' = 24.2 \times 0.5 = 12.1 \text{ m}$$

∴ Velocity of flue gases passing through the chimney,

$$V = 4.43 \sqrt{H'} = 4.43 \sqrt{12.1} = 15.4 \text{ m/s } \textbf{Ans.}$$

16.8. Condition for Maximum Discharge through the Chimney

We have already discussed in the last article that the height of hot gas column producing the draught,

$$H' = H \left[\left(\frac{m}{m+1} \times \frac{T_2}{T_1} \right) - 1 \right] \text{metres} \qquad \ldots (i)$$

and the velocity of flue gases through the chimney,

$$V = \sqrt{2gH'} = \sqrt{2gH\left[\left(\frac{m}{m+1}\times\frac{T_2}{T_1}\right)-1\right]} \text{ m/s}$$

where H = Height of chimney,

m = Mass of air actually used in kg/kg of fuel,

T_1 = Absolute temperature of the air outside the chimney or atmospheric temperature, and

T_2 = Absolute temperature of the flue gas inside the chimney.

Now consider a chimney discharging hot gases to the atmosphere under the action of the natural draught.

Let A = Area of cross-section of chimney in m^2, and

ρ = Density of hot gases in kg/m^3.

∴ Mass of hot gases discharged per second,

$$M = \text{Volume of hot gases} \times \text{Density of hot gases} = A\,V\rho \qquad \ldots (ii)$$

We know that density of the hot gas is inversely proportional to its temperature, *i.e.*

$$\rho \propto \frac{1}{T_2} \text{ or } \rho = \frac{K}{T_2}$$

where K is a constant of proportionality.

Now substituting the value of V and ρ in equation (*ii*),

$$M = A\sqrt{2gH\left[\left(\frac{m}{m+1}\times\frac{T_2}{T_1}\right)-1\right]}\times\frac{K}{T_2}$$

Substituting $A.K = K_1$, another constant, we have

$$M = \frac{K_1}{T_2}\sqrt{2gH\left[\left(\frac{m}{m+1}\times\frac{T_2}{T_1}\right)-1\right]}$$

Again substituting $K_1\sqrt{2gH} = K_2$, another constant,

$$M = \frac{K_2}{T_2}\sqrt{\left(\frac{m}{m+1}\times\frac{T_2}{T_1}\right)-1}$$

$$= K_2\sqrt{\left(\frac{m}{m+1}\times\frac{1}{T_1T_2}\right)-\frac{1}{T_2^2}} = K_2\left(\frac{m}{m+1}\times\frac{1}{T_1T_2}-\frac{1}{T_2^2}\right)^{1/2}$$

Differentiating M respect to T_2, for maximum discharge and equating to zero.

.*e.*

$$\frac{dM}{dT_2} = 0$$

$$K_2\times\frac{1}{2}\left(\frac{m}{m+1}\times\frac{1}{T_1T_2}-\frac{1}{T_2^2}\right)^{-1/2}\times\left(-\frac{m}{m+1}\times\frac{1}{T_1}\times\frac{1}{T_2^2}+\frac{2}{T_2^3}\right) = 0$$

or

$$K_2\times\frac{1}{2}\times\frac{-\frac{m}{m+1}\times\frac{1}{T_1}\times\frac{1}{T_2^2}+\frac{2}{T_2^3}}{\sqrt{\frac{m}{m+1}\times\frac{1}{T_1T_2}-\frac{1}{T_2^2}}} = 0$$

$$\therefore \quad -\frac{m}{m+1} \times \frac{1}{T_1 T_2^2} + \frac{2}{T_2^3} = 0$$

$$\frac{m}{m+1} \times \frac{1}{T_1 T_2^2} = \frac{2}{T_2^3} \quad \text{or} \quad \frac{m}{m+1} \times \frac{1}{T_1} = \frac{2}{T_2}$$

$$\therefore \quad T_2 = 2\left(\frac{m+1}{m}\right)T_1 \qquad \ldots (ii)$$

Thus we see that for maximum discharge, temperature of the flue gases (T_2) should be slightly more than the atmospheric temperature (T_1).

Notes : 1. The height of hot gas column (H') producing the draught for maximum mass of hot gases to be discharged is obtained by substituting the value of T_2 in equation (i),

$$H' = H\left[\left(\frac{m}{m+1} \times \frac{2(m+1)T_1}{m \times T_1}\right) - 1\right] = H \text{ metres}$$

It shows that for maximum discharge, the height of hot gas column producing the draught is equal to the height of the chimney.

2. We know that draught pressure,

$$h = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right) \text{mm of water}$$

$\therefore$ The draught pressure for maximum discharge,

$$h = 353\,H\left[\frac{1}{T_1} - \frac{m+1}{m} \times \frac{1}{2\left(\frac{m+1}{m}\right)T_1}\right] \qquad \ldots \left[\because T_2 = 2\left(\frac{m+1}{m}\right)T_1\right]$$

$$= \frac{353\,H}{2\,T_1} = \frac{176.5\,H}{T_1} \text{ mm of water}$$

Example 16.6. *A chimney is 30 m high and the temperature of atmosphere is 12° C. Calculate the draught produced in mm of water under the conditions of maximum discharge.*

Solution. Given : $H = 30$ m ; $T_1 = 12°\text{C} = 12 + 273 = 285$ K

We know that draught produced for maximum discharge,

$$h = \frac{176.5\,H}{T_1} = \frac{176.5 \times 30}{285} = 18.6 \text{ mm of water } \textbf{Ans.}$$

Example 16.7. *A chimney is 60 metres high and the temperature of atmospheric air is 27° C. If 15 kg of air / kg of fuel is used ; find for maximum discharge of hot gases : 1. the temperature of hot gases, and 2. the draught pressure in mm of water.*

Solution. Given : $H = 60$ m ; $T_1 = 27°\text{C} = 27 + 273 = 300$ K ; $m = 15$ kg / kg of fuel

1. Temperature of hot gases for maximum discharge

We know that temperature of hot gases for maximum discharge,

$$T_2 = 2\left(\frac{m+1}{m}\right)T_1 = 2\left(\frac{15+1}{15}\right)300 = 640 \text{ K} = 367°\text{C } \textbf{Ans.}$$

2. Draught pressure in mm of water

We know that draught pressure for maximum discharge,

$$h = \frac{176.5\,H}{T_1} = \frac{176.5 \times 60}{300} = 35.3 \text{ mm of water } \textbf{Ans.}$$

16.9. Power Required to Drive a Fan

The power of a fan (or air power) is the power required to do internal work on the air or gas to deliver its certain volume.

Let p = Draught pressure in $N/m^2 = 9.81 \times h$ mm of water,

v = Volume of air or gas flowing through the fan in m^3/min, and

η_f = Efficiency of the fan.

We know that work done by a fan

$$= \text{Pressure} \times \text{Volume} = p\,v \text{ N-m/min}$$

and power required to drive the fan or power of the motor driving the fan,

$$P = \frac{p\,v}{60 \times \eta_f} \text{ watts} \qquad \ldots (i)$$

Now let us find the value of P for forced draught fan and induced draught fan.

Let m = Mass of air actually used in kg / kg of fuel,

M = Mass of fuel in kg/min,

T_1 = Absolute temperature of outside air (cold air) in K, and

T_2 = Absolute temperature of hot gases in K.

$\therefore$ Mass of air used/min

$$= m\,M \text{ kg}$$

We know that the volume of air at N.T.P.,

$$v_0 = 0.773 \times \text{Mass of air used} = 0.773\, m\, M \text{ kg/min} \qquad \ldots \text{(Refer Art. 16.7)}$$

$\therefore$ Volume of air handled by a forced draught fan at temperature T_1 K,

$$v_1 = \frac{v_0\, T_1}{T_0} = \frac{0.773\, m\, M\, T_1}{273} = \frac{1}{353}\, m\, M\, T_1 \text{ m}^3 \qquad \ldots \left(\because \frac{v}{T_1} = \frac{v_0}{T_0}\right)$$

$\therefore$ Power required to drive the forced draught fan,

$$P = \frac{p\, m\, M\, T_1}{60 \times 353 \times \eta_f} = \frac{9.81\, h\, m\, M\, T_1}{60 \times 353 \times \eta_f} = \frac{h\, m\, M\, T_1}{60 \times 36 \times \eta_f} \text{ watts}$$

Now mass of flue gases drawn by the induced draught fan,

$$= (m + 1) \text{ kg / kg of fuel}$$

Mass of fuel per min

$$= M \text{ kg}$$

$\therefore$ Mass of flue gases handled by induced draught fan

$$= M\,(m + 1) \text{ kg/min}$$

We know that the volume of flue gases at N.T.P. is equal to the volume of air used at N.T.P.

$\therefore$ Volume of flue gases at 0° C,

$$v_0 = 0.773\, m\, M \text{ kg/min}$$

and volume of flue gases handled by induced draught fan at T_2 K,

$$v_2 = \frac{v_0 \times T_2}{T_0} = \frac{0.773\, m\, M\, T_2}{273} = \frac{m\, M\, T_2}{353} \text{ m}^3$$

∴ Power required to drive the induced draught fan,

$$P = \frac{p\, m\, M\, T_2}{60 \times 353 \times \eta_f} = \frac{h\, m\, M\, T_2}{60 \times 36 \times \eta_f} \text{ watts}$$

Note : The comparison of the power required to drive the induced draught and forced draught fan can be made by assuming that :

(*i*) both the fans have the same efficiency, and

(*ii*) they produce the equal draught.

$$\therefore \quad \frac{\text{Power required for I.D. fan}}{\text{Power required for F.D. fan}} = \frac{T_2}{T_1}$$

Example 16.8. *A boiler fitted with a forced draught fan has the following particulars :*

Mass of air required = 20 kg/kg of fuel
Mass of fuel used = 1500 kg/h
Temperature of outside air = 42° C
Temperature of chimney gas = 168° C
Draught pressure = 40 mm of water
Efficiency of fan = 70%

Determine the power required to drive the fan. If the boiler is equipped with induced draught fan, instead of forced draught fan, what will be the power required to drive it ?

Solution. Given : $m = 20$ kg / kg of fuel ; $M = 1500$ kg/h $= 25$ kg/min ; $T_1 = 42°$ C $= 42 + 273 = 315$ K ; $T_2 = 168°$ C $= 168 + 273 = 441$ K ; $h = 40$ mm of water ; $\eta_f = 70\% = 0.7$

Power required to drive the forced draught fan

We know that power required to drive the forced draught fan,

$$P_1 = \frac{h\, m\, M\, T_1}{60 \times 36 \times \eta_f} = \frac{40 \times 20 \times 25 \times 315}{60 \times 36 \times 0.7} = 4167 \text{ W}$$

$$= 4.167 \text{ kW} \quad \textbf{Ans.}$$

Power required to drive the induced draught fan

We know that power required to drive the induced draught fan,

$$P_2 = \frac{h\, m\, M\, T_2}{60 \times 36 \times \eta_f} = \frac{40 \times 20 \times 25 \times 441}{60 \times 36 \times 0.7} = 5833 \text{ W}$$

$$= 5.883 \text{ kW} \quad \textbf{Ans.}$$

16.10. Efficiency of Chimney

It may be defined as the ratio of the energy required to produce the artificial draught (expressed in metres head or J/kg of flue gas) to the mechanical equivalent of extra heat carried away per kg of flue gases due to the natural draught.

Let H' = Height of the flue gas column or the artificial draught produced in metres.

T_2 = Temperature of flue gases in chimney with natural draught in K,

T = Temperature of flue gases in chimney with artificial draught in K,

c_p = Specific heat of flue gases in kJ/kg K. Its value may be taken as 1.005 kJ/kg K.

We know that energy required to produce the artificial draught, per kg of flue gas

$$= H' g \text{ J/kg of flue gas}$$

and extra heat carried away per kg of flue gas due to natural draught

$$= 1 \times c_p (T_2 - T) \text{ kJ/kg}$$

$\therefore$ Mechanical equivalent of extra heat carried away

$$= 1000\, c_p (T_2 - T) \text{ J/kg of flue gas}$$

and efficiency,
$$\eta_c = \frac{H' g}{1000\, c_p (T_2 - T)}$$

Notes : 1. In the above expression the value of H' may be substituted as :

$$H' = H\left[\left(\frac{m}{m+1} \times \frac{T_2}{T_1}\right) - 1\right] \text{ metres}$$

2. The efficiency of chimney is less than 1 percent.

Example. 16.9. *In a chimney of height 50 metres, temperature of flue gases with natural draught is 367° C. The temperature of waste gases by using artificial draught is 127° C. The temperature of outside air is 27° C. If air supplied is 19 kg/kg of fuel burnt, determine the efficiency of chimney. Assume* $c_p = 1.005$ *kJ/kg K for flue gases.*

Solution. Given : $H = 50$ m ; $T_2 = 367°$ C $= 367 + 273 = 640$ K ; $T = 127°$ C $= 127 + 273 = 400$ K ; $T_1 = 27°$ C $= 27 + 273 = 300$ K ; $m = 19$ kg/kg of fuel ; $c_p = 1.005$ kJ/kg K

We know that height of the artificial draught,

$$H' = H\left[\left(\frac{m}{m+1} \times \frac{T_2}{T_1}\right) - 1\right] = 50\left[\left(\frac{19}{19+1} \times \frac{640}{300}\right) - 1\right] = 51.33 \text{ m}$$

$\therefore$ Efficiency of chimney,

$$\eta_c = \frac{H' g}{1000\, c_p (T_2 - T)} = \frac{51.33 \times 9.81}{1000 \times 1.005\,(640 - 400)}$$

$$= 0.0021 \text{ or } 0.21\,\% \text{ Ans.}$$

EXERCISES

1. Find the draught in mm of water column produced by a chimney 36 m high when the mean temperature of hot gases is 300° C, the temperature of outside air is 27° C and 19 kg of air is supplied per kg of fuel burnt in the furnace. **[Ans. 19 mm of water]**

2. A boiler uses 14 kg of air per kg of fuel. The temperature of the hot gases inside the chimney is 597° C and that of outside air 17° C. If the draught produced is 26 mm of water, determine the minimum height of the chimney required. **[Ans. 33.2 m]**

3. A 30 m high chimney is used to produce a natural draught of 15 mm of water. The temperature of hot gases in the chimney is 287° C. If the temperature of outside air is 27° C ; find the mass of air used per kg of fuel. **[Ans. 15.6 kg/kg of fuel]**

4. Calculate the height of chimney required to generate a pressure difference of 100 mm of water if the mean temperature of gases in the chimney is 150° C and the ambient temperature is 30° C. Neglect flow friction in the chimney. Assume usual value of R for air. **[Ans. 302 m]**

5. A chimney is 30 m high. The temperature of outside air is 21° C. The air is supplied at the rate of 18 kg/kg of fuel for the complete combustion of fuel. Find the temperature of the hot gases inside the chimney if the draught produced is 16 mm of water. **[Ans. 286° C]**

6. A boiler is provided with a chimney of 25 m height. The boiler house temperature is 30° C and the temperature of flue gases leaving the chimney is 300°C. If the air supplied to the boiler is 19 kg per kg of fuel,

estimate : 1. Draught in mm of water ; and 2. Velocity of flue gases passing through the chimney with 50% loss of draught in friction. [Ans. 13.24 mm of water ; 14 m/s]

7. A chimney 30 m high is full of hot gases at a temperature of 307° C. The air required for the complete combustion of 1 kg of fuel is 18 kg. If the temperature of atmospheric air is 27° C, find the draught :

1. in terms of water column, and 2. in terms of column of hot gases.

[Ans. 16 mm of water ; 25 m]

8. A chimney has a height of 60 metres. The temperature of air is 27° C. Find the draught in mm of water when the temperature of chimney gases is such as to cause the mass of these gases discharged in a given time to be maximum. [Ans. 35.3 mm of water]

9. Calculate the efficiency of chimney from the following data :

Temperature of flue gases with natural draught = 350° C ; Temperature of waste gases with artificial draught = 150° C ; Temperature of atmospheric air = 38° C ; Amount of air supplied/kg of fuel = 20 kg ; Height of chimney = 40 m ; Specific heat of flue gases = 1.005 kJ/kg K. [Ans. 0.177%]

QUESTIONS

1. What is the significance of draught in boiler practice ?

2. What are the functions of a boiler chimney ? Why is no chimney provided on a locomotive boiler ?

3. Describe briefly various types of artificial draught system used in steam boilers indicating their main advantages.

4. Explain the terms forced draught, induced draught and balanced draught.

5. What are the advantages of artificial draught system over natural draught system ?

6. Deduce a relation for the calculation of natural draught in a boiler plant and state the parameters on which the draught depends.

7. Prove that for maximum mass of hot gases discharged through the chimney,

$$\frac{T_2}{T_1} = \frac{2(m+1)}{m}$$

where T_1 = Absolute temperature of cold air,

T_2 = Absolute temperature of hot air, and

m = Mass of air supplied in kg/kg of fuel.

8. Show that under maximum discharge conditions, the draught produced in terms of hot gas column is equal to the height of chimney.

9. What is the relation between draught pressure (h), height of chimney (H) and absolute temperature of outside air (T_1), when the discharge of hot gases is maximum.

10. Deduce an expression for the power required to drive (a) a forced draught fan, and (b) an induced draught fan.

11. Define efficiency of chimney and write the expression to calculate the same.

OBJECTIVE TYPE QUESTIONS

1. The air pressure at the fuel bed is reduced below that of atmosphere by means of a fan placed at or near the bottom of the chimney to produce a draught. Such a draught is called

(*a*) natural draught (*b*) induced draught

(*c*) forced draught (*d*) balanced draught

2. The draught may be produced by a

(*a*) mechanical fan (*b*) chimney (*c*) steam jet (*d*) all of these

3. The draught in locomotive boilers is produced by a
   (*a*) chimney (*b*) centrifugal fan (*c*) steam jet (*d*) none of these
4. The draught produced by a steam jet issuing from a nozzle placed in the chimney, is called
   (*a*) induced steam jet draught (*b*) forced steam jet draught
   (*c*) chimney draught (*d*) none of these
5. The chimney draught varies with
   (*a*) climatic conditions (*b*) temperature of furnace gases
   (*c*) height of chimney (*d*) all of these
6. The mechanical draught produces .... draught than natural draught.
   (*a*) more (*b*) less
7. The mechanical draught ...... the amount of smoke.
   (*a*) increases (*b*) decreases (*c*) does not effect
8. The efficiency of the plant ...... with the mechanical draught.
   (*a*) increases (*b*) decreases (*c*) remains constant
9. The velocity of flue gases (V) through the chimney under a static draught of H' metres is given by
   (*a*) $4.43\,H'$ (*b*) $4.43\sqrt{H'}$ (*c*) $(4.43\,H')^2$ (*d*) $4.43\,(H')^2$
10. Which of the following statement is wrong ?
    (*a*) The mechanical draught reduces the height of chimney.
    (*b*) The natural draught reduces the fuel consumption.
    (*c*) A balanced draught is a combination of induced and forced draught.
    (*d*) all of the above
    (*e*) none of the above

ANSWERS

1. (*b*)	2. (*d*)	3. (*c*)	4. (*a*)	5. (*d*)
6. (*a*)	7. (*b*)	8. (*a*)	9. (*b*)	10. (*b*)