8.1 Introduction

A steam boiler is a closed vessel, strongly constructed of steel, in which steam is generated from water by the application of heat. The steam generated is used for producing power and for industrial work and heating work. The steam boiler is also known as steam generator. The function of a steam boiler or generator is to convert chemical energy of fuel by combustion into heat and to transfer this heat to water and thus to produce steam.

The following terms are commonly used in connection with various types of boilers and thus, their application and their meaning be clearly understood:

- **Boiler shell** consists of one or more steel plates bent into cylindrical form and riveted or welded together. The ends of the shell are closed by means of end plates or heads, which are made flat, or concave. The shell together with closing heads is called the drum.

- **Setting** forms the walls of the combustion chamber. It confines the heat to the boiler and forms a passage through which the gases pass. The passages so formed for the gases are called flues. The boiler setting also provides support for some types of boilers.

- **Grate** in a coal or wood fired boiler is a platform in the furnace upon which the fuel is burned. The grate consists of cast iron bars which are spaced apart so that air for combustion can pass through them. The area of the grate surface on which the fire reeds, in a coal or wood fired boiler, is usually expressed in square metres.

- **Furnace** is also called a firebox. It is the space above the grate and below the boiler shell in which the fuel is burnt.

- **Volume of the shell** that is occupied by water is termed water space. The steam space is the entire shell volume, less that occupied by water and tubes.

- **Water level** is a level at which water stands in the boiler shell. The remaining space above the water level is called steam space.

- **Heating surface** is the part of the boiler surface that is exposed to the fire and to the hot gases from the fire as they (hot gases) pass from the furnace to the chimney.

- **Mounting** is the term usually referred to such items as safety valves, main stop valve, high-steam and low-water alarm, feed check valve, pressure gauge, water-level gauge, blow-off cock, etc. Special provision is always made on the boiler to mount them. A boiler can not function safely without the above mentioned mountings.

- **Accessories** is the term applied to those items which form an integral part of the boiler but are not mounted on the boiler. Superheater, economiser, feed pump etc., are considered as accessories.
Blowing-off is the act of removing the floating impurities that float at the water level, and is termed surface blow-off. This is done by means of some kind of surface blow-off appliance.

The terms boiler and steam generator carry practically the same meaning or sense. However, boiler is an old name used for a unit which generates saturated steam. The name steam generator is a modern expression and is used for unit which includes in its integral construction, quite separate units, such as an economiser, a superheater, an air preheater, etc. The main boiler with these accessories is now-a-days called steam generator.

8.2. Classification of Boilers

Boilers may be classified according to relative position of the water and the hot furnace gases under the two main classes:

- Fire-tube boilers and shell or tank boiler, in which furnace gases pass through the tubes, these tubes being surrounded by water which is to be evaporated.
- Water-tube boilers, in which furnace gases pass over the external surface of the tubes through which water is circulated.

Boilers may be further classified according to the following:

.. Their form—vertical or horizontal boilers.
.. Their construction—tank or tubular boilers.
.. The service to which they are put—land (stationary), portable, marine or locomotive boilers.

The principal types of boilers belonging to the shell or tank and fire-tube class are:

- Cornish and Lancashire boilers,
- Simple vertical boilers,
- Cochran boilers,
- Locomotive boilers, and
- Scotch marine boilers.

The boilers belonging to water-tube class are:

* Babcock and Wilcox boilers,
* Stirling boilers, and
* Yarrow boilers.

8.3 Shell or Tank type Boilers

The shell or tank type of boilers are particularly suitable for stationary work where working pressure and power required are moderate. These boilers give reliability, ease of operation, and easy steaming even with impure feed water. Although these boilers are economical steam generators, they raise steam slowly on account of the large quantity of water they store, and because of their restricted fire space and slowness of the water circulation. The boilers belonging to this class are: Cornish and Lancashire boilers.

8.3.1 Cornish Boiler: The Cornish boiler was first introduced by Comish engineer from whom it derives its name. It consists of a cylindrical shell with flat ends through which passes a single flue tube (or furnace tube) usually centred on the vertical centre
The part of the heating surface is on the external shell. The products of combustion pass from the fire grate to the end of the furnace, or flue tube. The gases then enter the side flues and return to the front end of the boiler. The gases now enter the bottom flue through which they pass to back end of the boiler and then to the chimney. The brickwork setting should be well maintained to reduce air in-leakage. The longitudinal section and other details of this boiler are similar to that of the Lancashire boiler (fig. 8-3) described hereafter.

Figure 8-1 shows Cornish boiler shell in section, and in fig. 8-2 is given cross-section through the boiler and brickwork setting. These two figures will be readily understood from what has been already said. The four cross-tubes inserted in the flue tube (fig. 8-2) must be specially noted. They are called galloway tubes, and their object is to improve the circulation of water in the boiler when heated by the furnace gases; its specific gravity being thereby lowered, and an ascending or rising current of water is set up in the galloway tubes. This draws the cold water from the bottom of the boiler to be heated in turn.

Some of the galloway tubes are vertical and other diagonal; the object of this is to break up the current of flue gases passing along the furnace tube and to produce a scrubbing (rubbing) action of the gases on the outside walls of tubes. This arrangement increases the heating surfaces of the tubes, as every portion of the hot gases will, in turn, be brought into contact with plates having water to be heated on the other side.
boilers are now built with a shortened furnace tube and fitted with smoke tubes for pressures up to 14 bar and having evaporative capacity of 3,000 kg per hour. Cornish boilers fitted with smoke tubes are known as multi-tubular boilers. It may be said that Cornish boiler is simple and with due care it can be an economical steam generator.

8.3.2 Lancashire Boilers: This boiler is very widely used as a stationary boiler because of its good steaming quality and because it can also burn coal of inferior quality. This boiler is only a modification of the Cornish boiler. It differs from the Cornish boiler in having two internal furnaces or flue tubes instead of one. The Lancashire boiler has cylindrical shell usually from 2 to 3 metres in diameter and from 8 to 9.5 m long. The main features of the Lancashire boiler and its brickwork setting are shown in fig. 8-3. The boiler consists of a cylindrical shell with flat ends, and two furnace tubes pass right through this. There are two side flues and one bottom flue formed by brickwork setting. These flues provide part of the heating surface on the main external shell. The Lancashire boiler differs from the Cornish boiler in one or more ways. The difference is in the manner or order of conducting the hot flue gases through the flues. Here, the gases from the furnace pass to back end of the boiler where they dip (go down) and enter the bottom flue and travel through it to the front end of the boiler. The gases then divide themselves here and enter the side flues and travel through them to the back end of the boiler and then to the chimney.

This type of boiler is often fitted with cross-tubes called galloway tubes, as in the Cornish boiler (fig. 8-2). They are fitted across the furnace tubes. They provide an increased heating surface and improve the circulation of the water.

The boiler is provided with a blow-off cock at the bottom of the front end, and a feed check valve with a feed pipe on the front end plate. The mountings usually provided on the boiler are: pressure gauge, water level gauge (or water level indicator), stop valve, safety valve, high-steam and low-water safety valve, fusible plug, and anti-priming pipe. The accessories provided in large size boiler of this type are: superheater, economiser, and feed pump.
Some Lancashire boilers are fitted with shortened furnace and a number of smoke tubes. These smoke tubes increase the heating surface of the boiler. Lancashire boilers fitted with smoke tubes are known as multi-tubular boilers. They are also sometime called economical boilers.

The features which have made the Lancashire boiler so popular are as under:
- Simple in design – there is little to go wrong.
- Ease of operation – it will put up with rough treatment.
- The ratio of the volume of the boiler to its rated evaporative capacity is high, consequently it is able to meet heavy peak loads without very great variation in steam pressure.

The disadvantages of Lancashire boiler are:
- The shell construction restricts the maximum working pressure to about 17.5 bar.
- It occupies considerable floor space.
- There is so large a water capacity and so little encouragement to water circulation, especially between the furnace tubes and the bottom of the shell, that it is impossible in emergency to raise steam pressure rapidly from the cold water.
- Brickwork setting is expensive in the first cost and troublesome in maintenance.
- The grate area is restricted by the diameter of the internal furnace tubes or flue tubes.

Cornish and Lancashire boilers can be compared as shown in table 8-1.

Table 8-1 Comparison of Cornish and Lancashire Boilers

<table>
<thead>
<tr>
<th>Feature</th>
<th>Cornish</th>
<th>Lancashire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of shell</td>
<td>1.25 - 2 m</td>
<td>2 - 4 m</td>
</tr>
<tr>
<td>Length of shell</td>
<td>5 - 8 m</td>
<td>8 - 10 m</td>
</tr>
<tr>
<td>Steam pressure</td>
<td>10 - 14 bar</td>
<td>15 - 20 bar</td>
</tr>
<tr>
<td>Steam capacity</td>
<td>2,000 - 4,000 kg/hr</td>
<td>8,000 - 10,000 kg/hr</td>
</tr>
<tr>
<td>No. of internal flue tubes</td>
<td>One</td>
<td>Two</td>
</tr>
<tr>
<td>No. of side flues</td>
<td>Two</td>
<td>Two</td>
</tr>
<tr>
<td>No. of bottom flues</td>
<td>One</td>
<td>One</td>
</tr>
<tr>
<td>Path of flue gases</td>
<td>Front to back through one internal flue (furnace) tube, back to front through two side flues, and front to back through one bottom flue.</td>
<td>Front to back through two internal flue tubes, back to front through one bottom flue and front to back through two side flues.</td>
</tr>
<tr>
<td>Initial cost</td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td>Popularity</td>
<td>Less</td>
<td>More</td>
</tr>
</tbody>
</table>

8.4 Fire-tube Boiler

A fire-tube or smoke-tube boiler is one in which the hot products of combustion (hot gases) flow through the inside of tubes, known as smoke tubes, and water surrounding the tubes. The fire-tube boiler belongs to the old class of boilers, but they have still a place of usefulness where the steam pressure does not exceed about 10 bar and where a moderate quantity of steam is required. They have the advantage of low cost and compact design. Their evaporative capacities range from 200 to 3,000 kg of water per hour. Their thermal efficiencies vary from 65 to 68 per cent under normal conditions, and smaller size of these are easily portable. Boilers belonging to this class are: Simple vertical boiler, Vertical boiler with horizontal smoke tubes (Cochran boiler), Locomotive boiler, and Scotch marine boiler.
Fire-tube boilers are also termed as economical boilers. These boilers permit higher steam output evaporation capacity than that permitted by the Lancashire or Cornish boilers for a given floor space. These boilers have much less water capacity and so they require less time to raise steam from cold water.

8.4.1 Simple Vertical Boiler: The simplest form of a vertical boiler is illustrated in fig. 8-4. it consists of a cylindrical shell surrounding a nearly cylindrical fire box. At the bottom of the fire box is the grate. The uptake tube passes from the crown of the fire-box to the crown of the shell, and on the top of this uptake tube is fitted the chimney. The fire-box is fitted with two cross-tubes marked F. The cross-tubes are fitted slightly inclined to ensure efficient circulation of water. Hand holes are provided for cleaning the cross-tubes. A man-hole is also provided for cleaning and inspection of the boiler.

These boilers are used for small powers and where space is limited. The maximum working pressure is about 10 bar.

8.4.2 Cochran Boiler: This is one of the best type of vertical multi-tubular boilers. Figure 8-5 illustrates its design. It is made in numerous designs and sizes of evaporative capacities ranging from 150 to 3,000 kg of water per hour and for working pressures upto 20 bar and is suitable for different types of fuels. This boiler gives thermal efficiency of about 70 per cent with coal firing, and about 75 per cent with oil firing.

The boiler consists of a cylindrical shell with its crown having a hemispherical shape. Such a shape of the crown plate gives enough strength to withstand the bulging effect of the inside steam pressure.

The fire-box is constructed in one piece and has no joints. The fire-box too has a crown of hemispherical shape. The shape is particularly advantageous for the absorption of the radiant heat from the furnace. The convection heat surfaces are provided by a large number of horizontal smoke tubes (about 150). The hot products of combustion from the fire box enter through the small flue-pipe F into the combustion chamber CC and strike on the boiler shell plate which forms the back of the combustion chamber. The back plate of the combustion chamber is lined with fire-bricks and can be conveniently dismantled and removed for cleaning smoke tubes. The back plate directs the gases into the smoke tubes.
The gases after passing through the horizontal smoke tubes enter the smoke box SB and then to the uptake or chimney. Most of the smoke tubes are fixed in the vertical tube plates by being expanded in the holes but some of them are fixed by screwing into the holes. The screwed tubes form stays to the vertical tubes and prevent them from bulging out due to the inside steam pressure. A number of hand holes are provided around the outer shell for cleaning purposes. The flat top of the combustion chamber CC is strengthened by gusset stays as shown in fig. 8-5.

Vertical multi-tubular boilers (Cochran boilers) have the advantage of taking up a comparatively small floor space or area and are used where space is limited. It is self contained and stronger from design point of view. As there are no seams (joints) in the furnace, this source of trouble is eliminated.

8.4.3 Locomotive Boiler: The locomotive boiler is a horizontal fire-tube boiler with an internal fire box as shown in fig. 8-6. This boiler requires a large heating surface and a large grate area upon which coal can be burnt at a rapid rate. This is obtained by providing a large number of smoke tubes and by having strong induced draught (current of air) by means of steam jet.

The boiler consists of a cylindrical shell having a rectangular fire box at one end and a smoke-box at the other end. The fire-box is connected to the smoke-box by a number of horizontal smoke tubes. The hot gases from the furnace pass through these tubes into the smoke-box and are then discharged from the short chimney. The necessary draught is obtained by the steam exhausted from the engine cylinder. The exhaust steam is discharged in the form of a jet, with the help of a blast pipe and nozzle, placed at the base of the smoke-box shown in fig. 8-6. The jet of steam drives the gases upward from the smoke-box into the short chimney so as to create partial vacuum in the smoke box. This induces a strong draught (current of air) through the furnace box and tubes.

The fire-box is made of front plate, back plate, two side plates and a crown, riveted together to form a rectangular box. These inside plates are separated from the outside plates by a space which forms a water space. On the top of the shell and in front of the fire-box, an opening is provided over which is situated a dome shaped chamber known as the steam dome (fig. 8-7). Steam is taken to engine cylinders from the elevated dome so that it may contain as small amount of water particles as possible.

The last heating surface of the boiler is that which surrounds the fire-box. The part of the smoke tubes nearest to the fire-box is the most effective heating surface.

The side plates of the fire-box are stayed to the outer plates of the shell by means of screwed and riveted copper stays. The flat front tube plate is stayed to the flat smoke-box tube plate by means of longitudinal stays. The flat crown plate of the
fire-box requires to be well stayed to prevent it from collapsing under the pressure at its top. The staying is done by means of girder stays called fire-box roof stays (fig. 8-7).

The Locomotive boiler has the following advantages:
- Compactness,
- High steaming capacity,
- Fair economy, and
- Portability or Mobility.

It has also some disadvantages such as:
- Large flat surface needs sufficient bracing (supporting),
- There is corrosion in the water legs on account of sedimentary deposits, and
- The difficulty of reaching the inside for cleaning.

On ships, either fire-tube or water-tube boilers are used. The fire-tube type is used where lightness and high speed are not required as in heavy ships. The water-tube type is used where fast steaming and high pressure steam is required as in naval and fast passenger ships. The common types of marine boilers are: single and double ended Scotch marine boilers, Yarrow marine boilers, and Babcock and Wilcox marine boilers.

8.4.4 Single-ended Scotch Marine Boiler: Figure 8-8 illustrates a single-ended marine boiler commonly known as Scotch type. The cylindrical shell of this boiler contains from one to four cylindrical corrugated steel furnaces. The furnaces FB are internally fired and are surrounded by water. At the back end of the furnace is the combustion chamber CC which is also surrounded by water. Each furnace usually has its own combustion chamber but in some cases two or more furnaces open into common combustion chamber. A large number of fire tubes run from the front tube plate to the back tube plate. The hot gases in the furnaces pass forward, due to the draught, into the combustion chambers, and then through the tubes to smoke-box situated at the front end of the boiler, from where they move through uptake to the chimney.

The walls of the combustion chamber are the best heating surface of the boiler. The furnace tubes, the smoke tubes and the combustion chambers, all being surrounded by water, give a very large heating surface area in proportion to the cubical size of the boiler.
The flat ends of the shell are stayed by longitudinal stays. Some of the smoke tubes are screwed into the tube plates and work as stays for the flat surfaces of tube plates. The flat plate of the combustion chambers are stayed by the screw stays, while their flat tops are strengthened by the girder stays as shown in fig. 8-8. Doors D are provided in the front end for cleaning the smoke tubes.

8.4.5 Double-ended Scotch Marine Boiler: They have furnaces at each end. They look like single-ended boiler placed back to back. The furnace tubes at each end open into a centrally placed combustion chamber from which the hot gases pass through the smoke tubes to the smoke boxes, one at each end of the boiler. A double-ended boiler has the advantage of being lighter, cheaper and occupying less space as compared with single-ended boiler for the same evaporation capacity.

8.5 Water-tube Boilers

Water-tube boilers have water inside the tubes and hot gases surrounding the tubes. These boilers are used extensively because they can be built for high pressures and large evaporative capacities. They are safe, quick steaming, and flexible in construction and operation. They consist of small drums in contrast to the shell or tank type boilers. The drum forms a small part of the total heating surface, the greater part of heating surface being provided by a number of water tubes fitted outside the drum in the furnace.

Units have been constructed in which steam is produced at the critical pressure of 220.9 bar, and evaporative capacity of half million kg of steam per hour have already been reached. In modern power stations, steam temperature of about 1,000 K at the stop valve is now available.

The water-tube boilers may be classified into four groups according to the following:

- Service to which they are put:Stationary or Marine,
- Position of drum:Vertical, Cross, or Longitudinal.
- Type of tubes used: Straight tube or Bent tube, and
- Method of circulation: Natural circulation or Forced circulation.

8.5.1 Babcock and Wilcox Water-tube Boiler: This is best known water-tube boiler and is made of one or more horizontal, steam and water drums. The drum is connected to a series of front end and rear (back) end headers by short riser tubes. A series of inclined water tubes of solid drawn mild steel are connected to these headers. Each nest of tubes is made of several vertical rows. The tubes are expanded into headers which are provided with staggered or zigzag holes. Figure 8-9 illustrates the Babcock and Wilcox water-tube boiler of the land type.

The staggered arrangement of the water tubes will allow the surface of every tube to be exposed to the hot gases. A hand hole is provided in the header in front of each tube, which allows cleaning and inspection of tubes. Each hole is covered by a steel cap which is secured in its position by a steel clamp.

The hot gases from the furnace are forced to move upwards between the water tubes by fire brick baffles provided. They then move downwards between the tubes and then to chimney or stack. The movement of gases in this manner facilitates the heat transfer even to the highest part of the tubes. The feed water enters the front of the drum, passes to the back of the drum, and then descends through the down coming vertical tubes and enters the headers. The water then enters the water tubes, moves upwards through the inclined tubes and finally rises through the front riser tubes to the drum. The circulation of water is produced due to difference of density of water which in turn is due to difference of temperature in the front and rear (back) parts of the furnace. Thus, a thermo-siphon effect is created which results in continuous and rapid circulation of water.

The steam and water drum of the boiler is suspended from horizontal beams by means of metallic slings or straps. The horizontal beams in turn are supported on cast iron columns. This arrangement makes the boiler unit independent of the brickwork which eliminates troubles due to expansion. The brickwork around the boiler is only meant to enclose the furnace and the hot gases. A mud drum is provided at the lowest part of the inclined tubes. The sediment in water collects in the mud drum from where it is blown off by means of blow-off valve at regular intervals.

The boiler is provided with the usual mountings, as well as a superheater. The soot from the gases accumulating on the surface of the water tubes is removed at intervals, either by mechanical scrapers or it is blown off by high pressure steam blowers. This is necessary to keep the heat transfer by conduction effective.
8.6 Comparison between Water-tube Boilers and Fire-tube Boilers

These two types of boilers can best be compared by listing their advantages and disadvantages and compared with one another.

The advantage of water-tube boilers over the tank or shell and fire-tube boilers are as under:

.. Water-tube boilers generate steam of high pressure which has become a present day demand.
.. The water is divided into small portions, and therefore, water-tube boilers raise steam quickly.
.. The heating surface of water-tube boilers is much more effective than an equivalent area of surface in the ordinary tubular boilers.
.. The direction of water circulation in water-tube boilers is well defined. The circulation is rapid all over the boiler, keeping the boiler at a nearly constant temperature.
.. The arrangement of water-tube boilers is such that it forms a flexible construction. Every member of the boiler is free to expand without unduly expanding or compressing any other member. This feature gives prolonged life to the boiler.
.. Water-tube boilers are of sectional construction, and therefore, can be transported and erected more readily than the other types of boilers.
.. An accident to any one tube or fitting does not produce the destruction of the whole boiler. Hence, water-tube boilers are sometimes called safety boilers.

The disadvantages of water-tube boilers as compared with fire-tube boilers are as under:

- They are less suitable for use with impure and dirty water. If the water contains scale forming material, a small deposit of scale will lead to overheating and bursting of the tubes.
- They require more expert attention. The cost of their upkeep is relatively high.
- They are somewhat more difficult to inspect.

8.7 Factors for Boiler Selection

As there are many types of boilers, the factors to be considered for the selection of a boiler for particular purpose are as under:

- The pressure at which the boiler is to operate and quality of steam required i.e., whether wet, dry or superheated.
- Rate of steam generation i.e., quantity of steam per hour required to be produced.
- Availability of floor area.
- Efficiency of boiler in the same range i.e., amount of heat extracted per unit mass of fuel burnt.
- Easy accessibility for cleaning, repairs and inspection.
- The boiler must conform to the “Boiler Act”.
- Comparative initial cost.
- Erection facility i.e., erection of the boiler is easy or complex.

In short, the boiler selected should possess as many good qualities as necessary for the purpose for which it is to be used.
The high pressure and large evaporative capacity boilers (generators) are described in volume II. These boilers are specially used in big thermal stations for power generation. They have special provisions for water and flue gas circulation, water and air heaters, superheaters, coal pulverisation, etc.

8.8 Boiler Mountings

All boilers are fitted with fittings or mountings for the safety of the boilers, and for complete control of the process of steam generation.

The fittings are:

**Safety fittings**
- Safety valves
- Water-level indicator
- Combined high-steam and low-water safety valve
- Fusible plug

**Control fittings**
- Steam pressure gauge
- Feed check valve
- Junction or stop valve
- Blow-off cock or valve

8.8.1 Safety Valves: The main function of a safety valve is to prevent the steam pressure in a boiler exceeding the pre-determined maximum working pressure by automatically opening the valve and discharging the steam as soon as this maximum pressure is reached. Moreover, besides operating at the set pressure, safety valves must be capable of discharging the full evaporative capacity of the boiler, otherwise the possibility of continued pressure build up will remain. The great damage to the boiler which may result from safety valve failure needs no detailed description.

Safety valves may be classified into two distinct groups according to the method of loading the valve, namely,

- Weight loaded safety valves, and
- Spring loaded safety valves.

The valves in the first group (weight loaded) may be again subdivided into:

- Dead-weight safety valve, and
- Lever and weight safety valve (lever safety valve).

Dead-weight safety valve is perhaps the most simple type of safety valve in which the valve is loaded by the direct application of weights above the valve. Such a valve is known as dead-weight safety valve.

Figure 8-10 illustrates dead-weight safety valve made by M/s. Hopkinson & Co. In this safety valve the valve rests (sits) on the valve seat which is fixed to the top of
the vertical steel pipe by a ring and screws as shown. The ring has a feather cast on it, which acts as a guide for the valve. Suspended from the top of the valve is a large cast iron casing which acts as a weight carrier. A cast iron cover is fitted over the weights and weight carrier. The load on the valve is made up of weights, the weight of the weight carrier and cover, and the weight of the valve itself, and this load balances the pressure of steam on the valve. When this pressure becomes too high, the valve and the weight carrier will lift and surplus steam will escape to the enclosed discharge casing from which it is carried to the waste pipe.

The valve and weights which it carries are prevented from blowing away by a ring cast on the inside of weight carrier and stop screw fitted on discharge casing as shown in fig. 8-10. The condensed steam in the discharge casing is drained by drain pipe connected at the bottom.

The vertical steel pipe has a flange at the bottom for bolting to a mounting block which is connected to the boiler shell by rivets.

To find the dead-weight required (including casting and weights) for a valve of given area: multiply the area of the valve in m² by the steam pressure in N/m² or Pa at which the valve is required to lift or open. Thus, a valve of 8 cm diameter to blow off at 10 bar, requires the following weights:

\[
\text{Dead-weight} = \text{valve area} \times \text{pressure of steam}
\]

\[
= \pi \left( \frac{8}{100} \right)^2 \times (10 \times 10^5) = 5,026.55 \text{ N or } 512.4 \text{ kg}
\]

The dead-weight safety valve is probably the most reliable type of safety valve and actually gives quite a satisfactory performance during operation, but is suffers from certain disadvantages which entirely prevents its use on many types of boilers. One great drawback is its unsuitability for use on boilers where extensive vibrations and movements are experienced, as for example, in locomotive and marine boilers. A second disadvantage arose as higher pressure was introduced in the steam industry. This increase in working pressures brought with it the need for heavier valve loadings, which in turn, necessitated heavier and bulkier safety valves. Moreover, together with the rise in working pressures, there has been a marked increase in the evaporative capacity of boilers particularly since the introduction of the water-tube boilers and this has brought the need for safety valves possessing large discharge area. Now, the necessary loading for a safety valve varies proportionately to the square of the valve diameter and so, any increase in valve diameter made in order to obtain a large discharge area, will require a very great increase in valve loading.

From these considerations it will be seen that "the dead-weight safety valve has very limited range of application, being mainly for low pressure, low capacity, stationary boilers of the Cornish and Lancashire type.

Lever safety valve is very close to the dead-weight safety valve which is the lever and weight pattern safety valve. As will be seen from the diagrammatic sketch (fig. 8-11), the valve is loaded by means of a weighted lever which is pivoted about a fulcrum situated close to the valve. The actual value of the valve load \( L \) being dependent upon the lever ratio \( \frac{b}{a} \) viz.,

\[
L = W \times \frac{b}{a}
\]

.. (8.1)
This compares with the expression $L = W$ for a dead-weight safety valve, and since the lever ratio $b/a$ is usually about 8, it follows that the loading weight $W$ is something like 1/8th the weight necessary for a corresponding dead-weight valve. Consequently, lever and weight safety valves do not suffer to such an extent from the pressure limitations experienced by dead-weight safety valves and are occasionally used for pressures up to 40 bar. This type of valve is suitable for stationary boilers only as it is affected by vibration.

To find the weight $W$ (load on outer end of lever in N) for a given steam pressure, lever ratio $b/a$, and area of the valve in $m^2$.

Let $d =$ diameter of valve in $m$, and

$p =$ pressure of steam in $N/m^2$ or in Pa at which valve is about to open or lift.

If the effect of weight of valve and lever be omitted, we have, when valve is about to lift,

\[ \text{Moment of downward pressure} = \text{Moment of upward pressure} \]

\[ i.e., \ W \times b = \left( \frac{\pi d^2}{4} \times p \right) \times a \] .. (8.2)

An important disadvantage possessed by lever safety valve might be mentioned here. Due to the necessity of at least two pivoting points (at the fulcrum and at the valve spindle), the valves are liable to suffer, to much greater extent than other types, from the effect of friction which in bad cases may prevent the valve from opening when the pressure exceeds the maximum working pressure.

In order to prevent unauthorised changes, the weight $W$ is fitted on the lever by a pin and lock (now shown), or similar locking means.

For locomotive and marine boilers, both the dead-weight and lever safety valves are not suitable. Spring loaded safety valve is therefore mostly used on locomotives and marine boilers, as this type of valve is not affected by vibration.

Figure 8-12 illustrates a Ramsbottom spring loaded safety valve. It consists of two separate valves and seatings. The valves are held down on their seats by the helical spring and lever. The lever has two pivots, of which one is forged on the
lever and the other is joined to it by a pin. The spring is hooked to an arm of the lever midway between the valves. The lower end of the spring is hooked to the shackle which is secured to the valve chest by studs and nuts.

To prevent the valves from being blown away in the event of spring breaking, there are two links, one behind the other, on either side of the lever connected by pins at their ends. The upper pin passes through a slot in the lever arm and the lower pin passes through the shackle.

By pressing down or raising the lever the engine driver or boiler attendant can relieve the pressure from either valve separately and find out that the valve is not sticking on the seating and is free to act properly.

One disadvantage of this lever is that the load on the valve increases as the valves lift, so that the pressure required to just lift the valve is less than that required to open it fully.

8.8.2 Combined High-Pressure Steam and Low-Water Safety Valves: Description of safety valves would be incomplete if no reference is made to the most important fitting of Lancashire boiler and other internally fired boilers. This is the high-steam and low-water safety valve, sometimes known as compound safety valve. It is suitable for stationary boilers.

This valve was introduced by M/s. Hopkinson Ltd., U.K. in 1852. It is still regarded as a standard mounting on boilers. Although many improvements in design have been made since its introduction, the principle working remains basically the same (combining in one single fitting two separate and distinct features).

The first safety feature consists of a high-pressure steam valve held down on its seat partly by the dead weight and partly by the lever and weight. The second safety feature consists of a float device which gives warning of the near approach of a dangerously low water level.

The two essential features will be seen from the sectional view shown in fig. 8-13. The float A usually made of firebrick, is suspended from the end C of the cast iron lever BC, and when fully immersed in the water is balanced by the weights D suspended from the other end of the lever. An alternative type of float, whose use is to be recommended where the feed water is likely to have harmful effect on a firebrick float, is the all metal float. Much longer life may be expected from a float of this type. Both types of floats are incapable of floatation on their own account and in order to cause

Fig. 8-13 Combined high pressure steam and low-water safety valve.
them to follow the variation in water level, balance weights \( D \) must be placed on the opposite end of the lever \( BC \). The weight of the float \( A \) acting through the leverage provided, should be sufficient to lift the balance weight \( D \) and the hemispherical valve \( G \). When the water level falls and the float \( A \) is sufficiently uncovered, the balanced weight \( D \) will not be sufficient to balance the float \( A \) and the float will descend (float being heavier than the balance weight), causing the lever \( BC \) to move on its pivot. On the lever there are two projections one on the front and the other on the back of a boss on the lever through which the rod \( F \) passes. The descent of the float causes these projection on the lever to come in contact with the collar \( E \) fixed to the rod \( F \), and the hemispherical valve \( G \) is lifted and steam escapes, giving the boiler attendant due warning of fall in water level.

When the projections on the lever \( BC \) are clear of the collar \( E \) in the position shown in fig. 8-13 i.e., under normal working conditions, the high pressure steam valve \( S \) acts as an ordinary valve loaded partly by the dead weights \( H \) and partly by the loaded lever \( L \) (combined dead weight and lever safety valve). The low-water hemispherical valve \( G \) is held down against the steam pressure by dead weight \( H \) secured to a rod \( F \) connected to valve \( G \). When the steam pressure rises too high, both valves will rises as one, permitting a free escape of steam outside of the boiler house so as to discharge surplus steam into the atmosphere.

### 8.8.3 Water level Indicator

The most satisfactory water-level indicator is the glass tube water gauge. It makes the water-level in the boiler visible from the boiler room floor. The gauge is a glass tube, the lower end of which communicates with the water space of the boiler and the upper end with the steam space. There are usually two gauges provided on each boiler, one placed at the left hand side of the boiler front, and the other at the right hand side. Where the boiler drum is situated at considerable height from the floor, the water gauge is often inclined in order to make the water level visible from any position.

A common form of glass tube-gauge is shown in fig. 8-14. This is Hopkinson's absolute water gauge. \( AA \) is the front end plate of the boiler and \( WW \) is the water level. \( G \) is a very hard glass tube indicating water level and is connected to the boiler plate through stuffing boxes in hollow gunmetal casting having flanges \( F \) for bolting to the plate. There are two cocks \( C \) for controlling the passages of water and steam from the boiler. When these cocks are open, the water stands in the glass tube at the same level as in the boiler. A third cock \( B \), called a blow-through cock, is ordinarily closed and is for keeping the passages clear by frequent blowing through.

In the gauge shown in fig. 8-14, provision is made for automatically shutting off the steam and water supply to the glass tube when the glass tube gets broken. Upper and lower stuffing boxes are connected by hollow column \( H \). Balls \( P \) and \( Q \) are in positions shown in normal working condition. In case the glass tube gets broken, the rush of water from bottom passage and steam from top passage carries the balls \( Q \) and \( P \) in the positions shown dotted and shuts off the water and steam. Then the attendant can safely close the cock \( C \) and replace the broken glass tube.
In some cases the construction is simplified by removing the ball \( P \) and the hollow column \( H \). In this gauge only water will be shut off when the glass tube is broken, but there is much less danger from the rush of steam from the top than from a rush of water from the bottom because the water as soon as it escapes into atmosphere flashes into steam, the volume of which is much greater than the volume of steam issuing from the top of gauge.

In some large modern boilers, hydraulic and electric-operated water-level indicators are used. They are located at the operating floor level from where the water level can be more easily observed. For high pressure boilers, the water gauge is made with flat prismatic glass. The inner surface of the glass is grooved to form prisms. When the grooves are filled with water the appearance is dark, but when they are above water level they present a silvery appearance. The contrast is marked as to make reading easier from a distance.

### 8.8.4 Fusible Plug

The crown of the furnace of some boilers is fitted with a plug held in position by fusible metal or alloy. This plug under normal conditions is covered with water in the boiler which keeps the temperature of the fusible metal below its melting point. But when the water level in the boiler falls low enough to uncover the top of the plug, the fusible metal quickly melts, the plug drops out, and the opening so made allows the steam to rush into the furnace. The steam, thus, puts out the fire or gives warning that the crown of furnace is in danger of being overheated.

Figure 8-15 illustrates a common form of fusible plug. A is a hollow gunmetal plug screwed into the crown plate. B is a second hollow gunmetal plug screwed into the plug A, and C is a third hollow gunmetal plug separated from plug B by fusible metal. The inner surface of B and the outer surface of C are grooved as shown so that when the fusible metal is poured in, the plugs B and C are locked together. Hexagonal flange is provided in the base of plug A so that it can be removed by using a spanner. There is another hexagonal flange on B for fixing or removing plug B.

### 8.8.5 Steam Pressure Gauge

Each boiler must have a steam pressure gauge to show (or read) the pressure of steam in the boiler. The gauge is usually mounted on the front top of the shell or the drum. Its dial is graduated to read the pressure in \( \text{kN/m}^2 \) or \( \text{kPa} \) above atmospheric pressure. The most common type of pressure gauge used is the Bourdon pressure gauge.

Figure 8-16 is a single-tube Bourdon gauge with dial removed to show the interior mechanism. The essential feature of a Bourdon pressure gauge is the elliptical spring tube which is made of a special quality of bronze and is solid drawn. The one end of the tube is closed by a plug and the other end is connected to steam space of
the boiler. The closed end of tube is attached by links and pins to a toothed quadrant, which in turn meshes with a small pinion fitted on the central spindle. When steam pressure is supplied to interior of the elliptical tube, it tends to assume a circular cross-section, but before the tube can do so it must straighten out. This tendency to straighten moves the free end (closed end), turning the spindle by lever and gearing (pinion and quadrant), and causing the pointer to move and register the pressure on a graduated dial (not shown in the figure).

The movement of the free end of the tube is proportional to the difference between external and internal pressures on the tube. Since the outside pressure on the tube is atmospheric, the movement of the free end is a measure of the boiler steam pressure above atmospheric pressure, i.e., gauge pressure. The steam pressure gauge should be graduated to read at least 1½ times the set pressure of safety valve.

The gauge is connected to the boiler through U-tube siphon which is connected to the steam space of the boiler.

8.8.6 Feed Check Valve: The feed-water pipe carrying water from the feed pump usually enters the boiler in the water space of the boiler. A valve is placed in the feed pipe to control or regulate the flow of water into the boiler. The valve is attached directly to the boiler front. It is a non-return valve which permits flow of water in one direction only and automatically prevents the back flow of water from the boiler when the feed water pump is not working. The amount of water entering the boiler can be adjusted by controlling the lift of the valve. This valve is known as feed check valve or boiler feed valve.

A common design of feed check valve is shown in fig. 8-17. The lift of the check valve C is controlled by screwing down valve V. It is very important that check valve C is kept in perfect working condition. It can be cleaned and reground by closing the valve V even when the boiler is working. The flange is bolted to the front end of the boiler shell, at a point from which an internally perforated pipe leads (takes) the feed water to the boiler and distributes it near the working level of water in boiler.

8.8.7 Junction Valve or Stop Valve: A valve placed directly on a boiler and connected to the steam pipe which carries steam to the engine is called a junction valve. The valve is necessary for purpose of shutting off steam when not required. A valve placed in the steam pipe, leading (taking) steam to the engine and placed near the engine is called a stop valve, but junction valves are also very frequently called stop valves.

Stop or junction valves are operated by hand, and their function is to regulate the amount of steam and to shut it off altogether if required. There is no essential difference between the construction of a junction valve and that of a stop valve.

The common type of stop valve is shown in fig. 8-18. When used as a junction valve, the lower flange is bolted to the boiler at the highest point of the steam space. The valve seat S is screwed into the valve body by the aid of lugs L cast on its interior. The valve disc B has a renewable disc seat D.
The valve disc $B$ is connected with the spindle by the nut, $N$, the lower edge of which comes in contact with a collar on the end of the spindle. The spindle as it is raised or lowered, carries the disc with it but is free to rotate within the disc.

The spindle passes through a gland and stuffing box fixed in the cover of the valve body. The upper portion of the spindle is threaded and passes through a nut in a cross-head or yoke carried by two pillars, which are screwed into the cover of the valve body as shown. By turning the hand wheel fitted on the spindle, the valve spindle is raised or lowered.

8.8.8 Blow-off Cock: The blow-off pipe is attached at the lowest point of the boiler for the purpose of emptying the boiler when necessary, and for discharging the loose mud and sediment deposited from the feed water at the lowest point to which water circulates. A valve or a cock, known as blow-off cock, is placed on this pipe which can be opened to blow-off the dirt and sediment whenever necessary. Arrangements for automatic blow-off instead of manual are also available.

When several boilers are arranged to discharge into the same waste pipe, each blow-off cock should have with it an isolating valve which will prevent the discharge of one boiler from entering into another.

8.8.9 Manholes: These are openings on the boiler shell at suitable locations with covers. These openings allow a man to enter inside the boiler for inspection, cleaning and repairing.

Manholes are of oval shape, 40 cm x 30 cm is size. Due to oval shape, it is possible to fit the manhole cover or manhole door from inside of the manhole. This door is secured in position by bolts and bridge bars.

8.9 Boiler Accessories

Most of the boilers are fitted with accessories. The major functions of boiler accessories are:

.. to increase the efficiency of the boiler plant, and
.. to help in the smooth working of the boiler plant.

The principal steam boiler accessories attached to modern boilers are:

- Feed water pump,
- Injector,
- Economiser,
- Superheater, and
- Air pre-heater.

8.9.1 Feed Water Pump and Injector: The feed pump is used to deliver feed water to the boiler, and it is required to supply a quantity of water at least equal to that converted into steam and used by the engine. Feed Pumps may be either reciprocating or rotary pumps.
The feed pump is sometimes worked from the engine direct or from the shaft by an eccentric attached to the plunger. Pumps are also worked independently by using steam directly from the boiler. Such pumps are called direct-acting pumps.

A well-known form of a Duplex direct-acting reciprocating pump is shown in Fig. 8-19. In this steam pump there are two simple steam engine cylinders placed side by side. Steam distribution in each cylinder is obtained by means of slide valves. The slide valve is each cylinder steam chest is operated by the cross head on the piston rod of the opposite cylinder, through an arrangement of rods and rocker arms. In Fig. 8-19 one water pump and its steam cylinder is shown in section.

Fig. 8-19. Duplex direct-acting feed water pump.

The feed water pump is generally double-acting, i.e., it delivers water on each forward and backward stroke. There are suction and discharge valves for each side of the pump plunger. The two pumps work alternatively, thus keeping up a practically continuous flow of water.

Rotary feed pumps are generally of the high speed centrifugal type, driven directly by a small steam turbine or by an electric motor. Rotary pumps may be single-stage or multi-stage according to whether one impeller or more than one impellers are used. In the single-stage pump, the full pressure of water is obtained in one chamber in which the impeller revolves. In a multi-stage pump a number of impellers are keyed on the same shaft, each impeller working in its own chamber or stage. These pumps are also known as turbine pumps.

The injector is a simple appliance used to deliver feed water into the boiler using live steam from the same boiler. In this appliance there are no moving parts or plunger, the water being forced into the boiler by the action of steam flowing through a tapering nozzle. Its use is generally limited to small boilers and locomotive boilers. It is sometime fitted as a standby or reserve feed water pump owing to its cheapness and simplicity.

Where an injector is compared with a feed pump, the injector is more economical because all the heat in the steam used in the injector is returned to the boiler. The injector therefore works as feed water heater as well as a feed water pump. The boilers in which large quantity of feed water is required to be pumped, the usual practice is to use feed water pumps. Feed water pumps are more reliable and require lesser attention than injectors. The injectors, though economical, are not very reliable.

The working principle of the injector may best be explained by reference to the sketch shown in Fig. 8-20. The injector consists of a steam chamber with an outlet in the shape of a convergent nozzle. The position of this nozzle can be adjusted by means of the hand-wheel. By turning the hand-wheel the annular opening between the nozzle and mixing tube can be altered, thereby adjusting the amount of water supplied.
through the suction pipe. The steam admitted through the steam pipe and discharged from the nozzle, mixes with the water contained in mixing tube, where condensation of steam takes places. The jet then passes through the mixing chamber and enters the divergent tube, which reduces the velocity and increases the pressure of water, the increase of pressure being sufficient to open the non-return valve fitted in the delivery pipe and enters the boiler.

When the injector is started, the pressure in the mixing chamber is above the atmospheric pressure, and water and uncondensed steam pass out through the non-return valve and overflow pipe to atmosphere. As soon as the steam nozzle is brought into its correct position, jet action is established with the result that a pressure below atmospheric pressure (vacuum) is created in the mixing chamber, which causes the non-return valve to close and stop the overflow to atmosphere.

Regular operation of the injector is then established, but when the back pressure exerted upon the non-return valve in the delivery pipe becomes excessive so that it cannot be overcome by the injector, the water again fills the mixing chamber so that the vacuum is lost. Non-return valve in the overflow pipe, therefore, opens again and the water-steam mixture is discharged through the overflow pipe. As soon as normal back pressure is established again, the injector resumes its normal operation.

As a boiler feeding device, the injector has a limitation that hot water cannot be used for pumping because the operating steam must be condensed by mixing with cold water. Thus injector cannot be used where feed water is to be pre-heated or high proportion of condensate (condensed steam) is used again.

8.9.2 Feed Water Heater (Economiser) : A feed water heater (economiser) is an appliance in which the feed water is heated before it is supplied to the boiler. Feed water heaters may be of two classes:

.. Those which take the required heat from steam, which is generally the exhaust steam from a non-condensing engine, or the steam used may be fresh steam direct from the boiler, and

.. Those which take the heat from the waste furnace gases (flue gases).

Feed water heaters of the second class are called economisers.

One of the major heat losses in a boiler plant is the heat carried away by the flue gases. An economiser is a heat recovery appliance placed in the path of the flue gases (between the boiler and chimney) to pre-heat the feed water. An economiser consists of a number of horizontal or vertical tubes through which passes the feed water from the pump on its way to the boiler, whilst the hot flue gases pass over the external surface of the water tubes. The Green's vertical tube economiser (fig. 8-21), is fitted with scrapers which move up and down the water tubes by a mechanical drive, thereby keeping the exterior surface of the tubes free from soot deposits. The horizontal type (figure not given) needs some form of soot blower because of the fact that the
feed water \( \rightarrow \) hot gases \( \in \) vertical water tubes

Every economiser is fitted with a pressure gauge, a safety valve, a drain valve, an air release valve and two thermometers (for water temperature at inlet and outlet).

By-pass arrangements for the furnace gases and feed water must always be provided so that the economiser may be put out of action when necessary. Figure 8-22 shows an arrangement for diverting the hot gases to pass over the economiser tubes, i.e., when the economiser is in action.

The economiser is put out of action by closing the dampers \( A \) and \( B \), and opening damper \( C \). In this position of the dampers, the hot furnace gases pass direct to the chimney without passing over the economiser water tubes.

The advantages derived by the boiler from the use of an economiser are:

- Feeding the boiler with cold water results in cooling of the boiler metal. By pre-heating the feed water in the economiser, the temperature difference between the different parts of the boiler is reduced, which results in the reduction of stresses due to unequal expansion. Therefore by installing an economiser, the life of the boiler is increased.

- The economiser increases the heating surface of the boiler and therefore the evaporative capacity of the boiler is increased. Evaporation also becomes rapid and more rapid evaporation results in quick circulation of the water, which makes the heating surface more effective.

- The heat taken up by the economiser from the flue gases represents a saving of energy which may have been lost to the atmosphere. This saving of energy results in saving in fuel and an increase of the overall efficiency of the boiler plant.
Problem-1: A boiler generates dry saturated steam at a pressure of 11 bar. The feed water is heated by economiser before it is supplied to the boiler. If the feed water enters the economiser at 30°C and leaves at 90°C, find the percentage saving in heat by the use of economiser. Take specific heat of water as 4.187 kJ/kg K.

Enthalpy of 1 kg of dry saturated steam at 11 bar, \( H_s = 2,781.7 \text{ kJ/kg} \) (from steam tables)

Enthalpy of 1 kg of feed water at 30°C, \( h = 4.187 \times 30 = 125.61 \text{ kJ/kg} \)

\[ \therefore \text{Net heat required to produce 1 kg of dry saturated steam at 11 bar from feed water at 30°C} = H_s - h = 2,781.7 - 125.61 = 2,656.09 \text{ kJ/kg}. \]

Net heat required to produce 1 kg of dry saturated steam at 11 bar from feed water at 90°C (instead of at 30°C) = 2,781.7 - 90 \times 4.187 = 2,781.7 - 376.83 = 2,404.87 \text{ kJ/kg}.

\[ \therefore \text{Saving in heat by using feed water at 90°C instead of at 30°C (i.e., by the use of economiser)} = 2,656.09 - 2,404.87 = 251.22 \text{ kJ/kg}. \]

\[ \therefore \text{Percentage saving in heat} = \frac{251.22}{2,656.09} \times 100 = 9.46\% \]

8.9.3 Air Pre-heater: An air pre-heater is another appliance which enables to recover heat from the flue gases. It is installed between the economiser and the chimney. The air required for the purpose of combustion is drawn through the pre-heater where its temperature is raised. It is then passed through ducts (pipes) to the furnace. The air is passed through the tubes of the pre-heater internally whilst the hot flue gases are passed over the outside of the tubes.

The use of an air pre-heater in a boiler results in certain advantages listed as under:

- Pre-heated air gives higher furanace temperature, which results in more heat transfer to the water and steam per kg of fuel.
- Better combustion conditions are achieved, as the hot air tends to accelerate the chemical reaction between the oxygen and the inflammable constituent of the fuel (increases the percentage of CO2 in flue gases).
- Pre-heated air also tends to result in a short and more stable flame which reduces smoke production.
- It often enables a low grade coal to be burnt with less excess air.
- Use of pre-heater increases the efficiency of the boiler plant.

8.9.4 Superheaters: Superheating is effected by passing the boiler steam through a nest of steel tubes bent to U-form and expanded into mild steel boxes called headers. The whole arrangement is known as superheater. The use of a superheater enables the wet steam from the boiler to be completely dried and raised in temperature at constant pressure.

Superheaters are generally located in the path of furnace gases so that heat is recovered by the superheater from the hot gases. When the steam is superheated in this manner by the flow of hot gases, the superheater is called a convection superheater. Superheaters are sometimes placed in one or more walls of the boiler furnace where superheater tubes receive heat by direct radiation from the fire. Such a superheater is called a radiant superheater. This type of superheater is generally used where high degree of superheat is desired.
In large boilers, superheater may be an independent unit having its own furnace independently fired. Superheaters with separate furnaces are known as separately fired or portable superheaters.

Superheaters for water-tube boilers can be further classified with reference to their position in relation to the water tubes. If the superheater is placed in the space over the water tubes, it is termed over-deck (fig. 8-9). If it is between the water tubes located near the furnace, it is termed inter-deck and when placed between the banks of water tubes, it is termed inter-bank.

A form of superheater used with stationary boilers, specially those of Lancashire type is shown in fig. 8-23. This superheater consists of two mild steel boxes or heaters from which hang groups of solid drawn steel tubes bent to U-form as shown in fig. 8-23. The superheater is placed at the back of boiler where the temperature of flue gases is generally not less than 560°C.

All superheaters should be designed and constructed so as to give rapid transfer of heat from flue gases to the steam, be easily cleaned, and be free from the danger of being burnt out. When the temperature of the furnace gases does not exceed 725 K there is no danger of burning of tubes, but for higher temperatures, arrangement must be made to protect the tubes when no steam is passing through them, as for instance, when the prime mover supplied with steam is stopped for a short time.

The methods adopted for the purpose of protecting superheater unit from overheating are:

— Flooding (filling) the superheater with water from the boiler, this water being drained out before the delivery of steam to the prime mover is again started.

— Diverting the hot gases, or stopping their flow over the superheater.

The second method, i.e., diverting the hot gases, is adopted in the superheater shown in fig. 8-23. The superheater is put out of action by turning the damper upward in the vertical position. In this position of the damper, the gases pass directly into the bottom flue without passing over the superheater tubes.

Figure 8-23 also shows how the steam pipes may be arranged so as to pass the steam through the superheater or direct to the main steam pipe. When the steam is taken from the boiler direct to the main steam pipe, the valves A and B are closed and valve C is opened. When the steam is passed through the superheater, i.e., when the superheater is in action the valves A and B are opened and valve C is closed.

Problem-2: A boiler generates steam at a pressure of 8 bar and 0.8 dry. The steam after leaving the boiler stop valve enters the superheater where its temperature is raised...
to 200°C at constant pressure. Calculate the heat received by steam in the superheater per kg of steam. Take specific heat of superheated steam at constant pressure as 2.3 kJ/kg K.

From steam tables, at 8 bar,
\[ h = 721.11 \text{ kJ/kg}, \quad L = 2,048 \text{ kJ/kg} \text{ and } t_s = 170.43\text{°C}. \]

Enthalpy of wet steam entering the superheater
\[ = h + xL = 721.11 + 0.8 \times 2,048 = 2,359.51 \text{ kJ/kg}. \]

Enthalpy of superheated steam leaving the superheater
\[ = h + L + k_p(t_{sup} - t_s) = 721.11 + 2,048 + 2.3(200 - 170.43) = 2,837.12 \text{ kJ/kg}. \]
\[ \therefore \text{Heat received by steam in the superheater} = 2,837.12 - 2,359.51 = 477.61 \text{ kJ/kg}. \]

8.10 Fittings for Separating Water Particles from Steam

Boilers are fitted with an anti-priming pipe, water separator and steam trap to separate the water particles going along with the steam before being supplied to the engine.

When a boiler is generating steam rapidly, particles of water are thrown up into the steam from where they are carried away by the steam to the engine. This is known as ‘priming’. An anti-priming pipe is a device which prevents the carrying away of water particles with the steam. It is fitted to the boiler shell just above the steam space and underneath the steam stop valve. It is an iron box with closed ends. Its upper half is perforated with a number of slots (rectangular holes) through which the steam enters on the way to the main pipe. The steam current is broken up while it passes through the slots, causing the heavy water particles to separate out and fall back into the boiler through a small hole provided at bottom of the anti-priming pipe.

The object of a steam separator is to remove as far as possible fine particles of water carried along with steam on its way from the boiler to the engine. It is placed on the main steam pipe line leading from the boiler to the engine and as close as possible to the engine. A common type of separator contains baffle plates. The steam striking the baffle plates is suddenly deflected so that the direction of its flow is changed and the velocity of steam is reduced. The particles of water, due to their greater mass and inertia, strike the baffle plates and fall to the bottom of the separator.

Steam traps are devices used to collect and automatically discharge the water resulting from partial condensation of steam without allowing any steam to escape. The trap is so located that water from the condensation of the steam in the steam pipe flows by gravity to it. The rising level of water in the trap eventually causes a valve to open through a simple mechanism and the water is discharged through the opening. As soon as the water is discharged, the valve closes automatically so that the steam which follows the water can not escape with it. Steam traps are divided into two general classes:

.. Traps which depend for their action on the expansion of metals under heat, called expansion steam traps, and

.. Traps in which the discharge of condensed steam is controlled by floats or buckets called bucket steam traps or float steam traps.
8.11 Pressure Reducing Valves

When steam is required at a lower pressure than that supplied by a boiler, the steam is passed through a pressure reducing valve whose function is to maintain a constant reduced pressure on its delivery side. Low pressure steam is required in industry for process or heating purposes.

It is more difficult to keep pressure uniform with water-tube boilers, which hold a comparatively small quantity of water. Therefore, it is a practice to work such boilers at a pressure higher than that for which the engine is designed. The steam is then passed through a reducing valve on its way to the engine. The reducing valve maintains a constant reduced pressure on the engine side of the valve, while the higher pressure on the boiler side may be variable.

The principle upon which all reducing valves work is the principle of the throttle valve.

8.12 Scale Cleaners and Soot Blowers

A considerable amount of scale forming material may be removed from the feed water by using feed water heaters or by chemical treatment of feed water. However some scale will be deposited in boilers which requires some mechanical means for its removal. The scale can be removed from the accessible parts or parts of the boiler drum or shells by means of hammer and blunt chisel. However, scale formed in the water tubes of the boiler cannot be removed so easily and needs some mechanical tubes cleaners. The water tubes are freed from scale by a motor driven by pneumatic, electrical or water power. The loosened scale is carried away from the water tubes by the air or water used to drive the cutter.

Tubes and other surfaces exposed to the flue gases will have a layer of soot deposited on them. Such deposits reduce the rate of the heat transfer through the tubes. One method of cleaning the soot deposited on the surface of the tubes is by the use of soot blowers. The cleaning agent is steam issuing from nozzles.

8.13 Boiler Draught

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 difference in the static pressure available to produce the flow of air through the bed of fuel on the furnace grate to the chimney. This difference in static pressure is known as draught. The object of producing the draught in a boiler is (i) to provide an adequate supply of air for combustion of the fuel, (ii) to draw (move) the resulting hot gases through the system, and finally (iii) to discharge these gases to atmosphere through the chimney.

Draught is ordinarily measured by draught gauge known as manometer, and its intensity is expressed in mm of water. It is usually measured taking difference in level between the surface of two columns of water in the two legs of U-tube, one leg being connected with the chimney and the other open to atmosphere. Thus, the difference a (fig. 8-24) between the water levels at A and B in the two legs of U-tube is the draught in mm of water head. In ordinary chimneys, the draught is about
12 mm of water in small chimneys and about 20 mm in high (tall) chimneys.

The main factors which determine the amount of draught to be provided for are as under:

- Rate of burning the fuel,
- Type and condition (size, moisture content, etc.) of the fuel,
- Method of stoking or burning the fuel,
- Depth of fuel bed,
- Resistance in the flue gas circuit created by baffles, flues, smoke and water tubes, superheater, economiser, air pre-heater and dampers, etc.,
- Design of the combustion chamber or furnace.

8.14 Methods of Producing Draught

Draught may be classified as under:

- Natural draught produced by a chimney, and
- Artificial draught produced by a fan or steam jet.

8.14.1 Natural Draught: Natural draught is produced by the boiler chimney and therefore it is also known as chimney draught. The draught is produced due to the difference in weight between the column of hot gases inside the chimney and the weight of equal column of cold air outside the chimney. Roughly speaking, cold air outside weighs twice as much (volume by volume) as the hot gases inside the chimney, i.e., cold air outside is heavier than the hot gases inside the chimney. The pressure in the chimney is, therefore, less than the pressure of the outside air. As a result of this, the outside cold air will flow through the furnace into the chimney and the hot gases will pass up the chimney. The outside air rushing to the chimney will be utilised for combustion of the fuel in the furnace. The draught is measured by a draught gauge shown in fig. 8-24.

The amount of the draught produced in the boiler depends on the following factors:

- Climatic conditions – draught decreases with the increase of outside air temperature.
- Temperature of furnace gases – draught increases with the increase of furnace gas temperature.
- Height of chimney – draught increases with the increase of height of chimney.

8.14.2 Artificial Draught: When the rate of fuel burning required is to be very high, natural draught is not sufficient and it becomes necessary to provide an artificial draught by some mechanical means. An artificial draught may be produced by fan, blower, or steam jet. If the draught is produced by a fan, it is known as fan draught or mechanical draught and if produced by steam jet, it is known as steam jet draught.

Artificial draught reduces the necessary height of chimney and provides a draught that is easily controlled. The artificial draught is of two kinds, namely forced draught and induced draught. In the forced fan draught, the air passes through the fan before entering the furnace. The air is forced by the fan into the furnace at a pressure higher than that of the atmosphere. In the forced fan draught, the fan is placed at or near the base of the chimney. The fan draws the air through the furnace by reducing the pressure in the furnace below that of the atmosphere. This draught is similar in action to the natural draught. It is usually employed when economiser and air pre-heater are provided with the boiler.
In the forced steam jet draught, the draught is produced by placing the steam jet in the ash pit which is situated under the fire grate of the furnace. In such a case the air will be forced into the furnace by the steam jet and the draught produced will be the forced draught. In steam locomotive the draught is produced by the exhaust steam blast in the smoke box (see fig. 8-6), which reduces the pressure of the escaping gases below the atmospheric pressure and greatly increases the air-flow through the grate, smoke tubes and up the chimney. The exhaust steam from the steam locomotive engine (non-condensing) is used for producing draught. The system is simple and cheap. In this system the draught is automatically adjusted to suit the requirements. In the induced steam jet draught, the draught is produced by steam jet issuing from a nozzle placed in chimney. This will drag with it the surrounding gas and produce a partial vacuum in its neighbourhood. The air is, thus, drawn through the furnace by the difference in pressure created by the steam jet. The draught produced by the steam jet in this manner is of the induced type.

Balanced draught is the combination of the forced and induced draught systems. The forced draught supplies air for burning the fuel. The induced draught removes the gases from the furnace. A balanced draught system minimises the losses due to inward and outward leakages and is the best compromise between induced and forced draughts.

Forced and induced draughts can be compared as under:

- Forced draught system requires less fan power, since the fan has to handle only cold air.
- Forced draught gives better control than induced draught. With forced draught the air penetrates (enters) into the fire-bed better than that with the induced draught and therefore, the rate of burning of fuel is more.
- With forced draught all leakages are outward and therefore, there is a serious danger of blow out, if the fire doors are opened when the fan is operating. Care, therefore, has to be taken while opening the fire doors.
- With induced draught all leakages of air are inward and, therefore, heavy air infiltration (leakage) will occur, reducing the available draught unless all brickwork, joints etc., in the flue system are kept in good condition.
- The fan power required with induced draught is greater than forced draught, since in induced draught fan has to handle a large amount of the hot flue gases.
- With induced draught there will be an inrush of cold air into the furnace when the furnace doors are opened for firing or cleaning.

Artificial draught and natural draught: Induced draught artificially produced is better and more economical than the chimney draught. It is more widely used on large boiler plants. As the temperature of flue gases can be lowered with induced draught (artificial draught), the boiler efficiency is higher with induced draught than with natural or chimney draught. Induced draught created by a steam jet is not very economical from the point of view of steam consumption.

The artificial draught system has the following advantages over the natural or chimney draught:

- Higher evaporative power of the boiler,
- Burning of low grade fuel is possible,
- Proper control of combustion is possible,
- Smoke is greatly reduced,
— Chimney height required is less, and
— Over-all efficiency of the plant is higher.

The disadvantages of artificial draught are as under:
— Installation cost is higher,
— Running cost is higher, and
— Maintenance cost is more.

8.15 Chimney Height

The amount of natural draught produced in a boiler depends on the height of the chimney and the difference between temperature of the hot flue gases leaving the boiler and that of the outside cold air. A relationship between the height of a chimney and the draught it produces in terms of temperature of outside air and the average flue gas temperature, can be deduced in the following manner:

Let $m = \text{mass of air used in kg to burn 1 kg of fuel}$,
$T = \text{average absolute temperature of chimney gases in K}$, and
$T_a = \text{absolute temperature of the air outside the chimney in K}$.

Thus, mass of flue gases produced = $(m + 1)$ kg per kg of fuel burnt.

The volume of chimney gases produced may be taken as equal to the volume of air supplied. Since the volume of the solid or liquid fuel burnt is so small as compared with the volume of air supplied that it may be neglected.

Taking the volume of 1 kg of air at 0°C and 760 mm of Hg as 0.7734 m$^3$,
Volume of gases at 0°C = 0.7734 $m^3$ per kg of fuel burnt.

Since volume of gas is proportional to its absolute temperature (by Charle's law),

Volume of chimney gases at $TK = \frac{0.7734 \times T}{273}$ $m^3$/kg of fuel burnt,

and the density of chimney gases at temperature $TK$

$$\frac{(m+1)}{0.7734m \times \frac{T}{273}} = \frac{(m+1)}{0.7734m} \times \frac{273}{T} \text{ kg/m}^3.$$

Similarly, the density of atmospheric air at $T_aK$

$$\frac{m}{0.7734 \times \frac{T_a}{273}} = \frac{1}{0.7734} \times \frac{273}{T_a} \text{ kg/m}^3$$

Let $H$ in fig. 8-25 be height of the chimney required in metres, measured from the level of furnace grate.

The pressure exerted per square metre at the furnace grate level by a column of hot gas one metre in height = density of the gas.

∴ Pressure exerted by a column of hot chimney gas of $H$ metres height

$$\frac{\rho A H g}{A} = \rho g H \text{ N/m}^2$$

= density $\times$ 9.81$H$ N/m$^2$
Similarly, pressure due to column of outside (cold) air of same area and $H$ metres height is:

$$p = \frac{1}{0.7734} \times \frac{273}{T_a} \times m \times \frac{1 + \frac{m}{T} + \frac{273}{T}}{T} \times H \times 9.81 \text{ N/m}^2$$

Let $p$ be the pressure causing the draught in N/m$^2$. Since the pressure causing the draught is due to the difference of pressure due to column of hot gases within the chimney and the pressure due to an equal column of outside (cold) air,

The draught pressure is usually expressed in terms of mm of water column as indicated by the U-tube water pressure gauge called manometer.

Since the density of water is 1,000 kg/m$^3$, a water column of 1 metre or 1,000 mm height will exert a pressure of $1,000 \times 9.81$ N/m$^2$.

Let $h$ be draught pressure in mm of water, then the draught pressure, $p$ in N/m$^2$ is given as

$$p = \rho g h = 1,000 \times 9.81 \times \frac{h}{1,000} = 9.81 h \text{ N/m}^2$$

$$\therefore \quad h = \frac{p}{9.81} \text{ mm of water}$$

Substituting the value of $p$ from the eqn. (8.3), we have

$$h = \frac{273}{0.7734} H \left[ \frac{1}{T_a} - \frac{m + 1}{m} \times \frac{1}{T} \right] \text{ mm of water}$$

The theoretical draught obtained by calculation from eqn. (8.4) is known as **static draught**. The actual or available draught is less in value than the static draught due to:

- Frictional resistance to the flow of flue gases in the flue passages,
- Energy required to impart velocity to flue gases, and
- Losses in the bends and curves in the flue gas passages.
Problem-3: A chimney of 30 m height is full with hot gases at a temperature of 288°C. The outside air temperature is 21°C. If the available draught is 80 per cent of the theoretical draught, calculate the available draught. The air supplied for combustion is 18 kg per kg of fuel burnt. Take the density of air at 0°C and 760 mm of Hg to be 1.293 kg/m³.

Using eqn. (8.4),

\[ h = 353 \frac{H}{T_a} \left[ \frac{m+1}{m} \times \frac{1}{T} \right] \]

where \( h \) = draught in mm of water,
\( H \) = minimum height of chimney in m,
\( m \) = quantity of air used in kg per kg of fuel burnt,
\( T_a \) = absolute temperature of the outside (cold) air in K, and
\( T \) = absolute temperature of chimney flue gases in K.

Here, \( H = 30 \) m, \( m = 18 \) kg of air per kg of fuel burnt,
\( T_a = 21 + 273 = 294 \) K, and \( T = 288 + 273 = 561 \) K.

Substituting the above values in the eqn. (8.4), we get,

\[ h = 353 \times 30 \left[ \frac{1}{294} - \frac{18+1}{18} \times \frac{1}{561} \right] = 16.1 \text{ mm of water column} \]

\( \therefore \) Available draught = 0.8 x 16.1 = 12.88 mm of water column.

Problem-4: A boiler uses 18 kg of fuel per minute and is supplied with 18 kg of air per kg of fuel burnt. Determine the minimum height of the chimney required to produce a draught of 25 mm of water. The mean temperature of the chimney gases is 315°C and that of the outside air is 27°C.

Using eqn. (8.4), \( h = 353 \frac{H}{T_a} \left[ \frac{m+1}{m} \times \frac{1}{T} \right] \)

Here, \( h = 25 \) mm of water, \( m = 18 \) kg of air per kg of fuel burnt,
\( T_a = 27 + 273 = 300 \) K, and \( T = 315 + 273 = 588 \) K.

Substituting the above values in eqn. (8.4),

\[ 25 = 353 \times H \left[ \frac{1}{300} - \frac{18+1}{18} \times \frac{1}{588} \right] \]

\[ = 353 \times H \left( 0.0033 - 0.0016 \right) \]

\( \therefore \) \( H = 41.6 \) metres (minimum height of chimney)

Problem-5: How much air is used per kg of coal burnt in a boiler having a chimney of 30 m height to produce a draught of 16 mm of water when the temperature of the flue gases in the chimney is 317°C and that of the boiler house is 30°C?

Using eqn. (8.4), \( h = 353 \frac{H}{T_a} \left[ \frac{m+1}{m} \times \frac{1}{T} \right] \)

Here, \( H = 30 m \), \( h = 16 \) mm of water,
\( T_a = 30 + 273 = 303 \) K, and \( T = 317 + 273 = 590 \) K.
Substituting the above values in the eqn. (8.4),

\[ 16 = 353 \times 30 \left[ \frac{1}{303} - \frac{m+1}{m} \times \frac{1}{590} \right] \]

\[ \therefore \frac{16}{353 \times 30} = \frac{1}{303} - \frac{m+1}{590} \]

\[ \therefore \frac{m+1}{590} = \frac{1}{303} - \frac{16}{353 \times 30} \]

\[ \therefore m = \frac{1}{0.0561} = 17.83 \text{ kg of air per kg of fuel burnt.} \]

**Problem-6**: Estimate the mean temperature of the flue gases leaving the chimney 30 m high to produce a draught of 16 mm of water column, if 18 kg of air is required per kg of fuel burnt on the grate. The temperature of atmospheric air is 27°C. Take the density of air at 0°C and 760 mm of Hg as 1.293 kg/m³.

Using eqn. (8.4),

\[ h = 353 H \left[ \frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{T} \right] \]

Here, \( h = 16 \text{ mm of water}, \ m = 18 \text{ kg of air per kg of fuel burnt}, \) \( H = 30 \text{ m}, \) and \( T_a = 27 + 273 = 300 \text{ K}. \)

Substituting the above values in eqn. (8.4),

\[ 16 = 353 \times 30 \left[ \frac{1}{300} - \frac{18+1}{18} \times \frac{1}{T} \right] \]

\[ \therefore 16 = 10,590 \left[ 0.0033 - \frac{1.056}{T} \right] = 35.265 - \frac{11,183}{T} \]

\[ \therefore T = \frac{11,183}{19.265} = 580 \text{ K or } t = 307^\circ \text{C (temperature of flue gases)} \]

### 8.16 Maximum Discharge of Hot Flue Gases through the Chimney

The eqn. (8.4) may be modified to express the draught in terms of column of hot gases.

Let \( h_g \) (fig. 8-25) be the height of column of hot gases which would produce the pressure \( p \).

Pressure exerted by this column of hot gases, \( p = \text{density} \times h_g \times 9.81 \)

\[ \therefore p = \frac{m+1}{0.7734 m} \times \frac{273}{T} \times h_g \times 9.81 \]

Substituting this value of \( p \) in eqn. (8.3), we get,

\[ \frac{m+1}{0.7734 m} \times \frac{273}{T} \times h_g \times 9.81 = \frac{273 \times 9.81 H}{0.7734} \left[ \frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{T} \right] \]

\[ \therefore h_g = \frac{273 H}{0.7734} \left[ \frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{T} \right] \times \frac{0.7734 m}{m+1} \times \frac{T}{273} \]

Simplifying,

\[ h_g = H \left[ \frac{m}{m+1} \times \frac{T}{T_a} - 1 \right] \]

\[(8.5)\]
The chimney draught is more effective when the chimney will discharge a maximum mass of hot gases in a given time. This condition is produced when the absolute temperature of the chimney gases bears a certain ratio to the absolute temperature of the outside (cold) air.

The mass of gases discharged in a given time is proportional to the product of its density and velocity of its discharge.

Since, \( V^2 = 2gh_g \) i.e. \( V = \sqrt{2gh_g} \)

Substituting the value of \( h_g \) from eqn. (8.5), we have,

\[ V = \sqrt{2gh\left[\frac{m}{m+1} \times \frac{T}{T_a} - 1\right]} \]

And since the density of the hot gases is proportional to \( \frac{1}{T} \), the mass of the hot gases discharged,

\[ M = \frac{A}{T} \sqrt{2gh\left[\frac{m}{m+1} \times \frac{T}{T_a} - 1\right]} \]

where \( A \) is a constant of proportionality.

Putting \( B \) as another constant, the equation may be written as

\[ M = \frac{B}{T}\left[\sqrt{\frac{m}{m+1} \times \frac{T}{T_a} - 1}\right] \]

Differentiating \( M \) with respect to \( T \) for maximum discharge,

\[ \frac{dM}{dT} = \frac{B}{\sqrt{2}} \times \frac{\sqrt{\frac{m}{m+1} \times \frac{1}{T_a} - \frac{1}{T^2}}}{\sqrt{\frac{m}{m+1} \times \frac{1}{T_a} - \frac{1}{T^2}}} \]

For maximum discharge \( \frac{dM}{dT} = 0 \),

Therefore, the numerator of the above equation is zero, giving,

\[ \frac{m}{m+1} \times \frac{1}{T_a} = \frac{2}{T^3} \]

\( \therefore \frac{m}{m+1} \times \frac{1}{T_a} = \frac{2}{T} \)

\( \therefore T = 2 \times \frac{m+1}{m} \times T_a \)

This shows that maximum mass of hot gases are discharged when,

\[ T = 2\left[\frac{m+1}{m} \times T_a\right] \] \hspace{1cm} \ldots (8.6)

If this value of \( T \) is substituted in eqn. (8.5),
\[ h_g = H \left[ \frac{m}{m+1} \times \frac{2 \times \frac{m+1}{m} \times \frac{1}{T_a}}{1} \right] \]

\[ = H (2 - 1) = H \text{ metres} \]

which means that when maximum discharge takes place, height of the column of hot gases expressing the draught pressure will be equal to the height of the chimney.

From eqn. (8.4), \[ h = 353 H \left[ \frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{T} \right] \]

Using eqn. (8.6), for maximum discharge, \[ T = 2 \left( \frac{m+1}{m} \times T_a \right) \]

Substituting the value of \( T \) in eqn. (8.4), the draught in mm of water under the condition of maximum discharge is

\[ h = 353 H \left[ \frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{2 \times \left( \frac{m+1}{m} \times T_a \right)} \right] = 353 \times \frac{H}{2 T_a} \]

or \[ h = \frac{176.5 H}{T_a} \]

Problem-7 : A chimney 30 m high deals with flue gases at 288°C, when the outside air temperature is 21°C. The air supplied for combustion is 18 kg per kg of coal burnt. Calculate :

(i) the draught in mm of water column produced by the chimney,

(ii) the draught produced in terms of height of column of hot gases in metres,

(iii) the velocity of flue gases in the chimney, if 50% of the draught is lost in friction at the grate and passages, and

(iv) the draught produced in mm of water and the temperature of flue gases under the condition of maximum discharge.

(i) From eqn. (8.4), 

\[ h = 353 H \left[ \frac{1}{T_a} - \frac{m+1}{m} \times \frac{1}{T} \right] \]

Here, \( T_a = 21 + 273 = 294 \text{ K} \), \( T = 288 + 273 = 561 \text{ K} \)

\( H = 30 \text{ metres} \), and \( m = 18 \text{ kg of air/kg of fuel burnt} \).

Substituting the above values in eqn. (8.4), 

\[ h = 353 \times 30 \left[ \frac{1}{294} - \frac{18+1}{18} \times \frac{1}{561} \right] \]

\[ = 16.1 \text{ mm of water column} \]

(ii) From eqn. (8.5), height of column of hot gases,

\[ h_g = H \left[ \frac{m}{m+1} \times \frac{T}{T_a} - 1 \right] \]

Substituting the values in eqn. (8.5),
\[ h_g = 30 \left[ \frac{18}{18+1} \times \frac{561}{294} - 1 \right] \]

\[ = 30 \times 0.81 = 24.3 \text{ metres of hot gases column.} \]

(iii) As 50% of the draught is lost in friction,

Available draught, \( h = 24.3 \times 0.5 = 12.15 \text{ m.} \)

If \( V \) is the velocity of gases in m/sec.

then, \( V = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 12.15} = 15.45 \text{ m/sec.} \)

(iv) Using eqn. (8.7), the draught in mm of water under the condition of maximum

 discharge is

\[ h = \frac{176.5 H}{T_a} \]

Here, \( T_a = 21 + 273 = 294 \text{ K} \) and \( H = 30 \text{ m.} \)

\[ \therefore h = \frac{176.5 \times 30}{294} = 18 \text{ mm of water} \]

Using eqn. (8.6) for maximum discharge, temperature of the flue gases,

\[ T = 2 \left[ \frac{m+1}{m} \times T_a \right] \]

\[ = 2 \left[ \frac{19}{18} \times 294 \right] = 620 \text{ K or } t = 347^\circ \text{C (temperature of flue gases)} \]

8.17 Power Required to Drive the Draught Fan

The fan power or air power is the power required to move air or gas by the fan.

If \( p \) = draught pressure in bar (equivalent to draught in mm of water, \( h \)), and

\( v \) = volume of air or gas handled by the fan per second in m\(^3\), then,

The work done by the fan = \( 10^5 \times p \times v \) Joules per second, and hence

Air power = \( \frac{10^5 \times p \times v}{1,000} \) kJ/sec or kW

If \( \eta \) = efficiency of the fan,

Then, power required to drive the fan = \( \frac{10^5 \times p \times v}{1,000 \times \eta} \) kW \( \ldots (8.8) \)

Volume \( v \) of air handled by a forced draught fan can be calculated as under:

If \( m \) = mass of air supplied per kg of fuel burnt, and

\( M \) = mass of fuel burnt per second,

then the quantity of air supplied per second = \( m \times M \) kg.

If \( T_a \) = absolute temperature of outside (cold) air,

\( T_0 \) = absolute temperature of air at N.T.P. (273 K), and

\( V_o \) = volume of 1 kg of air at N.T.P. (0.7734 m\(^3\)),

Then, \( v = m \times M \times V_o \times \frac{T_a}{T_0} \) m\(^3\)/sec.
Substituting the value of \( v \) in eqn. (8.8),

Power required to drive a forced draught fan, i.e., Brake

\[
\text{Power of motor} = \frac{10^5 \times \rho \times M \times v_0 \times T_a}{1,000 \times \eta \times T_o} \text{ kW} 
\]  

(8.9)

Volume \( v \) of flue gases handled by an induced draught fan can be calculated as under: The mass of flue gases formed per kg of fuel = \((m + 1)\) kg. Therefore, for \( M \) kg of fuel burnt per second, mass of flue gases handled by induced draught fan per second = \( M (m + 1) \) kg

If \( T \) = absolute temperature of flue gases and assuming the density of flue gases to be that of air, then

\[
v = (m + 1) \times \frac{M \times v_0 \times T}{T_o} \text{ m}^3/\text{sec.} 
\]

Substituting the value of \( v \) in eqn. (8.8),

Power required to drive an induced draught fan, i.e. Brake

\[
\text{Power of Motor} = \frac{10^5 \times \rho \times (m +1) \times M \times v_o \times T}{1,000 \times \eta \times T_o} \text{ kW} 
\]  

(8.10)

Comparison of fan power for induced and forced draughts can be made from the following expression when both the fans have the same efficiency and produce equal draught:

\[
\frac{\text{Power required for induced draught fan}}{\text{Power required for forced draught fan}} = \frac{m+1}{m} \times \frac{T}{T_a} 
\]  

(8.11)

where \( T \) = absolute temperature of flue gases handled by induced draught fan,

\( T_a \) = absolute temperature of air handled by forced draught fan, and

\( m \) = quantity of air used in kg to burn 1 kg of fuel.

Problem-8: The following data was obtained during a test on two boilers working under similar conditions, except that the draught in the first boiler was produced by an induced draught fan and in the second boiler by a forced draught fan. Boiler house temperature was 20°C.

- Mean temperature of flue gases leaving the boilers \( \ldots 190°C \)
- Air supplied per kg of fuel burnt \( \ldots 19 \) kg
- Density of air under given conditions \( \ldots 1.205 \text{ kg/m}^3 \)
- Density of flue gases at the specified temperature \( \ldots 0.769 \text{ kg/m}^3 \)
- Combustion rate \( \ldots 150 \text{ kg of fuel per hour} \)
- Fan draught produced in each case \( \ldots 75 \text{ mm of water} \)
- Efficiency of fan in both cases \( \ldots 50\% \)

Calculate the brake power of fan in each case and make a comparison of fan power expended (used) in each case. Allow 20% leakage air in case of induced draught system and 10% in case of forced draught system.

Induced draught fan:
Mass of fuel burnt per second = \( \frac{150}{3,600} \) kg = 0.0417 kg.

Mass of gases produced per kg of fuel = 19 + 1 = 20 kg.

\[ \therefore \text{Mass of gases handled by the fan per second} = 20 \times 0.0417 = 0.834 \text{ kg.} \]

Volume of gases to be handled by the induced draught fan per second, including leakage air,

\[ v = \frac{0.834}{0.769} \times 1.2 = 1.3 \text{ m}^3. \]

Draught pressure, \( p = \frac{75}{13.6} \times \frac{1}{750} = 0.00753 \text{ bar} \)

Using eqn. (8.8), power of the motor to drive induced draught fan

\[ \frac{10^5 \times p \times v}{1,000 \times \eta} = \frac{10^5 \times 0.00753 \times 1.3}{1,000 \times 0.5} = 1.9578 \text{ kW} \]

Forced draught fan:

Volume of air to be handled by forced draught fan per second, including leakage air,

\[ v = \frac{19 \times 0.0417}{1.205} \times 1.1 = 0.723 \text{ m}^3; \text{ Draught pressure, } p = 0.00753 \text{ bar.} \]

Using eqn. (8.8) power of the motor required to drive forced draught fan.

\[ \frac{10^5 \times p \times v}{1,000 \times \eta} = \frac{10^5 \times 0.00753 \times 0.723}{1,000 \times 0.5} = 1.0888 \text{ kW} \]

\[ \frac{\text{Power for induced draught fan}}{\text{Power for forced draught fan}} = \frac{1.9578}{1.0888} = 1.8 \text{ (ratio of power)} \]

Alternatively, using eqn. (8.11), the ratio of power

\[ \frac{m+1}{m} \times \frac{1.2}{1.1} \times \frac{T}{T_a} \]

\[ = \frac{19 + 1}{19} \times \frac{1.2}{1.1} \times \frac{(190 + 273)}{(20 + 273)} = 1.8 \text{ (same as before)} \]

Problem-9: The mean temperature of flue gases in the chimney of boiler is 200°C, while the temperature of the air in the boiler house is 20°C. The boiler consumes 1,000 kg of fuel per hour and 18 kg of air is supplied to burn 1 kg of this fuel. Calculate the air power of the fan of this boiler plant to maintain a draught of 50 mm of water, when (a) the fan produces an induced draught, and (b) the fan produces forced draught. Volume of 1 kg of air at 0°C and 760 mm of Hg may be taken as 0.7734 m³.

(a) Air power of induced draught fan:

Mass of flue gases handled by induced draught fan per second

\[ = \frac{1,000}{3,600} \times (18 + 1) = 5.278 \text{ kg} \]

Volume of flue gases at N.T.P.(0°C) = 5.278 \times 0.7734 = 4.082 m³/second

\[ \therefore \text{Volume of flue gases handled by induced draught fan at } 200°C, \]
\[ v = 4.082 \times \frac{473}{273} = 7.0725 \text{ m}^3/\text{second} \]

Draught pressure, \( p = \frac{50}{13.6} \times \frac{1}{750} = 0.0049 \text{ bar} \)

Air power of the induced draught fan = \( \frac{10^5 \times p \times v}{1,000 \times \eta} \)
\[ = \frac{10^5 \times 0.0049 \times 7.0725}{1,000 \times 1} = 3.4655 \text{ kW} \]

Alternatively, using eqn. (8.10), Air power = \( \frac{10^5 \times p \times M(m+1) \times v_o \times T}{1,000 \times \eta \times T_o} \)
\[ = \frac{10^5 \times 0.0049 \times 1,000 \times (18 + 1) \times 0.7734 \times 473}{3,600 \times 1 \times 273} = 3.4655 \text{ kW (same as before)} \]

(b) Air power of forced draught fan:

Mass of air supplied by the fan per second = \( \frac{1,000 \times 18}{3,600} = 5.0 \text{ kg} \)

Volume of this air supplied at 0°C and 760 mm of Hg = \( 0.7734 \times 5.0 = 3.867 \text{ m}^3/\text{second} \)

\[ \therefore \text{Volume of this air supplied at 20°C, } v = 3.867 \times \frac{293}{273} = 4.15 \text{ m}^3/\text{second}. \]

Draught pressure, \( p = 0.0049 \text{ bar} \).

Air power of the forced draught fan
\[ = \frac{10^5 \times p \times v}{1,000 \times \eta} = \frac{10^5 \times 0.0049 \times 4.15}{1,000 \times 1} = 2.0335 \text{ kW} \]

Alternatively, using eqn. (8.9), Air power = \( \frac{10^5 \times p \times M \times m \times v_o \times T_a}{1,000 \times \eta \times T_o} \)
\[ = \frac{10^5 \times 0.0049 \times 1,000 \times 18 \times 0.7734 \times 293}{3,600 \times 1 \times 273} = 2.0335 \text{ kW (same as before)} \]

8.18 Performance of Boilers

The performance of steam boiler is judged by calculating quantity of heat produced by the utilizing heat of combustion of fuel. The evaporative capacity or output of a boiler is frequently given as the kilograms of water evaporated per hour. Since, the steam produced at various pressures and temperatures (from feed water at various temperatures) contains varying amounts of heat, the number of kilograms of water evaporated per hour is exact measure of its performance.

Efforts have been made to provide common basis for comparing the evaporative capacity (output) of boilers. For comparison purpose, the output of a boiler is expressed in terms of:

- Equivalent evaporation from and at 100°C per kg of coal burnt, and
- Evaporation per square metre of heating surface.
The amount of steam generated by the boiler in kilograms per hour at the observed pressure and temperature, quality of steam and feed water temperature (i.e. evaporation in kg per hour under actual working conditions), is called total evaporation. The actual evaporation \( m_a \) is expressed in terms of kilograms of steam generated per kilogram of fuel burned,

\[
\text{i.e. actual evaporation, } m_a = \frac{\text{total evaporation per hour}}{\text{fuel used per hour}}
\]

Different boilers generate different quantities of steam at different pressures and different dryness fraction and degrees of superheat, from feed water at different temperatures. To illustrate, boiler 'A' generates 8.5 kg of dry saturated steam per kg of coal at 13 bar, from feed water at 15°C, boiler 'B' generates 9.5 kg of wet steam per kg of coal at 11 bar and dryness fraction 0.98, from feed water at 30°C, and boiler 'C' generates 9 kg of super-heated steam per kg of coal at 14 bar and with 50°C of superheat, from feed water at 20°C.

It will be seen from the above illustration that all the three boilers are generating steam under different working conditions. Therefore, to provide common basis for comparing the evaporative capacity of boilers working under different conditions, it is necessary that the water be supposed to be evaporated under some standard conditions. The standard conditions adopted are: feed water supplied to the boiler at 100°C and converted into dry saturated steam at 100°C. Under these conditions the evaporation of 1 kg of water at 100°C requires 2,257 kJ to be converted into dry saturated steam at 100°C, which is the enthalpy of evaporation of steam at 100°C (1.01325 bar pressure).

Equivalent evaporation may be defined as the evaporation which would be obtained if the feed water were supplied at 100°C and converted into dry saturated steam at 100°C (1.01325 bar pressure).

Under actual working conditions of the boiler, let

\[
m_a = \text{actual mass of water evaporated in kg per kg of coal burnt under actual working conditions},
\]

\[
H = \text{Enthalpy of 1 kg of steam raised (produced) under actual working conditions in kJ},
\]

\[
h = \text{Enthalpy of 1 kg of feed water entering the boiler in kJ},
\]

\[
L_s = \text{Enthalpy of evaporation of 1 kg of steam at 100°C (2,257 kJ), and}
\]

\[
m_e = \text{equivalent evaporation in kg of water from and at 100°C per kg of fuel burnt.}
\]

Then, heat transferred to 1 kg of feed water in converting it to dry saturated steam or heat required to produce 1 kg of steam = \( H - h \) kJ and

Heat required to produce \( m_a \) kg of steam under actual working conditions

\[
= m_a (H - h) \text{ kJ}
\]

Equivalent evaporation in kg of water from and at 100°C per kg of fuel burnt,

\[
m_e = \frac{m_a (H - h)}{L_s} = \frac{m_a (H - h)}{2,257} \quad \ldots(8.12)
\]

For wet steam, \( m_e = \frac{m_a (H_{\text{wet}} - h)}{2,257} \)

Factor of equivalent evaporation is the ratio of heat absorbed by 1 kg of feed water under observed conditions (actual working conditions), to that absorbed by 1 kg
of feed water evaporated from and at 100°C (standard conditions).

\[ \text{Hence, factor of equivalent evaporation} = \frac{H - h}{L_s} = \frac{H - h}{2,257} \]  \hspace{1cm} (8.13)

The mass of water evaporated is also expressed in terms of evaporation per hour per square metre of heating surface of the boiler. This is obtained by dividing the total water evaporated per hour by the total area of heating surface in square metres.

i.e. evaporation per \( m^2 \) of heating surface = \( \frac{m \text{ kg per hour}}{\text{Total area of heating surface in } m^2} \)

where \( m \) is the actual mass of water evaporated in kg per hour.

Boiler efficiency or thermal efficiency of a boiler is defined as the ratio of the heat utilized by feed water in converting it to steam, to the heat released by complete combustion of the fuel used in the same time, i.e., output divided by the input to the boiler.

The output or the heat transferred to feed water is based on the mass of steam produced under the actual working conditions. The input to a boiler or heat released by complete combustion of fuel may be based on the higher calorific value of the fuel.

\[ \text{Boiler efficiency} = \frac{m_a (H - h)}{C.V} \]  \hspace{1cm} (8.14)

where \( m_a \) = actual evaporation in kg per kg of fuel burnt,

\( H \) = enthalpy of 1 kg of steam produced under actual working conditions in kJ,

\( h \) = enthalpy of 1 kg of feed water entering the boiler in kJ, and

\( C.V. \) = calorific value of fuel in kJ/kg.

If a boiler is provided with an economiser and a superheater, then each of these elements of a boiler will have its own efficiency. If the boiler, economiser and superheater are considered as single unit, the efficiency in that case is known as the overall efficiency of the boiler plant or efficiency of the combined boiler plant.

A good water-tube boiler should have a thermal efficiency of about 80%. A Lancashire boiler, with automatic stokers and well maintained brickwork should have an efficiency of about 75%. Where does the remainder of the heat (about 25% heat in the case of Lancashire boiler) go? Since it is not utilised in the boiler in converting water to steam, it is taken as losses and is distributed as follows:

1. **Heat lost to chimney gases or flue gases**:

   The chimney gases are made up of

   (a) dry flue gases, and (b) steam in flue gases formed from the combustion of hydrogen present in the fuel together with any moisture present in the fuel.

   **Heat lost to dry flue gases per kg of fuel burnt** = mass of dry flue gases in kg per kg of fuel \( (m_g) \times \) specific heat of dry flue gases \( (k_p) \) in kJ/kg K \( \times \) rise in temperature of flue gases in °C (difference between temperature of flue gases leaving the boiler, \( t_1 \) and temperature of the boiler room, \( t_0 \)),

   i.e. **Heat lost to dry flue gases per kg of fuel** = \( m_g \times k_p (t_1 - t_0) \) kJ

   **Heat lost to steam in flue gases per kg of fuel burnt**

   Now, mass of steam formed per kg of fuel burnt
Assuming that the steam in flue gases exists as superheated steam at atmospheric pressure and at flue gas temperature,

Heat lost to steam in the flue gases per kg of fuel burnt

\[ = 9H_2 + m \times (H_{sup} - h) \]

where \( t_1 \) = the temperature of flue gases leaving the boiler,

\( H_{sup} \) = enthalpy of 1 kg of superheated steam at atmospheric pressure (1.01325 bar) and at flue gas temperature in kJ,

\( k_p \) = specific heat of superheated steam in kJ/kg K,

\( h \) = enthalpy of 1 kg of water at boiler house temperature in kJ,

\( m \) = mass of moisture present in 1 kg of fuel, and

\( H_2 \) = mass of hydrogen present in 1 kg of fuel.

(2) Heat lost due to incomplete combustion (burning of carbon to CO):

Any CO present in flue gases is due to insufficient air supply. One kg of carbon burnt to CO releases only 10,130 kJ and one kg of carbon burnt to \( CO_2 \) releases 33,830 kJ. Thus the heat available in CO (formed due to incomplete combustion) per kg of carbon is 33,830 - 10,130 = 23,700 kJ. This means that the presence of CO in the flue gases is a loss due to incomplete combustion.

(3) Heat lost due to unburnt fuel falling through the grate bars:

When solid fuels are used, some of the fuel falls through the grate bars and is lost with ash. The heat loss is calculated by multiplying mass of unburnt fuel lost through grate bars by the calorific value of the fuel.

(4) Heat lost to external radiation:

Effective lagging (covering with asbestos) of the surface of boiler exposed to atmosphere is necessary to reduce this loss to a minimum.

Heat lost in items 2, 3 and 4 is found out as the difference of the gross heat supplied (released) per kg of fuel, and the heat transferred to feed water in converting it to steam per kg of fuel burnt and heat lost in item 1, i.e., heat carried by flue gases.

Problem-10: A boiler generates 800 kg of steam per hour at a pressure of 10 bar and with 50°C superheat, and burns 100 kg of coal per hour. If the calorific value of the coal is 30,000 kJ/kg and feed water temperature is 40°C, calculate:

(i) the factor of equivalent evaporation, (ii) the actual evaporation per kg of coal, (iii) the equivalent evaporation from and at 100°C per kg of coal, and (iv) the boiler efficiency.

Take specific heat of superheated steam at constant pressure as 2.1 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

(i) At 10 bar, \( H_s = 2,778.1 \) kJ/kg (from steam tables).

\[ H_{sup} = H_s + k_p(t_{sup} - t_s) = 2,778.1 + (2.1\times50) = 2,883.1 \text{ kJ/kg}. \]

\[ h = 4.187 \times (40 - 0) = 167.48 \text{ kJ/kg}. \]
:. Heat required to produce 1 kg of superheated steam from feed water at 40°C
\[ = H_{sup} - h = 2,883.1 - 167.48 = 2,715.62 \text{ kJ/kg} \]

Factor of equivalent evaporation \[ = \frac{H_{sup} - h}{2257} = 2,715.62 \frac{2257}{2257} = 1.203 \]

(ii) Actual evaporation \[ = m_a = \frac{800}{100} = 8 \text{ kg/kg of coal} \]

(iii) Equivalent evaporation in kg of water from and at 100°C per kg of coal,
\[ m_e = \frac{m_a (H_{sup} - h)}{2257} = \frac{8 \times 2,715.62}{2257} = 9.625 \text{ kg/kg of coal} \]

(iv) Boiler efficiency, \[ = \frac{m_a (H_{sup} - h)}{C.V.} = \frac{8 \times 2,715.62}{30,000} = 0.7243 \text{ or } 72.43\% \]

Problem-11: In a boiler test the following quantities were obtained:
Mean temperature of feed water, 15°C; mean boiler pressure, 12 bar; mean steam dryness fraction, 0.95; mass of coal burnt per hour, 250 kg; calorific value of coal, 32,400 kJ per kg; mass of water supplied to the boiler in 7 hours and 14 minutes, 16,500 kg; mass of water in the boiler at the end of the test was less than that at the commencement by 1,000 kg.
Calculate: (i) the actual evaporation per kg of coal, (ii) the equivalent evaporation from and at 100°C per kg of coal, and (iii) the thermal efficiency of the boiler.

(i) Total mass of steam raised in 7 hours and 14 minutes = 16,500 + 1,000 = 17,500 kg

:. Mass of steam raised per hour = \[ \frac{17,500}{7 \frac{14}{60}} = 2,417 \text{ kg}. \]

:. Actual evaporation of water per kg of coal, \[ m_a = \frac{2,417}{250} = 9.672 \text{ kg} \]

(ii) At 12 bar, \[ h = 798.65 \text{ kJ/kg and } L = 1,986.2 \text{ kJ/kg (from steam tables).} \]

Enthalpy of 1 kg of wet steam at 12 bar and 0.95 dry,
\[ H_{wet} = h + xL = 798.65 + 0.95 \times 1,986.2 = 2,685.54 \text{ kJ/kg} \]

Enthalpy of 1 kg of feed water, \[ h = (15 - 0) \times 4.187 = 62.8 \text{ kJ/kg} \]

:. Heat given to 1 kg of feed water in converting it to wet steam
\[ = H_{wet} - h = 2,685.54 - 62.8 = 2,622.74 \text{ kJ/kg} \]

Using eqn. (8.12), equivalent evaporation from and at 100°C,
\[ m_e = \frac{m_a (H_{wet} - h)}{2257} = \frac{9.672 \times 2,622.74}{2257} = 11.4 \text{ kg per kg of coal.} \]

(iii) Using eqn. (8.14), thermal efficiency of the boiler
\[ = \frac{m_a (H_{wet} - h)}{C.V.} \times 100 = \frac{9.672 \times 2,622.74}{32,400} \times 100 = 78.29\% \]

Problem-12: A boiler produces 2,400 kg of dry saturated steam per hour at a pressure of 12 bar (1.2 MPa) and the feed water is heated by an economiser to a temperature
of 120°C. 240 kg of coal of calorific value of 33,500 kJ/kg are fired per hour and it is found that 10% of the coal is unburnt. Find thermal efficiency of the boiler, and also of the boiler and grate combined. Take specific heat of water as 4.187 kJ/kg K.

Enthalpy of 1 kg of dry saturated steam at a pressure of 12 bar,

\[ H_s = 2,784.8 \text{ kJ/kg (from steam tables)}. \]

Enthalpy of 1 kg of feed water at 120°C, \( h = 4.187 \times (120 - 0) = 502.4 \text{ kJ/kg}\)

Heat given to 1 kg of feed water in converting it to dry saturated steam in boiler

\[ = H_s - h = 2,784.8 - 502.4 = 2,282.4 \text{ kJ/kg} \]

Mass of coal actually burnt = 240 x 0.9 = 216 kg

Thermal efficiency of the boiler considering 10 per cent of coal unburnt on the grate

\[ \frac{m_a (H_s - h)}{C.V.} = \frac{2,400}{216} \times 100 = 75.69\% \]

Thermal efficiency of the boiler and grate combined

\[ \frac{m_a (H_s - h)}{C.V.} = \frac{2,400}{33,500} \times 100 = 75.69\% \]

Problem-13 : In a boiler trial of 12 hours duration, 800 kg of coal were consumed and water evaporated was 6,400 kg and the mean steam pressure was 8 bar (800 kPa). The coal contained 2.5 per cent moisture and 3.5 per cent ash on mass basis. The feed water temperature was 30°C. Calorific value of coal is 31,000 kJ/kg. The steam produced is dry saturated. Take specific heat of water as 4.187 kJ/kg K. Determine :

(i) the thermal efficiency of the boiler, (ii) the equivalent evaporation from and at 100°C per kg of dry coal, and (iii) the equivalent evaporation from and at 100°C per kg of combustible.

(i) At 8 bar, \( H_s = 2,769.1 \text{ kJ/kg (from steam tables)}. \)

Enthalpy of one kg of dry saturated steam at 8 bar, \( H_s = 2,769.1 \text{ kJ/kg}. \)

Enthalpy of one kg of feed water at 30°C, \( h = 4.187 \times (30 - 0) = 125.61 \text{ kJ/kg}. \)

Heat transferred to 1 kg of feed water at 30°C in converting it to dry saturated steam at 8 bar \( = H_s - h = 2,769.1 - 125.61 = 2,643.49 \text{ kJ/kg}. \)

Actual evaporation per kg of coal, \( m_a = \frac{6,400}{800} = 8 \text{ kg} \)

Thermal efficiency of the boiler \( = \frac{m_a (H_s - h)}{C.V.} = \frac{8 \times 2,643.49}{31,000} \times 100 = 68.22\% \)

(ii) Actual water evaporated per kg of dry coal,

\[ m_a = \frac{6,400}{800 \times 0.975} = 8.206 \text{ kg/kg of dry coal} \]

Equivalent evaporation from and at 100°C,

\[ m_e = \frac{m_a (H_s - h)}{2,257} = \frac{8.206 \times 2,643.49}{2,257} = 9.61 \text{ kg/kg of dry coal} \]
(iii) Moisture and ash in coal = 2.5 + 3.5 = 6 per cent.

\[ \text{mass of combustible only} = 100 - 6 = 94 \text{ per cent of the total coal consumed.} \]

Mass of water evaporated per kg of combustible, \( m_a = \frac{6.400}{800 \times 0.94} = 8.51 \text{ kg} \)

Equivalent evaporation from and at 100°C,
\[ m_e = \frac{m_a (H_s - h)}{2.257} = \frac{8.51 \times 2.64349}{2.257} = 9.965 \text{ kg/kg of combustible.} \]

Problem-14: A boiler generates steam at 14 bar and 0.97 dry. The steam produced by the boiler then passes through the superheater where its temperature is raised to 305°C at constant pressure. If the boiler generates 1,200 kg of steam/hour, calculate the amount of heat received by the superheater per hour.

If the effectiveness of the above superheater is 60%, and if 5,000 kg/hr of flue gases pass over the superheater at an initial temperature of 285°C, find the temperature of the flue gases leaving the superheater. Take specific heat of the flue gases as 1.005 kJ/kg K and \( k_p \) of superheated steam as 2.1 kJ/kg K.

At 14 bar, \( h = 830.3 \text{ kJ/kg}, \; L = 1,957.7 \text{ kJ/kg}, \; H = 2,790 \text{ kJ/kg} \)

and \( t_s = 195.07°C \) (from steam tables).

Enthalpy of wet steam at 14 bar and 0.97 dry (before entering the superheater),
\[ H_{\text{wet}} = h + xL = 830.3 + 0.97 \times 1,957.7 = 2,731.2 \text{ kJ/kg} \]

Enthalpy of superheated steam at 14 bar and at 305°C (after leaving the superheater),
\[ H_{\text{sup}} = H_s + K_p (t_{\text{sup}} - t_s) = 2,790 + 2.1 (305 - 195.07) = 3,020.85 \text{ kJ/kg} \]

:. Heat received by 1 kg of wet steam in the superheater
\[ = 3,020.85 - 2,731.2 = 289.65 \text{ kJ/kg} \]

:. Heat received by steam per hour in the superheater
\[ = 1,200 \times 289.65 = 347,628 \text{ kJ/hr.} \]

For 60% effectiveness (efficiency) of the superheater, the heat supplied by the flue gases per hour
\[ = \frac{347,628}{0.6} = 579,380 \text{ kJ/hr.} \]

Heat lost by flue gases/hr = 5,000 \times 1.005 \times (285 - t)

Heat supplied by flue gases/hr = Heat lost by flue gases/hr.

i.e. 5,79,380 = 5,000 \times 1.005 \times (285 - t)

:. \[ t = 285 - \frac{5,79,380}{5,000 \times 1.005} = 169.7°C \]

i.e. Temperature of flue gases leaving the superheater = 169.7°C.

Problem-15: A boiler generates steam at the rate of 10 kg per kg of coal at a pressure of 12 bar, with a dryness fraction of 0.9. The boiler receives its feed water at a temperature of 110°C from an economiser which has received the feed water at 30°C. The steam raised by the boiler then passes through a superheater where its temperature is raised to 300°C at constant pressure. The coal has a calorific value of 34,000 kJ/kg.
Determine: (a) the equivalent evaporation at standard conditions per kg of coal, (b) the efficiency of the combined boiler plant, and (c) the percentage of available heat in 1 kg of coal utilized in boiler, economiser and superheater separately.

Take $k_p$ of superheated steam as 2.1 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

(a) At 12 bar (from steam tables), $H_s = 2,784.8$ kJ/kg, $h = 798.65$ kJ/kg, 
$L = 1,986.2$ kJ/kg and $t_s = 187.99$°C

Enthalpy of 1 kg of superheated steam,

$H_{sup} = H_s + k_p (t_s - t_s) = 2,784.8 + 2.1 (300 - 187.99) = 3,020.12$ kJ/kg

Enthalpy of 1 kg of feed water, $h = 4.187 \times (30 - 0) = 125.61$ kJ/kg

Heat given to feed water in converting it to superheated steam,

$H_{sup} - h = 3,020.12 - 125.61 = 2,894.49$ kJ/kg

Equivalent evaporation under standard conditions (from and at 100°C),

$m_e = \frac{m_a (H_{sup} - h)}{10 \times 2,894.49} = 12.82$ kg/kg of coal

(b) Efficiency of the combined boiler plant

Heat utilized in boiler, superheater and economiser per kg of coal

Heat in 1 kg of coal

$= m_a (H_{sup} - h) = \frac{10 \times 2,894.49}{C.V.} = 0.8513$ or 85.13%.

(c) Heat utilized in boiler alone per kg of coal

$= 10 \times 798.65 + 0.9 \times 1,986.2 - 110 \times 4.187$ = 21,256.6 kJ/kg of coal

Available heat in coal is 34,000 kJ/kg.

Percentage of heat available in 1 kg of coal utilized in the boiler

$= \frac{Heat utilized in boiler per kg of coal}{C.V.} \times 100 = \frac{21,256.6}{34,000} \times 100 = 62.52%$

Heat utilized by economiser per kg of coal

$= 10 \times 4.187 \times (110 - 30) = 3,349.6$ kJ/kg of coal.

Percentage of the heat available in one kg of coal utilized in the economiser

$= \frac{3,349.6}{34,000} \times 100 = 9.85%$

Heat absorbed in the superheater per kg of steam

$= [(1 - x) L + k_p (l_{sup} - l_s)]$ kJ

Heat absorbed by 10 kg of steam in the superheater

$= 10 [(1 - 0.9) \times 1,986.2 + 2.1 (300 - 187.99)] = 4,339.4$ kJ/kg of coal

Percentage of heat available in 1 kg of coal utilized in the superheater:

$= \frac{4,339.4}{34,000} \times 100 = 12.76%$
Problem-16: A boiler generates 1,000 kg of dry saturated steam per hour at a pressure of 10 bar. The feed water is heated by economiser before it is supplied to the boiler. If the feed water enters the economiser at 35°C and leaves at 95°C, find the percentage saving in heat by the use of the economiser.

If 2,500 kg per hour of flue gases pass over the economiser at 330°C and leave the economiser at 190°C, calculate the effectiveness (efficiency) of the economiser. Take specific heat of flue gases as 1-005 kJ/kg K and specific heat of water as 4-187 kJ/kg K.

Enthalpy of 1 kg of dry saturated steam at 10 bar, \( H_s = 2,778.1 \) kJ/kg (from steam tables).

Enthalpy of 1 kg of feed water at 35°C, \( h = 4.187 \times (35 - 0) = 146.55 \) kJ/kg.

.: Heat required to produce 1 kg of dry saturated steam at 10 bar from water at 35°C

\[
= H_s - h = 2,778.1 - 146.55 = 2,631.55 \text{ kJ/kg}
\]

Enthalpy of 1 kg of feed water at 95°C, \( h = 4.187 \times (95 - 0) = 397.77 \) kJ/kg.

.: Heat required to produce 1 kg of dry saturated steam at 10 bar from water at 95°C

\[
= H_s - h = 2,778.1 - 397.77 = 2,380.33 \text{ kJ/kg}
\]

.: Saving in heat by using feed water at 95°C instead of at 35°C (i.e. by heating water in the economiser)

\[
= 2,631.55 - 2,380.33 = 251.22 \text{ kJ/kg}
\]

.: Percentage saving in heat by the use of the economiser

\[
= \frac{251.22}{2,631.55} \times 100 = 9.58\%
\]

Heat received (or gained) by feed water from the flue gases in the economizer

\[
= 1,000 \times 4.187 \times (95 - 35) = 2,51,220 \text{ kJ/hr.}
\]

Heat rejected (or lost) by flue gases in the economiser

\[
= 2,500 \times 1.005 \times (330 - 190) = 3,51,750 \text{ kJ/hr.}
\]

.: Effectiveness (or efficiency) of the economiser = \( \frac{2,51,220}{3,51,750} \times 100 = 71.42\% \)

Problem-17: A Lancashire boiler is supplied with coal of calorific value 31,400 kJ/kg and an analysis of C, 82%; H₂, 6%; O₂, 9%; and ash, 3%. Calculate the minimum mass of air required per kg of coal. If the total air supplied is 1.4 times the minimum air required, calculate the mass of dry products of combustion per kg of coal burnt and the heat carried away by dry flue gases per kg of coal burnt if the average specific heat of flue gases is 1-005 kJ/kg K and the temperature of flue gases is 350°C and the boiler house temperature is 20°C. Determine also the thermal efficiency and equivalent evaporation from and at 100°C of the boiler if 2,250 kg of dry saturated steam is generated per hour at a pressure of 11 bar from feed water at 30°C, and 250 kg of coal are burnt per hour.

Using eqn. (7.1), minimum air required for combustion of 1 kg of coal
\[
\begin{align*}
= 100 \left[ \frac{2.67 C + 8 H + S - Q}{100} \right] \\
= \frac{100}{100} \left[ \frac{(2.67 \times 0.82) + (8 \times 0.06) - 0.09}{23} \right] = 11.21 \text{ kg/kg of coal.}
\end{align*}
\]

Total (actual air supplied = 1.4 \times 11.21 = 15.69 \text{ kg/kg of coal.}

\[\therefore\] Excess air supplied = 15.69 - 11.21 = 4.48 \text{ kg/kg of coal.}

The dry flue gases per kg of coal will consist of

1. \[CO_2 = C \times 3.67 = 0.82 \times 3.67 = 3.01 \text{ kg}\]
2. \[O_2 = 0.23 \times \text{excess air} = 0.23 \times 4.48 = 1.03 \text{ kg}\]
3. \[N_2 = 0.77 \times \text{actual air} = 0.77 \times 15.69 = 12.08 \text{ kg}\]

Total mass of dry products per kg of coal \((m_g) = 16.12 \text{ kg}\)

Using eqn. (7.2), heat carried away by dry flue gases per kg of coal

\[m_g \times k_p \left( t_f - t_0 \right) = 16.12 \times 1.005 \left( 350 - 20 \right) = 5,346.2 \text{ kgJ/kg of coal}\]

Enthalpy of 1 kg of dry saturated steam at 11 bar, \(H_s = 2,781.7 \text{ kJ/kg}\) (from steam tables).

Enthalpy of 1 kg of feed water before entering the boiler,

\[h = (30 - 0) \times 4.187 = 125.6 \text{ kJ/kg}\]

\[\therefore\] Heat given to 1 kg of feed water at 30°C in converting it to dry saturated steam at 11 bar in the boiler = \(H_s - h = 2,781.7 - 125.6 = 2,656.1 \text{ kJ/kg}\)

Using eqn. (8.14), thermal efficiency of the boiler

\[\frac{m_a (H_s - h)}{C.V.} = \frac{2,250}{100} \left( 2,656.1 \right) = 0.7613 \text{ or } 76.13\% \]

Using eqn. (8.12), equivalent evaporation from and at 100°C,

\[m_e = \frac{m_a (H_s - h)}{L_s} = \frac{2,250}{2,257} \left( 2,656.1 \right) = 10.59 \text{ kg/kg of coal}\]

**Problem-18**: During a trial on a Lancashire boiler plant consisting of an economiser, 8 kg of steam was generated per kg of coal burnt at a pressure of 12 bar and 0.9 dry. The boiler received its feed water at a temperature of 50°C from an economiser. The air supplied per kg of coal was 18 kg, and the calorific value of coal used was 31,400 \text{ kJ/kg}. If 70 per cent of the heat loss was carried away by the flue gases, calculate the temperature of flue gases leaving the boiler and entering the economiser. The boiler room temperature was 25°C and the specific heat of flue gases was 1.005 \text{ kJ/kg K}.

At 12 bar, \(h = 798.65 \text{ kJ/kg}\) and \(L = 1,986.2 \text{ kJ/kg}\) (from steam tables).

\[H_{wet} = h + xL = 798.65 + 0.9 \times 1,986.2 = 2,586.23 \text{ kJ/kg}\]

Enthalpy of 1 kg of feed water, \(h = (50 - 0) \times 4.187 = 209.35 \text{ kJ/kg}\)

\[\therefore\] Heat given to 1 kg of feed water in converting it to wet steam

\[= H_{wet} - h = 2,586.23 - 209.35 = 2,376.88 \text{ kJ/kg}\]
Amount of steam generated per kg of coal = 8 kg.

:. Heat utilized in boiler per kg of coal = 8 \times 2,376.88 = 19,015 \text{ kJ}

.: Heat lost per kg of coal = 31,400 - 19,015 = 12,385 \text{ kJ}.

70 per cent of this heat lost is carried away by the flue gases.

.: Heat carried away by the flue gases = 0.7 \times 12,385 = 8,669.5 \text{ kJ/kg of coal}

Mass of flue gases produced per kg of coal burnt = 18 + 1 = 19 kg.

Let \( m_g \) = mass of flue gases per kg of coal, 
\( t_1 \) = temperature of flue gases leaving the boiler, 
\( t_o \) = boiler room temperature, and 
\( k_p \) = specific heat of flue gases.

Then, heat carried away by flue gases per kg of coal burnt = \( m_g \times k_p \times (t_1 - t_o) \) kJ

i.e. 8,669.5 = 19 \times 1.005 \times (t_1 - 25)

\( t_1 = 479^\circ \text{C} \)

i.e. temperature of flue gases leaving the boiler and entering the economiser is 479°C.

Problem-19: In a boiler trial of 24 hours duration, 1,600 kg of coal were consumed and water evaporated was 12,800 kg and the mean steam pressure was 7.5 bar. The coal contained 3 per cent moisture and 3.9 per cent ash on mass basis. The feed water temperature was 35°C. Calorific value of coal is 30,300 kJ/kg. The steam produced is dry saturated.

Determine: (i) the thermal efficiency of the boiler, (ii) the equivalent evaporation from and at 100°C per kg of dry coal, and (iii) the equivalent evaporation from and at 100°C per kg of combustible.

(i) Enthalpy of dry saturated steam at 7.5 bar,
\( H_s = 2,766.4 \text{ kJ/kg (from steam tables)} \)

Enthalpy of 1 kg of feed water, \( h = (35 - 0) \times 4.187 = 146.55 \text{ kJ/kg} \)

:. Heat transferred to 1 kg of feed water in converting it to dry saturated steam = \( H_s - h = 2,766.4 - 146.55 = 2,619.85 \text{ kJ/kg} \)

Actual evaporation per kg of coal, \( m_a = \frac{12,800}{1,600} = 8 \text{ kg} \)

Thermal efficiency of the boiler
\[ \text{Thermal efficiency} = \frac{m_a(H_s - h)}{C.V.} = \frac{8 \times (2,619.85)}{30,300} \times 100 = 69.17\% \]

(ii) Mass of water evaporated per kg of dry coal, \( m_a = \frac{12,800}{1,600 \times 0.97} = 8.25 \text{ kg} \)

Equivalent evaporation from and at 100°C,
\[ m_e = \frac{8.25 \times (2,619.85)}{2,257} = 9.56 \text{ kg/kg of dry coal} \]

(iii) Moisture and ash in coal = 3 + 3.9 = 6.9 per cent.
Mass of combustible only = 100 - 6.9 = 93.1 per cent of the total coal consumed.

Mass of water evaporated per kg of combustible, \( m_a = \frac{12,800}{1,600 \times 0.931} = 8.593 \) kg

Equivalent evaporation from and at 100°C,

\[
m_a = \frac{8.593 \times (2.619 - 0.85)}{2.257} = 9.974 \text{ kg/kg of combustible.}
\]

Problem 20: The following data was obtained during the trial of a water-tube boiler:
Steam pressure, 15 bar; degree of superheat, 71.1°C; temperature of feed water, 92.6°C;
water evaporated, 3,223.8 kg per hour; coal fired, 417.3 kg per hour; ash, 43.3 kg per hour;
percentage of combustible in ash, 96.8; moisture in coal, 4.42%; heat value of one kilogram of dry coal, 30,800 kJ/kg.

Determine: (a) the efficiency of boiler plant including superheater, and (b) the efficiency of boiler and furnace combined. Take \( K_p \) of superheated steam = 2.1 kJ/kg K.

(a) At 15 bar (from steam tables), \( H_s = 2,792.2 \) kJ/kg.

Enthalpy of 1 kg of steam at 15 bar and with 71.7°C superheat,

\[
H_{sup} = H_s + K_p \times \text{degree of superheat} = 2,792.2 + 2.1 \times 71.7 = 2,942.8 \text{ kJ/kg}
\]

Enthalpy of 1 kg of feed water, \( h = (92.6 - 0) \times 4.187 = 387.7 \) kJ/kg

\[\therefore \text{Heat given to 1 kg of feed water in converting it to superheated steam} = H_{sup} - h = 2,942.8 - 387.7 = 2,555.1 \text{ kJ/kg}\]

Moisture in coal = 417.3 × \( \frac{4.42}{100} = 18.4 \) kg per hour.

\[\therefore \text{Dry coal fired per hour} = 417.3 - 18.4 = 398.9 \text{ kg.}\]

Actual evaporation per kg of dry coal, \( m_a = \frac{3,223.8}{398.9} = 8.07 \) kg.

Thermal efficiency of the boiler plant including superheater

\[
\text{Thermal efficiency} = \frac{m_a (H_{sup} - h)}{C.V.} = \frac{8.07 \times (2,555.1)}{30,800} \times 100 = 67.03\%
\]

(b) Combustible in ash per hour = 43.3 × \( \frac{9.68}{100} = 4.2 \) kg

This combustible in the ash is practically carbon whose calorific value may be taken as 34,000 kJ per kg.

Actual heat supplied per hour = heat of dry coal - heat of combustible in the ash

\[
= (398.9 \times 30,800) - (4.2 \times 34,000) = 1,21,43,320 \text{ kJ/hr.}
\]

Heat usefully utilized in the boiler per hour

\[\therefore \text{Heat utilized per hour} = 3,223.8 \times (2,555.1) = 82,37,131 \text{ kJ/hr} \]

\[\therefore \text{Efficiency of the boiler and furnace combined} = \frac{82,37,131}{1,21,43,320} \times 100 = 67.83\% \]

Note: Efficiency of the boiler and furnace combined, is found by using the input based upon the heat given out by the coal actually burnt on the fire grate (not taking...
into account the heat value of the coal which falls through the grate in the ash pit. When solid fuels are used, some coal is always lost with the ash, usually because molten ash freezes around pieces of coal and so prevents combustion. The mass of coal lost is determined by heating samples of ash and measuring the reduction of mass.

**Tutorial-8**

1. What is a steam boiler and what is its function? What are the uses of steam?

2. Explain the following terms used in boiler practice:
   - Boiler shell,
   - Fire grate,
   - Furnace,
   - Setting,
   - Steam space,
   - Mountings,
   - Blowing-off,
   - Gusset stays,
   - Flues.

3. (a) Classify boilers according to various factors. Give the name of at least one boiler of each type.
   (b) Give a diagrammatic sketch and describe the arrangement of the brickwork flues of a Cornish boiler. Indicate on it the path of the furnace gases to the chimney.

4. Describe, giving neat sketches, the construction of the furnace tubes of a Lancashire boiler. Explain how the successive sections are connected and how the furnace tube is fitted to the end plates. Why are Galloway tubes fitted?

5. (a) Describe, with neat sketches, the construction and working of a Lancashire boiler, showing therein the main fittings and the path of the flue gases to the chimney.
   (b) What are the advantages of a Lancashire boiler? What are its principal defects?

6. Describe, with the aid of sketches, the construction and working of a Co-chran boiler. Indicate on it the path of flue gases. What are the advantages of Co-chran boilers?

7. Sketch and describe the construction and working of a locomotive boiler. Describe the method of obtaining draught in this boiler. What are the characteristics of this boiler?

8. (a) Make a neat sketch of a locomotive boiler and explain its working. Describe the method of obtaining draught in such a boiler in the absence of a stack (or chimney) of appreciable height.
   (b) State the advantages and disadvantages of a locomotive boiler.

9. (a) Describe with the aid of sketches either a Lancashire boiler or a water-tube boiler.
   (b) Give an outline sketch showing the arrangement of water tubes and furnace in Babcock and Wilcox water-tube boiler. Indicate on it the path of the furnace gases and the water circulation.

10. (a) Distinguish between Cornish and Lancashire boilers. State their fields of application.
    (b) Distinguish between 'water-tube' and 'fire-tube' boilers and state under what circumstances each type would be used.

11. Mention the chief advantages and disadvantages of water-tube boilers.

12. State the advantages of water-tube boilers over fire-tube boilers and tank boilers.

13. What are the considerations which would guide you in determining the type of boiler to be employed for a specific purpose?

14. Explain the following statements:
   (a) Steam boiler is also known as steam generator.
   (b) Shell or tank type boilers are more suitable for moderate power generation.
   (c) Flat ends of Lancashire and Cornish boilers are stayed.
   (d) Furnace tubes of Lancashire and Cornish boilers are not made in one piece.
   (e) Fire-tube boilers have advantages of low cost and compact design.

15. (a) What are boiler mountings? Give their names.
    (b) What is a water level indicator? Give a sketch and description of any one type of water-level indicator.

16. (a) Draw a neat sketch of a pressure gauge used on a steam boiler, and explain its working.
    (b) Explain the action and give sketches showing the construction of the steam pressure gauge.

17. What is the function of the safety valve? Name the different types of safety valves, and name the boilers on which they are used.
18. Sketch and describe the construction and operation of a dead-weight safety valve and give its advantages and disadvantages.

19. Sketch and describe the construction of any one type of safety valve. In the valve you select explain the method to alter the setting of the valve so as to cause it to blow off at an increased pressure.

20. The diameter of a safety valve of the lever pattern is 9 cm. The weight of the lever is 50 N and centre of gravity is 38 cm from the fulcrum. The movable weight on the lever is 450 N. The weight of the valve is 15 N and distance from the fulcrum to the centre of the valve is 12 cm. Calculate the distance of the movable weight on the lever from the fulcrum in order that the valve may blow off at a steam pressure of 6 bar.

21. (a) What is the purpose of fitting the fusible plug in a boiler? What is its location in the boiler? Name the mountings that give warning of low water in a boiler.
   (b) Describe the construction and working of any one type of stop valve. What is its best location to carry out the function properly?

22. (a) Describe the construction and working of any one type of feed check valve. What is the function of a check valve?
   (b) Sketch and describe any pattern of a blow-off valve or cock. What precautions must be observed in this form of valve?

23. Explain the construction and working principle of a steam injector. State where and when it is used. What are the advantages and disadvantages of a steam injector?

24. Draw a neat sketch of the Babcock and Wilcox water-tube boiler. Name the mountings and accessories that are used on the boiler you have sketched and indicate their positions on the sketch you have drawn.

25. Name the different mountings and accessories with which the Babcock and Wilcox water-tube boiler is fitted. State their uses and give a neat sketch of any one of them.

26. Make a sketch of a water-tube boiler. Show the position of the superheater and economiser, and the path of furnace gases on the sketch you have drawn.

27. (a) What is a man hole? Describe its shape and cover.
   (b) A boiler, fitted with an economiser, generates dry saturated steam at 1.2 N/mm² ab (12 bar). If the feed water enters the economiser at 35°C and leaves at 90°C, find the percentage saving in heat by the use of the economiser.

28. (a) Mention the advantages of installing an air pre-heater with the boiler. Describe construction and working of an air pre-heater.
   (b) Describe with the help of a neat sketch any one type of superheater used with a Lancashire boiler. What are the advantages of installing a superheater with the boiler?
   (c) Steam is raised at 15 bar in a Lancashire boiler fitted with a superheater. Boiler feed is at 30°C and the steam leaves the boiler and enters the superheater with the dryness fraction of 0.95. The temperature of steam leaving the superheater is 300°C. Calculate the heat received per kg of steam in the superheater. Take \( k_p \) for superheated steam as 2.3 kJ/kg K.

29. What are the accessories used for delivering feed water to a boiler? Describe the working of a Duplex feed pump with the help of a neat sketch.

30. Write short notes on the following giving sketches wherever necessary:
   (a) Steam trap, (b) Fusible plug, (c) Economiser, (d) Superheater, (e) Pressure reducing valve, (f) Feed check valve, (g) High-steam and low-water safety valve, (h) Steam drier or Separator, (i) Air pre-heater, and (j) Steam injector.

31. Describe with the help of sketches the following devices fitted on a boiler for removing water particles from steam:
   (i) Anti-priming pipe,
   (ii) Steam separator, and
   (iii) Steam trap.

32. Draw a neat sketch of a Lancashire boiler and indicate on it the positions of its principal mountings. Show also on the sketch the path of the flue gases and the water level in the drum. Enumerate the accessories you would normally find on this type of boiler.

33. What do you understand by the term 'boiler draught'? What are the various types of draughts used in usual practice?
Estimate the minimum height of a chimney required to produce a draught of 16 mm of water, if 19 kg of air are required per kg of fuel burnt on the grate, the mean temperature of flue gases inside the chimney is 330°C and that of atmospheric air is 30°C.

34. Derive an expression connecting the height of a chimney and the draught it produces, in terms of temperature of outside air and the mean flue gas temperature.

Find the draught in mm of water column produced by a chimney 40 m high when the mean temperature of flue gases is 300°C and the temperature of outside air is 27°C, and 19 kg of air are supplied per kg of fuel burnt on the grate.

35. Distinguish between the following:
(i) Natural draught and artificial draught, and
(ii) Forced draught and induced draught.

Why an artificial draught is considered advantageous over a natural draught?

36. Estimate the minimum height of chimney required to produce a draught of 19 mm of water. The atmospheric air temperature is 25°C and the average flue gas temperature is 310°C. Air supplied per kg of fuel burnt is equal to 24 kg. Derive the formula you may use for establishing the height of the chimney.

37. Deduce the expression showing the relation between the draught, the height of the chimney and the temperature of flue gases, air, etc.

How much air will be used per kg of coal burnt in a boiler having a chimney of 45 metres height to produce a draught of 25 mm of water when the temperature of the flue gases in the chimney is 327°C and that of the boiler house is 27°C?

38. What is the function of a boiler chimney? Explain why there is no chimney in the case of a locomotive boiler?

Estimate the mean temperature of the flue gases leaving the chimney 40 m high to produce a draught of 20 mm water column if 19 kg of air are required per kg of fuel burnt on the grate. The temperature of atmospheric air is 30°C.

39. (a) State briefly what do you understand by natural and artificial draughts. What are the advantages of artificial draught over natural draught?
(b) Explain the different system of producing draught in a boiler giving their advantages and disadvantages.

40. Establish a condition of maximum discharge of flue gases through a chimney of a given height.

A chimney has a height of 35 m. The temperature of outside air is 20°C. Find the draught in mm of water when the temperature of chimney gases is such as to cause the mass of the gases discharged in a given time to be maximum.

41. A chimney 40 m high deals with flue gases at 300°C, when the outside air temperature is 27°C. The air supplied for combustion is 19 kg per kg of fuel burnt in the furnace. Calculate:
(i) the draught in mm of water column produced by the chimney,
(ii) the draught produced in terms of height of column of hot flue gases in metres,
(iii) the velocity of flue gases in the chimney, if 60% of the draught is lost in friction at the grate and passages, and
(iv) the draught produced in mm of water, and the temperature of flue gases under the condition of maximum discharge.

[17.92 kg, (i) 21.13 mm; (ii) 32.58 m; (iii) 16 m/sec; (iv) 23.53 mm, 358.6°C]

42. (a) Explain the terms mechanical draught and balanced draught.
(b) Distinguish between fan draught and steam jet draught.
(c) Explain the working principle of the steam jet draught.

43. An induced draught fan produced a draught of 23 mm of water. The temperature of the chimney gases leaving the boiler is 195°C and 18 kg of air is supplied per kg of fuel. If the fuel burnt is 50 kg per minute and the efficiency of the fan is 75%, find the power required to drive the fan. Volume of 1 kg of air at 0°C and 760 mm of Hg may be taken as 0.7734 m³.

[6.312 kW]
44. The following data refer to a boiler equipped with forced draught fan:

Draught produced, 38 mm of water; efficiency of the fan, 60%; fuel burnt, 3,000 kg per hour; temperature of chimney gases, 150°C; temperature of air in the boiler house, 35°C. If 19 kg of air is supplied per kg of fuel, calculate the power required to drive the fan.

What will be the power required if the forced draught fan is substituted by an induced draught fan? Volume of 1 kg of air at 0°C and 760 mm Hg may be taken as 0.7734 m³. Take the efficiency of the induced draught fan as 60%.

45. Explain the following terms as applied to steam boilers:
   (i) Equivalent evaporation from and at 100°C, (ii) Factor of equivalent evaporation, and (iii) Thermal efficiency.

46. The following particulars are taken from the reports of three steam boilers A, B and C:

A - 8.7 kg of dry saturated steam per kg of coal at 3.5 bar, from feed water at 15°C.

B - 9.5 kg of steam per kg of coal at 11 bar and 0.98 dry, from feed water at 60°C.

C - 9.3 kg of steam per kg of coal at 13 bar and with 50°C of superheat, from feed water at 20°C. Take specific heat of superheated steam at constant pressure as 2.3 kJ/kg K.

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

47. What do you understand by “Equivalent evaporation from and at 100°C as applied to a steam boiler?"

The following data were recorded during a test on a steam boiler:

The pressure of steam generated, 10 bar; condition of steam at boiler stop valve, 0.9 dry; temperature of feed water, 25°C; average quantity of steam generated per hour, 1,000 kg; average quantity of coal used per hour, 125 kg; calorific value of coal, 26,000 kJ/kg.

Calculate: (a) the thermal efficiency of the boiler, and (b) the equivalent evaporation from and at 100°C per kg of coal.

48. What do you understand by “factor of equivalent evaporation” of a boiler?

A steam boiler evaporates 5,625 kg of water per hour at a pressure of 11 bar and at a temperature of 250°C. It consumes 750 kg of coal per hour, having calorific value of 32,000 kJ/kg. The feed water temperature is 30°C. Find: (a) the actual evaporation per kg of coal, (b) the factor of equivalent evaporation, (c) the equivalent evaporation from and at 100°C per kg of coal, and (d) the thermal efficiency of the boiler.

Take specific heat of superheated steam at constant pressure as 2.3 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

49. What steps would you take to improve the thermal efficiency of a boiler?

A boiler generates dry saturated steam at a pressure of 11 bar. The feed water is heated by an economiser before it is supplied to the boiler. If the feed water enters the economiser at 30°C and leaves at 79°C, find the percentage saving in heat by the use of the economiser.

50. What do you understand by “evaporative capacity” of a steam boiler?

900 kg of feed water enter the economiser of a boiler per hour. The feed water enters the economiser at 35°C and leaves at 95°C. If 2,000 kg/hr of flue gases pass over the economiser at 320°C, determine the temperature of the flue gases which leave the economiser and pass to the chimney stack. Take the specific heat of the flue gases as 1.005 kJ/kg K and specific heat of water as 4.187 kJ/kg K. Assume that all the heat lost by the flue gases is taken up by the feed water.

51. 850 kg of feed water enter the economiser of a boiler per hour. The feed water enters the economiser at 30°C and leaves at 95°C. If 1,800 kg/hr of flue gases pass over the economiser at 300°C, determine the temperature of the flue gases which leave the economiser and pass to the chimney stack. Take specific heat of flue gases as 1.005 kJ/kg K and specific heat of water as 4.187 kJ/kg K. Assume that all the heat lost by the flue gases is taken up by the feed water.

52. A steam plant consists of an economiser, a boiler and a superheater. During a test lasting for one hour, the following observations were made:

Steam pressure, 13 bar; coal consumed, 700 kg; calorific value of coal, 28,000 kJ/kg; mass of water evaporated, 5,250 kg; temperatures of feed water entering the economiser, 35°C and leaving the economiser,
130°C; dryness fraction of steam leaving the boiler, 0.9; temperature of steam leaving the superheater, 322°C.

Determine: (a) the overall efficiency of the combined plant, and (b) the percentage of the available heat in coal utilized in the economiser, boiler and superheater separately.

Take specific heat of superheated steam at constant pressure as 2.1 kJ/kg K and specific heat of water as 4.187 kJ/kg K.

\[ (a) \ 78.06\%; \ (b) \ 10.65\%, \ 54.8\%, \ 12.61\% \]

53. In a boiler test the following quantities were obtained:

Mean temperature of feed water, 20°C; mean steam pressure, 10 bar; mean steam dryness fraction, 0.92; mass of coal burnt per hour, 130 kg; calorific value of coal, 31,500 kJ/kg; mass of water supplied to the boiler in 5 hours and 24 minutes, 5,500 kg; mass of water in the boiler at the end of the test was less than at the commencement by 500 kg. Calculate: (a) the actual evaporation per kg of coal, (b) the equivalent evaporation from and at 100°C per kg of coal, and (c) the thermal efficiency of the boiler.

\[ (a) \ 8.54 \ kg; \ (b) \ 9.58 \ kg; \ (c) \ 68.68\% \]

54. A boiler produces 1,700 kg of dry saturated steam per hour at a pressure of 10 bar. The feed water is heated by an economiser to a temperature of 120°C. If 190 kg of coal of a calorific value 31,000 kJ/kg are fired per hour, and it is ascertained that 8 per cent of the coal is unburnt, calculate:

(a) the thermal efficiency of the boiler, and
(b) the thermal efficiency of the boiler and grate combined.

Take specific heat of water as 4.187 kJ/kg K.

\[ (a) \ 71.39\%; \ (b) \ 65.8\% \]

55. In a boiler trial of 10 hours duration, 600 kg of coal was consumed and the water evaporated was 5,000 kg. The mean steam pressure was 8 bar and the steam produced was dry saturated. The coal contained 3 per cent of moisture and 4 per cent of ash on mass basis. The mean feed water temperature was 35°C. Calorific value of coal was 30,000 kJ/kg.

Determine: (a) the thermal efficiency of the boiler, and (b) the equivalent evaporation from and at 100°C per kg of combustible.

Take specific heat of water as 4.187 kJ/kg K.

\[ (a) \ 72.85\%; \ (b) \ 10.56 \ kg/kg \ of \ combustible \]

56. State what are the principal heat losses in a boiler plant. State what methods are adopted to minimise the losses.