

Natubhai V. Patel College of Pure & Applied Sciences
S. Y. B.Sc. Semester-4
Industrial chemistry/ IC (Vocational)
US04CICV01/US04CICH02: Chemical Plant Utilities
UNIT – 4

Syllabus

Internal combustion engines and external combustion engine, Steam power plant, Its working and thermodynamic analysis, Otto engine and Diesel engine.
Steam boilers – Their classification, Steam generation, Conditions of steam, Steam table.

4.0 INTERNAL COMBUSTION ENGINE

In an internal combustion engine a fuel is burned within the engine itself and the combusting products serve as the working medium acting for example piston in a cylinder.

4.1 CLASSIFICATION OF INTERNAL COMBUSTION ENGINE

There are several classifications according to

4.1.1 Types of fuel used

- Petrol engine
- Diesel engine
- Gas engine

4.1.2 Types of thermo cycles

- Otto cycle
- Diesel cycle

4.1.3 Speed

- low speed
- medium speed
- high speed

4.1.4 Cooling system

- Air cooled
- Water cooled

4.1.5 Type of Ignition

- Spark ignition
- compression ignition

4.1.6 Arrangement of piston

- Vertical
- Inclined
- Horizontal

4.1.7 Number of cylinders

- Single
- Multi cylinders

4.1.8 Types of application

- Stationary
- Automatic
- Aircraft

4.2 COMPARISON OF EXTERNAL AND INTERNAL COMBUSTION ENGINE

External Combustion Engine

- Example steam power plant
- Working fluid - liquid H₂O which is inert returns back to its original state
- It is a cyclic process, from liquid H₂O steam is produced and returns back in form of liquid
- Efficiency – low
- Heat transfer through metal wall is necessary
- Very large size
- Suitable for stationary application.
- It's object to generate power

Internal Combustion Engine

- Petrol and diesel engine
- Working fluid- fuel air mixture and don't returns to its original state
- It is noncyclic process. Air fuel mixture burns and products of Combustion rejected to surroundings
- High efficiency
- Heat transfer at high temperature, is necessary because heat is available within the work producing machine
- Small size
- Suitable for non-stationary application
- It's object to generate mechanical energy

4.3 THE STEAM POWER PLANT

In a steam power plant, the steam is an inert medium to which heat is transferred from burning fuel or from nuclear reactor. It is therefore characterized by large heat transfer surfaces

- For the absorption of heat by large heat transfer surfaces
- For the rejection of heat from the steam at a relatively low temperature in the condenser

The disadvantage is that when heat must be transferred through walls (as through the metal walls of the boiler tubes) the ability of the walls to withstand high temperatures and pressures imposes a limit on the temperature of heat absorption. In an internal combustion engine, on the other hand a fuel is burned within the engine itself and the combustion products serves as the working medium, acting for example on a piston in a cylinder. High temperature are internal and do not involve heat transfer surfaces.

Burning of fuel within the internal combustion engine complicates thermodynamics analysis. Moreover, fuel and air flow steadily into an internal combustion engine and combustion products flow steadily out of it; there is no working medium that undergoes a cyclic process, as does the steam in a steam power plant. However, for making simple analysis one imagine cycle engines with air as the working fluid that are equivalent in performance to actual internal combustion engines. In addition the combustion step is replaced by the addition to the air of an equivalent amount of heat. In each of the following sections, we first present a qualitative description of an internal combustion engine.

Quantitative analysis is then made of an ideal cycle in which air, treated as an ideal gas with constant heat capacities, is the working medium.

The Carnot-engine cycle which is operates reversibly and consists of two isothermal steps connected by two adiabatic steps. In the isothermal step at higher temperature T_H heat IQ_H is absorbed by the working fluid of the engine, and in the isothermal step at lower temperature T_c , heat IQ_c is discarded by the fluid. The work produced is $|W| = IQ_H - IQ_c$ and the thermal efficiency of tie Carnot engine is

$$\eta = \frac{|W|}{|Q_H|} = 1 - \frac{T_c}{T_H}$$

Clearly, η increases as T_H increases and as T_c decreases. Although the efficiencies of practical heat engines are lowered by irreversibility, it is still true that their efficiencies are increased when the average; temperature at winch heat is absorbed is increased and when the average temperature at which, heat is rejected is decreased.

Figure1 shows a simple steady-state steady-flow process in which steam generated in a boiler is expanded in an adiabatic turbine to produce work. The discharge stream from the turbine passes to a condenser from which it is pumped adiabatically back to the boiler.

The power produced by the turbine is much greater than that required by the pump, and the net power output is equal to the difference between the rate of heat input in the boiler \dot{Q}_H and the rate of heat rejection in the condenser \dot{Q}_C .

The property changes of the fluid as it flows through the individual pieces equipment may be shown as lines on a TS diagram, as illustrated in Figure 2. The sequence of lines represents a cycle. Indeed, the particular cycle shown is a Carnot cycle. In this idealization, step 1→2 is the isothermal absorption of heat T_H and is represented by a horizontal line on the TS diagram. This vaporization process occurs also at constant pressure and produces saturated-vapor steam from saturated-liquid water. Step 2→3 is a reversible, adiabatic expansion of saturated vapor to a pressure at which $T^{\text{sat}} = T_C$. This isentropic expansion process is represented by a vertical line on the TS diagram and produces a wet vapor. Step 3→4 is the isothermal rejection of heat at temperature T_C , and is represented by a horizontal line on the TS diagram. It is a condensation process, but is incomplete. Step 4→1 takes the cycle back to its origin, producing saturated-liquid water at point 1. It is an isentropic compression process represented by a vertical line on the TS diagram.

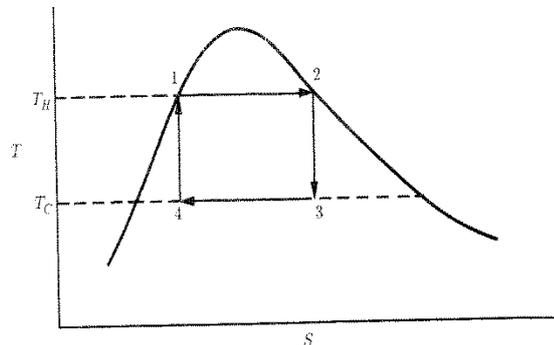
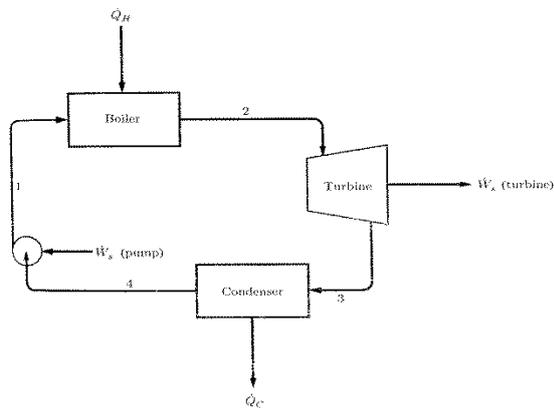


Figure 1: Simple steam power plant.

Figure 2: Carnot cycle on a TS diagram.

The thermal efficiency of this cycle is that of a Carnot engine, given by

$$\eta = 1 - \frac{T_C}{T_H}$$

As a reversible cycle, it could serve as a standard of comparison for actual steam power plants. However, severe practical difficulties attend the operation of equipment intended to carry out steps 2→3 and 4→1. Turbines that take in saturated steam produce an exhaust with high liquid content, which causes severe erosion problems. Even more difficult is the design of a pump that takes in a mixture of liquid and vapor (point 4) and discharges a saturated liquid (point 1).

For these reasons, an alternative model cycle is taken as the standard, at least for fossil-fuel-burning power plants. It is called the Rankine cycle, and differs from the cycle of Figure 2 in two major respects. First, the heating step 1→2 is carried well beyond vaporization, so as to produce a superheated vapor, and second, the cooling step 3→4 brings about complete condensation, yielding saturated liquid to be pumped to the boiler. The Rankine cycle therefore consists of the four steps shown by Figure 8.3, and described as follows:

1 → 2 A constant-pressure heating process in a boiler. The step lies along an isobar (the pressure of the boiler), and consists of three sections: heating of subcooled liquid water to its saturation temperature, vaporization at constant temperature and pressure, and superheating of the vapor to a temperature well above its saturation temperature.

- 2→3 Reversible, adiabatic (isentropic) expansion of vapor in a turbine to the pressure of the condenser. The step normally crosses the saturation curve, producing a wet exhaust. However, the superheating accomplished in step 1 → 2 shifts the vertical line far enough to the right on Fig. 8.3 that the moisture content is not too large.
- 3→4 A constant-pressure, constant-temperature process in a condenser to produce saturated liquid at point 4.
- 4→1 Reversible, adiabatic (isentropic) pumping of the saturated liquid to the pressure of the boiler, producing subcooled liquid. The vertical line (whose length is exaggerated in Figure 3) is very short, because the temperature rise associated with compression of a liquid is small.

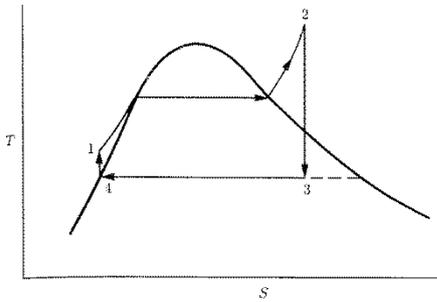


Figure 3: The Rankine cycle.

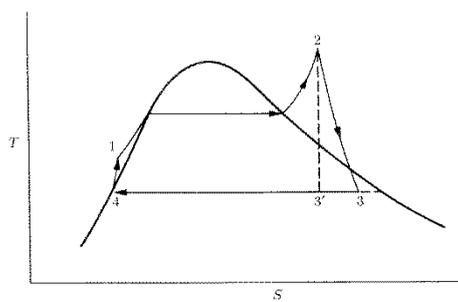


Figure 4 Simple practical power cycle

Power plants can be built to operate on a cycle that departs from the Rankine cycle solely because of the irreversibilities of the work-producing and work-requiring steps. We show in figure 4 the effects of these irreversibilities on steps 2→3 and 4→1. The lines are no longer vertical, but tend in the direction of increasing entropy. The turbine exhaust is normally still wet, but as long as the moisture content is less than about 10 percent, erosion problems are not serious. Slight sub-cooling the condensate in the condenser may occur, but the effect is inconsequential.

The boiler serves to transfer heat from a burning fuel to the cycle, and the condenser transfers heat from the cycle to the surroundings. Neglecting kinetic- and potential-energy changes reduces the energy relations, in equations (a) and (b),

$$\Delta \left(H + \frac{1}{2}u^2 + zg \right) m = Q + Ws \quad \dots\dots\dots(a)$$

$$\Delta H + \frac{\Delta u^2}{2} + g\Delta z = Q + Ws \quad \dots\dots\dots(b)$$

in either case to

$$Q = m\Delta H \quad \dots\dots\dots (1)$$

and

$$Q = \Delta H \quad \dots\dots\dots (2)$$

4.4 THE OTTO ENGINE

The most common internal-combustion engine, because of its use in automobiles, is the Otto engine. Its cycle consists of four strokes, and starts with an intake stroke at essentially constant pressure, during which a piston moving outward draws a fuel/air mixture into a cylinder. This is represented by line 0 →1 in figure 5.

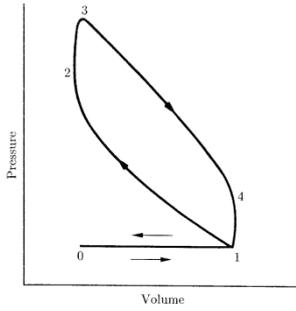


Figure 5: Otto internal combustion – engine cycle

During the second stroke (1→2→3), all valves are closed, and the fuel/air mixture is compressed, approximately adiabatically, along line 1 → 2; the mixture is then ignited, and combustion occurs so rapidly that the volume remains nearly constant while the pressure rises along line 2 → 3. It is during the third stroke (3→4→1) that work is produced. The high-temperature, high-pressure products of combustion expand, approximately adiabatically, along line 3→4; the exhaust valve then opens and the pressure falls rapidly at nearly constant volume along line 4 → 1. During the fourth or exhaust stroke (line 1→0), the piston pushes the remaining combustion gases (except for the contents of the clearance volume) from the cylinder. The volume plotted in the figure is total volume of gas contained in the engine between the piston and the cylinder head.

The effect of increasing the compression ratio, defined as the ratio of the volumes at the beginning and end of the compression stroke, is to increase the efficiency of the engine, i.e., to increase the work produced per unit quantity of fuel.

We demonstrate this for an idealized cycle, called the air-standard cycle, shown in above figure. It consists of two adiabatic and two constant-volume steps, which comprise a heat-engine cycle for which air is the working fluid. In step DA, sufficient heat is absorbed by the air at constant volume to raise its temperature and pressure to the values resulting from combustion in an actual Otto engine. Then the air is expanded adiabatically and reversibly (step AB), cooled at constant volume (step BC), and finally compressed adiabatically and reversibly to the initial state at D.

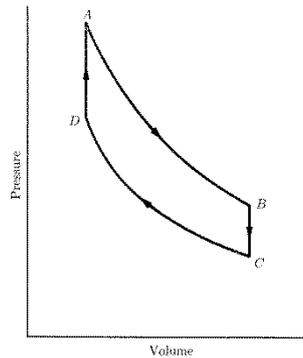


Figure 6: Air-standard Otto cycle.

The thermal efficiency η of the air-standard cycle shown in above figure 6 is simply

$$\eta = \frac{-Ws(net)}{Q_{DA}} = \frac{Q_{DA} + Q_{BC}}{Q_{DA}} \dots\dots\dots(3)$$

For 1 mol of air with constant heat capacities,

$$Q_{DA} = C_V(T_A - T_D)$$

$$Q_{BC} = C_V(T_C - T_B)$$

Substituting these expressions in Equation (3) gives

$$\eta = \frac{C_V(T_A - T_D) - C_V(T_B - T_C)}{C_V(T_A - T_D)}$$

or

$$\eta = 1 - \frac{T_B - T_C}{T_A - T_D} \dots\dots\dots(4)$$

The thermal efficiency is also related in a simple way to the compression ratio $r = V_C/V_D$. We replace each temperature in Equation (4) by an appropriate group PV/R , the ideal-gas equation. Thus

$$T_B = \frac{P_B V_B}{R} = \frac{P_B V_C}{R}$$

$$T_C = \frac{P_C V_C}{R}$$

$$T_D = \frac{P_D V_D}{R}$$

Substituting into Equation (4) leads to

$$\eta = 1 - \frac{V_C}{V_D} \left(\frac{P_B - P_C}{P_A - P_D} \right) = 1 - r \left(\frac{P_B - P_C}{P_A - P_D} \right) \dots\dots\dots (5)$$

For the two adiabatic, reversible steps, we have $PV^\gamma = \text{const.}$ Hence

$$P_A V_D^\gamma = P_B V_C^\gamma \quad (\text{Since } V_D = V_A \text{ and } V_C = V_B)$$

$$P_C V_C^\gamma = P_D V_D^\gamma$$

These expressions are combined to eliminate the volumes

$$\frac{P_B}{P_C} = \frac{P_A}{P_D}$$

Also,

$$\frac{P_C}{P_D} = \left(\frac{V_D}{V_C} \right)^\gamma = \left(\frac{1}{r} \right)^\gamma$$

These equations transform Equation (5) as follows

$$\eta = 1 - r \frac{(P_B - P_C - 1) P_C}{(P_A / P_D - 1) P_D} = 1 - r \frac{P_C}{P_D}$$

Or

$$\eta = 1 - r \left(\frac{1}{r} \right)^\gamma = 1 - \left(\frac{1}{r} \right)^{\gamma-1} \dots\dots\dots (6)$$

This equation shows that the thermal efficiency increases rapidly with the compression ratio r at low values of r , but more slowly at high compression ratios. This agrees with the results of actual tests on Otto engines.

4.5 THE DIESEL ENGINE

The Diesel engine differs from the Otto engine primarily in that the temperature at the end of compression is sufficiently high that combustion is initiated spontaneously. This higher temperature results because of a higher compression ratio that carries the compression step to a higher pressure. The fuel is not injected until end of the compression step, and then is added slowly enough that the combustion process occurs at approximately constant pressure.

For the same compression ratio, the Otto engine has a higher efficiency than the Diesel engine. However, pre-ignition limits the compression ratio attainable in the Otto engine. The Diesel engine therefore operates at higher compression ratios and consequently at higher efficiencies.

4.6 DIFFERENCE BETWEEN PETROL ENGINE AND DIESEL ENGINE

- | Petrol engine | Diesel engine |
|--|------------------------------|
| ➤ Fuel - Petrol | ➤ Diesel |
| ➤ Working cycle - Otto cycle(const vol.) | ➤ Diesel cycle (const press) |

- | | |
|---|--------------------------------------|
| ➤ Operation ratio - Low (5 to 10) | ➤ High (11 to 22) |
| ➤ Require ignition-external source of power | ➤ It do not required external source |
| ➤ Engine - Compact and less strong | ➤ Huge in size & more stronger |
| ➤ Cost – Low | ➤ High |
| ➤ Operation life - Short | ➤ Long |
| ➤ Pre-ignition - Possible | ➤ Not possible |
| ➤ Efficiency - 25 to 30% | ➤ Up to 45% |
| ➤ Application - Light duty | ➤ Heavy duty |

4.7 BOILER OR STEAM GENERATOR

A steam generator or a boiler is defined as a closed vessel in which water is converted into steam by burning of fuel in presence of air at desired temperature, pressure and at desired mass flow rate.

According to American society of Mechanical Engineers (A.S.M.E.), a steam generator or a boiler is defined as "a combination of apparatus for producing, finishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized.

Boiler or a steam generator is example of heat exchanger. (Heat exchangers are defined as a mechanical device for exchanging heat between hot fluid and cold fluid with maximum rate, with minimum investment and with minimum running cost).

4.7.1 Principle

In case of boiler, any type of fuel burn in presence of air and form flue gases which are at very high temperature (hot fluid). The feed water at atmospheric pressure and temperature enters the system from other side (cold fluid). Because of exchange of heat between hot and cold fluid, the cold fluid (water) temperature raises and it form steam. The flue gases (hot fluid) temperature decreases and at lower temperature hot fluid is thrown into the atmosphere via stack/chimney.

The function of boiler is to facilitate the generation of steam by providing the necessary heat transfer surfaces, space for storage of water and steam, furnace for burning the fuel and necessary equipments for control of safe operation The large variety of available boilers have cylindrical drum or shell and tubes except for the once through boilers in which drum is not used.

4.7.2 Function of a boiler

The steam generated is employed for the following purposes

- Used in steam turbines to develop electrical energy
- Used to run steam engines
- In the textile industries, sugar mills or in chemical industries as a cogeneration plant
- Heating the buildings in cold weather
- Producing hot water for hot water supply

4.7.3 IBR and non-IBR boilers

Boilers generating steam at working pressure below 10 bar and having water storage capacity less than 22.75 litres are called non-IBR boilers (Indian Boiler Regulations).

Boilers outside these limits are covered by the IBR and have to observe certain specified conditions before being operated.

4.8 CLASSIFICATION OF BOILERS

The different ways to classify the boilers are as follows

4.8.1 According to location of boiler shell axis

- Horizontal
- vertical
- Inclined boilers.

When the axis of the boiler shell is horizontal the boiler is called horizontal boiler. If the axis is vertical, the boiler is called vertical boiler and if the axis of the boiler is inclined it is known as inclined boiler.

Examples

Horizontal boiler: Lancashire boiler, Locomotive boiler, Babcock and Wilcox boiler etc.

Vertical boiler: Cochran boiler, vertical boiler etc.

4.8.2 According to the flow medium inside the tubes

- Fire tube
- Water tube boilers.

The boiler in which hot flue gases are inside the tubes and water is surrounding the tubes is called fire tube boiler. When water is inside the tubes and the hot gases are outside, the boiler is called water tube boiler.

Examples

Fire tube boilers: Lancashire, locomotive, Cochran and Cornish boiler

Water tube boiler: Simple vertical boiler, Babcock and Wilcox boiler.

4.8.3 According to boiler pressure

According to pressure of the steam raised the boilers are classified as follows

- Low pressure (3.5 - 10 bar)
- Medium pressure (10-25 bar)
- High pressure boilers (> 25 bar)

Examples

Low pressure: Cochran and Cornish boiler

Medium pressure: Lancashire and Locomotive boiler

High pressure: Babcock and Wilcox boiler.

4.8.4 According to the draft used

- Natural draft
- Artificial draft boilers

Boilers need supply of air for combustion of fuel. If the circulation of air is provided with the help of a chimney, the boiler is known as natural draft boiler. When either a forced draft fan or an induced draft fan or both are used to provide the flow of air the boiler is called artificial draft boiler.

Examples

Natural draft boiler: Simple vertical boiler, Lancashire boiler.

Artificial draft boiler: Babcock and Wilcox boiler, Locomotive boiler.

4.8.5 According to method of water circulation

- Natural circulation
- Forced circulation

If the circulation of water takes place due to difference in density caused by temperature of water, the boiler is called natural circulation boiler. When the circulation is done with the help of a pump the boiler is known as forced circulation boiler.

Examples

Natural circulation: Babcock & Wilcox boiler, Lancashire boiler

Forced circulation: Velox boiler, Lamont boiler, Loffler boiler

4.8.6 According to furnace position

- Internally fired
- Externally fired boilers

When the furnace of the boiler is inside its drum or shell, the boiler is called internally fired boiler. If the furnace is outside the drum the boiler is called externally fire boiler.

Examples

Internally fired boiler: Simple vertical boiler Lancashire boiler, Cochran boiler

Externally fired boiler: Babcock and Wilcox boiler

4.8.7 According to type of fuel used

- Solid
- Liquid
- Gaseous
- Electrical
- Nuclear energy fuel boilers

The boiler in which heat energy is obtained by the combustion of solid fuel like coal or lignite is known as solid fuel boiler. A boiler using liquid or gaseous fuel for burning is known as

liquid or gaseous fuel boiler. Boilers in which electrical or nuclear energy is used for generation of heat are respectively called as electrical energy headed boilers and nuclear energy heated boiler.

4.8.8 According to number of Tubes

- Single-tube
- Multi-tube boiler

A boiler having only one fire tube or water tube is called a single, tube boiler. The boiler having two or more, fire or water tubes is called multi tube boiler.

Examples

Single tube boiler: Cornish boiler, Vertical boiler.

Multi-tube boiler: Lancashire boiler, Locomotive boiler, Babcock and Wilcox boiler.

4.8.9 According to Boiler Mobility

- Stationary
- Portable
- Marine boilers

When the boiler is fixed at one location and cannot be transported easily it is known as stationary boiler. If the boiler can be moved from one location to another it is known as portable boiler. If the boiler can be moved from one location to another it is known as a portable boiler. The boilers which can work on the surface of water are called marine boilers.

Examples

Stationary: Lancashire, Babcock and Wilcox boiler, vertical boiler

Portable: Locomotive boiler.

Marine: Marine boilers

4.9 FACTORS AFFECTING THE SELECTION OF A BOILER

- Size of drum (Diameter and length)
- Rate of steam generation(kg/hr)
- Heating surface (Square meters)
- Working pressure (bar)
- No. of tubes / drum
- Type of boiler
- Manufacturer of boiler
- Initial cost
- Quality of steam
- Repair and inspection facility

4.10 COMPARISON BETWEEN WATER-TUBE AND FIRE TUBE BOILERS

Water Tube boiler	Fire Tube boiler
➤ Water is inside the tube and flue gases surrounded to it.	➤ Flue gases inside the tube and water surrounded to it.
➤ Operating pressure is up to 170-180 bar (high pressure boilers).	➤ Operating pressure is up to 25 bar (low and medium pressure boilers).
➤ Steam generation rate is very high (more than 3000 kg/hr)	➤ Less steam generation rate.
➤ Suitable for power plants.	➤ Suitable for small industries.
➤ Chance of explosion is more due to high steam pressure.	➤ Chance of explosion is less due to low steam pressure.
➤ Provide steam in power plants to develop electrical energy.	➤ Provide steam in chemical and pharmaceutical industries.
➤ Small chance of scale formation due to flue gases are in shell	➤ More chance of scale formation
➤ Example: Bobcock and Wilcox boiler	➤ Example: Vertical boiler, locomotive boiler, Lancashire boiler.

4.11 SIMPLE VERTICAL BOILER

4.11.1 Classification

Vertical, natural circulation, natural draft, single tubular, stationary, medium pressure, solid fuel fired, fired tube boiler with internally located furnace.

4.11.2 Construction and working

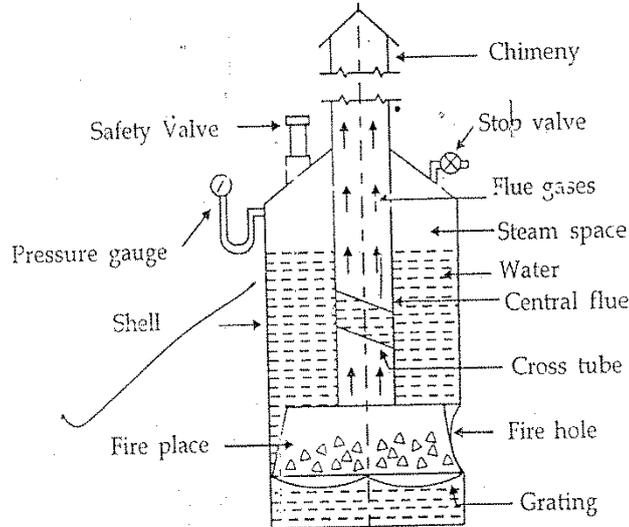


Figure: Simple Vertical boiler

Figure depicts a typical water tube boiler of early period. It has a cylindrical fire box surrounded by a cylindrical water shell connected by one inclined cross tube for improved water circulation. It is provided with standard safety control and inspection mountings.

Boiler drum is filled with water, the flue gas from the furnace rise in the tube. The exchange of heat takes place between water and flue gases. The water temperature raises and it converts into steam. The flue gases temperature drops and low temperature flue gases enters into environment via chimney. Due to provision of cross tube, the total heat transfer area increases and more amount of steam is available with the same amount of flue gases. They can built for small capacity and occupy small space. The boiler is fitted with all the mountings as per IBR.

4.12 STEAM BOILER MOUNTAINS

In accordance with the Indian boiler regulations the following mountings should be fitted to boilers.

- **Safety valves:** The function of the valve is to blow off the steam when the pressure of the steam in the boiler exceeds the working pressure
- **Water level Indicator:** Its function is to indicate level of water, its upper and open in steam space and lower and opens to water space
- **Pressure gauge:** It is for indicating the pressure of steam in a boiler
- **Steam stop valve:** It stops or allows the flow of steam from the boiler to the steam pipe.
- **Feed check valve:** It allows or stops the supply of water to the boiler
- **Blow off cock:** It is for removal of sediment periodically collected at the bottom of the boiler
- **Man hole:** It is provided in opening from which a man can enter in a boiler for cleaning
- **Fusible plug:** Its function is to extinguish fire in the furnace of a boiler when the water level in the boiler fails to an unsafe extent thereby preventing the explosion which may takes place furnace plate

4.13 BOILER ACCESSORIES

- Economizers
- Air pre-heaters

- Super heaters
- Feed pump
- Injectors

4.13.1 Economizers

Using economizer some of the heat recovered and sent back to the boilers in the feed water if an economizer is placed between the boiler and chimney.

The waste fire gases flow outside the economizer tubes and heat is transferred to the fuel water which flows upward inside the tubes. The external surfaces of the tubes are kept free from soot by scrapers which travels slowly and continuously up and down the tubes.

Advantages

- Fuel economy
- Long life of the boiler

4.13.2 Air pre-heaters

Air pre-heaters is installed between the economizer and the chimney and it abstracts heat from the fire gases and transfers to air a portion of the heat that otherwise could pass up the chimney to waste.

4.13.3 Super heaters

Steam consumption is reduced with the use of superheated super heater heats the steam produced also production in condensation losses takes place.

4.13.4 Feed pumps

It is used to pump the water from storage to boiler.

4.13.5 Injectors

It is also used to pump the water with for to the boiler.

4.14 CONDITIONS OF STEAM

Steam may occur in any of the following conditions

- Saturated steam which may be either dry or wet
- Super heated steam
- Supersaturated steam

4.14.1 Saturated steam

Saturated steam is any steam which cannot, have heat abstracted from it or be compressed at constant temperature without partially condensing. Saturated steam is a vapour at the temperature corresponding to the boiling point of the liquid at the imposed pressure.

4.14.2 Dry saturated steam and wet steam

If saturated steam does not contain any water, it is known as dry saturated steam. It contains just sufficient heat energy to maintain all of the water in a gaseous state, if saturated steam contains liquid particles, it is known as wet steam. It does not contain sufficient heat energy to maintain all water in gaseous states.

4.14.2.1 Dryness fraction of steam (x)

The proportion of water particles in the steam varies in case of wet steam. Therefore it is necessary to define the quality of the wet steam.

The dryness fraction of steam (x) is the ratio of mass of actual dry-saturated steam to the known quantities of total mass of wet steam.

Dryness fraction (x) = $\frac{\text{Mass of dry saturated steam in given steam}}{\text{Total mass of given wet steam}}$

$$x = \frac{m_s}{m_s + m_w}$$

Where m_s = mass of dry saturated steam in given mass of wet steam

m_w = mass of suspended water particles in the given mass of wet steam

Dryness fraction is a dimensionless term. The value of dryness fraction varies between zero and one i.e. $0 < x < 1$.

$x = 0$ for saturated liquid and $x = 1$ for dry saturated steam.

4.14.2.2 Wetness fraction

It is defined as ratio of the mass of suspended water particles in the given mass of wet steam to the total mass of given wet steam.

$$\begin{aligned} \text{Wetness fraction} &= \frac{m_w}{m_w + m_s} \\ &= \frac{m_w + m_s - m_s}{m_w + m_s} \\ &= \frac{m_w + m_s}{m_w + m_s} - \frac{m_s}{m_w + m_s} \\ &= 1 - \frac{m_s}{m_w + m_s} \\ &= 1 - x \end{aligned}$$

Wetness fraction = 1 - x

4.14.2.3 Priming

The wetness fraction expressed in percentage is known as priming.

$$\text{Priming} = 100 X (1 - x)$$

4.14.3 Dry saturated steam

The steam available at its saturation temperature corresponding to the given pressure and contain no moisture particles in suspended form is known as dry saturated steam.

The dryness fraction of dry saturated steam is one (x = 1).

4.14.4 Superheated steam

If the temperature of the steam is greater than that of the boiling point corresponding to the pressure of steam generation, the steam is known as superheated steam. The temperature of the steam may be increased above the saturation temperature by adding heat to steam, after all the water has been vaporized or after the steam has been separated from contact with water.

4.14.5 Supersaturated steam

Supersaturated steam at a particular saturation pressure has temperature loss and density greater than the corresponding values given in steam tables.

4.15 STEAM TABLES

The values tabulated in the steam tables are determined accurately by experiments. These values form the basis for many calculations concerned with steam engineering. These tables are to be used because vapours do not obey general gas law. The values given in the tables are for one kg of dry saturated steam but these values can also be employed for wet steam calculations.

4.15.1 Sensible heat

It is denoted by the letter *h_f* in steam tables. It is the quantity of heat in kJ required to raise the temperature of 1 kg of water from 0° C to the saturation temperature at which water begins to boil at the given pressure *P*.

4.15.2 Latent heat of vaporization

It is denoted by the letter *h_{fg}* in steam tables. It is the quantity of heat required to convert 1 kg of water at saturation temperature for a given pressure to one kg of dry saturated steam at the pressure *P*.

4.15.3 Enthalpy of steam

The first law of thermodynamics for the non-flow process is represented by

$$q = \Delta u + p dv$$

For initial state 1 to the final state 2.

$$\begin{aligned} q &= (u_2 - u_1) + P (v_2 - v_1) \\ &= (u_2 + Pv_2) - (u_1 + Pv_1) \\ &= h_2 - h_1 \\ &= \Delta h \end{aligned}$$

= change in specific enthalpy

Supplied heat = change in specific enthalpy for non-flow process at constant pressure processes.

4.15.4 Enthalpy of liquid (h_f)

The water is available at 0°C (state 1). By supply of heat the temperature of water raise and each up to state 2.

Enthalpy of liquid (h_f) = C_{p water} (t_f - 0) at given P; (kJ/kg)
 where, C_{p water} = Specific heat of water = 4.187 kJ/kg K
 t_f = temperature of water (°C)

4.15.5 Enthalpy of dry saturated steam (h_g)

It may be defined as the amount of heat required for 1 kg of water at 0°C to convert into 1 kg of dry saturated steam at given pressure. It is denoted by h_g.

h_g = h_f + h_{fg}

kJ/kg at given pressure

$$\left\{ \begin{array}{l} \text{Heat requires to raise} \\ \text{the temperature of} \\ \text{1kg of water to its} \\ \text{boiling point} \\ \text{temperature} \\ \text{of given ptesure} \end{array} \right\} + \left\{ \begin{array}{l} \text{Heat requires to} \\ \text{convert all the water} \\ \text{into dry saturated} \\ \text{steam at boiling} \\ \text{point temperature} \\ \text{at given ptesure} \end{array} \right\}$$

4.15.6 Enthalpy of wet steam

Wet steam contains some moisture particles in suspended form along with steam.

Enthalpy of wet steam (h) = h_f + x h_{fg} at given p (kJ/kg)

Enthalpy of wet steam (h) = $\left\{ \begin{array}{l} \text{Heat requires to raise} \\ \text{the temperature of} \\ \text{1kg of water to the} \\ \text{boiling point} \\ \text{temperature} \end{array} \right\} + \left\{ \begin{array}{l} \text{Heat requires to} \\ \text{convert the same} \\ \text{water into steam} \\ \text{with dryness} \\ \text{fraction x} \end{array} \right\}$

4.15.7 Enthalpy of superheated steam (h_{sup})

It is defined as the amount of heat required to convert 1 kg of water at its freezing point temperature to steam at its superheated temperature (t_{sup}) for given pressure.

∴ Enthalpy of superheated = h_f + h_{fg} + C_{ps} (t_{sup} - t_{sat})
 steam (h_{sup})

h_{sup} = h_g + C_{p steam} (t_{sup} - t_{sat}) at given p; kJ/kg

$$h_{sup} = \left\{ \begin{array}{l} \text{Heat requires to raise} \\ \text{the temperature of} \\ \text{1kg of water to the} \\ \text{boiling} \\ \text{temperature} \end{array} \right\} + \left\{ \begin{array}{l} \text{Heat requires to} \\ \text{convert the same} \\ \text{water into dry} \\ \text{saturated steam} \\ \text{at the same} \\ \text{temperature} \end{array} \right\} + \left\{ \begin{array}{l} \text{Heat requires to convert} \\ \text{the dry saturated steam} \\ \text{into superheated steam} \\ \text{at superheated} \\ \text{temperature (t}_{sup}) \end{array} \right\}$$

C_{p steam} = Specific heat of superheated steam
 = any value between 2 to 2.2 kJ/kg K

t_{sup} = Superheated temperature of steam (°C)

t_{sat} = Saturation temperature at given pressure (°C)

4.15.8 Degree of superheat

The temperature difference between the superheat steam temperature (t_{sup}) and the saturated steam (t_{sat}) at given pressure is known as degree of superheat.

Degree of superheat = (t_{sup} - t_{sat})

4.15.9 Specific volume of steam

The specific volume is the volume occupied by the unit mass of a substance. It is expressed in m³/kg. The volume of water and steam increases with the increase in temperature.

4.15.10 Specific volume of saturated water (v_a)

It is defined as the volume occupied by 1 kg of water at the saturation temperature at a given pressure.

4.15.11 Specific volume of dry saturated steam (v_g)

The volume occupied by 1 kg of dry saturated steam at a given pressure known as specific volume of dry saturated steam.

4.15.12 Specific volume of wet steam

Consider 1 kg of wet steam with dryness fraction x . This steam contains

- x kg of dry steam and
- $(1 - x)$ kg of water molecules in suspension

Specific volume of wet steam = Volume of dry steam at given pressure + Volume of water molecules in suspension

$$v = xv_g + (1-x)v_f$$

Generally, $(1 - x)v_f$ is very low and is often neglected

$$v = xv_g \text{ m}^3/\text{kg} \quad \dots (4.10)$$

The equation may be used to calculate the dryness fraction of steam.

4.15.13 Specific Volume of superheated steam

It is the volume occupied by 1 kg of superheated steam at a given pressure and superheated temperature, and is denoted as v_{sup} .

The superheated steam behaves like a perfect gas, therefore its specific volume is determined approximated applying Charle's law.

$$\frac{v_g}{T_s} = \frac{v_{sup}}{T_{sup}}$$

$$v_{sup} = v_g \frac{T_{sup}}{T_{sat}}$$

- Wehre,
- v_g = Specific volume of dry saturated steam of pressure p , m^3/kg
 - T_1 = Saturation temperature at pressure p , K
 - T_{sup} = Superheated temperature, K
 - v_{sup} = Specific volume of superheated steam at pressure p , m^3/kg

If given volume of steam, v is less than the specific volume of steam v_g at given pressure, then given steam is wet.

- If v is equal to v_g at given pressure, the given steam is dry and saturated.
- If v is greater than v_g at given pressure, the given steam is superheated steam.

4.15.14 Internal energy of steam

The enthalpy or the total heat energy of dry saturated steam at a given pressure will be equal to the sum of the sensible heat, latent heat and external work of evaporation. But the heat energy of external work of evaporation is not present in the steam as it has been spent in doing external work. The actual energy possesses in the steam comprises if only the sensible heat and latent heat. This actual energy stored in the steam is called internal energy. It is obtained by subtracting the external work of evaporation from the enthalpy and is denoted by u .

Definition

Internal energy of dry steam:

$$u_g = h_g - pv_g \text{ kJ/kg}$$

Internal energy of wet steam

$$u = hf - xh_{fg} - pxv_g \text{ kJ/kg}$$

Internal energy of superheated steam:

$$u_{sup} = h_{sup} - pv_{sup} \text{ kJ/kg}$$

4.15.15 Internal latent heat

It is algebraic difference between the enthalpy of evaporation at given pressure and work of evaporation.

$$\text{Internal latent heat} = h_{fg} - pv$$

- Where,
- h_{fg} = enthalpy of evaporation at given pressure, kJ/kg
 - P = pressure of steam, P_g
 - V = specific volume of steam
(dry, wet or superheated m^3/kg)