Natubhai V. Patel College of Pure & Applied Sciences
S. Y. B.Sc. Semester-4
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UNIT – 6

Introduction

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).

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.

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

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.

Classification of Boilers

The different ways to classify the boilers are as follows

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.

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.

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. 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.

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

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

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.

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.

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 stationary 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: Locomotove boiler.

Marine: Marine boilers

<u>Factors affecting the selection of a boiler</u>

One has to send the technical details to the manufacturer to purchase a boiler.

The technical details that are used to give information about a particular boiler include the following things

- 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

Detailed specifications of each boiler can be obtained from manufacturer's catalogue.

<u>Comparison between water-tube and fire tube boilers</u>

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.

<u>Simple Vertical Boiler</u>

Classification of boiler

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

Construction and working:

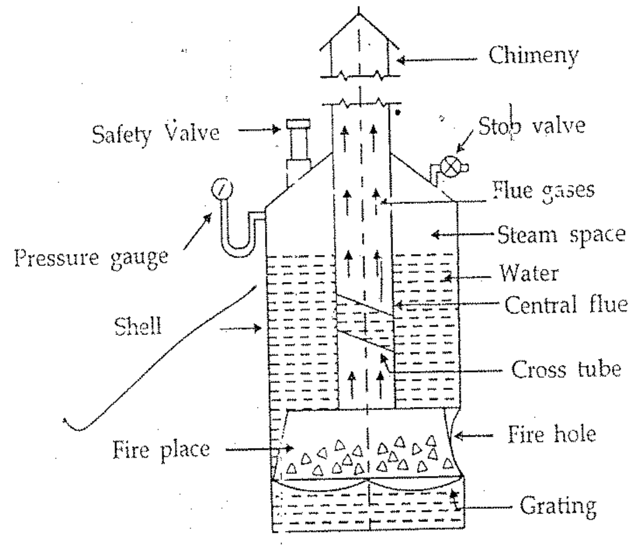

Figure: Simple Vertical boiler

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.

Cochran Boiler

Classification of boiler

Vertical drum axis, natural circulation, natural draft, multi tubular, low pressure, solid fuel fired fire tube boiler with internally located furnace.

Construction and working of boiler

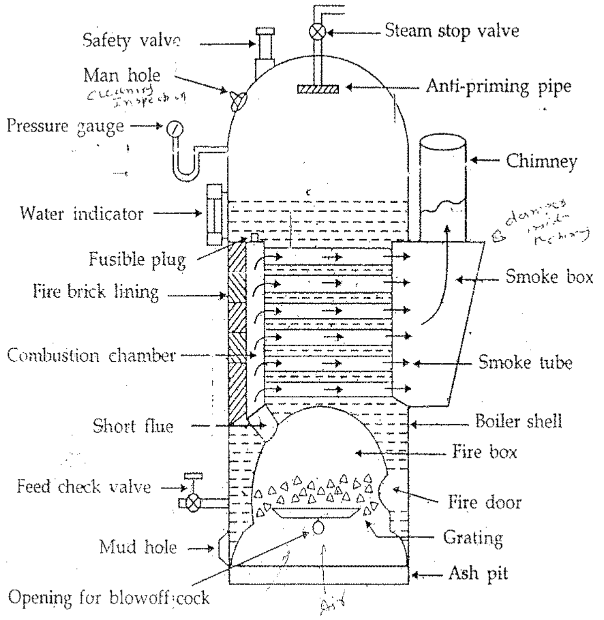

Figure: Cochran Boiler:

Figure depicts a Cochran boiler. It is a modified form of simple vertical boiler. It has a hemispherical crown to given maximum space for steam and very high strength to withstand high steam pressure.

Generated flue gas from the furnace pass through large number of smaller diameter tubes located horizontally in the boiler drum. The large heat transfer area is available for exchange of heat between water and flue gases. The water is converted into steam from the steam space it is supplied to the plant where the steam is required. Low temperature flue gases enter the environment via chimney. All the necessary mountings as per IBR is attached with above boiler.

The advantages of this boiler are its low chimney height, portability, high beaming rate and burning of clay kind of solid as well as liquid fuel. But it has poor efficiency for smaller unit, high head space, difficult to inspect and uneconomical in operation.

Locomotive boiler

Classification of boiler

Horizontal drum axis, natural circulation, artificial draft, multi-tubular, medium pressure, mobile, solid fuel fired, fired tube boiler with furnace located in tubes.

Construction and working

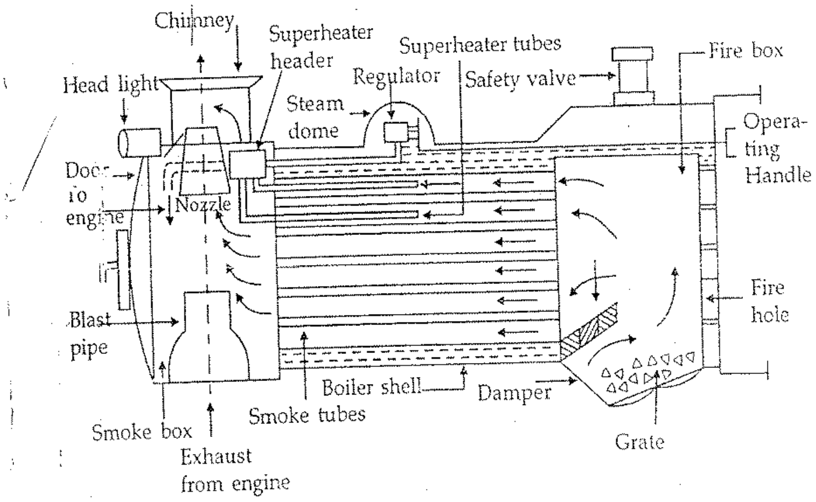

Figure: Locomotive boiler

It is multi-tubular boiler used in railway engines. It is a mobile boiler and steam generation rate is higher.

The boiler consists of large number of smaller diameter tubes located in a cylindrical shell along with a rectangular fire box at one end and a smoke box at the other end. Fuel burn on the inclined grate and flue gases enter into the tubes because of fire bridge arch.

The flue gases pass through number of tubes. Water is surrounded to the tubes. There is an exchange of heat between water and flue gases. The water convert into steam and the flue gases at lower temperature enter into chimney. The steam enters the super heater and the superheated steam is supplied to the steam engine via steam stop valve. The draft created in above case is of artificial type.

The chimney of this boiler is very short. As such enough draft cannot be created by chimney. The draft is obtained by passing the steam exhausted from the engine through a blast-pipe located in the smoke box. The steam passing through the nozzle above the blast pipe creates enough suction to draw in the air through the tubes. A circular door is provided at the end of smoke box for inspection and cleaning.

The rate of steam generation accelerated due to vibrations caused by the movement of the boiler. The boiler has a very low efficiency and cannot carry high overloads without suffering heavy damage due to overheating.

Babcock and wilcox boiler

Classification of boiler

Horizontal drum axis, natural circulation, natural draft, multitubular, high pressure, stationary, solid fuel fired, water tube boiler with furnace located externally.

Construction and working

Figure depicts Bobcock and Wilcox boiler. This is high pressure boiler used in power plants. It consists horizontal boiler drum connected by uptake header and down take header which in turn are connected by number of inclined tubes of water. The flue gases are exchange the heat with the water. The position of baffles cause the gas to move in zigzag way and more heat transfer is possible. A counter flow heating is used. The draft is regulated by dempers. The water enters the tube through down take header. Due to inclined tubes, the entire tube is not filled with the water. Due to exchange of heat, the steam is separated from the water and through uptake header, it enter the steam space inside the boiler drum. Anti priming pipe is provided to ensure that only the dry saturated steam enter the super heater via steam stop valve.

It can be built for any width and height because of sectional construction, good circulation, rapid steaming,, safe and free from explosion, fast response to overloads, ease of repair, maintenance and cleaning. It is costlier and fluctuation in water level.

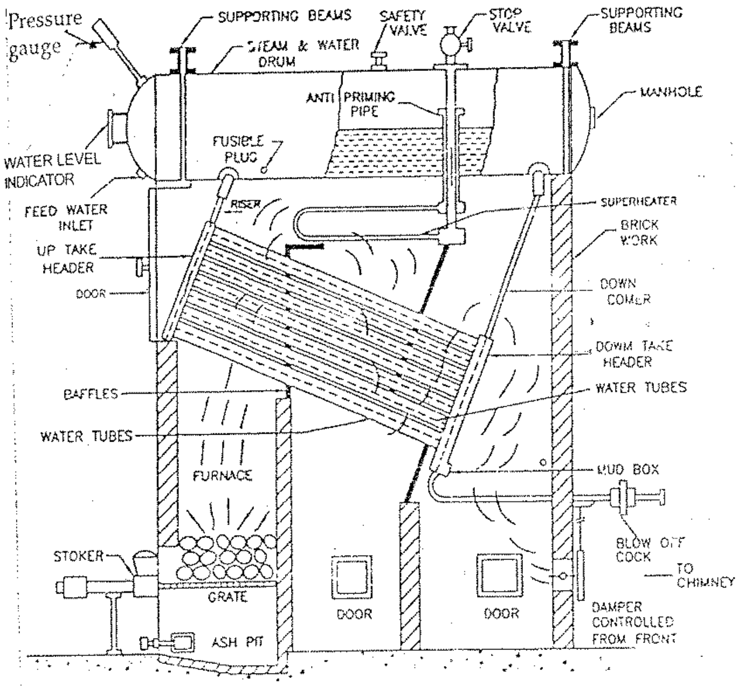

Figure: Babcock and Wilcox boiler

Lancashire Boiler

Classification of boiler

Horizontal drum axis, natural circulation, natural draft, two-tubular, medium pressure, stationary, fire tube boiler with furnace located internally.

Construction and working

Figure shows the constructional details of Lancashire boiler along with different boiler mountings, brick work, path of flue gases, furnace etc. Fuel is burnt on the grate and the flue gases can flow from one furnace end to other end of tubes (i.e. from front side to back side of furnace). This is first pass of flue gas through the boiler tubes. The water is surrounded to the tube. The heat between the water in the boiler drum and the flue gases inside the tube. So the steam is formed. Flue gases available at the backside of the furnace can be diverted in the downward direction due to presence of brick work. (Brick is a very poor conductor of heat energy and can works as insulating material for a given system). So the flue gases can flow from the bottom part of the boiler drum and exchange the heat with water. This is second pass of flue gases outside the tube. So the flue gases are available at front side. From front, because of brick work, they are divided into two side flues and once again flow backward from the sides of boiler drum and finally are expelled out to stack chimney through main flue. Dampers are provided at the end of side flues to regulate the flow of flue gases.

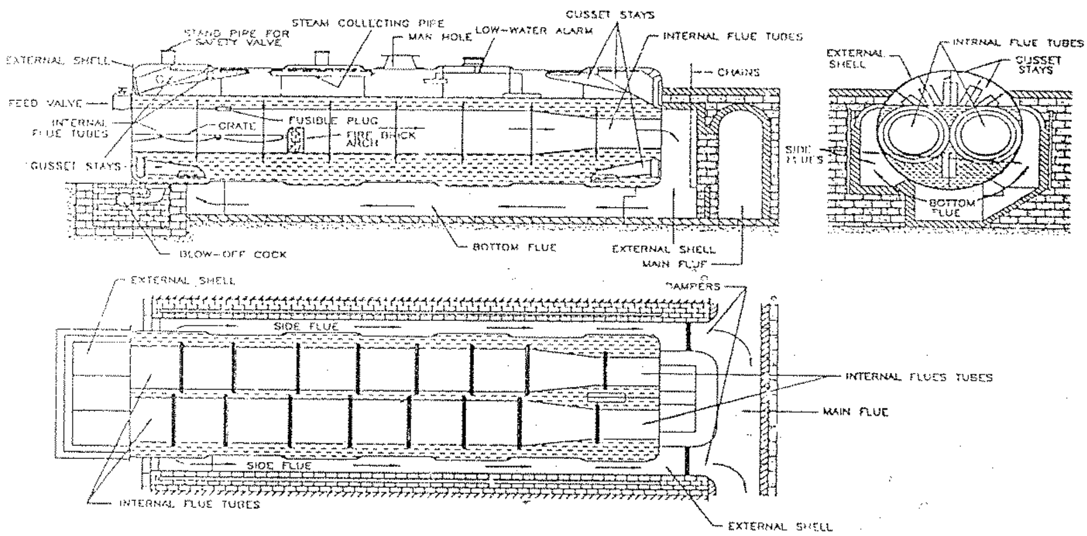

Figure: Lancashire boiller

The disadvantages of the boiler include more floor space, leakage problems through brick-settings, more steaming time, sluggish water circulation, limitation of high pressure of steam and limited space for grate area of furnace.

The advantage of Lancashire boiler are large steam space, load fluctuations can easily be met, easy to clean and inspect, reliable, easy to operate and maintain.

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

Boiler accessories

- Economizers
- Air pre-heaters
- Super heaters
- Feed pump
- Injectors

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 chimany.

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 soft by scrapers which travels slowly and continuously up and down the tubes.

Advantages

- Fuel economy
- Long life of the boiler

Air pre-heaters

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

Super heaters

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

Feed pumps

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

Injectors

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

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

Saturated steam

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

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 ail 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.

(a) 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.

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

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

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 friction 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.

(b) 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.

$$\text{Wetness fraction } = \frac{m_w}{m_w + m_s}$$

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

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

$$= 1 - \frac{m_s}{m_w + m_s}$$

$= 1 - x$

Wetness fraction $= 1 - x$

(c) Priming : The wetness fraction expressed in percentage is known as priming.

Priming = 100 X (1 - x)

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).

Superheated steam

If the temp, 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 temp, of the steam may be increased above the saturation temp, by adding heat to steam, after all the water has been vaporized or after the steam has been separated from contact with water.

Supersaturated steam

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

Steam tables

The values tabulated in the steam tables are determined accurately by experiments. These values from 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.

Sensible heat

It is donated by the latter Lt in steam tables. It is the mantite 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.

Latent heat of vaporization

It is denoted by the letter L 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.

Enthalpy of steam

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

$q = \Delta u + pdv$

For initial state 1 to the final state 2.

$$q = (u_2 - u_1) + P(v_2 - v_1)$$
$$= (u_2 + Pv_2) - (u_1 + Pv_1)$$
$$= h_2 - h_1$$
$$= \Delta h$$

= change in specific enthalpy

Supplied heat = change in specific enthalpy

for non-flow process at constant pressure processes.

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)

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 l 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

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

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)

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

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 (tsup) for given pressure.

:. Enthalpy of superheated steam (h_{sup}) = $h_f + h_{fg} + c_{ps}$ (tsup - tsat)

$h_{sup} = hg + C_{Psteam} (t_{sup} - t_{sat})$ at given p; kJ/kg

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

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

t_{sup} = Superheated temperature of steam (^{0}C)

t_{sat} = Saturation temperature at given pressure (^{0}C)

Degree of superheat

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

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

Specific volume of steam

The specific volume is the volume occupied by the unit mass of a substance. It is expressed in m^3/kg. The volume of water and steam increases with the increase in temperature.

Specific volume of saturated water (υ_a)

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

Specific volume of dry saturated steam (υ_g)

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

Specific volume of wet steam

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

- x kg j 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

$v = xv_g$ m^3/kg .... (4.10)

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

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.

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

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

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.

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 heal and latent heat. This actual energy stored in the steam is called internal energy. It is obtained by subtracting the external work of evaporation form the enthalpy and is denoted by υ.

Definition

Internal energy of dry steam:

$$υ_g = h_g – pv_g \text{ kJ/kg}$$

Internal energy of wet steam:

$$υ = hf – xh_{fg} – pxv_g \text{ kJ/kg}$$

Internal energy of superheated steam:

$$υ_{sup} = h_{sup} – pv_{sup} \text{ kJ/kg}$$

Internal latent heat

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

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 m3/kg)