4.7 ▶ STEAM GENERATORS/BOILERS

The steam generator is a combination of apparatus, which is used in power generation and supply of steam in various plants. Its main purpose is to transfer the heat produced by fuel to water; water is converted into different types of steam as per requirements, such as wet steam, saturated steam, and superheated steam. A steam generator is also known as a boiler. It may be defined as "*A combination of apparatus for producing, furnishing or recovering heat together with apparatus for transferring the heat so made available to water, which would be heated and vaporized to steam form*" (ASME).

4.7.1 Classification of Boilers

There is a number of models of a boiler having different industrial applications. The boiler can be classified on the following basis:

(i) Contents inside the tube
(ii) Firing system
(iii) Position of drum
(iv) Pressure
(v) Nature of water circulation

On the basis of contents of the tube, boilers can be classified as ***Fire tube boilers*** and ***water tube boilers***. In fire tube boilers, flue gas passes through the tube and the heat of flue gas is absorbed by tube and transferred to water surrounding the tube, for example, Cochran boiler, Locomotive boiler, Lancashire boiler, and Cornish boiler. But, in water tube boilers,

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water flows inside the tube and tube is kept in the path of flow of flue gas, for example, Babcock and Wilcox Boiler, Benson boiler, Loffler boiler, etc. Most of the high-pressure boilers are water tube boiler. In this boiler, tube absorbs the heat of flue gas flowing surrounding the tube and transferred to water passing through the tube. The difference between water tube and fire tube boilers are given in Table 4.1.

Table 4.1: Differences between water tube boilers and fire tube boilers

Water Tube Boilers	Fire Tube Boilers
1. Water flows inside the tube.	1. Flue gas flows inside the tube.
2. It is safer than fire tube boilers because a large part of the water of hottest part of the furnace is in small tubes which if rupture, only a comparatively small volume of water released into a flash of steam.	2. It is more dangerous compared to water tube boiler.
3. It is more efficient and economical.	3. It is less efficient and economical.
4. Pressure limit in water tube boilers is much higher than the fire tube boilers.	4. Pressure limit is very low. It is approx 16-20 bar.
5. Water tube boilers are most suitable for large size boiler.	5. Fire tube boilers are most suitable for small size boiler.
6. In this boiler, the steam production rate is very high.	6. The steam Production rate is low.
7. The water treatment plant is required due to the problem of scaling inside the tube.	7. There is no need of water treatment plant.

On the basis of firing system, boilers can be classified as ***Internal Fired Boilers*** and ***External Fired Boilers***. In internal fired boiler, firing takes place inside the boiler drum, i.e., furnace is located inside the drum, for example, Cochran boiler, Locomotive boiler, Lancashire boiler, etc. whereas in external fired boiler, furnace is outside the boiler drum and water is circulated inside the tube passing through the furnace, for example, Babcock and Wilcox Boiler.

On the basis of the position of the drum, boilers can be classified as a ***horizontal boiler***, ***inclined boiler***, and ***vertical boiler***. On the basis of pressure, the boiler can be classified as a low-pressure ***boiler***, high-pressure ***boiler***, and ***super critical boiler***. Low-pressure boilers operate below 80 bar; high-pressure boilers operate above 80 bar; and supercritical boilers operate at 221 bar and above. On the basis of the nature of the circulation of water, boilers can be classified *as **natural circulation boilers*** and forced circulation boiler. In natural circulation boilers, water circulates automatically due to the pressure difference created by the temperature difference. But, in forced circulated boilers, pumps are used to circulate the water through the tubes.

4.7.2 Requirements of a Good Boiler

A good boiler should have the following properties:

1. Low cost of installation, operation, and maintenance
2. Easy maintenance

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3. High efficiency
4. Safety
5. High transportability
6. High steam production rate
7. Good quality of steam
8. Quick steam generation capacity
9. Meeting fluctuating demand of steam, etc.

4.7.3 Cochran Boiler

It is fire tube, multitubular, internal fired and vertical boiler. Its maximum steam generation capacity is 3,500 kg/h. Its shell diameter and height are 2.75 meters and 5.8 meters, respectively. The fuel (coal) is fired on the grate in the furnace. The hot flue gas passes through the fire tube located in the water space and heat is transferred to the water. Water becomes hot in contact with the tube surface. Flue gas goes to the smoke box and finally in the atmosphere through the chimney. The circulation of water is natural; hot water rises up and cold water comes down as shown in Figure 4.10. The steam formed is collected at the upper space of the dome-shaped shell and supplied for use through a steam stop valve.

Components:

1. Hemispherical shell
2. Flue pipe
3. Combustion chamber
4. Smoke box
5. Chimney
6. Grate
7. Ash pit
8. Fire door
9. Furnace
10. Feed check valve
11. Pressure gauge
12. Water gage
13. Safety valve
14. Steam stop valve
15. Blow-off cock
16. Fusible plug

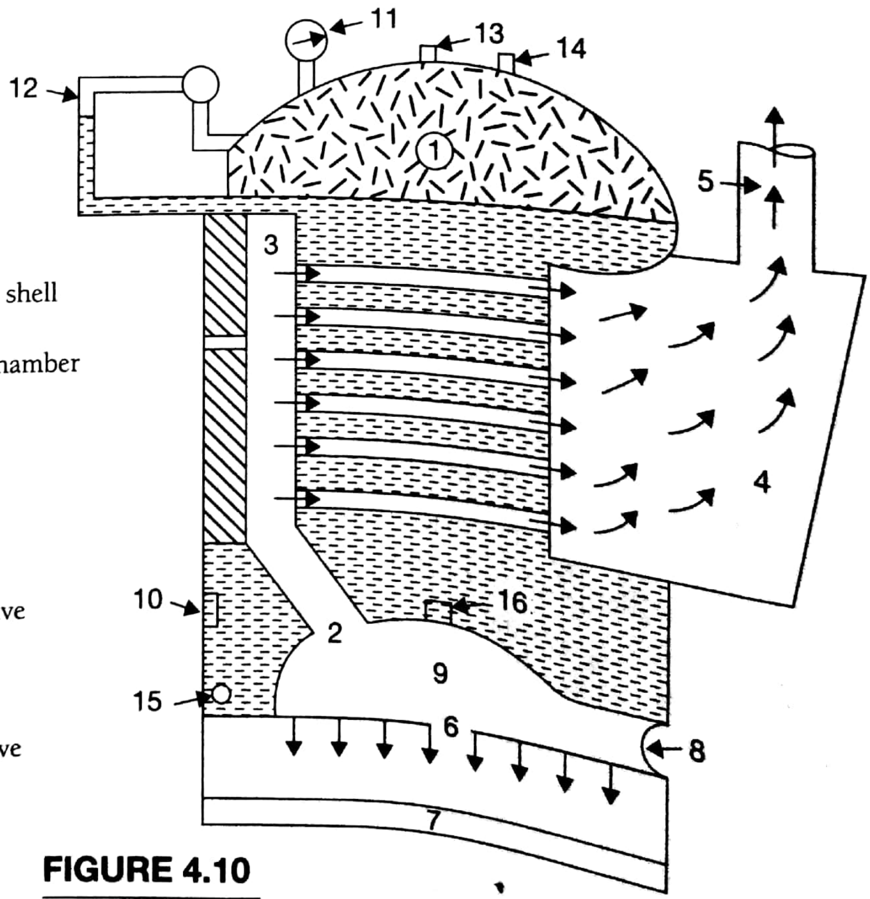

FIGURE 4.10

Cochran Boiler

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The flames and hot gasses produced as a result of combustion of coal on the grate, rise in the dome-shaped combustion furnace. The unburnt fuel is reflected back to the grate and hot flue gas passes through the fire tubes and dissipates the heat to the water. Finally, the flue gas escapes into the atmosphere through smoke-box and chimney. Water circulation is natural circulation. Hot water rises up and cold water comes down continuously. Steam is collected in the upper space of the boiler.

4.7.4 Babcock and Wilcox Boiler

Babcock and Wilcox boiler is a water tube, horizontal, multitubular, external fired boiler. It covers a wide range of pressures compared to fire tube boilers. It has a steam generating capacity of 20,000 to 40,000 kg/h. It operates at an average 20–22 bar, but it can be operated at the maximum 40–42 bar. Its tubes are inclined at 5° to 15° for natural circulation. The diameter and length of tubes are designed as per requirement of the pressure of steam. Baffles are arranged normally for two or three passes of combustion gas. All mounting and accessories are shown in Figure 4.11, which is explained later in this chapter. There is a natural circulation of water. Water circulates from drum to tube and tube to drum with the help of downtake and uptake headers. To get superheated steam, the steam collected in the

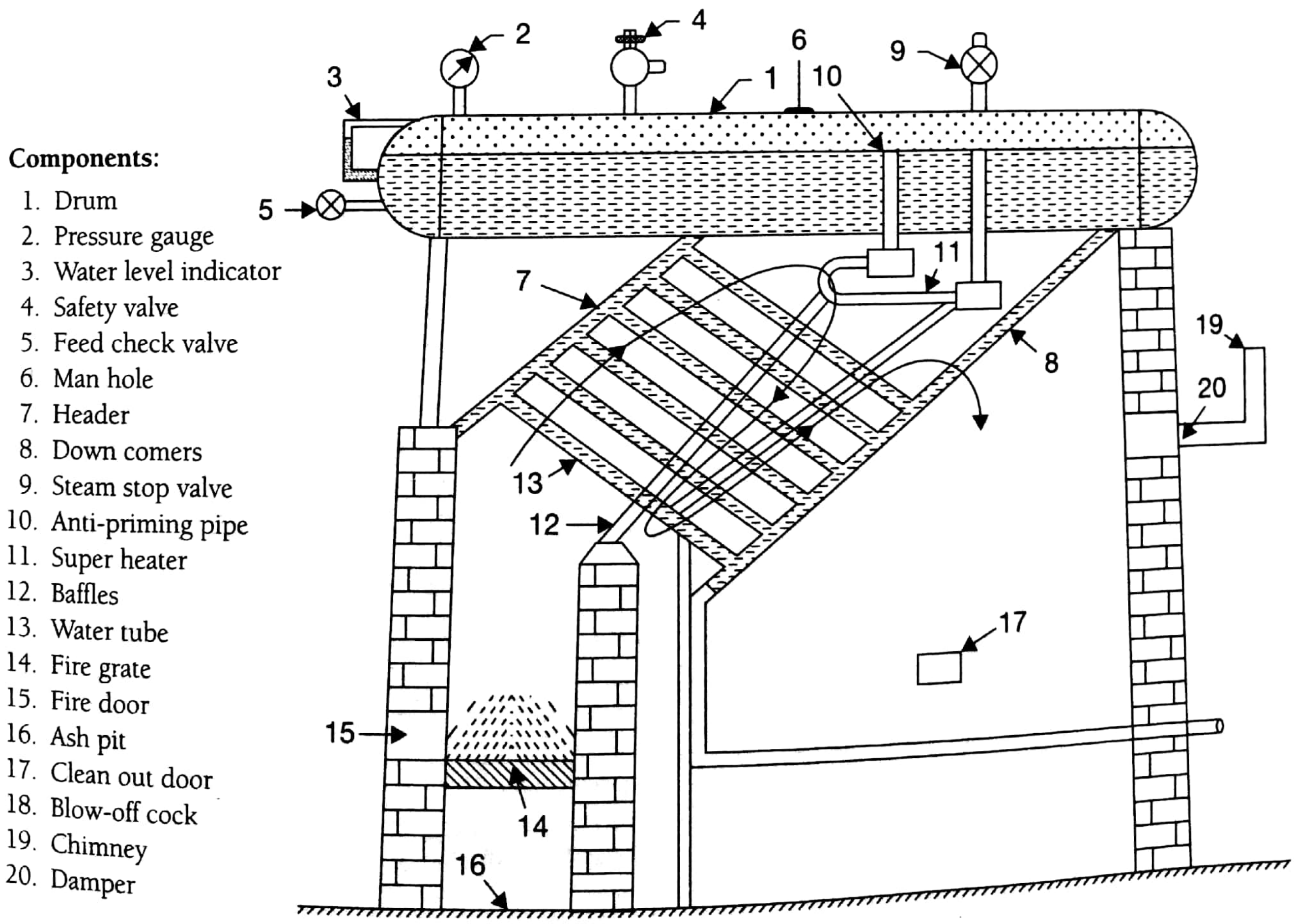

FIGURE 4.11

Babcock and Wilcox Boiler

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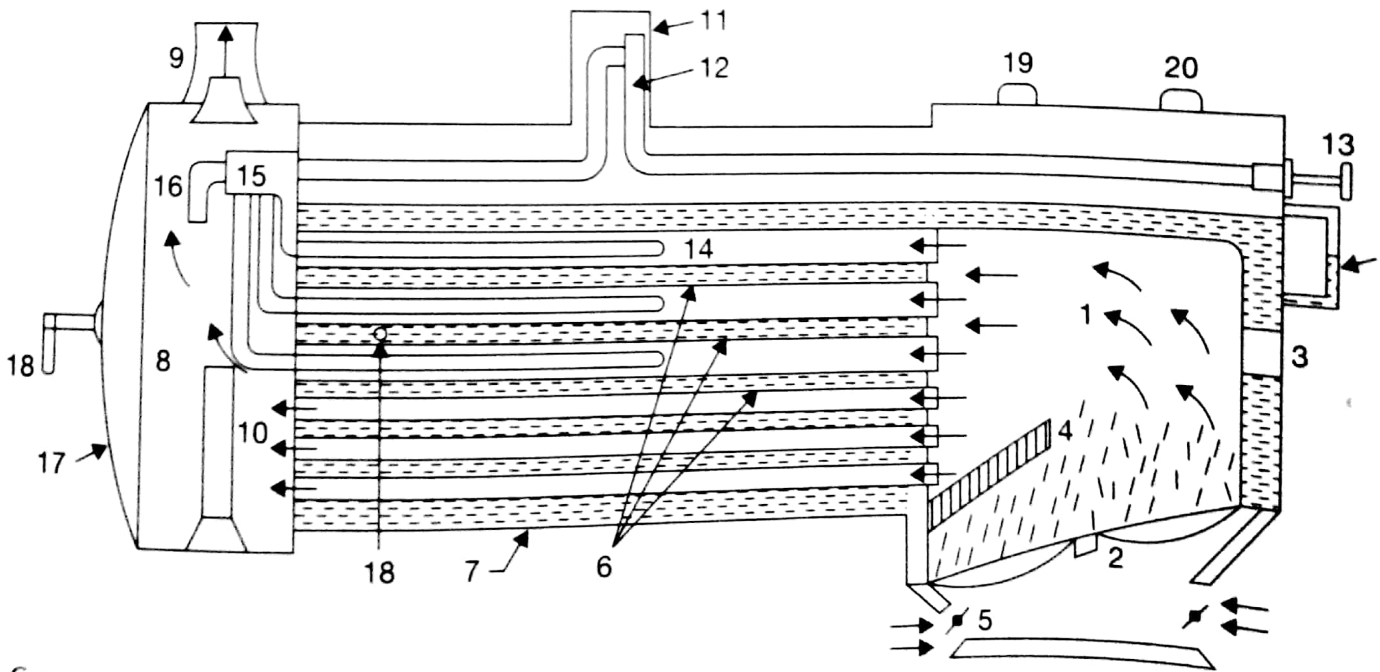
upper space of the drum is recirculated through superheater. The hot flue gas as a result of combustion rises up and moves in the direction as directed by the baffles. The tubes get exposure of hot gas and transfer the heat to the water flowing inside the tubes. Hot water rises and reaches into the boiler drum and cold water comes down into the tubes. Water circulates due to natural circulation produced by temperature differences.

4.7.5 Locomotive Boiler

The locomotive boiler is a fire tube, horizontal, multitubular, natural circulation, movable, artificial draught, internal fired boiler. It meets the fluctuating demand of steam; its chimney height is very short. Artificial draught is created by supplying steam. It is generally used in a steam engine. The functions of all the mountings and accessories are discussed in the separate section of this chapter. The locomotive boiler is a movable boiler; therefore, its chimney is kept very small. A forced draught is created using the flow of steam. The flue gas passes through the tube as directed in Figure 4.12 and transfer the heat to the water through the tube walls.



Components:

1. Fire box
2. Grate
3. Fire hole
4. Fire bridge arch
5. Ash pit
6. Fire tubes
7. Barrel (shell)
8. Smoke box
9. Chimney
10. Exhaust steam pipe
11. Steam dome
12. Regulator
13. Lever
14. Super heater tubes
15. Super heater header
16. Outlet pipe
17. Smoke box door
18. Feed check valve
19. Safety valve
20. Whistle
21. Water gauge

FIGURE 4.12

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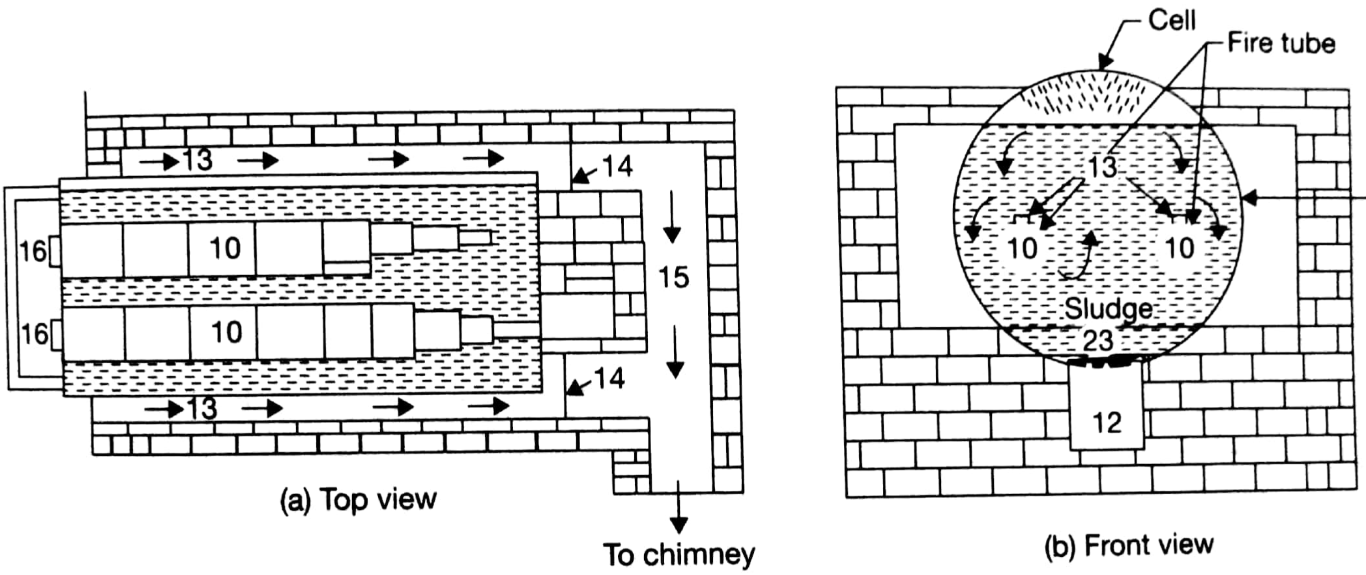
4.7.6 Lancashire Boiler

A Lancashire boiler is horizontal, fire tube, internal fired, natural circulation type boiler. There are two fire tubes. The fuel is burnt on the grate and the hot flue gas is produced. The flue gas moves along the furnace tubes and is deflected up by Fire Bridge. As soon as the flue gas reaches the back of main flue gas tubes, it deflects downwards and travels through the bottom flue gas tube as shown by arrows in Figure 4.13. The bottom flue is just below the water shell and heats the lower portion of the shell. After traveling from back to front, the flue gas bifurcates into separate paths in the side flues as shown by arrows in sectional side view. Now, it travels from front to back inside and heats the side of the water shell. These two streams of flue gas meet again in the main flue passing; through the damper, they are discharged to the atmosphere through the chimney.

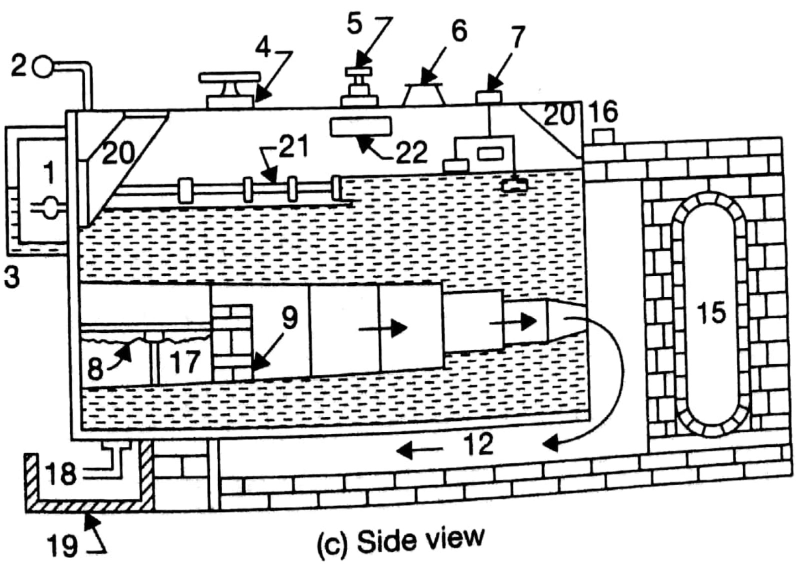


(a) Top view

(b) Front view

Components:

1. Feed check valve
2. Pressure gauge
3. Water level Indicator
4. Dead weight safety valve
5. Steam stop valve
6. Man hole
7. High steam low water safety valve
8. Fire grate
9. Fire bridge
10. Flue tubes
11. Boiler shell
12. Bottom flue
13. Side flue



(c) Side view

14. Dampers
15. Man hole
16. Doors
17. Ash pit
18. Blow-off cock
19. Blow-off pit (for disposal of blow-off water)
20. Gusset stays
21. Perforated feed pipe
22. Anti-priming device
23. Fusible plug

FIGURE 4.13

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4.8 ▶ Boiler Mountings

Boiler mountings are the components of boilers, which are mounted on the body of the boiler for safety and controlling the steam generation processes. There are following components which are used as mountings in boiler operation:

1. Safety valve, 2. Water level indicator, 3. Pressure gauge, 4. Fusible Plug, 5. Steam stop valve, 6. Feed check valve, 7. Blow-off cock, 8. Man and Mudhole.

4.8.1 Safety Valves

The safety valve is used to release the excess pressure inside the boiler drum. When the pressure inside the drum exceeds the working pressure, safety valves blow-off the steam into the atmosphere. Generally, four types of safety valves are used in boilers: (i) Dead weight safety valve, (ii) Spring loaded safety valve, (iii) Lever safety valve, and (iv) High steam low water safety valve.

Dead Weight Safety Valve

Steam pressure acting in an upward direction is counterbalanced by the dead weight of safety valve acting in the downward direction. When the steam pressure exceeds the dead weight of safety valve, valve rises from its valve seat and steam escapes into the atmosphere. The construction of dead weight safety valve is shown in Figure 4.14. There is a vertical steam pipe having a valve seat at its mouth. A valve is fitted in the valve seat. Above the valve, a dead weight is applied. When the steam pressure becomes higher than the dead weight, valve rises from the valve seat and steam at high pressure is released into the atmosphere. Again, when the steam pressure becomes normal, i.e., less than dead weight, the valve returns to the valve seat.

Spring Loaded Safety Valve

This type of safety valve is spring loaded. Spring force works against the steam pressure, when the steam pressure becomes high, valve lifted off the valve seat and steam is escaped out. A lever is attached to one end of spring as shown in Figure 4.15. When steam pressure comes down valve returns to valve seat due to the force of spring.

Lever Safety Valve

The lever safety valve works on the principle of the second system of the lever as shown in Figure 4.16. In this valve, there is a lever which can rotate about a fulcrum, but its movement

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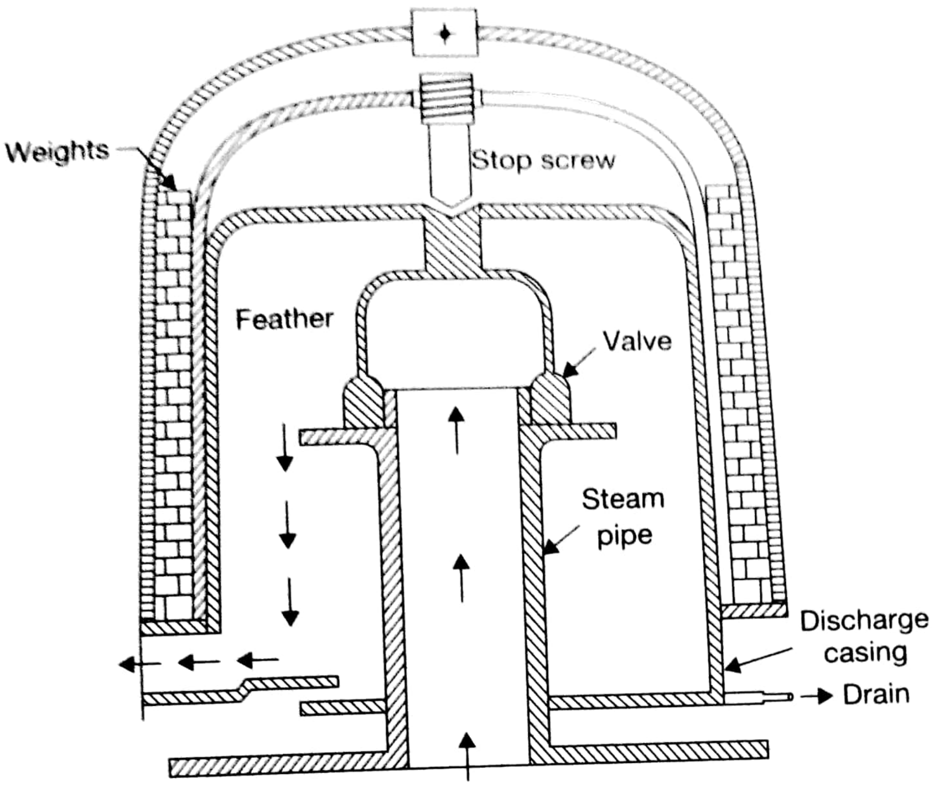

FIGURE 4.14

Dead Weight Safety Valve

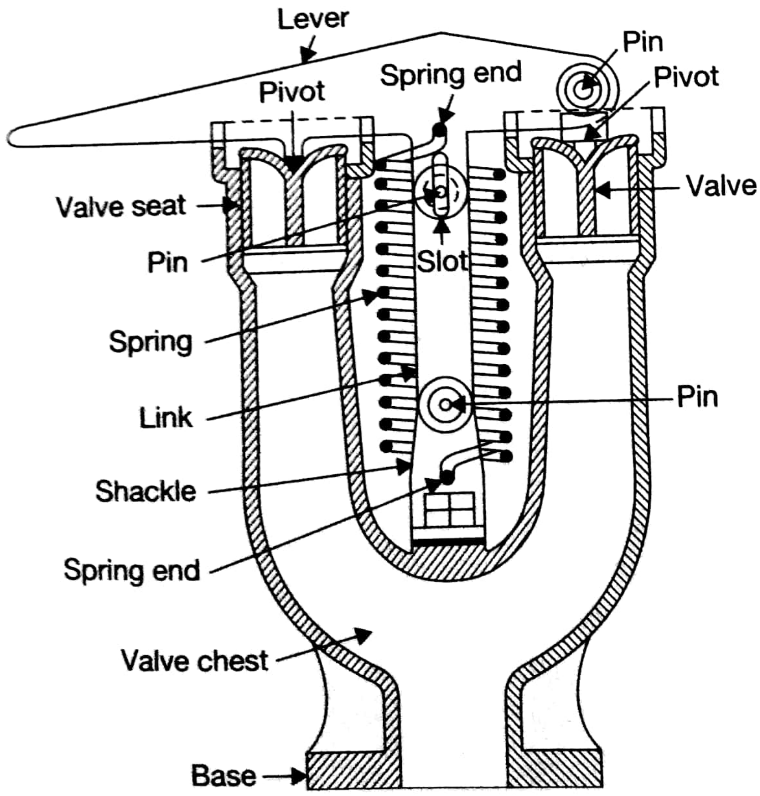

FIGURE 4.15

Spring Loaded Safety Valve

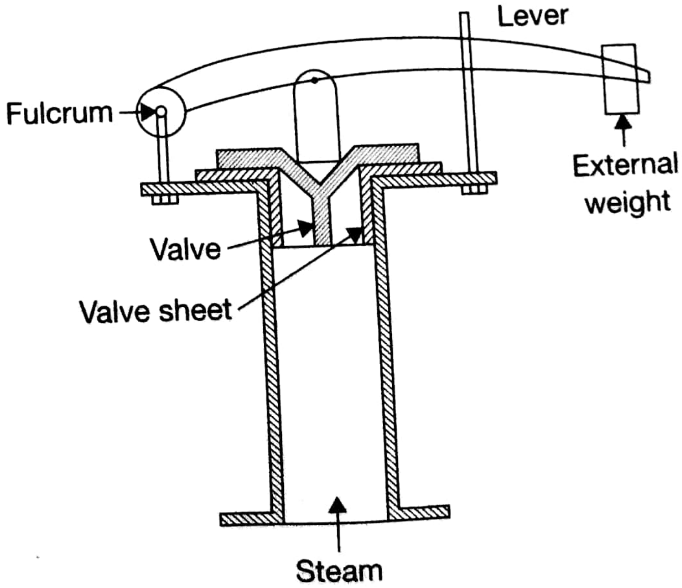

FIGURE 4.16

Lever Safety Valve

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4.8.3 Water Level Indicator

The function of the water level indicator is to show the water level inside the boiler drum. Total two water level indicators are provided on the boiler drum. The constructional details are shown in Figure 4.18. One end of the glass tubes is connected to steam space and the other end to the water space through a hollow pipe of Gunmetal bolted to the boiler. In case, tube breaks, two balls are provided that move to the dotted positions due to the rush of water in the passage. The steam will also rush from the upward hollow column and will push the balls in dotted positions.

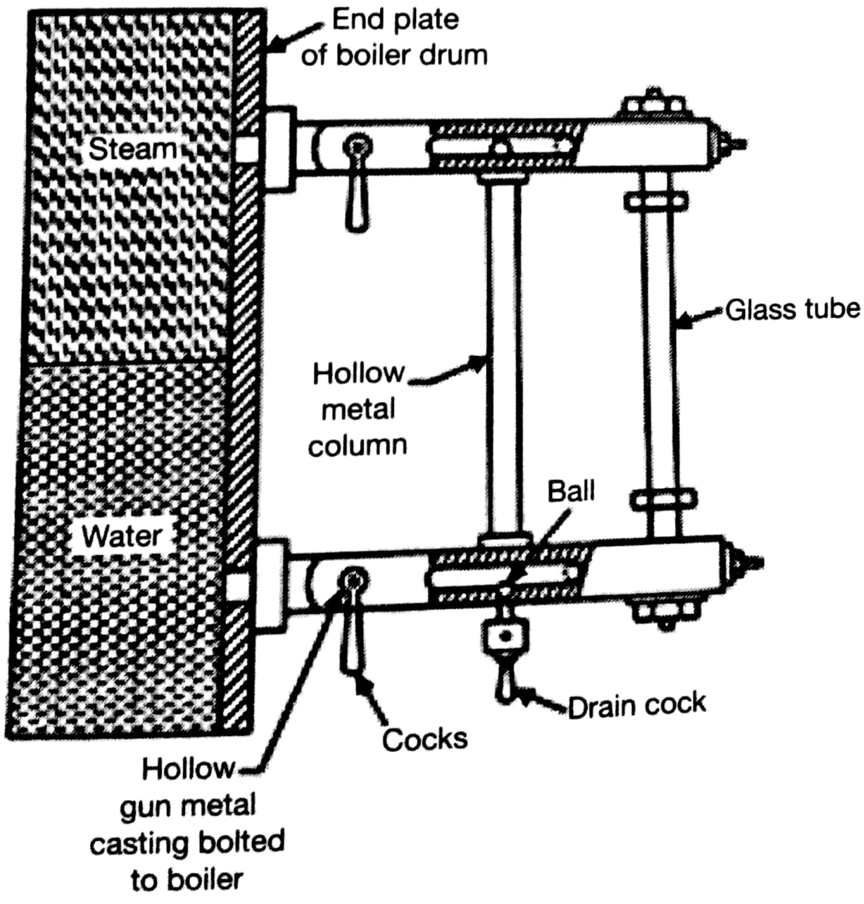

FIGURE 4.18

Water Level Indicator

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4.8.4 Pressure Gauge

Pressure Gauge is used to measure the pressure inside the boiler drum. The constructional details are shown in Figure 4.19. There is a tube spring, one end of which is connected to the steam space and the other end is closed and connected to a link. The link is connected to toothed quadrant meshed with the pinion. At the center of the pinion, a pointer is fixed which can rotate with pinion. The quadrant rotates about the pivot and magnifies the reading. Due to steam pressure, spring tube tends to become straight and moves the pinion, which rotates the quadrant and pinion. The deflection in the pointer is shown on graduation on the disc, which shows the pressure of steam in the drum.

4.8.5 Feed Check Valve

The function of feed check valve is to allow the flow of water under pressure from the feed pump to the boiler and to prevent the back flow of water in case of failure of the feed pump. The constructional details are shown in Figure 4.20. The valve rises under pressure and water is allowed to flow inside the drum. The pressure of feed pump is more than that of steam inside the drum which allows the flow of water into the drum, but when supply is stopped, the valve returns to its seat due to steam pressure and prevents backflow of water. This is a one-way valve.

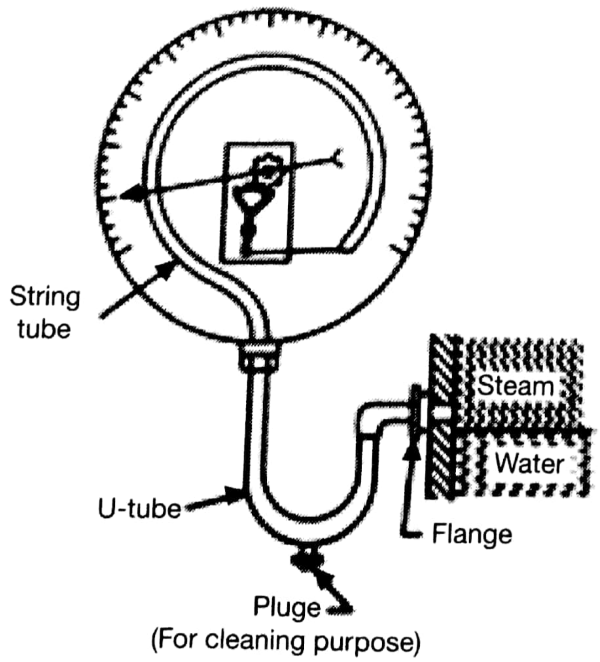

FIGURE 4.19

Pressure Gauge

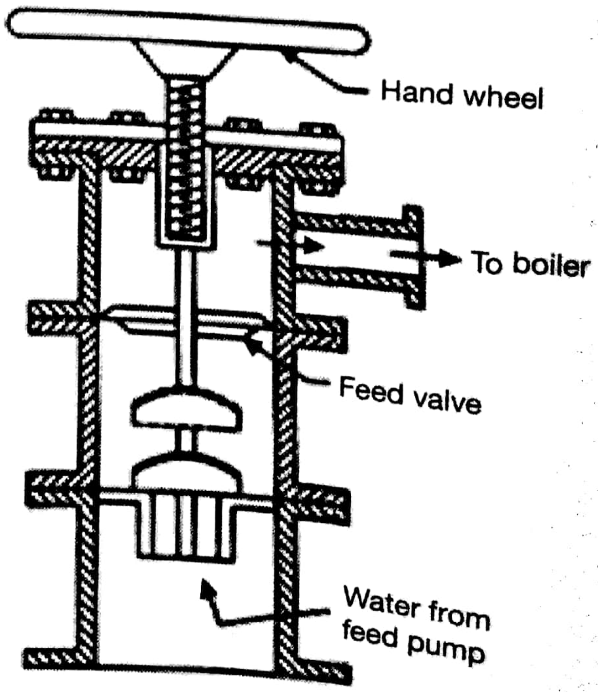

FIGURE 4.20

Feed Check Valve

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4.8.6 Steam Stop Valve

The function of steam stop valve is to stop or allow the flow of steam from the boiler to steam pipe or from the steam pipe to supply. The opening of the valve is controlled by a hand wheel. The constructional details of steam stop valve are very simple which is shown in Figure 4.21.

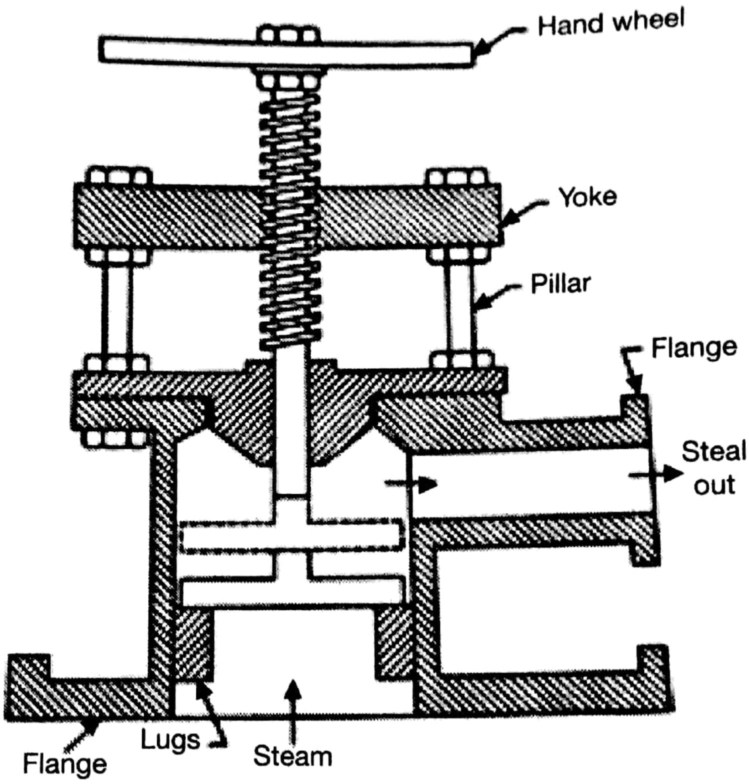

FIGURE 4.21

Steam Stop Valve

4.8.7 Blow-off Cock

The function of the blow-off cock is to blow down the sediments collected at the bottom of the drum or to empty the boiler or to lower down the water level in the drum. The blow-off cock is fitted at the lowest portion of the boiler. The casing is provided with two flanges, one is connected to the boiler and the other is connected to the steam pipe. The plug valve has a hole. When it is desired to discharge the water, the plug valve is turned in a manner so that the hole in the plug can align with the hole in casing and water can rush out of the boiler. The flow of water can be stopped by turning the plug such that its solid part comes in line with the hole in the casting. The constructional details are shown in Figure 4.22.

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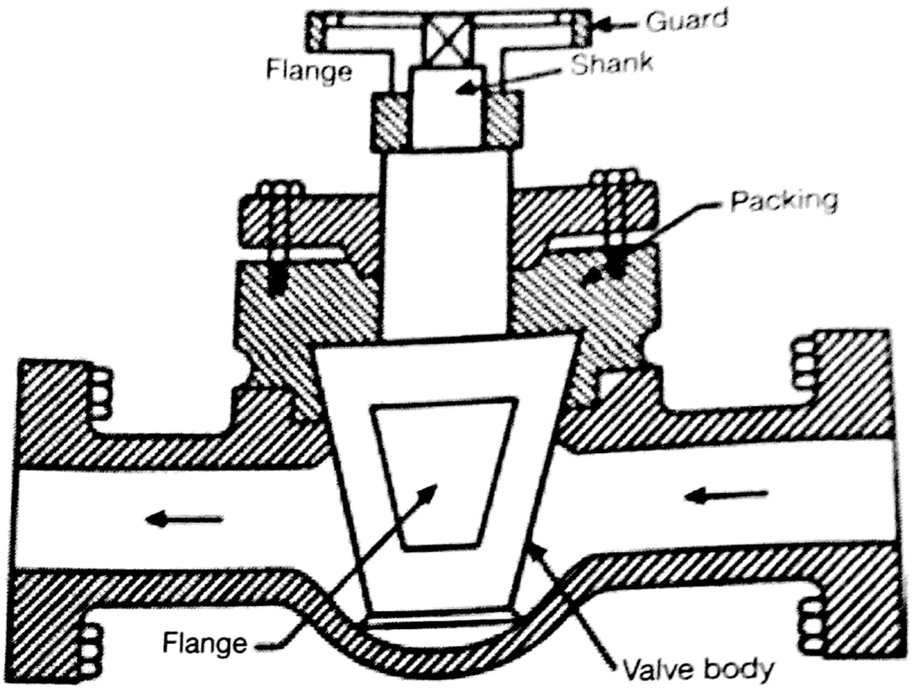

FIGURE 4.22

Blow-off Cock

4.8.8 Fusible Plug

The function of the fusible plug is to extinguish the fire in the fire box when the water level in the boiler comes down the limit. It prevents from blasting the boiler, melting the tube and overheating the firebox crown plate. The constructional details of the fusible plug are shown in Figure 4.23. It is located in the water space of the boiler. The fusible metal is protected from direct contact with water by Gunmetal and Copper plug. When water level comes down, the fusible metal melts due to high heat and copper plug drops down and holds in gun metal ribs. Steam comes in contact with fire and distinguishes it. Thus, it prevents from damages.

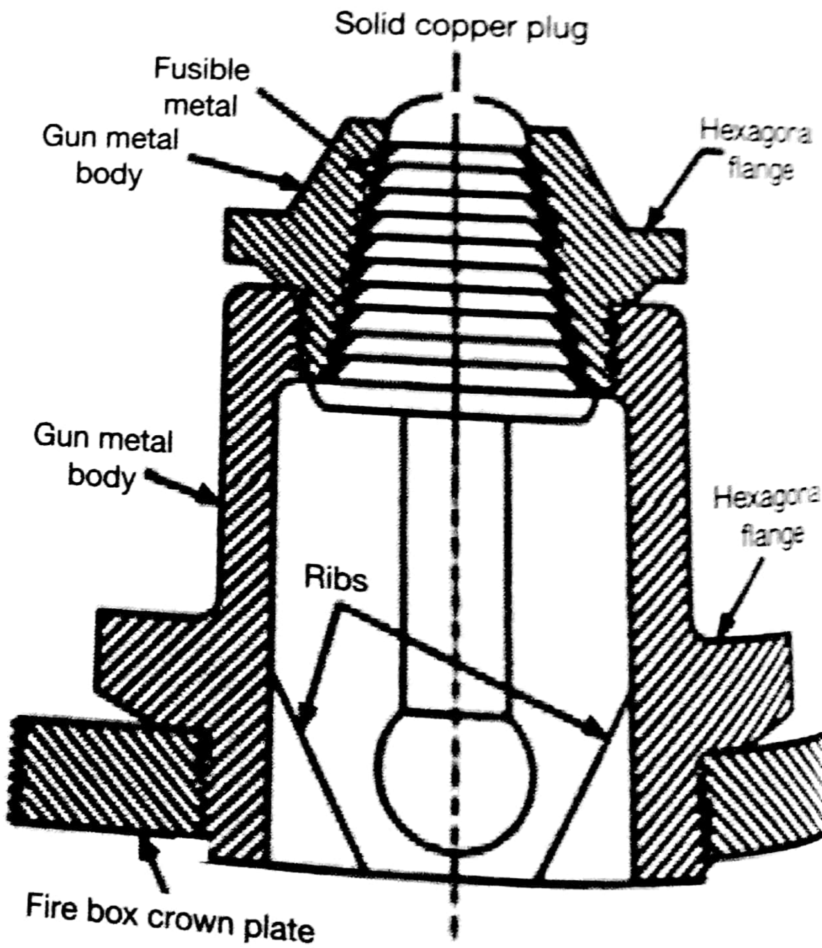

FIGURE 4.23

Fusible Plug

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4.8.9 Manhole

This is opening in the boiler. It is used for cleaning and inspection purpose. Through this hole, the operator enters the boiler in idle condition.

4.9 ► Boiler Accessories

The devices used in a boiler to increase its efficiency and quality of steam are known as accessories. The names of some important accessories are mentioned below:

1. Economizer,
2. Air preheater,
3. Super heater,
4. Steam trap,
5. Steam separator,
6. Injector.

4.9.1 Economizer

Economizer is a type of heat exchanger which exchanges some parts of the waste heat of flue gas to the feed water. It is installed between the exit of the furnace and entry into the chimney. Generally, the economizer is placed after feed pump to avoid the problem of priming in feed pump. If the economizer is installed before feed pump, some amount of water may be transformed into vapor, which can create a priming problem in feed pump. In this case, limit of temperature rise of water is fixed so that water cannot be transformed into steam. The constructional details of economizer are shown in Figure 4.24. It consists of vertical cast iron tubes attached with scrapers. The function of the scraper is to remove the soot deposited on the tube. Water flows through the tube to the boiler drum. These tubes are arranged in the path of the waste flue gas entering into the chimney. The flow of water is controlled by two valves attached to down header and up the header of the tubes. The waste heat of the flue gas is transferred to the tube material and then tube material to water.

Advantages

(i) It increases the power output of the plant. For a 6°C increase in temperature of water efficiency of boiler increases by 1%.
(ii) It increases the evaporation capacity.
(iii) It increases the life of boilers due to less thermal stress.

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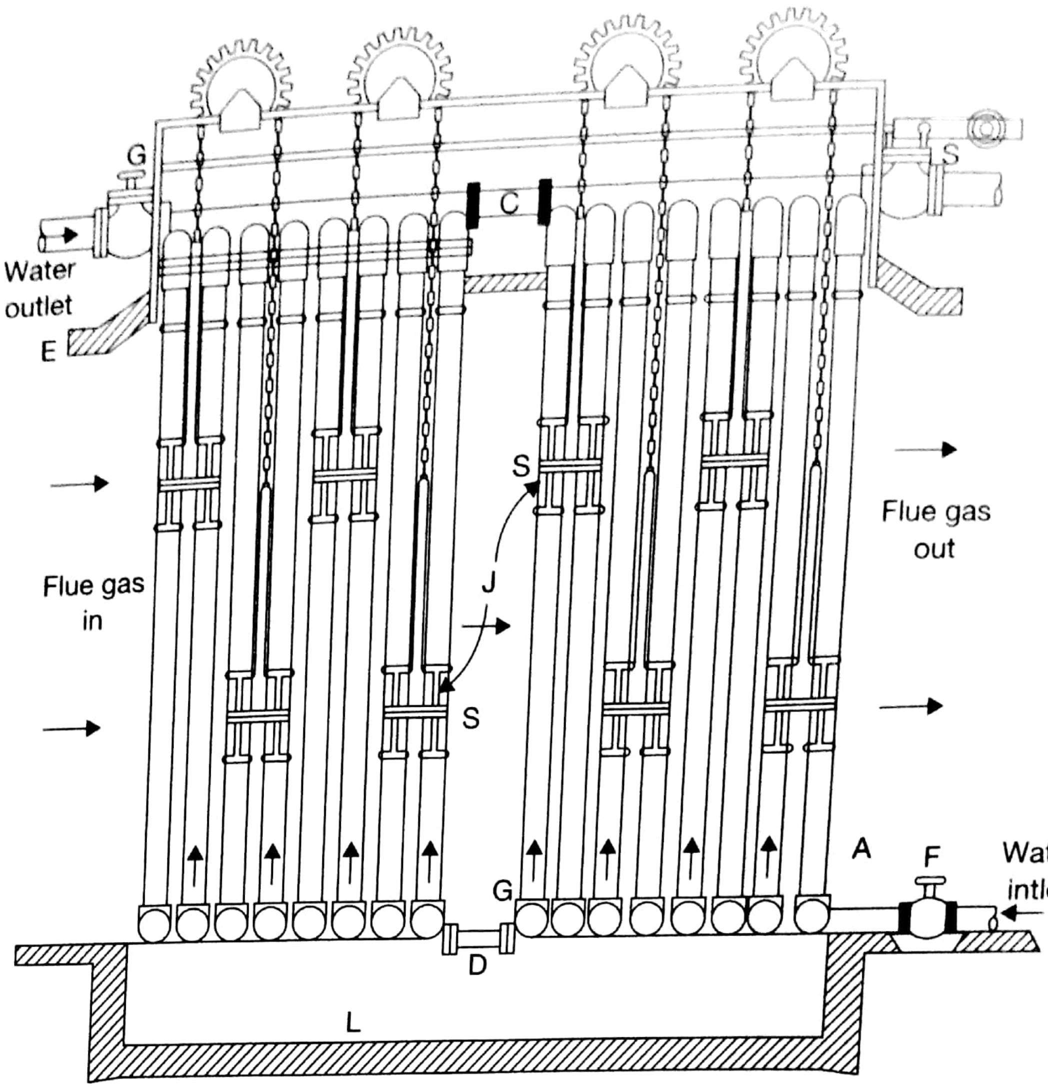

FIGURE 4.24

Economizer

4.9.2 Air Preheater

Air preheater is a device for recovery of waste heat from flue gas and is placed in the path of the waste flue gas going to the chimney. Waste heat if the flue gas is transferred to the air before its use to support economical combustion in a furnace. It is placed in the chimney and above economizer. If fuels used in the furnace are oil, gasses, or pulverized coal, the hot air supply is possible. But, in the case of stoker firing, the maximum temperature of the air is limited due to overheating of stoker parts. The constructional details of an air preheater are shown in Figure 4.25.

Advantages

(i) Due to high furnace temperature, water evaporation rate increase.
(ii) Boiler efficiency increases by 2 to 10%.
(iii) Low-grade fuel can be used.

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Disadvantages

Capital cost increases due to use of pre-heater and two fans (induced fan and forced draught fan) to create an artificial draught.

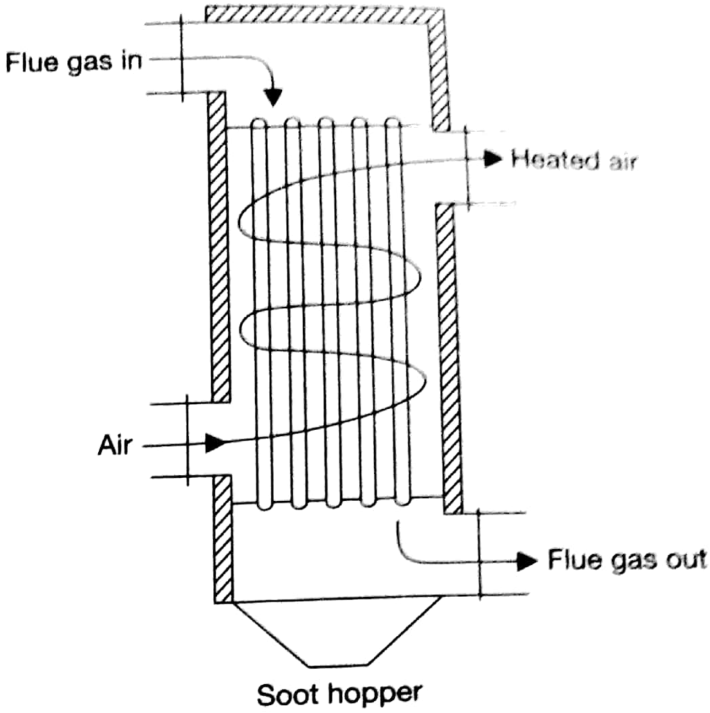

FIGURE 4.25

Air Preheater

4.9.3 Superheater

Steam generated in the boiler is wet due to contact with water. To get superheated steam, a device known as superheater is used in the boilers. The function of superheater is to superheat the steam up to the desired level. It is a surface heat exchanger, located in the path of the flue gas. The wet steam flows inside the tube and hot flue gas passed over the tubes. Constructional details of a superheater are shown in Figure 4.26.

Advantages

(i) Superheater increases the efficiency of prime movers due to the supply of steam at high-temperature and pressure.
(ii) It minimizes the condensation loss in a prime mover.
(iii) It eliminates the problems of erosion and corrosion in turbine blades.
(iv) It increases the capacity of the plant.
(v) It reduces the friction of the steam in a steam engine and other steam parts.

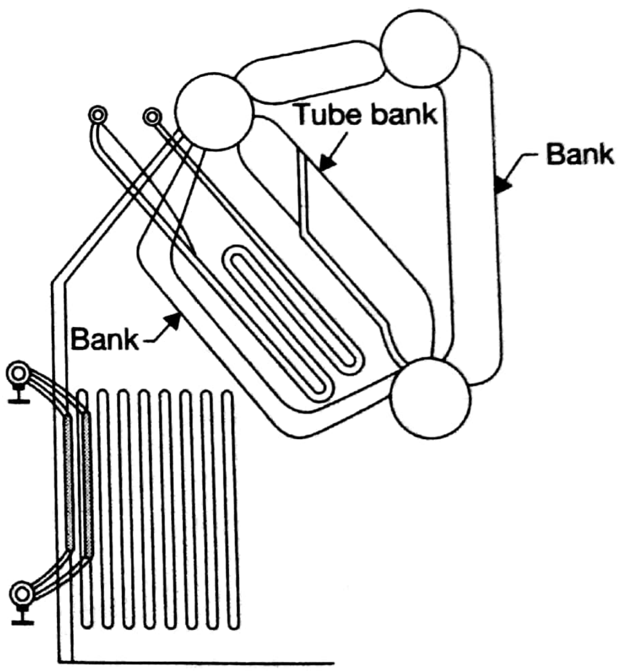

FIGURE 4.26

Superheater

4.9.4 Feed Pump

The function of feed pump is to feed the water to the boiler. Different types of feed pumps used in boilers are reciprocating, centrifugal, and injector. Centrifugal or rotary pumps are used where a large amount of water is required. For small boilers, reciprocating pump and injectors are used.

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4.9.5 Injector

The injector is a feed pump which is used to deliver feed water into the boiler under pressure. It is mostly used in vertical and locomotive boilers. It is not suitable for large power plants. It consists of a group of nozzles so arrange that the steam expanding in these nozzles imparts kinetic energy to a mass of water. The constructional details of the injector are shown in Figure 4.27.

Advantages

(i) It requires minimum space.

(ii) Maintenance cost is low.

(iii) The initial cost of installation is low.

(iv) It is thermally more efficient than feed pump.

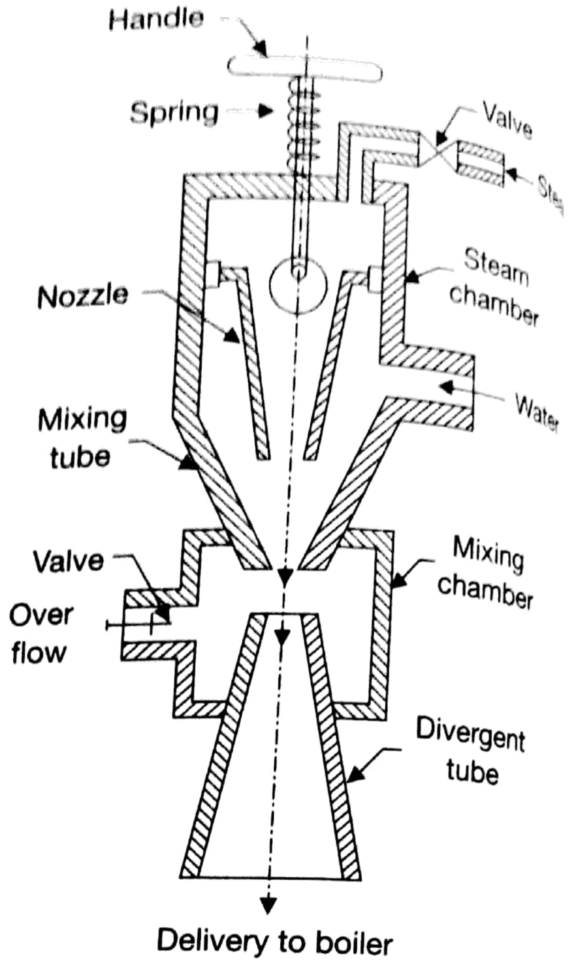

FIGURE 4.27

Steam Injector

4.9.6 Steam Trap

The function of a steam trap is to drain the water condensed due to partial condensation and jacket without allowing the steam to escape through it.

4.9.7 Steam Separator

The function of a steam separator is to separate the suspended water particles carried by steam on its way from the boiler to the engine of the turbine. It is installed in the mainstream pipe very near to the engine. The constructional details are shown in Figure 4.28.

The steam from the boiler enters the steam separator through a flange and moves down. During its passage down, it strikes the baffles and is deflected upward. The steam on striking the baffles causes the particles having the higher density to fall to the bottom of the separator with high inertia. Dry steam deflected up and comes out through the flange B. The separated water is collected at the bottom, which is drained out by drain cock and drain pipe.

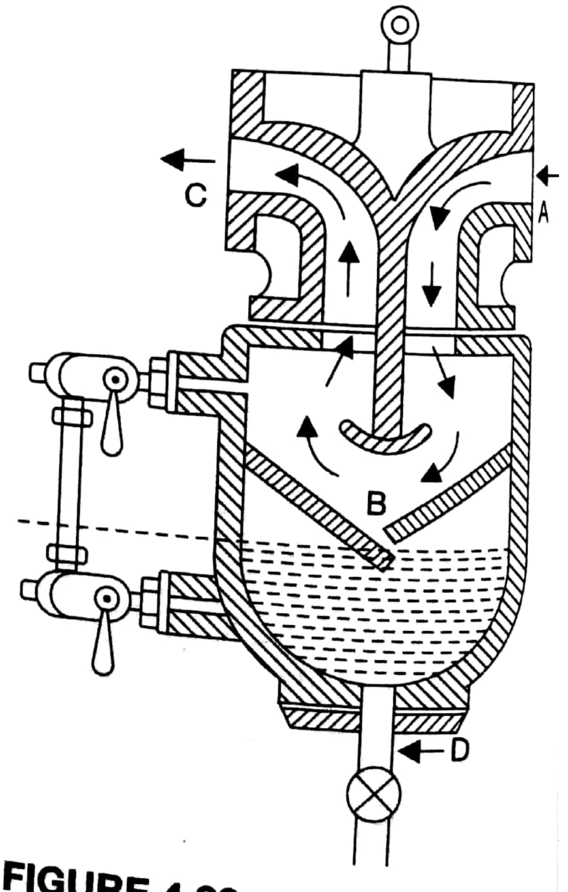

FIGURE 4.28

Steam Separator

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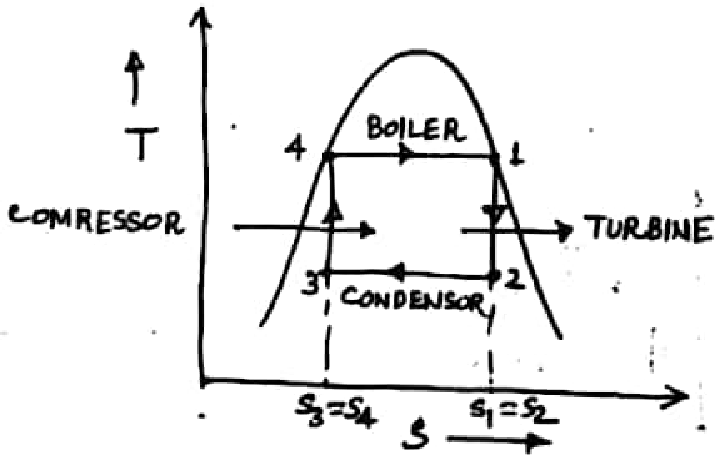
CARNOT VAPOUR CYCLE



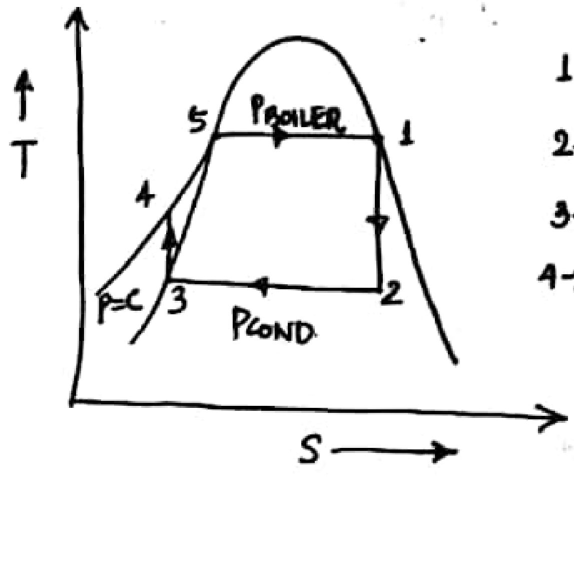
1 - 2 → Isentropic expansion

2-3 → Constant temperature H·R

3-4 → Isentropic compression

4-1 → Isothermal heat addition

RANKINE CYCLE



1-2 — Isentropic expansion

2-3 — constant pressure heat rejection

3-4 — Pump work $= W_p = v_{F_3} dp = v_{F_3}(P_{BOIL} - P_{cond})$

4-5-1 — Constant pressure heat addition

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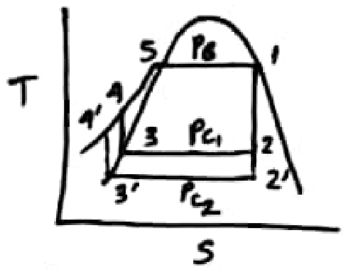
A) DECREASE IN CONDENSOR PRESSURE

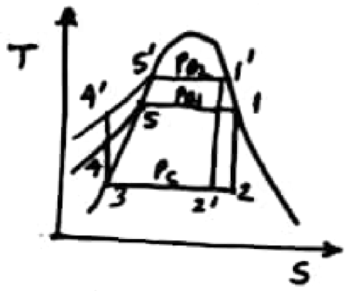


1) $W_T \uparrow$
2) $W_P \uparrow \rightarrow \int v_f\, dP$ → negligible
3) $\uparrow W_{net} = \uparrow W_T + \uparrow W_P$
4) $Q_S \uparrow$
5) Q_R (can't say)
6) $T_{MA} \downarrow$
7) $T_{MR} \downarrow\downarrow$
8) $\eta \uparrow$
9) $x_{2'} < x_2$ (Dryness fraction)

$x = \frac{m_v}{m_v + m_L}$

$\downarrow x \Rightarrow \downarrow$ vap $\Rightarrow$ Liq. $\uparrow \rightarrow$ Erosion of Turbine blade $\uparrow$

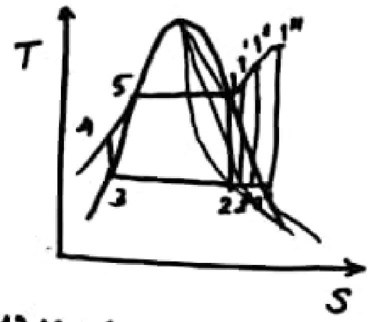
B) INCREASE IN BOILER PRESSURE



1) $W_T \uparrow$
2) $W_P \uparrow$
3) $W_{net} \uparrow = W_T \uparrow - W_P \uparrow$
4) Q_S = can't say
5) $Q_R \downarrow$
6) $T_{MA} \uparrow$
7) T_{MR} = constant
8) $\eta \uparrow$
9) $x_{2'} < x_2$; $x = \frac{m_v}{m_v + m_L}$

$\rightarrow \downarrow x \rightarrow$ vap $\downarrow \rightarrow$ Liquid $\uparrow$
$\rightarrow$ Erosion of blade $\uparrow$

C) SUPERHEATING



1) $W_T \uparrow$
2) $W_P \rightarrow$ no change
3) $W_{net} \uparrow = W_T \uparrow - W_P$
4) $Q_S \uparrow$
5) $Q_R \uparrow$
6) $T_{MA} \uparrow$
7) T_{MR} = Constant
8) $\eta \uparrow$
9) $x_{2'} > x_2$; $x = \frac{m_v}{m_v + m_L}$

$x \uparrow \rightarrow$ vap $\uparrow \rightarrow$ Liq $\downarrow$
$\rightarrow$ Erosion of blade $\downarrow$

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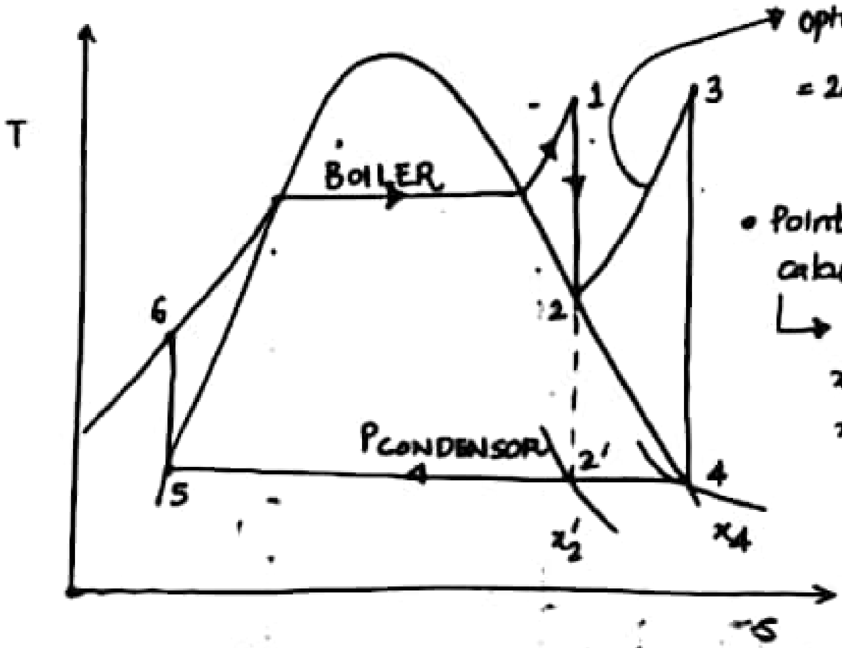

- Point 2 & 4 depends on calculation
  - → $x > 1$ → superheated
  - $x = 1$ → sat. vap
  - $x < 1$ → wet region

1) $W_T \uparrow = (h_1 - h_2) + (h_3 - h_4)$

2) W_P = constant = $v_{f5}(P_6 - P_5)$

3) $\uparrow W_{net} = \uparrow W_T - W_P$

4) $\uparrow Q_S = (h_1 - h_6) + (h_3 - h_2)$

5) $\uparrow Q_R$

6) $T_{MA} \uparrow$ or $\downarrow$

$$\eta = \frac{W_T - W_P}{Q_S} = \frac{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)}$$

7) $\eta \uparrow$ or $\downarrow$

8) $x_4 > x_2'$

$\uparrow x$ → vap $\uparrow$ → Liq. $\downarrow$ → Erosion of turbine blade $\downarrow$

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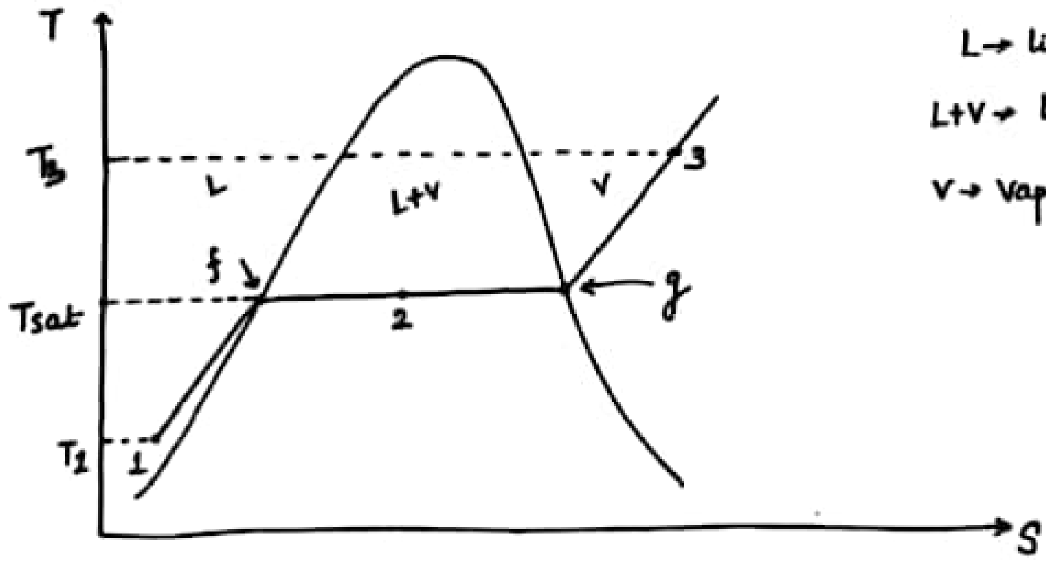
Enthalpy and Entropy at various points :-



L → liquid

L+V → liquid + Vapour

V → Vapour

① Subcooled

$$h_f - h_1 = C_{p_{Liq}}(T_{sat} - T_1)$$

$$s_f - s_1 = C_{p_{Liq}} \ln\left(\frac{T_{sat}}{T_1}\right)$$

② Wet region

$$h_2 = h_f + x_2 h_{fg} = h_f + x_2(h_g - h_f)$$

$$s_2 = s_f + x_2 s_{fg} = s_f + x_2(s_g - s_f)$$

$$Q_{Phase} = h_g - h_f$$

⇓

L·H·

$$\boxed{L \cdot H \cdot = h_g - h_f}$$

$$\boxed{s_g - s_f = \frac{L \cdot H \cdot}{T_{sat}} = \frac{h_{fg}}{T_{sat}}}$$

③ Superheated (Ideal gas)

$$h_3 - h_g = C_{p_v}(T_3 - T_{sat})$$

$$s_3 - s_g = C_{p_v} \ln \frac{T_3}{T_{sat}} - R \ln \frac{P_3}{P_{sat}} \rightarrow 0$$

$$\boxed{s_3 - s_g = C_{p_v} \ln\left(\frac{T_3}{T_{sat}}\right)}$$

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* **SIGN CONVENTION** :→

① Heat supplied to the system

$$Q_{supplied} = +ve$$

② Heat Rejected from the system

$$Q_{Rejected} = -ve$$

* **TYPES OF HEAT** :→

① **Sensible heat** → It is a form of energy interaction by the virtue of temperature difference.

② **Latent heat** → It is the amount of heat required to cause the phase change.

$$\text{Sensible heat} = mC\Delta T$$

$$\text{Latent heat} = m(LH)_{S/V/F}$$

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$$\text{Latent heat} = m(LH)_{S/V/F}$$

-10°C ice → 0°C ice → 0°C H_2O → 100°C H_2O → 100°C H_2O vapour → 150°C superheated steam

SH | LH | SH | LH | SH

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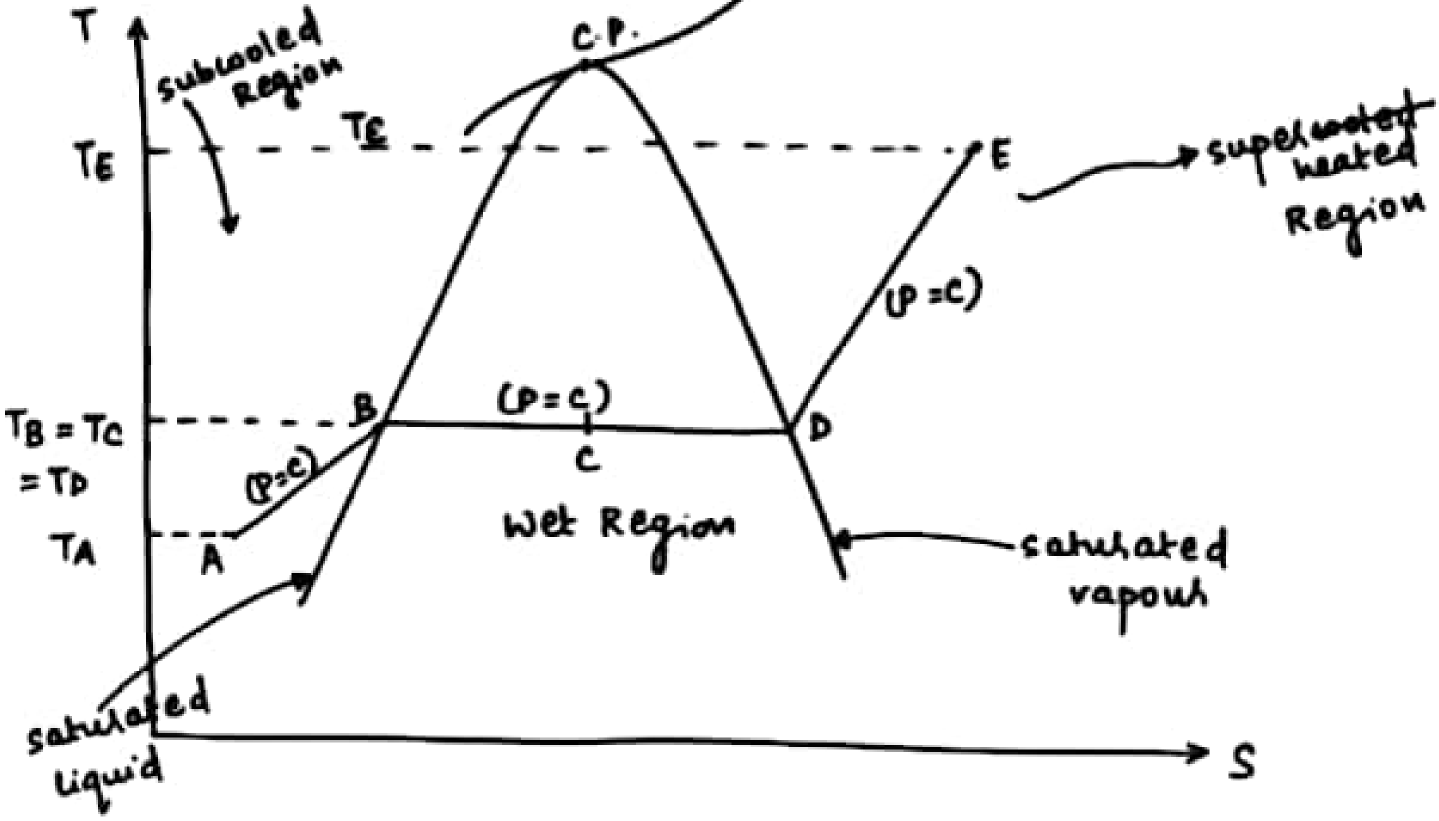
Representation of constant pressure line on T-S curve :-



at C.P. ⇒ $(CT)_{H_2O}$ = 374°C

⇒ $(CP)_{H_2O}$ = 221.2 Bar

Degree of superheating = $T_E - T_D$

" " subcooling or undercooling = $T_B - T_A$

Superheating :→ It is the process of increasing the tempr. at constant pressure above saturated vapour.

~~Dryness f~~ **Subcooling** :→ It is the process of decreasing the temperature at constant pressure below saturated liquid.

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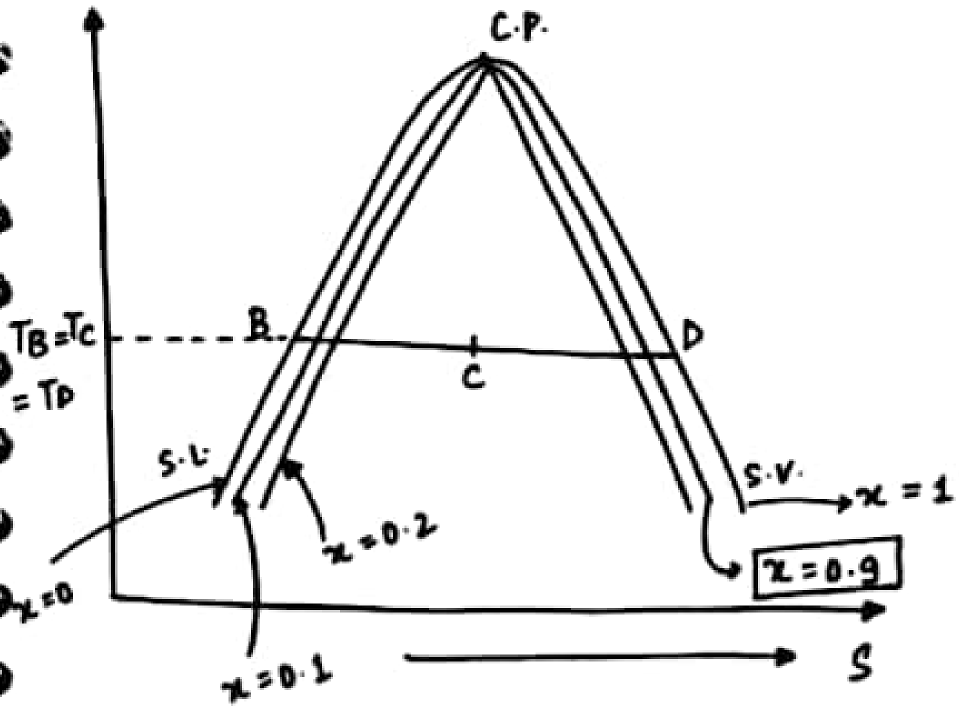
* Wet Region :- It is a mixture of liquid and vapour.

* C.P. (Critical Point) :- It is a point above which liquid will directly flash off into vapours.

NOTE :- The value of latent heat of vapourisation at critical point is 0.

* DRYNESS FRACTION OR QUALITY :→ (x)



$x = 0.20$ → 20% V, 80% L

$$x = \frac{m_v}{m_v + m_L}$$

x_B (sat. liquid) ⇒ $m_v = 0$, $x_B = 0$

x_D (sat. vapour) ⇒ $m_L = 0$, $x_D = 1$

$$0 \leq x \leq 1$$

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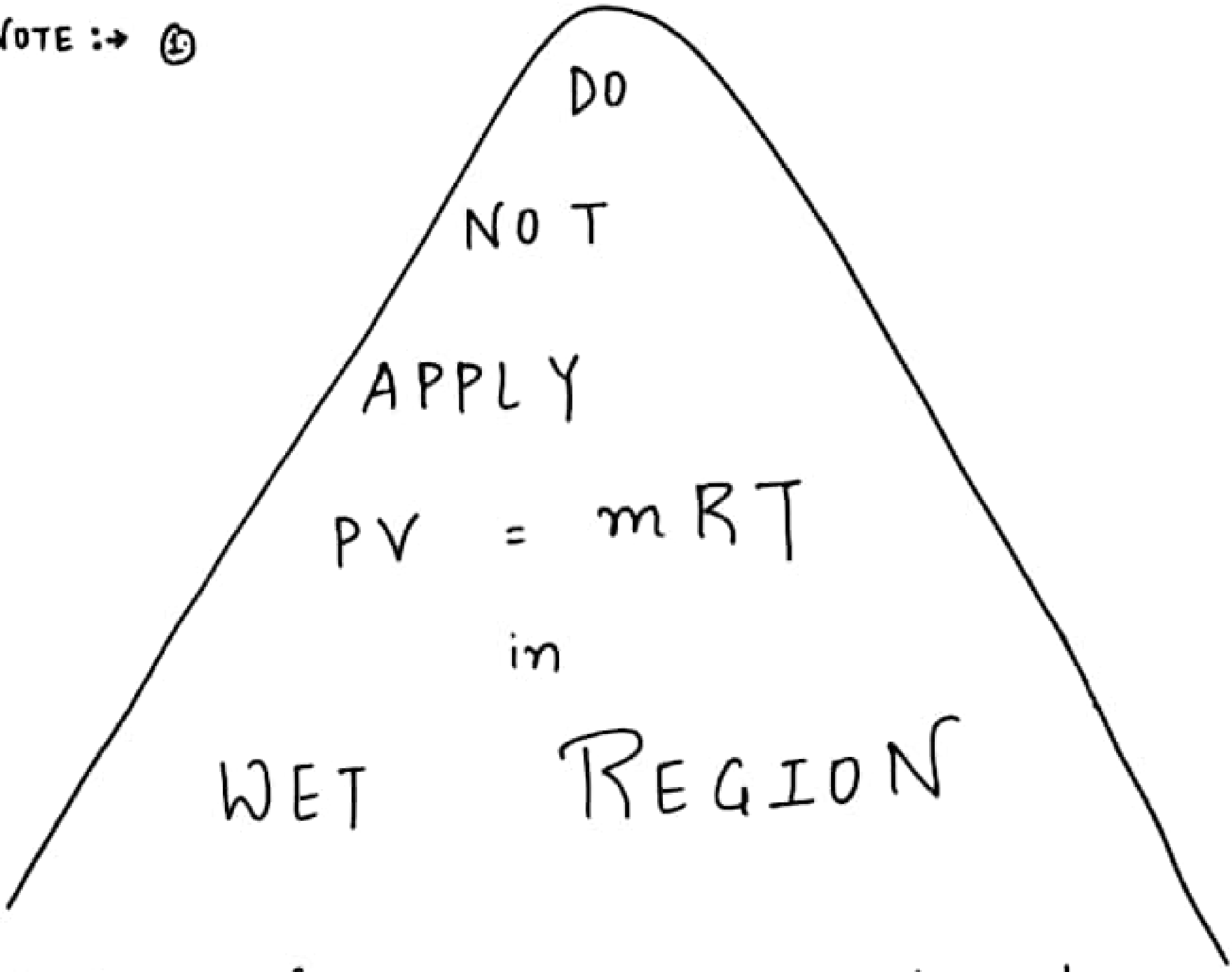
It is defined as the ratio of mass of vapour to the total mass of mixture. The value of dryness fraction is 0 for saturated liquid and the value of dryness fraction is 1 for saturated vapour.

NOTE :→ ①



② h_F s_F

h_g s_g

u_F v_F

u_g v_g

F → saturated liquid

g → saturated vapour

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③ The Reference state for the steam table is (163)

$u = 0$, $s = 0$] at 0.01°C (Triple point of water)

④ <u>MOLLIER'S</u> :→ It is a plot on h-s. The slope of constant pressure line on h-s curve is equal to absolute temperature. and the constant pressure line are of diverging nature in the superheated region.

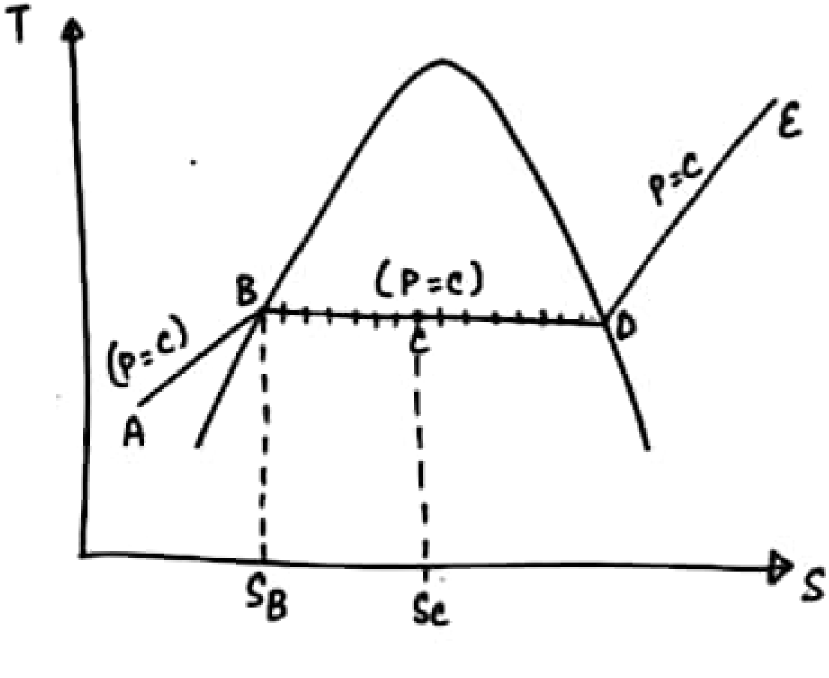
$$Tds = dh - vdP$$

$$P = C$$

$$Tds = dh$$

$$\boxed{\left(\frac{dh}{ds}\right)_P = T}$$

* The expression of enthalpy and entropy for the various states :-



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) The Reference state for the steam table is (169)

$u = 0$] at 0.01°C (Triple point of water)
$s = 0$]

) MOLLIER'S :→ It is a plot on h-s. The slope of constant pressure line on h-s curve is equal to absolute temperature. and the constant pressure line are of diverging nature in the superheated region.

$$T\,ds = dh - v\,dP$$

$$P = C$$

$$T\,ds = dh$$

$$\boxed{\left(\frac{dh}{ds}\right)_P = T}$$

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① h_B (sat. liquid) $= h_F$

② h_D (sat. vapour) $= h_g$

③ h_C (wet Region) $= h_B + x\, h_{Fg}$

$= h_F + x(h_g - h_F)$

④ $h_E = h_D + (C_p)_{vapour}(T_E - T_D) \longrightarrow \because (h_D < h_E)$

h_D or h_g

⑤ $h_A = h_B - (C_p)_{liq}(T_B - T_A) \longrightarrow (\because h_A < h_B)$

h_B or h_F

① $S_B = S_F$

② $S_D = S_g$

③ $S_C = S_B + x\, S_{FG}$

$= S_F + x(S_g - S_F)$

$= S_F + x\left(\frac{h_{Fg}}{T}\right)$

④ $S_E = S_D + (C_P)_{vapour} \ln\left(\frac{T_E}{T_D}\right)$

S_D or S_g

⑤ $S_A = S_B - (C_P)_{liq} \ln\left(\frac{T_B}{T_A}\right)$

S_B or S_F

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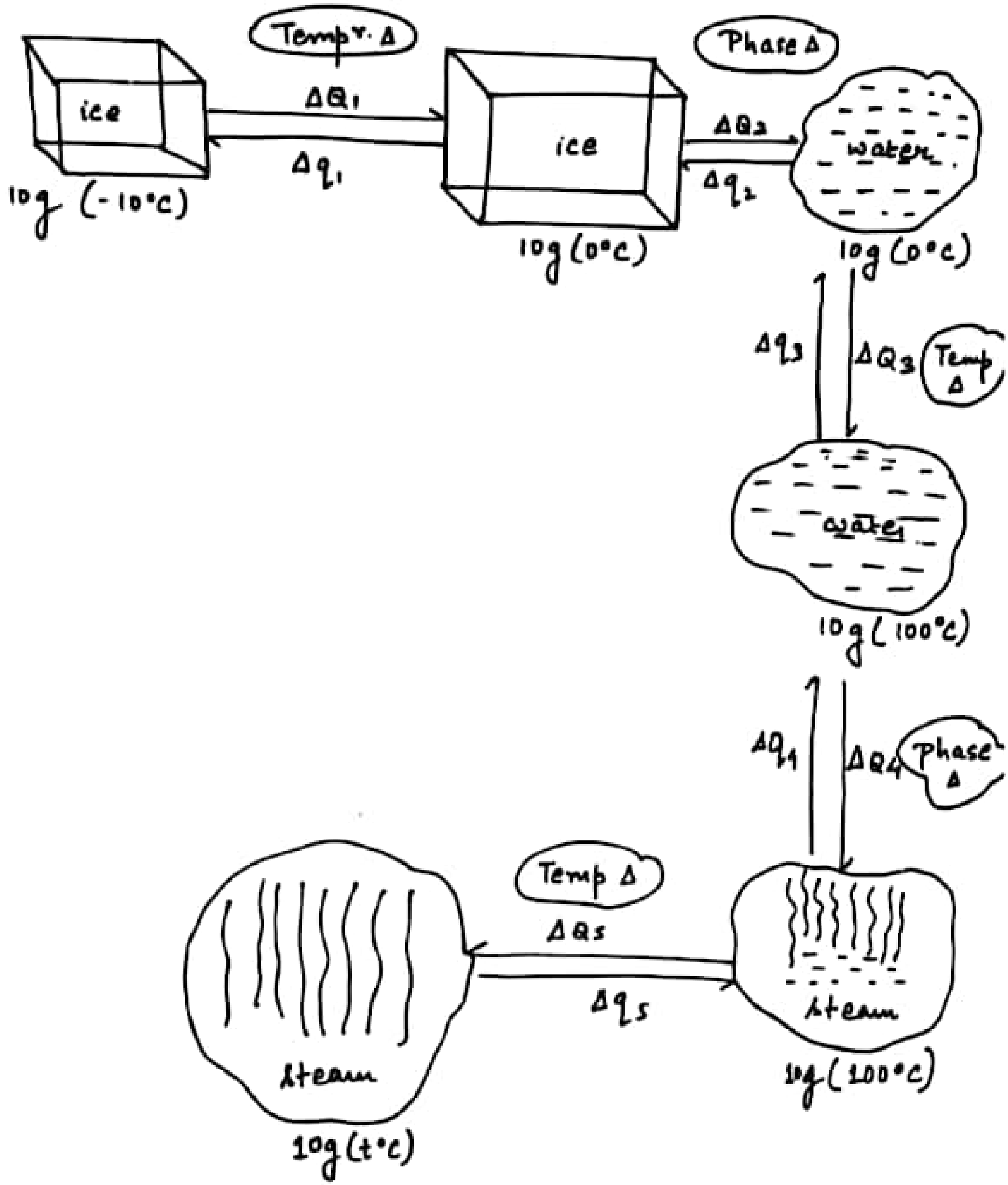
✓ Ice to steam Conversion



Temp Δ → sensible heat → $ms\Delta T = \Delta Q$, $C\Delta T = \Delta Q$

phase Δ → latent heat → $mL_f = \Delta Q$, $mL_v = \Delta Q$

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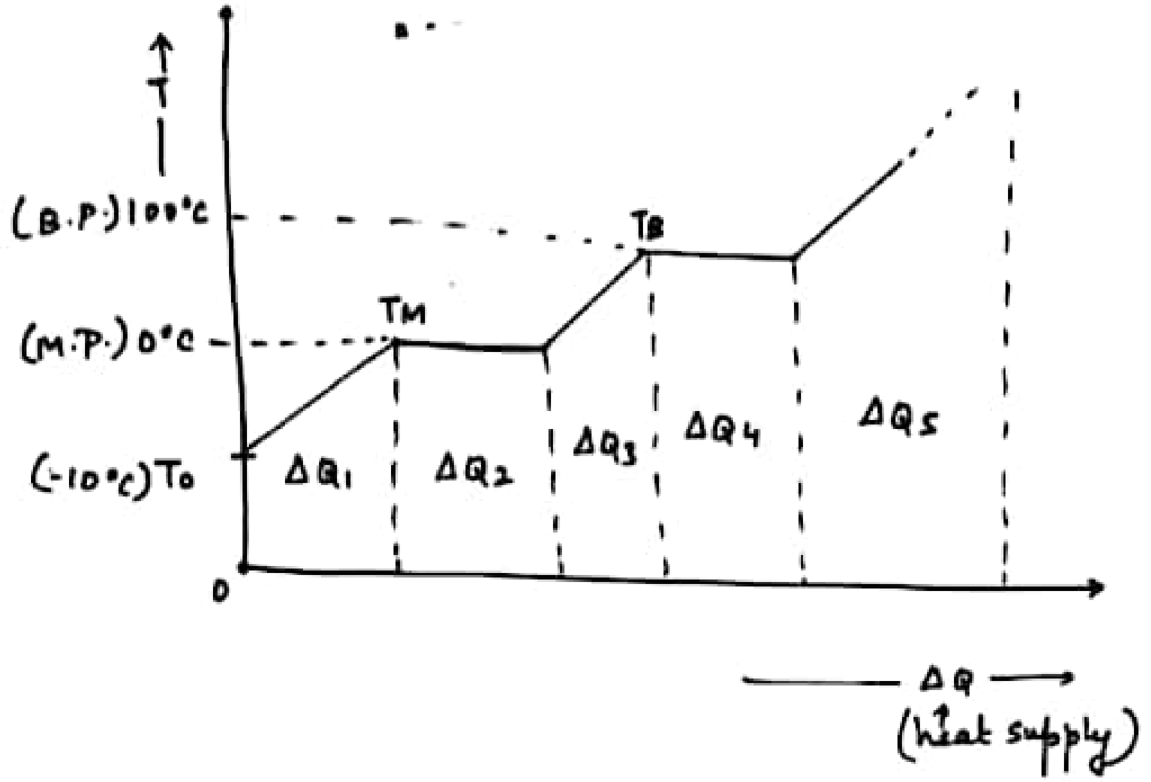
Graphical Representation (previous figr)



Heat Capacity (C)

$C = \frac{\Delta Q}{\Delta T}$ (J/K)

$\Delta Q = C \Delta T$

Specific Heat Capacity (S)

$S = \frac{\Delta Q}{m \Delta T}$ (J/kg·K)

$\Delta Q = m S \Delta T$

$\Rightarrow$ $mS = C$

Latent heat

$\frac{\Delta Q}{m} = L$ (J/Kg)

$\Delta Q = m L_f$ → solid ⇌ liquid

$\Delta Q = m L_v$ → liquid ⇌ water vapour or gas

Principle of Calorimetry (Energy Conservation)

Net heat Gained = Net heat lost.

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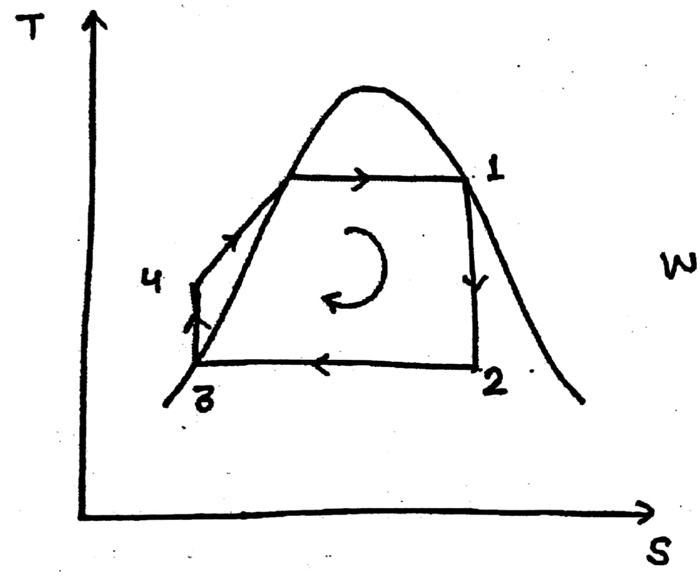
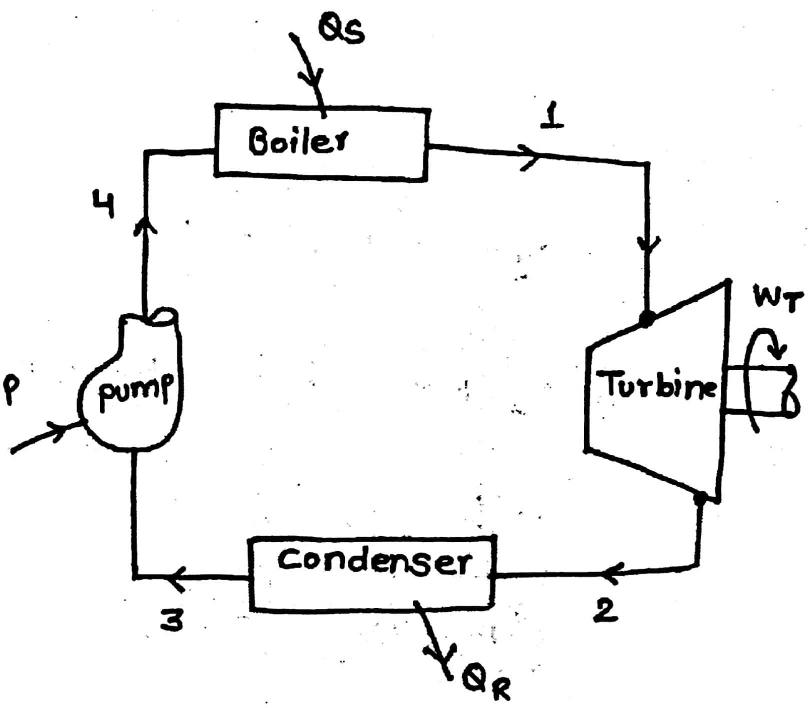
Rankine Cycle :-





$$\eta = \frac{W_{net}}{Q_s}$$

$$\boxed{\eta = \frac{W_T - W_P}{Q_s}}$$

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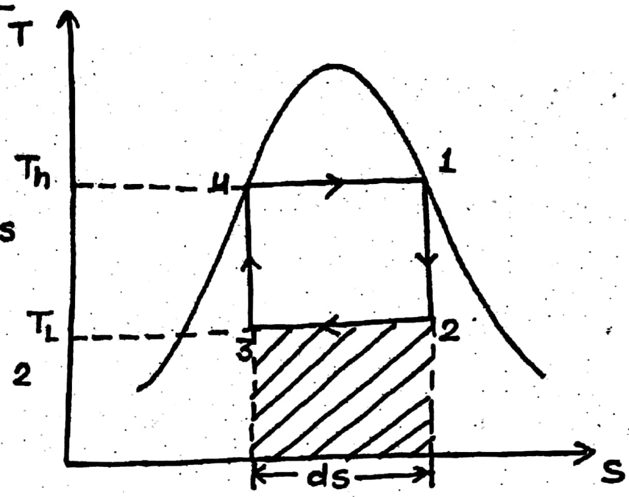
Carnot Vapour power Cycle:



Drawbacks:

(1) Saturated vapour which is entering the turbine at 1 leaves at 2 which is in wet region. The liquid which is present at state 2 may damage turbine blades due to high velocity.

(2) It is difficult to design a condenser which suddenly stops at point 3

(3) It is difficult to design a compressor which handles both liquid and vapour.

(4) As carnot vapour power cycle usages compressor, the compressor work is large and hence net work is less. [$W_{net} = W_T - W_C$]

$$\eta = 1 - \frac{Q_R}{Q_S} \Rightarrow 1 - \frac{T_L\, ds}{T_H \cdot ds}$$

$$\boxed{\eta = 1 - \frac{T_L}{T_h}}$$

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1-2 → Reversible adiabatic Expansion (Turbine)

2-3 → constant pressure heat Rejection (condenser)

3-4 → Rev. adiabatic compression (pump)

4-1 → constant pressure heat addition (boiler)

Analysis of the cycle :-

Assumptions:

(1) Each device is ~~fitted~~ treated as steady flow device.

(2) K.E & P.E. changes are Neglected.

Turbine (1-2) [Reversible adiabatic]

$$h_1 + \frac{c_1^2}{2} + z_1 g + q = h_2 + \frac{c_2^2}{2} + z_2 g + W$$

$$h_1 = h_2 + W$$

$$\boxed{W_{Turbine} = h_1 - h_2}$$

Condenser (2-3)

(No work)

$$h_2 + \frac{c_2^2}{2} + z_2 g + q = h_3 + \frac{c_3^2}{2} + z_3 g + W$$

$$\Rightarrow h_2 + q = h_3 \quad \text{(heat rejected)}$$

$$-q = h_2 - h_3.$$

$$\Rightarrow \boxed{q_{rejection} = h_2 - h_3}$$

$h_2 - h_3 = C_p(T_2 - T_3)$ Only for gas/air but here we used water so we can't write it for water.

Pump (3-4):

$$h_3 + \frac{c_3^2}{2} + z_3 g + q = h_4 + \frac{c_4^2}{2} + z_4 g + W$$

$$\boxed{W = h_3 - h_4}$$

$$\Rightarrow -W = h_4 - h_3 \Rightarrow \boxed{W_{pump} = h_4 - h_3}$$

-ve represent work done on the System.

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Neglected and when the process is reversible.

SFEE can be applied for rev. as well as irreversible process if the pumping process is reversible then work obtained for SFEE and $w = -vdp$ can be equated.

$$h_3 - h_4 = -vdp$$

$$\boxed{h_4 - h_3 = vdp}$$

- We know that $W_P = h_4 - h_3$, if the pump work is very small then it can be neglected therefore

$h_4 \simeq h_3$ when pump work is Negligible.

Boiler:- [4-1]

$$h_4 + \frac{C_4^2}{2} + z_4 g + q = h_1 + \frac{C_1^2}{2} + z_1 g + w \quad \text{[No work]}$$

$$h_4 + q = h_1$$

$$q = h_1 - h_4 \quad ; \quad \boxed{q_s = h_1 - h_4}$$

$$\eta = \frac{W_T - W_P}{Q_s}$$

$$\eta = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

$W_T = h_1 - h_2$

$q_R = h_2 - h_3$

$W_P = h_4 - h_3$

$q_s = h_1 - h_4$

When pump work is Negligible

$$h_4 = h_3$$

$$\eta = \frac{h_1 - h_2}{h_1 - h_4} \Rightarrow \boxed{\eta = \frac{h_1 - h_2}{h_1 - h_3}}$$

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4.3 ► THROTTLING CALORIMETER

Throttling calorimeter is a device used in the determination of the dryness fraction of steam. There is a sampling tube, which is placed in the steam main pipe. It consists of a hole facing upstream to get sample steam. The steam passes through the throttle valve and then flows into the inner cylinder. The main condition is that after throttling steam should be superheated. Normally, the degree of superheat should be 5°C. The pressure after throttling should be a few mm of H_g above atmospheric pressure as recorded by a manometer. The saturation temperature corresponding to this pressure can be found. If the temperature recorded by the thermometer is more than saturation temperature, it is confirmed that steam is superheated after throttling. Steam flows from the top of the inner cylinder to the annular space between inner and outer cylinders. The calorimeter is insulated from the surroundings. Before taking a temperature reading, the flow of the steam should be in the steady state and all parts to be heated to keep temperature remains constant. The constructional details of calorimeter are shown in Figure 4.7.

Let P_1 = Initial pressure of steam

P_2 = Final pressure = Atmospheric pressure + manometer reading

h_{f1} = Enthalpy of water at pressure, P_1

h_{fg1} = Enthalpy of vaporization at pressure, P_1

C_{pg} = Specific heat of superheated steam

t_{S2} = Saturation temperature at final pressure, P_2

t_{sup} = Temperature recorded by thermometer

x_1 = Dryness fraction of steam before throttling

During throttling, enthalpy remains constant, i.e., enthalpy before throttling = enthalpy after throttling.

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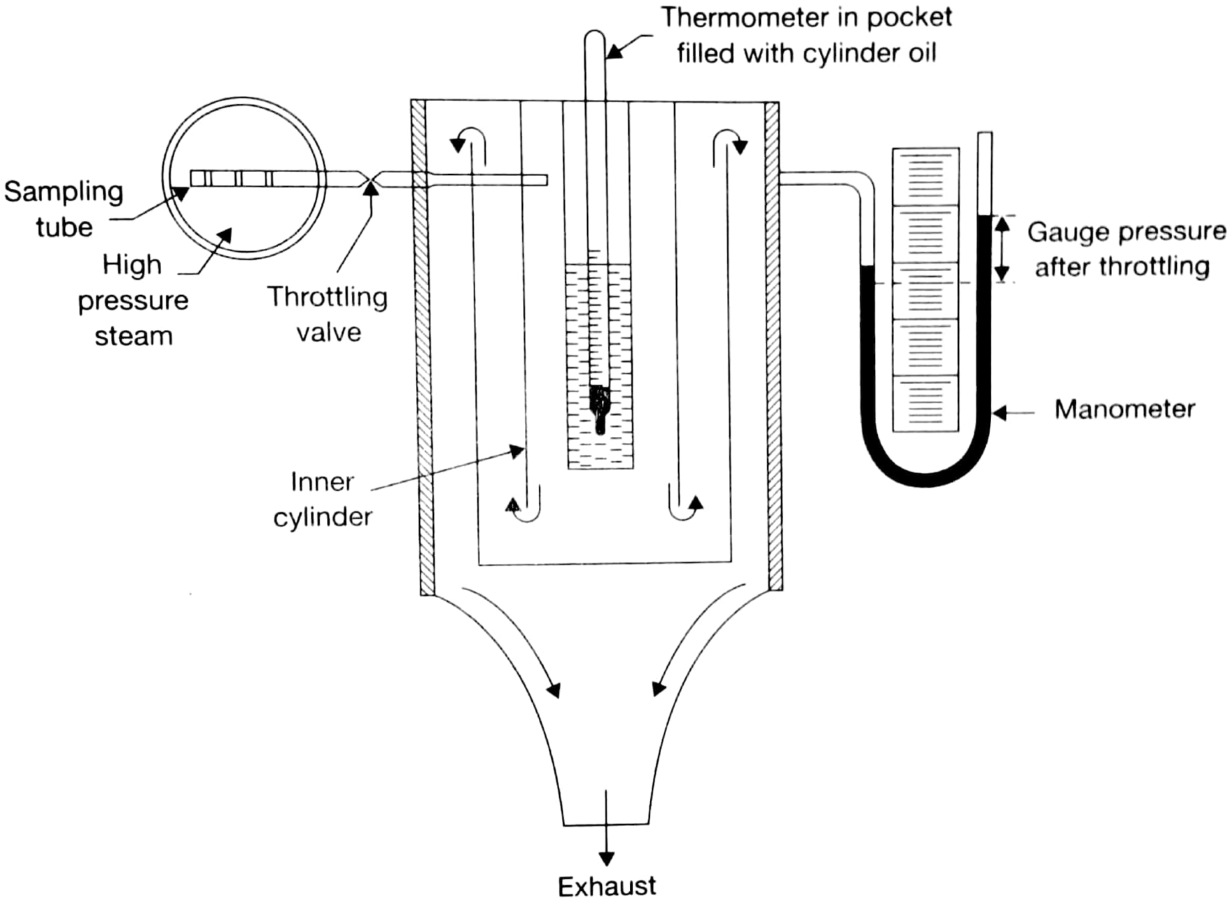

FIGURE 4.7

Throttling Calorimeter

Therefore, $h_{f1} + x_1 h_{fg} = h_{g2} + C_p\left(t_{\text{sup}} - t_{S2}\right)$

or, $$\boldsymbol{x_1} = \frac{\boldsymbol{h_{g2} + C_p\left(t_{\text{sup}} - t_{S2}\right) - h_{f1}}}{\boldsymbol{h_{fg}}};\ \text{where } C_p = 0.48$$

Limitation of the process is that the steam should be superheated after throttling.

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