

ସରକାରୀ ବହୁବୃତ୍ତି ବୈଷୟିକ ଶିକ୍ଷାନୁଷ୍ଠାନ କନ୍ଦମାଳ,
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(iii) State unit of Heat and work, 1st law of thermodynamics.

Heat :- The heat is defined as the energy transferred, without transfer of mass, across the boundary of system because of a temperature difference between the system and the surroundings.

→ It is usually represented by Q .

→ Its unit is Joule (J).

Specific heat :-

→ It may be defined as the amount of heat required to raise the temperature of a unit mass of any substance through 1° .

→ It is denoted by C .

→ Its SI unit is kJ/kgK .

→ For solids and liquids the volume do not change therefore they have one specific heat.

→ For gas it has two specific heat.

(A) specific heat at constant pressure (C_p)

(B) specific heat at constant volume (C_v)

→ C_p always greater than C_v .

Work :- It may be defined as the energy transferred across the boundary of system because of an intensive property difference other than temperature that exists between the system and surroundings.

Heat and work a path function :-

Comparison of heat and work :-

- Both heat and work are boundary phenomena that is they occur only at the boundary.
- The 'interaction' due to the temperature difference is heat and all other interactions are to be taken as work.
- Both work and heat are path functions that is they are in exact differentials.

Laws of Thermodynamics :-

- The following three laws of thermodynamics are important from the subject point of view.

(1) Zeroth Law of Thermodynamics

(2) First Law of Thermodynamics

(3) Second Law of Thermodynamics

Zeroth Law of Thermodynamics :-

This law states, when two systems, are each in thermal equilibrium with a third system, then the two systems are also in thermal equilibrium with one another.

First Law of Thermodynamics :-

It may be stated as follows -
a) The heat and mechanical work are mutually convertible.

$$\oint \delta Q = \oint \delta W$$

b) The energy can neither be created nor destroyed through it can be transformed from one form to another.

Limitations of First Law of Thermodynamics :-

→ When a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer.

→ The heat energy and mechanical work are mutually convertible.

Perfect Gases :-

A perfect gas may be defined as a state of a substance whose evaporation from its liquid state is complete, and strictly obeys all the gas laws under all conditions of temperature and pressure.

Laws of perfect gases :-

① Boyle's law $\rightarrow P \propto \frac{1}{V}$

② Charles' law $\rightarrow V \propto T$

③ Gay-Lussac law $\rightarrow P \propto T$

① Boyle's Law :- The absolute pressure of a given mass of a perfect gas varies inversely as its volume, when the temperature remains constant.

$$P \propto \frac{1}{V}$$

② Charles' Law :- The volume of a given mass of a perfect gas varies directly as its absolute temperature, when the absolute pressure remains constant.

$$V \propto T$$

③ Gay-Lussac Law :- The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, when the volume remains constant.

$$P \propto T$$

General Gas Equation :-

According to Boyle's Law

$$P \propto \frac{1}{V} \text{ or } V \propto \frac{1}{P}$$

and according to Charles' Law

$$V \propto T$$

It is thus obvious that

$$V \propto \frac{1}{P} \text{ and } T \text{ both or } V \propto \frac{T}{P}$$

$$PV \propto T \text{ or } PV = CT$$

$$P \propto \frac{1}{V}$$

$$\Rightarrow V \propto \frac{1}{P}$$

$$\Rightarrow V \propto \frac{T}{P}$$

$$\Rightarrow PV \propto T$$

$$\Rightarrow \boxed{PV = CT}$$

$$\Rightarrow \frac{PV}{T} = \text{constant (C)}$$

$$\Rightarrow \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} = \text{constant}$$

Example 2.1 :- A gas occupies a volume of 0.1 m^3 at a temperature of 20°C and a pressure of 1.5 bar . Find the final temperature of the gas, if it is compressed to a pressure of 7.5 bar and occupies a volume of 0.04 m^3 .

Solution :-

Given $V_1 = 0.1 \text{ m}^3$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$P_1 = 1.5 \text{ bar} = 1.5 \times 10^5 \text{ N/m}^2$$

$$V_2 = 0.04 \text{ m}^3$$

$$P_2 = 7.5 \text{ bar} = 7.5 \times 10^5 \text{ N/m}^2$$

we know that $T_2 = ?$

we know that

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\Rightarrow T_2 = \frac{P_2 V_2 T_1}{P_1 V_1}$$

$$\Rightarrow T_2 = \frac{7.5 \times 10^5 \times 0.04 \times 293}{1.5 \times 10^5 \times 0.1}$$

$$\Rightarrow T_2 = 5 \times \frac{4}{10} \times 293 \times \frac{10}{1}$$

$$\Rightarrow T_2 = 586 \text{ K} = 586 - 273 = 313^\circ\text{C}$$

~~$\therefore 586 - 273 = 313^\circ\text{C}$~~

(Ans)

(Ans)

Characteristic Equation of a Gas :-

$$PV \propto T$$

$$\Rightarrow PV = CT$$

$$\Rightarrow \frac{PV}{T} = C$$

$$\Rightarrow \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

for $m = 1 \text{ kg}$ of gas

$$PV_s = RT$$

$$\Rightarrow P \frac{V}{m} = RT$$

$$\Rightarrow \boxed{PV = mRT}$$

$$\Rightarrow P = \frac{mRT}{V} = \frac{m}{V} RT$$

$$\Rightarrow \boxed{P = \rho RT}$$

V_s = specific volume

R = characteristic constant gas

m = mass

ρ = Rho (Density)

$$V_s = \frac{V}{m}$$

$$\text{Density } (\rho) = \frac{m}{V} \quad (\because \rho = \text{Rho})$$

Specific Heats of a gas :-

→ The specific heat of a substance may be broadly defined as the amount of heat required to raise the temperature of its unit mass through one degree.

→ All the liquids and solids have one specific heat

→ A gas can have a number of specific heats where the following two types of specific heats of a gas are important from the subject point of view.

a) specific heat at constant pressure (C_p)

b) specific heat at constant volume (C_v)

Specific Heat at constant pressure :- It is amount of heat required to raise the temperature of a unit mass of a gas through one degree, when it is heated at constant pressure. It is generally denoted by c_p .

Specific heat at constant volume :- It is the amount of heat of a required to raise the temperature of a unit mass of gas, through one degree, when it is heated at a constant volume. It is generally denoted by c_v .

Relation between specific heats :-

Consider a gas enclosed in a container and being heated, at a constant pressure from the initial state 1 to the final state 2.

Let, m = mass of the gas

T_1 = Initial temperature of the gas

T_2 = Final temperature of the gas

v_1 = Initial volume of the gas

v_2 = Final volume of the gas

c_p = specific heat at constant pressure,

c_v = specific heat at constant volume

p = constant pressure

We know that the heat supplied to the gas at constant pressure,

$$Q_{1-2} = mc_p(T_2 - T_1)$$

As already discussed, a part of this heat is utilised in doing the external work, and the rest remains within the gas, and is used in increasing the internal energy of the gas.

$\therefore$ Heat utilised for external work,

$$W_{1-2} = P(V_2 - V_1) \quad \text{--- (i)}$$

and increase in internal energy,

$$dU = m c_v (T_2 - T_1) \quad \text{--- (ii)}$$

we know that

$$Q_{1-2} = W_{1-2} + dU \quad \text{--- (iii)}$$

$$\therefore m c_p (T_2 - T_1) = P(V_2 - V_1) + m c_v (T_2 - T_1) \quad \text{--- (iv)}$$

Using characteristic gas equation ($PV = mRT$),
we have

$$P V_1 = m R T_1$$

$$P V_2 = m R T_2$$

Now, substituting the value of $P(V_2 - V_1)$ in equation (iv)

$$m c_p (T_2 - T_1) = m R (T_2 - T_1) + m c_v (T_2 - T_1)$$

$$\Rightarrow \cancel{m c_p (T_2 - T_1)} = \cancel{m (T_2 - T_1)} \{c_v + R\}$$

$$\Rightarrow c_p = c_v + R$$

$$\Rightarrow c_p - c_v = R$$

Relation between specific heat is $\boxed{c_p - c_v = R}$

Ratio of specific heats :-

$$c_p - c_v = R$$

$$\frac{c_p}{c_v} = \gamma \quad (\text{Gamma})$$

$\Rightarrow$ Adiabatic Index

$$c_p - c_v = R$$

$$c_p = c_v + R$$

Divide

Dividing throughout by C_v

$$\frac{C_p}{C_v} = \frac{C_v + R}{C_v} = \frac{C_v}{C_v} + \frac{R}{C_v}$$

$$\Rightarrow \boxed{\gamma = 1 + \frac{R}{C_v}}$$

Note:-

- C_p always greater than C_v .
- Since C_p is greater than C_v . Hence the value of γ is always greater than unity.

Example - 2.2!

Given

$$V_1 = 3 \text{ m}^3$$

$$P_1 = 1.5 \text{ bar} = 1.5 \times 10^5 \text{ N/m}^2$$

$$T_1 = 25^\circ\text{C} = 25 + 273 = 298 \text{ K}$$

$$P_2 = 30 \text{ bar} = 30 \times 10^5 \text{ N/m}^2$$

$$T_2 = 60^\circ\text{C} = 60 + 273 = 333 \text{ K}$$

$$P_3 = 1.02 = 1.02 \times 10^5 \text{ N/m}^2$$

$$T_3 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$P_1 V_1 = m_1 R T_1$$

$$m_1 = \frac{P_1 V_1}{R T_1} = \frac{1.5 \times 10^5 \times 3}{287 \times 298}$$

$$= 5.26 \text{ kg}$$

Similarly,

$$P_2 V_2 = m_2 R T_2$$

$$m_2 = \frac{P_2 V_2}{R T_2} = \frac{30 \times 10^5 \times 3}{287 \times 333}$$

$$= 94.17 \text{ kg}$$

$$m = m_2 - m_1 = 94.17 - 5.26$$

$$= 88.91 \text{ kg} \quad (\text{m})$$

Let v_3 = volume of air pumped in

we know that

$$P_3 V_3 = m R T_3$$

$$V_3 = \frac{m R T_3}{P_3} = \frac{88.91 \times 287 \times 293}{1.02 \times 10^5}$$

$$= 73.3 \text{ m}^3$$

Pressure in the vessel after cooling

Let P_4 = pressure in the vessel after cooling

we know that temperature after cooling

$$T_4 = T_1 = 25^\circ\text{C} = 298 \text{ K}$$

$$\frac{P_4}{P_2} = \frac{T_4}{T_2}$$

$$P_4 = \frac{T_4 P_2}{T_2} = \frac{298 \times 30 \times 10^5}{333}$$

$$= 2684684.68 \text{ bar}$$

Example - 2.9 :-

Given

$$m = 1 \text{ kg}$$

$$V = 0.85 \text{ m}^3$$

$$T = 15^\circ\text{C} = 15 + 273 = 288 \text{ K}$$

$$P = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$\gamma = \frac{C_p}{C_v} = 1.4$$

we know that

$$Pv = MRT$$

$$R = \frac{Pv}{MT} = \frac{1 \times 10^5 \times 0.85}{1 \times 288} = 295 \text{ kJ/kg K}$$

we also know that

$$C_v = \frac{R}{\gamma - 1} = \frac{295}{1.4 - 1} = 737 \text{ kJ/kg K}$$

Specific heat of gas at constant pressure
we know that specific heat of gas at constant pressure,

$$C_p = 1.4 C_v = 1.4 \times 737 = 1031.8 \text{ kJ/kg K (Ans)}$$

Example 2.10 :-

Given

$$m = 26.7$$

$$C_{vm} = 21.1 \text{ kJ/kg K}$$

Characteristic gas constant

$$R = \frac{R_u}{M} = \frac{8.314}{26.7} = \frac{8.314}{26.7}$$

$\therefore R_u$ for all gases = 8.314 kJ/kg K

Let

C_{pm} = Molar specific heat at constant pressure

we know that

$$C_{pm} - C_{vm} = R_u \text{ or } C_{pm} = R_u + C_{vm}$$

$$= 8.314 + 21.1 = 29.414 \text{ kJ/kg K}$$

Ratio of specific heats

$$\gamma = \frac{C_{pm}}{C_{vm}} = \frac{29.414}{21.1} = 1.394 \text{ (Ans)}$$

Example 2.11 :-

Given,

$$m = 1 \text{ kg}$$

$$T_1 = 18.3^\circ\text{C} = 18.3 + 273 = 291.3 \text{ K}$$

$$T_2 = 93.4^\circ\text{C} = 93.4 + 273 = 366.4 \text{ K}$$

$$R = 0.264 \text{ kJ/kg K}$$

$$\gamma = \frac{C_p}{C_v} = 1.18$$

Let

C_p = specific heat at constant pressure

C_v = specific heat at constant volume

We know that

$$C_v = \frac{R}{\gamma - 1} = \frac{0.264}{1.18 - 1} = 1.47 \text{ kJ/kg K}$$

$$C_p = \gamma C_v = 1.18 \times 1.47 = 1.73 \text{ kJ/kg K}$$

Change in internal energy

$$\begin{aligned} du &= m C_v (T_2 - T_1) = 1 \times 1.47 (366.4 - 291.3) \\ &= 110.4 \text{ kJ} \end{aligned}$$

Change in enthalpy

$$dH = m C_p (T_2 - T_1) = 1 \times 1.73 (366.4 - 291.3)$$

$$= 130 \text{ kJ}$$

Example 2.12 :-

Given

$$P_1 = 275 \text{ kN/m}^2 = 275 \times 10^3 \text{ N/m}^2$$

$$V_1 = 0.09 \text{ m}^3$$

$$T_1 = 185^\circ\text{C} = 185 + 273 = 458 \text{ K}$$

$$T_2 = 15^\circ\text{C} = 15 + 273 = 288 \text{ K}$$

$$R = 290 \text{ J/kg K}$$

$$C_p = 1.005 \text{ kJ/kg K}$$

Amount of heat transferred

$$P_1 V_1 = m R T_1$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{275 \times 10^3 \times 0.09}{290 \times 458} = 0.186 \text{ kg}$$

We know that the amount of heat transferred

$$Q_{1-2} = m c_p (T_2 - T_1) = 0.186 \times 1.005 (288 - 458) \text{ kJ}$$

work done during the process

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \text{ or } V_2 = \frac{V_1 T_2}{T_1} = \frac{0.09 \times 288}{458} = 0.056 \text{ m}^3$$

$$W_{1-2} = P (V_2 - V_1) = 275 \times 10^3 (0.056 - 0.09)$$

$$= -9350 \text{ J} = -9.35 \text{ kJ}$$

(Ans)

Example - 2.13 :-

Given

$$C_p = 1.96 \text{ kJ/kg K}$$

$$C_v = 1.5 \text{ kJ/kg K}$$

$$V = 0.3 \text{ m}^3$$

$$m = 2 \text{ kg}$$

$$T_1 = 5^\circ\text{C} = 5 + 273 = 278 \text{ K}$$

$$T_2 = 100^\circ\text{C} = 100 + 273 = 373 \text{ K}$$

Molecular mass and gas constant

Let M = Molecular mass

R = Gas constant

We know that

$$R = C_p - C_v = 1.96 - 1.5 = 0.46 \text{ kJ/kg K}$$

$$M = \frac{R_u}{R} = \frac{8.314}{0.46} = 18 \text{ kg} \quad (\because R_u \text{ for all gases} = 8.314 \text{ kJ/kg K})$$

Heat transferred

We know that heat transferred,

$$Q_{1-2} = m C_v (T_2 - T_1) = 2 \times 1.5 (373 - 278) \\ = 285 \text{ kJ}$$

Change in internal energy

Let du = change in internal energy

we know that

$$Q_{1-2} = W_{1-2} + du = 0 + du = du$$

$$du = Q_{1-2} = 285 \text{ kJ}$$

Example - 2.14 :-

Given ,

$$V_1 = 2.5 \text{ m}^3$$

$$M = 1 \text{ kg-mole} = 28 \text{ kg}$$

$$T_1 = 100^\circ\text{C} = 100 + 273 = 373 \text{ K}$$

$$T_2 = 30^\circ\text{C} = 30 + 273 = 303 \text{ K}$$

$$\gamma = \frac{c_p}{c_v} = 1.4$$

Specific volume and pressure

$$V_s = \frac{V_1}{M} = \frac{2.5}{28} = 0.089 \text{ m}^3/\text{kg}$$

$$(\because R_u = 8314 \text{ J/kg mole})$$

Gas constant ,

$$R = \frac{R_u}{M} = \frac{8314}{28}$$

$$= 297 \text{ J/kg K}$$

we know that

$$P_1 V_1 = MRT_1$$

$$P_1 = \frac{MRT_1}{V_1} = \frac{28 \times 297 \times 373}{2.5}$$

$$= 1.24 \times 10^6 \text{ N/m}^2$$

$$= 12.4 \text{ bar } (\because 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2)$$

final pressure , change in specific internal energy and specific enthalpy

Let P_2 = final pressure of the gas

$$\text{we know } \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \text{ or } \frac{P_1}{T_1} = \frac{P_2}{T_2} (\because V_1 = V_2)$$

$$P_2 = \frac{P_1 T_2}{T_1} = \frac{12.4 \times 303}{373} = 10.07 \text{ bar}$$

Now, let us find out the values of C_p and C_v .

We know that $C_p - C_v = R$

$$1.4 C_v - C_v = 297$$

$$C_v = 297 / 0.4 = 742.5 \text{ J/kg}$$

$$= 0.7425 \text{ kJ/kg}$$

$$C_p = 1.4 C_v = 1.4 \times 0.7425 = 1.04 \text{ kJ/kg}$$

Change in specific internal energy

$$\begin{aligned} du &= C_v (T_2 - T_1) = 0.7425 (303 - 373) \\ &= -52 \text{ kJ/kg (Ans)} \end{aligned}$$

Change in specific enthalpy

$$\begin{aligned} dh &= C_p (T_2 - T_1) = 1.04 (303 - 373) \\ &= -72.8 \text{ kJ/kg (Ans)} \end{aligned}$$

Thermodynamic process of perfect gases:-

* When a system changes its state from one equilibrium state to another equilibrium state, then the path of successive states through which the system has passed is known as a thermodynamic process.

Classification of Thermodynamic processes:-

① Non-flow processes

② Flow processes

Non-flow processes:-

The processes occurring in closed systems which do not permit the transfer of mass across their boundaries are known as non-flow processes.

Flow processes:-

The processes occurring in open systems which permit the transfer of mass to and from the system, are known as flow processes.

Heating and Expansion of gases in non-flow processes

The heating and expanding of a gas may be performed in many ways. But the following are the different non-flow processes (reversible and irreversible) as applied to perfect gas.

- (1) Constant volume process (or Isochoric process)
- (2) Constant pressure process (or Isobaric process)
- (3) Hyperbolic process,
- (4) Constant temperature process (or Isothermal process)
- (5) Adiabatic process (or Entropic process) and
- (6) polytropic process

(1) Pressure - volume - temperature (P-V-T) relationship

We know that the general gas equation is

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Since the gas is heated at constant volume,

Therefore $V_1 = V_2$

$$\therefore \frac{P_1}{T_1} = \frac{P_2}{T_2} \text{ or } \frac{P}{T} = \text{constant}$$

(a) Work done by the gas

We know that $\delta W = p dv$

on integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p dv = p \int_1^2 dv$$

$$W_{1-2} = p(V_2 - V_1) = 0$$

(3) change in internal energy

we know that change in internal energy,

$$dU = m c_v dT$$

on integrating from state 1 to state 2,

$$\int_1^2 dU = m c_v \int_1^2 dT$$

$$\text{or } U_2 - U_1 = m c_v (T_2 - T_1)$$

(4) Heat supplied or heat transfer

we know that

$$\delta Q = dU + \delta W$$

on integrating from state 1 to state 2,

$$\int_1^2 \delta Q = \int_1^2 dU + \int_1^2 \delta W$$

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

Since $W_{1-2} = 0$, therefore heat supplied or heat transfer,

$$Q_{1-2} = U_2 - U_1 = m c_v (T_2 - T_1)$$

Example-3.3 :-

Given

$$V_1 = 0.3 \text{ m}^3$$

$$P_1 = 2 \text{ bar} = 0.2 \times 10^6 \text{ N/m}^2$$

$$T_1 = 77^\circ \text{C} = 77 + 273 = 350 \text{ K}$$

$$P_2 = 7 \text{ bar} = 0.7 \times 10^6 \text{ N/m}^2$$

$$C_p = 1.005 \text{ kJ/kg K}$$

$$C_v = 0.712 \text{ kJ/kg K}$$

$$R = 287 \text{ J/kg K}$$

Let T_2 = Temperature at the end of the process

We know that

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$T_2 = \frac{P_2 T_1}{P_1} = \frac{0.7 \times 10^6 \times 350}{0.2 \times 10^6} = 1225 \text{ K}$$

$$= 1225 - 273$$

$$= 952^\circ \text{C}$$

$$= 952 - 273$$

(2) Mass of the gas

Let m = Mass of the gas

We know that

$$P_1 V_1 = m R T_1$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{0.2 \times 10^6 \times 0.3}{287 \times 350} = 0.597 \text{ kg}$$

(3) Change in internal energy

We know that change in internal energy

$$dU = U_2 - U_1 = m c_v (T_2 - T_1)$$

$$= 0.597 \times 0.712 (1225 - 350) = 372 \text{ kJ}$$

(4) Change in enthalpy

We know that change in enthalpy,

$$dH = H_2 - H_1 = m c_p (T_2 - T_1)$$

$$= 0.597 \times 1.005 (1225 - 350)$$

$$= 525 \text{ kJ} \quad (\text{Ans})$$

Example - 3.4 :-

Given

$$C_p = 0.984 \text{ kJ/kg K}$$

$$C_v = 0.728 \text{ kJ/kg K}$$

$$m = 1 \text{ kg}$$

$$T_1 = 25^\circ \text{C} = 25 + 273 = 298 \text{ K}$$

$$T_2 = 200^\circ \text{C} = 200 + 273 = 473 \text{ K}$$

$$V_1 = 2 \text{ m}^3$$

Characteristic gas constant

we know that characteristic gas constant,

$$R = C_p - C_v = 0.984 - 0.728 \\ = 0.256 \text{ kJ/kg K}$$

Ratio of specific heats

we know the ratio of specific heats,

$$\gamma = C_p / C_v = 0.984 / 0.728$$

$$= 1.35$$

Heat added

we know that heat added during constant pressure operation,

$$Q_{1-2} = m C_p (T_2 - T_1) = 1 \times 0.984 (473 - 298) \\ = 172.2 \text{ kJ}$$

Workdone

we know that workdone during constant pressure operation,

$$W_{1-2} = P (V_2 - V_1) = m R (T_2 - T_1) \\ = 1 \times 0.256 (473 - 298) \\ = 44.8 \text{ kJ}$$

change in internal energy

we know that change in internal energy,

$$\Delta U = U_2 - U_1 = m C_v (T_2 - T_1)$$

$$= 1 \times 0.728 (473 - 298) \text{ kJ}$$

$$= 127.4 \text{ kJ}$$

Pressure and final volume of the gas if
the initial volume, $V_1 = 2 \text{ m}^3$

Let

$P_1 = P_2 =$ pressure of the gas, and

$V_2 =$ Final volume of the gas

we know that $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$ or $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

$$V_2 = \frac{V_1 T_2}{T_1} = \frac{2 \times 473}{298} = 3.17 \text{ m}^3$$

we also know that

$$P_1 V_1 = m R T_1$$

$$P_1 = \frac{m R T_1}{V_1} = \frac{1 \times 256 \times 298}{2} = 38140 \text{ N/m}^2$$

$$= 380140 \text{ N/m}^2$$

$$= 0.3814 \text{ bar}$$

(Ans)

Example 3.5 :-

Given,

$$V_1 = 0.14 \text{ m}^3$$

$$P = 1.5 \text{ bar} = 0.15 \times 10^6 \text{ N/m}^2$$

$$T_1 = 100^\circ\text{C} = 100 + 273 = 373 \text{ K}$$

$$V_2 = 0.112 \text{ m}^3$$

$$C_p = 1.005 \text{ kJ/kg K}$$

$$C_v = 0.712 \text{ kJ/kg K}$$

$$R = 285 \text{ J/kg K}$$

- (1) Temperature at the end of compression
Let T_2 = Temperature at the end compression

We know that

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$T_2 = \frac{V_2 T_1}{V_1} = \frac{0.112 \times 373}{0.14} = 298.4 \text{ K}$$
$$= 298.4 - 273$$
$$= 25.4^\circ\text{C}$$

- (2) Work done is compressing the gas

We know that work done in compressing the gas,

$$W_{1-2} = P(V_1 - V_2) = 0.15 \times 10^6 (0.14 - 0.112) = 4200 \text{ J}$$
$$= 4.2 \text{ kJ}$$

- (3) Decrease in internal energy

First of all, let us find the mass of gas (m) admitted for compression. We know that

$$P_1 V_1 = m R T_1$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{0.15 \times 10^6 \times 0.14}{285 \times 373} = 0.197 \text{ kg}$$

we know that decrease in internal energy,

$$dU = U_1 - U_2 = m c_v (T_1 - T_2)$$

$$= 0.197 \times 0.712 (373 - 298.4)$$

$$= 10.46 \text{ kJ}$$

(4) Heat given out by the gas

we know that heat given out by the gas

$$Q_{1-2} = m c_p (T_1 - T_2)$$

$$= 0.197 \times 1.005 (373 - 298.4)$$

$$= 14.77 \text{ kJ}$$

Example-3.6 :-

Given

$$v_1 = 0.4 \text{ m}^3$$

$$P_1 = 0.5 \times 10^6 \text{ N/m}^2$$

$$^*T = 80^\circ\text{C}$$

$$P_2 = 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2$$

Let us find the volume of air at the end of expansion,

$$P_1 V_1 = P_2 V_2 \text{ or } V_2 = \frac{P_1 V_1}{P_2}$$

$$= \frac{0.5 \times 10^6 \times 0.4}{0.1 \times 10^6}$$

and expansion ratio,

$$r = v_2/v_1 = 2/0.4 = 5$$

we know the work done by the air during expansion,

$$W_{1-2} = 2.3 P_1 V_1 \log r = 2.3 \times 0.5 \times 10^6 \times 0.4 \log 5$$

$$= 0.46 \times 10^6 \times 0.699$$

$$= 321540 \text{ J}$$

$$= 321.54 \text{ kJ}$$

Example 3.7 :-

Given,

$$v_1 = 0.1 \text{ m}^3$$

$$P_1 = 1.5 \text{ bar} = 1.5 \times 10^5 \text{ N/m}^2$$

$$v_2 = 0.5 \text{ m}^3$$

final pressure of gas

Let P_2 = final pressure of gas

we know

$$P_1 v_1 = P_2 v_2$$

$$P_2 = \frac{P_1 v_1}{v_2} = \frac{1.5 \times 10^5 \times 0.1}{0.5}$$

$$= 3 \text{ bar}$$

Heat supplied during the process

$$r = v_2/v_1$$

$$= \frac{0.5}{0.1}$$

$$= 5$$

work done during the process

$$W_{1-2} = 2.3 P_1 V_1 \log r = 2.3 \times 1.5 \times 10^5 \times 0.11095$$

$$= 3.45 \times 10^5 \times 0.699 = 241155 \text{ kJ}$$

Ans

Example - 3.9 :-

Given

$$m = 0.18 \text{ kg}$$

$$V_1 = 0.15 \text{ m}^3$$

$$T_1 = 15^\circ \text{C} = 15 + 273 = 288 \text{ K}$$

$$P_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$V_2 = 0.056 \text{ m}^3$$

$$P_2 = 4 \text{ bar} = 0.4 \times 10^6 \text{ N/m}^2$$

(1) - Gas Constant

Let R = Gas constant

$$P_1 V_1 = m R T_1$$

$$R = \frac{P_1 V_1}{m T_1} = \frac{0.1 \times 10^6 \times 0.15}{0.18 \times 288}$$

$$= 289.4 \text{ J/kg K}$$

$$= 0.2894 \text{ kJ/kg K}$$

(2) molecular mass of the gas

$$m = \frac{R_u}{R} = \frac{8314}{289.4} = 28.73 \text{ kg}$$

($\because R_u = 8314 \text{ J/kg K}$)

(3) Ratio of specific heats

$$\gamma = \frac{\log\left(\frac{P_2}{P_1}\right)}{\log\left(\frac{V_1}{V_2}\right)} = \frac{\log\left(\frac{4 \times 10^5}{1 \times 10^5}\right)}{\log\left(\frac{0.15}{0.056}\right)} = \frac{\log 4}{\log 2.678}$$

= 1.407 Ans

(4) Specific heat at constant temperature and volume

$$C_p - C_v = R \text{ or } 1.407 C_v - C_p = 0.2894$$

$$C_v = 0.2894 / 1.407 = 0.205 \text{ kJ/kg K}$$

$$C_p = 1.407 C_v = 1.407 \times 0.205 = 0.2894 \text{ kJ/kg K}$$

(5) change in internal energy

$$(\because \gamma = C_p/C_v = 1.407)$$

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{4}\right)^{\frac{1.407-1}{1.407}} = (0.25)^{0.287}$$

= 0.67

$$T_2 = T_1 / 0.67 = 288 / 0.67 = 430 \text{ K}$$

change in internal energy,

$$\Delta U = U_2 - U_1 = m C_v (T_2 - T_1)$$

$$= 0.18 \times 0.205 (430 - 288) \text{ kJ}$$

$$= 5.239 \text{ kJ}$$

Example - 3.8 :-

Given,

$$V_1 = 1 \text{ litre}$$

$$T_1 = 0^\circ\text{C} = 0 + 273 = 273 \text{ K}$$

$$V_2 = V_1/2 = 1/2 = 0.5 \text{ litre}$$

$$\gamma = 1.4$$

let T_2 = final Temperature of the gas

$$\text{we know that } \frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{\gamma-1} = \left(\frac{0.5}{1} \right)^{1.4-1}$$

$$= (0.5)^{0.4} = 0.758$$

$$T_2 = T_1 / 0.758 = 273 / 0.758 = 360.16 \text{ K}$$

$$= 360.16 - 273 = 87.16^\circ\text{C}$$

Ans

Example - 3.10 :-

Given

$$V_1 = 0.15 \text{ m}^3$$

$$P_1 = 3.8 \text{ bar} = 3.8 \times 10^5 \text{ N/m}^2$$

$$T_1 = 150^\circ\text{C} = 150 + 273 = 423 \text{ K}$$

$$P_2 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$dH = 70 \text{ kJ}$$

$$C_p = 1 \text{ kJ/kg K}$$

$$C_v = 0.714 \text{ kJ/kg K}$$

we know that Adiabatic Index,

$$\gamma = \frac{C_p}{C_v} = \frac{1}{0.714}$$

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.8}{1} \right)^{\frac{1.4-1}{1.4}} = (3.8)^{0.286} = 1.465$$

$$T_2 = T_1 / 1.465 = 423 / 1.465 = 288.7 \text{ K}$$

$$\frac{V_1}{V_2} = \left(\frac{P_2}{P_1} \right)^{\frac{1}{\gamma}} = \left(\frac{1}{3.8} \right)^{\frac{1}{1.4}} = (0.263)^{0.714} = 0.385$$

$$V_2 = V_1 / 0.385 = 0.15 / 0.385$$

$$R = C_p - C_v = 1 - 0.714 = 0.286 \text{ kJ/kg K}$$

$$P_1 V_1 = m R T_1$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{3.8 \times 10^5 \times 0.15}{286 \times 423} = 0.47 \text{ kg}$$

increase in enthalpy (ΔH)

$$Q = m c_p (T_3 - T_2) = 0.47 \times 1 (T_3 - 288.7) \text{ kJ}$$

$$T_3 = \frac{Q}{0.47} + 288.7 = 437.6 \text{ K}$$

heat at constant pressure

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \text{ or } V_3 = \frac{V_2 T_3}{T_2} = \frac{0.39 \times 437.6}{288.7} = 0.59 \text{ m}^3$$

$$= 0.59 \text{ m}^3$$

Work done during adiabatic expansion,

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{3.8 \times 10^5 \times 0.15 - 1 \times 10^5 \times 0.39}{1.4 - 1}$$

$$= 45000 \text{ J} = 45 \text{ kJ}$$

and work done during constant pressure heating

$$W_{2-3} = P_2 (V_3 - V_2) = 1 \times 10^5 (0.59 - 0.39) = 20000$$
$$= 20 \text{ kJ}$$

$$\therefore \text{Total work done, } W = W_{1-2} + W_{2-3} = 45 + 20$$
$$= 65 \text{ kJ} \quad \underline{\underline{\text{Ans}}}$$

Example - 3.11 :-

Given

$$V_1 = 0.336 \text{ m}^3$$

$$P_1 = 10 \text{ bar} = 10 \times 10^5 \text{ N/m}^2$$

$$T_1 = 150^\circ \text{C} = 150 + 273 = 423 \text{ K}$$

$$P_2 = 4 \text{ bar} = 4 \times 10^5 \text{ N/m}^2$$

$$V_3 = 0.336 \text{ m}^3$$

$$C_p = 0.996 \text{ kJ/kg K}$$

$$C_v = 0.703 \text{ kJ/kg K}$$

$$\gamma = \frac{C_p}{C_v} = \frac{0.996}{0.703}$$

$$= 1.417$$

we know that

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{10}{9} \right)^{\frac{1.417-1}{1.417}} = (2.5)^{0.294} = 1.31$$

$$T_2 = \frac{T_1}{1.31} = \frac{423}{1.31} = 323 \text{ K}$$

$$T_3 = T_2 = 323 \text{ K} = 50^\circ \text{C}$$

Final pressure of the gas

$$\frac{P_3}{T_3} = \frac{P_1}{T_1}$$

$$P_3 = \frac{T_3 P_1}{T_1} = \frac{323 \times 10 \times 10^5}{423} = 76 \text{ bar}$$

Change in internal energy

$$R = C_p - C_v = 0.996 - 0.703 = 0.293 \text{ kJ/kg K}$$

$$= 293 \text{ J/kg K}$$

we also know that

$$P_1 V_1 = m R T_1$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{10 \times 10^5 \times 0.336}{293 \times 423} = 2.7 \text{ kg}$$

Change in internal energy,

$$du = u_3 - u_1 = m C_v (T_3 - T_1) = 2.7 \times 0.703 (323 - 423)$$

$$= -189.81 \text{ kJ}$$

(Ans)

Example-3.12 :-

Given,

$$V_1 = 0.75 \text{ m}^3$$

$$P_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$T_1 = 290 \text{ K}$$

$$P_2 = 15 \text{ bar} = 15 \times 10^5 \text{ N/m}^2$$

$$V_3 = V_1 = 0.75 \text{ m}^3$$

$$R = 4126 \text{ J/kg}$$

$$C_p = 4.126 \text{ kJ/kg} \cdot \text{K}$$

$$C_p = 14.26 \text{ kJ/kg} \cdot \text{K}$$

$$C_p - C_v = R$$

$$C_v = C_p - R = 14.26 - 4.126 = 10.134 \text{ kJ/kg} \cdot \text{K}$$

$$\gamma = \frac{C_p}{C_v} = \frac{14.26}{10.134} = 1.407$$

We know that isentropic process 1-2,

$$P_1 (V_1)^\gamma = P_2 (V_2)^\gamma \text{ or } \left(\frac{V_1}{V_2} \right)^\gamma = \frac{P_2}{P_1}$$

$$V_2 = V_1 \left(\frac{P_1}{P_2} \right)^{\frac{1}{\gamma}} = 0.75 \left(\frac{1}{15} \right)^{\frac{1}{1.407}} = 0.75 \times 0.146 = 0.11 \text{ m}^3$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$T_2 = T_1 \times \frac{P_2 V_2}{P_1 V_1} = 290 \times \frac{15 \times 10^5 \times 0.11}{1 \times 10^5 \times 0.75}$$

$$= 638 \text{ K}$$

Now for isothermal process 2-3 ,

$$P_2 V_2 = P_3 V_3$$

$$P_3 = P_2 \times \frac{V_2}{V_3} = 15 \times 10^5 \times \frac{0.11}{0.75} = 22 \text{ bar}$$

(2) Heat added during isothermal expansion 2-3 ,

$$Q_{2-3} = 2.3 P_2 V_2 \cdot \log \left(\frac{V_3}{V_2} \right)$$
$$= 2.3 \times 15 \times 10^5 \times 0.11 \log \left(\frac{0.75}{0.11} \right)$$

$$= 316377.2 \text{ kJ}$$

(3) Change of internal energy during each process

$$P_1 V_1 = m R T_1, \text{ OR } m = \frac{P_1 V_1}{R T_1} = \frac{1 \times 10^5 \times 0.75}{4126 \times 290} = 0.06 \text{ kg}$$

change of internal energy during isentropic process ,

$$\Delta U = m C_v (T_2 - T_1) = 0.063 \times 10.134 (638 - 290)$$

$$= 222.17 \text{ kJ}$$

Example - 3.13 :-

Given

$$V_1 = 0.028 \text{ m}^3$$

$$P_1 = 1.25 \text{ bar} = 1.25 \times 10^5 \text{ N/m}^2$$

$$T_1 = 25^\circ\text{C} = 25 + 273 = 298 \text{ K}$$

$$V_2 = 0.0042 \text{ m}^3$$

$$\eta = 1.3$$

Final temperature

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{\gamma-1} = \left(\frac{0.0042}{0.028} \right)^{1.3-1}$$
$$= (0.15)^{0.3} = 0.566$$

$$T_2 = T_1 / 0.566 = 298 / 0.566 = 526.5 \text{ K}$$
$$= 526.5 - 273 = 253.5^\circ \text{C}$$

Work done during compression

$$P_1 V_1^\gamma = P_2 V_2^\gamma \quad \text{or} \quad \frac{P_1}{P_2} = \left(\frac{V_2}{V_1} \right)^\gamma = \left(\frac{0.0042}{0.028} \right)^{1.3} = 0.085$$

$$\therefore P_2 = P_1 / 0.085 = 1.25 / 0.085 = 14.7 \text{ bar} = 1.47 \times 10^6 \text{ N/m}^2$$

We know that work done during the compression

$$W_{1-2} = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1} = \frac{1.47 \times 10^6 \times 0.0042 - 1.25 \times 10^5 \times 0.028}{1.3 - 1}$$

$$= 8913 \text{ kJ}$$

Pressure at a constant volume

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} \quad \text{or} \quad P_3 = \frac{P_2 T_3}{T_2} = \frac{14.7 \times 298}{526.5}$$

$$= 8.32 \text{ bar}$$

Example - 3.14 :-

Given

$$m = 26.7$$

$$r = \frac{v_1}{v_2} = 12$$

$$\eta = 1.25$$

$$P_1 = 0.9 \text{ bar} = 0.9 \times 10^5 \text{ N/m}^2$$

$$T_1 = 333 \text{ K}$$

$$C_{vm} = 21.1 \text{ kJ/kg K}$$

$$m = 1 \text{ kg}$$

work done per kg of gas

we know that

$$P_1 v_1^\eta = P_2 v_2^\eta$$

$$P_2 = P_1 \left(\frac{v_1}{v_2} \right)^\eta = 0.9 (12)^{1.25}$$

$$= 20.1 \text{ bar} = 20.1 \times 10^5 \text{ N/m}^2$$

we also know that gas constant,

$$R = \frac{R_u}{M} = \frac{8314}{26.7} = 311.4 \text{ J/kg K}$$

$$P_1 v_1 = mRT_1 \text{ or } v_1 = \frac{mRT_1}{P_1} = \frac{1 \times 311.4 \times 333}{0.9 \times 10^5} \times 1.15 \text{ m}^3$$

$$v_2 = v_1 / 12 = \frac{1.15}{12} \times 1.15 = 0.096 \text{ m}^3$$

we know that work done

$$W_{1-2} = \frac{P_1 v_1 - P_2 v_2}{\eta - 1} = \frac{0.9 \times 10^5 \times 1.15 - 20.1 \times 10^5 \times 0.096}{1.25 - 1}$$

$$= -357.84 \text{ kJ}$$

Heat flow across the cylinder walls

Let T_2 = Final temperature

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{1}{12}\right)^{1.25-1} = 0.537$$

$$T_2 = T_1 / 0.537 = 333 / 0.537 = 620 \text{ K}$$

and specific heat at constant volume

$$C_v = C_{vm} / M = 21.1 / 26.7 = 0.79 \text{ kJ/kg K}$$

Change in internal energy

$$\begin{aligned} dU = U_2 - U_1 &= m C_v (T_2 - T_1) = 1 \times 0.79 (620 - 333) \\ &= 226.7 \text{ kJ} \end{aligned}$$

heat flow across the cylinder:

$$Q_{1-2} = W_{1-2} + dU = -357.84 + 226.7 = -131.1 \text{ kJ}$$

Characteristic gas constant

$$\begin{aligned} R &= \frac{R_u}{M} = \frac{8314}{26.7} = 311.4 \text{ J/kg K} \\ &= 0.3114 \text{ kJ/kg K} \end{aligned}$$

C_{pm} = Molar specific heat at a constant pressure

$$C_p - C_v = R \text{ or } C_p - 0.79 = 0.3114$$

$$C_p = 0.3114 + 0.79 = 1.1014 \text{ kJ/kg K}$$

$$C_{pm} = M C_p = 26.7 \times 1.1014 = 29.4 \text{ kJ/kg K}$$

Ratio of specific heats

$$\gamma = \frac{C_p}{C_v} = \frac{1.1014}{0.79} = 1.394 \quad (\text{Ans})$$

Example 3.15 :-

Given

$$D = 550 \text{ mm} = 0.55 \text{ m}$$

$$L = 750 \text{ mm} = 0.75 \text{ m}$$

$$V_1/V_2 = 13.5$$

$$P_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$T_1 = 316 \text{ K}$$

$$C_p = 0.996 \text{ kJ/kg K}$$

$$C_v = 0.707 \text{ kJ/kg K}$$

(1) Pressure and temperature ~~of~~ at the end of compression

Let P_2 and T_2

$$P_1 V_1^\gamma = P_2 V_2^\gamma$$

$$P_2 = P_1 \left(\frac{V_1}{V_2} \right)^\gamma = 1 \times 10^5 (13.5)^{1.37} \text{ N/m}^2$$
$$= 8536366.459 \text{ bar}$$

we know that

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{\gamma-1} = \left(\frac{1}{13.5} \right)^{1.37-1} = 0.3817$$

$$T_2 = T_1 / 0.3817 = 316 / 0.3817 = 827.87 \text{ K}$$

(2) Mass of the charge

Let m = mass of the charge

$$V_1 - V_2 = \frac{\pi}{4} \times D^2 \times L = \frac{\pi}{4} \times (0.55)^2 \times 0.75 = 0.178 \text{ m}^3$$

$$v_1 = \frac{v_1}{13.5} = 0.178$$

$$v_1 = 0.178 \times 13.5 / 12.5 = 0.192 \text{ m}^3$$

$$P_1 v_1 = m R T_1$$

$$m = \frac{P_1 v_1}{R T_1} = \frac{1 \times 10^5 \times 0.192}{289 \times 316} = 0.21 \text{ kg}$$

(3) Workdone during compression

$$W_{1-2} = \frac{m R (T_2 - T_1)}{n - 1} = \frac{0.21 \times 0.289 (828 - 316)}{1.37 - 1}$$

$$= 84.1 \text{ kJ}$$

(4) Heat rejected during compression

$$\gamma = \frac{C_p}{C_v} = \frac{0.996}{0.707} = 1.41$$

$$Q_{\text{rej}} = \frac{\gamma - 1}{\gamma - 1} \times \text{workdone during compression}$$

$$= \frac{1.41 - 1.37}{1.41 - 1} \times 84 = 8.195 \text{ kJ}$$

Example 3.16 :-

Given $v_1 = 0.2 \text{ m}^3$

$$P_1 = 1.2 \text{ bar} = 1.2 \times 10^5 \text{ N/m}^2$$

$$T_1 = 60^\circ\text{C} = 60 + 273 = 333 \text{ K}$$

$$P_2 = 1.2 \text{ bar} = 12 \times 10^5 \text{ N/m}^2$$

$$T_2 = 270^\circ\text{C} = 270 + 273 = 543 \text{ K}$$

$$P_1 = 2 P_2$$

$$C_p = 1.072 \text{ kJ/kg K}$$

$$R = 294 \text{ J/kg K} = 0.294 \text{ kJ/kg K}$$

maximum Temperature

since the process 2-3 is constant volume process,

$$\frac{P_2}{T_2} = \frac{P_3}{T_3}$$

$$T_3 = T_2 \times \frac{P_3}{P_2} = 543 \times \frac{2P_2}{P_2} = 1086 \text{ K} = 813^\circ \text{C}$$

Change in internal energy

$$P_1 V_1 = m R T_1 \quad \text{or} \quad m = \frac{P_1 V_1}{R T_1} = \frac{1.2 \times 10^5 \times 0.2}{0.294 \times 333}$$

$$C_v = C_p - R = 1.072 - 0.294 = 0.778 \text{ kJ/kg K}$$

$$\begin{aligned} dU = U_3 - U_1 &= m C_v (T_3 - T_1) = 245.14 \times 0.778 \\ &\quad (1086 - 333) \text{ K} = 143611.34 \text{ kJ} \end{aligned}$$

Heat transfer during process

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2} \right)^{\frac{n-1}{n}} \quad \text{or} \quad \frac{333}{543} = \left(\frac{1.2}{12} \right)^{\frac{n-1}{n}}$$

Taking log on both sides,

$$\log \left(\frac{333}{543} \right) = \frac{n-1}{n} \log \left(\frac{1.2}{12} \right) \quad \text{or} \quad \log 0.613 = \frac{n-1}{n} \log 0.1$$

$$-0.2125 = \frac{n-1}{n} (-1) \quad \text{or} \quad n = 1.27$$

$$W_{1-2} = \frac{m R (T_1 - T_2)}{n-1} = \frac{245.14 \times 0.294 (333 - 543)}{1.27 - 1}$$

$$= -56 \text{ kJ}$$

$$du = (U_2 - U_1) = m c_v (T_2 - T_1) = 245.14 \times 0.728$$

$$(543 - 333) = 40 \text{ kJ}$$

Heat transfer during compression process,

$$Q_{1-2} = W_{1-2} + du = -56 + 40 = -16 \text{ kJ (Ans)}$$

Example - 3.17

Given

$$V_1 = 60 \text{ liter} = 60 \times 10^{-3} \text{ m}^3$$

$$V_1 \cdot V_2 = 14.2$$

$$P_1 = 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2$$

$$T_1 = 80^\circ \text{C} = 80 + 273 = 353 \text{ K}$$

$$P_2 = 30 \text{ bar} = 3 \times 10^6 \text{ N/m}^2$$

$$V_3 = 2V_2$$

$$C_v = 0.712 \text{ kJ/kg K}$$

$$R = 0.293 \text{ kJ/kg K} = 293 \text{ J/kg K}$$

1. Index of Compression

Let n = index of compression

we know that,

$$P_1 V_1^n = P_2 V_2^n$$

$$\left(\frac{V_1}{V_2}\right)^n = \frac{P_2}{P_1}$$

$$(14.2)^n = \frac{3 \times 10^6}{0.1 \times 10^6} = 30$$

Taking log on both sides

$$n \log 14.2 = \log 30$$

$$n \times 1.152 = 1.477$$

$$n = 1.282$$

a. Temperature at the end of compression :-

Let T_2 = Temperature at the end of compression

we know that

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{1}{14.2}\right)^{1.282-1} = (0.0704)^{0.282} = 0.473$$

$$\therefore T_2 = T_1 / 0.473 = 353 / 0.473 = 746.3 \text{ K} \\ = 473.3^\circ \text{C}$$

3. Heat transfer

First of all let us find the mass of the charge (m) and the ratio of specific heats (γ)

we know that

$$P_1 V_1 = m R T_1 \text{ or } m = \frac{P_1 V_1}{R T_1} = \frac{0.1 \times 10^6 \times 60 \times 10^{-3}}{293 \times 353}$$

$$= 0.058 \text{ kg}$$

we know that transfer

$$Q_{1-2} = \frac{\gamma - \gamma}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1}$$

$$= \frac{1.41 - 1.282}{1.41 - 1} \times \frac{0.058 \times 0.293 (353 - 746.3)}{1.282 - 1}$$

$$= 0.3122 \times (-23.7)$$

$$= -7.4 \text{ kJ}$$

The negative sign indicates that the heat is rejected.

4. Heat received is constant pressure operation

First of all, let us find the temperature (T_3) at the end of constant pressure operation.

We know that

for constant pressure process 2-3

$$\frac{V_2}{T_2} = \frac{V_3}{T_3} \text{ or } T_3 = \frac{V_3 T_2}{V_2} = \frac{2V_2 \times 746.3}{V_2}$$

$$= 1492.6 \text{ K } (V_3 = 2V_2)$$

We know that heat received

$$Q_{2-3} = m c_p (T_3 - T_2) = 0.058 \times 1.005 (1492.5 - 746.3) \\ = 43.5 \text{ kJ}$$

Example-3.18

Given

$$V_1 = 0.15 \text{ m}^3$$

$$P_1 = 4 \text{ bar} = 0.4 \times 10^6 \text{ N/m}^2$$

$$T_1 = 423 \text{ K}$$

$$P_2 = 1 \text{ bar} = 0.1 \times 10^6 \text{ N/m}^2$$

$$dH = 67 \text{ kJ}$$

$$c_p = 1.009 \text{ kJ/kg} \cdot \text{K}$$

Let

m = mass of air

V_2 and T_2 = volume and temperature of air after adiabatic expansion.

V_3 and T_3 = volume and temperature of air after heating at constant pressure.

we know that ,

$$P_1 V_1 = mRT_1, \text{ or } m = \frac{P_1 V_1}{RT_1} = \frac{0.4 \times 10^6 \times 0.15}{287 \times 423}$$
$$= 0.494 \text{ kg}$$

($\because$ Taking $R = 287 \text{ J/kg.K}$)

$$P_1 (V_1)^\gamma = P_2 (V_2)^\gamma \text{ or } \left(\frac{V_2}{V_1}\right)^\gamma = \frac{P_1}{P_2}$$

$$V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} = 0.15 \left(\frac{4}{1}\right)^{\frac{1}{1.4}}$$
$$= 0.4036 \text{ m}^3$$

Thermodynamics process of perfect gasses

we know that work done during adiabatic expansion 1-2.

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{0.4 \times 10^6 \times 0.15 - 0.1 \times 10^6 \times 0.4036}{1.4 - 1}$$
$$= \frac{60000 - 40360}{0.4}$$
$$= 49100 \text{ J} = 49.1 \text{ kJ}$$

$$P_1 V_2 = mRT_2 \text{ or } T_2 = \frac{P_2 V_2}{mR}$$
$$= \frac{0.1 \times 10^6 \times 0.4036}{0.494 \times 287}$$
$$= 284.6 \text{ K}$$

$$Q_7 = m c_p (T_3 - T_2) = 0.494 \times 1.009 (T_3 - 284.6)$$
$$= 0.5 (T_3 - 284.6)$$

$$T_3 = \frac{67}{0.5} + 284.6 = 418.6 \text{ K}$$

$$\frac{V_1}{T_2} = \frac{V_3}{T_3} \quad \text{or} \quad V_3 = \frac{V_2 T_3}{T_2} = \frac{0.4036 \times 418.6}{284.6}$$

$$= 0.594 \text{ m}^3$$

$$W_{2-3} = P_2 (V_3 - V_2) = 0.1 \times 10^6 (0.594 - 0.4036)$$

$$= 19040 \text{ J}$$

$$= 19.04 \text{ kJ}$$

Total work done

$$W_{1-2-3} = W_{1-2} + W_{2-3}$$

$$= 49.1 + 19.04 = 68.14 \text{ kJ}$$

Index of expansion

$$68.14 \times 10^3 = \frac{P_1 V_1 - P_3 V_3}{n-1} = \frac{0.4 \times 10^6 \times 0.15 - 0.1 \times 10^6 \times 0.594}{n-1}$$

$$= \frac{600}{n-1}$$

$$\therefore n-1 = \frac{600}{68.14 \times 10^3} = 0.0088 \quad \text{or}$$

$$n = 1.0088$$

(Ans)

STEAM BOILERS

UNIT-02/
03

Introduction :- A steam generator or boiler, is usually a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel to water and ultimately to generate steam.

Important terms for steam boilers

- 1) Boiler shell :- It is made of steel plates bent into cylindrical form and riveted or welded together. The ends of the shell are closed by means of end plates. A boiler shell should have sufficient capacity to contain water and steam.
- 2) Combustion chamber :- It is the space, generally below the boiler shell, meant for burning fuel in order to produce steam from the water contained in the shell.
- 3) Grate :- It is a platform, in the combustion chamber, upon which fuel is burnt. The grate, generally, consists of cast iron bars which are spaced apart so that air can pass through them. The surface area of the grate, over which the fire takes place, is called grate surface.
- 4) Furnace :- (It is the space, above the grate and below the boiler shell, in which the fuel is actually burnt. The furnace is called fire box.

2931104 177372
5) Heating surface :- It is that part of boiler surface, which is exposed to the fire.

6) Mountings :- These are the fittings which are mounted on the boiler for its proper functioning. They include water.

7) Accessories :- These are the devices which form an integral part of a boiler.
Ex:- economiser, air preheater, superheater, separator etc

* Essentials of a good steam Boiler :-

1) It should produce maximum quantity of steam with the minimum fuel consumption.

2) It should be economical to instal, and should require little attention during operation.

3) It should rapidly meet the fluctation of load.

4) It should be capable of quick starting.

5) It should be light in weight.

6) It should occupy a small space.

7) The joints should be few and accessible for inspection.

8) The mud and other deposits should not collect on the heating plates.

9) The refractory material should be reduced to a minimum. But it should be sufficient to secure easy ignition and smokeless combustion of the fuel on reduced load.

- 10) The tubes should not accumulate soot or water deposits and should have a reasonable margin of strength to allow for wear or corrosion.
- 11) The water and flue gas circuits should be allowed a maximum fluid velocity without incurring heavy frictional losses.
- 12) It should comply with safety regulations as laid down in the Boiler Act.

Selection of a steam Boiler

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

Classification of steam Boilers :-

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

1) Fire tube or smoke tube boiler

2) Water tube boiler

➤ Fire tube boilers :- In fire tube steam boilers, the flames and hot gases, produced by the combustion of fuel, pass through the tubes which are surrounded by water. The heat is conducted through the walls of the tubes from the hot gases to the surrounding water.

Ex :- Simple vertical boiler, Cochran boiler, Lancashire boiler, Cornish boiler, Scotch marine boiler, Locomotive boiler and Velcon boiler.

➤ Water tube boilers :- In water tube steam boilers the water is contained inside the tubes which are surrounded by flames and hot gases from outside.

Ex :- Babcock and Wilcox boiler, Stirling boiler, La-mont boiler, Benson boiler, Yarrow boiler and Loeffler boiler.

➤ According to the position of the furnace :-

i) Internally fired boilers

ii) Externally fired boilers

i) Internally fired boilers :- The furnace is located inside the boiler shell. Most of the fire tube steam boilers are internally fired.

ii) Externally fired boilers :- The furnace is arranged underneath in a brick-work setting. Water tube steam boilers are always externally fired.

3) According to the axis of the shell :-

- i) Vertical boilers
- ii) Horizontal boilers

4) According to the number of tubes :-

- i) Single tube boilers
- ii) Multitubular boilers

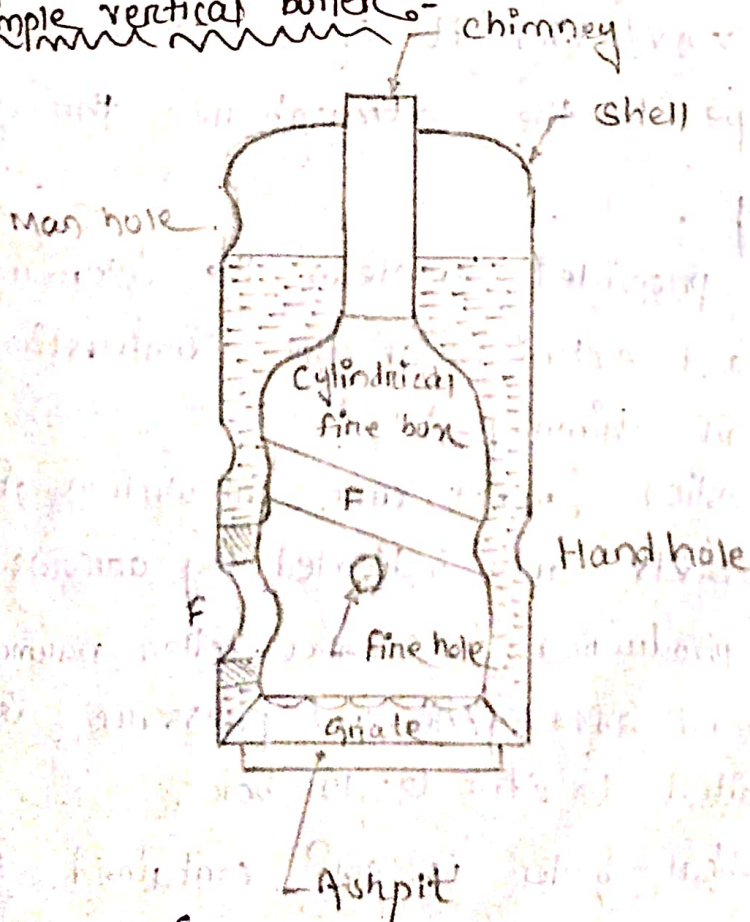
5) According to the method of circulation of water and steam :-

- i) Natural circulation boilers
- ii) forced circulation boilers

6) According to the use

- i) Stationary boilers
- ii) ~~Stationary~~ portable boilers

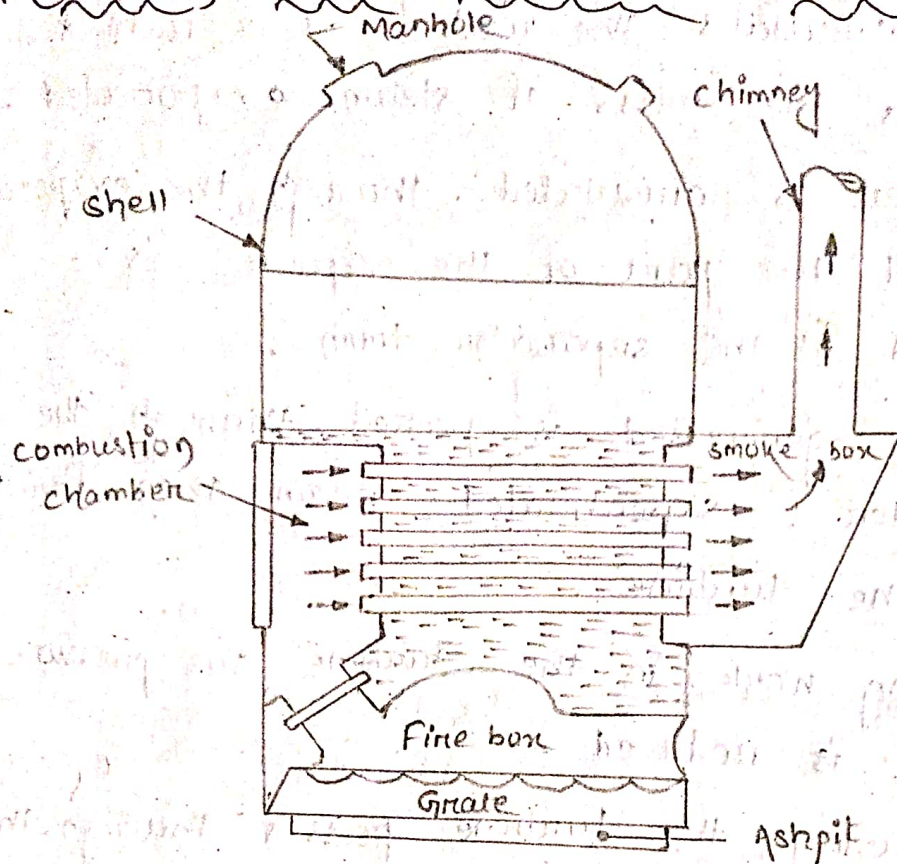
* Simple vertical boiler :-



(Simple vertical boiler)

- i) It consists of a cylindrical shell.
- ii) The grate portion full of water and remaining is the steam space.
- iii) The bottom of the fire box is grate on which fuel is burnt and the ash from it falls in ash pit.
- iv) The fire box is provided with two cross tubes. This increases the heating surface and the circulation of water.
- v) The cross tubes are fitted inclined. This ensures efficient circulation of water.
- vi) The ends of each cross tube are provided with hand holes to give access for cleaning the tubes.
- vii) The combustion gases after heating the water and thus converting it into steam. The steam escapes to the atmosphere through the chimney.
- viii) Man hole is provided to clean the interior of the boiler and exterior of the combustion chamber and chimney.
- ix) Flow of combustion gases and circulation of water in water jackets are indicated by arrows.
- x) The rate of production in such a boiler normally does not exceed 2500 kg/hr and pressure is normally limited to 7.5 to 10 bar .
- xi) A simple vertical boiler is self-contained and can be transported easily.

* Cochran Boiler or vertical Multitubular Boiler:-

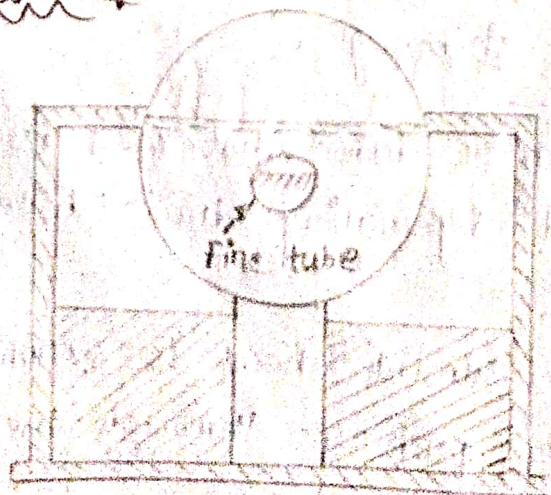


(Cochran Boiler)

- i) Air taken from the atmosphere is first passed through the air pre-heater, where it is heated by flue gases.
- ii) The hot air then passes through the furnace.
- iii) The flue gases after passing over boiler and super heater tubes, flow through the dust collector and then through economiser, air pre-heater and finally they are exhausted to the atmosphere through the chimney.
- iv) The feed water from hot well is supplied to a storage and separating drum (boiler) through the economiser.
- v) Most of the sensible heat is supplied to the feed water while passing through the economiser.

- vi) A pump circulates the water at a rate 8 to 10 times the mass of steam evaporated.
- vii) This water is circulated through the evaporator tubes and the part of the vapour is separated in the separator drum.
- viii) The steam generated is passed through the superheater. Superheated steam then flows through the turbine.
- ix) After doing work in the turbine the pressure of steam is reduced.
- x) Steam leaving the turbine passes through the condenser which maintains the low pressure of steam at the exhaust of turbine.
- xi) Steam pressure in the condenser depends upon flow rate and temperature of cooling water and on effectiveness of air removal equipment.
- xii) Cooling water circulating through the condenser may be taken from the various sources such as river, lake, sea or cooling water tower.

* Cornish Boiler :-



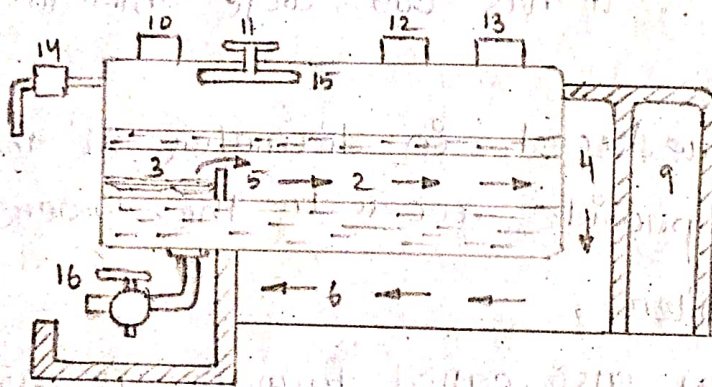
(Cornish Boiler)

i) It is similar to a Lancashire boiler in all respects, except there is only one flue tube in Cornish boiler instead of two in Lancashire boiler.

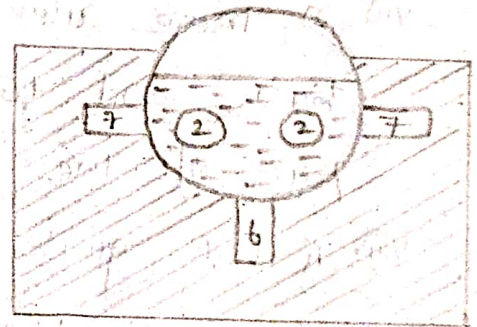
ii) The diameter of Cornish boiler is generally 1 m to 2 m and its length varies from 5 m to 7.5 m. The diameter of flue tube may be about 0.6 times that of shell.

iii) The capacity and working pressure of a Cornish boiler is low as compared to Lancashire boiler.

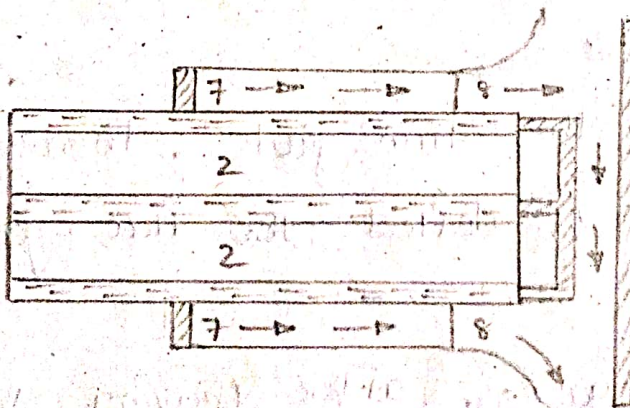
* Lancashire Boiler :-



(Elevation)



(Side)



(Plan)

i) It is a stationary, fire tube, internally fired, horizontal and natural circulation boiler.

ii) It is used where working pressure and power required are moderate.

iii) These boilers have a cylindrical shell of, 1.75 m to 2.75 m diameter.

iv) Its length varies from 7.25 m to 9 m. It has two internal flue tubes having diameter about 0.4 times that of shell.

v) This type of boiler is set in brick work forming external flue so that part of the heating surface is on the external shell.

vi) This boiler consists of a long cylindrical external shell (1) built of steel plates, is sectioned and riveted together. It has two large internal flue tubes.

vii) (2) These are reduced in diameter at the back end to provide access to the lower part of the boiler.

viii) A fire grate (3) also called furnace, is provided at one end of the flue tubes on which solid fuel is burnt.

ix) At the end of the fire grate, there is a brick arch (4) to deflect the flue gases upwards.

x) The hot flue gases, after leaving the internal flue tubes pass down to the bottom tube.

xi) (6) These flue gases move to the front of the boiler where they divide and flow into the side flue.

Comparison Between Water Tube and Fire Tube Boilers.

Water tube boiler

i) The water circulates inside the tubes which are surrounded by hot gases from the furnace.

ii) It generates steam at a higher pressure up to 165 bar.

iii) The rate of generation of steam is high upto 400 tonnes per hour.

iv) For a given power, the floor area required for the generation of steam is less about 5 m^2 per tonne per hour of steam generation.

v) Overall efficiency with economiser is upto 90%.

vi) It can be transported and erected easily its various parts can be separated.

vii) It is preferred for widely fluctuating loads.

Fine tube boiler

i) The hot gases from the furnace pass through the tubes which are surrounded by water.

ii) It can generate steam only up to 24.5 bar.

iii) The rate of generation of steam is low upto 9 tonnes per hour.

iv) The floor area required is more about 8 m^2 per tonne per hour of steam generation.

v) Its overall efficiency is only 75%.

vi) The transportation and erection is difficult.

vii) It can also cope reasonably with sudden increase in load but for a shorter period.

-: SIMPLE STEAM ENGINES :

* Steam engine :- A steam engine is a ~~high~~ used the high pressure steam generate that converts thermal energy from steam into mechanical work.

* Classification of steam engines :-

1) According to number of working strokes

(a) single acting steam engine

(b) Double acting steam engine

(a) single acting steam engine :- when steam is on one side of the piston, and one working stroke is produced during each revolution of the crankshaft is called single acting steam engine.

(b) Double acting steam engine :- when steam is on both sides of the piston and two working strokes are produced during each revolution of the crankshaft is called Double double acting steam engine.

* According to the position of the cylinder :

(a) Horizontal steam engine

(b) Vertical steam engine

(a) Horizontal steam engine :- when the axis of the cylinder is horizontal, it is said to be a horizontal steam engine.

(b) Vertical steam engine :- when the axis of the cylinder is vertical, it is called a vertical steam engine.

3) According to the speed of the crankshaft :-

(a) slow speed steam engine

(b) medium speed steam engine

(c) High speed steam engine

(a) slow speed steam engine :- when the speed of the crankshaft is less than 100 revolutions per minute (r.p.m) it is called slow speed steam engine.

(b) Medium speed steam engine :- when the speed of the crankshaft is between 100 r.p.m. and 250 r.p.m it is called medium speed steam engine.

(c) High speed steam engine :- when the speed of the crankshaft is above 250 rpm it is known as a high speed steam engine.

4) According to the type of exhaust :-

(a) Condensing steam engine

(b) Non-condensing steam engine

(a) Condensing steam engine :- A type of steam engine that uses a condenser to convert exhaust steam back into the atmosphere or a condens. liquid water.

(b) Non-condensing steam engine :- A type of steam engine that releases exhaust steam into the atmosphere, without condensing it back into liquid water.

→ According to the expansion of the steam, in the engine cylinder :-

(a) Simple steam engine

(b) Compound steam engine

(a) Simple steam engine :- when the steam is carried out in a single cylinder and then exhausted into the atmosphere or a condenser it is called Simple steam engine.

(b) Compound steam engine :- when the steam is completed in two or more cylinders the engine is called compound steam engine.

→ According to the method of governing employed :-

(a) Throttling steam engine

(b) Automatic ~~steam~~ cut-off steam engine

(a) Throttling steam engine :- when the engine speed is controlled by means of a throttling valve in the steam pipe, which regulates the pressure of steam to the engine, it is called throttling steam engine.

(b) Automatic cut-off steam engine :- when the speed is controlled by controlling the steam pressure with an automatic cut-off governor it is called an automatic cut-off steam engine.

Important parts of a steam engine :-

(1) Frame :- it is a heavy cast iron part, which supports all the stationary as well as moving parts and holds them in proper position. It generally, rests on engine foundations.

(2) Cylinder :- it is also a cast iron cylindrical hollow vessel, in which the piston moves to and fro under the steam pressure. Both ends of the cylinder are closed and made steam tight. In small steam engines, the cylinder is made an integral part of the frame.

(3) Steam chest :- it is casted as an integral part of the cylinder. It supplies steam to the cylinder with the movement of D-slide ~~valve~~ valve.

(4) D-slide valve :- It moves in the steam chest with simple harmonic motion. Its function is to exhaust steam from the cylinder at proper movement.

(5) Inlet and exhaust ports :- These are holes provided in the body of the cylinder for the movement of steam. The steam is admitted

from the steam chest alternately to either sides of the cylinder through the inlet ports. The steam, after doing its work in the cylinder, is exhausted through the exhaust port.

(6) piston :- It is a cylindrical disc, moving to and fro, in the cylinder because of the steam pressure. Its function is to convert heat energy of the steam into mechanical work. Piston rings, made from cast iron, are fitted in the grooves in the piston. Their pressure is to prevent the leakage of steam.

(7) piston rod :- It is a circular rod, which is connected to the piston on one side and cross head to the other. Its main function is to transfer motion from the piston to the cross-head.

(8) Cross-head :- It is a link between the piston rod and connecting rod. Its function is to guide motion of the piston rod and to prevent it from bending.

(9) Connecting rod :- It is made of forged steel, whose one end is connected to the cross head and the other to the crank. Its function is to convert reciprocating motion of the piston into rotary motion of the crank.

(10) Crank shaft :- It is the main shaft of the engine having a crank. The crank works on the lever principle and produces rotary motion of the shaft. The crank shaft is supported on main bearing of the engine.

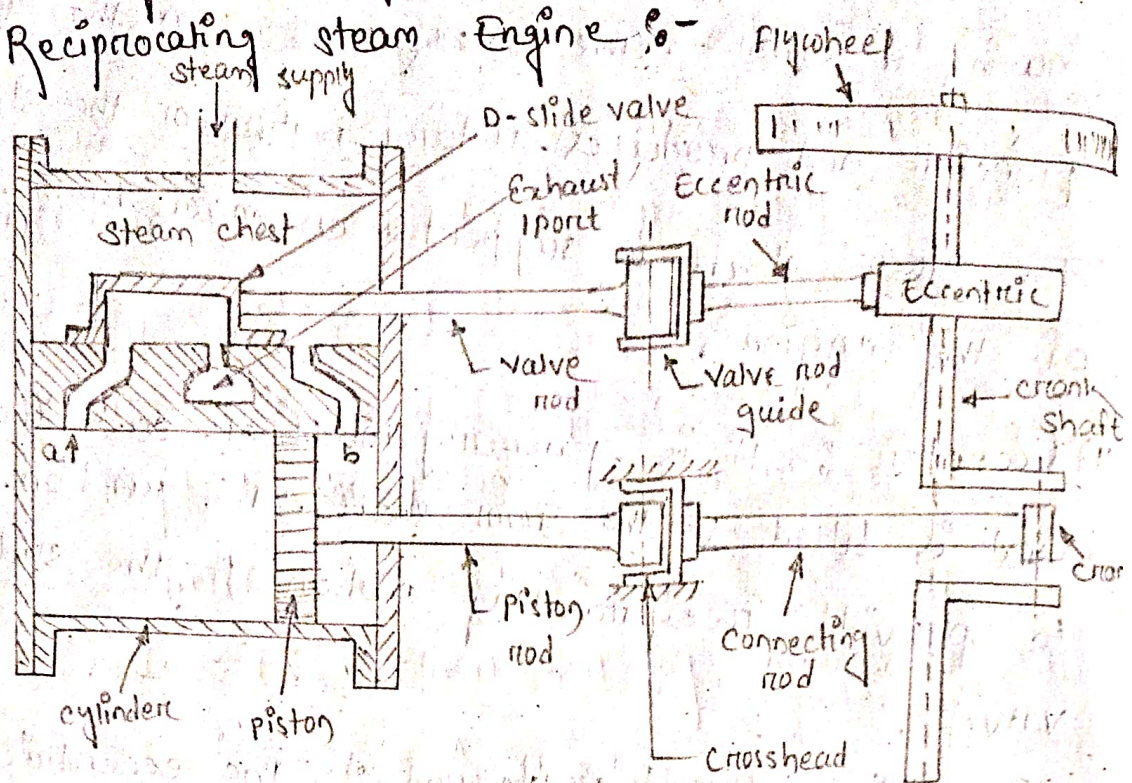
(11) Eccentric :- It is generally made of cast iron, and is fitted to the crank shaft. Its function is to provide reciprocating motion to the slide valve.

(12) Eccentric rod and valve rod :- The eccentric rod is made of forged steel, whose ~~one~~ one end is fixed to the eccentric and other to the valve rod. Its function to convert rotary motion of the crank shaft into to and fro motion of the valve rod. The valve rod connects the eccentric and the D-slide valve. Its function is to provide simple harmonic motion to the D-slide valve.

(13) Flywheel :- It is a heavy cast iron wheel, mounted on the crank shaft. Its function is to prevent the fluctuation of engine. It also prevent the jerks to the crank shaft.

(14) Governor :- It is a device to keep the engine speed, more or less, uniform at all load conditions. It is done either by controlling the quantity or ~~pressure~~ pressure of the steam supplied to the engine.

* Working of a single cylinder Double Acting Horizontal Reciprocating steam Engine :-



- i) The superheated steam at a high pressure from the boiler is led into the steam chest.
- ii) After that the steam makes its way into the cylinder through any of the ports 'a' or 'b' depending upon the position of the D-slide valve.
- iii) When port 'a' is open, the steam rushes to the left side of the piston and forces it to the right.
- iv) At this stage, the slide valve covers the exhaust port and the other steam port 'b'.
- v) Since the pressure of steam is greater on the left side than that on right side, the piston moves to the right.
- vi) When the piston reaches near the end of the cylinder, it closes the steam port 'a' and exhaust port.

vii) The steam port 'b' is now open, and the steam rushes to the right side of the piston.

viii) This forces the piston to the left and at the same time the exhaust steam goes out through the exhaust pipe, and thus completes the cycle of operation.

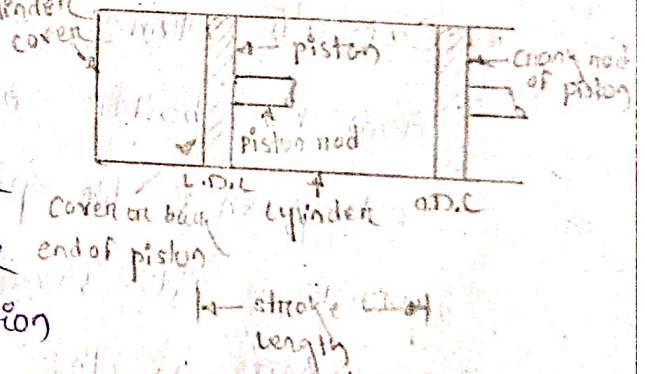
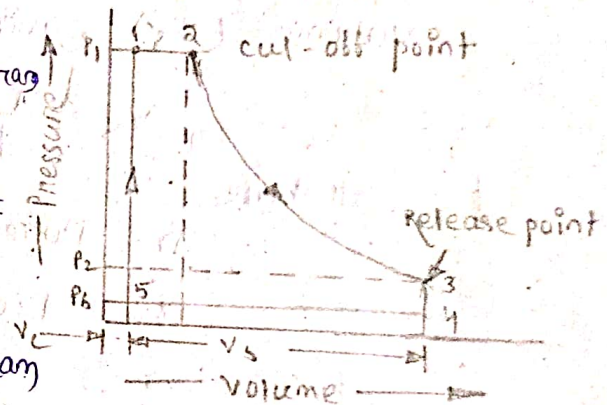
ix) The same process is repeated in other cycles of operation and as such the engine works.

* Important terms used in steam engine :-

The "theoretical indicator diagram" for a simple steam engine.

The following are some important terms used in steam engine.

(1) Bore :- The internal diameter of the cylinder of the engine is known as bore.



(2) Dead centres :- The extreme positions of the piston inside the cylinder during its motion are known as dead centres. There are two dead centres,

(a) Inner dead centre (I.D.C.)

(b) Outer dead centre (O.D.C.)

(a) Inner dead centre (I.D.C.) :- In a horizontal engine, the inner most position of the piston is called I.D.C.

(b) Outer dead centre (O.D.C.) :- the outer most position of the piston towards the crank end is called O.D.C.

(3) clearance volume :- The volume of space between the cylinder cover and the piston, when the piston is at I.D.C position is called Clearance volume (V_c). It is represented as a percentage of stroke volume.

(4) Stroke volume or swept volume :- The volume swept by the piston when it moves from I.D.C to O.D.C is known as stroke volume or swept volume (V_s). mathematically stroke volume,

$$V_s = \frac{\pi}{4} \times D^2 \times L$$

where

D = Bore or internal diameter of the cylinder

L = length of the stroke

(5) Cut-off volume :- Theoretically, the steam from the boiler enters the clearance space and pushes the piston outward doing external work. At some point during outward movement of the piston, the supply of steam is stopped. The point or the volume where the cut-off of steam takes place is called the point of cut-off or cut-off volume.

(6) Average piston speed :- The distance travelled by the piston per unit time is known as average piston speed. Mathematically,

$$\text{Average piston speed} = LN \text{ m/min for single acting steam engine}$$
$$= 2 LN \text{ m/min for double acting steam engine}$$

where,

L = Length of the stroke in metres.

N = speed in R.P.M

~~(7)~~ Mean effective pressure :- The average pressure on the piston during the working stroke is called mean effective pressure. It is given by the mean depth of the p-v diagram. Mathematically,

$$P_m = \frac{\text{work done per cycle}}{\text{stroke volume}}$$

* Indicator Diagram of a simple steam engine :-

(1) The opening and closing of steam ports is instantaneous.

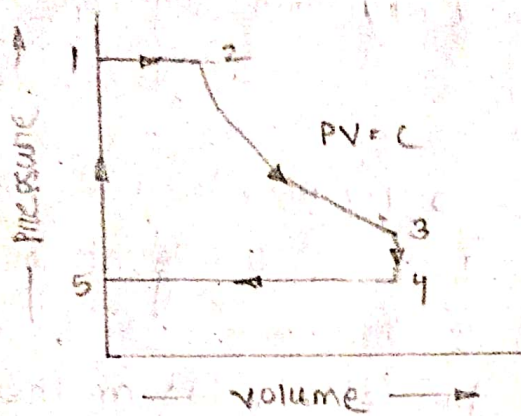
(2) There is no pressure drop due to condensation.

(3) There is no wire drawing due to restricted valve opening.

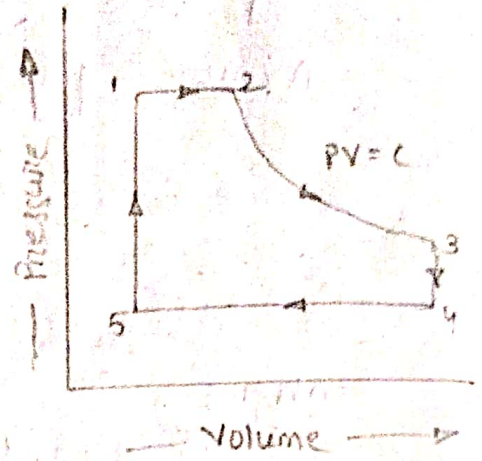
(4) The steam is admitted at boiler pressure and exhausted at condenser pressure.

(5) The expansion of the steam is hyperbolic ($pv=c$).

* Theoretical or Hypothetical Indicator Diagram:
The theoretical or Hypothetical indicator diagram without clearance and with clearance



without clearance



with clearance

(1) Process 1-2 :- At point 1, the steam is admitted into the cylinder through the inlet port. As the piston moves towards right, therefore the steam is admitted at constant pressure, since the supply of steam is cut-off at point 2, therefore this point is known as cut-off point.

(2) Process 2-3 :- At point 2, expansion of steam in the cylinder, starts with movement of the piston till it reaches the dead end. This expansion takes place hyperbolically and pressure falls considerably.

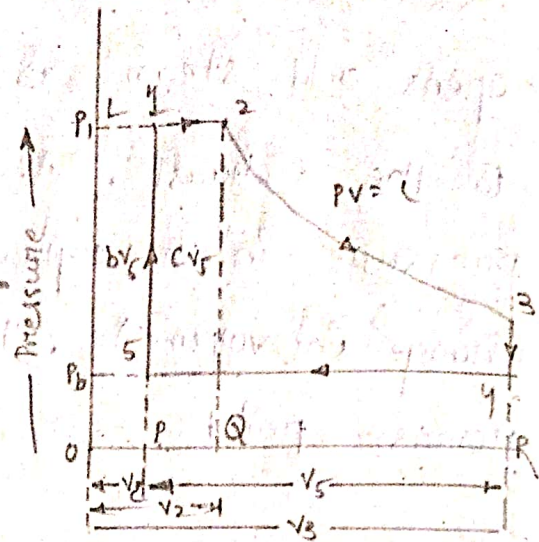
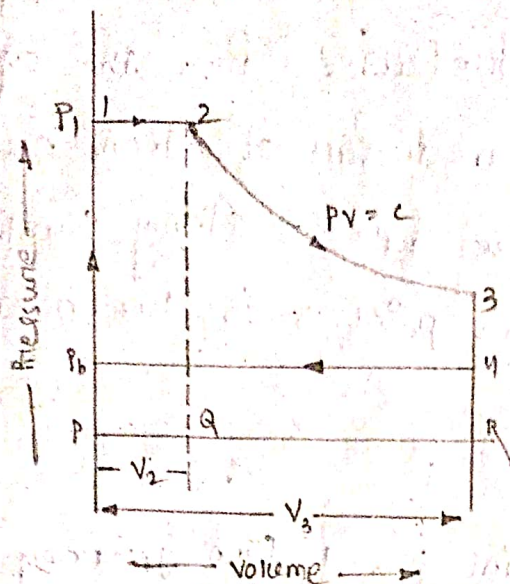
(3) process 3-4 :- At point 3, the exhaust port opens and steam is released from the cylinder to the exhaust. As a result of steam exhaust, pressure in the cylinder falls suddenly (without change in volume). The point 3 is known as release point.

(4) Process 4-5 :- At point 4, return journey of the piston starts. Now the used steam is exhausted at constant pressure, till the exhaust port is closed, and the inlet port is open. The steam pressure at point 4 is called back pressure.

(5) Process 5-1 :- At point 5, the inlet port is opened and some steam suddenly enters into the cylinder, which increases the pressure of steam (without change in volume). This process continues till the original position is restored.

* Theoretical or Hypothetical Mean effective pressure

The theoretical or hypothetical mean effective pressure may be determined as discussed below, by considering the theoretical indicator diagram without clearance and with clearance.



(a) without clearance

(b) with clearance

(i) Considering the theoretical or hypothetical indicator diagram without clearance:-
The theoretical or hypothetical or hypothetical indicator diagram without clearance is shown in fig (a).

Let

P_1 = Initial or admission pressure of steam or boiler pressure.

P_b = Back pressure or condenser pressure

V_2 = volume of steam in the cylinder at the point of cut-off

V_3 = stroke volume or swept volume or piston displacement volume. It is the volume of steam in the cylinder at the end of stroke.

We know that the theoretical or hypothetical work done per cycle

= Area of figure 12345

= Area 12QP + Area RQ - Area 45PR

= $P_1 V_2 + 2.3 P_1 V_2 \log (V_3/V_2) - P_b V_3$

and theoretical or hypothetical mean effective pressure,

$$\begin{aligned} P_m &= \frac{\text{work done per cycle}}{\text{stroke volume}} \\ &= \frac{P_1 V_2 + 2.3 P_1 V_2 \log(V_3/V_2) - P_b V_3}{V_3} \\ &= P_1 \times \frac{V_2}{V_3} + 2.3 P_1 \times \frac{V_2}{V_3} \log(V_3/V_2) - P_b \\ &= \frac{P_1}{\pi} (1 + 2.3 \log \pi) - P_b \end{aligned}$$

where $\pi = V_3/V_2 =$ Expansion ratio
= Volume of steam in the cylinder at the end of stroke
Volume of steam at the point of cut-off

ⓧ Considering the theoretical or hypothetical indicator diagram with clearance :-

The theoretical or hypothetical indicator diagram with clearance is shown in fig (b)

Let $P_1 =$ Initial or admission pressure of steam or boiler pressure

$P_b =$ back pressure or condenser pressure

$V_c =$ clearance volume of the cylinder

$V_2 =$ volume of steam at the point of cut-off.

$V_5 =$ Stroke volume or swept volume or piston displacement volume.

$V_3 =$ Total volume of steam in the cylinder
 $= V_c + V_5$

$b = \text{Ratio of clearance volume to stroke volume} = V_c / V_s$

$c = \text{Ratio of volume between the points of admission and cut-off of steam to the stroke volume} = (V_2 - V_c) / V_s$

We know that theoretical or hypothetical work done per cycle

$$= \text{Area of figure 12345}$$

$$= \text{Area 12QP} + \text{Area 23PQ} - \text{Area 45PR}$$

$$= P_1(V_2 - V_c) + 2.3 P_1 V_2 \log(V_3 / V_2) - P_b V$$

and theoretical or hypothetical mean effective pressure

$$P_m = \frac{\text{work done per cycle}}{\text{stroke volume}}$$

$$= \frac{P_1(V_2 - V_c) + 2.3 P_1 V_2 \log(V_3 / V_2) - P_b V_3}{V_3}$$

$$= P_1 \left(\frac{V_2 - V_c}{V_3} \right) + 2.3 \frac{P_1 V_2}{V_3} \log \left(\frac{V_3}{V_2} \right) - P_b$$

$$= P_1 c + 2.3 P_1 \left(\frac{P V_s + C V_3}{V_3} \right) \log \left(\frac{V_c + V_3}{b V_3 + C V_3} \right)$$

$$= P_1 c + 2.3 P_1 (b + c) \log \left(\frac{b + 1}{b + c} \right) - P_b$$

Example - 17.1

Sol. Given

$$P_1 = 11.5 \text{ bar}$$

$$V_2 = 0.5 V_3$$

$$P_b = 0.15 \text{ bar}$$

we know that expansion ratio,

$$r = V_2/V_1 = V_3/0.5 V_3 = 2$$

we know that theoretical mean effective pressure,

$$\begin{aligned} P_m &= \frac{P_1}{r} (1 + 2.3 \log r) - P_b \\ &= \frac{11.5}{2} (1 + 2.3 \log 2) - 0.15 \\ &= 9.58 \text{ bar} \quad (\text{Ans}) \end{aligned}$$

Example - 17.2

Sol. Given

$$P_1 = 12 \text{ bar}$$

$$b = V_c/V_s = 1/10 = 0.1$$

$$c = (V_2 - V_c)/V_s = 0.25$$

$$P_b = 1.1 \text{ bar}$$

we know that mean effective pressure,

$$\begin{aligned} P_m &= P_1 c + 2.3 P_1 (b+c) \log \left(\frac{b+1}{b+c} \right) - P_b \\ &= 12 \times 0.25 + 2.3 \times 12 (0.1 + 0.25) \log \left(\frac{0.1 + 1}{0.1 + 0.25} \right) - 1.1 \\ &= 3 + 9.66 \log 3.143 - 1.1 \\ &= 6.7 \text{ bar} \quad (\text{Ans}) \end{aligned}$$

Example - 17.3

Given

$$P_1 = 8.4 \text{ bar}$$

$$V_2 = 0.35 V_3$$

$$P_n = 1.25 \text{ bar}$$

$$k = 0.75$$

We know that expansion ratio

$$r = V_3/V_2 = V_3/0.35 = 2.86$$

We know that theoretical mean effective pressure

$$P_a = P_m \times k = 4.77 \times 0.75$$

$$= 3.58 \text{ bar} \quad (\text{Ans})$$

Diagram Factor :-

The diagram factor is the ratio of the area of actual indicator diagram, to the area of theoretical or hypothetical indicator diagram. It is denoted by k .

$$k = \frac{\text{Area of actual indicator diagram}}{\text{Area of theoretical indicator diagram}}$$

We know that the area of the indicator diagram represents the work done per stroke.

$$k = \frac{\text{Actual work done per stroke}}{\text{Theoretical work done per stroke}}$$

We also know that work done per stroke
 $= \text{Mean effective pressure} \times \text{swept volume}$

$$\text{Actual work done per stroke} = \text{Actual m.e.p} \times \text{swept volume}$$

and theoretical work done per stroke

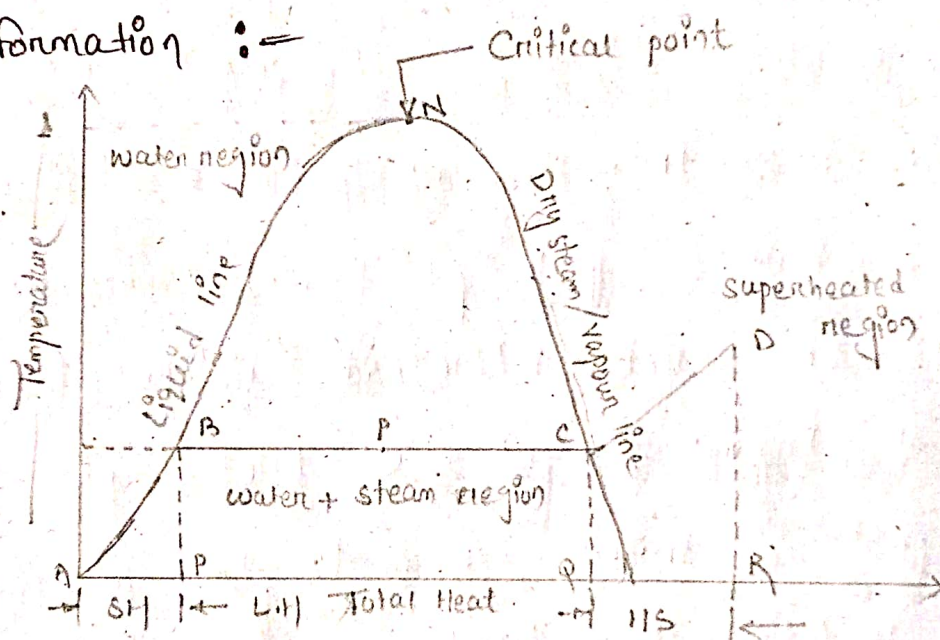
$$= \text{Theoretical m.e.p} \times \text{swept volume}$$

$$k = \frac{\text{Actual mean effective pressure (P}_n\text{)}}{\text{Theoretical mean effective pressure (P}_m\text{)}}$$

- ∴ FORMATION AND PROPERTIES OF STEAM

* Introduction :- Steam is a vapour of water, and is invisible when pure and dry. It is used as the working substance in the operation of steam engines and steam boilers.

* Temperature Vs Total heat graph during steam formation :-



→ The process of steam formation, whose abscissa represents the total heat and the vertical ordinate represents the temperature. The point A represents the initial condition of water at 0°C and pressure P . super

→ Superheated steam from water at freezing point, the heat is absorbed in the following three stages :-

(1) The heating of water up to boiling temperature of saturation temperature (t) is shown by AB. The heat absorbed by the water is AP, known as sensible heat or liquid heat or total heat of water.

(2) The change of state from liquid to steam is shown by BC. The heat absorbed during this stage is PQ, known as latent heat of vaporisation.

(3) The superheating process is shown by CD, the heat absorbed during this stage is QR, known as heat of superheat. Line AR represents the total heat of the superheated steam.

Important Terms for steam :-

Wet steam :- when the steam contains moisture or particles of water in suspension, it is said to be wet steam.

Dryness fraction or quality of wet steam :- it is the ratio of the mass of actual dry steam, to the mass of same quantity of ^{wet} steam.

$$x = \frac{m_g}{m_g + m_f} = \frac{m_g}{m}$$

where

m_g = mass of actual dry steam

m_f = mass of water in suspension

m = mass of wet steam = $m_g + m_f$

(3) Dry saturated steam :- When the wet steam is further heated and it does not contain any suspended particle of water, it is known as dry saturated steam.

(4) Super heated steam :- When the dry steam is further heated at a constant pressure, thus raising its temperature, it is said to be super heated steam.

(5) Sensible heat of water :- It is the amount of heat absorbed by 1kg of water, when heated at a constant pressure from the freezing point (0°C) to the temperature of formation of steam i.e., saturation temperature (t_s). The sensible heat is also known as liquid heat.

$$\text{Sensible heat of water} = \text{mass} \times \text{sp heat} \times \text{rise in temperature}$$

(6) Latent heat of vaporisation :- It is the amount of heat absorbed to evaporate 1kg of water at its boiling point or saturation temperature without change of temperature. It is denoted by h_{fg} .

7) Enthalpy or total heat of steam :- It is the amount of heat absorbed by water from freezing point to saturation temperature plus the heat absorbed during evaporation.

$$\therefore \text{Enthalpy or total heat of steam} = \text{sensible heat} + \text{latent heat}$$

8) The enthalpy of wet steam $(h) = h_f + x h_{fg}$

where x is the dryness fraction of steam.

9) The enthalpy of Dry steam $h = h_g = h_f + h_{fg}$

10) The enthalpy of super heated steam

$h_{sup} = \text{Total heat for dry steam} + \text{Heat for super heated steam}$

$$= h_f + h_{fg} + C_p (t_{sup} - t)$$

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

11) Specific volume of steam :- It is the volume occupied by the steam per unit mass at a given temperature and pressure and is expressed in m^3/kg .

$$P \propto \frac{1}{v}$$

i) specific volume of wet steam, $v = x v_g \text{ m}^3/\text{kg}$

ii) specific volume of dry steam, $v = v_g \text{ m}^3/\text{kg}$

Example - 7.1

→ Given, $p = 8 \text{ bar}$
 $x = 0.8$

Enthalpy of 1 kg of steam.

from steam tables corresponding to a pressure of 8 bar we find that

$$h_f = 720.9 \text{ kJ/kg and}$$

$$h_{fg} = 2046.5 \text{ kJ/kg}$$

we know that enthalpy of 1 kg of wet steam

$$\begin{aligned} h &= h_f + h_{fg} = 720.9 + 0.8 \times 2046.5 \\ &= 2358.1 \text{ kJ} \end{aligned}$$

Heat required to raise 1 kg of this steam from water at 20°C.

$$F \rightarrow E = (A \rightarrow F) - (A \rightarrow F)$$

Example - 7.2

Given, $m = 1 \text{ kg}$

$P = 6 \text{ bar}$

$T_{\text{sup}} = 25^\circ$

$C_p = 2.3 \text{ kJ / kg}^\circ\text{C}$

$t_w = 25^\circ\text{C}$

$x = 0.9 \text{ bar}$

Corresponding to pressure of 6 bar we find that

$$h_f = 670.4 \text{ kJ / kg}$$

$$h_{fg} = 2085 \text{ kJ / kg}$$

$$t = 158.8^\circ\text{C}$$

(1) When steam is wet

$$\begin{aligned} h &= h_f + x h_{fg} \\ &= 670.4 + 0.9 \times 2085 \\ &= 2546.9 \text{ kJ} \end{aligned}$$

Since the water is at a temperature of 25°C , therefore Heat already in water $= 4.2 \times 25$
 $= 105 \text{ kJ}$

$$\begin{aligned} \therefore \text{Heat actually required} &= 2546.9 - 105 \\ &= 2441.9 \text{ kJ} \end{aligned}$$

(2) When steam is dry saturated

We know that enthalpy or total heat of 1 kg of dry saturated steam.

$$\begin{aligned} h_g &= h_f + h_{fg} \\ &= 670.4 + 2085 = 2755.4 \text{ kJ} \end{aligned}$$

$$\begin{aligned} \therefore \text{Heat actually required} &= 2755.4 - 105 \\ &= 2650.4 \text{ kJ} \end{aligned}$$

③ (3) When the heat is superheated
we know that enthalpy of 1kg of superheated
steam .

$$\begin{aligned}h_{\text{sup}} &= h_g + C_p (t_{\text{sup}} - t) \\&= 2755.4 + 2.3 (250 - 158.8) \\&= 2965.16 \text{ kJ}\end{aligned}$$

$$\begin{aligned}\therefore \text{Heat actually required} &= 2965.16 - 105 \\&= 2860.16 \text{ kJ}\end{aligned}$$