

# PROPERTIES OF STEAM

## 2.0 INTRODUCTION :

Matter can exist in any form, solid, liquid, vapour or gas. If a solid metal is heated, at some temperature it melts and becomes a liquid. Further heating transforms liquid metal into a vapour and ultimately a gas. Each change of state from one form to another is called a change of 'phase'. During change of phase, we find, either addition or removal of heat. The temperature at which the phase change occurs depends upon the substance and varies according to the pressure maintained.

'Gas' is the state of substance of which evaporation from the liquid is complete. Substance like air, oxygen, nitrogen, hydrogen, etc., are treated as gases within the temperature limits of applied thermodynamics. They are fluids which cannot be liquified by the application of pressure at constant temperature. A 'vapour' is a partially evaporated liquid containing pure gaseous state together with liquid particles in suspension. Vapour may be easily condensed back to liquid state or it may be further evaporated to become a perfectly dry gas. Vapour used in engineering applications are wet steam, ammonia, sulphur dioxide, carbon dioxide etc.

Steam on account of heat energy contained by it, is used in steam engines of locomotives, water pumping systems, pneumatic presses and forges etc., Steam is the main source of energy in steam turbines used for power generation.

It should be noted that Gas Laws which you have studied earlier do not apply to vapour.

## 2.1 FORMATION OF STEAM :

There are three distinct stages in the production of steam from water. They are explained as follows with the help of a temperature Vs enthalpy (total heat) diagram (Fig. 2.1).

(Chapter-2)



It should be noted that steam is invariably formed at constant pressure.

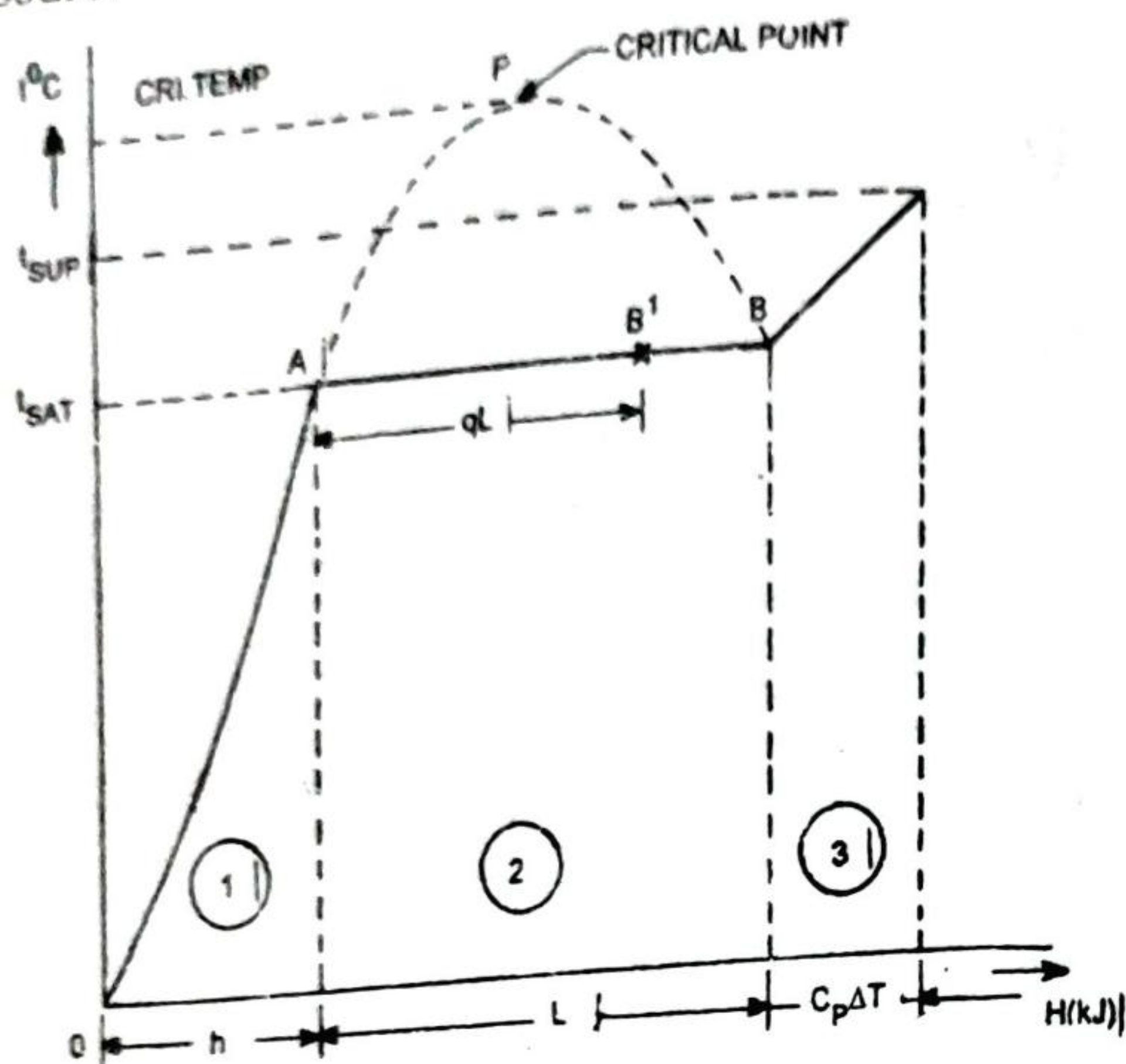


Fig. 2.1

**Stage 1 : (OA)** This is the warming phase in which temperature of water increases upto saturation temperature,  $t_{sat}$ .

Saturation temperature corresponds with the boiling point of water and varies with the pressure at which water is heated. Higher the pressure higher is the saturation temperature.

The heat energy supplied to produce this temperature rise is called 'sensible heat' or the 'liquid heat' ( $h$ ) or liquid enthalpy.

Sensible heat or liquid enthalpy is defined as the quantity of heat absorbed by 1 kg water when it is heated from its freezing point i.e.,  $0^{\circ}\text{C}$  to boiling point.

**Stage 2 : (AB)** It is an evaporation stage. Water evaporates at constant temperature ( $t_{sat}$ ) and transforms into dry saturated steam. Point 'B' represents this state of steam. Line AB represents evaporation of water at constant temperature and of course, constant pressure. The state of steam between the extreme points A and B is wet indicating incomplete evaporation. For example point 'B' on the line AB indicates such a state. Partially evaporated steam will have water particles under suspension in it and hence called wet steam.



The heat energy supplied during evaporation is called 'enthalpy of evaporation' or 'Latent heat of steam or 'Latent heat of evaporation' (L). Its value depends on the pressure at which water is heated. Higher the pressure lower is the latent heat.

Enthalpy of evaporation or Latent heat is defined as the heat required to convert 1 kg water at given pressure and temperature into steam at the same pressure and temperature.

**Stage 3 : (BC)** This phase begins only when evaporation of water is complete and all dry saturated steam is formed. Further supply of heat produces superheated steam which is accompanied by a rise in temperature. The amount of heat energy supplied in the superheat phase is called 'superheat enthalpy' given by  $C_p \Delta T$  per kg where  $C_p$  = mean sp. heat of steam and  $\Delta T$  is degree of superheat.

Note that temperature change takes place only during the transfer of heat when a substance is in a single phase. Observe it in OA and BC stages. If a two phase mixture exists then the temperature remains constant until a complete change of state takes place (line AB).

Any intermediate point between A and B, say B' represents incomplete state of evaporation. That is, steam is wet at B' containing a few droplets of moisture under suspension. The heat supplied during the stages AB' is  $qL$  where  $q$  is a fraction called dryness fraction ( $q < 1$ ).

Point P in the diagram is a critical point at which latent heat is zero. Temperature corresponding to this point is called critical temperature ( $374^\circ \text{C}$ ).

## 2.2 DRYNESS FRACTION :

It is defined as the ratio of mass of dry saturated steam to the mass of wet steam containing it.

Let  $M$  = mass of wet steam (kg)

$m$  = mass of water particles (moisture) in suspension (kg)

Then,  $(M - m)$  = mass of pure dry sat. steam (kg) and

Dryness fraction,  $q = \frac{M - m}{M}$  (no units).



2.4

**Note :** If  $M = 1$ , then  $q = (1 - m)$  kg

In other words, 1 kg wet steam contains  $q$  kg dry saturated steam  $q$  being dryness fraction.

Quality of steam is expressed as percentage of dryness fraction.

For ex., if 10 kg wet steam contains 2 kg moisture, then,

$$q = \frac{10 - 2}{10} = 0.8$$

Hence quality of steam is 80%.

### 2.3 ENTHALPY FORMULAE :

Considering a unit mass of fluid ( $m = 1$  kg) we arrive at following calculations. Refer to Fig. 2.1.

Liquid enthalpy or sensible heat =  $h$  kJ/kg

Enthalpy of dry saturated steam

$$H_s = \text{Liquid enthalpy} + \text{Enthalpy of evaporation}$$

$$\text{i.e., } H_s = h + L \text{ kJ/kg}$$

Enthalpy of dry saturated steam is the quantity of heat required to convert 1 kg water at  $0^\circ\text{C}$  into dry saturated steam at constant pressure.

$$\text{Enthalpy of wet steam, } H_s = h + qL \text{ kJ/kg}$$

Enthalpy of superheated steam,

$$H_{\text{sup}} = \text{Enthalpy of dry sat steam} + \text{superheat enthalpy}$$

$$\text{i.e., } H_{\text{sup}} = H_s + C_p \Delta T$$

where  $\Delta T =$  degree of superheat

$=$  superheat steam temp.,  $-$  saturation temperature

$$= (t_{\text{sup}} - t_{\text{sat}})^\circ\text{K}$$

Being a constant pressure heating process,

$$\text{the superheat enthalpy} = mC_p \Delta T \text{ kJ}$$

$$\text{and specific enthalpy} = C_p \Delta T \text{ kJ/kg}$$

$C_p =$  mean value of specific heat of steam at constant pressure

$$= 2.0934 \text{ kJ/kg K.}$$



## 2.4 TEMPERATURE-ENTHALPY DIAGRAM: (T-H CHART):

Fig. 2.2 shows temperature - enthalpy graph drawn for a wide range of pressures. If all the liquid enthalpy (sensible heat) points obtained at different temperatures are joined we get 'saturated liquid line'. If all the dry saturated steam points are joined by means of a smooth curve we get a 'saturated vapour line'. This line and the saturated liquid line enclose an area in which the steam is wet. To the left of saturated liquid line state of fluid is water. To the right of saturated vapour line steam is in superheated form. The wet steam area has constant dryness lines drawn in it as shown dotted. Points lying along such a line have same dryness fraction.

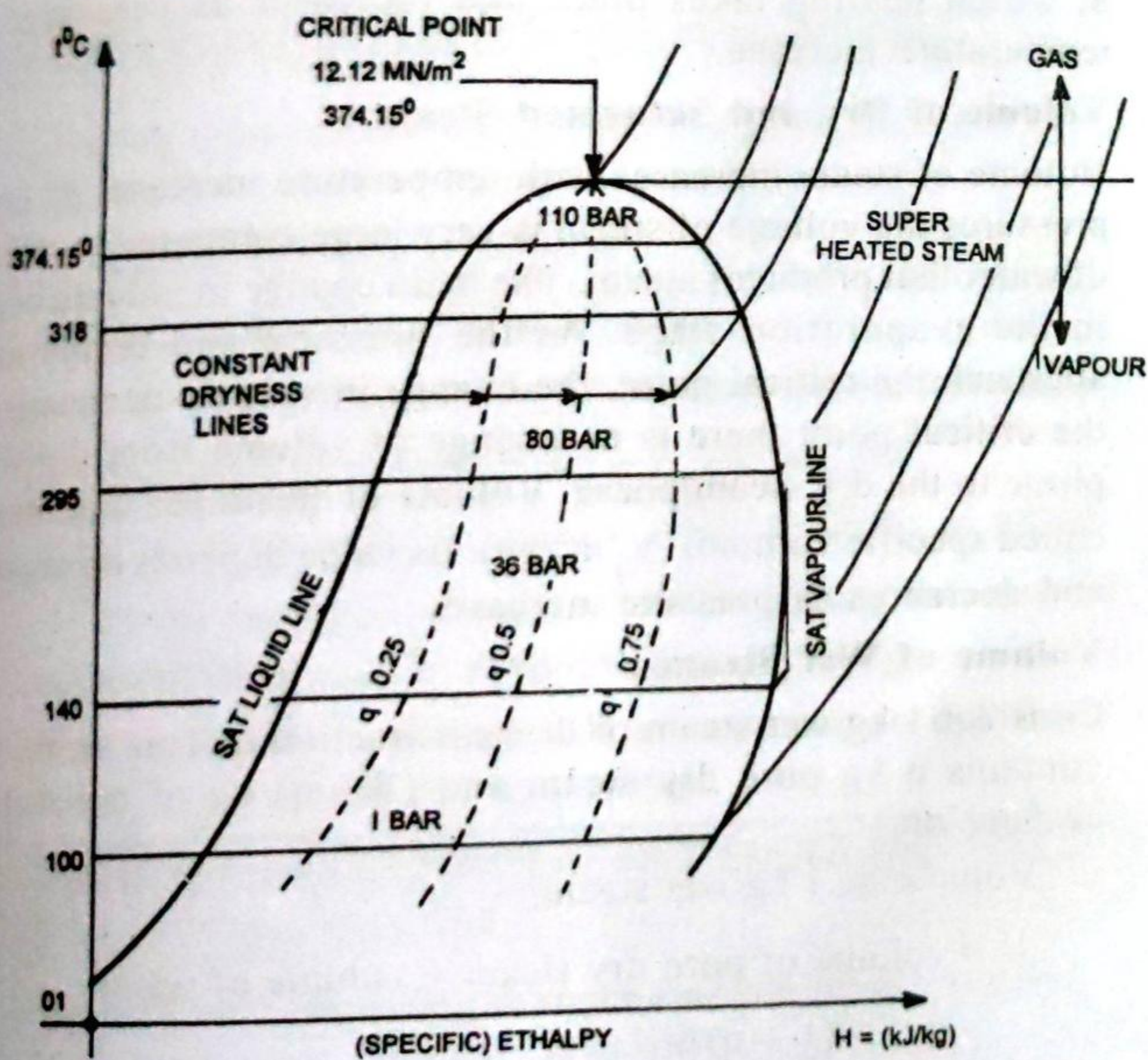


Fig. 2.2

The saturated liquid line and the saturated vapour line when continued upward eventually meet at a common point called 'critical point'. This point occurs at a pressure of 221.2 bar (22.12 MN/m<sup>2</sup>) and a temperature of 374.15°C. It will be

(Chapter-2)



noticed that as the pressure increases towards the critical pressure, the enthalpy of evaporation (latent heat) reduces until it finally becomes zero at the critical point. This implies that at the critical point the water changes directly into dry saturated steam.

The critical point is the division between the behaviour of fluid as a vapour and as a gas. At temperature higher than the critical temperature the vapour becomes a gas.

## 2.5 VOLUME OF FLUID :

### Volume of Saturated Water :

If the quantity of water expressed in cubic metres. Specific volume ( $v_w$ ) is given in  $m^3/kg$ . Its value depends on the pressure at which heating takes place and increases as pressure and temperature increase.

### Volume of Dry and Saturated Steam :

Volume of steam increases with temperature increase. At lower pressures the volume of steam is very large compared to volume of water that produces steam. The main change in volume occurs in the evaporation stage. As the pressure and temperature approach the critical point, the change in volume decreases. At the critical point there is no change of volume from the water phase to the dry steam phase. Volume of steam per unit mass is called specific volume. ( $V_s m^3/kg$ ). Its value depends on pressure and decreases as pressure increases.

### Volume of Wet Steam :

Consider 1 kg wet steam of dryness fraction  $q$ . This steam then contains  $q$  kg pure dry steam and  $(1 - q)$  kg of moisture in suspension.

∴ Volume of 1 kg wet steam,

$$v_s' = \text{volume of pure dry steam} + \text{volume of water}$$

$$= qv_s + (1 - q)v_w$$

$(1 - q)$  is negligible compared to  $q$  and  $v_w$  is negligible compared to  $v_s$ . Hence product of  $(1 - q)v_w$  is sensibly neglected.

∴ Volume of 1 kg wet steam is,

$$v_s' = qv_s$$



### Volume of Superheated Steam :

Superheated steam behaves as a gas. Referring to superheat stage (point B to C in Fig. 2.1) and applying Charles's law for constant pressure heating,

$$\frac{v_B}{T_B} = \frac{v_C}{T_C} \quad \dots \quad v_B = v_s ; v_C = v_{\text{sup}} \\ T_B = T_{\text{sat}} ; T_C = T_{\text{sup}}$$

$$\therefore \frac{v_s}{T_{\text{sat}}} = \frac{v_{\text{sup}}}{T_{\text{sup}}}$$

$$v_{\text{sup}} = v_s \times \frac{T_{\text{sup}}}{T_{\text{sat}}} \text{ m}^3/\text{kg}$$

(specific volume of superheated steam)

## 2.6 EXTERNAL WORK OF EVAPORATION :

During evaporation, we observed that change in volume takes place.

At a given pressure  $p$  ( $\text{kN/m}^2$ )

Let  $v_w$  = Specific volume of water

$v_s$  = Specific volume of dry and saturated steam.

Then change in volume =  $(v_s - v_w) \text{ m}^3/\text{kg}$  and

work of evaporation =  $p (v_s - v_w) \text{ kN.m/kg}$  or  $\text{kJ/kg}$

$v_w$  being negligible compared to  $v_s$  value, external work of evaporation is usually considered as  $p v_s \text{ kJ/kg}$ .

If steam is wet at a particular stage, external work of evaporation is  $p v'_s \text{ kJ/kg}$  where  $v'_s = q v_s \text{ m}^3/\text{kg}$ .

## 2.7 TRUE OR INTERNAL LATENT HEAT AND INTERNAL ENERGY OF STEAM :

We have seen that during evaporation (line AB in Fig. 2.1) quantity of heat absorbed by steam is called Latent Heat. This heat also includes (heat equivalent of) work of evaporation ( $p v_s$ ). The quantity  $(L - p v_s)$ , then may be called internal or true latent heat ( $L'$ ). Thus, latent heat is the sum of true or internal latent heat and external work of evaporation.

$$L = L' + p v_s$$

(Chapter-2)



we have, enthalpy,  $H_s = h + L$

$$H_s = h + L' p v_s$$

The quantity  $(h + L')$  i.e., sum of sensible heat and internal latent heat is called internal energy ( $U$ ) of steam.

Hence,  $H_s = U + p v_s$  and

$$U = H_s - p v_s$$

Internal energy of steam is, therefore, enthalpy minus work of evaporation.

For wet steam with dryness fraction 'q', internal energy

$$U = H'_s - p v'_s$$

$$\text{where } H'_s = h + qL$$

$$\text{and } v'_s = q v_s$$

For superheated steam at  $t_{\text{sup}}$  degrees of temperature

$$U = H_{\text{sup}} - p v_{\text{sup}}$$

$$\text{where } H_{\text{sup}} = H_s + C_p \Delta T$$

$$\text{and } v_{\text{sup}} = v_s \times \frac{T_{\text{sup}}}{T_{\text{sat}}}$$

## 2.8 ENTROPY OF STEAM :

Entropy is a property of a system. It increases if heat is added to the system, decreases if heat is removed from the system and remains constant when there is no heat transfer from and to the system. If  $dQ$  is a small change in heat transferred at  $T^{\circ}\text{K}$ , then

$$\frac{dQ}{T} = dQ \text{ represents change of entropy in the system.}$$

Entropy of vapour is studied in three stages as follows.

### Liquid Entropy or Entropy of Water ( $\phi_w$ ) :

Consider unit mass of water ( $m = 1 \text{ kg}$ ) being heated from  $0^{\circ}\text{C}$  ( $273^{\circ}\text{K}$ ) upto its saturation temperature  $t_{\text{sat}}$  ( $T_{\text{sat}}^{\circ}\text{K}$ ) at a given pressure. Then liquid heat or sensible heat supplied is,

$$Q = C_{pw} \Delta T \quad \dots C_{pw} = \text{sp. heat of water}$$

$$\text{and } dQ = C_{pw} \Delta T$$

$$= 4.187 \approx 4.2 \frac{\text{kJ}}{\text{kgK}}$$

$$\frac{dQ}{T} = C_{pw} \frac{dT}{T}$$



By definition of entropy,  $\frac{dQ}{T} = d\phi$  or  $ds$

i.e., change of entropy

$$\therefore d\phi = C_{pw} \cdot \frac{dT}{T}$$

$$\int_1^2 d\phi_1 = C_{pw} \int_1^2 \frac{dT}{T}$$

$$\phi_2 - \phi_1 = C_{pw} \log_e \frac{T_2}{T_1}$$

Here  $\phi_2 - \phi_1 = \phi_2$ ;  $T_1 = 273^0 \text{ K}$ ;  $T_2 = T_{\text{sat}}^0 \text{ K}$

$$\text{Here, } \boxed{\phi_w = C_{pw} \log_e \frac{T_{\text{sat}}}{273}} \text{ kJ/kg} - \text{K.}$$

### Entropy of Evaporation : ( $\phi_e$ )

We know that evaporation of water at a given pressure takes place at constant temperature ( $t_{\text{sat}}$ ). Heat supplied to fluid during evaporation is Latent heat or enthalpy of evaporation ( $L$ ).

$$\text{Entropy of evaporation, } \phi_e = \frac{L}{T_{\text{sat}}} \text{ kJ/kg} - \text{K}$$

it can also be seen from  $T - \phi$  diagram (Fig. 2.3), enthalpy of evaporation = area under AB

$$L = \phi_e (T_{\text{sat}} - 0)$$

$$\boxed{\phi_e = \frac{L}{T_{\text{sat}}}}$$

For wet steam with dryness fraction  $q$  (at point B'), entropy of

$$\text{evaporation, } \phi'_e = \frac{qL}{T_{\text{sat}}}$$



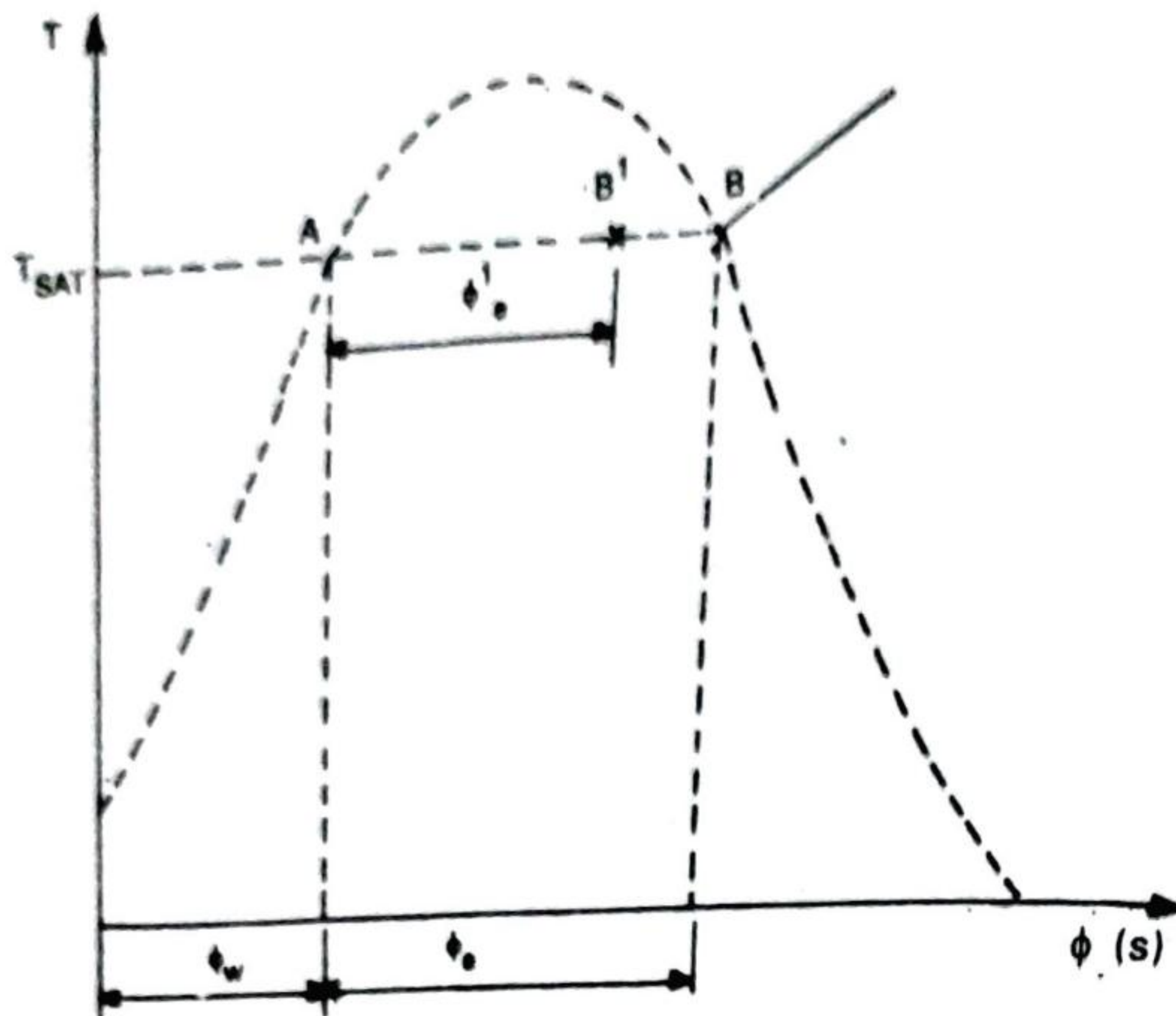


Fig. 2.3

### Entropy of Saturated Steam ( $\phi_s$ ) :

The specific entropy of dry and saturated steam is the sum of liquid entropy and entropy of evaporation.

$$\phi_s = \phi_w + \phi_e$$

$$\phi_s = \phi_w + \frac{L}{T_{sat}} \text{ kJ/kg - K}$$

For a wet vapour, specific entropy is given by

$$\phi'_s = \phi_w + \phi'_e$$

$$\phi'_s = \phi_w + \frac{qL}{T_{sat}}$$

where  $q$  = dryness fraction

### Entropy of Superheated Steam ( $\phi_{sup}$ ) :

Consider unit mass of steam in a superheated state at a temperature of  $T_{sup}$ . We have, superheat enthalpy,

$$C_p \Delta T = C_p (T_{sup} - T_{sat}) \quad \text{.....at a given pressure}$$



By definition of entropy,

$$d\phi = C_p \frac{\Delta T}{T} = C_p \frac{dT}{T}$$

$$= C_p \int_1^2 \frac{dT}{T} = C_p \log_e \frac{T_2}{T_1}$$

Here  $\phi = \phi_{sh}$

$T_1 = T_{sat}$  and  $T_2 = T_{sup}$

(Superheating starts from  $T_{sat}$  to  $T_{sup}$ )

$$\therefore \phi_{sh} = C_p \log_e \frac{T_{sup}}{T_{sat}}$$

Thus for a superheated steam at  $T_{sup}^{\circ}\text{K}$ .

Total entropy = liquid entropy + entropy of evaporation  
+ entropy of superheated steam

$$\phi_{sup} = \phi_w + \phi_e + \phi_{sh}$$

$$\therefore \phi_{sup} = \phi_s + C_p \log_e \frac{T_{sup}}{T_{sat}}$$