

# PROPERTIES OF STEAM

## 4.1 INTRODUCTION

Steam may be defined as water vapours suspended in air. It may be wet, saturated or superheated. Vapours may be considered as a fluid in a gaseous state. It may contain liquid particles in suspension and its temperature is not far from its boiling point. When it is cooled or expanded, it condenses into its liquid state. Vapours in general do not obey gas laws of Boyle and Charles.

Steam has vast industrial applications as a working medium in steam engines and steam turbines. It is also extensively used in processing equipments.

## 4.2 PURE SUBSTANCE

A pure substance is a substance that has a chemically homogeneous and fixed chemical composition irrespective of the phase or phases in which it exists. The pure substance is sometimes also called one component system. A mixture of ice, water and steam is an example of a pure substance since the chemical composition of the three phases is the same. Steam is regarded as the most important pure substance in engineering practice.

A substance cannot be treated as pure if it undergoes a chemical reaction. A mixture of oxygen and carbon monoxide is a pure substance as long as it remains fixed in composition. If some of the CO combines with some of the  $O_2$  to form  $CO_2$ , the system does not involve a pure substance during the process because its chemical composition is changing. The state of a pure substance at rest is specified completely by the values of two independent intensive properties.

## 4.3 PHASE

The phase of a substance is any homogeneous part of a system that is physically distinct. Each phase in a system is separated from other phases by interfaces called phase boundaries.

In general, a pure substance exists in the following three phases :

- (i) solid, (ii) liquid, and (iii) vapour or gaseous phase.

Under certain conditions, all three phases may co-exist. For examples, water has three phases : ice, water, and steam. In a system consisting of an ice cube in liquid water, there are two phases, solid and liquid, and the phase boundary is the surface of the ice cube.

A gas mixture is always a single phase, because the molecules of the constituent gases intermingle completely throughout the entire volume of the gas and make the mixture homogeneous. There could be more than one solid or liquid phase of a substance as in the case of sulphur which exists in three solid phases of monoclinic, rhombic and amorphous forms at room temperature.

A system composed of liquid water with a layer of oil on top of it would clearly involve two phases with a planar phase boundary separating the two.

#### 4.4 CONSTANT PRESSURE FORMATION OF STEAM

Consider a unit mass of ice at  $-20^{\circ}\text{C}$  and 1 atm contained in a cylinder-piston system as shown in Fig. 4.1. Let the ice be heated slowly so that its temperature is increased at constant pressure. Let

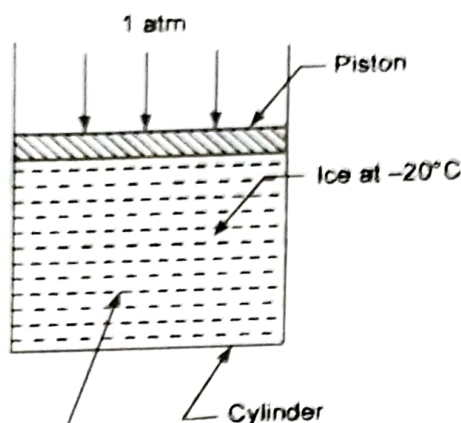


Fig. 4.1

the state changes be plotted on temperature — heat added condiments, as shown in Fig. 4.2. The distinct regimes of heating are :

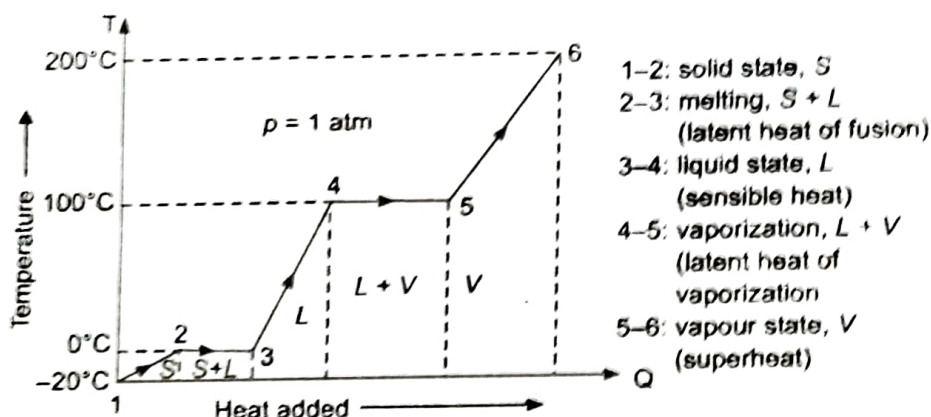


Fig. 4.2 T-Q diagram for phase changes of ice into steam.

- 1 – 2 : The temperature of ice increases from  $-20^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ , the freezing temperature at atmospheric pressure.
- 2 – 3 : Ice melts into water at a constant temperature of  $0^{\circ}\text{C}$ . At state 3, the melting process ends. The heat added during the process 2-3 is called the latent heat of fusion of ice or simply latent heat of ice.
- 3 – 4 : The temperature of water increases on gradual addition of more heat from  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ , the boiling point of water.
- 4 – 5 : On further heating beyond point 4, water starts boiling and ends at state 5. Water will gradually turn into steam and there is no rise in temperature. This steam contains some water particles and is called **wet steam**. With further addition of heat all the water particles disappear and steam becomes dry saturated at point 5. The heat addition during process 4-5 is called the latent heat of vaporisation of steam or simply latent heat of steam.
- 5 – 6 : This process is called superheating and the steam obtained is called the superheated steam. Let the temperature of steam corresponding to point 6 be  $t_{\text{sup}}^{\circ}\text{C}$ . Then  $(t_{\text{sup}} - t_{\text{sat}})^{\circ}\text{C}$  is called the degree of superheat, where  $t_{\text{sat}}^{\circ}\text{C}$  is the saturation temperature at the given pressure.

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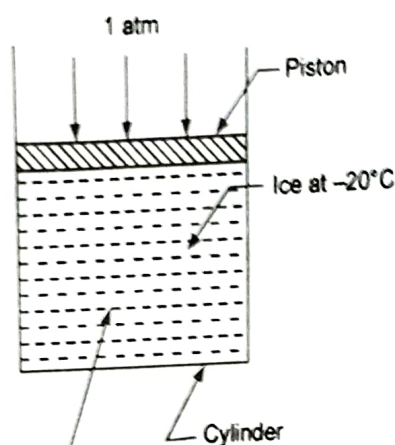


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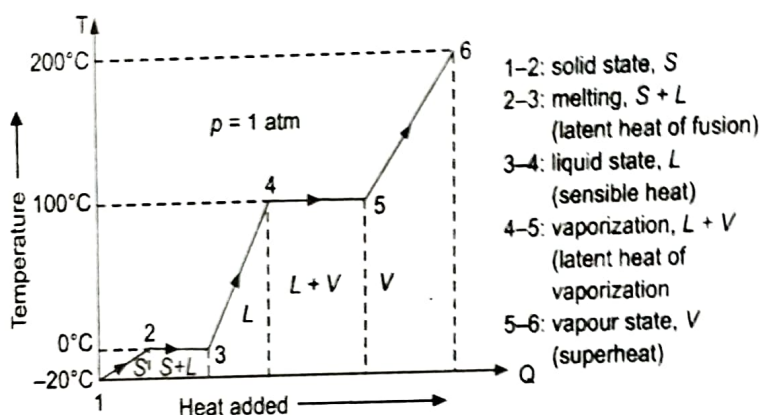


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- 4 – 5 : On further heating beyond point 4, water starts boiling and ends at state 5. Water will gradually turn into steam and there is no rise in temperature. This steam contains some water particles and is called wet steam. With further addition of heat all the water particles disappear and steam becomes dry saturated at point 5. The heat addition during process 4-5 is called the latent heat of vaporisation of steam or simply latent heat of steam.
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### 4.5 T-V DIAGRAM FOR FORMATION OF STEAM

The temperature-volume diagram for phase changes of ice into steam is shown in Fig. 4.3.

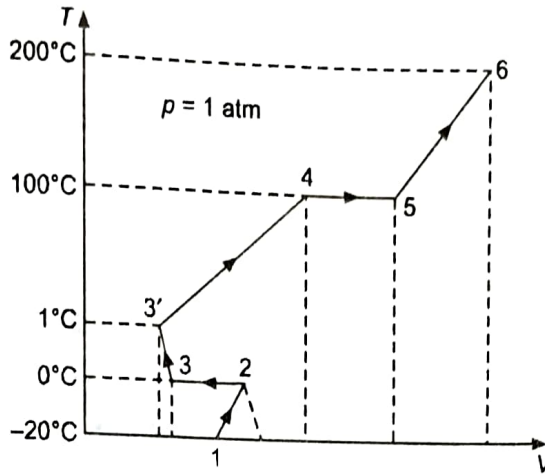


Fig. 4.3 T-V diagram for phase changes of ice into steam.

The volume changes during various process are :

- 1 – 2 : Volume increases from  $V_1$  to  $V_2$  as ice temperature increases to  $0^\circ\text{C}$ .
- 2 – 3 : The volume of water decreases as ice melts at  $0^\circ\text{C}$ .
- 3 – 3' : The volume of water slightly decreases from  $0^\circ\text{C}$  to  $4^\circ\text{C}$ .
- 3' – 4 : The volume of water increases due to thermal expansion.
- 4 – 5 : There is a large increase in volume of water due to formation of steam.
- 5 – 6 : The volume of vapour increases.

### 4.6 p-v DIAGRAM FOR SATURATION CURVE

The working fluid in power cycles is most often the liquid and interest is confined to the liquid-vapour region only. The  $p$ - $v$  diagram then becomes as shown in Fig. 4.4.  $ABCD$  is the typical isotherm of a pure substance on the  $p$ - $v$  diagram. The isotherm passing through the critical point is called the critical isotherm and the corresponding temperature is known as the critical temperature ( $t_c$ ). The pressure and volume at the critical point are known as critical pressure ( $p_c$ ) and critical volume ( $v_c$ ) respectively.

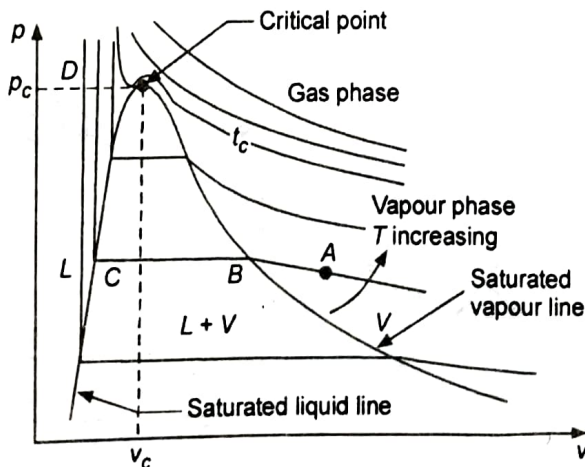


Fig. 4.4 Saturation curve on  $p$ - $v$  diagram.

## 4.7 T-v DIAGRAM FOR WATER

Consider 1 kg of water contained in a vessel and heated at constant pressure. Let us plot the constant pressure lines that represents the state through which water passes as it is heated from initial state. The line  $ABCD$  in Fig. 4.5 represents such a constant pressure line at 1 atm. The various portions of this line represent different states of water as follows :

**AB :** Heating of liquid to saturation temperature. If the temperature of liquid is less than saturation temperature at a given pressure, the liquid is said to be sub-cooled or compressed.

**BC :** Change of phase at constant temperature from liquid to vapour state. The points  $B$  and  $C$  are called the saturated liquid and saturated vapour states respectively.

**CD :** Superheating of vapour and both temperature and volume increase. When the temperature of vapour is higher than saturation temperature at a given pressure, it is called superheated vapour.

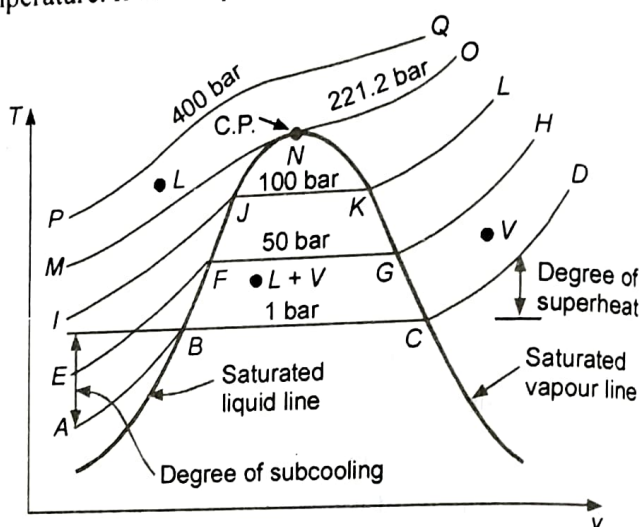


Fig. 4.5 T-v diagram for water.

If the heating process is repeated at different pressures such as 50 bar, 100 bar, curves such as  $EFGH$  and  $IJKL$  respectively are obtained. The locus of points like  $B$ ,  $F$ ,  $J$  etc. is called saturated liquid line and that of  $C$ ,  $G$ ,  $K$  etc. as saturated vapour line. If the pressure is increased beyond a certain value called the critical pressure (212.2 bar), the constant temperature portion disappears. This corresponds to the critical state.

## 4.8 T-s DIAGRAM FOR A PURE SUBSTANCE

The  $T$ - $s$  diagram for a pure substance like water is shown in Fig. 4.6. The  $T$ - $s$  diagram for liquid-vapour transformation only is shown in Fig. 4.7. At a particular pressure;  $s_f$  is the specific entropy of saturated liquid, and  $s_g$  that of saturated vapour. The entropy change of the system during the phase change from liquid to vapour is  $s_{fg} = s_g - s_f$ .

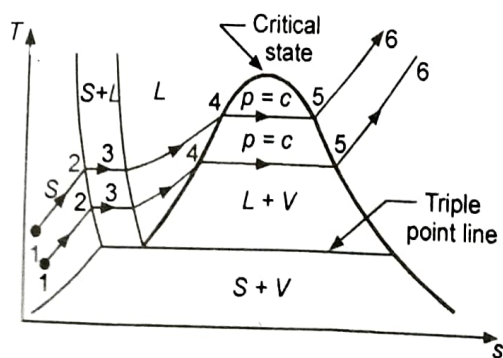


Fig. 4.6 Phase equilibrium diagram on  $T$ - $s$  coordinates.

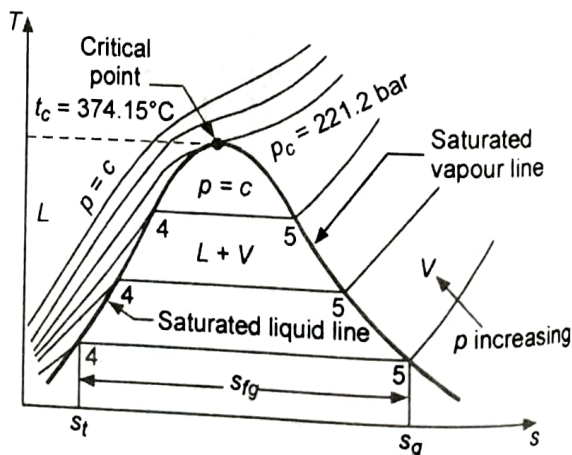


Fig. 4.7 Saturation (or vapour) dome for water.

## 4.9 PROPERTIES OF STEAM

### 1. Enthalpy or Total Heat of Water, $h_f$

It is defined as the quantity of heat required to raise the temperature of one kg of water from  $0^\circ\text{C}$  to its boiling point or saturation temperature corresponding to the pressure applied. It is also called enthalpy of saturated water or liquid heat and is represented by  $h_f$ .

$$h_f = \text{specific heat of water, } c_{pw} \times \text{rise in temperature} \\ = 4.187 \times \Delta t, \text{ kJ/kg}$$

### 2. Latent Heat of Steam, $h_{fg}$

Latent heat of steam at a particular pressure may be defined as the quantity of heat required to convert one kg of water at its boiling point into dry saturated steam at the same pressure. It is denoted by  $h_{fg}$ .

### 3. Dryness Fraction

It is defined as the ratio of mass of dry steam actually present to the mass of wet steam. It is denoted by  $x$ .

Let  $m_s$  = mass of dry steam, kg  
 $m_w$  = mass of water vapour in steam, kg Water vapour = wet steam  
 $x$  = dryness fraction of the sample

Then 
$$x = \frac{m_s}{m_s + m_w} \quad \dots(4.1)$$

For dry steam,  $m_w = 0$  and  $x = 1$

The quality of steam is the dryness fraction expressed as a percentage.

$$\text{Quality of steam} = 100x$$

**Wetness fraction** 
$$= 1 - x = m_w / (m_s + m_w)$$

The wetness fraction expressed in percentage is called priming.

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

### 4. Enthalpy of wet steam

It may be defined as the quantity of heat required to convert one kg of water at  $0^\circ\text{C}$ , at constant pressure, into wet steam.

$$h = h_f + xh_{fg} \quad \dots(4.2)$$

When steam is dry saturated, then  $x = 1$

and 
$$h_g = h_f + h_{fg} \quad \dots(4.3)$$

### 5. Total Enthalpy of Superheated Steam

Let  $c_{ps}$  = specific heat of superheated steam  
 $t_s$  = temperature of formation of steam,  $^\circ\text{C}$   
 $t_{\text{sup}}$  = temperature of superheated steam,  $^\circ\text{C}$

Then heat of superheat 
$$= c_{ps}(t_{\text{sup}} - t_s)$$

$$h_{\text{sup}} = (h_f + h_{fg}) + c_{ps}(t_{\text{sup}} - t_s) \quad \dots(4.4a)$$

$$= h_g + c_{ps}(t_{\text{sup}} - t_s) \quad \dots(4.4b)$$

## 4.10 STEAM TABLES

In actual practice, it is quite cumbersome to calculate the relation between various quantities like pressure, temperature, volume, enthalpy, latent heat and entropy, etc. of steam. Such quantities have been determined experimentally and recorded in the form of tables, known as steam tables. The values of various quantities given in these tables are for 1 kg of steam which is dry saturated. Values for unknown pressure or temperature can be calculated by linear interpolation between two consecutive values. Such tables are given at the end of the book.

## 4.11 SPECIFIC VOLUME OF WET STEAM

The specific volume of steam is the volume of 1 kg of dry steam, and is represented by  $v_g$  in  $\text{m}^3/\text{kg}$ .

$$\text{Density of steam} = \frac{1}{v_g} \text{ kg/m}^3 \quad \dots(4.5)$$

Let  $v_f$  = volume of 1 kg of water,  $\text{m}^3/\text{kg}$

$$\text{Then volume of 1 kg of wet steam} = x v_g + (1 - x) v_f \quad \dots(4.6a)$$

Now  $v_f \ll v_g$

$$\therefore \text{Volume of 1 kg of wet steam} = x v_g \quad \dots(4.6b)$$

$$\text{Density of wet steam} = \frac{1}{x v_g} \text{ kg/m}^3 \quad \dots(4.7)$$

## 4.12 SPECIFIC VOLUME OF SUPERHEATED STEAM

The volume of superheated steam at a given pressure can be found by assuming the superheated steam behaves as a perfect gas obeying gas laws.

Let

- $p$  = pressure under which the steam is superheated.
- $v_g$  = specific volume of dry saturated steam
- $T_s$  = temperature of formation of steam in K corresponding to  $p$ .
- $T_{\text{sup}}$  = temperature to which steam is super heated in K.
- $v_{\text{sup}}$  = superheated volume of steam at pressure  $p$ .

Applying Charle's law at the constant pressure  $p$ , we have

$$\frac{v_g}{T_s} = \frac{V_{\text{sup}}}{T_{\text{sup}}}$$

$$\text{or } v_{\text{sup}} = \frac{T_{\text{sup}}}{T_s} \times v_g \quad \dots(4.8)$$

## 4.13 INTERNAL ENERGY OF STEAM

The internal energy of steam may be defined as the actual heat energy stored in steam above the freezing point of water. It is the difference between the total heat of steam and the external work of evaporation.

Consider 1 kg of steam at a pressure  $p$  bar.

Let

- $u$  = internal energy of steam
- $h_g$  = total heat of dry saturated steam
- $v_g$  = specific volume of dry saturated steam