2 STEAM AND ITS PROPERTIES

A *vapour* is partially evaporated liquid carrying particles of liquid in it. Vapours do not obey gas laws but at high temperatures and low pressures their behaviours are very similar to gases. Steam is a vapour of water and is generated by supplying heat to water. Steam is most widely used as heat transport fluid. It is a pure substance and it has high thermal capacity. Steam is used for heating and as working substance in the steam engines and steam turbines.

Formation of steam at constant pressure

The action of heat in the formation of steam from water is illustrated in fig. 2.1. Consider a cylinder fitted with a piston, which moves freely in it. One kilogram of water at 0°C is taken in the cylinder and the piston is loaded by the weight W to ensure constant pressure as shown in fig. 2.1a. Let v be the initial volume occupied by the water. The condition of water at 0°C is represented by a point A on the temperature - enthalpy diagram as shown in fig. 2.2. When the water inside the cylinder is heated, there is a raise in temperature and this rise will continue till boiling point is reached. The temperature at which water starts boiling depends on the pressure acting on it. This boiling temperature is known as the *temperature of formation of steam or saturation temperature*. During heating of water upto boiling point there is a slight increase in volume of water as shown in fig. 2.1b. The heating of water from 0°C to the saturation temperature t_s is shown by the line AB on temperature-enthalphy diagram as shown in fig. 2.2.

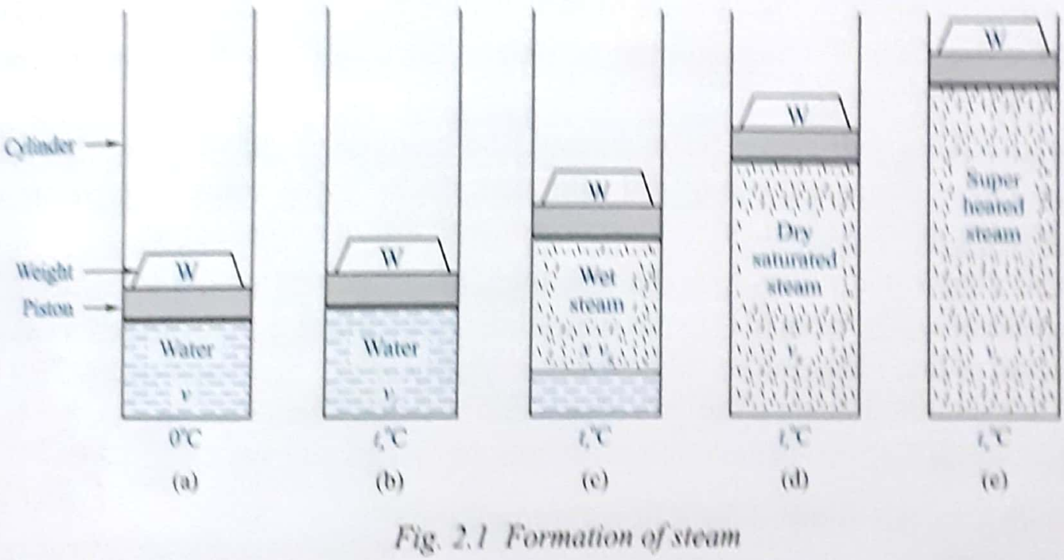

Fig. 2.1 Formation of steam

Further addition of heat to water at its saturation point does not cause any further increase of its temperature but there is only a change of state from water to steam until the whole amount of water is converted into steam. So long as the steam is in contact with water, it is called *wet steam* as in fig. 2.1c and if all the water particles associated with steam are evaporated as shown in fig. 2.1d, the steam so obtained is called *dry saturated steam*. The heating of water at the saturation temperature t_s into dry saturated steam at the same temperature is represented by line BC as shown in fig. 2.2.

If the dry saturated steam is further heated at constant pressure, its temperature and volume increases as shown in fig. 2.1e. The steam so obtained is called *superheated steam* which behaves like a prefect gas. The process of heating the dry saturated steam is called *super heating* and is represented by the curve CD as shown in fig. 2.2.

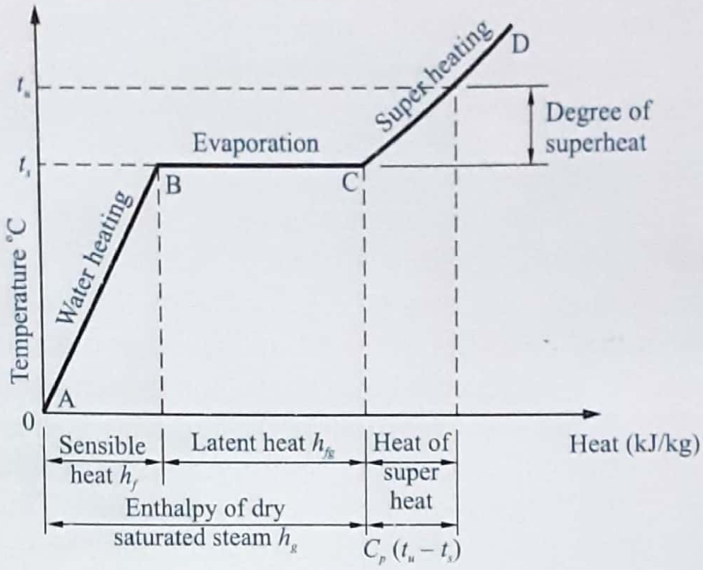

Fig. 2.2 Graphical representation of formation of steam

Terms relating to steam formation

Sensible heat of water h_f: The amount of heat required to raise the temperature of one kilogram of water from 0° C to saturation temperature is defined as *sensible heat or enthalpy of saturated water*.

Latent heat or hidden heat h_{fg}: The amount of heat required to convert one kilogram of water at saturation temperature into dry saturated steam at the same temperature and pressure is known as *latent heat of evaporation* or *enthalpy of evaporation*.

Enthalpy of dry saturated steam h_g: The amount of heat required to raise the temperature of one kilogram of water from 0° C to the saturation temperature, and to convert it into dry saturated steam at that temperature is known as *enthalpy of dry saturated steam*. Thus the enthalpy of dry saturated steam is the sum of sensible heat and latent heat i.e., $h_g = h_f + h_{fg}$

Condition of steam

The steam may exit in any of the following conditions :

1. Wet steam
2. Dry saturated steam, and
3. Superheated steam

Wet steam : Steam which is generated when in contact with the water surface is wet steam, as some of the water particles may leave the water surface and so it is a mixture of steam and water particles. The temperature of wet steam is equal to the saturation temperature. The quality of wet steam is indicated by dryness fraction. *Dryness fraction* is defined as the ratio of the mass of dry steam actually present to the mass of steam containing it.

In a sample of wet steam, let

m_g = Mass of dry steam in kg

m_f = Mass of water in suspension in kg

$$\therefore \text{ Dryness fraction } x = \frac{\text{Mass of dry steam in the mixture}}{\text{Mass of the mixture}} = \frac{m_g}{m_g + m_f}$$

Enthalpy of wet steam $H_w = h_f + x\,h_{fg}$ kJ/kg

Wetness fraction is another term associated with wet steam. It is the raito of mass of water particles or moisture in suspension to the mass of steam containing it.

$$\therefore \text{ Wetness fraction } \quad y = \frac{m_f}{m_g + m_f}$$

$$= 1 - \frac{m_g}{m_f + m_g} = 1 - x$$

The wetness fraction when expressed in percentage is called *priming*.

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

Dry saturated steam : If saturated steam contains no water particles at its saturation temperature, it is called *dry saturated steam.* For dry saturated steam the dryness fraction is equal to one.

$\therefore$ Enthalpy of dry saturated steam $H_s = h_f + h_{fg} = h_g$ kJ/kg

Superheated steam : If the temperature of steam is raised above the saturation temperature, then it is called *superheated steam.* Steam is generally superheated at constant pressure. If t_u be the temperature of the superheated steam and t_s its saturation temperature, then $(t_u - t_s)$ is called *degree of superheat.* The enthalpy of superheated steam is equal to the sum of the sensible heat, latent heat and heat of superheating.

i.e.,

$$H_u = h_f + h_{fg} + C_p(t_u - t_s)$$

$$= h_g + C_p(t_u - t_s) \text{ kJ/kg}$$

where C_p is the mean specific heat of the superheated steam at constant pressure in kJ/kg°C or kJ/kg K.

Advantages of superheated steam :

1. Its capacity to do work is increased.
2. Superheated steam results in an increase in thermal efficiency.
3. Superheating is done in a superheater, which receives its heat from waste furnace gases, which would have otherwise passed uselessly through the chimney.

Specific volume of steam : The specific volume of steam is defined as the volume of unit mass of steam at a given temperature and pressure.

Specific volume of wet steam : If the steam has a dryness fraction of x, then 1 kg of this steam will contain x kg of dry steam and $(1-x)$ kg of water. If v_f is the volume of 1 kg of water in m^3 and V_g is the volume of 1 kg of perfect dry steam in m^3 then

Volume of 1 kg of wet steam = Volume of dry steam + Volume of water

$$\therefore \quad v_w = x\,v_g + (1-x)\,v_f$$

The value of v_f at low pressures is very small and is generally neglected. Thus in general, the volume of 1 kg of wet steam or the specific volume of wet steam

$$v_w = x\,v_g \text{ m}^3/\text{kg}$$

and density of wet steam $\rho = \dfrac{1}{v_w} = \dfrac{1}{x\,v_g}$ kg/m^3

Specific volume of dry saturated steam : The specific volume v_g of dry saturated steam is the volume occupied by 1 kg of dry saturated steam.

$\therefore$ Density of dry saturated steam $\rho = \dfrac{1}{v_g}$ kg/m^3

Specific volume of superheated steam : As superheated steam behaves like a perfect gas, its volume can be determined in the same way as the gases.

Let v_g = Specific volume of dry saturated steam in m^3/kg

T_s = Absolute saturation temperature in K

v_u = Specific volume of superheated steam in m^3/kg

T_u = Absolute temperature of superheated steam in K

By Charle's law,

$$\frac{p\,v_g}{T_s} = \frac{p\,v_u}{T_u}$$

$\therefore$ Specific volume of superheated steam $v_u = \dfrac{T_u \times v_g}{T_s}$ m^3/kg

Steam tables

The steam tables provide the properties of 1 kg of dry and saturated steam. The pressures in the steam table are in bar (1 bar = 10^5 N/m^2 = 10^5 Pa) absolute. If gauge pressures are given, they must be converted to absolute pressure by adding atmospheric pressure to them.

i.e., Absolute pressure (bar) = Gauge pressure (bar) + 1.013

The initial temperature of water is taken as 0 °C in the steam table. If the initial temperature of water is other than 0°C, the enthalpy of steam will be calculated from the steam table by deducting the amount of heat contained initially by the water.

External work done during evaporation

When water is evaporated to form wet steam, its volume increases, and thus external work is done by steam due to increase in volume. The energy for doing work is obtained during the absorption of the latent heat. This work is called external work of evaporation.

Let p = Pressure in bar (1 bar = 10^5 N/m^2 = 100 kN/m^2 = 0.1 MN/m^2 = 0.1 MPa)

v_g = Volume of steam in m^3/kg

v_f = Volume of water in m^3/kg

x = Dryness fraction

$\therefore$ External work done $E = 100\,p\,(v_g - v_f)$ kJ/kg ..... (1)

Neglecting v_f being small,

$$E = 100\,p\,v_g \quad \text{kJ/kg} \qquad \text{..... (2)}$$

For wet steam, $E = 100\,p\,x\,v_g$ kJ/kg ..... (3)

The above external work of evaporation is included in the latent heat of steam. Thus, the latent heat actually consists of the true latent heat plus the external work of evaporation. This true latent heat is called *internal latent heat* and may be found by subtracting the external work of evaporation from the total latent heat.

$\therefore$ Internal latent heat $= h_{fg} - 100\,p\,v_g$ kJ/kg ..... (4)

Internal energy of steam

Internal energy is defined as the actual energy stored in the steam. As per the previous articles, the total heat of steam is the sum of sensible heat, internal latent heat and the external work of evaporation. Work of evaporation is not stored in the steam as it is utilised in doing external work. Hence, the internal energy of steam could be found by subtracting work of evaporation from the total heat.

The internal energy U for dry saturated steam is

$$U_s = H_s - 100\,p\,v_g = h_g - 100\,p\,v_g \quad \text{kJ/kg} \qquad \text{..... (1)}$$

For wet steam, the internal energy is

$$U_w = H_w - 100\,p\,x\,v_g = h_f + x\,h_{fg} - 100\,p\,x\,v_g \quad \text{kJ/kg} \qquad \text{..... (2)}$$

and for superheated steam,

$$U_u = H_u - 100\,p\,v_u = h_g + C_p\,(t_u - t_s) - 100\,p\,v_u \quad \text{kJ/kg} \qquad \text{..... (3)}$$

Example 1 : Determine the dryness fraction of steam if 1.8 kg of water is in suspension with 90 kg of dry steam.

Data: $m_f = 1.8$ kg, $m_g = 90$ kg

Solution:

Dryness fraction $$x = \frac{m_g}{m_g + m_f} = \frac{90}{90 + 1.8} = \mathbf{0.9804}$$

Choose the correct answer:

1. The condition of steam in boiler drum is always
   (a) Wet (b) Dry (c) Saturated (d) Super heated
2. Charle's law is
   (a) $p_1v_1=p_2v_2$ if T is constant (b) $p_1/T_1=p_2/T_2$ if v is constant
   (c) $v_1/T_1=v_2/T_2$ if p is constant (d) None of the above
3. Dry saturated steam contains
   (a) Water (b) No water
   (c) Mixture of water and steam (d) None of the above
4. The sum of internal energy and work done is known as
   (a) Wet steam (b) Entropy (c) Super heated steam (d) Enthalpy
5. If x is the mass of dry steam and y is the mass of water in suspension, then dryness fraction is equal to
   (a) $\frac{x}{x+y}$ (b) $\frac{y}{x+y}$ (c) $\frac{x}{x-y}$ (d) $\frac{y}{x-y}$
6. Latent heat of evaporation is defined as
   (a) Amount of heat required to raise the temeperature of 1 kg of water from 0°C to saturation temperature
   (b) Amount of heat required to convert 1 kg of water at saturation temperature into dry saturated steam at the same temperature and pressure
   (c) Amount of heat required to raise the temperature of 1 kg of water from 0°C to saturation temperature and to convert it into dry saturated steam at that temperature
   (d) None of the above
7. The specific volume of water when heated at 0°C
   (a) Increases first and then decreases (b) Decreases first and then increases
   (c) Increases steadily (d) Decreases steadily
8. The latent heat of vaporization at critical point is
   (a) Less than zero (b) Greater than zero (c) Equal to zero (d) Cannot say
9. Volume per kg of wet steam with dryness fraction x is given by
   (a) xv_g (b) x^2v_g (c) $x(v_g - v_f)$ (d) xv_f
10. Actual energy stored in the steam is called
    (a) Internal latent heat (b) Sensible heat
    (c) Internal energy of steam (d) Latent heat of evaporation

12. Enthalpy of superheated steam is
(a) $h_f + x h_{fg}$ (b) h_g (c) $h_f + C_p(T_u - T_s)$ (d) $h_g + C_p(T_u - T_s)$
13. Enthalpy of wet steam is
(a) h_f (b) h_{fg} (c) $h_f + h_{fg}$ (d) $h_f + x h_{fg}$
14. The difference between superheated temperature and the saturation temperature of steam is called
(a) Degree of super heat (b) Latent heat of vaporization
(c) Sensible heat (d) None of these
15. Specific volume of superheated steam is
(a) $= v_g \times \frac{T_s}{T_u}$ (b) $= v_g \times \frac{T_u}{T_s}$ (c) $= v_f \times \frac{T_s}{T_u}$ (d) $= v_f \times \frac{T_u}{T_s}$

Review questions

1. Explain the formation of steam at constant pressure with suitable sketches.
2. Define the following terms:
(i) Sensible heat, (ii) Latent heat, and (iii) Total heat of evaporation.
3. Explain the following terms:
(i) Wet steam, (ii) Dry saturated steam, and (iii) Superheated steam.
4. Define the following :
(i) Dryness fraction, and (ii) Degree of superheat.
5. What is the difference between dry steam and wet steam?
6. List out the advantages of superheated steam.
7. Calculate the enthalpy of steam at a pressure of 30 bar absolute if,
i) Its dryness fraction is 0.75
ii) It is superheated to 400 °C [Ans.: 2353.8 kJ/kg, 3217.7 kJ/kg]

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Volume of 1 kg of wet steam = Volume of dry steam + Volume of water

$$\therefore \quad v_w = x\,v_g + (1-x)\,v_f$$

The value of v_f at low pressures is very small and is generally neglected. Thus in general, the volume of 1 kg of wet steam or the specific volume of wet steam

$$v_w = x\,v_g \text{ m}^3/\text{kg}$$

and density of wet steam $\rho = \dfrac{1}{v_w} = \dfrac{1}{x\,v_g}$ kg/m^3

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i.e., Absolute pressure (bar) = Gauge pressure (bar) + 1.013

The initial temperature of water is taken as 0 °C in the steam table. If the initial temperature of water is other than 0°C, the enthalpy of steam will be calculated from the steam table by deducting the amount of heat contained initially by the water.

External work done during evaporation

When water is evaporated to form wet steam, its volume increases, and thus external work is done by steam due to increase in volume. The energy for doing work is obtained during the absorption of the latent heat. This work is called external work of evaporation.

Let p = Pressure in bar (1 bar $= 10^5\ \text{N/m}^2 = 100\ \text{kN/m}^2 = 0.1\ \text{MN/m}^2 = 0.1$ MPa)

v_g = Volume of steam in m^3/kg

v_f = Volume of water in m^3/kg

x = Dryness fraction

$\therefore$ External work done $E = 100\,p\,(v_g - v_f)$ kJ/kg ..... (1)

Neglecting v_f being small,

$$E = 100\,p\,v_g \quad \text{kJ/kg} \qquad ..... (2)$$

For wet steam, $E = 100\,p\,x\,v_g$ kJ/kg ..... (3)

The above external work of evaporation is included in the latent heat of steam. Thus, the latent heat actually consists of the true latent heat plus the external work of evaporation. This true latent heat is called *internal latent heat* and may be found by subtracting the external work of evaporation from the total latent heat.

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Internal energy is defined as the actual energy stored in the steam. As per the previous articles, the total heat of steam is the sum of sensible heat, internal latent heat and the external work of evaporation. Work of evaporation is not stored in the steam as it is utilized in doing external work. Hence, the internal energy of steam could be found by subtracting work of evaporation from the total heat.

The internal energy U for dry saturated steam is

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For wet steam, the internal energy is

$$U_w = H_w - 100\,p\,x\,v_g = h_f + x\,h_{fg} - 100\,p\,x\,v_g \quad \text{kJ/kg} \qquad ..... (2)$$

and for superheated steam, the internal energy is

$$U_u = H_u - 100\,p\,v_u = h_g + C_p(t_u - t_s) - 100\,p\,v_u \quad \text{kJ/kg} \qquad ..... (3)$$

Example 1 : Determine the dryness fraction of steam if 1.8 kg of water is in suspension with 90 kg of dry steam.

Data: $m_f = 1.8$ kg, $m_g = 90$ kg

Solution:

Dryness fraction $$x = \frac{m_g}{m_g + m_f} = \frac{90}{90 + 1.8} = \mathbf{0.9804}$$

Example 2 : Find the enthalpy of 6 kg of steam at a pressure of 10 bar absolute, if it is

i) Wet with a dryness fraction of 0.9, ii) Dry saturated, and iii) Superheated at a temperature of 200 °C. Assume specific heat as 2.3 kJ/kg K

Data: $m = 6$ kg, $p = 10$ bar, $x = 0.9$, $t_{su} = 200$ °C, $C_p = 2.3$ kJ/kg K

Solution:

From steam tables, at 10 bar absolute pressure, (refer appendix 1), the properties of steam are;

Saturation temperature $t_s = 179.88$ °C

Specific enthalpy of water $h_f = 762.61$ kJ/kg

Specific enthalpy of steam $h_g = 2776.2$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2776.2 - 762.61 = 2013.59$ kJ/kg

[The value of h_{fg} can also be obtained directly from certain steam tables]

i) Enthalpy of 1 kg of wet steam $H_w = h_f + x\,h_{fg} = 762.61 + 0.9 \times 2013.59 = 2574.84$ kJ

$\therefore$ Enthalpy of 6 kg of wet steam $= 6 \times 2574.84 =$ **15449.05 kJ**

ii) Enthalpy of 1 kg of dry saturated steam $H_s = h_f + h_{fg} = h_g = 2776.2$ kJ

$\therefore$ Enthalpy of 6 kg of dry saturated steam $= 6 \times 2776.2 =$ **16657.2 kJ**

iii) Enthalpy of 1 kg of superheated steam

$$H_{su} = h_f + h_{fg} + C_p(t_{su} - t_s) = h_g + C_p(t_{su} - t_s)$$
$$= 2776.2 + 2.3\,(200 - 179.88) = 2822.476 \text{ kJ}$$

$\therefore$ Enthalpy of 6 kg of superheated steam $= 6 \times 2822.476 =$ **16934.86 kJ**

Example 3 : Determine the quantity of heat required to generate 1 kg of steam at a pressure of 7 bar absolute from water at a temperature of 25 °C.

i) When the dryness fraction is 0.88, ii) When the steam is just dry, and

iii) When it is superheated at constant pressure to 270 °C, assuming the mean specific heat of superheated steam to be 2.3 kJ/kg K.

Data: $m = 1$ kg, $p = 7$ bar, $t_i = 25$ °C, $x = 0.88$, $t_{su} = 270$ °C, $C_p = 2.3$ kJ/kg K

Solution:

From steam tables (appendix 1), for 7 bar absolute pressure, properties of steam are;

Saturation temperature $t_s = 164.96$ °C

Specific enthalpy of water $h_f = 697.06$ kJ/kg

Specific enthalpy of steam $h_g = 2762$ kJ/kg

Also from the steam tables (appendix 2),

The amount of heat contained initially by water at 25 °C $h_i = 104.77$ kJ/kg

The initial amount of heat h_i in the unit mass of water can also be calculated by the formula $h_i = C_{pw}\, t_i$, where C_{pw} is the specific heat of water at constant pressure and t_i is the initial temperature of water.

Latent heat of evaporation $h_{fg} = h_g - h_f = 2762 - 697.06 = 2064.94$ kJ/kg

Enthalpy of wet steam $H_w = h_f + x\,h_{fg}$

i.e., Heat required to convert 1 kg of water at 0°C into wet steam

$= 697.06 + 0.88 \times 2064.94 = 2514.21$ kJ/kg

Heat required to convert 1 kg of water at 25 °C into wet steam

$= H_w -$ Heat contained by water initially h_i

$= 2514.2 - 104.77 =$ **2409.44 kJ**

ii) Enthalpy of dry saturated steam $H_s = h_f + h_{fg} = h_g$

$= 2762$ kJ/kg

Heat required to convert 1 kg of water at 25°C into dry saturated steam is

$= H_s -$ Heat contained by water initially h_i

$= 2762 - 104.77 =$ **2657.23 kJ**

iii) Enthalpy of superheated steam $H_u = h_g + C_p(t_u - t_s)$

$= 2762 + 2.3\,(270 - 164.96) = 3003.59$ kJ/kg

Heat required to convert 1kg of water at 25 °C into superheated steam is

$= 3003.59 - 104.77 =$ **2898.8 kJ**

Example 4: What amount of heat be required to produce 4 kg of steam at pressure of 6 bar at 250°C from water at 30°C? The mean specific heat of super heated steam is 2.2 kJ/kg K. Specific heat of water is 4.18 kJ/kg K. The properties of steam at 6 bar are; $h_f = 670.4$ kJ/kg, $h_{fg} = 2085$ kJ/kg and $t_s = 158.8$°C **[VTU, Jan 2009]**

Data: Mass of the steam $m = 4$ kg

Absolute pressure $p = 6$ bar

Super heated temperature $t_u = 250$°C

Initial temperature of water $t_i = 30$°C

Mean specific heat of super heated steam $C_p = 2.2$ kJ / kg K

Specific heat of water $C_{pw} = 4.18$ kJ/kg K

Specific enthalpy of water $h_f = 670.4$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2085$ kJ/kg

Saturation temperature $t_s = 158.8$°C

Solution:

Specific enthalpy of steam $h_g = h_{fg} + h_f$

$= 2085 + 670.4 = 2755.4$ kJ/kg

Enthalpy of super heated steam $H_u = h_g + C_p(t_u - t_s)$

$= 2755.4 + 2.2 \times (250 - 158.8) = 2956.04$ kJ

Initial amount of heat in the water $h_i = C_{pw} \times t_i = 4.18 \times 30 = 125.4$ kJ/kg

Heat required to convert 1 kg of water at 30°C into super heated steam is

$= H_u - h_i = 2956.04 - 125.4 = 2830.64$ kJ/kg

Heat required to convert 4 kg of water at 30° into super heated steam is

$= 4 \times 2830.64 = 11322.56$ kJ

Example 5: Find the enthalpy of 1 kg of steam at 12 bar when the steam is i) 22 % wet, ii) dry saturated and iii) super heated to 250°C. At 12 bar, the steam has the following properties; t_s=188°C, h_f = 798.43 kJ/kg, h_{fg} = 1984.3 kJ/kg, C_p = 2.25 kJ/kgK

[VTU, Jan 2011]

Data: Mass of the steam $m = 1$ kg

Absolute pressure $p = 12$ bar

Wetness fraction $y = 22\% = 0.22$

Super heated temperature $t_u = 250$°C

Saturation temperature $t_s = 188$°C

Specific enthalpy of water $h_f = 798.43$ kJ/kg

Latent heat of evaporation $h_{fg} = 1984.3$ kJ/kg

Specific heat of super heated steam $C_p = 2.25$ kJ/kg K

Solution:

i) Dryness fraction $x = 1 - y = 1 - 0.22 = 0.78$

Enthalpy of 1 kg of wet steam $H_w = h_f + x\,h_{fg}$

$= 798.43 + 0.78 \times 1984.3 = 2346.184$ kJ

ii) Enthalpy of 1 kg of dry saturated steam $H_s = h_f + h_{fg}$

$= 798.43 + 1984.3 = 2782.73$ kJ

iii) Enthalpy of 1 kg of super heated steam $H_u = h_f + h_{fg} + C_p(t_u - t_s)$

$= 798.43 + 1984.3 + 2.25 \times (250 - 188)$

$= 2922.23$ kJ

Example 6: Determine the total heat content per unit mass at the following state using the steam tables. Assume $C_p = 2.0934$ kJ/kg K. i) 10 bar absolute and 300°C, ii) 100 kPa gauge and 250°C, iii) Dry steam at 100 kPa absolute, iv) Steam at 12 bar absolute and 95% dry.

[VTU, Jan 2014]

Solution:

i) Absolute pressure $p = 10$ bar

Super heated temperature $t_u = 300$°C

From steam table, for 10 bar pressure (appendix-1)

Saturation temperature $t_s = 179.88$°C

Specific enthalpy of steam $h_g = 2776.2$ kJ/kg

Enthalpy of 1 kg of super heated steam $H_u = h_g + C_p(t_u - t_s)$

$= 2776.2 + 2.0934 \times (300 - 179.88) = 3027.66$ kJ

ii) Gauge pressure = 100 kPa = 100×10^3 Pa = 1×10^5 Pa = 1 bar (Gauge)

Super heated temperature $t_u = 250$°C

Absolute pressure (bar) = Gauge pressure (bar) + 1.013 = 1 + 1.013 = 2.013 bar

From steam table, for 2.013 bar pressure, the approximate steam properties are;

Saturation temperature $t_s = 120.23$°C

Specific enthalpy of steam $h_g = 2706.3$ kJ/kg

Enthalpy of 1 kg of super heated steam $H_u = h_g + C_p(t_u - t_s)$

$= 2706.3 + 2.0934 \times (250 - 120.23) = 2977.96$ kJ

iii) Dry steam at absolute pressure $p = 100$ kPa = 10^5 Pa = 1 bar

From steam table for 1 bar absolute pressure;

Specific enthalpy of steam $h_g = 2675.4$ kJ/kg

Enthalpy of 1 kg of dry saturated steam $H_s = h_g = 2675.4$ kJ

iv) Absolute pressure $p = 12$ bar

Dryness fraction $x = 0.95$

From steam table, for 12 bar absolute pressure,

Saturation temperature $t_s = 187.96$°C

Specific enthalpy of water $h_f = 798.43$ kJ/kg

Specific enthalpy of steam $h_g = 2782.7$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2782.7 - 798.43 = 1984.27$ kJ/kg

Enthalpy of 1 kg of wet steam $H_w = h_f + x\, h_{fg} = 798.43 + 0.95 \times 1984.27$

$= 2683.487$ kJ

Example 7 : Determine the heat required to produce 6 kg of dry saturated steam at 6 bar absolute pressure from water at 30°C. The specific heat of water is 4.18 kJ/kg K.

Data: $m = 6$ kg, $p = 6$ bar, $t_i = 30°C$, $C_{pw} = 4.18$ kJ/kg K

Solution :

From steam table, corresponding to a pressure of 6 bar (refer appendix 1).

Saturation temperature $t_s = 158.84°C$

Specific enthalpy of water $h_f = 670.42$ kJ/kg

Specific enthalpy of steam $h_g = 2755.5$ kJ/kg

Amount of heat initially contained in the water at 30°C, $h_i = C_{pw}\, t_i$

$$= 4.18 \times 30 = 125.4 \text{ kJ/kg}$$

or from table (appendix 2), the heat contained by the water at 30°C, $h_i = 125.66$ kJ/kg

Heat required to convert 1 kg of water at 0°C in to dry saturated steam

$$h_g = 2755.5 \text{ kJ/kg}$$

Heat required to convert 1 kg of water at 30°C in to saturated steam $= h_g - h_i$

$$= 2755.5 - 125.4 = 2630.1 \text{ kJ/kg}$$

∴ Heat required to produce 6 kg of dry saturated steam

$$= 6 \times 2630.1 = \mathbf{15780.6\ kJ}$$

Example 8 : What is the enthalpy of 5 kg steam under the following conditions? (i) 0.8 bar absolute pressure and 90% dry. (ii) 20 bar absolute pressure at 300°C.

Take the specific heat of superheated steam as 2.25 kJ/kg K. **[VTU, Jan 2004]**

Solution:

i) $m = 5$ kg, $p = 0.8$ bar, $x = 90\% = 0.9$

From steam table, at pressure of 0.8 bar absolute (refer appendix 1),

Saturation temperature $t_s = 93.512°C$

Specific enthalpy of water $h_f = 391.72$ kJ/kg

Specific enthalpy of steam $h_g = 2665.8$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2665.8 - 391.72 = 2274.08$ kJ/kg

Enthalpy of 1 kg of wet steam $H_w = h_f + x\, h_{fg}$

$$= 391.72 + 0.9 \times 2274.08 = 2438.392 \text{ kJ/kg}$$

Enthalpy of 5 kg of wet steam $= 5 \times 2438.392 = \mathbf{12191.96\ kJ}$

ii) $m = 5$ kg, $p = 20$ bar, $t = 300°C$, $C_p = 2.25$ kJ/kg K

From steam table, at pressure of 20 bar absolute (refer appendix 1),

Saturation temperature $t_s = 212.37°C$

Specific enthalpy of water $h_f = 908.54$ kJ/kg

Specific enthalpy of steam $h_g = 2797.2$ kJ/kg

Since the given steam temperature is greater than the saturation temperature, the steam is superheated i.e., $t_s = 300$°C

Enthalpy of 1 kg of superheated steam $H_s = h_g + C_p(t_s - t_s)$ kJ/kg

$$= 2797.2 + 2.25\,(300 - 212.37) = 2994.37 \text{ kJ/kg}$$

$\therefore$ Enthalpy of 5 kg of super heated steam $= 5 \times 2994.37 =$ **14971.85 kJ**

Example 9 : Steam is at 9 bar pressure absolute and dryness fraction of 0.98. Find the quality and temperature of the steam when: (i) The steam loose 50 kJ/kg at constant pressure (ii) The steam receives 150 kJ/kg at constant pressure. **[VTU, July 2005]**

Data: $p = 9$ bar, $x = 0.98$, $h_r = 50$ kJ/kg, $h_a = 150$ kJ/kg

Solution: From steam table, at 9 bar absolute pressure (refer appendix 1),

Saturation temperature $t_s = 175.36$°C

Specific enthalpy of water $h_f = 742.64$ kJ/kg

Specific enthalpy of steam $h_g = 2772.1$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2772.1 - 742.64 = 2029.46$ kJ/kg

Enthalpy of the given wet steam $H_w = h_f + x\,h_{fg}$

$$= 742.64 + 0.98 \times 2029.46 = 2731.51 \text{ kJ/kg}$$

i) Enthalpy after the rejection of 50 kJ/kg $= 2731.51 - 50$

$$H_w = 2681.51 \text{ kJ/kg}$$

Since this heat is less than the specific enthalpy of steam h_g, the steam is wet.

$\therefore$ $H_w = h_f + x\,h_{fg}$

i.e., $2681.51 = 742.64 + x \times 2029.46$

$\therefore$ Dryness fraction $x =$ **0.9554**

The temperature of steam $t = t_s =$ **175.36°C**

ii) Enthalpy after the addition of 150 kJ/kg $= 2731.51 + 150 = 2881.51$ kJ/kg

This heat is greater than the specific enthalpy of steam h_g, hence the steam is superheated.

$\therefore$ $H_s = h_g + C_p(t_s - t_s)$

i.e., $2881.51 = 2772.1 + 2.3\,(t_s - 175.36)$ (Take $C_p = 2.3$ kJ/kg K)

$\therefore$ Temperature of superheated steam $t_s =$ **233.99°C**

Example 10 : 2 kg of wet steam is heated at a constant pressure of 2 bar until its temperature increases to 150°C. The heat transferred is 2100 kJ. Find the initial dryness fraction of steam. Take the specific heat of steam as 2.1 kJ/kg K. The properties of steam at 2 bar pressure are given below. **[VTU, Jan 2006]**

p(bar)	t_s(°C)	v_f(m³/kg)	v_g(m³/kg)	h_f(kJ/kg)	h_g(kj/kg)
2	120.23	0.001061	0.8857	504.5	2706.5

Data: $m=2$ kg, $p=2$ bar, $t_u=150$°C, $h_u=2100$ kJ, $C_p=2.1$ kJ/kg K

Solution:

Latent heat of evaporation $h_{fg}=h_g-h_f=2706.5-504.5=2202$ kJ/kg

Enthalpy of 1 kg of superheated steam $H_u=h_g+C_p(t_u-t_s)$

$$= 2706.5+2.1\,(150-120.23)=2769.017 \text{ kJ/kg}$$

Heat transferred per kg $h_a=\dfrac{2100}{2}=1050$ kJ/kg

$\therefore$ Initial enthalpy of steam $=H_u-h_a=2769.017-1050=1719.017$ kJ/kg

This heat is less than the specific enthalpy of steam h_g.

Hence the steam is wet

Also, $\quad H_w = h_f+x\,h_{fg}$

i.e., $\quad 1719.017 = 504.5+x\times 2202$

$\therefore$ Dryness fraction $x =$ **0.55155**

Example 11 : Steam at a pressure of 8 bar has a temperature 200°C. What is its specific enthalpy? What is its specific volume? Assume the specific heat of steam to be 2.25 kJ/kg K. The properties of steam at 8 bar pressure are given below. **[VTU, July 2006]**

p(bar)	t_s(°C)	v_f(m³/kg)	v_g(m³/kg)	h_f(kJ/kg)	h_{fg}(kJ/kg)	h_g(kJ/kg)
8.0	170.4	0.001115	0.24026	720.9	2046.5	2767.4

Data: $p=8$ bar, $t_u=200$°C, $T_u=273+200=473$ K, $t_s=170.4$°C, $T_s=273+170.4=443.4$ K, $C_p=2.25$ kJ/kg K, $v_g=0.24026$ m³/kg, $h_g=2767.4$ kJ/kg

Solution:

Since the saturation temperature 170.4°C is less than the given steam temperature of 200°C, the steam is super heated.

Enthalpy of superheated steam $H_u=h_g+C_p(t_u-t_s)$

$$= 2767.4+2.25\,(200-170.4)= \mathbf{2834\ kJ/kg}$$

Specific volume of super heated steam $v_u=\dfrac{T_u}{T_s}\times v_g$ m³/kg

$$= \frac{473}{443.4}\times 0.24026= \mathbf{0.25623\ m^3/kg}$$

Example 12 : Find the total enthalphy of 0.6 kg of steam with an initial dryness fraction of 0.7 is heated at constant pressure of 7 bar till its temperature rises to 250°C. From steam table, at 7 bar; $h_f = 679.1$ kJ/kg, $h_{fg} = 2064.9$ kJ/kg, $t_s = 165$°C, $C_p = 2.25$ kJ/kg K.

[VTU, Jan 2013]

Data: $m = 0.6$ kg, $x = 0.7$, $p = 7$ bar, $t_u = 250$°C, $h_f = 679.1$ kJ/kg, $h_{fg} = 2064.9$ kJ/kg, $t_s = 165$°C, $C_p = 2.25$ kJ/kg K

Solution:

Since the temperature of steam t_u (250°C) is greater than the saturation temperature t_s (165°C), the steam is superheated steam.

Enthalpy of 1 kg of superheated steam $H_u = h_f + h_{fg} + C_p(t_u - t_s)$ kJ/kg

$= 679.1 + 2064.9 + 2.25\,(250 - 165) = 2935.25$ kJ/kg

$\therefore$ Enthalpy of 0.6 kg of superheated steam $= 0.6 \times 2935.25 = 1761.15$ kJ

Example 13 : Find the specific volume, enthalpy and internal energy of steam at a pressure of 10 bar absolute and 0.92 dry.

Data: $p = 10$ bar, $x = 0.92$

Solution:

From steam tables (appendix 1), at 10 bar absolute pressure,

Saturation temperature $t_s = 179.88$ °C

Specific volume of steam $v_g = 0.1943$ m³/kg

Specific enthalpy of water $h_f = 762.61$ kJ/kg

Specific enthalpy of steam $h_g = 2776.2$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2776.2 - 762.61 = 2013.59$ kJ/kg

Enthalpy of wet steam $H_w = h_f + x\,h_{fg}$

$= 762.61 + 0.92 \times 2013.59 =$ **2615.1 kJ/kg**

Specific volume of wet steam $v_w = x\,v_g$

$= 0.92 \times 0.1943 =$ **0.1788 m³/kg**

Internal energy of wet steam $U_w = H_w - 100\,p\,x\,v_g$

$= 2615.1 - 100 \times 10 \times 0.92 \times 0.1943 =$ **2436.3 kJ/kg**

Example 14: Determine the dryness fraction, specific volume, and internal energy of steam at 8 bar absolute pressure, if its enthalpy is 2400 kJ/kg.

Data: $p = 8$ bar, $H_w = 2400$ kJ/kg

Solution:

From steam tables, at 8 bar absolute pressure, the properties of steam are;

Saturation temperature $t_s = 170.41$ °C

Specific volume of steam $v_g = 0.2403\ m^3/kg$

Specific enthalpy of water $h_f = 720.94\ kJ/kg$

Specific enthalpy of steam $h_g = 2767.5\ kJ/kg$

Latent heat of evaporation $h_{fg} = h_g - h_f = 2767.5 - 720.94 = 2046.56\ kJ/kg$

Enthalpy of wet steam $H_w = h_f + x\,h_{fg}$

i.e., $2400 = 720.94 + 2046.56\,x$

$\therefore$ Dryness fraction $x = \mathbf{0.82}$

Specific volume of wet steam $v_w = x\,v_g$

$= 0.82 \times 0.2403 = \mathbf{0.19705\ m^3/kg}$

Internal energy of wet steam $U_w = H_w - 100\,p\,x\,v_g$

$= 2400 - 100 \times 8 \times 0.82 \times 0.2403 = \mathbf{2242.36\ kJ/kg}$

Example 15 : Determine the density of 1 kg of steam initially at a pressure of 5 bar absolute, having a dryness fraction of 0.78. If 100 kJ are added at constant pressure, determine the condition, density, and enthalpy for the final state.

Data: $m = 1$ kg, $p = 5$ bar, $x = 0.78$, heat addition $h_a = 100$ kJ

Solution:

From steam tables, at a pressure of 5 bar absolute, (refer appendix 1)

Saturation temperature $t_s = 151.84\,°C$

Specific volume of steam $v_g = 0.3747\ m^3/kg$

Specific enthalpy of water $h_f = 640.12\ kJ/kg$

Specific enthalpy of steam $h_g = 2747.5\ kJ/kg$

Latent heat of evaporation $h_{fg} = h_g - h_f = 2747.5 - 640.12 = 2107.38\ kJ/kg$

Specific volume of wet steam $v_w = x\,v_g$

$= 0.78 \times 0.3747 = 0.29227\ m^3/kg$

Density of wet steam $\rho = \dfrac{1}{x\,v_g} = \dfrac{1}{0.29227} = \mathbf{3.42\ kg/m^3}$

Enthalpy of wet steam $H_w = h_f + x\,h_{fg}$

$= 640.12 + 0.78 \times 2107.38 = 2283.88\ kJ/kg$

Enthalpy of wet steam after adding 100 kJ

$= 2283.88 + 100 = \mathbf{2383.88\ kJ/kg}$

This heat is less than h_g. Again the steam is wet.

$\therefore$ $H_w = h_f + x\,h_{fg}$

i.e., $2383.88 = 640.12 + 2107.38\,x$

$\therefore$ Dryness fraction $\quad x = \mathbf{0.827}$

Density of wet steam $\quad \rho = \dfrac{1}{x\,v_g} = \dfrac{1}{0.827 \times 0.3747} = \mathbf{3.227\ kg/m^3}$

Example 16 : Find the temperature, enthalpy, and internal energy of superheated steam at a pressure of 20 bar absolute of specific volume 0.125 m^3/kg. Take specific heat of steam as 2.3 kJ/kg K.

Data: $p = 20$ bar, $v_u = 0.125\ m^3/kg$, $C_p = 2.3$ kJ/kg K

Solution:

From steam tables, at pressure of 20 bar,

Saturation temperature $\quad t_s = 212.37\,°C$

Specific volume of steam $\quad v_g = 0.09954\ m^3/kg$

Specific enthalpy of steam $\quad h_g = 2797.2$ kJ/kg

Absolute temperature of saturated steam $T_s = 212.37 + 273 = 485.37$ K

Absolute temperature of superheated steam $T_u = \dfrac{v_u}{v_g} \times T_s$

$$= \frac{0.125}{0.09954} \times 485.37 = \mathbf{609.52\ K}$$

Enthalpy of superheated steam $H_u = h_g + C_p\,(T_u - T_s)$

$$= 2797.2 + 2.3\,(609.52 - 485.37) = \mathbf{3082.745\ kJ/kg}$$

Internal energy of super heated steam $U_u = H_u - 100\,p\,v_u$

$$= 3082.745 - 100 \times 20 \times 0.125 = \mathbf{2832.745\ kJ/kg}$$

Example 17 : One kg of steam at 7 bar occupies a volume of 0.24 m^3. Determine the condition, enthalpy, and internal energy of the contents.

Data: $m = 1$ kg, $p = 7$ bar, $v = 0.24\ m^3$

Solution:

From steam tables, at pressure of 7 bar absolute, (refer appendix 1)

Saturation temperature $\quad t_s = 164.96\,°C$

Specific volume of steam $\quad v_g = 0.2727\ m^3/kg$

Specific enthalpy of water $\quad h_f = 697.06$ kJ/kg

Specific enthalpy of steam $\quad h_g = 2762$ kJ/kg

As the given specific volume of 0.24 m^3 is less than the specific volume of dry saturated steam of 0.2727 m^3/kg, the steam should be wet.

Latent heat of evaporation $\quad h_{fg} = h_g - h_f = 2762 - 697.06 = 2064.94$ kJ/kg

Specific volume of wet steam $v_w = x\,v_g$

i.e., $0.24 = 0.2727x$

$\therefore$ Dryness fraction $x = \mathbf{0.88}$

Enthalpy of wet steam $H_w = h_f + x h_{fg}$

$= 697.06 + 0.88 \times 2064.94 = \mathbf{2514.2\ kJ/kg}$

Internal energy of wet steam $U_w = H_w - 100\,p\,x\,v_g$

$= 2514.2 - 100 \times 7 \times 0.88 \times 0.2727 = \mathbf{2346.2\ kJ/kg}$

Example 18 : Determine the conditions of steam from the following data:

(a) Pressure is 10 bar absolute and temperature 200 °C,

(b) Pressure is 8 bar absolute and specific volume of 0.22 m^3/kg, and

(c) Pressure is 12 bar absolute and enthalpy of 2600 kJ/kg

Solution:

(a) $p = 10$ bar, $t = 200$ °C

From steam tables, at pressure of 10 bar absolute,

Saturation temperature $t_s = 179.88$ °C

Since the saturation temperature 179.88 °C is less than given steam temperature of 200 °C, the steam is superheated.

$\therefore$ Degree of superheat $= t - t_s = 200 - 179.88$

$= \mathbf{20.12\ °C}$

(b) $p = 8$ bar, $v = 0.22$ m^3/kg

From steam tables, at pressure of 8 bar absolute,

Specific volume of steam $v_g = 0.2403$ m^3/kg

Since the value of v_g is greater than the given volume of steam, the steam is wet.

$\therefore$ Dryness fraction $x = \dfrac{v}{v_g} = \dfrac{0.22}{0.2403} = \mathbf{0.9155}$

(c) $p = 12$ bar, $H = 2600$ kJ/kg

From steam tables, at pressure of 12 bar absolute,

Specific enthalpy of water $h_f = 798.43$ kJ/kg

Specific enthalpy of steam $h_g = 2782.7$ kJ/kg

Since the value of specific enthalpy of steam h_g is greater than the given enthalpy of 2600 kJ/kg, the steam is wet

Latent heat of evaporation $h_{fg} = h_g - h_f$

$= 2782.7 - 798.43 = 1984.27$ kJ/kg

Enthalpy of wet steam $H_w = h_f + x h_{fg}$

i.e., $2600 = 798.43 + 1984.27\,x$

$\therefore$ Dryness fraction $x = \mathbf{0.908}$

Example 19 : Steam at a pressure of 0.8 MPa absolute and dryness fraction of 0.8, calculate,

(a) External work done during evaporation

(b) Internal latent heat of steam.

Data: $x = 0.8,\ p = 0.8\,\text{MPa} = 0.8 \times 10^6\,\text{Pa} = 8\,\text{bar} \quad (\because 1 \times 10^5\,\text{Pa} = 1\,\text{bar})$

Solution:

From steam tables, corresponding to a pressure of 8 bar absolute, (refer appendix 1)

Specific volume of steam $v_g = 0.2403\,\text{m}^3/\text{kg}$

Specific enthalpy of water $h_f = 720.94\,\text{kJ/kg}$

Specific enthalpy of steam $h_g = 2767.5\,\text{kJ/kg}$

Latent heat of evaporation $h_{fg} = h_g - h_f$

$= 2767.5 - 720.94 = 2046.56\,\text{kJ/kg}$

(a) External work done during evaporation $E = 100\,p\,x\,v_g$ (neglecting v_f)

$= 100 \times 8 \times 0.8 \times 0.2403 = \mathbf{153.792\ kJ/kg}$

(b) Internal latent heat of steam $= x\,h_{fg} - 100\,p\,x\,v_g$

$= 0.8 \times 2046.56 - 153.792 = \mathbf{1483.456\ kJ/kg}$

Example 20 : One kilogram of superheated steam at 15 bar pressure contains 2900 kJ of heat energy. Find the temperature of superheated steam. The specific heat of superheated steam is 2.3 kJ/kg K.

Data: $p = 15\,\text{bar},\ H_u = 2900\,\text{kJ/kg},\ C_p = 2.3\,\text{kJ/kg K}$

Solution:

From steam tables, corresponding to a pressure of 15 bar absolute,

Saturation temperature $t_s = 198.29\,^\circ\text{C}$

Specific enthalpy of steam $h_g = 2789.9\,\text{kJ/kg}$

Enthalpy of superheated steam $H_u = h_g + C_p(t_u - t_s)$

i.e., $2900 = 2789.9 + 2.3\,(t_u - 198.29)$

$\therefore$ Temperature of superheated steam $t_u = \mathbf{246.159\,^\circ C}$

Example 21 : Find the specific volume and density of steam when its pressure is 0.6 MPa absolute when the condition of steam is (i) Wet having dryness fraction 0.8. (ii) dry and (iii) Superheated to 250°C.

Solution:

i) *Wet steam*

$p = 0.6\text{ MPa} = 0.6 \times 10^6\text{ Pa} = 6\text{ bar},\ x = 0.8,\ t_u = 250^\circ\text{C}$

From steam table, at pressure of 6 bar absolute (refer appendix 1),

Saturation temperature $t_s = 158.84^\circ\text{C}$

Specific volume of water $v_f = 0.0011009\ m^3/\text{kg}$

Specific volume of steam $v_g = 0.3155\ m^3/\text{kg}$

Specific volume of wet steam $v_w = x\,v_g + (1-x)\ v_f \simeq x\,v_g$

$$= 0.8 \times 0.3155 + (1-0.8) \times 0.0011009 = \mathbf{0.25262\ m^3/kg}$$

Density of wet steam $\rho = \dfrac{1}{v_w} = \dfrac{1}{0.25262} = \mathbf{3.9585\ kg/m^3}$

ii) *Dry saturated steam*

From steam table, the specific volume of dry saturated steam $v_g = \mathbf{0.3155\ m^3/kg}$

Density of dry saturated steam $\rho = \dfrac{1}{v_g} = \dfrac{1}{0.3155} = \mathbf{3.1696\ kg/m^3}$

iii) *Superheated steam*

Absolute temperature of saturated steam $T_s = 158.84 + 273 = 431.84\text{ K}$

Absolute temperature of superheated steam $T_u = 250 + 273 = 523\text{ K}$

Specific volume of superheated steam $v_u = \dfrac{T_u}{T_s} \times v_g$

$$= \frac{523}{431.84} \times 0.3155 = \mathbf{0.3821\ m^3/kg}$$

Density of superheated steam $\rho = \dfrac{1}{v_u} = \dfrac{1}{0.3821} = \mathbf{2.6171\ kg/m^3}$

Example 22: Determine the specific volume and density of 1 kg of steam at 7 bar, when the condition of steam is; i) Wet having dryness fraction of 0.9, ii) Dry, iii) Super heated to 250°C. For 7 bar pressure, $T_s = 437.96$ K, $v_f = 0.0011\ \text{m}^3/\text{kg}$ and $v_g = 0.2727\ \text{m}^3/\text{kg}$
[VTU, Jan 2015]

Data: Mass of steam $m = 1$ kg

Absolute pressure $p = 7$ bar

Absolute temperature of saturated steam $T_s = 437.96$ K

Specific volume of water $v_f = 0.0011\ \text{m}^3/\text{kg}$

Specific volume of steam $v_g = 0.2727\ \text{m}^3/\text{kg}$

Solution:

i) Dryness fraction $x = 0.9$

Specific volume of wet steam $v_w = x\,v_g + (1-x)\,v_f$

Neglecting v_f being small, $v_w = x\,v_g = 0.9 \times 0.2727 = 0.24543\ \text{m}^3/\text{kg}$

Density of wet steam $\rho = \dfrac{1}{v_w} = \dfrac{1}{0.24543} = 4.0745\ \text{kg/m}^3$

ii) Specific volume of dry saturated steam $v_g = 0.2727\ \text{m}^3/\text{kg}$

Density of dry saturated steam $\rho = \dfrac{1}{v_g} = \dfrac{1}{0.2727} = 3.667\ \text{kg/m}^3$

iii) Absolute temperature of super heated steam $T_u = 250 + 273 = 523\ \text{K}$

Specific volume of super heated steam $v_u = \dfrac{T_u}{T_s} \times v_g$

$$= \frac{523}{437.96} \times 0.2727 = 0.32565\ \text{m}^3/\text{kg}$$

Density of super heated steam $\rho = \dfrac{1}{v_u} = \dfrac{1}{0.32565} = 3.0708\ \text{kg/m}^3$

Example 23: A tank contain 80 kg of water and 4 kg of water vapour under saturation conditions at 20°C. Calculate the volume of tank and the wetness fraction of the mixture.

Data: Mass of water $m_f = 80\ \text{kg}$

Mass of vapour $m_g = 4\ \text{kg}$

Saturation temperature $t_s = 20^\circ\text{C}$

Solution:

From steam table for saturation temperature $t_s = 20^\circ\text{C}$

Specific volume of water $v_f = 0.0010017\ \text{m}^3/\text{kg}$

Specific volume of steam $v_g = 57.84\ \text{m}^3/\text{kg}$

Volume of water $V_f = m_f v_f = 80 \times 0.0010017 = 0.080136\ \text{m}^3$

Volume of vapour $V_g = m_g v_g = 4 \times 57.84 = 231.36\ \text{m}^3$

Total volume $V = V_f + V_g = 0.080136 + 231.36 = 231.44\ \text{m}^3$

Wetness fraction $x = \dfrac{m_f}{m_f + m_g} = \dfrac{80}{80+4} = 0.952 = 95.2\%$

Example 24 : Determine the specific volume and density of 1 kg of steam at 7×10^5 Pa when the condition of steam is i) Wet, having dryness fraction 0.9 ii) Dry, iii) Super heated to 250°C. Use the extract of the steam table.

Absolute pressure P (bar)	Temperature T_s (K)	Specific volume of steam v_g (m^3/kg)
7	437.92	0.273341

[VTU, July 2009]

Solution:

i) *Wet steam:*

$P = 7\times10^5\,Pa = 7\,bar,\quad x=0.9,\quad T_s = 437.92\,K,\quad v_g = 0.273341\,m^3/kg$

Specific volume of wet steam $v_w = x\,v_g$

$$= 0.9\times0.273341 = \mathbf{0.246007\,m^3/kg}$$

Density of wet steam $\rho = \dfrac{1}{v_w} = \dfrac{1}{0.246007} = \mathbf{4.065\,kg/m^3}$

ii) *Dry steam:*

Specific volume of dry saturated steam $v_g = \mathbf{0.273341\,m^3/kg}$

Density of dry steam $\rho = \dfrac{1}{v_g} = \dfrac{1}{0.273341} = \mathbf{3.658\,kg/m^3}$

iii) *Super heated steam:*

Absolute temperature of super heated steam $T_u = 250+273 = 523\,K$

Absolute temperature of saturated steam $T_s = 437.92\,K$

Specific volume of superheated steam $v_u = \dfrac{T_u}{T_s}\times v_g$

$$= \frac{523}{437.92}\times0.273341 = \mathbf{0.32645\,m^3/kg}$$

Density of super heated steam $\rho = \dfrac{1}{v_u} = \dfrac{1}{0.32645} = \mathbf{3.0633\,kg/m^3}$

Example 25 : Determine the density of 1 kg of steam initially at a pressure of 10 bar absolute having a dryness fraction of 0.78. If 500 kJ are added at constant pressure, determine the condition and internal energy for the final state of steam. Take the specific heat of superheated steam as 2.1 kJ/kg K. **[VTU, Jan 2003]**

Data: $m=1\,kg,\ p=10\,bar,\ x=0.78,\ C_p=2.1\,kJ/kg\,K$

Solution:

Heat addition $h_a = 500\,kJ$

From steam tables, at pressure of 10 bar absolute, (refer appendix 1)

Saturation temperature $t_s = 179.88°C$

Specific volume of steam $v_g = 0.1943\,m^3/kg$

Specific enthalpy of water $h_f = 762.61$ kJ/kg

Specific enthalpy of steam $h_g = 2776.2$ kJ/kg

Latent heat of evaporation $h_{fg} = h_g - h_f = 2776.2 - 762.61 = 2013.59$ kJ/kg

Specific volume of wet steam $v_w = x\,v_g = 0.78 \times 0.1943 = 0.151554\ \text{m}^3/\text{kg}$

$$\text{Density of wet steam } \rho = \frac{1}{x\,v_g} = \frac{1}{v_w} = \frac{1}{0.151554} = \mathbf{6.598\ kg/m^3}$$

Enthalpy of wet steam $H_w = h_f + x\,h_{fg} = 762.61 + 0.78 \times 2013.59 = 2333.21$ kJ/kg

Enthalpy of steam after adding 500 kJ is,

$$H = 2333.21 + 500 = 2833.21\ \text{kJ/kg}$$

This heat is greater than h_g, hence the steam is superheated.

Enthalpy of superheated steam $H_u = h_g + C_p(t_u - t_s)$ kJ/kg

i.e., $\quad 2833.21 = 2776.2 + 2.1 \times (t_u - 179.88)$

$\therefore$ Temperature of superheated steam $t_u = 207.03^\circ$C

By Charle's law, $\dfrac{p\,v_g}{T_s} = \dfrac{p\,v_u}{T_u}$

$$\text{Specific volume of super heated steam } v_u = \frac{T_u}{T_s} \times v_g = \frac{(207.03 + 273)}{(179.88 + 273)} \times 0.1943$$

$$= 0.2059\ \text{m}^3/\text{kg}$$

Internal energy of super heated steam is

$$U = h_g + C_p(t_u - t_s) - 100\,P\,v_u$$

$$= 2776.2 + 2.1\,(207.03 - 179.88) - 100 \times 10 \times 0.2059$$

$$= \mathbf{2627.315\ kJ/kg}$$

Review questions

1. Explain the formation of steam at constant pressure with suitable sketches.
2. Define the following terms: (i) Sensible heat, (ii) Latent heat, and (iii) Total heat of evaporation.
3. Explain the following terms: (i) Wet steam, (ii) Dry saturated steam, and (iii) Superheated steam.
4. Define the following : (i) Dryness fraction, and (ii) Degree of superheat.
5. What is the difference between dry steam and wet steam?
6. List out the advantages of superheated steam.
7. Define the following terms: i) Specific volume, ii) Latent heat, iii) Dryness fraction and iv) Degree of super heat.
8. With the help of temperature enthalpy diagram, explain the mechanism of formation of steam.

9. Calculate the enthalpy of steam at a pressure of 30 bar absolute if, i) Its dryness fraction is 0.75, ii) It is superheated to 400 °C [Ans.: 2353.8 kJ/kg, 3217.7 kJ/kg]
10. Determine the enthalpy and internal energy of 1 kg of steam at i) 13 bar and saturated ii) 80 °C and saturated. [Ans.: 2785.4 kJ/kg, 2589 kJ/kg, 2643.8 kJ/kg, 2482.35 kJ/kg]
11. Calculate the specific volume of steam at 250 °C and dryness fraction of 0.8. [Ans.: 0.04003 m³/kg]
12. Determine the density of steam initially at 17 bar having a dryness fraction of 0.8. If 300 kJ/kg of heat is supplied at constant pressure, determine the condition, density and enthalpy. [Ans.: 10.72 kg/m³, 0.956 dry, 8.97 kg/m³, 2709.08 kJ/kg]
13. Determine the external work done during evaporation of water at 25 bar absolute pressure into steam of dryness fraction 0.84. [Ans.: 167.81 kJ/kg]
14. For a sample of steam at a pressure of 8 bar absolute and 0.9 dry, calculate, (i) External work of evaporation, and (ii) Internal latent heat. [Ans.: 173 kJ/kg, 1668.9 kJ/kg]
15. State the conditions of steam from the following data. i) Pressure of 10 bar and total heat is 2700 kJ/kg, ii) Pressure of 8 bar and total heat is 2800 kJ/kg, iii) Pressure of 6 bar and temperature is 180 °C, iv) Pressure of 4 bar and temperature is 143.62 °C [Ans.: wet, superheated, superheated, dry]
16. Define and explain the following : i) Dryness fraction, ii) Specific volume, iii) Enthalpy of superheated steam, iv) Internal energy (VTU, Jan 2003)
17. Find the enthalpy of 1 kg steam at 12 bar when steam is i) Dry saturated, ii) 22% wet iii) Super heated to 250°C. Take $C_p = 2.25$ kJ/kg K (VTU, July 2003)
[Hint: $x = 1 - 0.22 = 0.78$] [Ans.: 2782.7 kJ/kg, 2346.16 kJ/kg, 2922.29 kJ/kg]
18. Find the enthalpy of 0.5 kg steam at a pressure of 10 bar absolute for the following conditions. (i) It is 1.5% wet, (ii) It is dry saturated and (iii) It is at a temperature of 200°C. Assume the specific heat as 2.3 kJ/kg K. (VTU, Jan 2007)
[Ans.: 1373 kJ, 1388.1 kJ, 1411.24 kJ]
19. Find the internal energy of 3 kg of steam at 10 bar pressure having a dryness fraction of 0.85. (VTU, Jan 2008)
[Ans: 8871.675 kJ]
20. Find the enthalpy of 1 kg of steam at 10 bar absolute, when the steam is; i) Dry saturated, ii) 20% wet, iii) Super heated to 220°C. Assume the specific heat of super heated steam as 2.25 kJ/kg K. At 10 bar, the properties of steam are; $t_s = 180$°C, $h_f = 762$ kJ/kg, $h_g = 2792$ kJ/kg. [VTU, Jan 2010]
21. Determine the specific volume and density of 1 kg of steam at a pressure of 7×10^5 Pa when the condition of steam is; i) Wet having dryness fraction of 0.9, ii) Dry and iii) Super heated to 250°C. The saturation temperature is 437.92 K and the specific volume of steam $v_g = 0.273341$ m³/kg. [VTU, July 2009]