Unit – 1

STEAM FORMATION AND PROPERTIES:

Introduction: - All the substance under suitable conditions of temperature and pressure can exist in one of the three states via solid, liquid or gas. But water is one of the pure substance that exists in all the three phases namely in solid phase as ice, liquid phase as water and gaseous phases as vapour (steam).

Most of the practical problems in thermal engineering are concerned with liquid and gaseous phase rather than the solid phase. Water, which is liquid at normal temperature begins to boil to form steam when heat sufficiently. In practice, steam is generated in steam generators or popularly known as BOILERS.

Definition of Steam: Steam can be defined as it is a mixture of water and air or it can also be defined as vapour of water.

The important properties of steam are

1. Pressure
2. Temperature
3. Specific volume
4. Enthalpy
5. Internal energy
6. Entropy

Formation of steam at constant pressure:

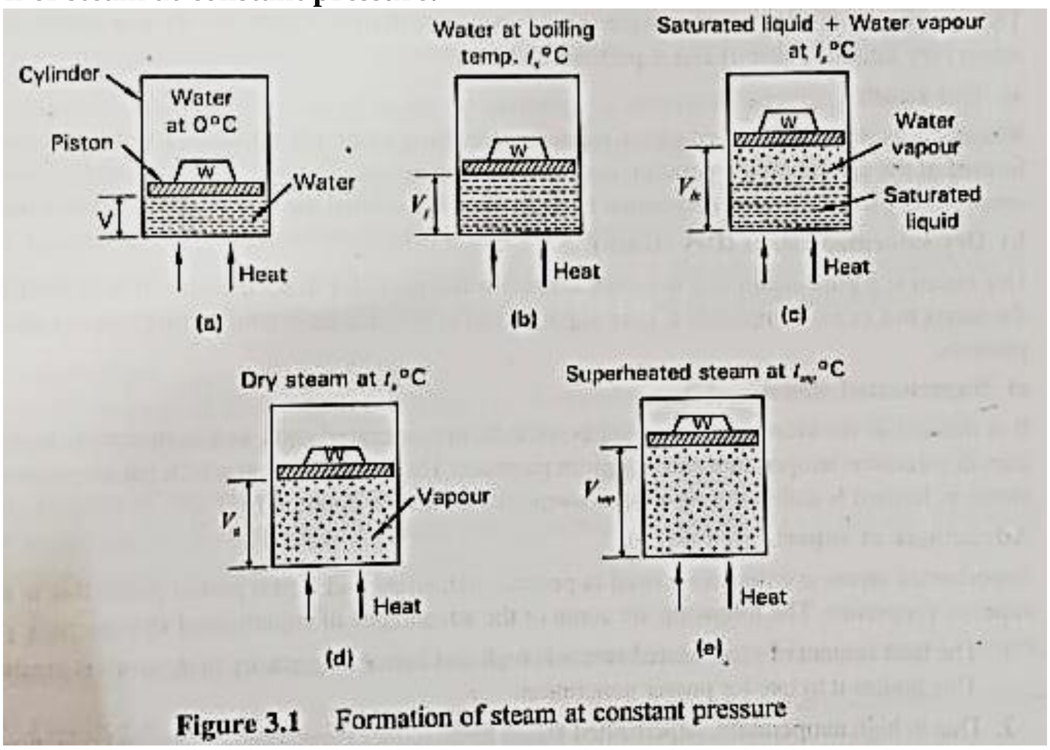

Figure 3.1 Formation of steam at constant pressure

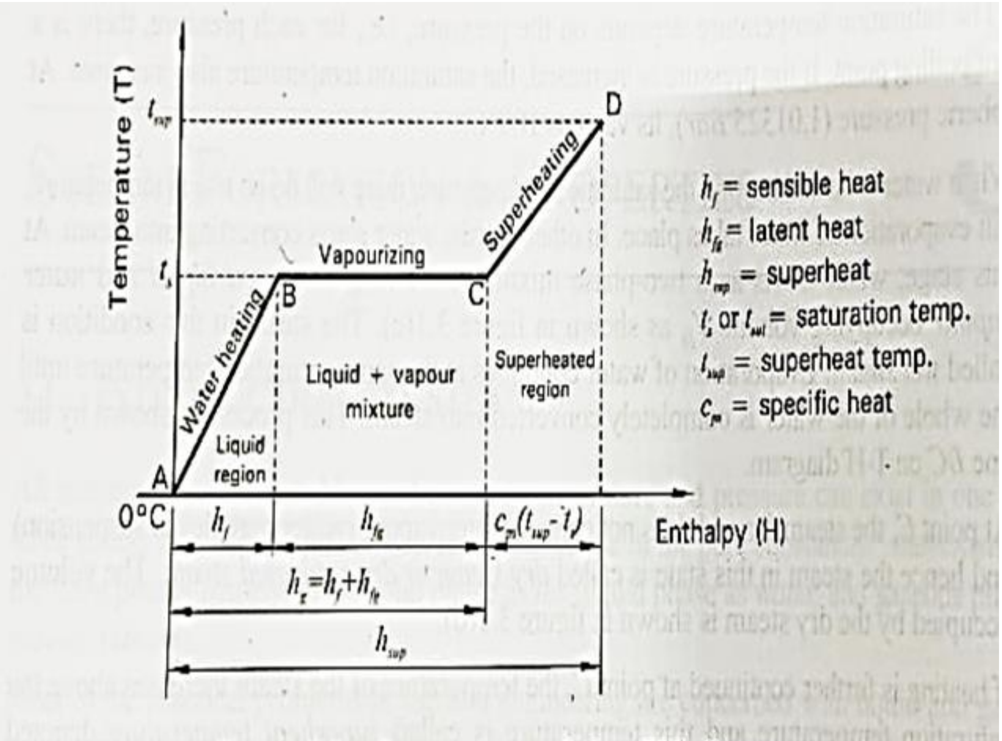

Figure 3.2 Temperature-cnthalpy (TH) diagram

- Consider 1 kg of water at 0^0C taken in a cylinder, on which a constant pressure P is exerted. Point A on the temperature-enthalpy graph (Figure 3.2).

- When this water is heated its temperature rises till the boiling point is reached. This temperature is called saturation temperature (Ts). Point B on the graph.

- Further addition of heat, initiates the evaporation of water while the temperature remains at saturation temperature until all of water is converted into steam. Point C on the graph.

- On heating the steam further, it increases the temperature of steam above the saturated temperature to superheated steam.

Enthalpy (h) is the sum of the internal energy (u) and the product of pressure (p) and volume (v) at constant pressure given by the equation:

$$h=u+pv.$$

When a process occurs at constant pressure, the heat evolved (either released or absorbed) is equal to the change in enthalpy

1. **Saturation temperature (T_S):** It is defined as the temperature at which the water begins to boil at constant pressure.

2. **Sensible heat (h_f):** It is the amount of heat required to convert 1 kg of water from 0^0C to saturation water at the saturation temperature (boiling point - **(T_S)**) at constant pressure. It is also known as enthalpy of the liquid.

Sensible heat (h_f) for water at 0^0C can get from steam table. If water is not at 0^0C (more than 0^0C) then the Sensible heat (h_f) = $C_{pw}(T_s - T_{water})$ KJ/Kg (where Cpw = specific heat of water = 4.18 kJ/kg°K)

3. Latent heat of evaporation (h_{fg}): It is the amount of heat required to evaporate 1 kg of water at saturation temperature **(T_s)** to 1 kg of dry steam at the same saturation temperature **(T_s)** at constant pressure. Also known as enthalpy of evaporation.

4. Degree of superheat: The amount of heat required to increase the temperature of dry steam from its saturation temperature **(T_s)** to any desired higher temperature **(T_{sup})** at constant pressure is called degree of superheat and is given by

$$C_{ps}(T_{sup}-T_s) \text{ KJ/Kg}$$

5. Enthalpy of superheated steam: The amount of heat required to convert 1 kg of water from 0^0C to the to 1 kg of super-heated steam at any desired higher temperature **(T_{sup})** at constant pressure is called enthalpy of superheated steam.

STATES OF STEAM: - The steam as it is being generated can exist in 3 states as wet steam, dry saturated steam and superheated steam.

• **Wet Steam:** It is defined as a two-phase mixture of water molecules and steam at saturation temperature.
Dryness fraction of steam: A wet steam has different proportions of water molecules and dry steam. Hence, the quality of wet steam is specified by the dryness fraction which indicates the amount of dry steam in the given quantity of wet steam and is denoted by **x.** It is defined as the ratio of mass of dry steam in a given quantity of wet steam to the total mass of wet steam.

It is defined as the ratio of mass of dry steam in a given quantity of wet steam to the total mass of steam.

Let m_g = mass of dry steam

m_f = mass of water molecules

Dryness fraction, $x = \dfrac{m_g}{m_g + m_f}$

• *The dryness fraction of wet steam is less than 1.*

• *The dryness fraction of dry steam is 1*

• **Dry Steam (dry saturated steam):** As wet steam is heated further, the water molecules in the steam get converted into vapour. Dry steam is the steam at saturation temperature having no water molecules in it. Point C.

• **Superheated Steam:** It is defined as the steam which is heated beyond its dry state to temperatures higher than its saturated temperature at the given pressure.

ENTHALPY (h), kJ/kg: It is the amount of heat required to raise the temperature of 1 kg of water from 0^0C to the desired form of water at constant pressure. It is the sum of the internal energy and work done at constant pressure.

Enthalpy of Dry Saturated Steam (hg): It is the amount of heat required to convert 1 kg of water from 0^0C to 1 kg of dry saturated steam at saturation temperature (**T_s**) at constant pressure.

$$h_g = h_f + h_{fg} \quad \text{KJ/Kg}$$

Enthalpy of Wet Steam (h): It is the amount of heat required to convert 1 kg of water from 0^0C to 1 kg of wet steam to the specified dryness fraction at saturation temperature (**T_s**) at constant pressure.

$$h = hf + xhfg \quad KJ/Kg$$

Enthalpy of Superheated Steam (h_{sup}): It is the amount of heat required to convert 1 kg of water from 0^0C to 1 kg of superheated steam to the stated super-heated steam temperature (**T_{sup}**) at constant pressure. It is the sum of enthalpy of dry steam and the amount of superheat.

$$h_{sup} = h_g + C_{ps}(T_{sup} - T_s) \text{ KJ/Kg}$$

$$h_{sup} = h_f + h_{fg} + C_{ps}(T_{sup} - T_s) \text{ KJ/Kg}$$

(where Cps = specific heat of steam = 2.25 kJ/kg^{o}K)

Where C_{ps} is the specific heat of superheated steam.

The important properties of steam are

1. Pressure	4. Enthalpy
2. Temperature	5. Internal energy
3. Specific volume	6. Entropy

Specific volume (v) in m^3 /kg: It is the volume occupied by the unit mass of a substance.

Specific Volume of Saturated water (V_f): It is the volume occupied by 1 kg of saturated water at saturation temperature **(T_s)** at a given pressure. (Can get this value from steam table)

Specific Volume of Dry Saturated Steam (V_g): It is the volume occupied by 1 kg of dry saturated steam at saturation temperature **(T_S)** at a given pressure. (Can get this value from steam table)

Specific Volume of Dry Saturated Steam (V_{sup}): It is the volume occupied by 1 kg of super-heated steam at super-heated temperature **(T_{sup})** at a given pressure. (Can **NOT** get this value from steam table.) The equation to find **(V_{sup})** is

$$\frac{vg}{vsup} = \frac{TS}{Tsup}$$

Specific Volume of Wet Steam (v_w): It is the volume occupied by 1 kg of wet steam to the specified dryness fraction and saturation temperature **(T_S)** at a given pressure. $v = xv_g$

Internal Energy of Steam: The total heat energy of a dry saturated steam at a constant pressure is the sum of the sensible heat and latent heat. But in latent heat a portion is used for external work. Therefore, the actual energy stored in the steam is the sensible heat and the internal latent heat. This actual energy stored in the steam is called internal energy of steam.

It is defined as the difference between the enthalpy of the steam and the external work of evaporation.

External work of evaporation (W) : When water is evaporated to form saturated steam, its volume increases from $\mathbf{V_f}$ to $\mathbf{V_g}$ at a constant pressure, and thus external work is done by steam due to increase in volume. The energy for doing the work is obtained during the absorption of latent heat. This work is called external work of evaporation.

and is given by **External work of evaporation (W) = 100 P (V_g – V_f)** in kJ

External work of evaporation of dry steam (Wg) = 100 P (V_g) in kJ (**V_f** is neglected due to its small quantity)

External work of evaporation of wet steam (Ww) = 100 P (xV_g) in kJ

External work of evaporation of super-heated steam (Wsup) = 100 P (V_{sup}) in kJ

Internal Latent Heat (U): The amount of heat required for phase change of 1 kg of water at saturation temperature **(T_S)** from liquid to vapor at given constant pressure and is given by

Internal Latent Heat (U): latent heat - External work of evaporation of dry steam = **hg** – **Wg** in kJ/kg

Pressure unit

1bar = 1 N/m^2 = 10^5 Pascal= 0.1 MPa (Mega Pascal)

Numericals

1. Determine the dryness fraction of steam if 0-8 of water is in suspension with 45 kg of dry steam.
   Solution:

   The condition of steam is wet steam, because it is a mixture of water & dry steam
   The total Mass of wet steam = mass of dry steam + mass of water molecules = 45 +0.8 = 45.8 kg
   Thus, in 45-8 kg of wet steam, the dry steam is 45 kg.
   The dryness fraction of wet steam is the ratio of the mass of actual dry steam to the mass of wet steam containing it.
   Dryness fraction, x = 45/45-8 = 0.982 (i.e. Steam is 98.2% dry or 1.8% wet.)

2. How much heat is needed to convert 1 kg of feed water at 20ºC into dry saturated steam at 10 bar (1 MPa or 1000 KPa)? Take specific heat of water as 4.187 kJ/kg K.

From steam tables, at 10 bar,

Saturation temp (Ts) = 179.91’C, Enthalpy of saturated water, h_f = 762.81 kJ/kg and enthalpy of evaporation, h_{fg} - 2,015.3 kJ/kg

Method1:

Enthalpy of dry saturated steam at 10 bar (above 0’C), $h_g = h_f + h_{fg}$ = 762.81 + 2,015.3 = 2,778.11 kJ/kg.

Enthalpy of 1 kg of feed water at 20’C above 0’C = C_{pw} (T_{water} - 0) = 4.187 (20-0) = 83.74 kJ/kg.

Heat supplied to convert 1 kg of feed water at 20’C into dry saturated steam at 10 bar = enthalpy of dry saturated steam - enthalpy of feed water = 2,778.11 - 83.74 = 2,694.37 kJ/kg.

Method2:

Enthalpy of saturated water at 20’C , $h_{f\ at\ 20}$ = C_{pw} (Ts - T_{water}) = 4.187 (179.91-20) = 669.543

Enthalpy of dry saturated steam = $h_{f\ at\ 20}$ + h_{fg} = 669.543 + 2015.3 = 2684.8 kJ/kg

3. Find the specific volume and enthalpy of 3 kg of steam at 9bar when the condition of steam is (a) wet with dryness fraction 0.98 (b) dry saturated and (c)super-heated, the temperature of steam 240°C

   From steam tables, at 9 bar,

Saturation temp (Ts) = 175.38’C, Enthalpy of saturated water, h_f = 742.83 kJ/kg and enthalpy of evaporation, h_{fg} – 2031.19 kJ/kg, Enthalpy of dry saturated steam (h_g) = 2773.9 kJ/kg, Specific volume of saturated water (v_f) = 0.00112 m^3/kg, Specific volume of dry saturated steam (v_g) = 0.2150 m^3/kg. x= 0.98

(a) Enthalpy of wet steam (h_w) =(h_f +x*h_{fg})*3 = (742.83 + 0.98*2031.19)*3 = (2733.39 kJ/kg)*3 = 8200.18 kJ and
Specific volume of wet steam (v_f) =(x* v_g)*3 = (0.98* 0.2150 m^3/kg)*3 = (0.2107 m^3/kg)*3= 0.6321 m^3

(b) Enthalpy of dry saturated steam (h_g)= (h_f +h_{fg})*3 = (742.83 + 2031.19)*3 = (2774.02 kJ/kg)*3 = 8322.06 kJ and
Specific volume of dry steam (v_g) = (vg)*3 = (0.2150 m^3/kg)*3 = 0.645 m^3

(c) Enthalpy of super-heated steam (h_{sup})= (hg + C_{ps} (Tsup – T_s))*3 = ((h_f +h_{fg}) +C_{ps} (Tsup – T_s))*3 = ((742.83 + 2031.19)+2.1(240-175.38))*3 = (2909.72 kJ/kg)*3 = 8729.16 kJ and
Specific volume of super-heated steam (v_{sup}) =
$= \left(vg * \frac{Tsup}{Ts}\right) * 3$ = (0.2150 * $\frac{240+273}{175.38+273}$)= (0.2459 m^3/kg)*3 = 0.7379 m^3

4. Determine the conditions of steam from the following data:–
a) Pressure is 10 bar and temperature 200°C,–
b) Pressure is 12 bar and enthalpy of 2600 kJ/kg.
c) Pressure is 10 bar and the total heat is 2832 kJ/kg
d) Pressure is 10 bar and specific volume is 0.23 m3/kg

Solution:
a) At P= 10 bar, T= 200°C
From steam tables, at pressure of 10 bar,
Ts= 179.88°C.
Since the saturation temperature {179.88 °C} is less than given steam temperature of [200°C],
therefore the steam is superheated and
Degree of superheated temperature = Tsup- Tsat= 20.12 °C

Solution:
a)At P= 10 bar, T= 200°C From steam tables, at pressure of 10 bar, Tsat= 179.88°C. Since the saturation temperature {179.88 °C} is less than given steam temperature of [200°C], therefore the steam is superheated and Degree of superheat = T- Tsat= 20.12 °C
b) At Pressure is 12 bar and enthalpy of dry saturated steam = 2784.8 kJ/kg , which is greater than the given enthalpy 2600 kJ/kg. Therefore the given steam condition is wet steam, the dryness fraction of the steam is
h_w = h_f +x*h_{fg}= 2785.4 = 2600 + x* 1986.2
x= (2785.4 -2600)/1986.2 = 0.0933 = 9.3 % wet and 90.7 % dry steam

c) At Pressure is 10 bar
Enthalpy of dry saturated steam (h_g)= 2778.1 kJ/kg , Ts= 179.91°C
The given enthalpy 2832 kJ/kg is more than h_g= 2778.1 kJ/kg
Therefore the given steam condition is super-heated steam steam,

The temperature of the super–heated steam is

h_{sup}= (hg + C_{ps} (Tsup – T_s)) = 2832 =2778.1+ 2.1(Tsup -179.91)

= 2.1 *Tsup=431.81, Tsup = 205.5°C

d) At Pressure is 10 bar

Enthalpy of dry saturated steam (h_g)= 2778.1 kJ/kg , Ts= 179.91°C, v_g= 0.19444 m^3/kg

The given specific volume is 0.23 m^3/kg is greater than v_g= 0.19444 m^3/kg.

Therefore the given steam condition is super-heated steam steam,

The temperature of the super–heated steam is

$(\frac{v_{sup}}{Tsup}) = \left(\frac{vg}{Ts}\right)$ = T_{sup}) = $\left(Ts * \frac{Vsup}{vg}\right)$ = ((179.91+273)*($\frac{0.23}{0.19444}$) = 535.74 K = 262.7 °C

5. A mixture of wet steam at a pressure of 1 Mpa is found to have a quality of 85%. Determine its enthalpy, external work of evaporation, internal energy, specific volume & density.

Solution:

The Pressure is 1 Mpa = 1*10*105 Pa = 10 bar (where 105 Pa = 1bar)

X = 0.85

From steam tables, at 10 bar,

Saturation temp (Ts) = 179.91'C, Enthalpy of saturated water, hf = 762.81 kJ/kg and enthalpy of evaporation, hfg - 2,015.3 kJ/kg, vg= 0.19444 m3/kg

Enthalpy of wet steam (hw) =(hf +x*hfg) = 762.81 + (0.85*2015.3) = 2475.81 kJ

External work of evaporation = (Ww) = 100 P (x*Vg) = 100 *10*(0.85*0.19444) = 165.27 kJ

Internal energy = Enthalpy of steam – external work of evaporation = hw - Ww =2475.81 - 165.27 =2310.54 kJ

Specific volume = Vw = x*Vg = 0.85*0.19444 = 0.165274 m3/kg

Density = (mass/volume) = (1/ Vw) = (1/ 0.165274) =6.05 kg/m3

6.A steam initially will be at 9 bar and dryness fraction 0.98. find the final quality and temperature of the steam at each of the following operations. (a) When steam losses 50 kJ/kg at constant pressure (b) when steam receives 150 kJ/kg at constant pressure.

Solution:

From steam tables, at 9 bar,

Enthalpy of saturated water, h_f = 742.83 kJ/kg enthalpy of evaporation, h_{fg} – 2031.19 kJ/kg,

Enthalpy of dry saturated steam (h_g) = 2773.9 kJ/kg,

Enthalpy of wet steam (h_w) =(h_f +x*h_{fg}) = 742.83 + (0.98*2031.19) = 2733.39 kJ

(a) When steam losses 50 kJ/kg at constant pressure

New Enthalpy of wet steam (h_w) = 2733.39 – 50 = 2683.39 kJ

2683.39 kJ is less than h_g and more than h_f, therefore the new condition of the steam is wet steam with new dryness fraction

h_w = h_f +x*h_{fg}= 2683.39 = 742.83 + x* 2031.1

x= (2683.39 -742.83)/2031.1 = 0.955 = 95.5 % Dry and 4.5 % wet

(b) when steam receives 150 kJ/kg at constant pressure New Enthalpy of wet steam

(h_w) = 2733.39 + 150 = 2883.39 kJ

For example, enthalpy of dry steam is equal to the sum of sensible heat, internal latent heat external work of evaporation. But work of evaporation is not stored in the steam, as it is utili in doing external work, say movement of piston. Hence, internal energy of steam is found subtracting external work of evaporation from enthalpy of dry steam.

2883.39 kJ is more than h_g therefore the new condition of the steam is super heated steam with temperature

h_{sup} = (h_g + C_{ps} (Tsup – T_s)) = 2883.9 =2773.9+ 2.1(Tsup -175.38)

= 2.1 *Tsup=478.298, Tsup = 227.7°C

Internal energy (U) = Enthalpy of steam – external work of evaporation

- For *wet steam, internal energy* $U_w = h_f + x.h_{fg} - 100..P.x.V_g$ *kJ/kg.*
- For *dry steam* $U_g = h_g - 100.P.V_g$ *kJ/kg.*
- For *superheated steam,* $U_{sup} = h_{sup} - 100.P.V_{sup}$

$$= [h_g + C_{ps}(t_{sup} - t_s)] - 100.P.V_{sup} \quad kJ/kg.$$

3.5 NUMERICAL PROBLEMS

Problem 1 Determine the dryness fraction of steam, which has 1.5 kg of water in suspens with 50 kg of steam.

Solution :

Step 1 Data

Mass of water particles m_f = 1.5 kg Mass of dry steam m_g = 50 kg

Step 2 To find dryness fraction x

$$\text{w.k.t. dryness fraction} = x = \frac{m_g}{m_f + m_g} = \frac{50}{1.5 + 50} = 0.97$$

$\therefore$ **dryness fraction = x = 0.97**

Problem 2 8 kg of wet steam contains 1.56 kg of water particles in suspension. What is t dryness fraction of steam.

Solution :

Step 1 Data

Mass of wet steam = 8 kg Mass of water particles m_f = 1.56 kg

$\therefore$ Mass of dry steam present $m_g = 8 - 1.56 = 6.44$ kg

Step 2 To find dryness fraction x

$$\text{w.k.t. dryness fraction} = x = \frac{m_g}{m_f + m_g} = \frac{6.44}{1.56 + 6.44} = 0.805$$

$\therefore$ **dryness fraction = 0.805**

Problem 3 Calculate the enthalpy of steam at a pressure of 30 bar if its dryness fractio is 0.75. *MQP (2002 scheme) - 05 n*

Solution :

Step 1 Data

Pressure $p = 30$ bar   Dryness fraction $x = 0.75$

Step 2 To find enthalpy of steam (h).

Since $x = 0.75$ is less than 1, the given steam is wet.

w.k.t. enthalpy of wet steam $= h_w = h_f + x\, h_{fg}$ ---- [1]

Note Since pressure (P) is given in the problem, the properties (h_f & h_{fg}) from steam tables has to read on pressure basis.

From steam tables for pressure, $P = 30$ bar, we have, $h_f = 1008.3$ kJ/kg and $h_{fg} = 1794$ kJ/kg

$\therefore$ equation (1) reduces to, $h_w = 1008.3 + [0.75 \times 1794] = 2353.8$

$\therefore$ **enthalpy of wet steam** $\boldsymbol{h_w = 2353.8}$ **kJ/kg**

Problem 4 Find the enthalpy of 1 kg of steam at 12 bar when steam is (i) dry saturated (ii) 22% wet, and (iii) superheated to 250°C. Assume specific heat of the superheated steam as 2.25 kJ/kg K.

July 2003 - 08m & Jan 2010

Solution :

Step 1 Data

Mass of steam $= m = 1$ kg   Pressure $P = 12$ bar

From steam tables, corresponding to a pressure of 12 bar, we have

$t_{sat} = t_s = 188^\circ$C, $h_f = 798.4$ kJ/kg, $h_{fg} = 1984.3$ kJ/kg, and $h_g = 2782.7$ kJ/kg

Step 2 To find enthalpy of dry saturated steam (h_g)

w.k.t. for dry saturated steam, enthalpy $= h_g = h_f + h_{fg} = 798.4 + 1984.3 = 2782.7$

$\therefore$ $\boldsymbol{h_g = 2782.7}$ **kJ/kg of steam**

Step 3 To find enthalpy (h) when steam is 22% wet

w.k.t. enthalpy of wet steam $= h_w = h_f + x\, h_{fg}$ ---- [1]

but $x = ?$

If steam is 22% wet, then it is $100 - 22 = 78\%$ dry.

i.e., $x = 0.78$

$\therefore$ equation (1) reduces to, $h_w = 798.4 + [0.78 \times 1984.3] = 2346.15$

$\boldsymbol{h_w = 2346.15}$ **kJ/kg**

Step 4 To find enthalpy when steam is superheated to 250°C.

w.k.t. enthalpy of superheated steam $= h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat})$

where $C_{ps} = 2.25$ kJ/kg K, and $t_{sup} = 250^\circ$C

$\therefore h_{sup} = 2782.7 + 2.25\,(250 - 188) = 2922.2$

$\boldsymbol{h_{sup} = 2922.2}$ **kJ/kg of steam**

Problem 5 Find the enthalpy of 0.5 kg of steam at a pressure of 10 bar absolute for the following conditions. (i) it is 1.5% wet, (ii) it is dry saturated, (iii) it is at a temperature of 200°C. Assume specific heat as 2.3 kJ/kg K.

Jan 2007 - 06 m

Solution :

Step 1 Data

$$\text{Mass of steam } m = 0.5 \text{ kg} \qquad \text{Pressure } P = 10 \text{ bar}$$

From steam tables, corresponding to $P = 10$ bar, we have

$t_{sat} = 179.9°\text{C}$, $h_f = 762.6$ kJ/kg, $h_{fg} = 2013.6$ kJ/kg and $h_g = 2776.2$ kJ/kg

Step 2 To find enthalpy when steam is 1.5% wet.

w.k.t. for wet steam, $h_w = h_f + x\, h_{fg}$ ---- [1]

but $x = ?$

If steam is 1.5% wet, then it will be 100 – 1.5 = 98.5% dry

$\therefore$ dryness fraction $= x = 0.985$

equation (1) reduces to, $h_w = 762.6 + (0.985 \times 2013.6) = 2746$ kJ/kg

$\therefore$ for 0.5 kg of steam $h_w = 0.5 \times 2746$

$$\mathbf{h_w = 1373 \text{ kJ}}$$

Step 3 To find enthalpy of dry steam

w.k.t. for dry saturated steam, enthalpy $h_g = h_f + h_{fg} = 762.6 + 2013.6 = 2776.2$

$h_g = 2776.2$ kJ/kg of steam

$\therefore$ for 0.5 kg of steam, $h_g = 0.5 \times 2776.2 = 1388.1$

$$\mathbf{h_g = 1388.1}$$

Step 4 To find enthalpy of superheated steam at 200°C.

w.k.t. for superheated steam, $h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat})$ where $t_{sup} = 200°\text{C}$

$h_{sup} = 2776.2 + 2.3\,(200 - 179.9) = 2822.43$ kJ/kg of steam

$\therefore$ for 0.5 kg of steam, $h_{sup} = 0.5 \times 2822.43 = 1411.21$

$$\mathbf{h_{sup} = 1411.21 \text{ kJ}}$$

Problem 6 What is the enthalpy of 5 kg steam under the following condition : (i) 0.8 bar absolute and 90% dry, and (ii) 20 bar absolute and at 300°C. Specific heat of superheated steam is 2.25 kJ/kg K.

Feb. 04 - 04 m

Solution :

Step 1 Data

$$\text{Mass of steam } m = 5 \text{ kg} \qquad C_{ps} = 2.25 \text{ kJ/kg K}$$

Step 2 To find enthalpy when $P = 0.8$ bar and 90% dry

Steam is 90% dry, i.e., $x = 0.9$ dryness fraction of steam

Since $x < 1$, the steam is in wet condition

$\therefore$ enthalpy of wet steam $= h_w = h_f + x\, h_{fg}$ ---- [1]

From steam tables, at P = 0.8 bar, we have, h_f = 391.7 kJ/kg & h_{fg} = 2274.1 kJ/kg

∴ equation (1) reduces to, $h_w = 391.7 + (0.9 \times 2274.1) = 2438.4$ kJ/kg of steam

∴ For 5 kg of steam, enthalpy = $h_w = 2438.4 \times 5$

$$h_w = \mathbf{12192\ kJ}$$

Step 3 To find enthalpy h when P = 20 bar & temperature 300°C

From steam tables, at P = 20 bar, we have, t_{sat} = 212.4°C, and h_g = 2797.2 kJ/kg

Since the temperature 300°C is greater than t_{sat} = 212.4°C, the given steam is in superheated state.

w.k.t. for superheated steam, $h_{sup} = h_g + C_{ps}(t_{sup} - t_{sat})$ ---- [1]

$$\therefore h_{sup} = 2797.2 + 2.25(300 - 212.4) = 2994.3 \text{ kJ/kg}$$

∴ for 5 kg of steam, $h_{sup} = 2994.3 \times 5 = 14971.5$

$$h_{sup} = \mathbf{14971.5\ kJ}$$

Problem 7 By actual measurement, the enthalpy of saturated steam at 190°C is 2500 kJ/kg. What is the quality of steam.

Solution :

Step 1: Data

Saturation temperature t_{sat} = 190°C Enthalpy of saturated steam = h_w = 2500 kJ/kg

Since saturation temperature (t_{sat}) is given in the problem, the properties of steam from steam tables hand book has to be read on temperature basis. Note that in previous problems, the properties of steam was recorded on pressure basis.

From steam tables, corresponding to t_{sat} = 190°C, we have,

P = 12.551 bar, h_f = 807.5 kJ/kg, h_{fg} = 1976.8 kJ/kg & h_g = 2784.3 kJ/kg

w.k.t. enthalpy of steam = $h = h_f + x\,h_{fg}$

$$2500 = 807.5 + x(1976.8)$$

$$x = \mathbf{0.8561}$$

∴ Quality of steam = 0.8561 × 100 = 85.61%

i.e., the steam is 85.61% dry and 14.39 % wet.

Problem 8 A mixture of wet steam at a pressure of 10 bar is found to have a quality of 85%. Determine its enthalpy, internal energy, specific volume and density.

Solution :

Step 1 Data

State of steam = WET, Pressure = P = 10 bar

Quality of steam = 85% ∴ Dryness fraction = x = 0.85

From steam tables, corresponding to P = 10 bar, we have,

t_{sat} = 179.9°C, h_f = 762.6 kJ/kg, h_{fg} = 2013.6 kJ/kg, h_g = 2776.2 kJ/kg, & V_g = 0.19430

Step 2 To find enthalpy of wet steam

w.k.t. for wet steam, $h_w = h_f + x\, h_{fg} = 762.6 + (0.85 \times 2013.6)$

$$\textbf{Enthalpy} = h_w = \mathbf{2474.16 \ \ kJ/kg}$$

Step 3 To find internal energy $U_w = ?$

w.k.t. Internal energy for wet steam $= U_w = [h_f + x\, h_{fg}] - 100\, P \cdot x \cdot V_g$ kJ/kg

$$U_w = (2474.16) - [100 \times 10 \times 0.85 \times 0.19430]$$

Internal energy of wet steam $= U_w =$ **2309 kJ/kg**

Step 4 To find specific volume of wet steam $V_w = ?$

w.k.t. specific volume of wet steam $= V_w = x\, V_g$ m^3/kg

$$V_w = 0.85 \times 0.19430$$

$$V_w = \mathbf{0.1651 \ \ m^3/kg}$$

Step 5 Density of wet steam $= \rho_w = ?$

w.k.t. density of wet steam $= \rho_w = \dfrac{1}{x\, V_g} = \dfrac{1}{(0.85 \times 0.19430)} = 6.057$ $\quad \rho_w = \mathbf{6.057 \ \ kg/m^3}$

Problem 9 Steam at a pressure of 8 bar has temperature of 200°C. What is the specific enthalpy? What is its specific volume. Assume specific heat of steam to be 2.25 kJ/kg K

July 2006 - 08 m

P (bar)	t (°C)	V_f m^3/kg	V_g m^3/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

Solution :

Step 1: Data

$$\text{Pressure} = P = 8 \text{ bar} \quad C_{ps} = 2.25 \text{ kJ/kg K}$$

Since the saturation temperature $t_{sat} = 170.4$°C is less than the given temperature of steam (200°C), the steam is in superheated state. $\therefore\ t_{sup} = 200$°C

Step 2 To find specific volume of superheated steam (V_{sup})

w.k.t. Specific volume of superheated steam $= V_{sup} = \dfrac{t_{sup}}{t_{sat}} \times V_g$ where t_{sup} & t_{sat} must be in Kelvin.

$$\therefore\ V_{sup} = \left(\frac{200+273}{170.4+273}\right) \times 0.24026$$

$$\textbf{Specific volume } V_{sup} = \mathbf{0.2563 \ \ m^3/kg}$$

Step 3 To find specific enthalpy of superheated steam (h_{sup})

w.k.t. for superheated steam, enthalpy, $h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat}) = 2767.4 + 2.25\,(200 - 170.4)$

$$\textbf{Enthalpy} = h_{sup} = \mathbf{2834 \ \ kJ/kg}$$

Problem 10 Calculate the specific volume and enthalpy of 8 kg of steam at 1.2 MPa (i) when the steam is 12% wet (ii) when the steam is superheated at 300°C. *MQP (2002 scheme) - 08 m*

Solution :

Step 1 Data

Mass of steam $= m = 8$ kg Pressure $= P = 1.2$ MPa

$P = 1.2 \times 10^6$ N/m^2 (Mega $= 10^6$ & 1 Pa $= 1$ N/m^2)

$P = 12$ bar ($\because$ 1 Bar $= 10^5$ N/m^2)

From steam tables, at $P = 12$ bar, we have

$t_{sat} = 188^{\circ}$C, $h_f = 798.4$ kJ/kg, $h_{fg} = 1984.3$ kJ/kg, $h_g = 2782.7$ kJ/kg, and $V_g = 0.16321$ m^3/kg

Step 2 When steam is 12% wet

when steam is 12% wet, it will be 88% dry. $\therefore$ dryness fraction $= x = 0.88$

w.k.t. specific volume of wet steam $= V_w = x\, V_g = 0.88 \times 0.16321$

$V_w = 0.14362$ m^3/kg of steam

$\therefore$ For 8 kg of steam, specific volume $= 8 \times 0.14362$

$\mathbf{V_w = 1.149\ m^3}$

w.k.t. Enthalpy of wet steam $= h_w = h_f + x\, h_{fg} = 798.4 + (0.88 \times 1984.3)$

$h_w = 2544.58$ kJ/kg of steam

$\therefore$ For 8 kg of steam, enthalpy $= 2544.58 \times 8$

$\mathbf{h_w = 20356.67\ kJ}$

Step 3 When steam is superheated at 300°C

w.k.t. Specific volume of superheated steam $V_{sup} = \dfrac{t_{sup}}{t_{sat}} \times V_g = \left(\dfrac{300+273}{188+273}\right) \times 0.16321 = 0.20286$

$V_{sup} = 0.20286$ m^3/kg of steam

$\therefore$ For 8 kg of steam, $V_{sup} = 8 \times 0.20286 = 1.622$

$\mathbf{V_{sup} = 1.622\ m^3}$

w.k.t. enthalpy of superheated steam $= h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat})$

Assume $C_{ps} = 2.25$ kJ/kg K when not specified in the problem

$h_{sup} = 2782.7 + 2.25\,(300 - 188) = 3034.7$ kJ/kg of steam

$\therefore$ For 8 kg of steam, $h_{sup} = 8 \times 3034.7 = 24277.6$ $\mathbf{h_{sup} = 24277.6\ kJ}$

Problem 11 Determine the specific volume & density of 1 kg of steam at a pressure of 7×10^5 Pa when the condition of steam is, (i) wet, having dryness fractions 0.9, (ii) dry, and (iii) superheated at 250°C. If required, use the extract of the steam table provided below: *July 2009 - 09 m*

P	t_s	V_g
7 bar	437.92 K	0.273341 m^3/kg

Solution :

Step 1 Data

Mass of steam = m = 1 kg

Pressure = $P = 7 \times 10^5$ Pa $= 7 \times 10^5$ N/m^2 (1Pa = 1 N/m^2)

P = 7 bar (1 Bar = 10^5 N/m^2)

Step 2 When steam is wet with $x = 0.9$

w.k.t. specific volume of wet steam = $V_w = x\ V_g = 0.9 \times 0.273341$

$$V_w = \mathbf{0.246\ \ m^3/kg}$$

$$\text{Density of wet steam} = \rho_w = \frac{1}{x\ V_g} = \frac{1}{(0.9 \times 0.273341)} = 4.065$$

$$\rho_w = \mathbf{4.065\ \ kg/m^3}$$

Step 3 When steam is dry

w.k.t. Specific volume of wet steam = $V_g = x\ V_g$. But, for dry steam $x = 1$

∴ Specific volume of dry steam = $V_g = 0.273341$ m^3/kg (from extract of steam tables)

$$\text{density of dry steam} = \rho_g = \frac{1}{x\ V_g} = \frac{1}{V_g} = \frac{1}{0.273341} = 3.658$$

$$\rho_g = \mathbf{3.658\ \ kg/m^3}$$

Step 4 When steam is superheated to 250°C

$$\text{w.k.t. Specific volume of superheated steam} = V_{sup} = \frac{t_{sup}}{t_{sat}} \times V_g = \left(\frac{250 + 273}{437.92}\right) \times 0.273341$$

$$V_{sup} = \mathbf{0.3264\ \ m^3/kg}$$

$$\text{Density of superheated steam} = \rho_{sup} = \frac{1}{V_{sup}} = \frac{1}{0.3264} = 3.063$$

$$\rho_{sup} = \mathbf{3.063\ \ kg/m^3}$$

Problem 12 Determine the condition of steam in the following cases

(a) at a pressure of 5 Bar, the total heat is 2654 kJ/kg

(b) at a pressure of 10 bar, the total heat is 2832 kJ/kg

(c) at a pressure of 20 bar and temperature 222°C.

(d) at a pressure of 10 bar & specific volume 0.23 m^3/kg

Solution :

Step 1 When $P = 5$ bar

Total heat or enthalpy = h = 2654 kJ/kg

From steam tables, at P = 5 bar, we have, $h_g = 2747.5$ kJ/kg (enthalpy of dry steam)

Since the given total heat or enthalpy of steam (h) is less than the enthalpy of dry steam (h_g), the steam is in WET condition.

Step 2 When $P = 10$ bar

$$\text{Total heat or enthalpy} = h = 2832 \text{ kJ/kg}$$

From steam tables, at $P = 10$ bar, we have, $h_g = 2776.2$ kJ/kg

Since the given total heat $h > h_g$, the steam is in superheated state.

Step 3 When $P = 20$ bar and temperature = 222°C

From steam tables, at $P = 20$ bar, we have, $t_{sat} = 212.4$°C

Since the temperature of the given steam (222°C) is greater than the saturation temperature (212.4°C), the steam is in the superheated state.

Step 4 When $P = 10$ bar & specific volume 0.23 m³/kg

From steam table, at $P = 10$ bar, specific volume of dry steam = $V_g = 0.19430$ m³/kg

Since the specific volume of the given steam ($V = 0.23$ m³/kg) is greater than the specific volume of dry steam ($V_g = 0.19430$ m³/kg), the steam is in the superheated state.

Problem 13 By actual measurement, the enthalpy of saturated steam at 190°C is 2500 kJ/kg. What is the quality of steam. If 500 kJ of heat is added at constant pressure, what is the final state of steam. Also determine its final temperature. ***Aug 2001***

Solution :

Step 1 To determine quality of steam

Saturation temperature = t_{sat} = 190°C Enthalpy = $h = 2500$ kJ/kg

From steam tables, corresponding to $t_{sat} = 190$°C, we have, $h_g = 2784.3$ kJ/kg

Since the enthalpy of given steam $h < h_g$, the steam is in WET condition.

$$\text{WKT, for wet steam } h_w = h_f + x\, h_{fg} \quad \text{---- [1]}$$

$$\text{From tables, at } t_{sat} = 190^\circ\text{C}, \; h_f = 807.5 \text{ kJ/kg} \;\; \& \;\; h_{fg} = 1976.8 \text{ kJ/kg}$$

$$\therefore \text{ equation (1) becomes, } 2500 = 807.5 + (x \times 1976.8) \quad \text{or} \quad \mathbf{x = 0.856}$$

$$\therefore \textbf{Quality of steam} = \mathbf{85.6\%}$$

Step 2 Heat addition process

If 500 kJ of heat is added, then total enthalpy = 2500 + 500 = 3000 kJ/kg

Since 3000 kJ/kg is greater than h_g (2784.3 kJ/kg), the steam after heat addition becomes SUPERHEATED.

To find temperature of superheated steam (t_{sup}) = ?

w.k.t. for superheated steam, $h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat})$

$$\text{Assume } C_{ps} = 2.25 \text{ kJ/kg k}$$

$$\therefore 3000 = 2784.3 + 2.25\,(t_{sup} - 190)$$

$$t_{sup} = \mathbf{285.86^\circ C}$$

Problem 14 A steam initially will be at 9 bar and dryness fraction 0.98. Find the final quality and temperature of the steam at each of the following operations. (a) when steam loses 50 kJ/kg at constant pressure (b) when steam receives 150 kJ/kg at constant pressure *Jan 2000 & July 05*

Solution :

Step 1 Data

$$\text{Pressure} = P = 9 \text{ bar, Dryness fraction} = x = 0.98$$

From steam tables, at $P = 9$ bar, we have,

$t_{sat} = 175.4°\text{C}$, $h_f = 742.6$ kJ/kg, $h_{fg} = 2029.5$ kJ/kg and $h_g = 2772.1$ kJ/kg

Step 2 To find the enthalpy of given steam

Since $x = 0.98$ is less than 1, the given steam is WET

w.k.t. for wet steam, enthalpy $= h_w = h_f + x\, h_{fg} = 742.6 + (0.98 \times 2029.5)$

$$\boldsymbol{h_w = 2731.51 \text{ kJ/kg}}$$

Step 3 When steam loses 50 kJ/kg of heat

Let h_1 be the enthalpy in this condition

When steam loses 50 kJ of heat, the total enthalpy is $h_1 = h_w - 50$

$$h_1 = 2731.51 - 50 = 2681.51$$

$$\therefore \boldsymbol{h_1 = 2681.51 \text{ kJ/kg}}$$

Since $h_1 < h_g$, the steam is wet.

To find quality of steam:

For wet steam $h = h_f + x\, h_{fg}$ where $h = h_1 = 2681.5$ kJ/kg

$$2681.51 = 742.6 + (x \times 2029.5)$$

$$x = 0.955$$

$$\therefore \quad \textbf{Quality of steam = 95.5\%}$$

Step 4 When steam receives 150 kJ/kg of heat

Let h_2 be the enthalpy in this condition. $\therefore\ h_2 = h_w + 150$

$$h_2 = 2731.51 + 150 = 2881.51$$

$$\therefore\ h_2 = 2881.51 \text{ kJ/kg}$$

Since $h_2 > h_g$, the steam is superheated

To find $t_{sup} = ?$

w.k.t. $h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat})$ ---- [1]

Assume $C_{ps} = 2.25$ kJ/kg K

$h_{sup} = h_2 = 2881.51$ kJ/kg

$\therefore$ equation (1) becomes, $2881.51 = 2772.1 + 2.25\,(t_{sup} - 175.4)$

$$\boldsymbol{t_{sup} = 224°\text{C}}$$

Problem 15 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.

Assume $C_{steam} = 2.1$ kJ/kg K. If required use the extract of the steam table provided below.

Jan 2006 - 08 m

P (bar)	t (°C)	V_f (m³/kg)	V_g (m³/kg)	h_f (kJ/kg)	h_g (kJ/kg)
2.0	120.23	0.001061	0.8857	504.5	2706.5

Solution : In the present problem, the enthalpy of wet steam has to be calculated, which in turn helps us to obtain the dryness fraction of steam.

Step 1 Data

$$\text{Mass of wet steam} = 2 \text{ kg}$$

$$t_{sup} = 150°\text{C} \quad (\because \text{ given temperature} > t_{sat} \ 120.23°\text{C})$$

$$\text{Pressure} = P = 2 \text{ bar}$$

Heat transfered = enthalpy= 2100 kJ for 2 kg of steam

$$\therefore \text{ for 1 kg of steam } = \frac{2100}{2} = 1050 \text{ kJ/kg}$$

$$C_{steam} = C_{ps} = 2.1 \text{ kJ/kg K}$$

Step 2 To find initial dryness fraction of steam

$$\text{w.k.t. } h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat}) = 2706.5 + 2.1\,(150 - 120.23)$$

$$\therefore\ h_{sup} = 2769.01 \text{ kJ/kg}$$

Heat supplied for 1 kg of wet steam = 1050 kJ

$\therefore$ Heat initially present in wet steam $= 2769.01 - 1050 = 1719.01$ kJ/kg

$$\text{i.e., enthalpy of wet steam } = h_w = 1719.01 \text{ kJ/kg}$$

$$\text{w.k.t. } h_w = h_f + x\,h_{fg} \qquad \text{- - - - [1]}$$

Note Value of h_{fg} is not provided in the extract of steam tables. However h_{fg} can be obtained by using $h_{fg} = h_g - h_f$ $(\because h_g = h_f + h_{fg})$

$$\text{i.e., } h_{fg} = 2706.5 - 504.5 = 2202 \text{ kJ/k}$$

$$\therefore \text{ equation (1) becomes, } 1719.01 = 504.5 + (x \times 2202)$$

$$x = 0.55$$

$\therefore$ initial dryness fraction of steam was $\boldsymbol{x = 0.55}$

Problem 16 3 kg of steam is generated at 5 bar from water at 34°C. Determine the quantity of heat required when, (a) steam is wet, having dryness fraction 0.8, (b) steam is dry saturated, and (c) steam is superheated to 240°C. Assume $C_{ps} = 2.25$ kJ/kg K and $C_{pw} = 4.187$ kJ/kg K

Solution :

Step 1 Data

Mass of steam = 3 kg, Pressure = $P = 5$ bar   Initial temperature of water = 34°C

C_{ps} = 2.25 kJ/kg K, C_{pw} = Specific heat of water = 4.187 kJ/kg

From steam tables, at $P = 5$ bar, we have

$t_{sat} = 151.8^\circ C$, $h_f = 640.1$ kJ/kg. $h_{fg} = 2107.4$ kJ/kg and $h_g = 2747.5$ kJ/kg

Note In all the previous problems, the properties of steam were determined for water at 0°C. However, in the present problem, the initial temperature of water is 34°C, which means that there is some amount of heat already present in water. The problem can be best understood by plotting the T-H diagram as shown in figure. P.16 below.

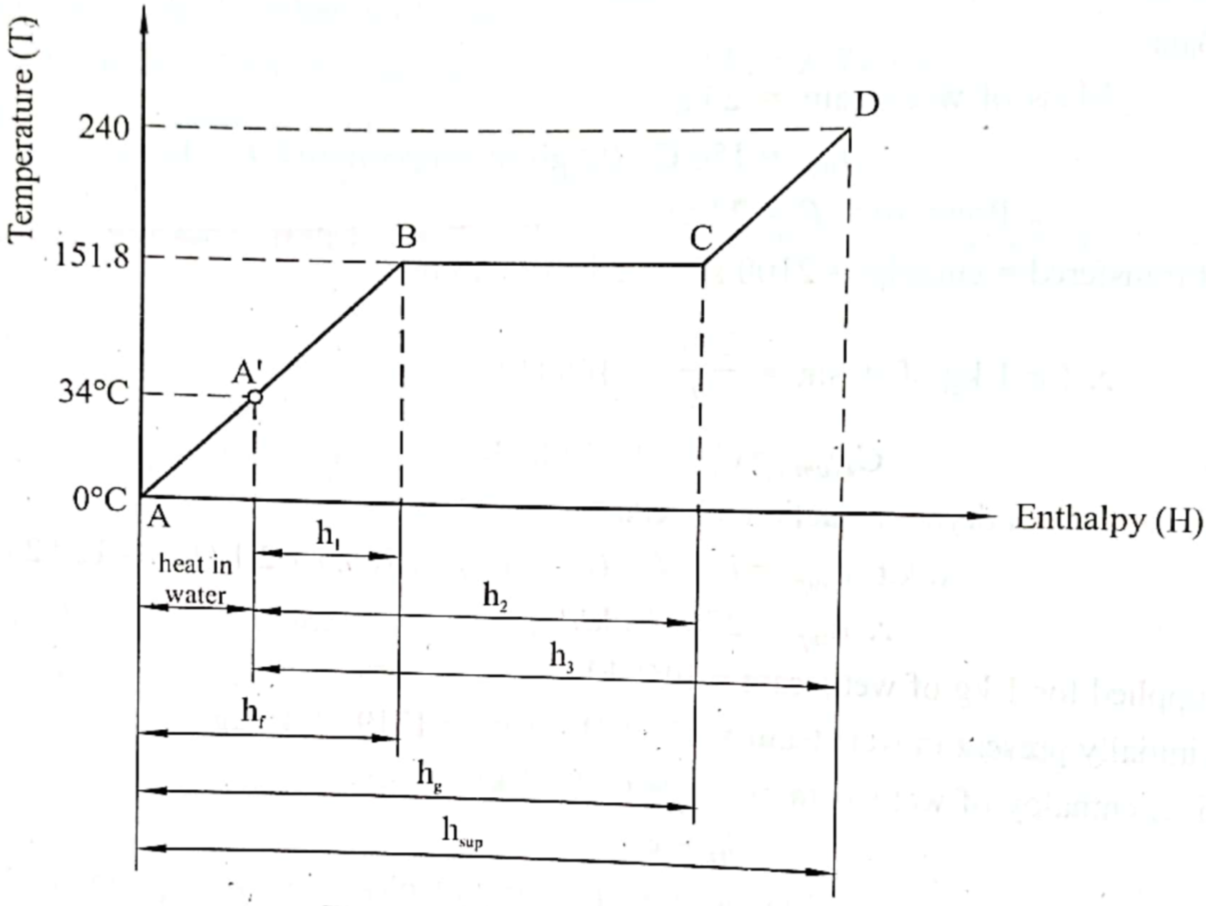

Figure P.16 T-H diagram

∴ Heat already in water (portion AA') = $m\ C_{pw} \Delta T$ (m = Mass of water = 1 kg)

ΔT = change in temperature= $34^\circ C - 0^\circ C = 34^\circ C$

∴ Heat already in water $= 1 \times 4.187 \times 34 = 142.35$ kJ/kg

Step 2 When steam is wet with $x = 0.8$

Let h_w = heat required to convert 1 kg of water at 0°C into wet steam

w.k.t. enthalpy of wet steam (between points A & B) = $h_w = h_f + x\ h_{fg} = 640.1 + (0.8 \times 2107.4)$

$$h_w = 2326.02 \text{ kJ/kg}$$

Let h_1 = actual quantity of heat supplied to produce 1 kg of wet steam from water whose initial temperature is 34°C

$$\therefore h_1 = h_w - \text{heat already in water}$$
$$= 2326.02 - 142.35$$
$$h_1 = 2183.67 \text{ kJ/kg of steam}$$

$\therefore$ to produce 3 kg of steam, heat required = $h_1 = 3\times2183.67$

$$h_1 = \mathbf{6551.01\ kJ} \quad \textbf{for 3 kg of steam}$$

Thus 6551.01 kJ of heat is required to produce 3 kg wet steam from water at 34°C.

Step 3 When steam is dry saturated

Let h_g = heat required to convert 1 kg of water at 0°C into dry steam

Let h_2= actual heat required to produce 1 kg of dry steam from water at 34°C

$$\therefore\ h_2 = h_g - \text{heat already in water}$$
$$= 2747.5 - 142.35$$
$$h_2 = 2605.15 \text{ kJ/kg of steam}$$

$\therefore$ To produce 3 kg of steam, heat required = 3×2605.15

$$h_2 = \mathbf{7815.45\ kJ} \quad \textbf{for 3 kg of steam}$$

Thus 7815.45 kJ of heat is required to produce 3 kg of dry steam from water at 34°C.

Step 4 When steam is superheated to 240°C.

Let h_{sup}= heat required to convert 1 kg of water at 0°C to superheated steam

$$\text{w.k.t. } h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat}) = 2747.5 + 2.25(240 - 151.8)$$
$$h_{sup} = 2945.95 \text{ kJ/kg of steam}$$

Let h_3 = actual heat required to produce 1 kg of superheated steam from water at 34°C.

$$\therefore\ h_3 = h_{sup} - \text{heat already in water}$$
$$= 2945.95 - 142.35$$
$$h_3 = 2803.6 \text{ kJ/kg of steam}$$

$\therefore$ To produce 3 kg of steam, heat required = $3 \times 2803.6 = 8410.8$ kJ.

Thus 8410.8 kJ of heat is required to produce 3 kg of superheated steam from water at 34°C.

$$h_3 = \mathbf{8410.8\ kJ}$$

Problem 17 How much heat energy is required to generate 2 kg of dry saturated steam at 7 bar from feed water at 25°C. ***Jan 07 - 05 m***

Solution :

Step 1 Data

Mass of dry steam = m = 2 kg, Pressure = 7 bar Initial temperature of water = 25°C.

From steam tables, at P = 7 bar, we have,

t_{sat} = 165°C, h_f = 697.1 kJ/kg, h_{fg} = 2064.9 kJ/kg & h_g = 2762 kJ/kg

The details are plotted on the T-H diagram as shown in figure P.17

Step 2 To find h_1

Heat initially present in water (AA') = $m\ C_{pw}\ \Delta T$ (m = 1 kg of water & C_{pw} = 4.18 kJ/kg K)

$$= 1\times 4.18 \times (25 - 0) = 104.5 \text{ kJ/kg}$$

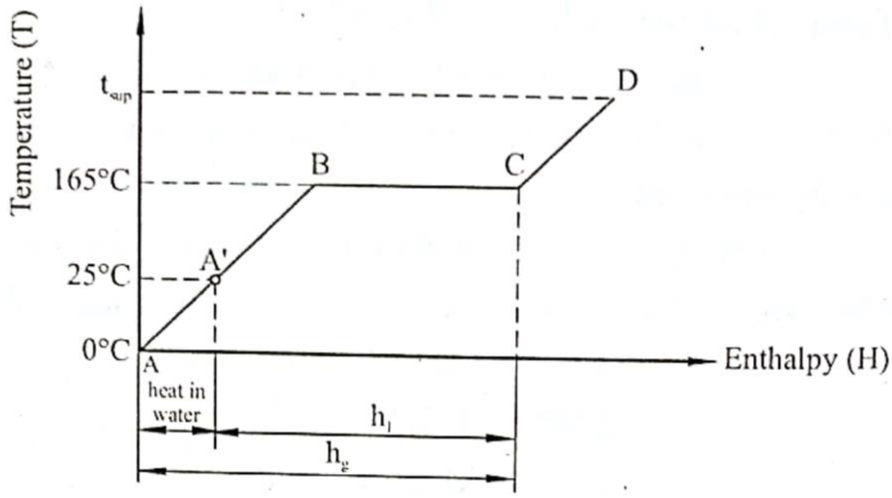

Figure P.17 T-H diagram

Let h_g = heat required to convert 1 kg of water at 0°C into dry saturated steam.

w.k.t. enthalpy of dry steam = $h_g = h_f + h_{fg}$

From steam tables, at P = 7 bar, we have, h_g = 2762 kJ/kg

Let h_1 = actual heat required to produce 1 kg of dry steam from water at 25°C

$$\therefore h_1 = h_g - \text{heat already in water} = 2762 - 104.5$$

$$h_1 = 2657.5 \text{ kJ/kg of steam}$$

$\therefore$ to generate 2 kg of dry steam, heat required, $h_1 = 2 \times 2657.5 = 5315$

$$\boldsymbol{h_1 = 5315 \text{ kJ} \quad \text{for 2 kg of dry steam}}$$

Problem 18 What amount of heat would be required to produce 4 kg of steam at a pressure of 6 bar and temperature of 250°C from water at 30°C. Take C_{pg} = 2.2 kJ/kg K, specific heat of water = 4.18 kJ/kg K. At 6 bar h_f = 670.4 kJ/kg, h_{fg} = 2085 kJ/kg, T_s = 158.8°C. ***Jan 2009 - 06 m***

Solution :

Step 1 Data

Mass of steam = m = 4 kg, Pressure = 6 bar

Since 250°C > T_{sat} (158.8°C), the steam is in the superheated state

$\therefore t_{sup}$ = 250°C

Temperature of water = 30°C

$C_{pg} = C_{ps}$ = 2.2 kJ/kg K, h_f = 670.4 kJ/kg, h_{fg} = 2085 kJ/kg, t_{sat} = 158.8°C, & C_{pw} = 4.18 kJ/kg K

The details are plotted on the TH diagram as shown in figure.P.18.

Step 2 To find h_1

Heat already present in water (AA') $= m\, C_{pw}\, \Delta T$

$= 1 \times 4.18 \times (30 - 0)$ (m = 1 kg of water)

= 125.4 kJ/kg

Let h_{sup} heat required to convert 1 kg of water at 0°C into superheated steam

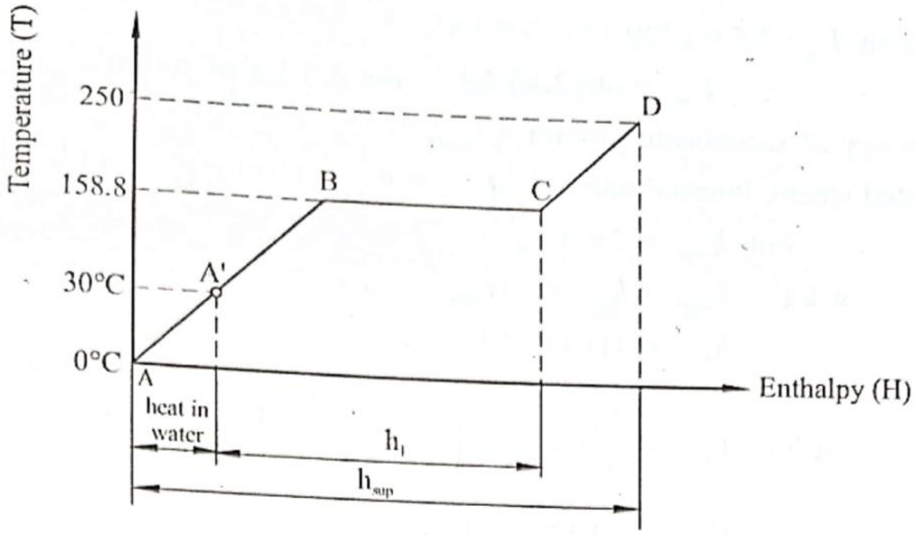

Figure P.18 T-H diagram

w.k.t. for superheated steam= $h_{sup} = h_g + C_{ps}(t_{sup} - t_{sat})$

$$h_g = h_f + h_{fg} = 670.4 + 2085 \text{ (from data)}$$

$$h_g = 2755.4 \text{ kJ/kg}$$

$$\therefore\ h_{sup} = 2755.4 + 2.2\,(250 - 158.8) = 2956.04 \text{ kJ/kg of steam}$$

Let h_1 = actual heat required to produce 1 kg of superheated steam from water at 30°C.

$$\therefore\ h_1 = h_{sup} - \text{heat already in water} = 2956.04 - 125.4$$

$$h_1 = 2830.64 \text{ kJ/kg of steam}$$

$\therefore$ to generate 4 kg of steam, heat required = $h_1 = 4\times2830.64$

$$\boldsymbol{h_1 = 11322.56 \text{ kJ for 4 kg of steam}}$$

Problem 19 Find the internal energy of 2.5 kg of steam at 20 bar, when (i) it is wet, its dryness fraction being 0.9, (ii) it is superheated, its temperature being 350°C. (take the specific heat of steam as 2.3 kJ/kg K). ***Feb 2005 - 06 m***

Solution :

Step 1 Data

Mass of steam = m = 2.5 kg, Pressure = 20 bar

From steam tables, at P = 20 bar, we have,

$t_{sat} = 212.4^\circ$C, $h_f = 908.5$ kJ/kg, $h_{fg} = 1888.7$ kJ/kg, $h_g = 2797.2$ kJ/kg, & $V_g = 0.09955$ m³/kg

Step 2 To find internal energy of wet steam (U_w).

Given, dryness fraction = x = 0.9

w.k.t. for wet steam, internal energy, $U_w = h_w - 100\,P.x.V_g$ kJ/kg ---- [1]

but h_w = ?

for wet steam $h_w = h_f + x\,h_{fg} = 908.5 + (0.9\times1888.7) = 2608.33$

$\therefore$ equation (1) becomes, $U_w = 2608.33 - (100\times20\times0.9\times0.09955) = 2429.14$ kJ/kg of steam

$\therefore$ for 2.5 kg of steam, $U_w = 2.5 \times 2429.14 = 6072.85$

$$\therefore \quad U_w = 6072.85 \text{ kJ} \quad \text{for 2.5 kg of steam}$$

Step 3 Internal energy of superheated steam = U_{sup} = ?

w.k.t. for superheated steam, internal energy = $U_{sup} = h_{sup} - (100.P.V_{sup})$ kJ/kg ---- [2]

$$\text{but } h_{sup} = ? = V_{sup}$$

$$\text{w.k.t. } h_{sup} = h_g + C_{ps}(t_{sup} - t_{sat}) = 2797.2 + 2.3\,(350 - 212.4)$$

$$h_{sup} = 3113.68 \text{ kJ/kg}$$

$$\text{w.k.t. } V_{sup} = \frac{t_{sup}}{t_{sat}} \times V_g = \left(\frac{350+273}{212.4+273}\right) \times 0.09955$$

$$V_{sup} = 0.1277 \text{ m}^3\text{/kg of steam}$$

$\therefore$ equation (2) becomes, $U_{sup} = 3113.68 - (100 \times 20 \times 0.1277) = 2858.28$ kJ/kg of steam

$\therefore$ for 2.5 kg of steam, $U_{sup} = 2858.28 \times 2.5$

$$U_{sup} = 7145.7 \text{ kJ} \quad \text{for 2.5 kg of steam}$$

Problem 20 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 of heat is added at constant pressure, determine the condition and internal energy for the final state of steam. Take specific heat of superheated steam = 2.1 kJ/kg K.

Jan 2003 - 10 m

Solution :

Step 1 Data

Mass of steam = m = 1 kg, Pressure = 10 bar, Dryness fraction = $x = 0.78$

Heat added to steam = 500 kJ, C_{ps} = 2.1 kJ/kg K

From steam tables, at P = 10 bar, we have,

$t_{sat} = 179.9^\circ$C, $h_f = 762.6$ kJ/kg, $h_{fg} = 2013.6$ kJ/kg, $h_g = 2776.2$ kJ/kg, & $V_g = 0.19430$ m^3/kg

Step 2 To find density of steam

Since $x < 1$, the steam is WET

$$\text{w.k.t. for wet steam, density} = \rho_w = \frac{1}{x\,V_g} = \frac{1}{(0.78 \times 0.19430)} = 6.598$$

$$\text{Approximately } \rho_w = 6.6 \text{ kg/m}^3$$

Step 3 Condition of steam on heat addition

By data, 500 kJ of heat was added to wet steam

w.k.t. Enthalpy of wet steam = $h_w = h_f + x\,h_{fg} = 762.6 + (0.78 \times 2013.6) = 2333.2$ kJ/kg

Let h_1 be the enthalpy after heat addition

$$\therefore \; h_1 = 500 + 2333.2$$

$$h_1 = 2833.2 \text{ kJ/kg}$$

Since $h_1 > h_g$ (2776.2 kJ/kg), the steam is superheated after heat addition

$$\therefore h_1 = h_{sup} = 2833.2 \text{ kJ/kg}$$

To find internal energy of superheated steam

$$\text{w.k.t. } U_{sup} = h_{sup} - 100\, P.V_{sup} \qquad \text{----[2]}$$

$$\text{but } V_{sup} = ?$$

$$\text{w.k.t. } V_{sup} = \frac{t_{sup}}{t_{sat}} \times V_g \qquad \text{----[2]}$$

$$\text{But } t_{sup} = ?$$

using $h_{sup} = h_g + C_{ps}\,(t_{sup} - t_{sat})$, we have,

$$2833.2 = 2776.2 + 2.1\,(t_{sup} - 179.9)$$

$$t_{sup} = 207.04^\circ\text{C}$$

$$\therefore \text{ equation (2) becomes, } V_{sup} = \left(\frac{207.04 + 273}{179.9 + 273}\right) \times 0.19430$$

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

Substituting V_{sup} in equation (1) we have, $U_{sup} = 2833.2 - (100 \times 10 \times 0.2059)$

$$\mathbf{U_{sup} = 2627.3 \text{ kJ/kg}}$$

Problem 21 A mixture of saturated water and saturated steam at a temperature of 250°C is contained in a closed vessel of 0.1 m³ capacity. If the mass of saturated water is 2 kg, find the mass of steam in the vessel. Also find the pressure, specific volume, dryness fraction and the enthalpy of the mixture. Use the properties of the steam given the table below. ***July 08 - 10 m***

Saturation temperature °C	Saturation pressure bar	Specific enthalpy of saturated Liquid kJ/kg	Specific enthalpy of saturated Vapour kJ/kg	Specific volume of saturated Liquid m³/kg	Specific volume of saturated Vapour m³/kg
250	39.77	1085.8	2800.4	0.0012513	0.05004

Solution :

Step 1 Data collection

$$\text{Saturation temperature} = t_{sat} = 250^\circ\text{C}$$

$$\text{Volume of vessel} = 0.1 \text{ m}^3$$

$$\text{Mass of saturated water} = 2 \text{ kg}$$

Step 2 To find mass of steam in the vessel

The vessel contains a mixture of *saturated water* and *saturated steam* (dry steam).

$$\therefore \text{Total volume} = \underbrace{m_f\, v_f}_{\text{saturated water}} + \underbrace{m_g\, V_g}_{\text{Saturated vapour}} \quad ----[1]$$

where m_f = mass of saturated water = 2 kg

v_f = volume of saturated water = 0.0012513 m³/kg (by data)

m_g = mass of saturated steam = ?

V_g = volume of saturated steam = 0.05004 m³/kg (by data)

$\therefore$ equation (1) becomes, $0.1 = (2\times0.0012513) + (m_g \times 0.05004)$

mass of saturated steam in the vessel m_g = 1.948 kg

$\therefore$ Total mass of mixture $= m_f + m_g = 2+1.948$

mass of mixture $= 3.948$ kg

Step 3 To find pressure P

From the extract of steam tables provided in the problem, we have,

at $t_{sat} = 250^\circ\text{C}$, pressure $= P = 39.77$ bar

Step 4 To find specific volume of mixture

Specific volume of the mxiture is the volume of unit mass of mixture at the given temperature and pressure

$$\therefore \text{Specific volume of mixture} = \frac{0.1}{3.948} = 0.02532$$

Specific volume of mixture = 0.02532 m³/kg

Step 5 To find dryness fraction of the mixture

$$\text{w.k.t. dryness fraction} = x = \frac{m_g}{m_f + m_g} = \frac{1.948}{2+1.948} = 0.4934$$

dryness fraction of mixture = x = 0.4934

Step 6 Enthalpy of mixture

enthalpy of mixture = enthalpy of saturated water + enthalpy of saturated steam

$$= m_f h_f + m_g h_g$$

$$= (2\times1085.8) + (1.948\times2800.4)$$

enthalpy of mixture = 7626.78 kJ