

PROPERTIES OF PURE SUBSTANCE: UNIT-IV

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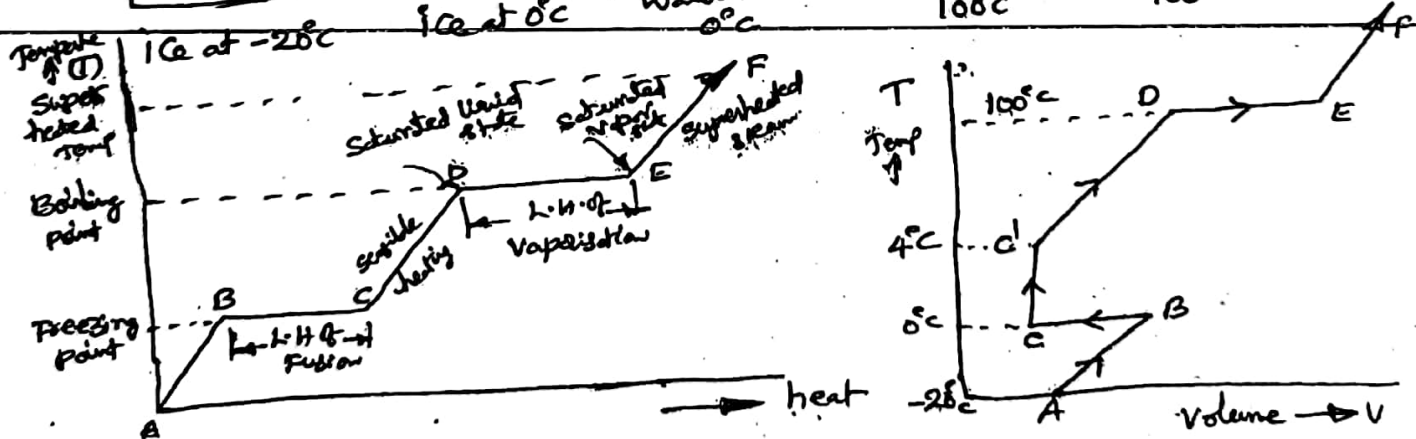
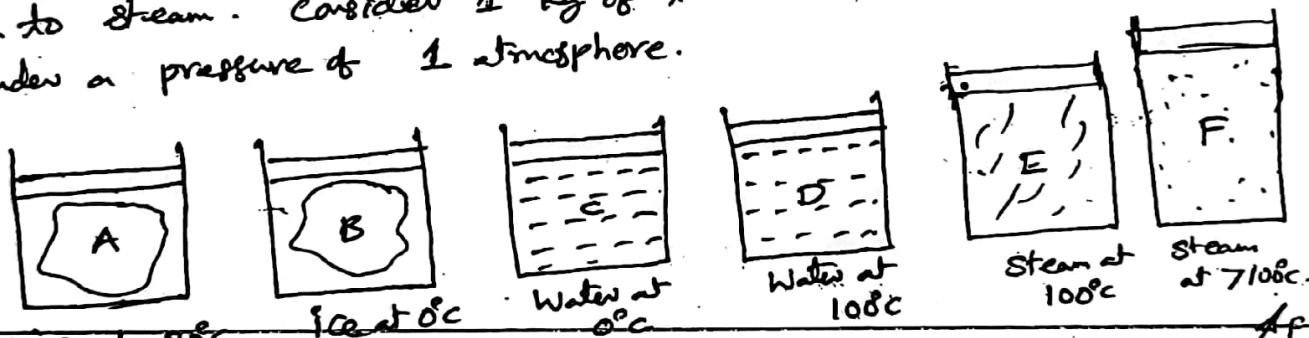
A pure substance may be defined as a substance, which is chemically homogeneous and has a fixed chemical composition. Any substance that appears with invariable chemical composition in either phase (or) a combination of phases may be treated as a pure substance. Water, nitrogen, helium and CO₂ are pure substances.

Phases of a pure substance:- There are three principle phases of a substance. Solid, liquid and gaseous phases.

We will study the behaviour of water in all the three phases in thermodynamic plots on P-V, P-T, T-S and h-s co-ordinates.

* important.
Phase Transformation Σ Ice at -20°C to superheated steam above 100°C

To understand the properties of a substance during its phase change let us consider the example of ice converting into steam. Consider 1 kg of ice at -20°C in a cylinder under a pressure of 1 atmosphere.



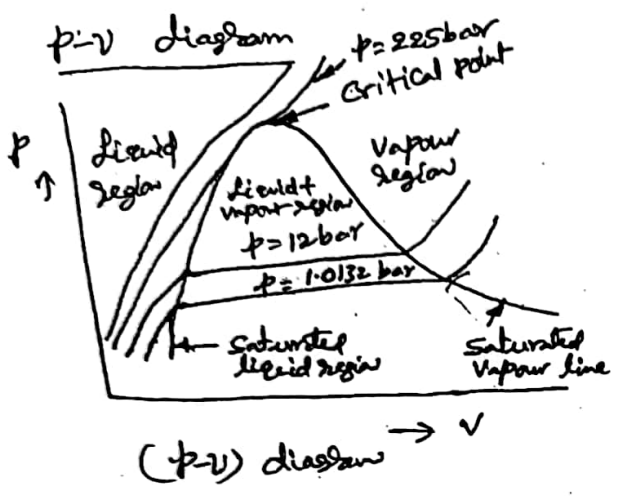
Latent heat of fusion (Enthalpy of fusion):- The quantity of heat required to convert solid into liquid at a constant temperature is known as latent heat of fusion (or) Enthalpy of fusion. For water latent heat of fusion at 1 atmosphere is 335 kJ/kg .

Freezing point temperature:- The temp at which the substance changes its phase is known as freezing point temperature. The freezing point temp. depends on the pressure. It increases with increase of pressure.

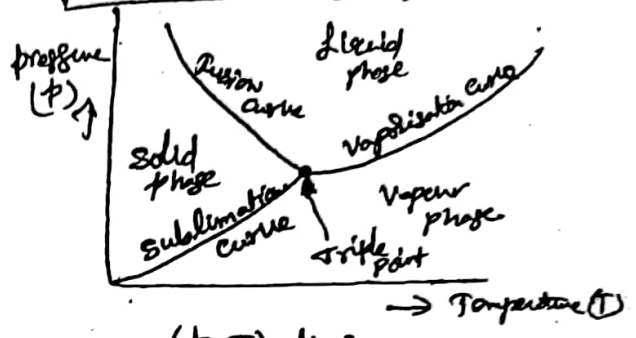
Latent heat of vaporization:-

The quantity of heat required to convert liquid into steam at constant temperature is known as latent heat of vaporisation. For water latent heat of vaporisation at 1 atmosphere is 2256.9 KJ/kg.

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Pressure-Temperature diagram of a pure substance (p-T) diagram.



The p-T diagram of a pure substance is generally called phase diagram.

Since it shows solid, liquid and vapour regions of a substance simultaneously.

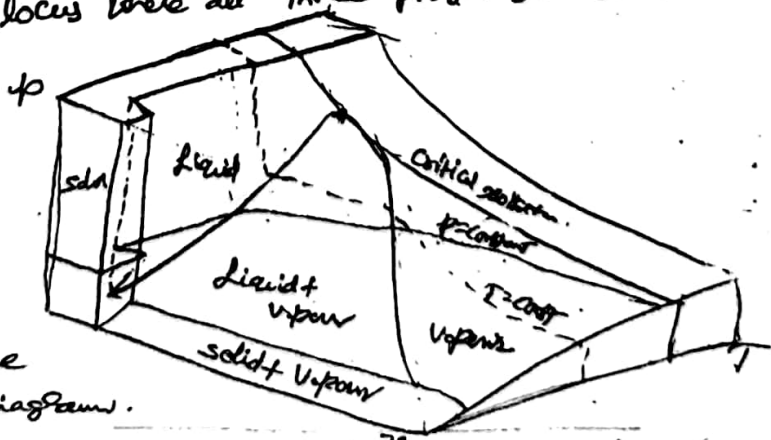
Each single phase of a pure substance is separated by saturation lines. The sublimation line separates the solid and vapour regions, the vaporisation line separates the liquid and vapour regions, and the fusion line separates the solid and liquid regions.

The slope of the fusion line is negative. It indicates that the melting point of it decreases with increasing pressure.

Triple point:- The sublimation, fusion and vaporisation lines meet a point called triple point. Triple point can be defined as a locus where all three phases of a substance co-exist.

p-v-T diagram

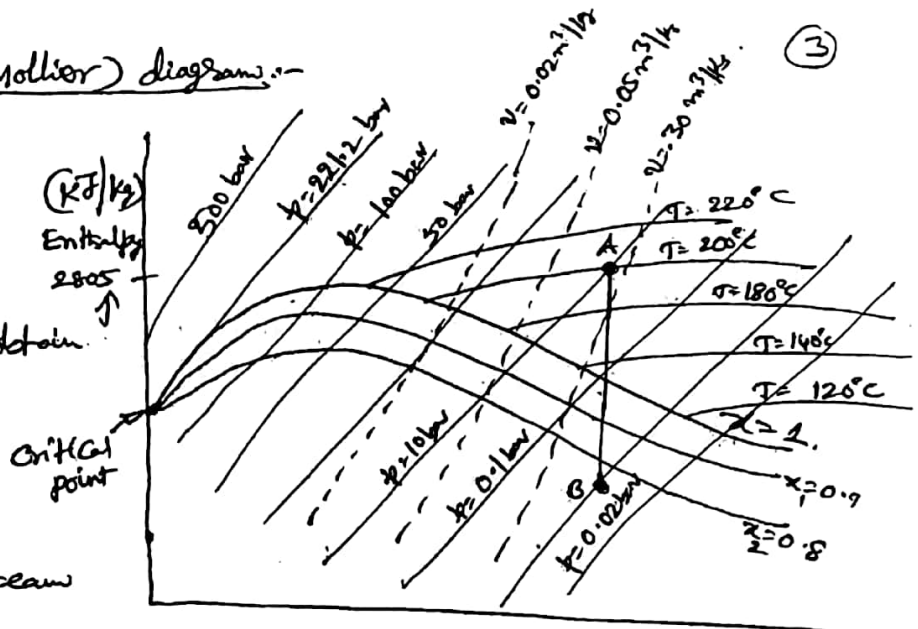
The relationship among pressure, specific volume and temp. of a pure substance can be better understood by the three dimensional p-v-T diagram.



The figure shows a p-v-T surface for water, which expands on freezing. It shows p-v, p-T and T-v diagrams simultaneously on three dimensional plot. A constant temp. line is drawn in the figure passing through the critical isotherm. is called critical isotherm.

Enthalpy - Entropy (Mollier) diagrams:-

The enthalpy-entropy diagram is referred as Mollier diagrams. It is most commonly used to obtain properties of steam with reasonable accuracy, while analysing the steady flow devices such as steam turbines, nozzles etc.



The use of the mollier chart eliminates the complex calculation of work and it is also convenient to use.

on (h-s) chart, pressure range is from 0.01 bar to 1000 bar and a temperature up to 800°C. The saturation curve (above $x=1$), below saturation line, the dryness fraction is below 1, and called wet region. The properties above $x=1$ called dry & superheated region.

Important Terms for Steam

- Wet steam:- Steam contains moisture (oo) particles of water in suspension is called wet steam. Evaporation of water is not complete.
- Dry steam:- When wet steam is further heated, it does not contain any suspended particles of water & known as dry saturated steam. It behaves as a perfect gas. Steam absorbs full latent heat.
- Superheated steam:- When dry steam is further heated at constant pressure, thus raising its temperature, it is said to be superheated steam. Since pressure is constant, the volume of superheated steam increases. Superheated steam is obtained in a super heater.
- Dryness fraction (oo) Quality of steam:- It is the ratio of the mass of the actual dry steam to the mass of dry steam + the mass of wet steam.

$$\therefore x = \frac{m_d}{(m_d + m_w)} = \frac{m_d}{m}$$
 where $m_d \rightarrow$ Mass of dry steam
 $m_w \rightarrow$ Mass of wet steam.
- Sensible heat of water:- It is the amount of heat absorbed by 1 kg of water, when heated at constant pressure without phase change.

$$\therefore \text{Sensible heat} = \text{mass of water} \times \text{Specific heat} \times \text{Rise in temperature}$$

$$\therefore h_f = m_w \times 4.187 (dT)$$

6. Latent heat of vaporization:- It is the amount of heat absorbed to evaporate 1 kg of water at its boiling temperature (or) saturation temperature without change of temperature. It is denoted by h_{fg} . If it is wet steam, then latent heat of vaporization = $x \cdot h_{fg}$.

7. Enthalpy (or) Total heat of steam: It is the amount of heat absorbed by water to its saturation temperature plus heat absorbed during evaporation.

Enthalpy (or) Total heat of steam = sensible heat + latent heat.

$$h = h_f + h_{fg} = h_g \rightarrow \text{Dry steam}$$

$$h = h_f + x \cdot h_{fg} \rightarrow \text{Wet steam}$$

* $[T_{sup} - T_{sat}] \rightarrow$ degree of superheat

$$h = h_g + c_p [T_{sup} - T_{sat}] \rightarrow \text{Superheated steam}$$

8. Specific volume of steam:-

It is the volume occupied by the steam per unit mass at a given temperature and pressure, and is expressed by m^3/kg .

$$\text{Volume of wet steam} = x \cdot v_g + (1-x) v_f \quad \begin{matrix} v_f \rightarrow \text{volume of water per kg} \\ v_g \rightarrow \text{volume of dry steam per kg} \end{matrix}$$

Since v_f is very small,

$$\therefore \text{Volume of 1 kg of wet steam} = v = x v_g, \text{ m}^3/\text{kg}.$$

For Dry steam:- $v_g \text{ m}^3/\text{kg}$.

$$\text{For Super heated steam, } \frac{v_{sup}}{v_{sat}} = \frac{v_g}{v_{g, \text{sat}}}$$

Steam tables and their use:-

The properties of dry saturation steam like its temperature of formation [saturation temp], sensible heat, latent heat, enthalpy, total heat, specific volume, entropy vary with pressure can be found explicitly.

Internal energy of steam (u) It is the actual heat energy stored in steam, above the freezing point of water.

Internal energy of steam = Enthalpy (or) total heat - External work done during evaporation.

$$\text{For Wet steam, internal energy, } u = h_f + x \cdot h_{fg} - 100 p x \cdot v_g \text{ kJ/kg}$$

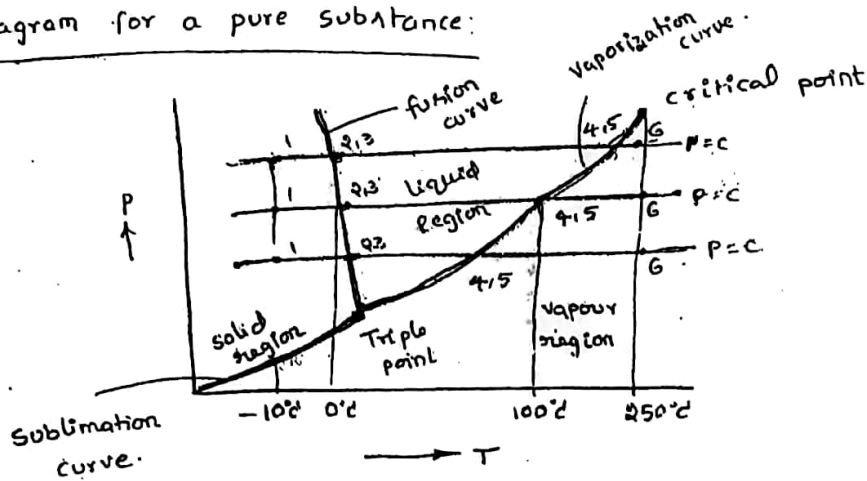
$$\text{For Dry steam, } u = h_f + h_{fg} - 100 p v_g, \text{ kJ/kg}$$

$$\text{For Superheated steam, } u = h_g + c_p (t_{sup} - t_{sat}) - 100 p v_{sup}.$$

Measurement of dryness fraction of steam

1. Barrel calorimeter
2. Separating calorimeter
3. Throttling calorimeter
4. Combined separating and throttling calorimeter.

P-T Diagram for a pure substance:



phase Equilibrium Diagram on P-T coordinates

The state changes of a pure substance upon slow heating at diff. constant pressures are shown in fig. If these state changes are plotted on P-T coordinates the diagram as shown in fig.

if the heating of ice at -10°C to steam at 250°C at the constant pressure of 1 atm is considered 1-2 is the solid (ice) heating

2-3 is the melting of ice at 0°C , 3-4 is

The liquid heating 4-5 is the vaporization of water at 100°C and 5-6 is the heating in the vapour phase. The process will be reversed from state 6 to state 1 upon cooling. The curve passing through the 2, 3 points is called the fusion curve and the curve passing through 4, 5 points

[which indicate the vaporization or condensation at diff. temp. &

pressures] is called the vaporization curve. If the vapor pressure of a solid is measured at diff. temperatures, and these are plotted the sublimation curve will be obtained. The fusion curve, the vaporization curve and the sublimation curve meet at the triple point.

The slopes of the sublimation and vaporization curves for all substances are positive. The slope of the fusion for most substances is positive ^{but} for water it is negative.

⑤
Prob Calculate the enthalpy of 1 kg of steam at a pressure of 8 bar and dryness fraction of 0.8. How much heat would be required to raise 2 kg of this steam from water at 20°C?

Sol. Enthalpy of 1 kg of steam.

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

$$h_f = 720.9 \text{ kJ/kg and } h_{fg} = 2046.5 \text{ kJ/kg.}$$

We know that enthalpy of 1 kg of wet steam,

$$h = h_f + x \cdot h_{fg} = 720.9 + 0.8 \times 2046.5 = 2358.1 \text{ kJ.}$$

Heat required to raise 2 kg of this steam from water at 20°C.

$$\text{heat already in water} = 4 \times 20 = 84 \text{ kJ.}$$

and heat required per kg of steam,

$$= 2358.1 - 84 = 2274.1 \text{ kJ.}$$

$$\text{heat required for 2 kg of steam} = 2 \times 2274.1 = 4548.2 \text{ kJ.}$$

Prob Determine the quantity of heat required to produce 1 kg of steam at a pressure of 6 bar at a temperature of 250°C, under the following conditions.

- 1) When the steam is wet having a dryness fraction of 0.9
- 2) When the steam is dry saturated
- 3) When the steam is superheated at a constant pressure at 250°C assuming the mean specific heat of superheated steam to be 2.3 kJ/kgK.

Sol. Given, pressure, $p = 6 \text{ bar}$, $t_w = 25^\circ\text{C}$; $x = 0.9$; $t_{sp} = 250^\circ\text{C}$
 $C_p = 2.3 \text{ kJ/kgK.}$

From steam tables corresponding to a pressure of 6 bar, we find that
 $h_f = 670.4 \text{ kJ/kg}$; $h_{fg} = 2085 \text{ kJ/kg}$ and $t_{sat} = 158.8^\circ\text{C}.$

1) When the steam is wet,

enthalpy (or) total heat of 1 kg of steam,

$$h = h_f + x \cdot h_{fg} = 670.4 + 0.9 \times 2085 = 2546.9 \text{ kJ.}$$

Since the water is at a temperature of 25°C,

$$\text{Heat already in water} = 4 \times 25 = 105 \text{ kJ.}$$

$$\text{Heat actually required} = 2546.9 - 105 = \underline{2441.9 \text{ kJ.}}$$

2) When the steam is dry saturated

$$h_g = h_f + h_{fg} = 670.4 + 2085 = h_g = 2755 \text{ kJ/kg}$$

$$\text{Heat actually required} = h_g - 105 = 2755 - 105 = 2650.4 \text{ kJ.}$$

3. When the steam is superheated

$$h_{sup} = h_g + C_p [T_{sup} - T_{sat}] = 2755.4 + 2.3(250 - 158.8) = 2965.16 \text{ kJ/kg}$$

Heat actually received = $2965.16 - 105 = 2860.16 \text{ kJ}$ ✓

PROG determine the condition of steam in the following cases.

1. At a pressure of 10 bar and temperature 200°C
2. At a pressure of 10 bar and volume $0.175 \text{ m}^3/\text{kg}$.

1. At a pressure of 10 bar and temperature 200°C

From steam tables, corresponding to a pressure of 10 bar, we find that

$$v_g = 0.194 \text{ m}^3/\text{kg}; \quad h_f = 762.6 \text{ kJ/kg}; \quad \text{and } T_{sat} = 179.9^\circ\text{C}$$

Since the saturation temperature at 10 bar is 179.9°C is lower than the given temperature of steam 200°C , the given steam is superheated.

The degree of superheat = $T_{sup} - T_{sat} = 200 - 179.9 = 20.1^\circ\text{C}$ ✓

2. Condition of steam at a volume of $0.175 \text{ m}^3/\text{kg}$

Since the volume of given steam ($0.175 \text{ m}^3/\text{kg}$) is less than specific volume of dry saturated steam ($0.194 \text{ m}^3/\text{kg}$), therefore, the given steam is wet.

The dryness fraction = $\frac{v_g \text{ wet steam}}{v_g \text{ dry steam}} = \frac{0.175}{0.194} = 0.902$ ✓

PROG Steam enters an engine at a pressure of 12 bar with a 67°C of superheat. It is exhausted at a pressure of 0.15 bar and 0.95 dry. Find the drop in enthalpy of the steam.

SOL: From steam tables, corresponding to 12 bar, $h_g = h_f + h_{fg} = 2782 \text{ kJ/kg}$

Enthalpy (or) total heat of 1 kg of steam (superheated) is

$$h_{sup} = h_g + C_p [T_{sup} - T_{sat}] = 2782 + 2 \times 67^\circ\text{C}$$

$$= 2916.7 \text{ kJ/kg}$$

[∵ since $C_p = 2 \text{ kJ/kg K}$ then $T_{sup} - T_{sat} = 67^\circ\text{C}$ given]

From steam tables, at pressure of 0.15 bar,

$$h_f = 226 \text{ kJ/kg}; \quad h_{fg} = 2373.2 \text{ kJ/kg}$$

Enthalpy (or) total heat of 1 kg of wet steam

$$= h_{wet} = h_f + x h_{fg} = 226 + 0.95 \times 2373.2 = 2411 \text{ kJ/kg}$$

Drop in enthalpy of steam = $h_{sup} - h_{wet} = 2916.7 - 2411 = 505.7 \text{ kJ/kg}$

PROG Determine the volume of 1 kg of superheated steam at a pressure of 20 bar and a temp of 300°C .

SOL

Given, $p = 20 \text{ bar}; \quad T_{sup} = 300^\circ\text{C} = 300 + 273 = 573 \text{ K}$

From steam tables at a pressure of 20 bar,

$$T_{sat} = 212.4^\circ\text{C} + 273 = 485.4 \text{ K}$$

$$v_g = 0.1 \text{ m}^3/\text{kg}$$

we know that, the superheated steam obeys Charles's law ⑦

$$\frac{V_g}{T_{sat}} = \frac{V_{sup}}{T_{sup}}$$

$$V_{sup} = \frac{V_g}{T_{sat}} \times T_{sup} = \frac{0.1}{485.4} \times 573 = 0.118 \text{ m}^3/\text{kg} \checkmark$$

PROB. A boiler is supplied with feed water at a pressure of 4.5 bar. The water is converted into steam at a pressure of 5.5 bar and a temperature of 188°C. Determine the quantity of heat supplied per kg of steam.

SOL. At a pressure of 5.5 bar
 $h_g = 2751.7 \text{ kJ/kg}$, $T_{sat} = 155.5^\circ\text{C}$
 \therefore since the given temp of steam (188°C) higher than saturation temperature
 $h_{sup} = h_g + c_p [T_{sup} - T_{sat}] = 2751.7 + 2.1 [188 - 155.5] = 2820 \text{ kJ/kg}$
 Since, water is supplied at 4.5 bar, the heat in feed water = $4.2 \times 45 = 189 \text{ kJ}$.
 \therefore Heat actually required = $2820 - 189 = 2631 \text{ kJ/kg} \checkmark$

Internal energy of steam:-

It is the actual heat energy stored in steam, above freezing point of water
 For wet steam, internal energy of steam = Enthalpy @ total heat - External work done during evaporation

$$u = h - 100 p v_g \text{ --- ① wet steam}$$

$$u = h_g - 100 p v_g \text{ --- ② dry}$$

$$u = h_{sup} - 100 p v_{sup} \text{ --- ③ superheated.}$$

PROB. Calculate the internal energy of 1 kg of steam at a pressure of 10 bar when the steam is (a) 0.9 dry (b) dry saturated.
 From steam tables, corresponding to a pressure of 10 bar,

$$h_f = 762.6 \text{ kJ/kg}; h_{fg} = 2013.6 \text{ kJ/kg}; v_g = 0.1943 \text{ m}^3/\text{kg}$$

(a) internal energy of 1 kg of steam when it is 0.9 dry ($x = 0.9$)

$$u = h_f + x h_{fg} - 100 p x v_g = 762.6 + 0.9 \times 2013.6 - 100 \times 0.9 \times 0.1943$$

$$= 2400 \text{ kJ} \checkmark$$

(b) internal energy of 1 kg of steam when it is dry saturated

$$u = h_f + h_{fg} - 100 p v_g = 762.6 + 2013.6 - 100 \times 10 \times 0.1943$$

$$= 2581.9 \text{ kJ}$$

⑤

PROB steam at 18 bar and dryness 0.9 is heated at constant pressure until dry and saturated. Find the increase in volume, heat supplied and work done per kg of steam.

If the volume is kept constant, find how much heat must be extracted to reduce the pressure to 14 bar.

SOL: Given, $p = 18 \text{ bar}$; $x = 0.9$; $p_1 = 14 \text{ bar}$.

From steam tables corresponding to a pressure of 18 bar, we find

$h_f = 884.5 \text{ kJ/kg}$, $h_{fg} = 1910.3 \text{ kJ/kg}$; $h_g = 2794.8 \text{ kJ/kg}$
 $v_g = 0.1103 \text{ m}^3/\text{kg}$.

Increase in volume
 $= \text{Volume of dry steam} - \text{Volume of wet steam}$
 $= v_g - x v_g = 0.1103 - 0.9 \times 0.1103 = 0.011 \text{ m}^3/\text{kg}$.

Increase in Heat supplied
 $= h_g - h_{\text{wet}} = 2794.8 - [h_f + x h_{fg}]$
 $= 2794.8 - [884.5 + 0.9 \times 1910.3] = 191 \text{ kJ/kg}$.

Increase in work done
 $= 100 p [v_g - x v_g] = 100 \times 18 [0.1103 - 0.0993] = 19.8 \text{ kJ/kg}$

Heat extracted to reduce the pressure to 14 bar

During constant volume process, no work is done and extraction of heat will result in the reduction of internal energy of steam.

From steam tables, corresponding to a pressure of 14 bar,

$h_{f1} = 830.1 \text{ kJ/kg}$, $h_{fg1} = 1957.7 \text{ kJ/kg}$; $v_{g1} = 0.1407 \text{ m}^3/\text{kg}$.

$x_1 =$ Dryness fraction of steam

Since the volume is constant,

$v_g = x_1 v_{g1}$ $\therefore x_1 = \frac{v_g}{v_{g1}} = \frac{0.1103}{0.1407} = 0.78$

Now, internal energy of steam at a pressure of 18 bar,

$u = h_g - 100 p v_g = 2794.8 - 100 \times 18 \times 0.1103 = 2596.3 \text{ kJ/kg}$

internal energy of steam at a pressure of 14 bar,

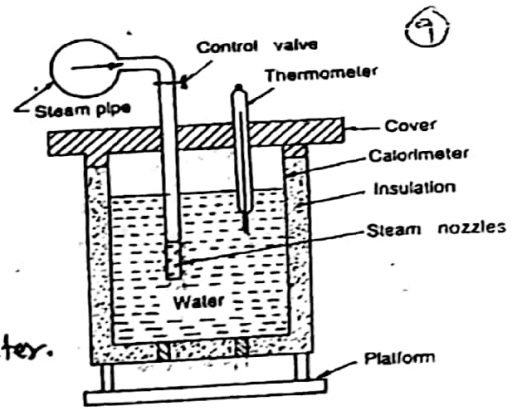
$u_1 = h_{f1} + x_1 h_{fg1} - 100 p_1 x_1 v_{g1}$
 $= 830.1 + 0.78 \times 1957.7 - 100 \times 14 \times 0.78 \times 0.1407$
 $= 2203 \text{ kJ/kg}$.

Heat extracted to reduce pressure = $u - u_1 = 2596.3 - 2203 = 393.3 \text{ kJ/kg}$

* Barrel calorimeter

In barrel calorimeter, the known mass of steam sample and of known pressure is condensed by mixing it with a known mass of cold water. The steam condenses into water, there by increasing the mass and temperature of the water in the calorimeter.

The heat supplied by the condensing steam is determined, with the help of the initial and final temperatures of the water and calorimeter.



Barrel calorimeter.

Let p = pressure of the steam in bar

t = Temp. of steam formed

h_{fg} = latent heat of steam at pressure p (from steam tables)

m_c = mass of the calorimeter.

C_c = specific heat of the calorimeter.

m_e = water equivalent of the calorimeter = $m_c \times C_c$.

m_s = mass of steam condensed

m_w = mass of cold water in calorimeter.

t_1 = initial temp. of water and calorimeter

t_2 = final temp. of water and calorimeter

C_w = specific heat of water

x = dryness fraction of steam sample.

According to law of conservation of energy, heat lost by steam is equal to

heat gained by water and calorimeter.

$$m_s [x h_{fg} + C_w (t - t_1)] = (m_w C_w + m_c C_c) (t_2 - t_1)$$

From this expression, the dryness fraction of steam (x) may be determined.

Q. **Prob** In a laboratory experiment on wet steam by a barrel calorimeter, the following observations were recorded.

Mass of copper calorimeter = 1 kg

Mass of calorimeter + water = 3.8 kg

Mass of calorimeter + water + steam = 4 kg

Initial temperature of water = 10°C

Final temperature of water = 50°C

Steam pressure = 5.5 bar

If the specific heat of copper is 0.406 kJ/kgK, determine dryness fraction of steam.

Sol: Mass of steam, $m_s = (4 - 3.8) = 0.2$ kg.

From steam tables, corresponding to a pressure of 5.5 bar,

$t = 155.5^\circ\text{C}$, $h_{fg} = 2095.5$ kJ/kg.

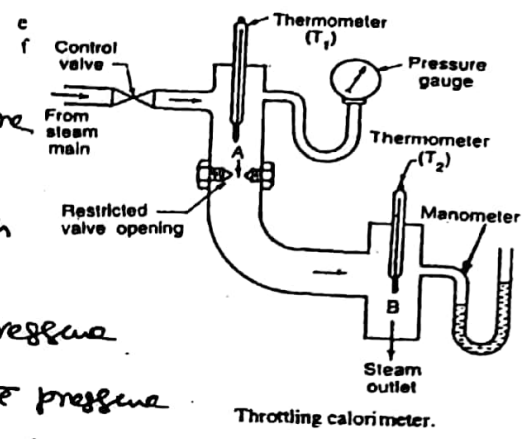
x = Dryness fraction of steam.

According to law of conservation of energy,
 Heat lost by steam = Heat gained by water
 $m_s [x \cdot h_{fg} + c_w (t - t_2)] = [m_w c_w + c_c m_c] (t_2 - t_1)$
 $0.2 [x \times 2095.5 + 4.2(155.5 - 50)] = (2.8 \times 4.2 + 1 \times 0.406)(50 - 10)$

Dryness fraction, $x = 0.95$ ✓

Throttling calorimeter

A throttling calorimeter used to determine the dryness fraction of steam. It consists of a separator A into which steam is admitted through a control valve from the steam main. The pressure and temperature are measured by the pressure gauge and the thermometer T_1 provided in this section.



The steam is then throttled through a narrow aperture of restricted valve openings, its total heat remaining constant. The steam is in superheated state after throttling at a lower pressure than previous. The temperature and pressure of steam leaving the calorimeter B is noted by thermometer T_2 and manometer respectively.

Total heat before throttling = total heat after throttling

At pressure p_1 , $h_{f1} + x h_{fg1} = h_{g2} + c_p [t_{sup} - t_{sat2}]$. At pressure p_2 .

PROB. On a throttling calorimeter, the steam is admitted at a pressure of 10 bar. If it is discharged at atmospheric pressure and 110°C after throttling, determine the dryness fraction of steam. Assume, specific heat of steam is 2.2 kJ/kgK .

SOL. $p_1 = 10 \text{ bar}$; $p_2 = 1.013 \text{ bar}$; $t_{sup} = 110^\circ\text{C}$; $c_p = 2.2 \text{ kJ/kgK}$.
 $x =$ Dryness fraction of steam.

From steam table, corresponding to a pressure of 10 bar,
 $h_{f1} = 762.6 \text{ kJ/kg}$; $h_{fg1} = 2013.6 \text{ kJ/kg}$.
 and corresponding to a pressure of 1.013 bar,
 $h_{g2} = 2676 \text{ kJ/kg}$; $t_{sat2} = 100^\circ\text{C}$

\therefore we have, $h_{f1} + x h_{fg1} = h_{g2} + c_p [t_{sup} - t_{sat2}]$
 $762.6 + x \times 2013.6 = 2676 + 2.2 (110 - 100)$
Dryness fraction $\therefore x = \frac{2698 - 762.6}{2013.6} = 0.961$ ✓

Separating Calorimeter, -

The separating calorimeter is used to determine the dryness fraction of steam by mechanically separating the water particles from the wet steam.

The wet steam enters at the top of the calorimeter through a control valve. It strikes the perforated cup and thereby quick reversal of direction of motion. The water particles due to their greater moment of inertia tend to move on, and consequently get separated from the mixture. The separated water gets collected at the bottom of the inner chamber.

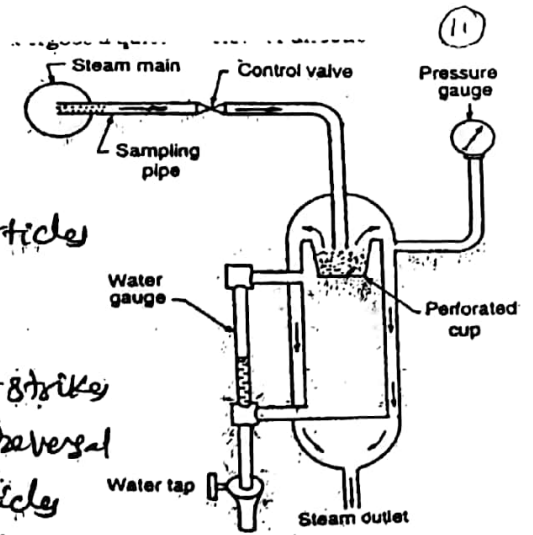


Fig. 30. Separating calorimeter.

The amount of dry steam leaving at the outer chamber of the calorimeter may be measured by condensing it in a weighed quantity of cold water.

Let m = Mass of water collected in a certain time
 M = Mass of dry steam passing in the same time
 x = Dryness fraction of wet steam.

$$\therefore \text{Dryness fraction, } x = \frac{\text{Mass of dry steam}}{\text{Mass of dry steam} + \text{Mass of water}}$$

$$x = \frac{M}{M+m}$$

Combined Separating & Throttling Calorimeter

In this calorimeter, the wet steam is first collected in a perforated collecting pipe and then passed through a separating calorimeter.

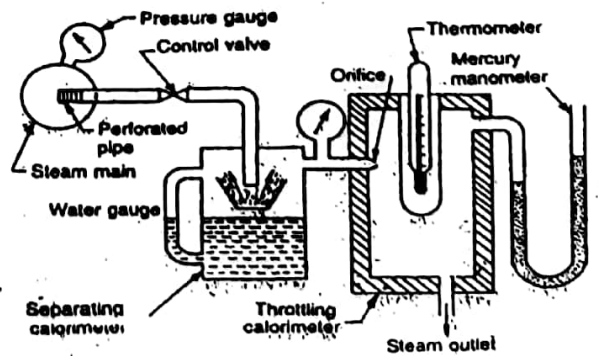
A part of the water is removed by a separating calorimeter owing to quick change of direction of flow.

The resulting semi-dry steam is throttled into a throttling calorimeter. This method ensures that the steam will be superheating after throttling.

Let x_1 = Dryness fraction of steam considering separating calorimeter

x_2 = Dryness fraction of steam entering the throttling calorimeter

Actual dryness fraction of steam in the steam main $x = x_1 \times x_2$



Combined separating and throttling calorimeter.

Entropy of Steam: The entropy of steam is also an important property, which increases with the addition of heat and decreases with its removal. (12)

The ~~increase in~~ entropy of steam consists of

1. Increase in entropy of water during heating from freezing point to boiling point corresponding to pressure at which water is being heated
2. Increase in entropy during evaporation
3. Increase in entropy during superheating.

Entropy of wet steam:- $S_f + x \frac{h_{fg}}{T} = S_f + x \cdot S_{fg}$

Entropy of dry steam:- $S_f + S_{fg} = S_g$

Entropy of superheated steam:- $S_g + C_p \ln \frac{T_{sup}}{T_{sat}}$

PROB Find the entropy of 1 kg of dry saturated steam at a pressure of 5.2 bar. The boiling point of water at this pressure is given as 152.6°C and its total heat at this temperature is 2120 kJ/kg .

SOL The value of entropy of dry saturated steam (S_g) may be directly read from steam tables corresponding to a pressure of 5.2 bar.

From steam tables at 5.2 bar; $S_f = 1.86 \text{ kJ/kgK}$
 $S_{fg} = 4.96 \text{ kJ/kgK}$

$\therefore S_g = S_f + S_{fg} = 1.86 + 4.96 = 6.82 \text{ kJ/kgK}$ ✓

PROB Calculate entropy of 1 kg of wet steam with dryness fraction of 0.9 at a pressure of 8.4 bar.

SOL From steam tables at 8.4 bar,
 $S_f = 2.066 \text{ kJ/kgK}$; $S_{fg} = 4.577 \text{ kJ/kgK}$.

\therefore Entropy of 1 kg of wet steam, $S = S_f + x S_{fg} = 2.066 + 0.9 \times 4.577 = 6.186 \text{ kJ/kgK}$.

PROB Determine the entropy of per kg of superheated steam at a pressure of 20 bar and a temp. of 250°C . Pressure C_p for superheated steam as 2.2 kJ/kgK .

SOL $p = 20 \text{ bar}$; $T_{sup} = 250^\circ\text{C} = 250 + 273 = 523 \text{ K}$; $C_p = 2.2 \text{ kJ/kgK}$.

From steam tables, corresponding to 20 bar pressure,
 $T = 212.4^\circ\text{C} = 212.4 + 273 = 485.4 \text{ K}$ $S_g = 6.337 \text{ kJ/kgK}$.

Entropy of 1 kg of superheated steam
 $S_{sup} = S_g + C_p \ln \frac{T_{sup}}{T_{sat}} = 6.337 + 2.2 \ln \frac{523}{485.4} = 6.5 \text{ kJ/kgK}$ ✓

UNIT-4

Vapour processes:- The following steps are suggested to solve Vapour process problems :-

- ① Find final condition of steam; $v_{wet2} = x \cdot v_{g2}$ OR $v_{dry2} = v_{g2}$ OR $v_{sup2} = T_{sup2} \times \frac{v_g}{T_{sat}}$
- ② change in internal energy, $u_2 - u_1 = \frac{h_2 - 100 p_2 v_2}{100} - (h_1 - 100 p_1 v_1)$
 $[h_{wet} = h_f + x \cdot h_{fg}; h_{dry} = h_f + h_{fg} = h_g; h_{sup} = h_g + c_{ps} [T_{sup} - T_{sat}]$
- ③ Work done, $W_{1-2} = \int p dv$

$W_{1-2} = 0$	$W_{1-2} = p_2 (v_2 - v_1)$	$W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1}$	$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$	$W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$
const. volume	const. pressure	isothermal	polytropic	adiabatic
- ④ obtain Heat transfer, $Q_{1-2} = (u_2 - u_1) + W_{1-2}$

① Constant volume process

consider 1 kg of wet steam at pressure p_1 , dryness fraction x , heated to pressure p_2 at const. volume. since, volume is constant

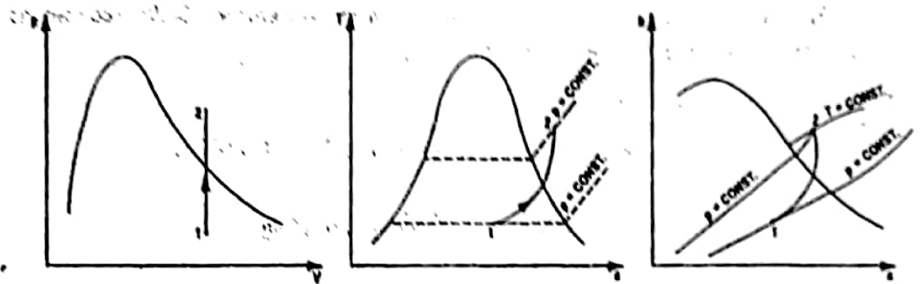


Fig. 7.12 Constant Volume Process

$x_1 v_{g1} = x_2 v_{g2} \Rightarrow x_2 = \frac{x_1 v_{g1}}{v_{g2}}; \text{ if } x_2 > 1, \text{ then final state is superheated.}$
 $\therefore x_1 v_{g1} = v_{sup2} = \left(\frac{v_{g2}}{T_{sat2}} \right) \times T_{sup2}$

② $u_2 - u_1 = \frac{h_2 - 100 p_2 v_2}{100} - (h_1 - 100 p_1 v_1)$

③ $W_{1-2} = 0$; ④ $Q_{1-2} = (u_2 - u_1) + 0 = (u_2 - u_1)$

PROB- The steam contained in a closed vessel of fixed volume 0.14 m^3 , exerts a pressure of 10 bar at 250°C . If the vessel is cooled to pressure falls to 3.5 bar. determine the heat transfer and change in entropy.

SOL- From steam tables At pressure $p_1 = 10 \text{ bar}$; $t_{sat1} = 138.9^\circ\text{C}$, so the superheated steam temp is 250°C which is more than t_{sat1} .

\therefore At 10 bar and 250°C ; $v_{sup1} = 0.2328 \text{ m}^3/\text{kg}$; $h_{sup1} = 2943 \text{ kJ/kg}$; $s = 6.926 \text{ kJ/kgK}$.

mass of steam in the vessel, $m = \frac{V}{v_{sup1}} = \frac{0.14}{0.2328} = 0.6014 \text{ kg}$.

At: 3.5 bar (p_2); $h_{f2} = 584.3 \text{ kJ/kg}$; $h_{fg2} = 2147.3 \text{ kJ/kg}$; $v_{g2} = 0.5237 \text{ m}^3/\text{kg}$

$s_{f2} = 1.727 \text{ kJ/kgK}$; $s_{fg2} = 5.212 \text{ kJ/kgK}$.

Final state dryness fraction $v_{sup2} = x_2 v_{g2} \Rightarrow x_2 = \frac{v_{sup1}}{v_{g2}} = \frac{0.2328}{0.5237} = 0.4443 \text{ (wet)}$.

\therefore Change in entropy = $[h_2 - 100 p_2 v_2] - [h_1 - 100 p_1 v_1] = [h_f + x_2 h_{fg} - 100 p_2 v_2] - [h_{sup1} - 100 p_1 v_{sup1}]$
 $= [584.3 + 0.4443 \times 2147.3] - [2943 - 100 \times 10 \times 0.2328] = 2710.2 \text{ kJ/kg}$

$$\therefore \text{Heat Transfer, } Q_{1-2} = m \cdot [u_2 - u_1] \\ = 0.6014 [-1253.34] = -753.76 \text{ kJ}$$

$$\text{Change in entropy, } S_2 - S_1 = m \cdot [(S_{f2} + x_2 \cdot S_{g2}) - (S_{f1} + x_1 \cdot S_{g1})] \\ = 0.6014 [(1.727 + 0.4443(5.212)) - 6.926] \\ = -0.6014 \times 2.883 = -1.734 \text{ kJ/kgK}$$

Constant pressure process:-

Consider 1 kg of steam with dryness fraction, heated at constant pressure to final condition 2.

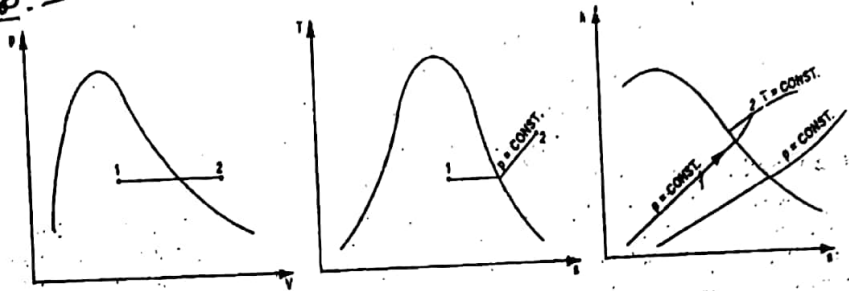


Fig. 7.13 Constant Pressure Process

- ② $W_{1-2} = \text{Workdone} = p_2 [v_2 - v_1]$
 ③ change in internal energy, $(u_2 - u_1) = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$
 ④ Heat transfer, $Q_{1-2} = W + (u_2 - u_1) = (h_2 - h_1)$

PROB. one kg of steam at pressure of 20 bar and dryness fraction 0.85 is heated at a constant pressure to 300°C. Determine (a) Heat transferred (b) workdone (c) change in internal energy.

SOL. At 20 bar, $t_g \approx t_{sat} = 212.4^\circ\text{C}$. The final condition (state 2) is superheated with a temperature of 300°C.

$$\text{At 20 bar, } h_f = 908.6 \text{ kJ/kg; } h_{fg} = 1888.7 \text{ kJ/kg} \\ v_{g1} = 0.099549 \text{ m}^3/\text{kg} \\ h_1 = h_{wet1} = h_f + x_1 h_{fg} = 908.6 + 0.85(1888.7) = 2514 \text{ kJ/kg}$$

and final condition (state 2)

At 20 bar ($p_1 = p_2$) and 300°C (t_{sup})

$$h_2 = 3025 \text{ kJ/kg; } v_2 = v_{sup2} = 0.1255 \text{ m}^3/\text{kg}$$

$$\therefore \text{Heat transfer, } Q_{1-2} = (h_2 - h_1) = 3025 - 2514 = 511 \text{ kJ/kg}$$

$$\text{Workdone, } W_{1-2} = 10^5 [p_2 v_2 - p_1 v_1] = 10^5 [20 \times 0.1255 - 0.85 \times 0.099549] \\ = 81.767 \text{ kJ/kg}$$

$$\therefore \text{change in internal energy, } (u_2 - u_1) = Q - W = 511 - 81.767 = 429.23 \text{ kJ/kg}$$

Constant temperature process

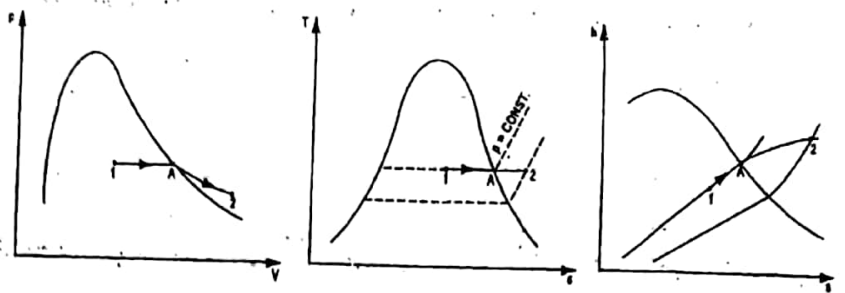


Fig. 7.14 Isothermal Process

isothermal (constant temperature process):

consider 1 kg of steam expands from state 1 to 2 isothermally.

The laws of governing isothermal process: $p_1 v_1 = p_2 v_2$
 $p_1 (x_1 v_{g1}) = p_2 (x_2 v_{g2})$

If $x_2 = \text{less than } 1$; $v_2 = x_2 v_{g2}$

$x_0 x_2 > 1$; $v_{sup2} = T_{sup2} \times \frac{v_{g2}}{T_{sat2}} = v_2$

$\therefore W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1}$

$u_2 - u_1 = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$

$\therefore Q = W + (u_2 - u_1)$ B.

PROB. A quantity of dry saturated steam occupies 0.2634 m^3 at 15 bar. Determine the final condition of steam if it is compressed until the volume is halved. If the compression is carried out in an isothermal manner, determine heat rejection during the compression.

SOL. At 15 bar, $v_g = 0.1317 \text{ m}^3/\text{kg}$ $h_f = 844.7 \text{ kJ/kg}$
 dry saturated ($x=1$) $h_{fg} = 1945 \text{ kJ/kg}$ $h_g = 2789 \text{ kJ/kg}$.

mass of steam, $m = \frac{V}{v_g} = \frac{0.2634}{0.1317} = 2 \text{ kg}$.

Final condition; $v_2 = \frac{v_1}{2} = \frac{0.1317}{2} = 0.0659 \text{ m}^3/\text{kg}$.

Condition:- since the steam is in wet region; the pressure also remains constant [for wet steam, P & T are constant].

$x_2 \cdot v_{g2} = v_2 \Rightarrow x_2 = \frac{0.0659}{0.1317} = 0.5$

$h_2 = h_{f2} + x_2 \cdot h_{fg2} = 844.7 + 0.5(1945.2) = 1817 \text{ kJ/kg}$

\therefore Heat transferred, $Q = m [h_2 - h_1] = 2 [1817.3 - 2789.9]$
 $= -1945.2 \text{ kJ}$ [Heat rejection]

polytropic process: -

polytropic process is given by

$$pV^n = \text{constant}$$

For polytropic expansion

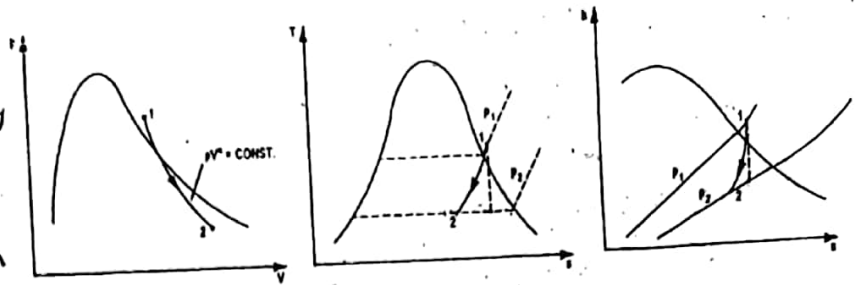


Fig. 7.16 polytropic process

$$\Rightarrow v_2 = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}} \cdot \frac{v_1 v_1}{v_2}$$

$$\text{If } n < 1; v_2 = \alpha_2 \cdot v_{g2}$$

$$\text{If } n > 1; v_2 = T_{sat2} \times \frac{v_{g2}}{T_{sat2}}$$

$$\therefore W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1}$$

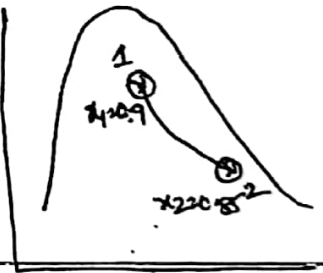
$$Q_{1-2} = (u_2 - u_1) + W; (u_2 - u_1) = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$$

Prob: Steam at 3 bar and 0.9 dry expands in a cylinder till the volume is 4 times at the beginning. The law of expansion is $pV^{1.1} = \text{constant}$. Find the change in internal energy, work done and steam condition at the end of the process.

Sol: From steam tables at $p_1 = 3 \text{ bar}$, $h_{f1} = 561.4 \text{ kJ/kg}$, $h_{g1} = 2163 \text{ kJ/kg}$

The specific volume of vapour, $v_{g1} = 0.6058 \text{ m}^3/\text{kg}$.

$$\therefore \text{Initial volume, } v_1 = x_1 v_{g1} = 0.9 \times 0.6058 = 0.545 \text{ m}^3/\text{kg}$$



$$\text{Final volume, } v_2 = 4 \cdot v_1 = 4 \times 0.545 = 2.18 \text{ m}^3/\text{kg}$$

$$\text{According to law of expansion, } p_1 v_1^{1.1} = p_2 v_2^{1.1} \Rightarrow p_2 = p_1 \left(\frac{v_1}{v_2}\right)^{1.1}$$

$$\text{Find pressure. } \therefore p_2 = 3 \left[\frac{1}{4}\right]^{1.1} = 0.6529 \text{ bar}$$

$$\therefore \text{we know the value, } v_2 = 2.18 \text{ m}^3/\text{kg}$$

From steam tables, ~~Final volume~~, At $p_2 = 0.652 \text{ bar}$, $v_{g2} = 2.548 \text{ m}^3/\text{kg}$.

$$\text{To find final condition of steam, } v_2 = x_2 \cdot v_{g2}; \Rightarrow 2.18 = x_2 \times 2.548 \Rightarrow x_2 = 0.85$$

$$\therefore \text{At } p_2 = 0.652 \text{ bar; } h_{f2} = 368 \text{ kJ/kg; } h_{g2} = 2492 \text{ kJ/kg}$$

$$\therefore \text{Initial enthalpy; } h_1 = h_{f1} + x_1 h_{fg1} = 561.4 + 0.9 \times 2163 = 2508 \text{ kJ/kg}$$

$$h_2 = h_{f2} + x_2 h_{fg2} = 368 + 0.85 \times 2492 = 2486 \text{ kJ/kg}$$

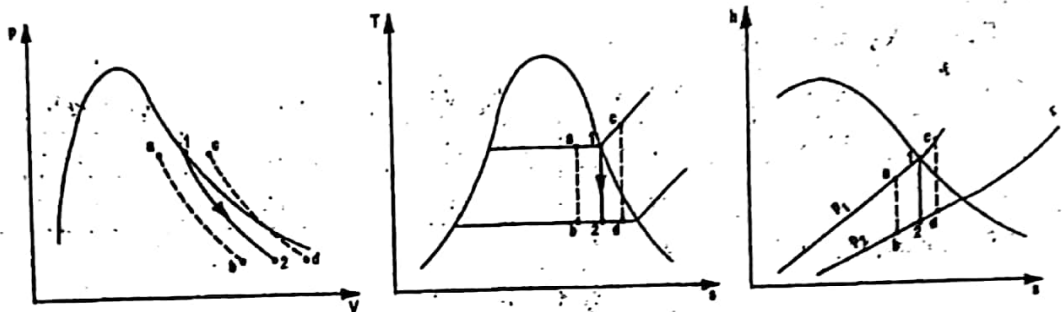
$$\text{change in internal energy (kJ)} = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$$

$$= (2486 - 100 \times 0.652 \times 2.18) - (2508 - 100 \times 3 \times 0.545)$$

$$\text{Work done, } W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1} = \frac{(100 \times 3 \times 0.545 - 70.65 \times 2.18)}{1-1}$$

$$= 218 \text{ kJ/kg}$$

Adiabatic process [Isentropic process] :-



In Adiabatic process, no heat transfer takes place, but work is done due to expansion of internal energy. As there is no heat transfer, entropy remains constant. Therefore, adiabatic process is also referred as isentropic process. It is represented by vertical line on $h-s$ and $T-s$ diagrams.

Consider 1 kg of steam expands isentropically from P_1 to P_2 .

$$\text{Entropy before expansion} = \text{Entropy after expansion}; \quad S_1 = S_2$$

For Adiabatic process, $P_1 V_1^n = P_2 V_2^n$; $W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1}$

$n \rightarrow 1.13$ for wet steam

1.3 for superheated steam

1.35 for dry steam

$$Q_{1-2} = 0$$

PROB. 4 kg of steam expands adiabatically from 16 bar and 250°C to 0.6 bar in a steam turbine such that steam is dry and saturated at the end of expansion. Calculate work done by steam.

From superheated steam table At $P_1 = 16 \text{ bar}$ & $T_{sup} = 250^\circ\text{C}$

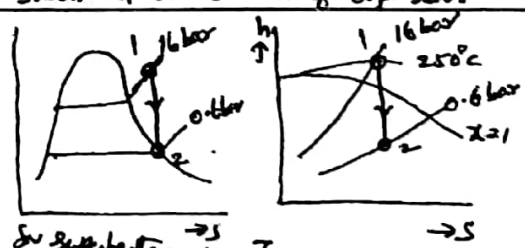
$$v_1 = v_{sup} = 0.1483 \text{ m}^3/\text{kg}$$

For superheated steam initially $P_1 v_1^{1.3} = P_2 v_2^{1.3}$ [$n=1.3$ for superheated steam]

$$\Rightarrow v_2 = v_1 \left[\frac{P_1}{P_2} \right]^{1/1.3} = 0.1483 \left[\frac{16}{0.6} \right]^{0.769} = 0.1483 [26.6]^{0.769} = 1.85 \text{ m}^3/\text{kg}$$

$$\therefore \text{Work done, } W_{1-2} = \frac{P_1 v_1 - P_2 v_2}{n-1} = 100 \left[\frac{16 \times 0.1483 - 0.6 \times 1.85}{1.3-1} \right] = 420.9 \text{ kJ/kg}$$

For 4 kg; $W_{1-2} = 4 \times 420.9 = 1683 \text{ kJ/kg}$



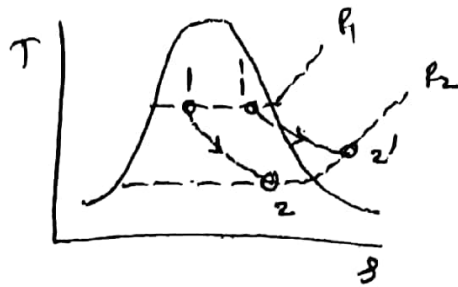
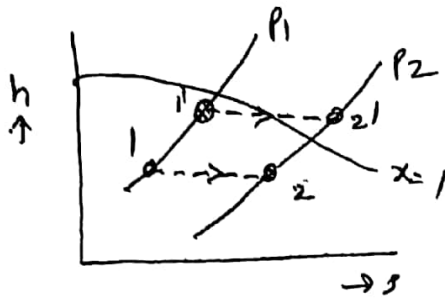
Throttling process :-

Flow of fluid through a restricted passage causes pressure drop is called throttling process. For example, flow through partially opened valve, capillary tube and porous plug is regarded as throttling process. During throttling process, Enthalpy remains constant, but quality of steam is impaired due to internal friction.

For throttling process, $h_1 = h_2$

For final condition is superheated,

$$h_{f1} + x_1 h_{fg1} = h_{g2} + c_p [t_{sup2} - t_{sat2}]$$



PROB.

Steam initially at a pressure of 10.5 bar and 0.96 dry throttled at a pressure of 1 bar. Find final condition of steam. Also calculate change in entropy per kg of steam.

P bar	$t_{sat}, ^\circ C$	$h_f, \text{KJ/kg}$	$h_{fg}, \text{KJ/kg}$	$h_g, \text{KJ/kg}$	$S_f, \text{KJ/kgK}$	$S_g, \text{KJ/kgK}$
10.5	182	772.0	2006	-	2.159	6.566
1	99.63	-	-	2675.4	-	7.36

Take c_p for superheated steam = 2.1 KJ/kgK.

SOL.

For, Throttling process

$$h_{f1} + x_1 h_{fg1} = h_{g2} + c_p (t_{sup2} - t_{sat2})$$

$$772 + 0.96 (2006) = 2675 + 2.1 (t_{sup2} - 99.63)$$

$$t_{sup2} = 110.27^\circ C$$

Entropy at 10.5 bar and 0.96 dry

$$S_1 = S_{f1} + x_1 S_{fg1} = S_{f1} + x_1 (S_{g1} - S_{f1})$$

$$= 2.159 + 0.96 (6.566 - 2.159) = 6.3897 \text{ KJ/kgK.}$$

Entropy at 1 bar and 110.27°C

$$S_2 = S_{g2} + c_{p3} \ln \frac{T_{sup2}}{T_{sat2}} = 7.36 + 2.1 \ln \frac{(110.27 + 273)}{(99.63 + 273)}$$

$$= 7.419 \text{ KJ/kgK.}$$

$$\therefore \text{Change in Entropy, } S_2 - S_1 = 7.419 - 6.3897 = 1.0293 \text{ KJ/kgK.}$$

+