Chapter 3

Properties of Pure Substances

CHAPTER HIGHLIGHTS

- *Introduction*
- *Gibbs Phase Rule*
- *Phase Transformation*
- *Latent Heat of Fusion*
- *Saturation Temperature and Saturation Pressure*
- *Property Diagrams for Phase Change Processes*
- *P–T Diagram*
- *Different Regions*
- *Wet Region*
- *Enthalpy at Various Points*
- *Mollier Diagram*
- *Various Plots*
- *Clausius–Clapeyron Equation*
- *Determination of Dryness Fraction of Steam*

INTRODUCTION

- A substance that has a fixed chemical composition throughout is called a pure substance. For example, water, nitrogen, helium, CO_2.
- Air is a mixture of several gases, but it is often considered to be a pure substance because it has a uniform chemical composition.

Pure substance	Not a Pure Substance
1. air	(a) air + diesel vapour
2. air + liquid air	(b) air + petrol vapour
3. steam	(c) air + fuel vapour
4. steam + water	(d) gaseous combustion products

Phases

- A substance exists in different phases. For example at room temperature and pressure, copper is solid, mercury is a liquid and nitrogen is a gas.
- Even though there are three principal phases – solids, liquids and gases – a substance may have several phases within a principal phase, each with a different molecular structure carbon for example may exist as graphite or diamond in the solid phase. Helium has two liquid phases, iron has three solid phases.
- If a system contains more than one phase, they are separated by a phase boundary.
- A system which is uniform throughout both in chemical composition and physical state is called a phase.
- When temperature or pressure is increased all substances change their specific volumes
- The molecules in a solid are arranged in a three dimensional pattern that is repeated throughout.

In liquid phase the molecules are not in fixed positions but they are moving (rotating or translating) freely. In solid phase, the molecules spacing are similar as of liquid phase but the molecules are in fixed position. In gaseous phase, the molecules are far apart from each other and the orders of the molecules are disordered.

GIBBS PHASE RULE

$$P + F = C + 2$$

Where

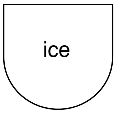
P = number of phases

F = Degree of freedom or minimum number of independent variables required to fix the state

C = number of components

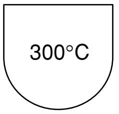
Example:

1.



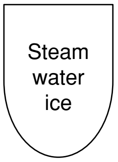
$P = 1$
$C = 1$
$1 + F = 1 + 2$
$F = 2$

2.



$P = 2$
$C = 1$
$2 + F = 1 + 2$
$F = 1$

3.



$P = 3$
$C = 1$
$3 + F = 1 + 2$
$F = 0$

PHASE TRANSFORMATION

When the temperature and pressure changes, the phase transformation occurs.

Phase Transformation of H_2O	Process Name
1. Solid → Liquid	Melting or Fusion of ice
2. Liquid → Solid	Freezing or solidification
3. Liquid → Vapour	Vaporization
4. Vapour → liquid	Condensation
5. Solid → vapour	Sublimation
6. Vapour → solid	Ablimation

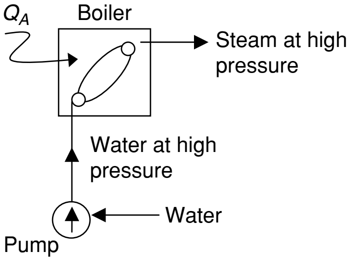
NOTES

1. For general substances:
   Solid → liquid; melting (substance expands)
   Liquid → solid; freezing (substance contracts)
2. For water
   Ice(s) → water(L) → melting (substance contracts)
   Water(L) → ice(s) → Freezing (substance expands)

Steam

It is most popularly used pure substance. Since used as working substance in power plants.

Steam Generation

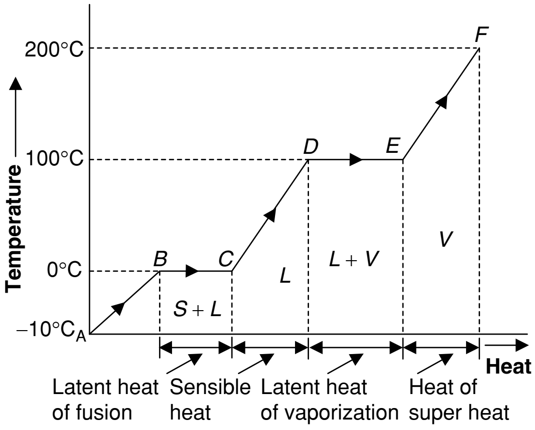


Water is supplied to the boiler at high pressure where heat is added continuously to produce steam.

Phase Transformation (Ice into Steam) at Constant Pressure

Let 1 kg of ice at –10°C contained in a cylinder under atmospheric pressure undergoing heating process. The following observations were made during phase change process.

Temperature–Heat Diagram



AB: Solid state
BC: melting
CD: Liquid state
DE: Vaporization
EF: Vapor state
S: Solid state
L: Liquid state
V: Vapour state

Latent Heat of Fusion

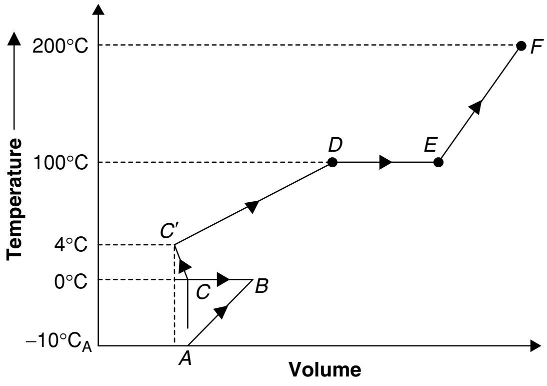
The quantity of heat required to transform ice into water at constant temperature (i.e., 0°C) is called latent heat of fusion or enthalpy of fusion.

Latent heat of fusion at 1 atm = 335KJ/Kg
Latent heat of vaporization at 1 atm = 2256.9 kJ/kg

Sensible Heat

'The quantity of heat required to change the temperature from liquid state to vaporization point is called the sensible heat.'

Temperature–Volume Diagram



A – B: Solid state
B – C: Melting
C – C′: Liquid at 4°C
C – D: Liquid state
D – E: Vaporization
E – F: Vapour state

NOTE

Water has maximum density and minimum volume at 4°C.

Compressed Liquid and Saturated Liquid

The liquid phase which is not about to vapourise is called compressed liquid or subcooled liquid.

A liquid that is about to vapourise when addition of heat is given is known as the saturated liquid.

Saturated Vapour and Superheated Vapour

A vapour which is about to condense on removal of heat from it is known as saturated vapour.

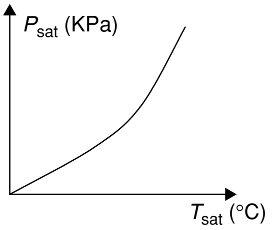
A vapour that is not about to condense is called as superheated vapour.

Useful tip: Let us consider the temperature of a vapour as 300°C. If we transfer some heat from the vapour, the temperature may drop somewhat but no condensation will take place as long as the temperature remains above 100°C.

Saturation Temperature and Saturation Pressure

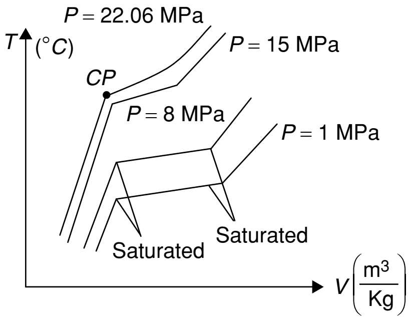
At a given pressure, the temperature at which a pure substance changes its phase is called the saturation temperature T_{sat}.

Likewise, at a given temperature, the pressure at which a pure substance changes its phase is called the saturation pressure P_{sat}.



PROPERTY DIAGRAMS FOR PHASE CHANGE PROCESSES

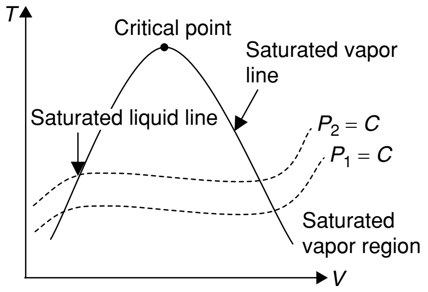
T–V Diagram



As the pressure increases, the saturation line (saturated liquid line and saturated vapour line) shrinks and merges on a point which is known as critical point. At this point, the latent heat becomes zero, the pressure is 221.2 bar and temperature is 374°C. The superheated vapour phase of H_2O lies at the right side of the saturated vapour line and in this region known as superheated region, the substance exists in a single phase only.

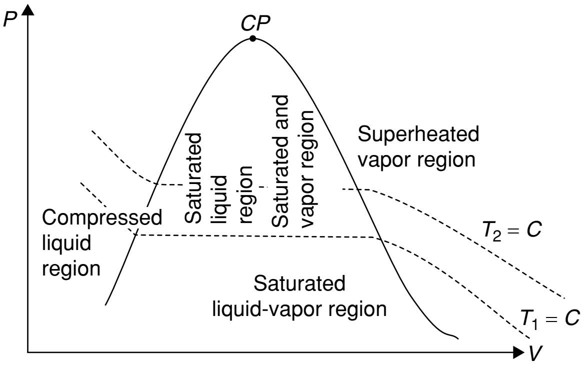
Useful tip: The saturated liquid states can be connected by a line called the saturated liquid line and saturated vapour states can be connected by a line called the saturated vapour line.

The compressed liquid phase are located at the left side of the saturated liquid line and in the region known as subcooled region, the substance also exists in a single phase only. The wet liquid is a two-phase region in which liquid and vapour exists in equilibrium condition and is located between saturated vapour line and saturated liquid line.

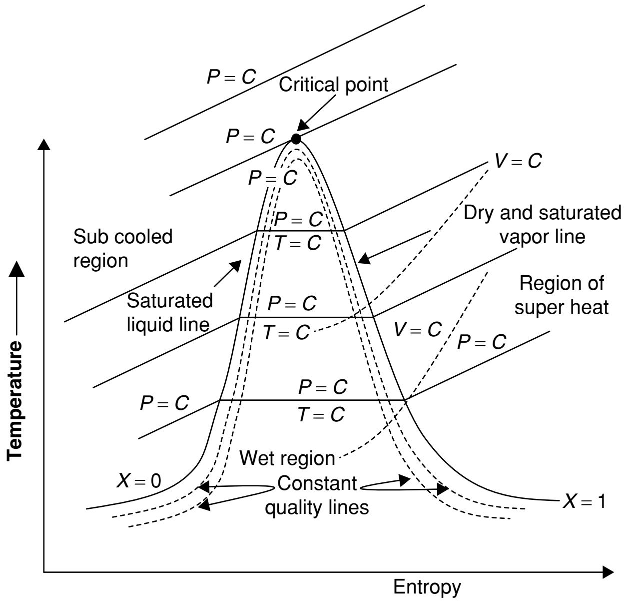


P–V Diagram

The general shape of the P–V diagram of a pure substance is very much like the T–V diagram, but the $T = C$ lines have

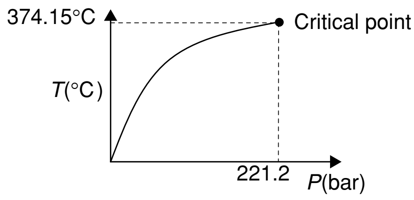


T–S Diagram



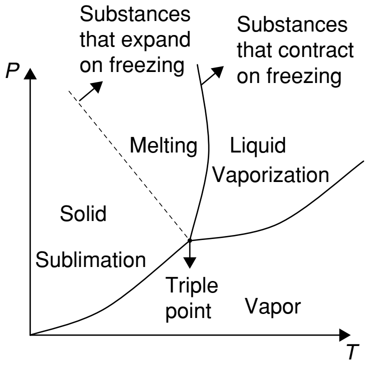
NOTES

1. If the temperature is given P_{sat} is fixed
2. If the pressure is given T_{sat} is fixed
3. $P_{sat}\uparrow \rightarrow T_{sat}\uparrow$



4. With increasing Temperature boiling point increases.
5. Pressure and Temperature dependent properties for pure substance, i.e., depend on one another.
6. If pressure increases – Latent heat decreases.
7. At critical point Latent heat of vaporization is zero i.e., $h_{fg} = 0$.
8. Sensible heat responsible for increase the Temperature.
9. Latent heat responsible for phase change.

P–T Diagram



Useful tip: Triple point is a point at which it exists as a solid, liquid or vapour. For water, the triple point temperature and pressure are 0.01°C and 0.6117 KPa respectively.

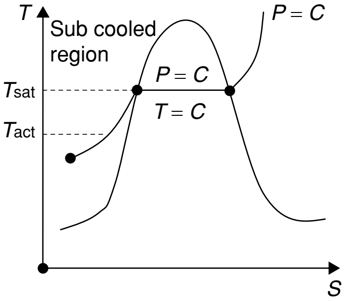
Useful tip: The sublimation and vaporization line has positive slope and fusion line has –ve slope for water. This –ve slope is due to the anomalous expansion of water on freezing.

Useful tip: Only 3 fluids have –ve slope for fusion line. They are water, antimony and bismuth. Others are having +ve slope for fusion curve.

DIFFERENT REGIONS

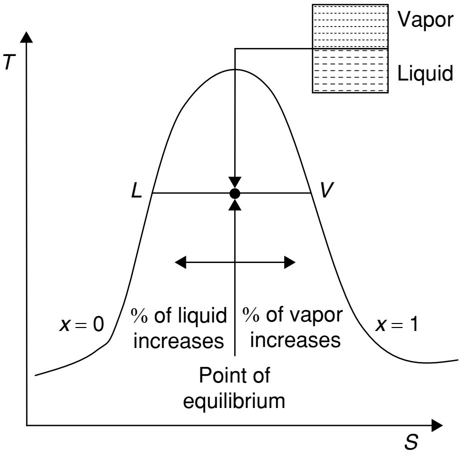
Sub Cooled Region or Under Cooled Region

- If the Temperature of substance is less than saturation temperature, referred as sub cooled region.
- Degree of sub cooling = $T_{\text{sat}} - T_{\text{act}}$



Wet Region: (Two Phase Mixture Region)

- In this region both liquid and vapour exists in equilibrium at saturation temperature.
- The relative amount of each phase present in wet region determines the quality (or) dryness fraction' of steam
- It is denoted by letter 'x'



$$\text{Dryness fraction '}x\text{'} = \frac{\text{mass of Dry steam}}{\text{Total mass of mixture}}$$

$$'x' = \frac{m_s}{m_s + m_w} = \frac{m_g}{m_g + m_w}$$

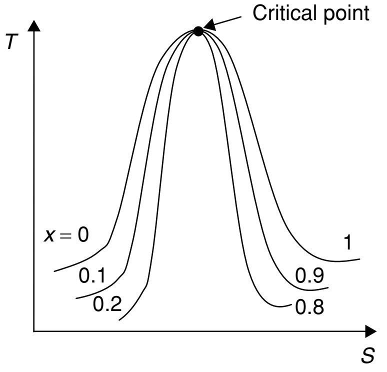
$g \rightarrow$ gas
$s \rightarrow$ steam
$w \rightarrow$ water
'x' is intensive property

NOTES

1. For saturated liquid $x = 0$
2. For saturated vapour $x = 1$
3. Wetness fraction $= 1 - x$

$$= \frac{m_w}{m_s + m_w}$$

Example: The dryness fraction of steam is 0.9 means 0.9 kg of steam + 0.1 kg of suspended water particles, wetness fraction = 0.1



at critical point

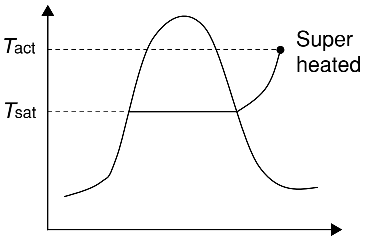
$P_c = 221.2$ bar

$T_c = 374.15°\text{C}$

$V_c = 0.00317\ \text{m}^3/\text{kg}$

Super Heated Region

If the substance temperature is greater than saturation temperature it can be referred as super heated region



That is, $T_{\text{act}} > T_{\text{sat}}$

$T_{\text{sup}} > T_{\text{sat}}$

Degree of super heat = $T_{\text{sup}} - T_{\text{sat}}$

Specific Volume of Mixture

Let

$V \rightarrow$ Total volume of mixture

$m \rightarrow$ mass of mixture.

$m_f \rightarrow$ mass of fluid, $V_f \rightarrow$ volume of fluid

$m_g \rightarrow$ mass of gas, $V_g \rightarrow$ volume of gas

$$m = m_f + m_g$$

$$V = V_f + V_g$$

$$mv = m_f v_f + m_g v_g$$

$$V = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$$

$$V = \left(\frac{m_f}{m_f + m_g}\right) v_f + \left(\frac{m_g}{m_f + m_g}\right) v_g = (x)V_g + (1 - x)V_f$$

$$V = V_f + x\,(V_g - V_f)$$

but $V_g >> V_f \qquad V_f \approx 0$

$$V = x\,V_g$$

Similarly

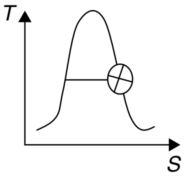
$$h = h_f + x(h_g - h_f)$$

$$s = s_f + x(s_g - s_f)$$

$$u = u_f + x(u_g - u_f)$$

Specific Volume in Various Regions

1. Dry and saturated state



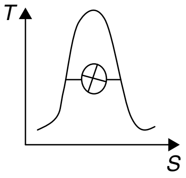
$$V = V_g$$

$$V = V_f + x(V_g - V_f)$$

$$x = 1$$

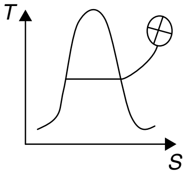
$$V = V_g$$

2. Wet region



$$V = V_f + x(V_g - V_f)$$

3. Super heated state



$$\frac{P_s V_s}{T_s} = \frac{P_{\text{sup}} \cdot V_{\text{sup}}}{T_{\text{sup}}}$$

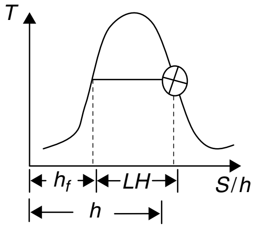
Since $P = C$

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

$$V_{\text{sup}} = T_{\text{sup}} \times \frac{V_{\text{sat}}}{T_{\text{sat}}}$$

Enthalpy at Various Points

1. Dry and saturated condition



$$h = h_f + LH$$

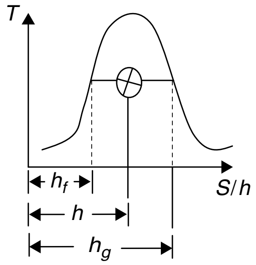
$$h_g = h_f + LH$$

$$LH = h_g - h_f$$

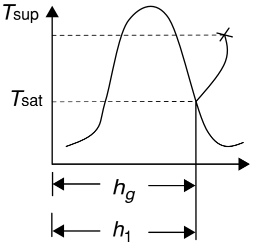
2. Point is in wet region

$$h_g - h_f = LH$$

$$h = h_f + xh_{fg}$$



3. When the point is in superheat region



$$h = h_g + \Delta h$$

$$dh = c_p \, \Delta T$$

$$h = h_g + c_{p\text{ vapour}}\,(T_1 - T_{\text{sat}})$$

NOTE

C_p of vapour = 4.2KJ/Kg

Entropy at Various Points

1. When the point is on saturated vapour curve

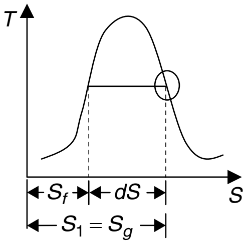
$$S_1 = S_f + dS$$

$$ds = S_g - S_f$$

$$ds = \frac{\delta Q}{T} = \frac{L.H}{T_{\text{sat}}}$$

$$\delta Q = LH$$

$$S = S_f + \frac{LH}{T_{\text{sat}}}$$



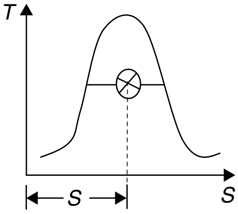
2. When the point is in wet region

$$S = S_f + x(ds) = S_f + x(S_g - S_f)$$

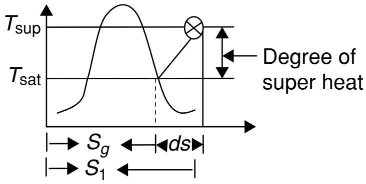
$$S = S_f + x\left(\frac{L.H}{T_{\text{sat}}}\right)$$

NOTE

$$S_f = S_w = C_{pw} \ln\left(\frac{T_{\text{sat}}}{273}\right)$$



3. When the point is in super heated region



$$S = S_g + dS$$

$$ds = S_f - S_i = C_p \ln\left(\frac{T_f}{T_i}\right) - R \ln\left(\frac{P_f}{P_i}\right)$$

$$= C_p \ln\left(\frac{T_f}{T_i}\right); \text{ Since } P_f = P_i$$

$$S_f - S_i = C_p \ln\left(\frac{T_{\text{sup}}}{T_{\text{sat}}}\right)$$

$$S_{\text{sup}} = S_g + C_{p\text{ vapour}} \ln\left(\frac{T_{\text{sup}}}{T_{\text{sat}}}\right)$$

MOLLIER DIAGRAM

The enthalpy – entropy(h – s) diagram is known as the Mollier diagram.

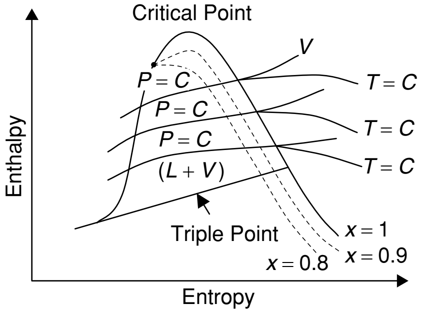
$TdS = dh - VdP$

$TdS = dh$ at constant pressure, i.e., $dP = 0$

$$\left(\frac{dh}{dS}\right)_P = T$$

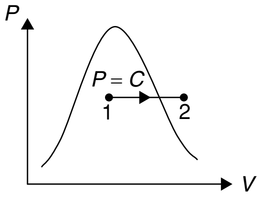
Useful tip: The slope of Mollier diagram is equal to its absolute temperature 'T'.

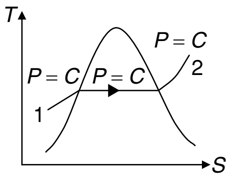
H–S Diagram

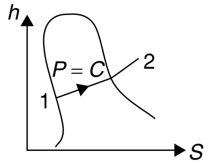


VARIOUS PLOTS

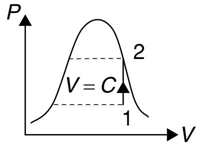
Isobaric Process ($P = C$)

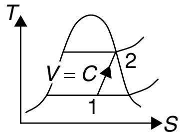


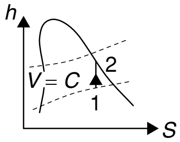




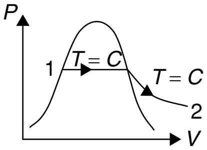
Isochoric Process ($V = C$)

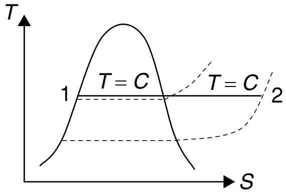


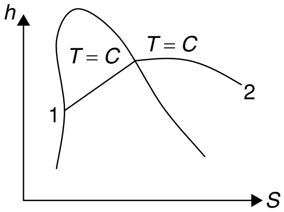




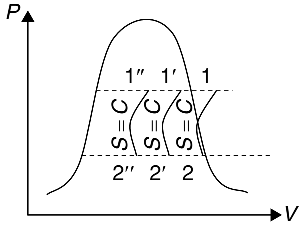
Isothermal Process

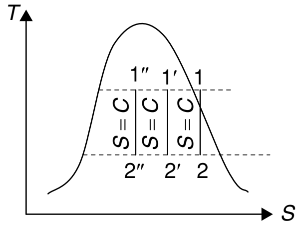


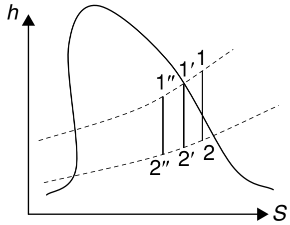




Adiabatic Process ($S_1 = S_2$)







Useful tip: On a *P*–*V* diagram, triple point looks like a line. On energy–volume diagram, triple point looks like a triangle.

Clausius–Clapeyron Equation

The approximations made in obtaining the Clausius–Clapeyron equation for liquid–vapour phase transition are

- The volume of the liquid phase is negligible compared to the volume of the gaseous phase.
  Therefore
  $$\Delta V = V_g - V_f = V = \frac{RT}{P}$$
- The vapour phase is an ideal gas.
- The Clausius–Claperon equation is
  $$\left(d\ \ln\frac{P}{dT}\right) = \left(\frac{h_{fg}}{RT^2}\right)$$
- If h_{fg} is assumed to be constant over a small temperature range, then
  $$\ln\left(\frac{P_2}{P_1}\right) = \left(\frac{h_{fg}}{R}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$
  $$\text{(Or)}\ \ln P = \left(\frac{h_{fg}}{RT}\right) + \text{constant}$$
- A plot of (In *P*) $Vs\left(\frac{1}{T}\right)$ yields a straight line with a slope $\left(\frac{-h_{fg}}{R}\right)$

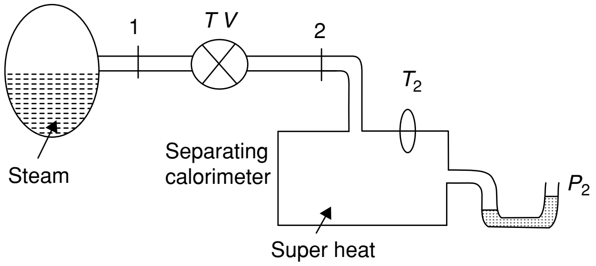
Determination of Dryness Fraction of Steam

Dryness fraction is determined by using 3 methods.

1. Throttling calorimeter
2. Separating and throttling calorimeter
3. Electrical calorimeter

Throttling Calorimeter

It is used for steam having dryness fraction greater than 90%.



Here, high pressure steam is throttled to low pressure such that after throttling, steam becomes superheated. After throttling pressure 'P_2' and temperature 'T_2' are noted. For good results, after throttling, the degree of superheat must be atleast 5 – 10°C. According to the noted P_2 and T_2, from superheat tables, enthalpy h_2 and entropy S_2 are obtained.

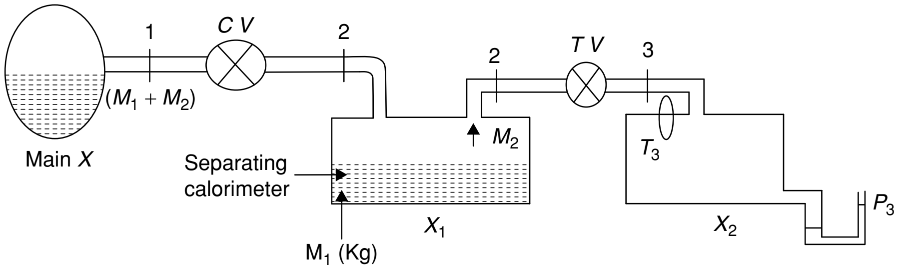
In a throttling process, $h_1 = h_2$

$$h_{f_1} + x(h_{g_1} - h_{f_1}) = h_2$$

From this equation we can calculate the dryness fraction 'x'.

Separating and Throttling Calorimeter

It is used for steam having dryness fraction less than 90%.



Steam from the main is first passed through a separator, where some part of the moisture separates out due to the sudden change in direction and falls by gravity and the partially dry vapour is then throttled and taken to the superheated region. 'm_1' represents the separated moisture and 'm_2' represents the 'kg' of mass throttled and then condensed to water. 'h_3' can be found out from the superheated table. Then $h_2 = h_3$ due to throttling'

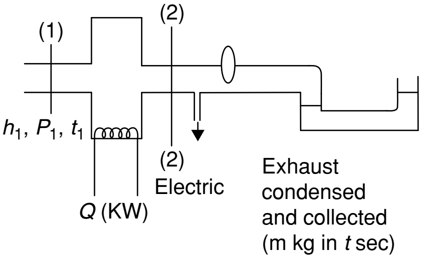
$$hf_2 + x_2 (hg_2 - hf_2) = h_3$$

x_2 can be found from this equation

x_1 is obtained by $x_1 = \dfrac{m_2}{m_1 + m_2}$

Dryness fraction in the boiler $\boxed{x = x_1 x_2}$

Electrical Calorimeter



Here, the sample of steam is passed in steady flow through an electric heater. The electrical energy input 'Q' should be sufficient to take the steam to the superheated region where pressure P_2 and temperature t_2 are measured. If 'I' is the current flowing through the heater in amperes and 'V' is the voltage across the coil, then at steady state, $Q = V_I \times 10^{-3}$ kW

If 'm' is the mass of steam taken in 't' seconds under steady flow condition, then the steady, flow energy equation for the heater (as control volume) gives $m_1 h_1 + Q = m_1 h_2$ where 'm_1' is the steam flow rate in kg/s

$$\left(m_1 = \frac{m}{t}\ kg/s\right)$$

$$h_1 + \frac{Q}{m_1} = h_2$$

With h_2, Q and m_1 being known, h_1 can be calculated. Now $h_1 = h_{f1} + x_1 h_{fg1}$. Hence '$x_1$' can be evaluated.

Solved Examples

Example 1: A vessel of volume 0.06 m^3 contains a mixture of saturated water and saturated steam at a temperature of 99.63°C. If the mass of the liquid present in the vessel is 10 kg then the specific internal energy (in kJ/kg) of the system will be

Saturated table is given below:

T (°C)	**P(MPa)**	**v_f(m^3/kg)**	**v_g(m^3/kg)**	**h_f(kJ/kg)**	**h_g(kJ/kg)**
99.63	0.1	0.001043	0.0694	417.6	2675.5

(A) 496.3
(B) 417.6
(C) 568.76
(D) 471.3

Solution:

Volume of liquid, $V_f = m_f \times v_f = 10 \times 0.001043$

$\Rightarrow \quad V_f = 0.01043$ m^3/kg

Volume of vapour, $V_g = 0.06 - 0.01043$

$= 0.04957$ m^3/kg

Mass of vapour, $m_g = \dfrac{V_g}{v_g} = \dfrac{0.04957}{0.0694} = 0.714265$ kg

Dryness fraction, $x = \dfrac{m_g}{m_f + m_g} = \dfrac{0.714265}{10.714265}$

$\Rightarrow \quad x = 0.0667$

Now specific volume, $v = v_f + xv_{fg}$

$\Rightarrow \quad v = 0.001043 + [0.0667 \times (0.0694 - 0.001043)]$

$\Rightarrow \quad v = 0.005602 \text{ m}^3/\text{kg}$

Specific enthalpy, $h = h_f + xh_{fg}$

$\Rightarrow \quad h = 417.6 + 0.0667\,[2675.5 - 417.6]$

$\Rightarrow \quad h = 568.2$ kJ/kg

Specific internal energy, $u = h - pv$

$\Rightarrow \quad u = 568.2 - [0.1 \times 10^3 \times 0.005602]$

$\Rightarrow \quad u = 568.76$ kJ/kg

Example 2: A rigid closed container of 10 m^3 volume contains saturated steam at 1 MPa. Due to the heat losses from the container to the surrounding, the pressure reduces to 0.1 MPa. The surrounding temperature is given as 27°C. The heat lost by the container to the surrounding in MJ is

P(MPa)	v_f(m³/kg)	v_g(m³/kg)	u_f(kJ/kg)	u_g(kJ/kg)	h_f(kJ/kg)	h_g(kJ/kg)
0.1	0.001043	1.694	417.3	2506.1	417.4	2675.5
1.0	0.001127	0.1944	761.7	2583.6	762.8	2778.1

(A) 1927.3 (B) 198.3 (C) 19.27 D) 99.16

Solution:

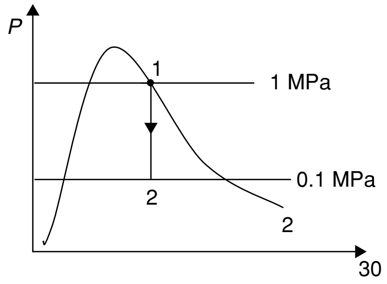
$V = 10\ m^3$

Process: V = Constant, $\delta Q = dU + \delta W$

But $\delta W = 0 \Rightarrow \delta Q = dU = U_2 - U_1$

$h_1 = h_g = 2778.1$ kJ/kg

$v_1 = v_2 = v_f + x_2\, v_{fg}$



$\Rightarrow 0.1944 = 0.001043 + x_2(1.694 - 0.001043)$

$\Rightarrow x_2 = 0.1142$

$u_1 = u_g = 2583.6$ kJ/kg and $u_2 = u_f + x_2\, u_{fg}$

$\Rightarrow u_2 = 417.3 + 0.1142\,(2506.1 - 417.3)$

$\Rightarrow u_2 = 655.84$ kJ/kg

$\therefore \quad u_1 - u_2 = 2583.6 - 655.84 = 1927.76$ kJ/kg

Now $v = \dfrac{V}{m} \quad \Rightarrow \quad 0.1944 = \dfrac{10}{m}$

$\Rightarrow m = 51.44$ kg

$\therefore\ \delta Q = -1927.76 \times 51.44$

$\Rightarrow \delta Q = 99.163$ MJ [Loss]

Example 3: Steam initially at 0.1 MPa, 300°C expands isentropically in a steam turbine to 40°C. For 2 kg of steam, the ideal work output of the turbine will be

Saturated table at 40°C

T(°C)	*P*(kPa)	h_f(kJ/kg)	h_{fg}(kJ/kg)	s_f(kJ/kg-K)	s_{fg}(kJ/kg-K)
40	7.384	167.57	2406.7	0.5725	7.6845

Super heated table at $P = 0.1$ MPa, $T = 300°C$

$h = 3073.3$ kJ/kg, $S = 8.2158$ kJ/kg-K

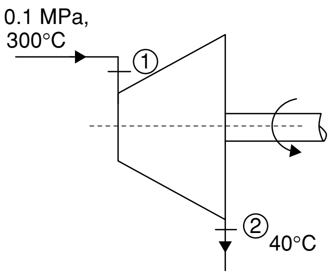
(A) 943.72

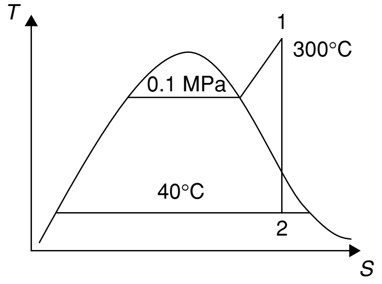
(B) 1123.67

(C) 1025.87

(D) 883.61

Solution:





$s_1 = 8.2158$ kJ/kg-K

$h_1 = 3074.3$ kJ/kg

Now $W = [h_1 - h_2]m$ [SFEE]

Now $s_1 = s_2 \quad \Rightarrow \quad 8.2158 = [s_f + x_2 s_{fg}]$

$\Rightarrow \quad 8.2158 = 0.5725 + x_2\,(7.6845)$

$\Rightarrow \quad x_2 = 0.994638$

$h_2 = [h_f + x_2\, h_{fg}] = 167.57 + 0.994638\,(2406.7)$

$\Rightarrow \quad h_2 = 2561.365$ kJ/kg

$W = m[h_1 - h_2] = 2[3074.3 - 2561.365]$

$\Rightarrow \quad W = 1025.87$ kJ

EXERCISES

Practice Problems I

Direction for questions 1 to 16: Select the correct alternative from the given choices.

1. A sample of steam weighing 4.7 kg if the total heat of the sample is 11000 kJ and the steam pressure is 5 bar (absolute). Then dryness fraction of a sample of steam is the properties of steam at 5.0 bar are $h_f = 640.2$ kJ/kg; $h_{fg} = 2108.5$ kJ/kg

(A) 0.806
(B) 0.851
(C) 0.901
(D) 0.98

Direction for questions 2 to 4: Determine the quantity of heat required (KJ/kg) to generate one kg of steam at a pressure of 7.8 bar absolute from water at a temperature of 25°C

2. When the dryness fraction is 0.88

(A) 2000
(B) 2417.4
(C) 3200
(D) 3515.4

3. When the steam is just dry

(A) 3215
(B) 2663
(C) 2514
(D) 1525

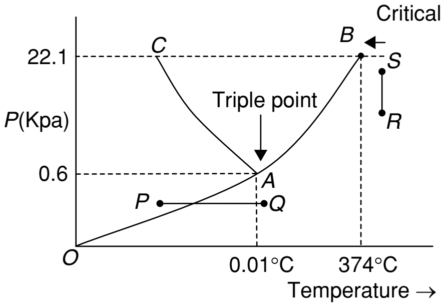
4. When it is superheated at constant pressure to 270°C assuming mean specific heat of super heated steam to be 2.5

(A) 1500.5
(B) 2242.5
(C) 2812.4
(D) 2915.1

Steam properties

Pressure (bar)	Saturation Temp (°C)	h_f(KJ/kg)	h_g(KJ/kg)	h_{fg}(KJ/kg)
7.8	169.4	716.5	2768	2051.6

5. The critical point and triple point data for water are
$T_c = 374°C$; $P_c = 22.1\ MP_a$
$T_T = 0.01°C$; $P_T = 0.6\ KP_a$



Indicate the phase change that will occur in the following cases

(i) Ice at 0.5 Kpa is heated isobarically
(ii) Water vapour at 400°C is compressed isothermally

(A) (i) along *PQ* (ii) along *RS*
(B) (i) along *RS* (ii) along *PQ*
(C) (i) along *OS* (ii) along *AS*
(D) (i) along *AS* (ii) along *OA*

6. 8 kg of water at 35°C is converted into steam at a pressure of 16 bar absolute with 130°C super heat. The average value of specific heat and volume of superheated steam in kJ/kg K and m^3/kg respectively are

Properties of stem at 16 bar:

Pressure Bar	Saturation Temp (°C)	(V_g) m^3/kg	(h_g) KJ/kg	h_{sup} (KJ/kg)
16	201.4	0.124	2794.0	3104

(A) 2.385, 0.258
(B) 0.157, 2.385
(C) 0.258, 0.157
(D) 2.385, 0.157

7. The mass of 0.1 m^3 of wet steam at an absolute pressure of 8.5 bar and having dryness fraction of 0.75 is

(A) 0.153kg
(B) 0.20kg
(C) 0.587kg
(D) 0.625kg

8. Steam at 20 bar and 295°C passes through a pipe at a velocity of 120 m/s. If steam flows at the rate of 500 kg/h, the diameter of the pipe in mm is

The steam properties at 20 bar

Pressure (bar)	Saturation temp (°C)	V_g (m^3/kg)
20	212.4	0.0996

(A) 13.1
(B) 15.2
(C) 18.3
(D) 20.4

9. The external work done and the internal latent heat of steam at a pressure of 10 bar absolute and of dryness fraction 0.9 respectively in kJ/kg are,

The Properties of steam at 10 bar

P (bar)	V_g (m^3/kg)	h_{fg} (KJ/kg)
10	0.194	2015.3

(A) 174.6,1639
(B) 180, 2000
(C) 189, 2200
(D) 195, 2500

Direction for questions 10 to 11: Find the total heat and internal energy in kJ/kg of steam at a pressure of 3 bar

10. When the steam is just dry and saturated

(A) 2543, 2725
(B) 2725, 2543
(C) 1745, 1825
(D) 1825, 1745

11. When the steam has a dryness fraction of 0.8 are

(A) 1147, 1292
(B) 2147, 2292
(C) 2292, 2147
(D) 1292, 1147

At 3 bar, the properties of steam are

P (bar)	T_{sat} (°C)	V_g(m^3/kg)	h_f(KJ/kg)	h_{fg} (KJ/kg)
3	133.5	0.606	561.6	2163.8

Direction for questions 12 and 13: Steam at a pressure of 8 bar and 0.95 dry is expanded to a pressure of 1.7 bar.

Properties of steam:

P (bar)	T_{sat} (°C)	h_f	h_{fg}	S_f	S_{fg}
8	170.4	721.1	2048.0	2.046	4.617
1.7	115.2	483.2	2211.2	1.475	5.706

12. The final condition of steam when the expansion is adiabatic

(A) 0.865 (B) 0.866
(C) 0.867 (D) 0.868

13. The final condition of steam when the expansion is throttling

(A) 0.984 (B) 0.985
(C) 0.986 (D) 0.987

14. In an experiment to determine the dryness fraction of steam, the mass of water separated was 1.2 kg in 15 mts and the mass of steam passed out at the same time was 4.8 kg. The dryness fraction is

(A) 40% (B) 25%
(C) 50% (D) 80%

15. At critical point, i.e., p = 225.65 kg/cm^2, the latent enthalpy of vaporization is

(A) Maximum (B) Minimum
(C) Zero (D) None of the above

16. In a piston cylinder arrangement, a constant pressure of 7 bar is maintained in the cylinder by the weight in the piston. The steam flowing from the main pipe at 7 bar and 300°C enters the cylinder. The final temperature in °C is

(A) 200°C (B) 300°C
(C) 400°C (D) 600°C

Practice Problems 2

Direction for questions 1 to 2: Steam at 12 bar absolute pressure 0.95 dry is contained inside a vessel having a volume of $2m^3$. The delivery valve is opened and the steam is blown off. The period of blowing is so regulated that the pressure drops to 5 bar. The delivery valve is then closed and the vessel is cooled until the pressure becomes 4 bar. Determine

1. The mass of steam blown off

(A) 10 kg (B) 5.5 kg
(C) 2.5 kg (D) 2 kg

2. The dryness fraction of steam in the vessel after cooling

(A) 1 (B) 0.985
(C) 0.785 (D) 0

Assume that total heat per kg of steam in the vessel remains constant while blowing off

The properties of steam are tabulated below:

Pressure (bar)	Specific Volume (m^3/kg)	Sensible heat (KJ/kg)	Latent Heat (KJ/kg)
12	0.163	798.6	1986.2
5	0.375	640.2	2108.5
4	0.463	604.7	2133.8

Direction for questions 3 to 4: 5 kg of steam expands adiabatically from 16 bar and 250°C to 0.6 bar in a steam turbine such that the steam is dry and saturated at the end of expansion Determine

3. The work done by the steam in kJ/kg

(A) 267.8 (B) 525.6
(C) 1000.2 (D) 1235

4. Work lost due to irreversibility in kJ

(A) 20.56 (B) 222.5
(C) 1000.4 (D) 1531.75

The properties of steam are tabulated below:

Pressure (bar)	Enthalpy (KJ/kg)		Entropy (KJ/kg k)	
0.6	h_f	h_{fg}	S_f	s_{fg}
	360	2293	1.145	6.386

For super heated steam

Pressure and Temp (bar)	(%)	Enthalpy (KJ/kg)	Entropy (KJ/kg k)
16	250°	2920.8	6.6782

5. A vessel of volume 1.0 m^3 contains a mixture of liquid water and steam in equilibrium at 1.0 bar. Given that 90% of the volume is occupied by the steam. The dryness fraction of the mixture is

(A) 0.98 (B) 5.266×10^{-3}
(C) 0.67 (D) 0.522×10^{-3}

Assume at 1.0 bar V_f = 0.001 m^3/kg, V_g = 1.7 m^3/kg

6. In the vicinity of the triple point, the vapour pressure of liquid and solid ammonia are given by $\ell n(P) = 15.16 - 3063/T$ and $\ell nP = 18.70 - 3754/T$ respectively where P is in atmospheres and T is in Kelvin The temperature at triple point in K is

(A) 150.50 (B) 147.5
(C) 130 (D) 195.19

7. Given below is an extract from steam tables.

Temperature (P_{sat}) (°C)	Pressure (bar)	Specific Volume (m^3/kg)		Enthalpy (KJ/kg k)	
41.5	0.080	(V_f)	(V_g)	h_f	h_g
		0.001008	18.10	173.9	2577.0
311.1	100	0.001452	0.0180	1407	2724.7

Specific enthalpy of water in kJ/kg at 100 bar and 41.5°C is

(A) 202.12 (B) 183.89
(C) 150.2 (D) 100.2

Direction for questions 8 to 9: Dry and saturated steam at 10 bar expands in a cylinder to 1.8 bar with a dryness fraction of 0.8 according to the law $PV^n = C$ Determine.

8. The index of expansion

(A) 1.4 (B) 1.35
(C) 1.23 (D) 1.20

9. Work done by the steam during the expansion process in kJ/kg is

(A) 231.8 (B) 300.2
(C) 352.6 (D) 400

The properties are tabulated below:

Pressure (bar)	Saturation Temp (°C)	Specific Volume (m^3/kg)	
108	116.9	V_f	V_g
		0.001058	0.977
10	179.9	0.001127	0.194

10. The dryness fraction of steam if 3 kg of water is in suspension with 85 kg of dry and saturated steam is

(A) 0.960 (B) 0.965
(C) 0.968 (D) 0.99

11. For the above problem the wetness fraction is

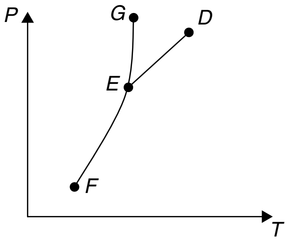
(A) 0.35 (B) 0.965
(C) 3.5 (D) 0.035

12. During a test on separating calorimeter the following observations were taken

Mass of water separated = 0.5 kg/min
Mass of steam passing through calorimeter = 5 kg/min
The dryness fraction is

(A) 0.902 (B) 0.905
(C) 0.909 (D) 0.99

13. Consider the phase diagram of a certain substance as shown in the given figure. Match List-I (process) with List-II (curves/lines) and select the correct answer using the codes given below the lists.



List–I	List–II
1. Vaporization	(a) EF
2. Fusion	(b) EG
3. Sublimation	(c) ED

Codes:

	a	b	c
(A)	1	3	2
(B)	1	2	3
(C)	3	2	1
(D)	3	1	2

14. Steam enters an adiabatic turbine steadily at 500°C and 5 MPa and leaves at 60 (KPa) The minimum possible dryness fraction of steam at the turbine exit is approximately

Super heated $t = 500$°C

Pressure	T_{sat} (°C)	S_f(KJ/kg k)	S_g(KJ/kg k)	S (KJ/kg k)
5 Mpa	151.9	1.861	6.821	8.087
60 Kpa	36.2	0.521	8.33	------

(A) 90% (B) 95.2%
(C) 96.5% (D) 96.8%

15. Saturated liquid water at 0.6 Mpa and 1000 kg/hr of steam at 0.6 MPa and 350°c enter steadily in to an insulated mixing chamber. At 0.6 MPa, the enthalpy of saturated liquid and saturated vapour are 359.9 kJ/kg and 2653.5 kJ/kg respectively Also, the enthalpy of super heated steam 350°C is 3179.5 kJ/kg.

The quality of mixture existing the chamber is 0.9. The mass flow rate of saturated liquid water in kg/hr is

(A) 654.364 (B) 525.35
(C) 435.25 (D) 300

16. Match List-I with List-II and select the correct answer using the codes given below the lists:

List-I	List-II
1. Volume expansivity (β)	(a) $\frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$
2. Adiabatic compressibility (K_B)	(b) $\frac{-1}{V}\left(\frac{\partial V}{\partial P}\right)_S$
3. Joule-Kelvin co efficient (μ_T)	(c) $\frac{1}{C_P}\left[T\left(\frac{\partial V}{\partial T}\right)_P - V\right]$
	(d) $\left(\frac{\partial P}{\partial V}\right)_S$

Codes:

	a	b	c
(A)	3	2	1
(B)	1	2	3
(C)	2	1	3
(D)	3	1	2

17. Vender waal's equation of state is given by

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT$$

The value of R in terms of P_C, V_C, and T_C is

(A) $\frac{8}{3}\frac{P_C V_C}{T_C}$ (B) $\frac{3 P_C V_C}{T_C}$

(C) $\frac{6}{3}\frac{P_C V_C}{T_C}$ (D) None

18. The Clausius-Clapeyron equation gives the slope of a curve in

(A) P–V diagram
(B) p–h diagram
(C) P–T diagram
(D) T–S diagram

19. On a P-V-T surface, the triple point and critical point are seen respectively.

(A) Point, Point (B) Point, Line
(C) Line, Point (D) Line, Line

20. For a given volume of dry saturated steam, Clapeyron's equation is given by

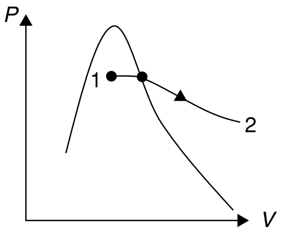
(A) $V_g - V_f = \frac{dT_S}{dp} \times \frac{T_S}{h_g - h_f}$

(B) $V_g - V_f = \frac{dT_S}{dp} \times \frac{h_g - h_f}{T_S}$

(C) $V_g - V_f = \frac{dp}{dT_S} \times \frac{h_g - h_f}{T_S}$

(D) $V_g - V_f = \frac{dp}{dT_S} \times \frac{T_S}{h_g - h_f}$

21. The process 1–2 for steam shown in the given figure is



(A) Isobaric
(B) Isentropic
(C) Isenthalpic
(D) Isothermal

22. Match List-I (Apparatus) with List-II (Thermo dynamic process) and select the correct answer using the code given below the lists:

List-I	List-II
1. Throttling calorimeter	(a) Isobaric process
2. Separating calorimeter	(b) Isochroric process
3. Sling psychrometer	(c) Isenthalpic process
4. Gas thermometer	(d) adiabatic process

Codes:

	a	b	c	d
(A)	3	1	2	4
(B)	1	2	3	4
(C)	3	4	2	1
(D)	1	3	4	2

23. One kg of steam sample contains 0.8 kg dry steam; its dryness fraction is

(A) 0.2
(B) 0.8
(C) 1.0
(D) 0.6

24. If x_1 and x_2 be the dryness fractions obtained in separating calorimeter and throttling calorimeter respectively, then the actual dryness fraction of steam will be

(A) $x_1 x_2$
(B) $x_1 + x_2$
(C) $\frac{x_1 + x_2}{2}$
(D) $\frac{1}{\frac{1}{x_1} + \frac{1}{x_2}}$

25. If x is the weight of dry steam and y is the weight of water in suspension, then dryness fraction is equal to

(A) $\frac{y}{x+y}$

(B) $\frac{x}{x+y}$

(C) $\frac{x}{x-y}$

(D) $\frac{y}{x-y}$

PREVIOUS YEARS' QUESTIONS

Direction for questions 1 and 2: The following table of properties was printed out for saturated liquid and saturated vapour of ammonia. The titles for only the first two columns are available. All that we know is that the other columns (columns 3 to 8) contain data on specific properties, namely, internal energy (kJ/kg), enthalpy (kJ/kg)/ and entropy (kJ/kgK).

T(°C)	*P*(kPa)						
–20	190.2	88.76	0.3657	89.05	5.6155	1299.5	1418.0
0	429.6	179.69	0.7114	180.36	5.3309	1318.0	1442.2
20	857.5	272.89	1.0408	274.30	5.0860	1332.2	1460.2
40	1554.9	368.74	1.3574	371.43	4.8662	1341.0	1470.2

1. The specific enthalpy data are in columns **[2005]**

(A) 3 and 7
(B) 3 and 8
(C) 5 and 7
(D) 5 and 8

2. When saturated liquid at 40°C is throttled to –20°C, the quality at exit will be **[2005]**

(A) 0.189
(B) 0.212
(C) 0.231
(D) 0.788

3. Given below is an extract from steam tables.

Temperature (°C)	P_{sat} (bar)	Specific Volume (m³/kg) Sat.liquid/vapour		Enthalpy (kJ/kg) Sat.liquid/vapour	
45	0.09593	0.001010	15.26	188.45	2394.8
342.24	150	0.001658	0.010337	1610.5	2610.5

Specific enthalpy of water in kJ/kg at 150 bar and 45°C is **[2006]**

(A) 203.60 (B) 200.53
(C) 196.38 (D) 188.45

4. Water has a critical specific volume of 0.003155 m³/kg. A closed and rigid steel tank of volume 0.025 m³ contains a mixture of water and steam at 0.1 MPa. The mass of the mixture is 10 kg. The tank is now slowly heated. The liquid level inside the tank **[2007]**

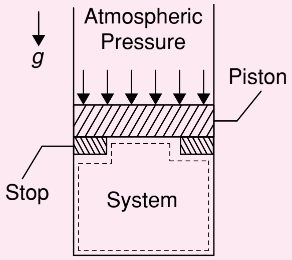
(A) Will rise
(B) Will fall
(C) Will remain constant
(D) May rise or fall depending on the amount of heat transferred.

5. Which combination of the following statements is correct?

P: A gas cools upon expansion only when its Joule-Thomson coefficient is positive in the temperature range of expansion.
Q: For a system undergoing a process, its entropy remains constant only when the process is reversible.
R: The work done by a closed system in an adiabatic process is a point function.
S: A liquid expands upon freezing when the slope of its fusion curve on Pressure Temperature diagram is negative. **[2007]**

(A) R and S
(B) P and Q
(C) Q, R and S
(D) P, Q and R

Direction for questions 6 to 8: In the figure shown, the system is a pure substance kept in a piston-cylinder arrangement. The system is initially a two phase mixture containing 1 kg of liquid and 0.03 kg of vapour at a pressure of 100 kPa. Initially, the piston rests on a set of stops, as shown in the figure. A pressure of 200 kPa is required to exactly balance the weight of the piston and the outside atmospheric pressure. Heat transfer takes place into the system until its volume increases by 50%. Heat transfer to the system occurs in such a manner that the piston, when allowed to move, does so in a very slow (quasi-static/quasi-equilibrium) process. The thermal reservoir from which heat is transferred to the system has a temperature of 400°C. Average temperature of the system boundary can be taken as 175°C. The heat transfer to the system is 1 kJ, during which its entropy increases by 10 J/K.



Specific volume of liquid (v_f) and vapour (v_g) phases, as well as values of saturation temperatures, are given in the table below.

Pressure (kPa)	Saturation Temperature T_{sat} (°C)	v_f (m³/kg)	v_g(m$_3$/kg)
100	100	0.001	0.1
200	200	0.0015	0.002

6. At the end of the process, which one of the following situations will be true? **[2008]**

(A) Superheated vapour will be left in the system
(B) No vapour will be left in the system
(C) A liquid + vapour mixture will be left in the system
(D) The mixture will exist at a dry saturated vapour state

7. The work done by the system during the process is **[2008]**

(A) 0.1 kJ (B) 0.2 kJ
(C) 0.3 kJ (D) 0.4 kJ

8. The net entropy generation (considering the system and the thermal reservoir together) during the process is closest to **[2005]**

(A) 7.5 J/K (B) 7.7 J/K
(C) 8.5 J/K (D) 10 J/K

9. A rigid container of volume 0.5 m³ contains 1.0 kg of water at 120°C (v_f = 0.00106 m³/kg, v_g = 0.8908 m³/kg). The state of water is: **[2015]**

(A) Compressed liquid
(B) Saturated liquid
(C) A mixture of saturated liquid and saturated vapor.
(D) Superheated vapor

10. For water at 25°C, $dp_s/dT_s = 0.189$ kPa/K (P_s is the saturation pressure in kPa and T_s is the saturation temperature in K) and the specific volume of dry saturated vapour is 43.38 m³/kg. Assume that the specific volume of liquid is negligible in comparison with that of vapour. Using the Clausius-Clapeyron equation, an estimate of the enthalpy of evaporation of water at 25°C (in kJ/kg) is ________. **[2016]**

11. The INCORRECT statement about the characteristics of critical point of a pure substance is that: **[2016]**

(A) there is no constant temperature vaporization process
(B) it has point of inflection with zero slope
(C) the ice directly converts from solid phase to vapor phase
(D) saturated liquid and saturated vapor states are identical

ANSWER KEYS

EXERCISES

Practice Problems 1

1. A **2.** B **3.** B **4.** D **5.** A **6.** D **7.** C **8.** A **9.** A **10.** B
11. C **12.** D **13.** D **14.** D **15.** C **16.** B

Practice Problems 2

1. B **2.** C **3.** A **4.** D **5.** B **6.** D **7.** B **8.** C **9.** A **10.** B
11. D **12.** C **13.** B **14.** D **15.** A **16.** B **17.** A **18.** C **19.** C **20.** B
21. D **22.** A **23.** B **24.** A **25.** B

Previous Years' Questions

1. D **2.** B **3.** D **4.** A **5.** A **6.** A **7.** D **8.** C **9.** C
10. 2400–2500 **11.** C