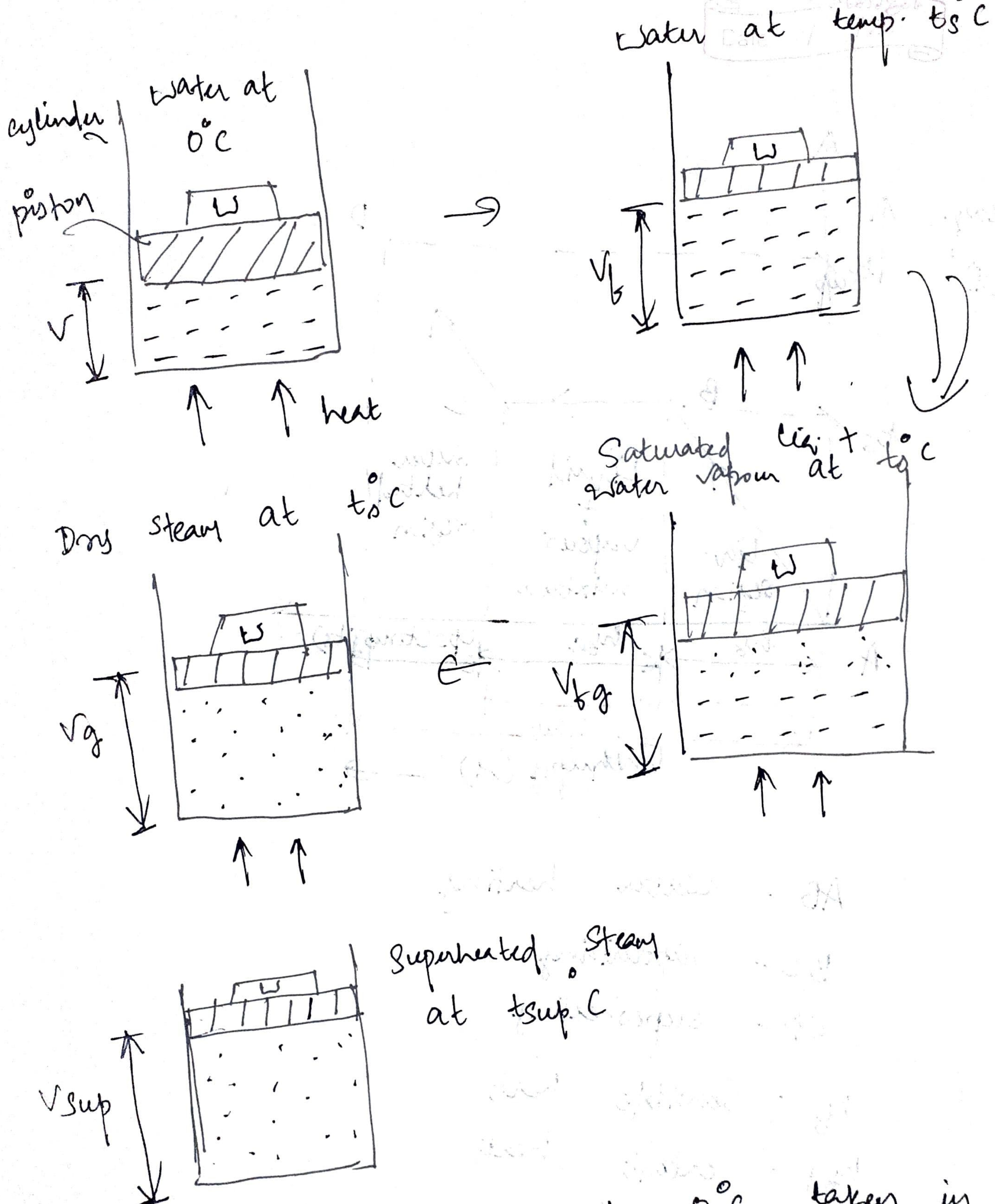
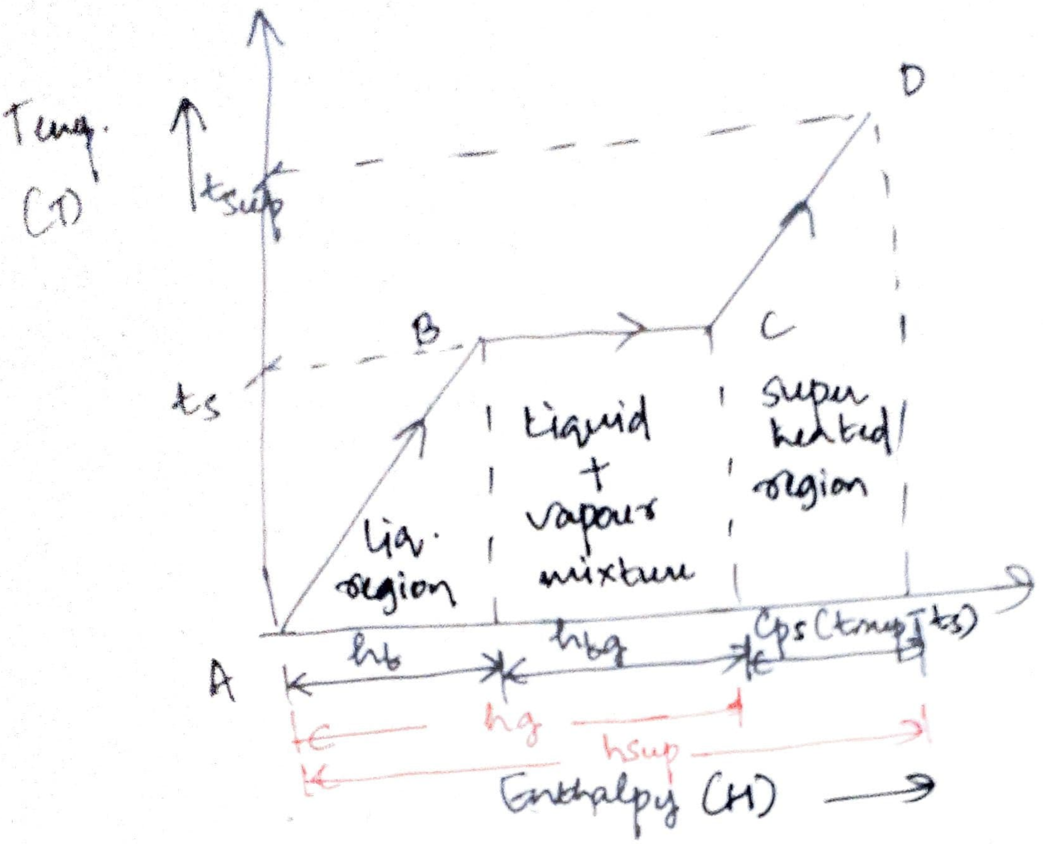
(i) Formation of Steam at const. pressure



Consider 1 kg of water at 0°C taken in a cylinder fitted with a freely moving piston. weight W is placed on the piston. Let V be the volume occupied by the water. Initial condition of 1 kg of water is point 'A'.

- on heating, the temperature of water rises and at a certain temperature water begins/starts boiling, known as Saturation temp; ts (boiling pt. for one atmosphere pressure).



AB - water heating

BC - vapourizing

CD - Superheating

h_f - Sensible heat

h_{fg} - latent heat

h_{sup} - superheat

t_s - saturation temp.

t_{sup} - Superheat temp.

When water is heated beyond the saturation temp., there will be no rise in temp., but evaporation of water takes place

~~Progress~~ At this stage, water exists as a two-phase mixt. containing liquid particles and dry/vapour particles. Steam here is known as wet steam.

- Evaporation of water continues at t_s until the whole of wet steam is completely converted into dry steam. (Line BC)
- upon further heating, the temp. of steam increases above saturation temp. t_s and steam acquires superheated state. the corresponding temp. here is known as superheat temp. (CD)
- If pressure is increased, the saturation temp. also increases.

Types of Steam

a) Wet Steam: Two-phase mixture containing saturated liquid and vapour formed at the saturation temperature and given pressure. It contains small water particles that will become vapours if further heat is provided.

b) Dry Steam :- It is the one that exists completely in vapour form at the saturation temp. and at a given pressure.

c) Superheated Steam: It is defined as the steam that is heated beyond its dry state to a temp. higher than its saturation temp. at a given pressure.

Advantages of Superheated Steam

- the heat content of Superheated Steam is high and hence capacity to do work is greater which is useful for power generation.
- It gives higher thermal efficiency and minimizes the specific consumption of steam when used in turbines
- Erosion/corrosion of turbine blades are minimized due to absence of moisture content.

STEAM PROPERTIES

Dryness fraction (x)

- Defined as ratio of mass of dry particles present ~~in a known quantity of~~ ~~ass~~ to the total mass of steam mixture.

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

m_g = mass of dry particles

m_f = mass of suspended water particles

for wet steam, $0 < x < 1$

for dry steam, $x = 1$

Sensible heat (enthalpy of saturated water)

Amount of heat required to convert 1 kg of water from 0°C to saturation temp. (t_s) at a given pressure. It is denoted by h_f.

Latent heat of evaporation - Amt. of heat required to convert 1 kg of water at the saturation temp. (t_s) to 1 kg of dry steam at the same temp. (t_s) and given pressure.

Superheat

It is the amount of heat required to raise the temp. of dry steam above its saturation temp. at a given pressure.

Degree of Superheat

It is defined as the difference between the superheat temp. (t_{sup}) and saturation temp. (t_s).

Enthalpy of Steam (h), in KJ/kg

Enthalpy (total heat) is defined as the sum of internal energy (U) and the product of pressure (P) and volume (V).

$$h = U + PV$$

Enthalpy of Steam is the amount of heat energy contained in a unit mass of Steam.

Enthalpy of wet Steam, (h_w)

It is the amount of heat required at a given pressure to convert 1 kg of water at 0°c to 1 kg of wet Steam at a given dryness fraction. in KJ/kg

$$h_w = h_f + x\, h_{fg}$$

h_f = Sensible heat

h_{fg} = latent heat of evaporation

x = dryness fraction.

Enthalpy of dry Saturated Steam (dry steam)

It is the amount of heat required at a given pressure to convert 1 kg of water at 0°c to 1 kg of dry steam ($x = 1$) at the Saturation temperature.

$$h_g = h_f + h_{fg}$$

Enthalpy of Superheated Steam, (h_{sup})

It is the amount of heat required at a given pressure to convert 1 kg of water at 0°C to 1 kg of Superheated Steam at the given Superheat temp.

$$h_{sup} = h_g + C_{ps}(t_{sup} - t_s)$$

t_{sup} = Superheat temperature

t_s = Saturation temp.

t_{sup} = Superheat temp.

C_{ps} = Specific heat of Superheated Steam.

Specific volume of Saturated water, V_f

volume occupied by 1 kg of water at the Saturation temp. and at a given pressure.

Specific volume of wet Steam, V_w

It is the volume of 1 kg of wet Steam at the Saturation temp and given pressure

$$\boxed{V_w = x V_g}$$

V_g = specific vol. of dry Steam

Specific vol. of dry Steam, V_g

It is the volume occupied by 1 kg of dry saturated Steam at the Saturation temp. and at a given pressure.

Specific vol. of Superheat Steam, V_{sup}

It is the volume occupied by 1 kg of Superheated Steam at the Superheat temp. (t_{sup}) and at a given pressure.

Superheated Steam behaves like a perfect gas. Applying Charles laws,

$$\frac{V_{sup}}{t_{sup}} = \frac{V_g}{t_s}$$

$$V_{sup} = \frac{V_g \cdot t_{sup}}{t_s}$$

t_{sup} & t_s should be in Kelvin

External work of evaporation

When water at saturation temp. is heated at constant pressure, it gets converted into steam by absorbing latent heat. A part of this latent heat is used to move the piston due to the increase in volume of steam during evaporation. The work done due to change in vol. of steam from V_f to V_g is called external work of evaporation.

External work of evaporation, $W = 100\, p(V_g - V_f)$

p = pressure in bars

V_f is small and can be neglected

$\therefore W = 100 \cdot p \cdot V_g$

kJ/kg

for wet steam, $W_w = 100\, p \cdot x \cdot V_g$

for dry steam, $W_g = 100\, p \cdot V_g$

for superheated steam, $W_{sup} = 100\, p \cdot V_{sup}$

the remaining part of the latent heat is used to overcome the internal resistance of water molecules to the change of phase of substance. It is called internal latent heat.

Internal latent heat $= x h_{fg} - 100\, P \cdot x \cdot V_g$ in KJ/kg

Internal energy

obtained by subtracting the external work of evaporation from enthalpy of steam.

for wet steam,

$$\left.\begin{aligned} U_w &= h_f + x h_{fg} - 100 \cdot p \cdot x \cdot V_g \\ U_g &= h_g - 100 \cdot p \cdot V_g \\ U_{sup} &= h_{sup} - 100\, p \cdot V_{sup} \end{aligned}\right\} \text{in KJ/kg}$$

Numericals

1) Show that in a constant pressure process, the amount of heat supplied to convert water into steam is equal to the change in enthalpy.

Soln: Enthalpy, $h = u + Pv$

from 1st law of thermodynamics,

$$dQ = du + p \cdot dv \quad -(1)$$

$du = dQ - p \cdot dv$

change in I.E = heat added to system − work done by system

where Q = heat supplied

Now, $d(p \cdot v) = v \cdot dp + p \cdot dv$

$$\therefore p \cdot dv = d(Pv) - v \cdot dp \quad -(2)$$

Eq^n. ② in eq^n. ① gives,

$$dQ = du + d(p.v) - v.dp$$

$$dQ = d[u + pv] - v.dp \quad -③$$

for constant pressure process, $dp = 0$

$\therefore$ Eq^n. ③ $\Rightarrow$

$$dQ = d[u + pv]$$

$$\underline{dQ = dh} \quad (\because h = u + pv)$$

P2) A steam initially will be at 9 bars and dryness fraction 0.98. Find the final quality and temperature of 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 const. pressure.

Soln:

$p = 9$ bars

$x = 0.98$

at $p = 9$ bars,

$t_s = 175.36°C$

$h_f = 742.64$ KJ/kg

$h_g = 2772.1$ KJ/kg

$h_{fg} = 2029.5$ KJ/kg

$h_w = h_f + x\,h_{fg}$

$h_w = 742.64 + (0.98)(2029.5)$

$h_w = 2731.51$ KJ/kg

a) When steam loses 50 KJ/Kg.

let h_1 be the enthalpy at this condition.

$h_1 = h_w - 50$

$h_1 = 2731.51 - 50 = \underline{2681.51 \text{ KJ/Kg}}$

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

let x_1 be the new dryness fraction,

$h_1 = h_f + x_1 h_{fg}$

$2681.51 = (742.64) + (x_1)(2029.5)$

$\underline{x_1 = 0.955}$

b) When steam receives 150 KJ/Kg

let h_2 be the new enthalpy.

$\therefore h_2 = h_w + 150$

$h_2 = 2731.51 + 150 = 2881.51$ KJ/Kg

now, $h_2 > h_g \Rightarrow$ Steam is Superheated.

Enthalpy of Superheated Steam,

$h_{sup} = h_g + C_{ps}(t_{sup} - t_s)$

here $h_2 = h_{sup}$

$\therefore h_2 = (2772.1) + 2.25\,(t_{sup} - 175.36)$ 2881.51

$\underline{t_{sup} = 224\,°C}$

P3) 3 kgs of steam is generated at 5 bars from water at 34°C. Determine the quantity of heat required when

a) Steam is wet, having dryness fraction of 0.8.

b) Steam is dry saturated

c) Steam is superheated to 240°C

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

$C_{pw} = 4.187$ kJ/kg K

Soln:- At $p = 5$ bars

$t_s = 151.85°C$

$h_f = 640.1$ kJ/kg $\qquad h_{fg} = 2107.4$ kJ/kg

$h_g = 2747.5$ kJ/kg

a) When steam is wet, $x = 0.8$

Enthalpy of wet steam.

$h_w = h_f + x\,h_{fg}$

$h_w = (640.1) + (0.8)(2107.4)$

$h_w = 2326.02$ kJ/kg

∴ Net heat required $= h_w - C_{pw}(34 - 0)$

$= 2326.02 - 4.187(34 - 0)$

$= 2326.02 - 142.35$

$= 2183.66$ kJ/kg

for 03 kgs total heat required is 2183.66×03

$= 6550.98$ kJ

b) Steam is dry,

enthalpy, $h_g = 2747.5$ kJ/kg

net heat required $= h_g - C_{pw}(34-0)$

$= 2747.5 - 4.187(34-0)$

$= 2605.14$ kJ/kg

for 03 kgs, total heat required is

$(2605.14)(03) = 7815.42$ kJ

c) Steam is superheated to $240°C$,

enthalpy, $h_{sup} = h_g + C_{ps}(t_{sup} - t_s)$

$h_{sup} = (2747.5) + (2.25)(240 - 151.85)$

$h_{sup} = 2945.8$ kJ/kg

net heat required $= h_{sup} - C_{pw}(34-0)$

$= 2945.8 - 4.187(34-0)$

$= 2803.48$ kJ/kg

now for 03 kgs, total heat required $= 03 \times 2803.48$

$= 8410.44$ kJ

P4) A vessel of $0.05\,m^3$ capacity contains a mixture of saturated water and saturated steam at a temp. of $280°C$. The mass of liquid present is 10 kg. Find the a) total mass of steam present in the vessel b) Enthalpy c) Specific vol. d) Internal energy.

Soln.

vol. of vessel $= 0.05\,m^3$

at $t_s = 280°C$,

$p = 64.2$ bars

$h_f = 1236.8$ kJ/kg $\quad h_{fg} = 1543.6$ kJ/kg

$h_g = 2780.4$ kJ/kg

$v_f = 0.0013324\ m^3/kg$

$v_g = 0.030126\ m^3/kg$

vol. of wet steam $= m_f v_f + m_g v_g$

$0.05 = (10)(0.0013324) + m_g(0.030126)$

$\underline{m_g = 1.217\ kg}$

total mass of steam $= 10 + 1.217$

$\underline{= 11.217\ kg}$

Dryness fraction, $x = \dfrac{1.217}{11.217} = \underline{0.108}$

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

$h_w = 1236.8 + (0.108)(1543.6)$

$\underline{h_w = 1403.5\ kJ/kg}$, for 11.217 kgs it is 15,743 kJ

Specific vol. of wet steam, $V_w = x V_g$

$V_w = (0.108)(0.030126)$

$\underline{V_w = 0.00325\ m^3/kg}$

for 11.217 kgs it is $\underline{0.0364\ m^3}$

Internal energy of wet steam.

$u_w = h_f + x h_{fg} - 100\, p \cdot x \cdot v_g$

$u_w = (1403.5) - 100\,(64.202)(0.108)(0.030126)$

$u_w = 1382.61$ KJ/kg

for 11.217 kg of steam,

$u_w = 15508.74$ KJ

P5) 2 kg of wet steam is heated at a constant pressure of 2 bars until its temp. increases to 150°C. the heat transferred is 2100 KJ. Find the initial dryness fraction. Assume $C_{ps} = 2.1$ KJ/kgK

Soln:- at p = 2 bars, $t_s = 120.23°C$

$h_f = 504.70$ KJ/kg, $h_g = 2706.3$ KJ/kg ∴ $h_{fg} = h_g - h_f$
$= 2201.6$ KJ/kg

Since temp = 150°c > t_s, steam has acquired superheated state.

for 1 kg heat transferred is $\frac{2100}{02} = 1050$ KJ

$h_{sup} = h_g + C_{ps}(t_{sup} - t_s)$

$= 2706.3 + 2.1(150 - 120.23) = 2768.82$ KJ/kg

h_{sup}

Now $h_w = 2768.82 - 1050 = 1718.82$ KJ/kg

$h_w = h_f + x h_{fg}$

$1718.82 = (504.70) + x(2201.6)$

$x = 0.5514$, is the initial dryness fraction (before 1050 KJ was added for 1 kg
or 2100 KJ " " to 2 kgs)

P.6) Calculate the specific volume and enthalpy of 8 kgs of steam at 1.2 MPa, when
a) the steam is 12% wet
b) when the steam is superheated to 300°C.

Sol^n.
$m = 8$ kg

$p = 1.2 \times 10 \times 10^5$ Pa
$= \underline{12 \text{ bars}}$ (∵ 10^5 Pa = 1 bar)

from steam tables at $p = 12$ bars,

$t_s = 188°C$

$h_f = 798.4$ kJ/kg

$h_{fg} = 1984.3$ kJ/kg

$h_g = 2782.7$ kJ/kg

$v_g = 0.163$ m^3/kg

a) when $x = 0.88$,

$h_w = h_f + x h_{fg}$

$h_w = (798.4) + (0.88)(1984.3)$

$h_w = \underline{2544.58 \text{ kJ/kg}}$

for 8 kgs of steam enthalpy is 2544.58×08

$= \boxed{20{,}356.67 \text{ kJ}}$

Specific vol., $v_w = x v_g$

$v_w = (0.88)(0.163) = \underline{0.1434 \text{ m}^3\text{/kg}}$

for 8 kgs it is $\underline{1.1472 \text{ m}^3}$

b) when steam is superheated to 300°C

$h_{sup} = h_g + C_{ps}(t_{sup} - t_s)$

$h_{sup} = (2782.7) + (2.25)(300 - 188)$

$h_{sup} = \underline{3034.7 \text{ kJ/kg}}$

bar)

kg/kg

08

for 8 kgs it is 3034.7×08

$\Rightarrow$ 24277.6 kJ

Specific vol. of Superheated Steam, $V_{sup} = V_g \cdot \frac{t_{sup}}{t_s}$

$$V_{sup} = (0.163) \times \frac{(300 + 273)}{(188 + 273)}$$

$$V_{sup} = 0.202 \ m^3/kg$$

vol. of 8 kgs of Superheated Steam,

$0.202 \times 08 \Rightarrow 1.62 m^3$

Steam boilers

A Steam boiler or generator is a closed vessel in which the Steam at the desired pressure and temperature is generated from water by application of heat. the Steam thus generated may be used for following purposes:-

i) to generate power for Steam engines & Steam turbines

ii) for process work in cotton mills, Sugar mills, paper mills, breweries, chemical industries etc.

iii) for home heating in cold countries.

Classification of boilers

1) According to relative position of water and hot/flue gases

i) Fire tube boiler ii) water tube boiler

i) Fire tube boiler: here the hot flue gases from the boiler furnace flow through the tubes, which are surrounded with water.

Ex: Lancashire, Cochran, Locomotive