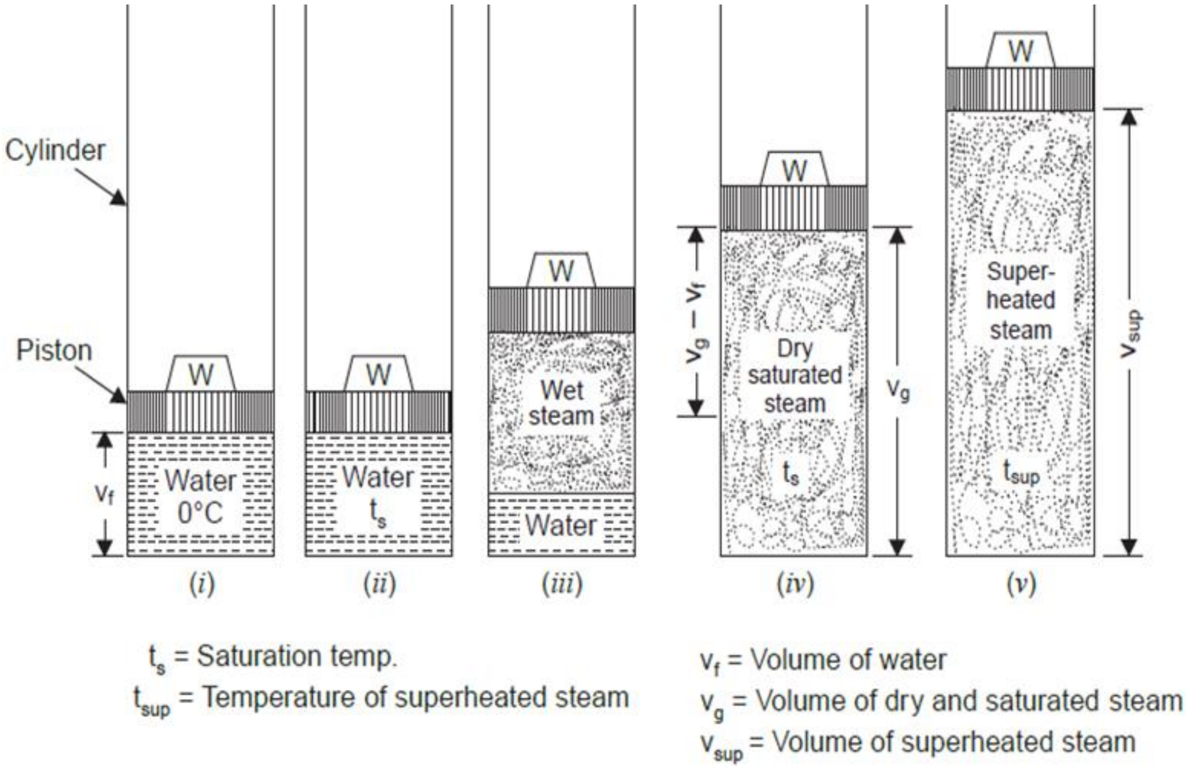
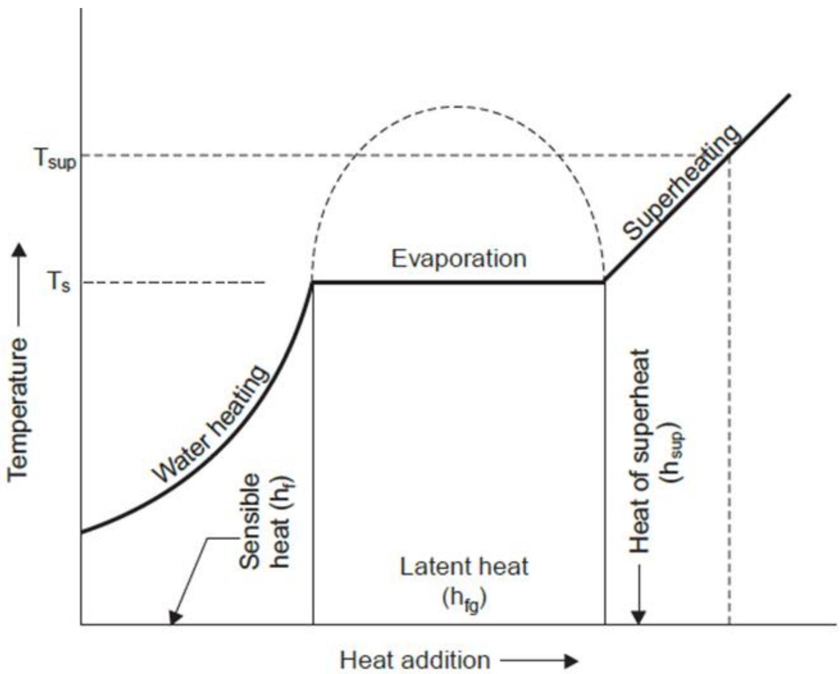
Steam Formation and Applications

T-h diagram (Formation of steam at constant pressure)





Consider water at room temperature (20°C) and normal atmospheric pressure (1 atm) in a piston-cylinder device. The water is in liquid phase, and it is called compressed liquid or subcooled liquid (not about to vaporize)

If we add heat to water, its temperature will increase; let us say until 50°C. Due to the increase in temperature, the specific volume v will increase. As a consequence, the piston will move slightly upward therefore maintaining constant pressure (1 atm).

Now, if we continue to add heat to the water, the temperature will increase further until 100°C. At this point, any addition of heat will vaporize some water. This specific point where water starts to vaporize is called saturated liquid

If we continue to add heat to water, more and more vapor will be created, while the temperature and the pressure remain constant (T = 100°C and P = 1 atm). The only property that changes is the specific volume. These conditions will remain the same until the last drop of liquid is vaporized. At this point, the entire cylinder is filled with vapor at 100°C. This state is called saturated vapor

The state between saturated liquid (only liquid) and saturated vapor (only vapor) where two phases exist is called saturated liquid-vapor mixture

After the saturated vapor phase, any addition of heat will increase the temperature of the vapor, this state is called superheated vapour

Saturation Temperature and Saturation Pressure

The temperature at which water starts boiling depends on the pressure. In other words, water starts boiling at 100 ºC but only at 1 atm. At different pressures, water boils at different temperatures.

At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature (Tsat).

At a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure (Psat).

- **Tsat = f (Psat)**

- p = 1atm = 101.3 kPa, T = 100^0 C
- p = 500 kPa, T = 151.9^0 C
- T and P are dependent during phase change
- **Compressed liquid** -- not about to evaporate
- **Saturated liquid** -- about to evaporate
- **Saturated liquid-vapor mixture** --two phase
- **Saturated Vapor** -- about to condense
- **Superheated Vapor** -- not about to condense

- **Latent Heat**-Latent heat is the amount of energy absorbed or released during phase change
- **Latent heat of fusion** -- melting/freezing=333.7 kJ/kg for 1 atm H_2O
- **Latent heat of vaporization** --boiling/condensation=2257.1 kJ/kg for 1 atm H_2O
- **IMPORTANT TERMS RELATING TO STEAM FORMATION**
- **Sensible heat of water (h_f)/heat of liquid/enthalpy of liquid**: The amount of heat required to raise the temperature of 1 kg of water from 0^0C (freezing point) to the saturation temperature(Boiling Point) at a given constant pressure. It is reckoned from 0°C where sensible heat is taken as zero. If 1 kg of water is heated from 0°C to 100°C the sensible heat added to it will be 4.18 × 100 = 418 kJ but if water is at say 20°C initially then sensible heat added will be 4.18 × (100 – 20) = 334.4 kJ.
- **Latent heat of vaporization-(hfg)/Enthalpy of vaporization**: The amount of heat required to evaporate 1kg of water at saturation temperature to 1 kg of dry steam at the same saturation temperature at given constant pressure is called latent heat of vaporization.
- **Degree of superheat:** The difference b/w the superheated temperature and saturation temperature
- **Wet steam:** When the steam contains moisture or suspended water particles it is said to be wet steam (or) it is a two phase mixture of entrained water particles and steam in thermal equilibrium at a saturation temperature corresponding to a given pressure.
- **Dry saturated steam:** When the wet steam is further heated and it does not contain any suspended water molecules then it is known as dry saturated steam.
- **Superheated steam:** When the dry saturated steam is heated further at a given constant pressure, its temperature rises beyond its saturation temperature. The steam in this state is called superheated steam.
- **Dryness fraction (x)/quality of wet steam**: The quality of wet steam is specified by the dryness fraction which indicates the amount of dry steam present in the given quantity of wet steam.
- It is defined as the ratio of mass of actual dry steam present in a known quantity of wet steam to the total mass of wet steam.
- $x=m_g/(m_f+m_g)$
- The dryness fraction of wet steam will be less than 1 and for dry saturated steam it is always equal to 1
- Thus, if in 1 kg of wet steam 0.9 kg is the dry steam and 0.1 kg is the water particles then $x = 0.9$
- **Enthalpy of steam(h):** It is the sum of the internal energy and product of the pressure and volume
- $H = U + PV$ (kJ)

- The enthalpy per unit mass is $h = u+Pv$ (kJ/kg)
- **Total heat or enthalpy of wet steam (h)**: It is defined as the quantity of heat required at constant pressure to convert 1 kg of water at 0°C into 1 kg of wet steam at specified dryness fraction. It is the sum of total heat of water and the latent heat.
- Mathematically, $h = h_f + x\, h_{fg}$
- **Enthalpy of dry saturated steam (h_g)**: It is defined as the total amount of heat supplied at a given constant pressure to convert 1 kg of water at 0°C into 1 kg of dry saturated steam at its saturation temeprature.
- Mathematically, $h = h_f + h_{fg}$
- **Enthalpy of superheated steam** (h_{sup}) : It is defined as the total amount of heat supplied at a given constant pressure to convert 1 kg of water at 0°C into 1 kg of super heated steam at the stated superheated temperature.
- $h_{sup} = h_f + h_{fg} + c_{ps} (T_{sup} – T_s)$
- c_{ps} =specific heat of superheated steam at constant pressure, the value of which varies from 2.0 to 2.1 kJ/kg K depending upon pressure and temperature
- **Specific Volume:** Volume occupied by unit mass of the substance, expressed in m^3/kg
- **Specific volume of saturated water (v_f)** ; It is the volume occupied by 1kg of water at saturation temperature at a given pressure
- **Specific volume of wet steam (v)**: If the steam has dryness fraction of x, then 1 kg of this steam will contain x kg of dry steam and (1 – x) kg of water. If v_f is the volume of 1 kg of water and vg is the volume of 1 kg of perfect dry steam (also known as specific volume), then volume of 1 kg of wet steam = volume of dry steam + volume of water. $= x.v_g + (1 – x)v_f$
- **Note. The volume of v_f at low pressures is very small and is generally neglected. Thus in general, the** volume of 1 kg of wet steam is given by, $x*v_g$ and density $1 /x*v_g$ kg/m^3.
- **$v=x.vg$ m^3/kg**
- **Specific volume of dry saturated steam (v_g):** It is the volume occupied by 1kg of dry saturated steam at a given pressure
- **Specific Volume of superheated steam (v_{sup}):** It is the volume occupied by 1kg of superheated steam at a given pressure and saturation temperature**.** As superheated steam behaves like a perfect gas its volume can be found out in the same way as the gases.
- If, v_g = Specific volume of dry steam at pressure p
- T_s = Saturation temperature in K,
- T_{sup} = Temperature of superheated steam in K, and
- v_{sup} = Volume of 1 kg of superheated steam at pressure p

$$\frac{p \cdot v_g}{T_s} = \frac{p \cdot v_{\mathrm{sup}}}{T_{\mathrm{sup}}}$$

$$v_{sup} = \frac{v_g\, T_{sup}}{T_s}$$

EXTERNAL WORK DONE DURING EVAPORATION

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

As at low pressure v_f is very small and hence neglected,

External work of evaporation per kg of dry saturated steam is= $\mathbf{p\,.v_g}$, kJ

External work of evaporation per kg of wet steam is= $\mathbf{p.\ x\ .v_g}$, kJ

External work of evaporation per kg of Superheated steam = $\mathbf{p.\ v_{sup}}$, kJ

INTERNAL ENERGY OF STEAM

The internal energy of steam is defined as the difference b/w the enthalpy of steam and external work of evaporation.

Internal energy of dry steam= $u_g = h_g - p.v_g$, kJ/kg

Internal energy of wet steam= $u = h - p.x.v_g$, kJ/kg

Internal energy of superheated steam= $u_{sup} = h_{sup} - p.v_{sup}$, kJ/kg

ENTROPY OF WET STEAM

The total entropy of wet steam is the sum of entropy of water (s_f) and entropy of evaporation (s_{fg}).

$S_{wet} = s_f + x * s_{fg}$

If steam is dry and saturated, *i.e.*, $x = 1$, then

$S_g = s_f + s_{fg}$

ENTROPY OF SUPERHEATED STEAM

S_{sup} = Entropy of dry saturated steam + change of entropy during Superheating

$$= s_f + \frac{h_{fg}}{T_s} + c_{ps} \log_e \left(\frac{T_{sup}}{T_s} \right) = s_g + c_{ps} \log_e \left(\frac{T_{sup}}{T_s} \right)$$

Applications of steam in industry:

- Power generation
- Heating and Sterilization
- Propulsion
- Atomization
- Cleaning
- Moisturization
- Humidification etc.