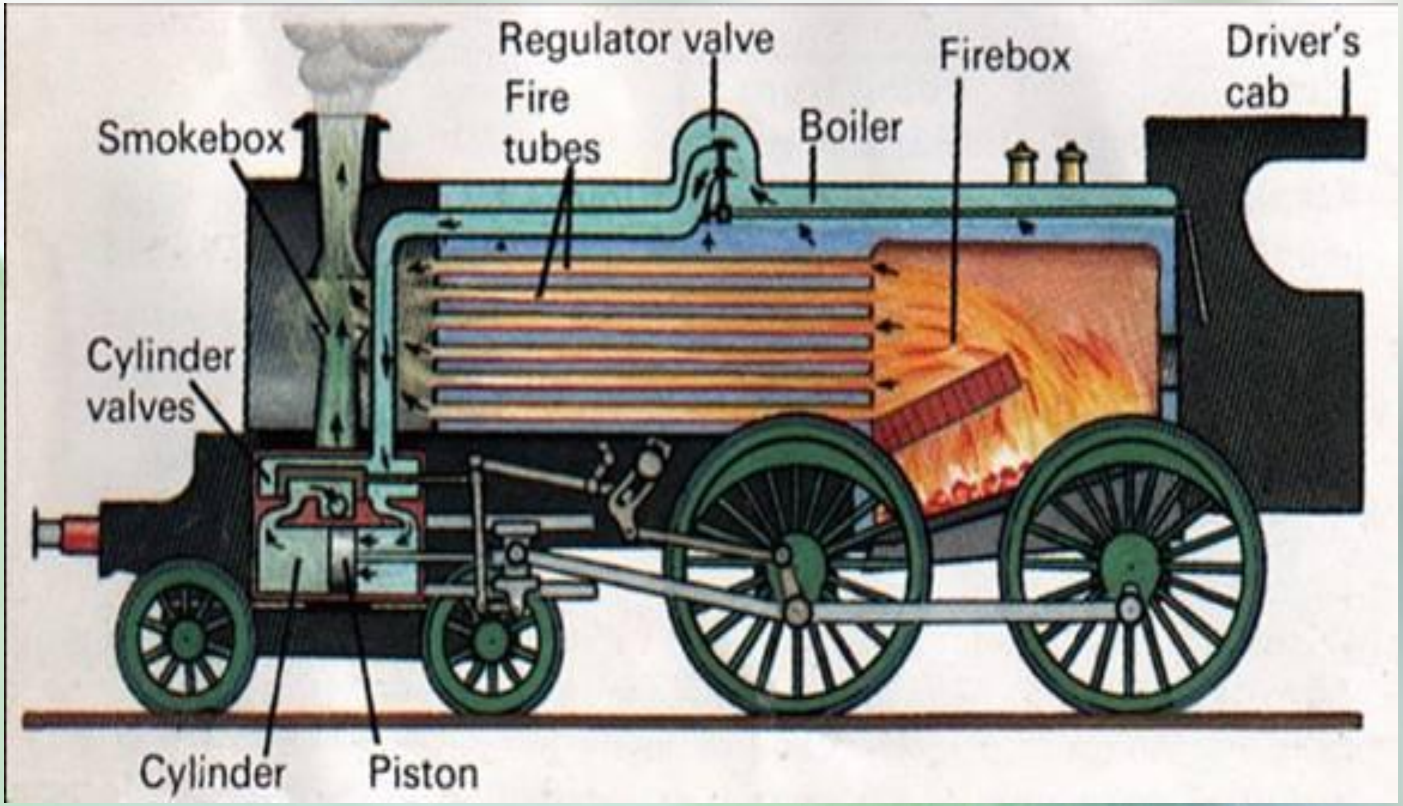


PROPERTIES OF STEAM

By: Mudit M. Saxena

Dept. of Mech. Engg.

INTRODUCTION:

- Steam is the vapour of water.

- Vapours are an intermediate phase between liquid and gas.
- Vapours do not obey the gas laws but when they are superheated to high temperature and low pressure, their behaviour is similar to gases and their laws can be used upto a degree of accuracy.
- Steam is used in a heat engine to produce power.

STEAM FORMATION

- Temperature of water is raised by addition of heat with the help of fuels and at different pressures, steam starts forming at different temperatures.

- Thermal energy enters into the engine in the form of steam. It has the following properties:
  - Steam is produced by water which is available cheaply everywhere.
  - Steam can carry a large amount of heat energy for each unit of water.
  - Steam is a useful medium since it is colourless, odourless, and tasteless and does not harm any body.
  - Exhaust coming out of the prime-mover can also be used for regeneration process, feed water, etc.

STEAM FORMATION

- Since steam is a vapour, it does not obey the laws of an ideal gas unless it is highly superheated and as such pressure, temperature and specific volumes are not correlated by simple gas equations.

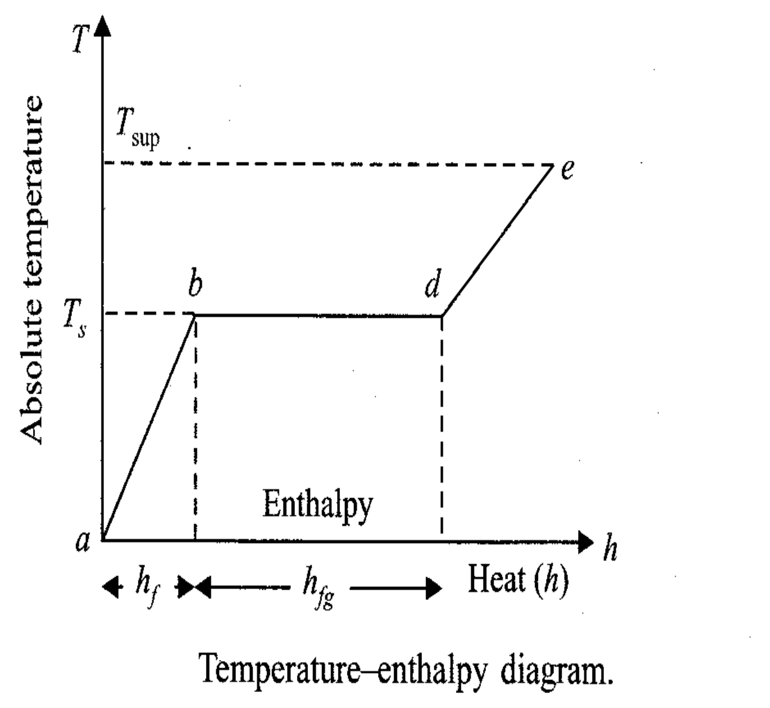
- The amount of heat addition to water or vapours depends upon the pressure at which this energy addition takes place.

SENSIBLE HEAT

Sensible Heat

The heat which changes the temperature of a substance is called sensible heat. There is no state change at that time. It is shown in diagram as 'ab'

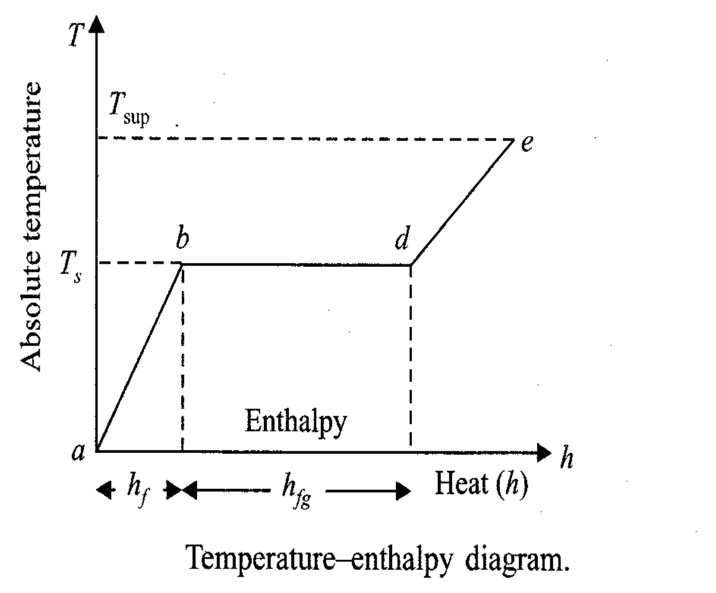
- If the water is heated at atmospheric pressure of 1 kg/cm^2, the temperature of water will rise to about 100°C before vapours start forming.
- The state of liquid where no vapour is formed is known as sensible heat. It is shown up to state b where vapours just start forming and are shown by the line *ab* and denoted by h_f.



Temperature–enthalpy diagram.

LATENT HEAT

- After saturated water stage 'b' further heating of water starts forming vapour but the temperature of water remains constant.
- Vapours have started forming, but they are wet and associated with liquid.
- Addition of heat now makes no difference in temperature but energy is added to the system and called latent heat which is represented by the line *bd*.
- During the heating process from *b* to *d*, steam remains wet and represented by a term named dryness fraction.

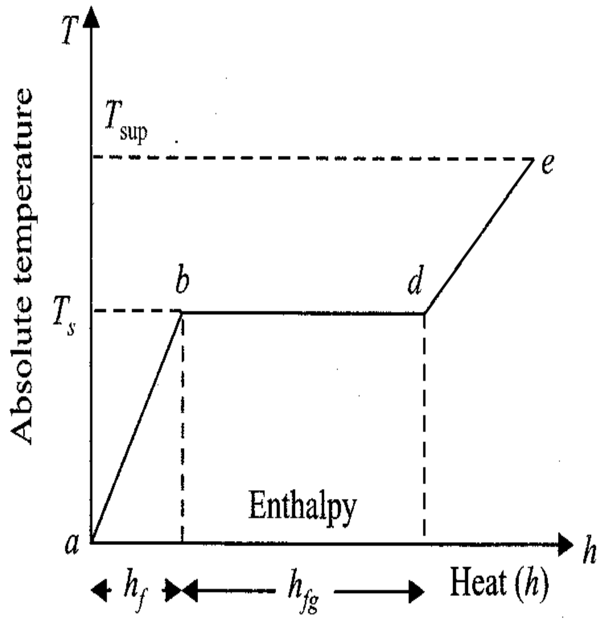


Temperature–enthalpy diagram.

The heat responsible for the change of state of a substance is called **Latent Heat**. There is no change in temperature during the state change.

DRYNESS FRACTION

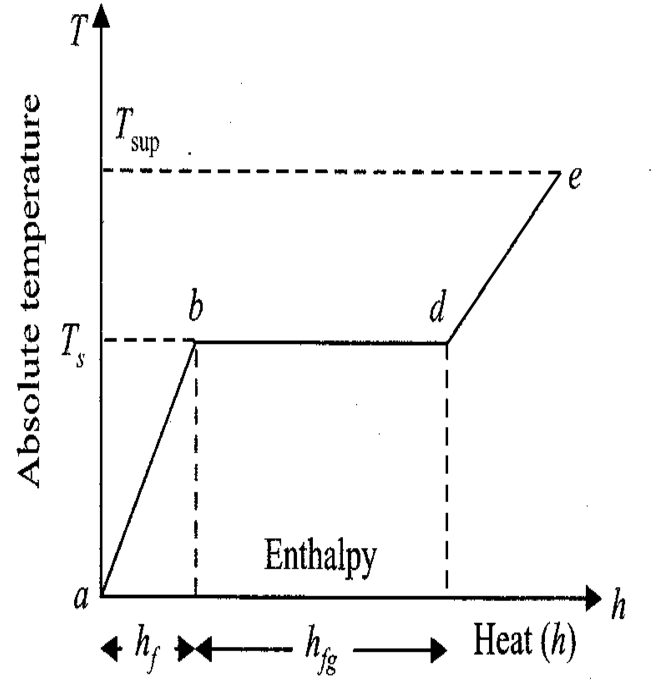
- Dryness fraction is defined as the ratio of mass of vapour to total mass of steam and is represented by x.
- This means that in the steam **'x'** portion of steam is dry and **'1-x'** portion is liquid.



Temperature–enthalpy diagram.

LATENT HEAT OF EVAPORATION

- The heat received during evaporation of water to convert it into dry vapours is known as latent heat of evaporation which is denoted by h_{fg}



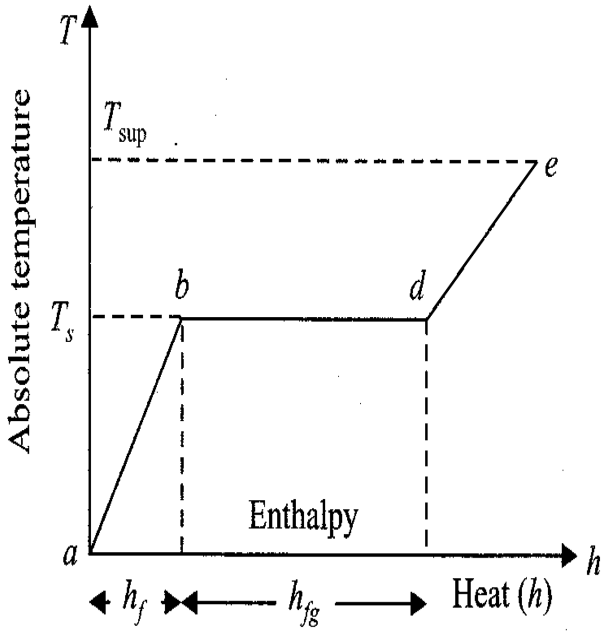
Temperature–enthalpy diagram.

HEAT OF SATURATED STEAM

- The total heat received by liquid from the assumed datum (0°C very often) till the dry and saturated vapours are formed is known as heat of saturated steam and denoted by h_g which is equal to $h_f + h_{fg}$.

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

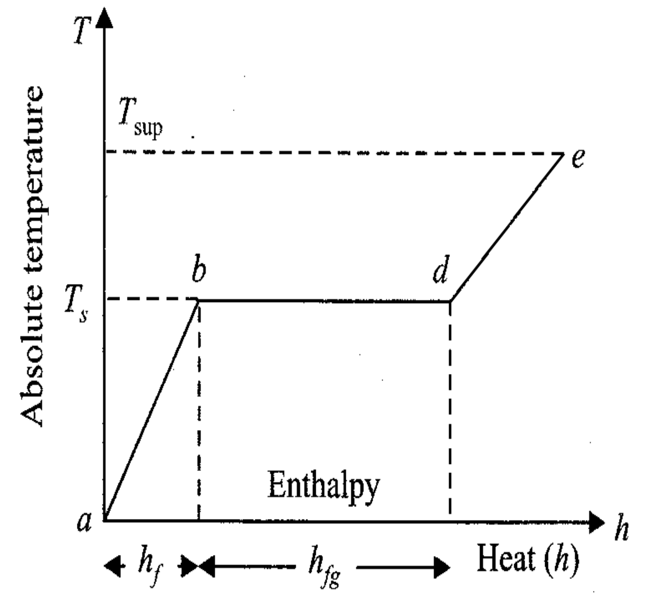
- This state of vapours is represented by point `d' on the temperature- enthalpy diagram.



Temperature–enthalpy diagram.

SUPERHEATED STEAM

- From the dry and saturated condition, if vapours receive heat further, they become superheated.
- Thus, the addition of heat to the vapours in the zone *d*-*e* increases the temperature of vapours. The addition of heat in this phase of vapour is known as **heat of superheat.**
- The temperature above the vapour saturation and up to the superheated vapour temperature is known as the **degree of superheat** and often presented as $\mathbf{T_{sup}}$.
- During the process of superheat, steam behaves approximately as a gas and the laws of gases could be applied.



Temperature–enthalpy diagram.

THE ADVANTAGES OF USING SUPERHEATED STEAM:

- Heat energy in steam increases during superheating which means the work carried out by steam per unit mass is more than the dry and saturated steam.

- During superheating, the temperature of steam increases beyond the dry and saturated limit. An increase in temperature also increases the thermal efficiency of the engine.

- Since the superheated steam is at a higher temperature, chances of that becoming wet during expansion in turbine blades reduces. It considerably reduces the corrosion and also loss of energy during expansion.

ENTHALPY OF STEAM

- Steam is used for power production which is generated due to the enthalpy of steam.
- Energy equation in its usual notation is given by
- $Q = du + dw = (u_2 - u_1) + P(v_2 - v_1)$
- Heat is **usually supplied at constant pressure** and estimations are carried out. Thus,
- $Q = (u_2 + pv_2) - (u_1 + pv_1) = h_2 - h_1$
- ***The heat supplied to the steam is equal to the change in enthalpy of the steam.***

ENTHALPY OF SATURATED LIQUID

- Enthalpy of liquid *(h_f)* up to its saturation temperature in liquid phase is known as enthalpy of saturated liquid. Enthalpy of liquid at point b shown in Figure saturated liquid enthalpy and its values at different pressures for water are given in the steam table with reference to point `a' which is at 0°C. This can also be calculated approximately from the following equation:

$$h_f = C_{pw}(t_{sat} - 0)$$

- where *C* the **specific heat of water = 4.187 kJ/kg K** and t_{sat} is the saturation temperature corresponding to steam formation pressure.

- However, the specific heat at constant pressure changes with temperature, so at higher pressure and temperature, the difference between the actual value of h_f and the calculated value obtained by using the above equation is more.

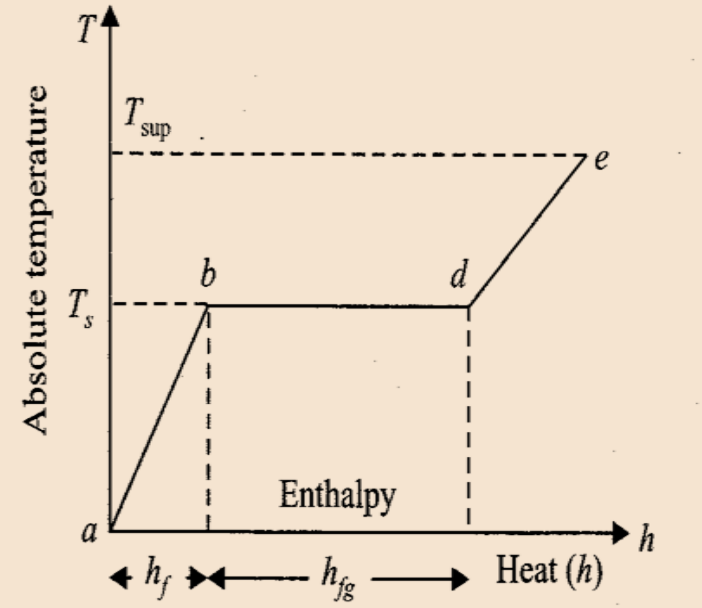
- Therefore, it is recommended that steam table value *of* h_f *be* used for estimation.

ENTHALPY OF EVAPORATION

- Enthalpy of water taken from saturated liquid to covert it into dry and saturated vapours is known as enthalpy of evaporation which is shown by the line *bd* in Figure. It is also known as latent heat of water and denoted by h_f.

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

- where h_g is the enthalpy of the dry and saturated steam and its value is given in the steam table at specific pressure.

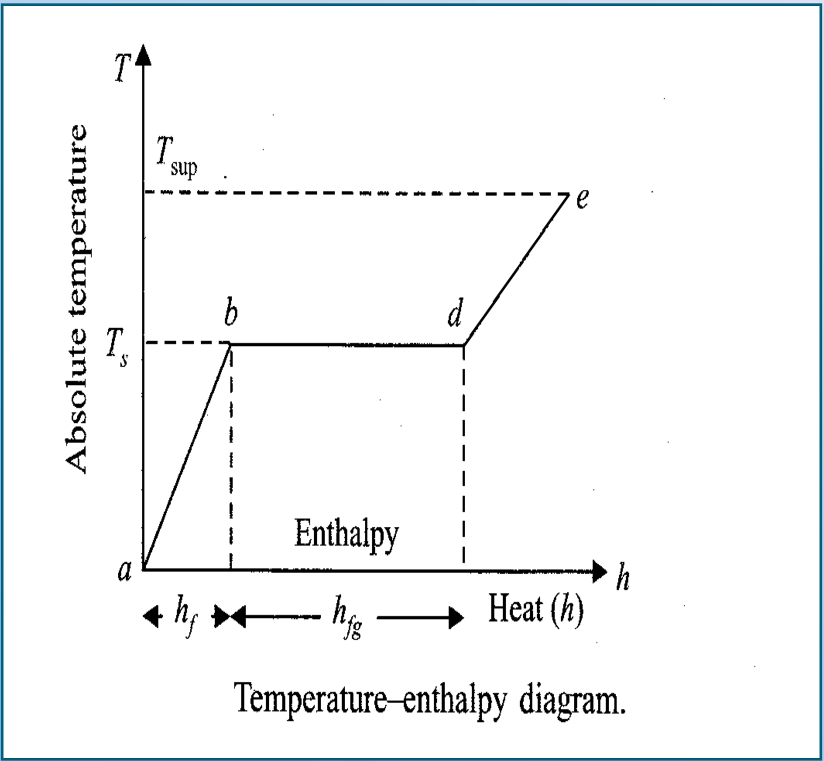


Temperature–enthalpy diagram.

DRYNESS FRACTION

- The term 'dryness fraction' is related to wet steam which evaporates and used to find the state in the zone *bd*.
- Dryness fraction is defined as the ratio of the mass of the actual dry steam to the total mass of mixture (wet steam).
- It is normally denoted by 'x'.

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



Temperature–enthalpy diagram.

WETNESS FRACTION

Wetness Fraction

$$\text{Wetness fraction} = \frac{m_w}{m_w + m_s} = \frac{m_w + m_s - m_s}{m_w + m_s}$$

$$= 1 - \frac{m_s}{m_w + m_s}$$

$$= 1 - x$$

$$\text{Wetness fraction} = 1 - x$$

Wetness fraction + Dryness Fraction = 1

QUALITY OF STEAM & WETNESS FRACTION

Quality of Steam = Dryness fraction x 100

$$\text{Quality of steam} = \frac{m_s}{m_s + m_w} \times 100$$
$$= 100x$$

Priming = Wetness Fraction x 100

$$\text{Priming} = 100(1 - x)$$

$$\text{Quality of steam} + \text{Priming} = 100x + 100(1 - x)$$
$$= 100$$

ENTHALPY OF WET STEAM

- It is the quantity of enthalpy which is required to convert 0°C water to the required quality of steam at constant pressure and is represented by h.
- The amount of heat contained in unit mass of wet steam of quality x can be estimated at that pressure.
- The unit mass of wet steam contains x amount of dry saturated steam and 1- x

$$\begin{aligned} h &= (1-x)h_f + x \cdot h_g \\ &= h_f + x(h_g - h_f) \\ &= h_f + xh_{fg} \end{aligned}$$

ENTHALPY OF SUPERHEATED STEAM

- Heating of steam after it becomes dry and saturated is known as superheating and normally carried out at constant pressure.

- The additional amount of heat supplied to the steam during superheating is called `heat of superheat' and can be estimated as carried out for ideal gases.

- It is often presumed that superheated steam behaves like a gas and therefore laws of ideal gas may be used for the estimation of various parameters.

- The polytropic process applicable to superheated steam is often taken as $n = 1.3$, which means that the law $PV^{1.3} = K$ (constant) holds good for superheated steam. Therefore,

$$\boxed{\text{Heat of superheat steam} = C_{ps}(T_{\text{sup}} - T_s)}$$

ENTHALPY OF SUPERHEATED STEAM

$$\text{Heat of superheat steam} = C_{ps}(T_{\text{sup}} - T_s)$$

T_{sup} = temperature of superheated steam

T_s = saturated steam or water temperature at that pressure

C_{ps} = specific heat of superheated steam and it varies from 2.0 to 2.1 kJ/kg·K depending upon the pressure and temperature of steam and $T_{\text{sup}} - T_s$ is the difference in steam temperature with respect to saturation temperature steam at that pressure and known as 'degree of superheat'.

$$\text{Total heat of superheated steam} = h_{\text{sup}} = h_f + h_{fg} + C_{ps}(T_{\text{sup}} - T_s)$$

h_{sup} can also be directly read from the steam table given normally for the degree of superheat at that specific pressure.

∴ Total heat of superheated steam is given by

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

DEGREE OF SUPERHEAT AND HEAT OF SUPERHEAT

Degree of Superheat:

- At a specified pressure, if the steam is superheated, then the difference in the temperature of the steam and the saturation temperature at that pressure is known as **degree of superheat.**

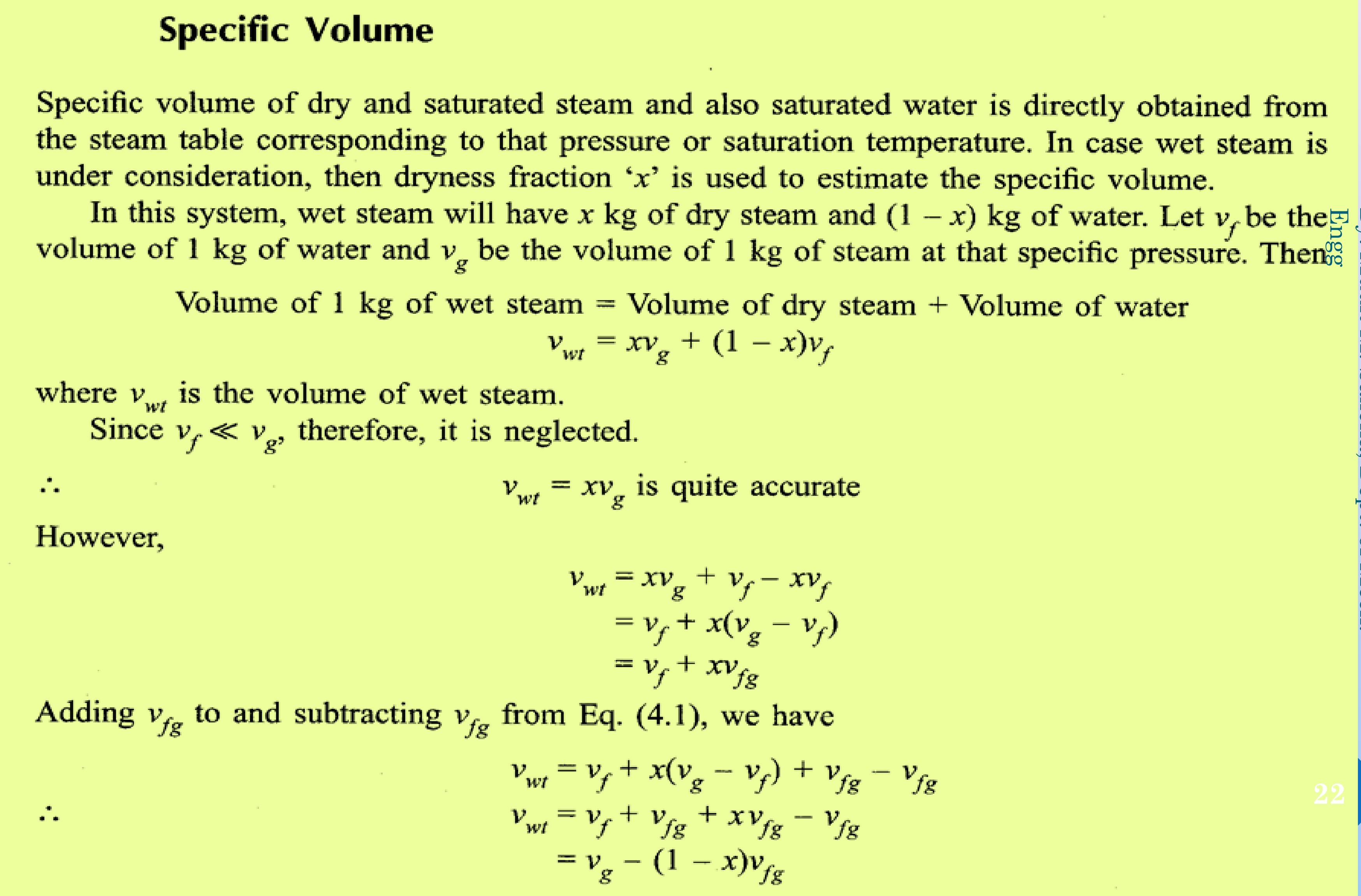
$$\text{Degree of superheat} = T_{\text{sup}} - T_{\text{sat}}$$

Heat of Superheat:

- It is the difference between the enthalpy of superheated steam and the saturated steam enthalpy at the same pressure.

$$\text{heat of superheat} = C_p(T_{\text{sup}} - T_{\text{sat}}) \text{ kJ/kg of steam}$$

SPECIFIC VOLUME



Specific Volume

Specific volume of dry and saturated steam and also saturated water is directly obtained from the steam table corresponding to that pressure or saturation temperature. In case wet steam is under consideration, then dryness fraction 'x' is used to estimate the specific volume.

In this system, wet steam will have x kg of dry steam and $(1 - x)$ kg of water. Let v_f be the volume of 1 kg of water and v_g be the volume of 1 kg of steam at that specific pressure. Then

Volume of 1 kg of wet steam = Volume of dry steam + Volume of water

$$v_{wt} = xv_g + (1 - x)v_f$$

where v_{wt} is the volume of wet steam.

Since $v_f \ll v_g$, therefore, it is neglected.

$$\therefore \quad v_{wt} = xv_g \text{ is quite accurate}$$

However,

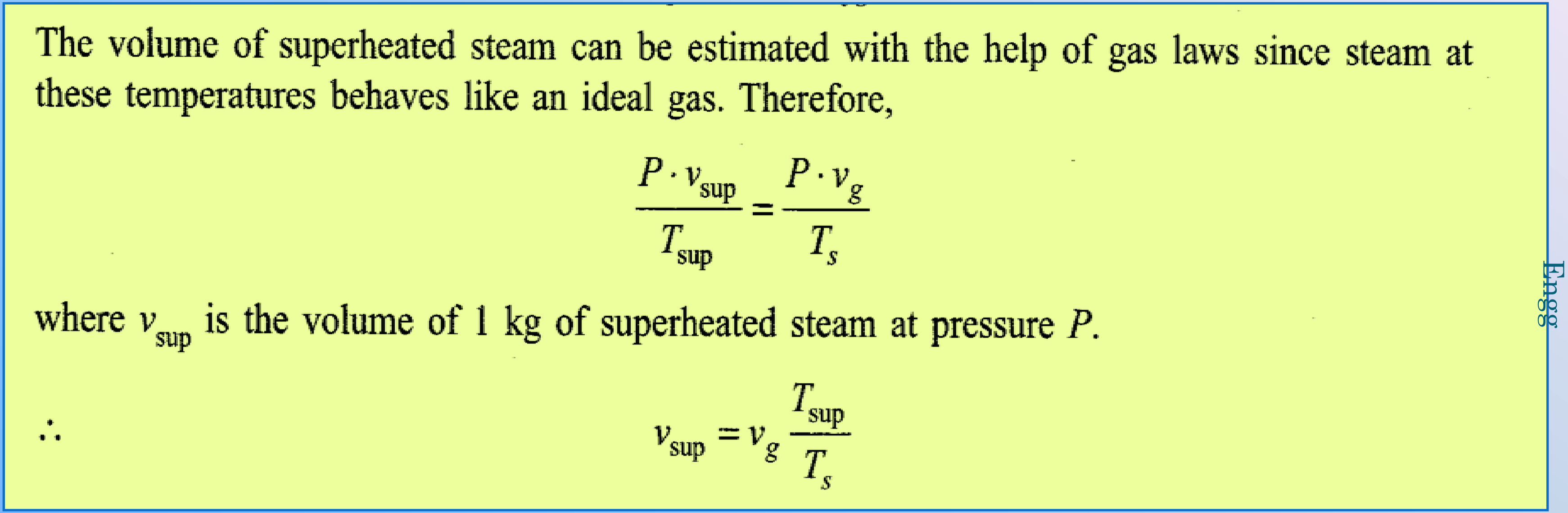
$$\begin{aligned} v_{wt} &= xv_g + v_f - xv_f \\ &= v_f + x(v_g - v_f) \\ &= v_f + xv_{fg} \end{aligned}$$

Adding v_{fg} to and subtracting v_{fg} from Eq. (4.1), we have

$$v_{wt} = v_f + x(v_g - v_f) + v_{fg} - v_{fg}$$

$$\begin{aligned} \therefore \quad v_{wt} &= v_f + v_{fg} + xv_{fg} - v_{fg} \\ &= v_g - (1 - x)v_{fg} \end{aligned}$$

VOLUME OF SUPERHEATED STEAM



The volume of superheated steam can be estimated with the help of gas laws since steam at these temperatures behaves like an ideal gas. Therefore,

$$\frac{P \cdot v_{\text{sup}}}{T_{\text{sup}}} = \frac{P \cdot v_g}{T_s}$$

where v_{sup} is the volume of 1 kg of superheated steam at pressure P.

$$\therefore \qquad v_{\text{sup}} = v_g \frac{T_{\text{sup}}}{T_s}$$

Density of Steam (p)

If the specific volume of any steam is v m^3/kg, then its density (ρ) will be I/v or if density (p) is known, then specific volume v = 1/ρ.

THERMODYNAMIC PROPERTIES

- The working fluid in any system has six basic thermodynamic properties which explain the state of the working medium completely.
- These six thermodynamic properties may not be independent and may be specific at specific conditions and are tabulated in the steam table at different pressure and saturation temperature conditions.
- The **basic thermodynamic properties are:**

  Pressure (P), Temperature (T), Volume (v), Internal energy (u), Enthalpy *(h)* Entropy (s).

  These properties are estimated at different conditions and various power/energy parameters which are used in specific applications.

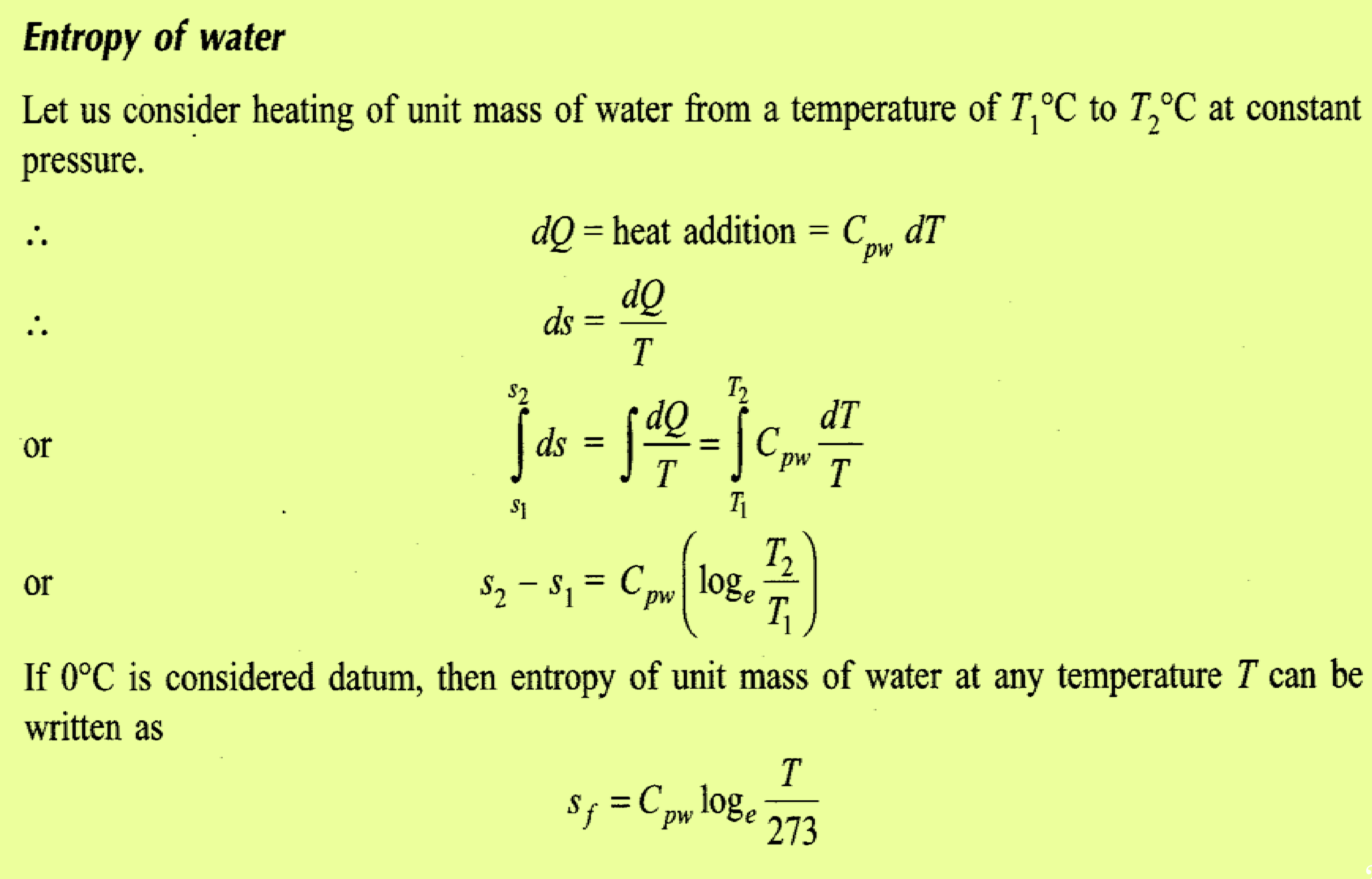
ENTROPY

- Entropy is a thermodynamic property and mathematically defined as

$$s = \int \frac{dQ}{T}$$

- where dQ is the heat transfer in kJ and T is the temperature in kelvin (K).
- It is also used to denote the state of medium or body similar to pressure, temperature, volume, enthalpy, etc. But it cannot be measured by instruments such as temperature, pressure, etc.
- The normal unit used to measure entropy is kJ/kg.K
- Entropy is a function of heat and temperature.
- The increase in entropy is small if heat is added at high temperature and it is large when addition of heat is added at lower temperature.

ENTROPY OF WATER



Entropy of water

Let us consider heating of unit mass of water from a temperature of T_1°C to T_2°C at constant pressure.

$$\therefore \qquad dQ = \text{heat addition} = C_{pw}\, dT$$

$$\therefore \qquad ds = \frac{dQ}{T}$$

or

$$\int_{s_1}^{s_2} ds = \int \frac{dQ}{T} = \int_{T_1}^{T_2} C_{pw} \frac{dT}{T}$$

or

$$s_2 - s_1 = C_{pw}\left(\log_e \frac{T_2}{T_1}\right)$$

If 0°C is considered datum, then entropy of unit mass of water at any temperature T can be written as

$$s_f = C_{pw} \log_e \frac{T}{273}$$

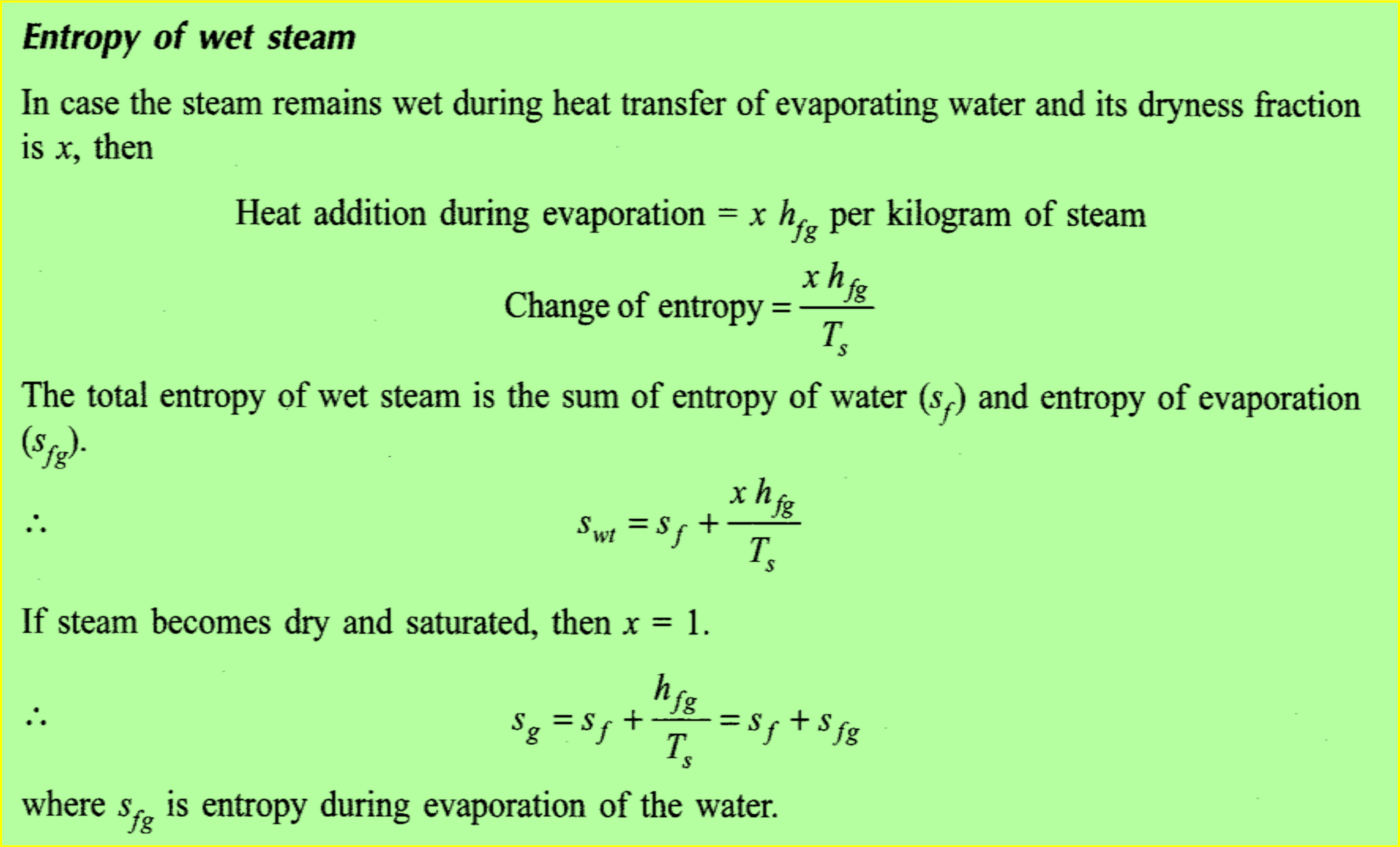
ENTROPY OF EVAPORATION

- During the process of evaporation, temperature of the medium remains constant while heat is added and change of phase is taken place.
-

$$\text{Change of entropy} = ds = \frac{dQ}{T}$$

$$s_2 - s_1 = \frac{Q}{T}$$

ENTROPY OF WET STEAM



Entropy of wet steam

In case the steam remains wet during heat transfer of evaporating water and its dryness fraction is x, then

$$\text{Heat addition during evaporation} = x\, h_{fg} \text{ per kilogram of steam}$$

$$\text{Change of entropy} = \frac{x\, h_{fg}}{T_s}$$

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

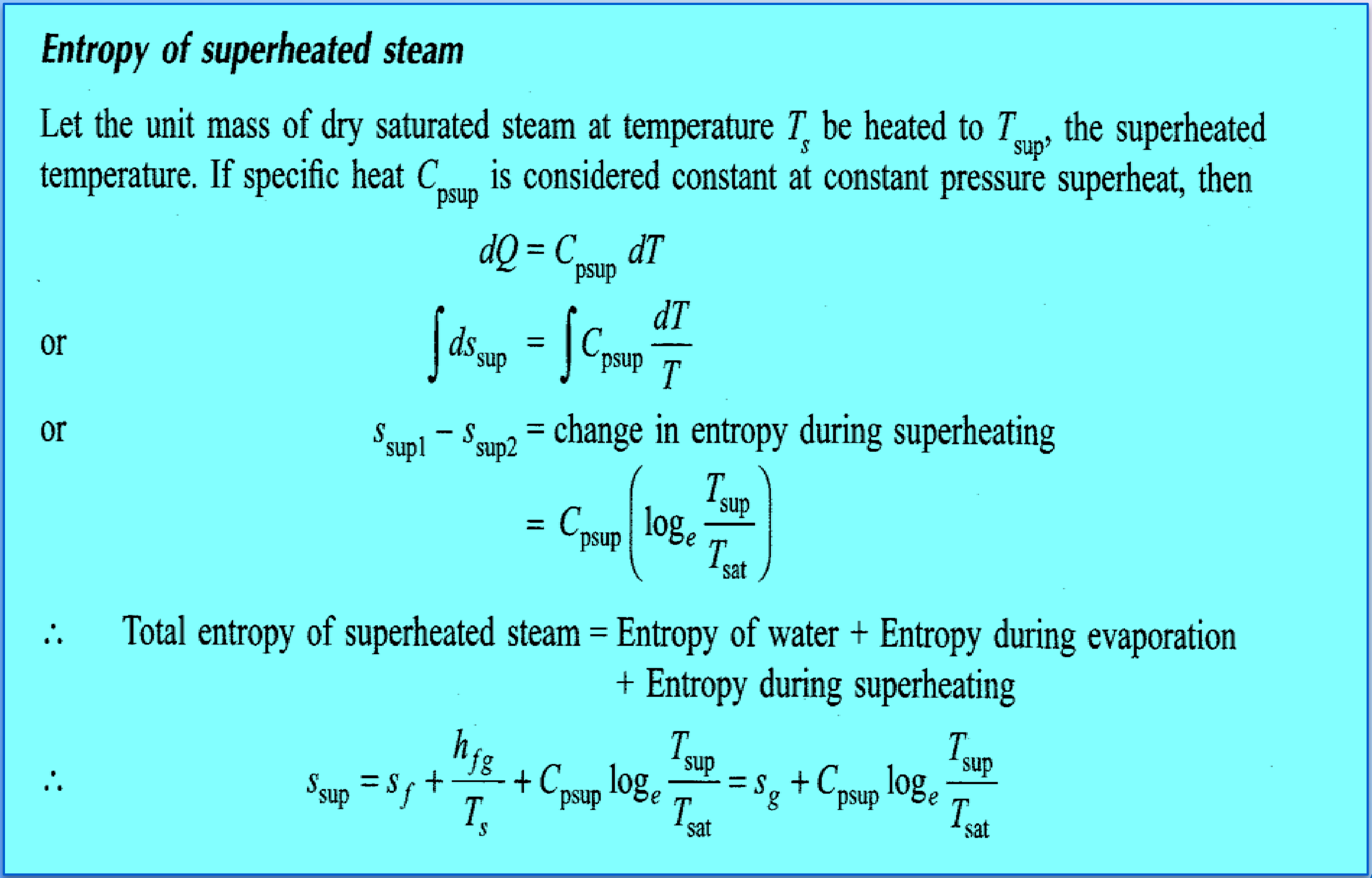
$$\therefore \qquad s_{wt} = s_f + \frac{x\, h_{fg}}{T_s}$$

If steam becomes dry and saturated, then $x = 1$.

$$\therefore \qquad s_g = s_f + \frac{h_{fg}}{T_s} = s_f + s_{fg}$$

where s_{fg} is entropy during evaporation of the water.

ENTROPY OF SUPERHEATED STEAM



Entropy of superheated steam

Let the unit mass of dry saturated steam at temperature T_s be heated to T_{sup}, the superheated temperature. If specific heat C_{psup} is considered constant at constant pressure superheat, then

$$dQ = C_{psup}\, dT$$

or
$$\int ds_{sup} = \int C_{psup} \frac{dT}{T}$$

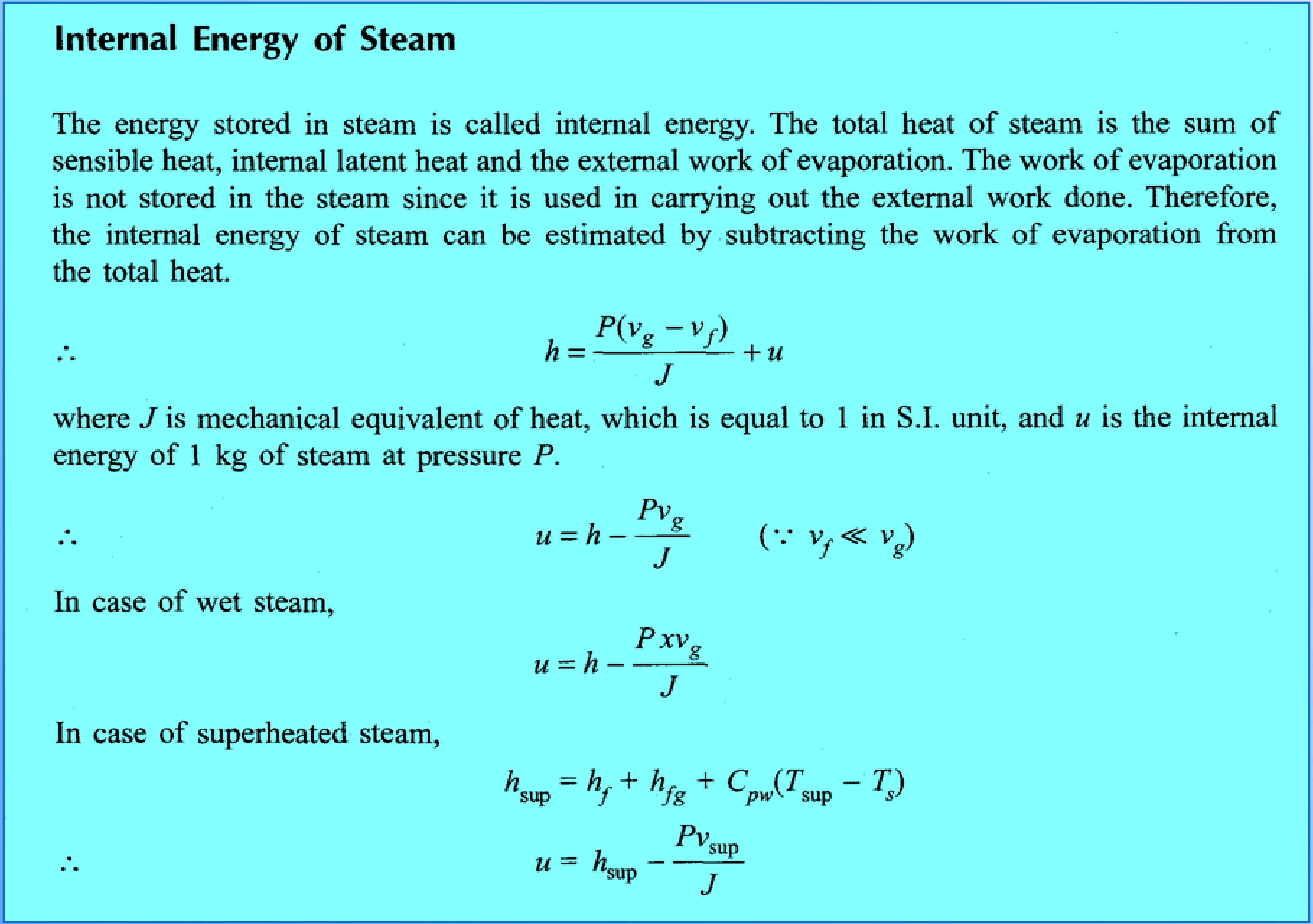
or
$$s_{sup1} - s_{sup2} = \text{change in entropy during superheating}$$

$$= C_{psup} \left(\log_e \frac{T_{sup}}{T_{sat}} \right)$$

∴ Total entropy of superheated steam = Entropy of water + Entropy during evaporation + Entropy during superheating

∴
$$s_{sup} = s_f + \frac{h_{fg}}{T_s} + C_{psup} \log_e \frac{T_{sup}}{T_{sat}} = s_g + C_{psup} \log_e \frac{T_{sup}}{T_{sat}}$$

INTERNAL ENERGY OF STEAM



Internal Energy of Steam

The energy stored in steam is called internal energy. The total heat of steam is the sum of sensible heat, internal latent heat and the external work of evaporation. The work of evaporation is not stored in the steam since it is used in carrying out the external work done. Therefore, the internal energy of steam can be estimated by subtracting the work of evaporation from the total heat.

$$\therefore \qquad h = \frac{P(v_g - v_f)}{J} + u$$

where J is mechanical equivalent of heat, which is equal to 1 in S.I. unit, and u is the internal energy of 1 kg of steam at pressure P.

$$\therefore \qquad u = h - \frac{Pv_g}{J} \qquad (\because\ v_f \ll v_g)$$

In case of wet steam,

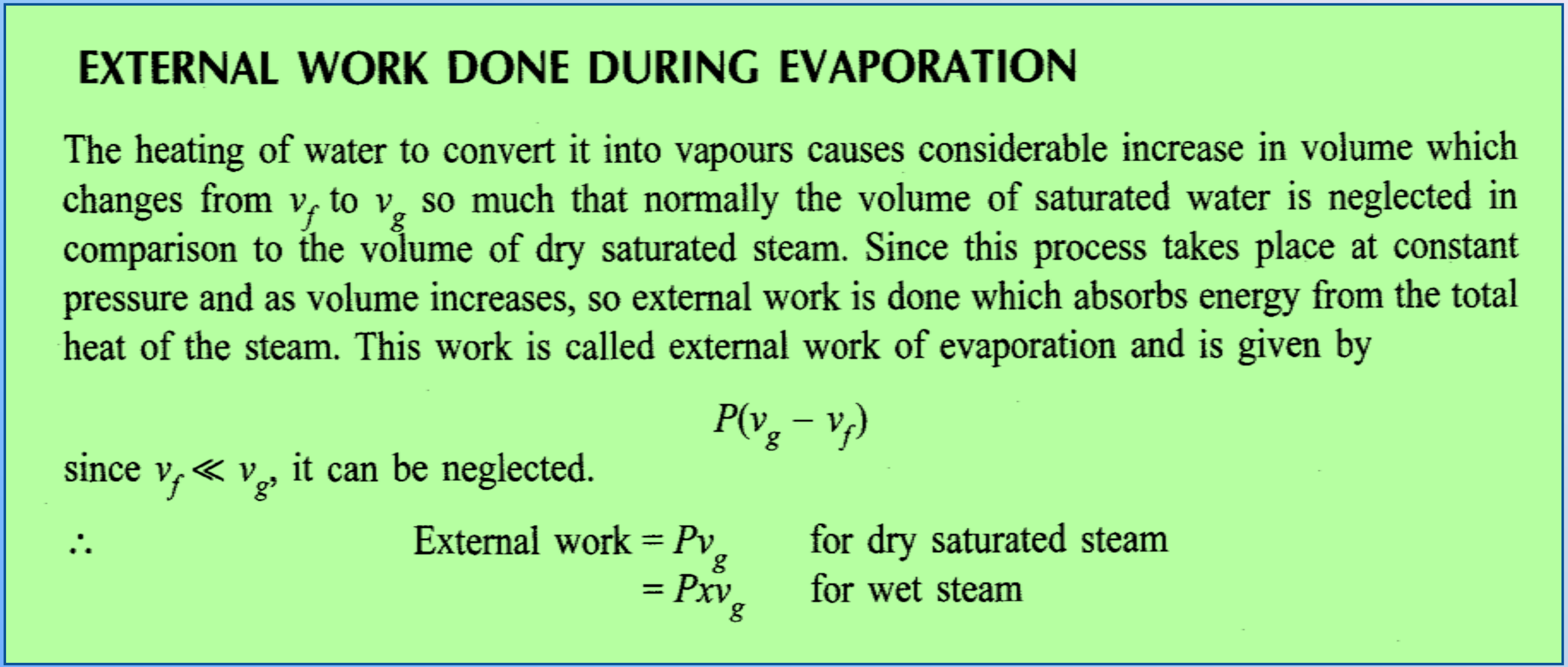
$$u = h - \frac{P x v_g}{J}$$

In case of superheated steam,

$$h_{sup} = h_f + h_{fg} + C_{pw}(T_{sup} - T_s)$$

$$\therefore \qquad u = h_{sup} - \frac{Pv_{sup}}{J}$$

WORK DONE DURING EVAPORATION



EXTERNAL WORK DONE DURING EVAPORATION

The heating of water to convert it into vapours causes considerable increase in volume which changes from v_f to v_g so much that normally the volume of saturated water is neglected in comparison to the volume of dry saturated steam. Since this process takes place at constant pressure and as volume increases, so external work is done which absorbs energy from the total heat of the steam. This work is called external work of evaporation and is given by

$$P(v_g - v_f)$$

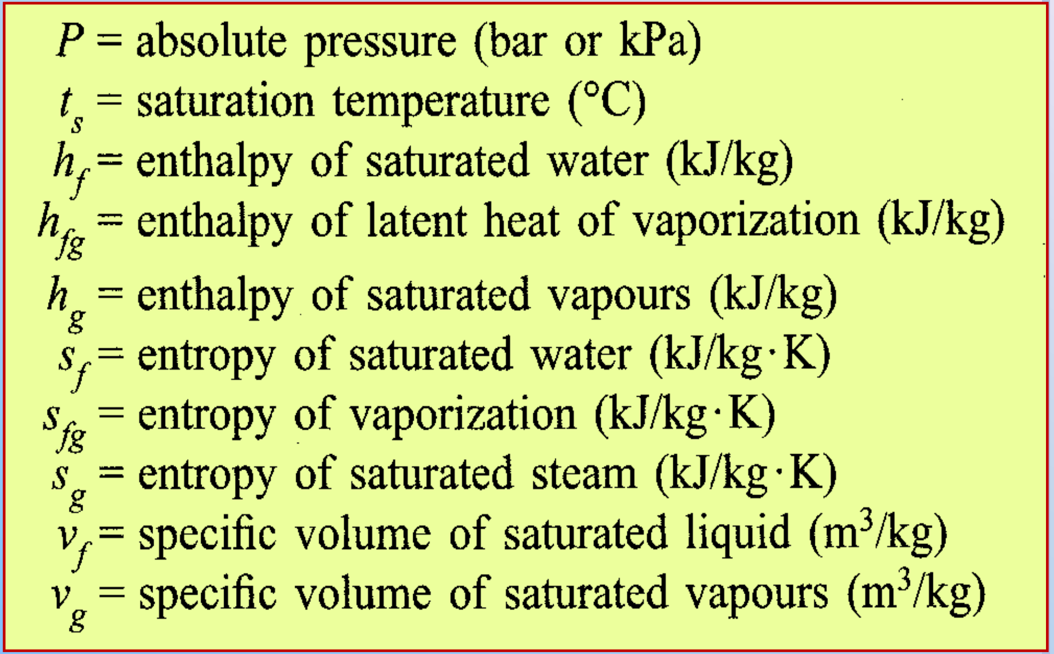
since $v_f \ll v_g$, it can be neglected.

$$\therefore \quad \text{External work} = Pv_g \quad \text{for dry saturated steam}$$

$$= Pxv_g \quad \text{for wet steam}$$

STEAM TABLE

- The magnitudes of these properties are estimated and determined practically and also tabulated in the form of tables for water which are known as steam tables.
- These properties are tabulated in tables right from water to steam and to superheated steam and are very useful in estimating energy available from steam at different stages.



P = absolute pressure (bar or kPa)

t_s = saturation temperature (°C)

h_f = enthalpy of saturated water (kJ/kg)

h_{fg} = enthalpy of latent heat of vaporization (kJ/kg)

h_g = enthalpy of saturated vapours (kJ/kg)

s_f = entropy of saturated water (kJ/kg·K)

s_{fg} = entropy of vaporization (kJ/kg·K)

s_g = entropy of saturated steam (kJ/kg·K)

v_f = specific volume of saturated liquid (m^3/kg)

v_g = specific volume of saturated vapours (m^3/kg)

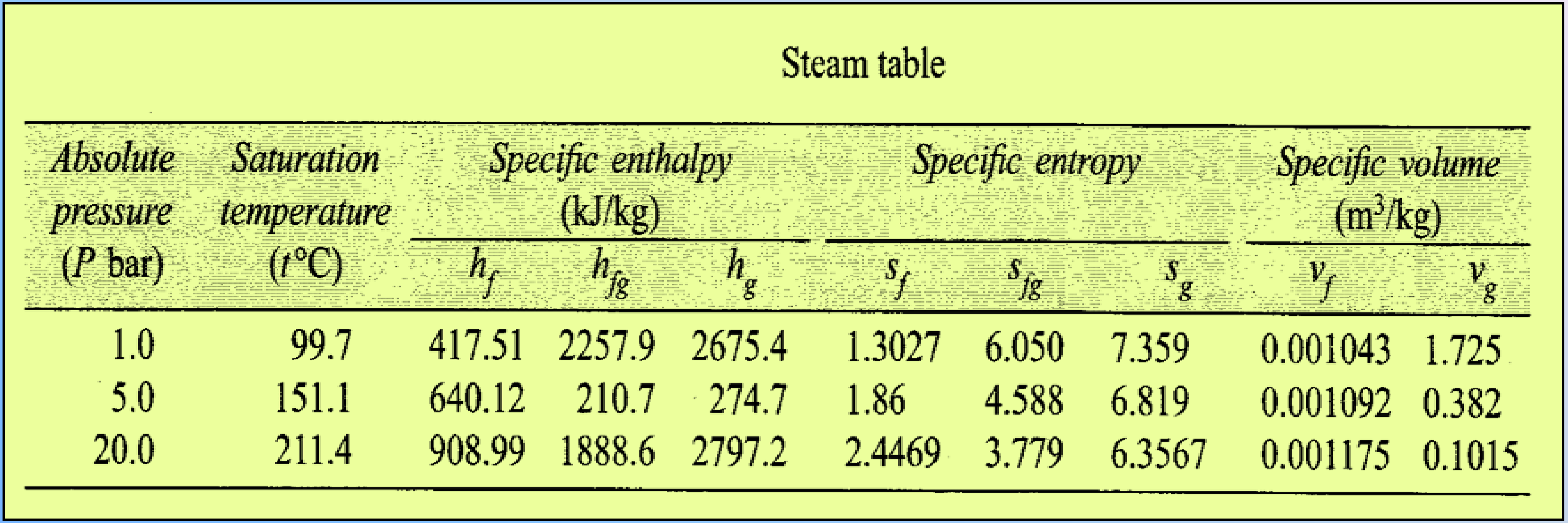
By: Mudit M. Saxena, Dept. of Mech. Engg

PROPERTIES WHICH CAN BE CALCULATED FROM STEAM TABLE

P = absolute pressure (bar or kPa)
t_s = saturation temperature (°C)
h_f = enthalpy of saturated water (kJ/kg)
h_{fg} = enthalpy of latent heat of vaporization (kJ/kg)
h_g = enthalpy of saturated vapours (kJ/kg)
s_f = entropy of saturated water (kJ/kg·K)
s_{fg} = entropy of vaporization (kJ/kg·K)
s_g = entropy of saturated steam (kJ/kg·K)
v_f = specific volume of saturated liquid (m^3/kg)
v_g = specific volume of saturated vapours (m^3/kg)

$h_{fg} = h_g - h_f$; enthalpy of evaporation (kJ/kg)
$s_{fg} = s_g - s_f$; change of entropy during evaporation (kJ/kg·K)
$v_{fg} = v_g - v_f$; change of specific volume during evaporation (m^3/kg)
$u = h - Pv$; the internal energy of steam is tabulated using the steam table.

STEAM TABLE AT A GLANCE



Steam table

Absolute pressure (*P* bar)	Saturation temperature (*t*°C)	Specific enthalpy (kJ/kg)			Specific entropy			Specific volume (m^3/kg)	
		h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_g
1.0	99.7	417.51	2257.9	2675.4	1.3027	6.050	7.359	0.001043	1.725
5.0	151.1	640.12	210.7	274.7	1.86	4.588	6.819	0.001092	0.382
20.0	211.4	908.99	1888.6	2797.2	2.4469	3.779	6.3567	0.001175	0.1015

NON-FLOW PROCESS

- The working medium undergoes a series of changes during a process particularly when heat or work transfer takes place.

- This means a change in the state of medium takes place during heat or work transfer and is described by the thermodynamic properties of the medium.
- Since steam has vapour before its saturation conditions, therefore gas laws are not applicable but they can be used for steam which is in superheated state to the great extent.

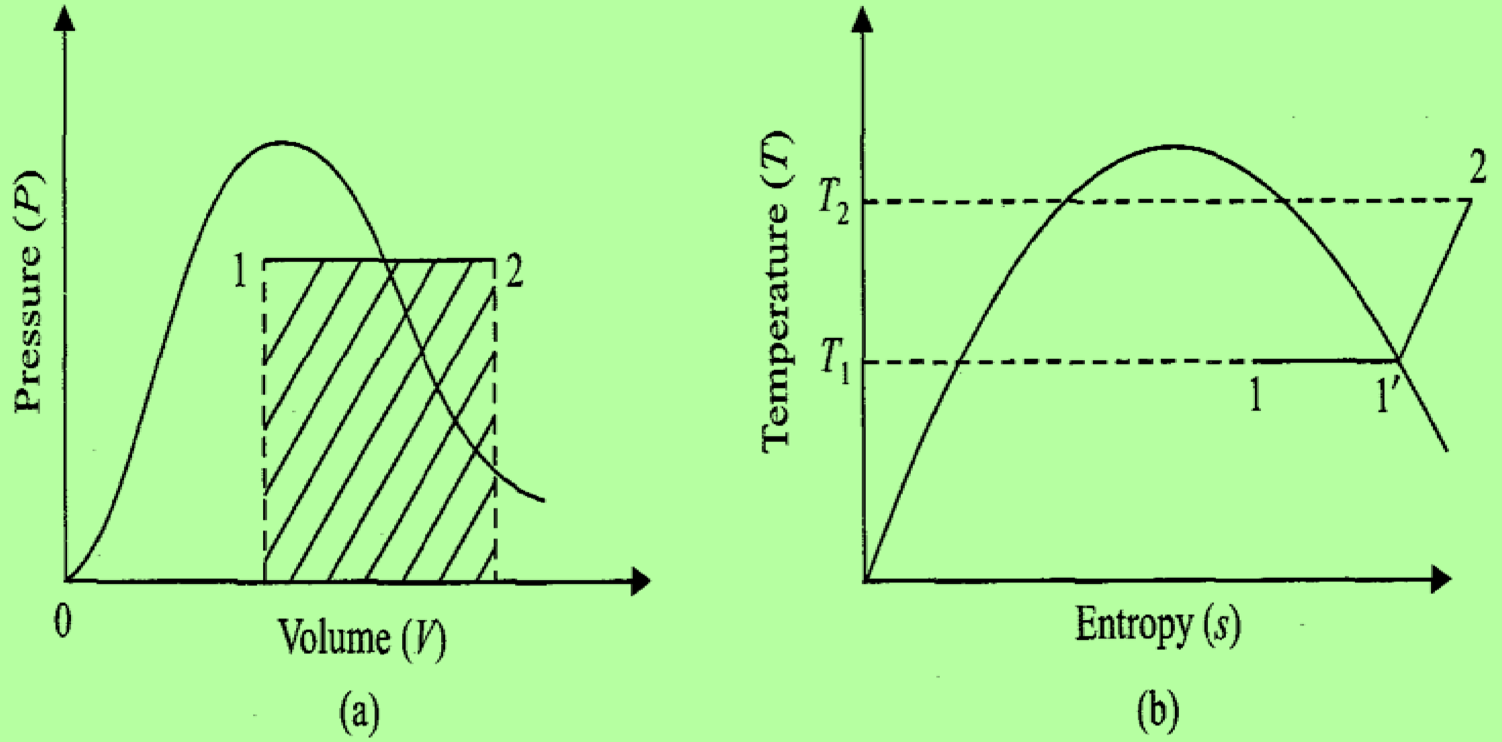
- In a closed system, the medium does not move out of the system and the process takes place in the enclosed boundary.

- In the vapour phase, gas equations cannot be used for steam. However, all the equations shall be described as discussed during properties of the steam.

Major non-flow processes:

- 1. Constant pressure process 2. Constant volume process,
- 3. Constant temperature process 4. Hyperbolic process,
- 5. Polytropic process 6. Adiabatic process and
- 7. Throttling process.

CONSTANT PRESSURE PROCESS



Heating of steam at constant pressure.

CONSTANT PRESSURE PROCESS

Work done

Work of significance during the non-flow process is the displacement work assuming no significant change in dimensions of the container where medium is undergoing thermodynamic changes.

$$\therefore \qquad W = \text{work done} = \int_{V_1}^{V_2} P\,dV = P(V_2 - V_1)$$

State 1 is the wet steam and state 2 is the superheated steam and therefore volumes at 1 and 2 need to be estimated accordingly.

For wet steam,

$$V_1 = xv_g$$

For superheated steam,

$$V_2 = v_g \times \frac{T_{\text{sup}}}{T_s}$$

The change in internal energy is given by

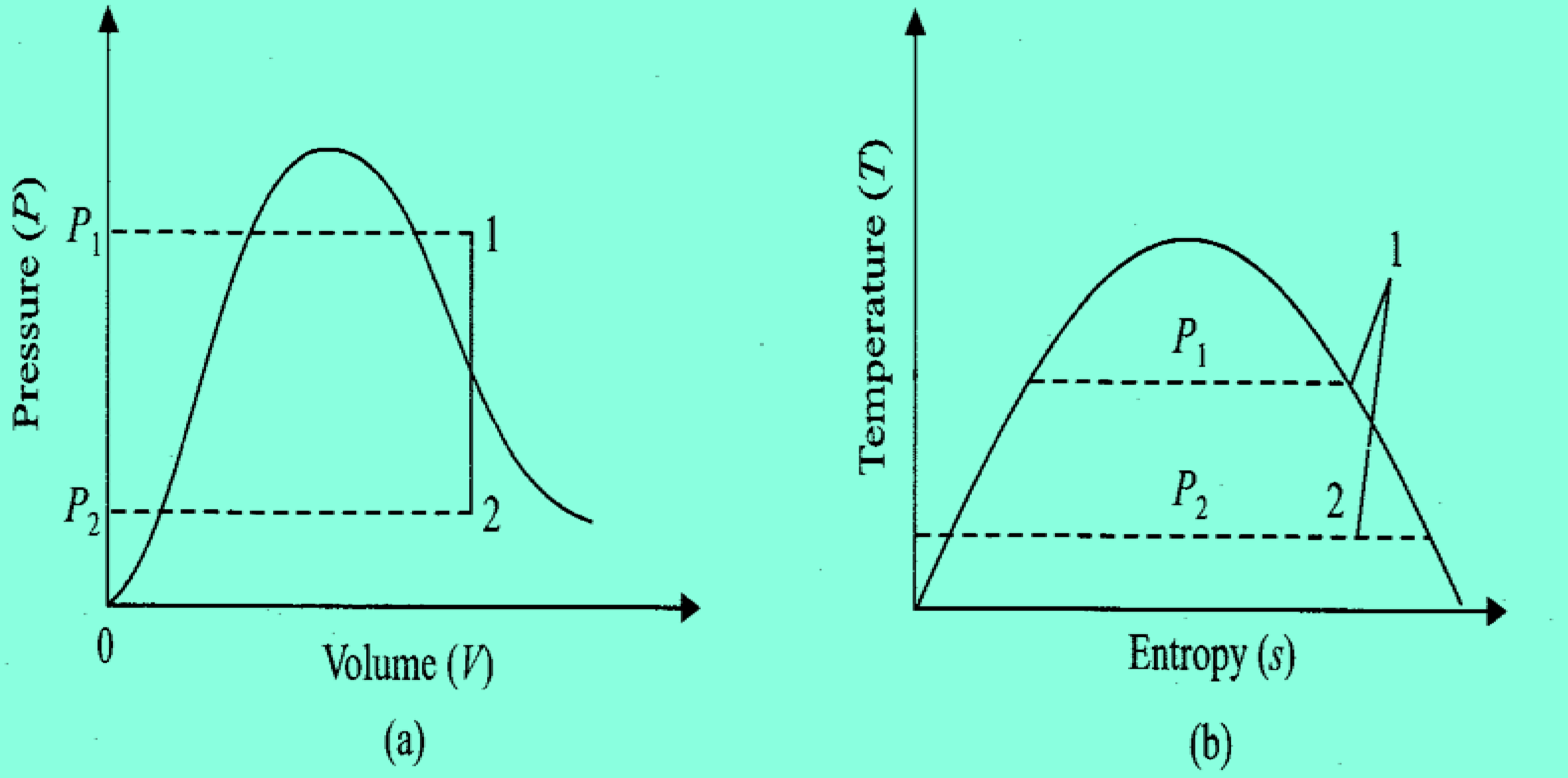
$$\begin{aligned} u_2 - u_1 &= (h_2 - PV_2) - (h_1 - PV_1) \\ &= (h_2 - h_1) - (PV_2 - PV_1) \text{ kJ/kg} \end{aligned}$$

The heat transferred is given by

$$\begin{aligned} dq = dw + du &= P(V_2 - V_1) + [(h_2 - h_1) - P(V_2 - V_1)] \\ &= h_2 - h_1 \end{aligned}$$

Heat transferred = Change in enthalpy during the process

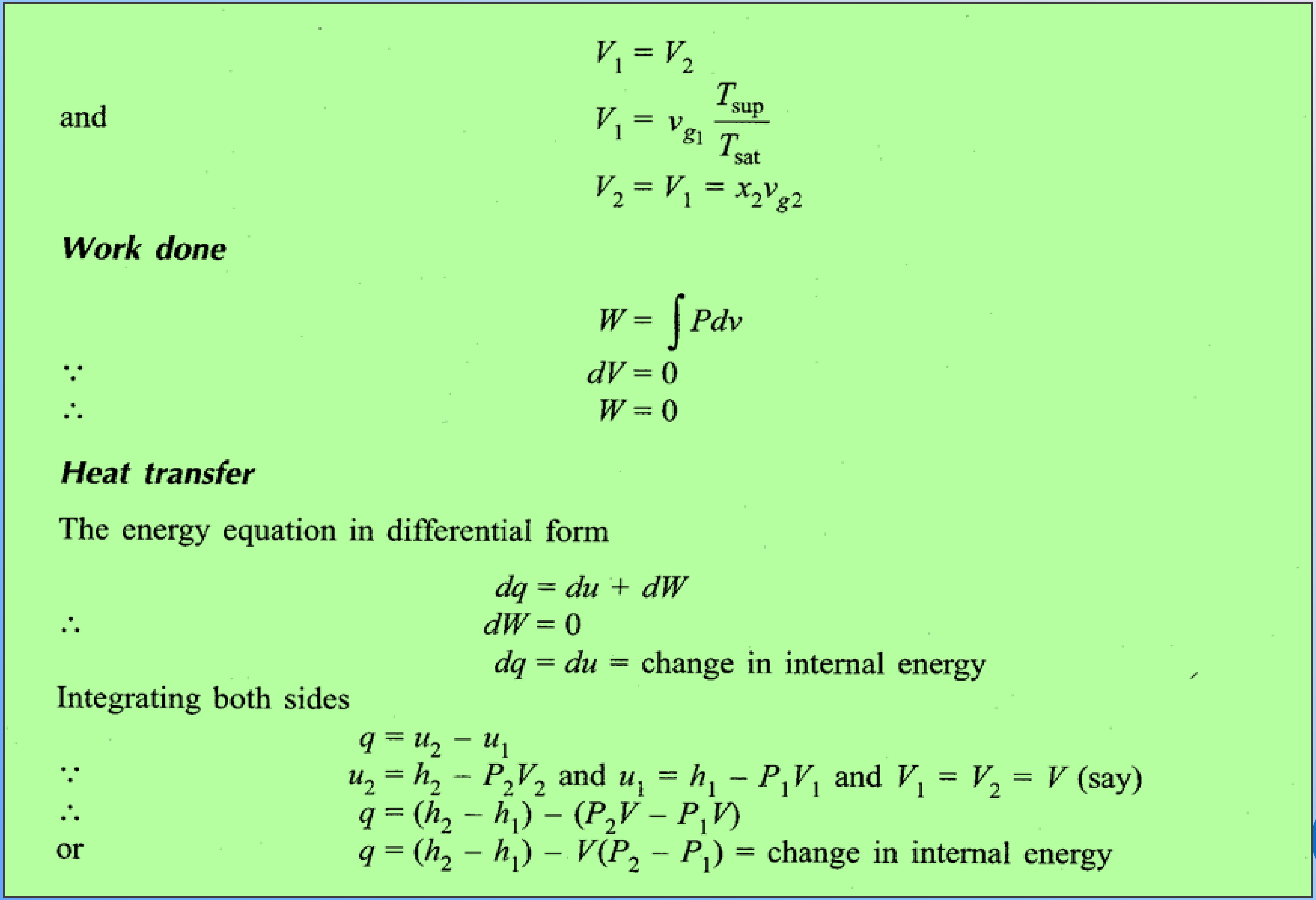
CONSTANT VOLUME PROCESS:



(a) (b)

Constant volume process.

CONSTANT VOLUME PROCESS



$$V_1 = V_2$$

and $$V_1 = v_{g_1} \frac{T_{sup}}{T_{sat}}$$

$$V_2 = V_1 = x_2 v_{g2}$$

Work done

$$W = \int P dv$$

$\because$ $$dV = 0$$

$\therefore$ $$W = 0$$

Heat transfer

The energy equation in differential form

$$dq = du + dW$$

$\therefore$ $$dW = 0$$

$$dq = du = \text{change in internal energy}$$

Integrating both sides

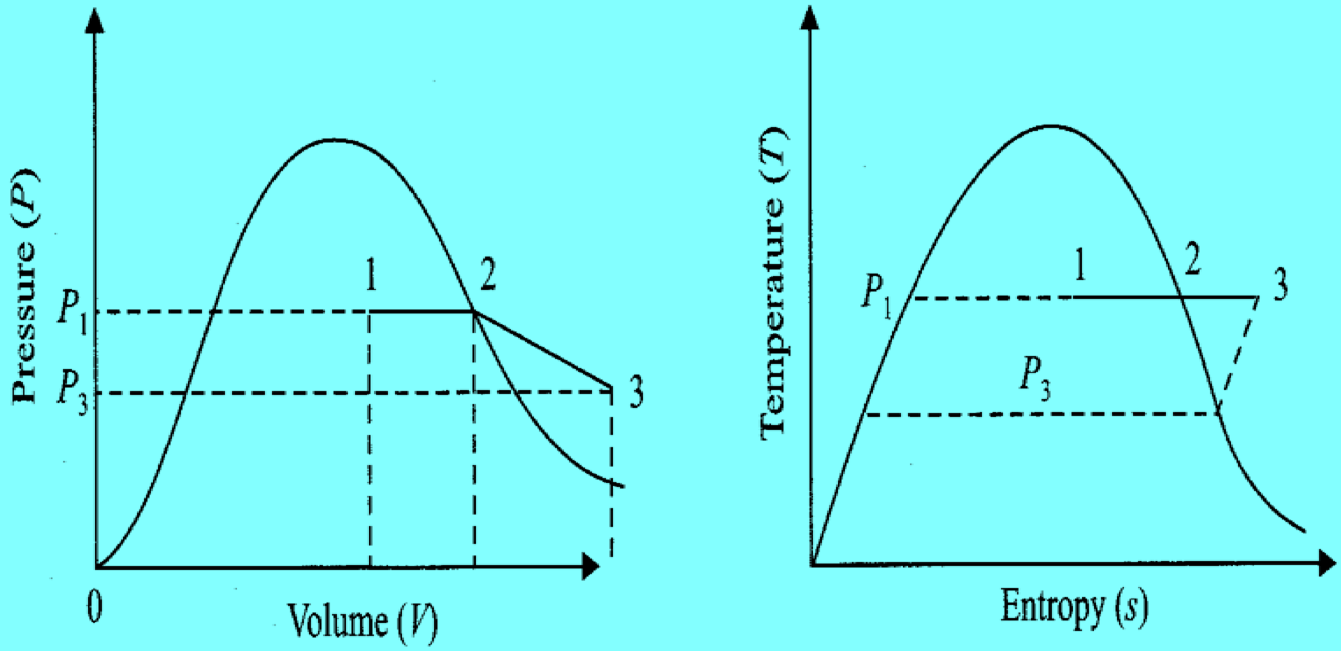
$$q = u_2 - u_1$$

$\because$ $$u_2 = h_2 - P_2V_2 \text{ and } u_1 = h_1 - P_1V_1 \text{ and } V_1 = V_2 = V \text{ (say)}$$

$\therefore$ $$q = (h_2 - h_1) - (P_2V - P_1V)$$

or $$q = (h_2 - h_1) - V(P_2 - P_1) = \text{change in internal energy}$$

CONSTANT TEMPERATURE PROCESS

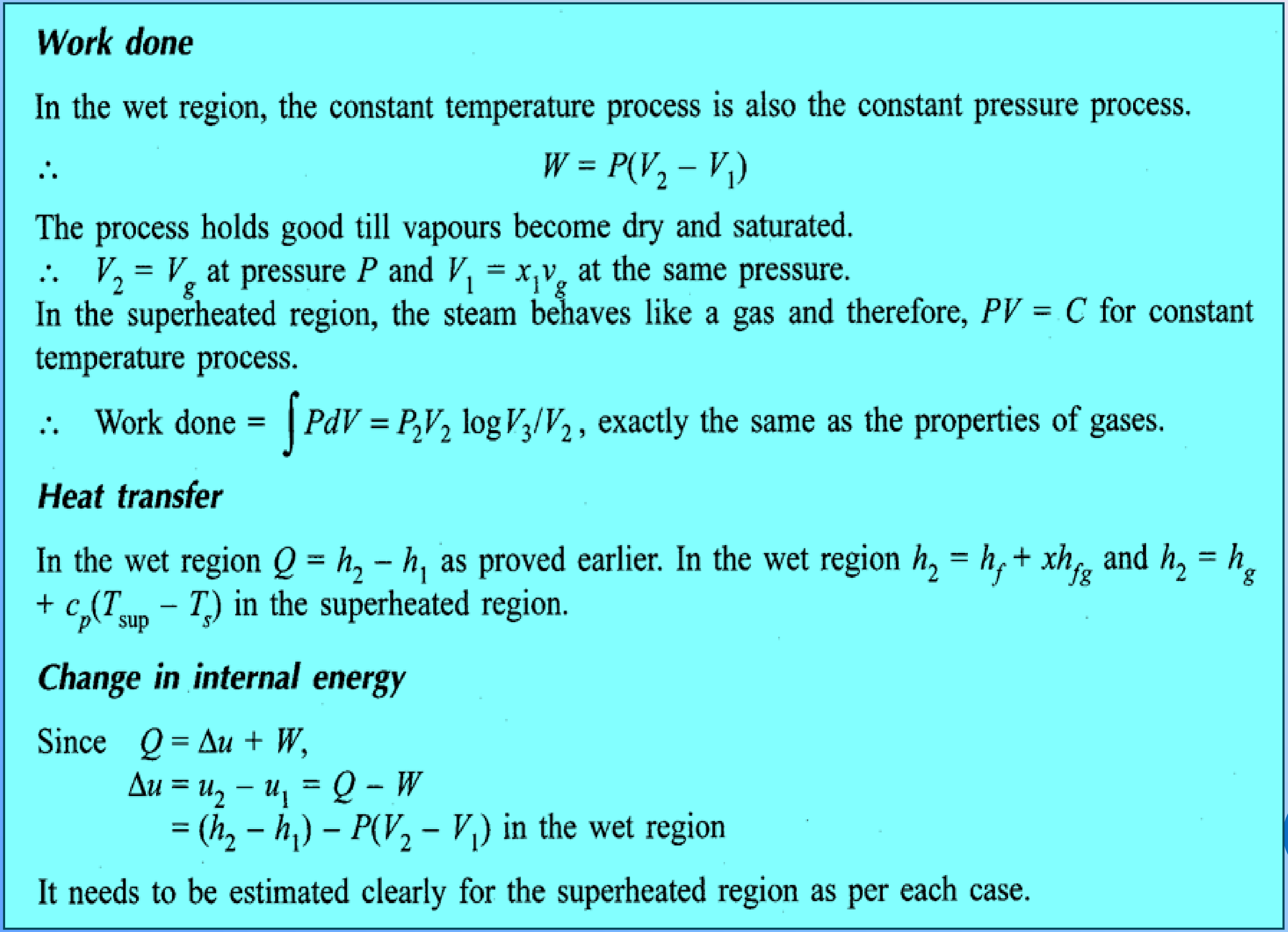


(a)

(b)

Constant temperature process.

WORK DONE DURING CONSTANT TEMPERATURE PROCESS



Work done

In the wet region, the constant temperature process is also the constant pressure process.

$$\therefore \qquad W = P(V_2 - V_1)$$

The process holds good till vapours become dry and saturated.

$\therefore \quad V_2 = V_g$ at pressure P and $V_1 = x_1 v_g$ at the same pressure.

In the superheated region, the steam behaves like a gas and therefore, $PV = C$ for constant temperature process.

$\therefore \quad$ Work done $= \int PdV = P_2V_2 \log V_3/V_2$, exactly the same as the properties of gases.

Heat transfer

In the wet region $Q = h_2 - h_1$ as proved earlier. In the wet region $h_2 = h_f + xh_{fg}$ and $h_2 = h_g + c_p(T_{sup} - T_s)$ in the superheated region.

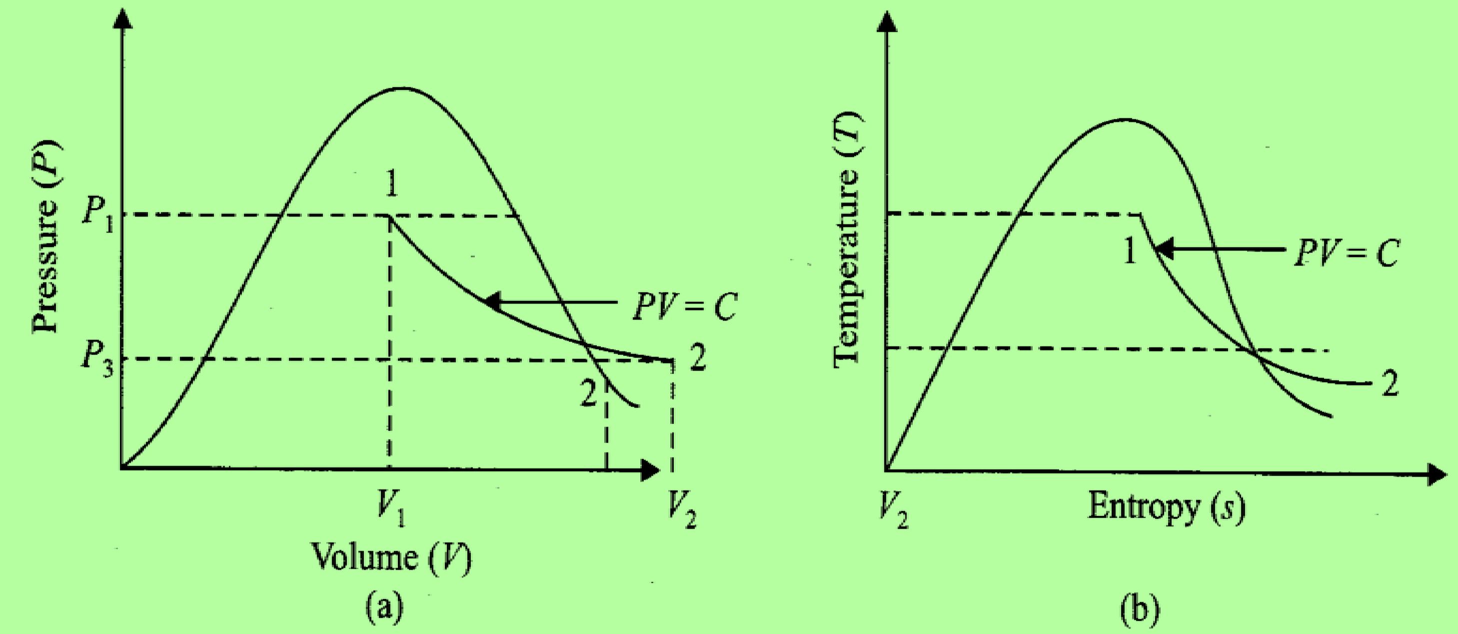
Change in internal energy

Since $\quad Q = \Delta u + W,$

$$\Delta u = u_2 - u_1 = Q - W$$
$$= (h_2 - h_1) - P(V_2 - V_1) \text{ in the wet region}$$

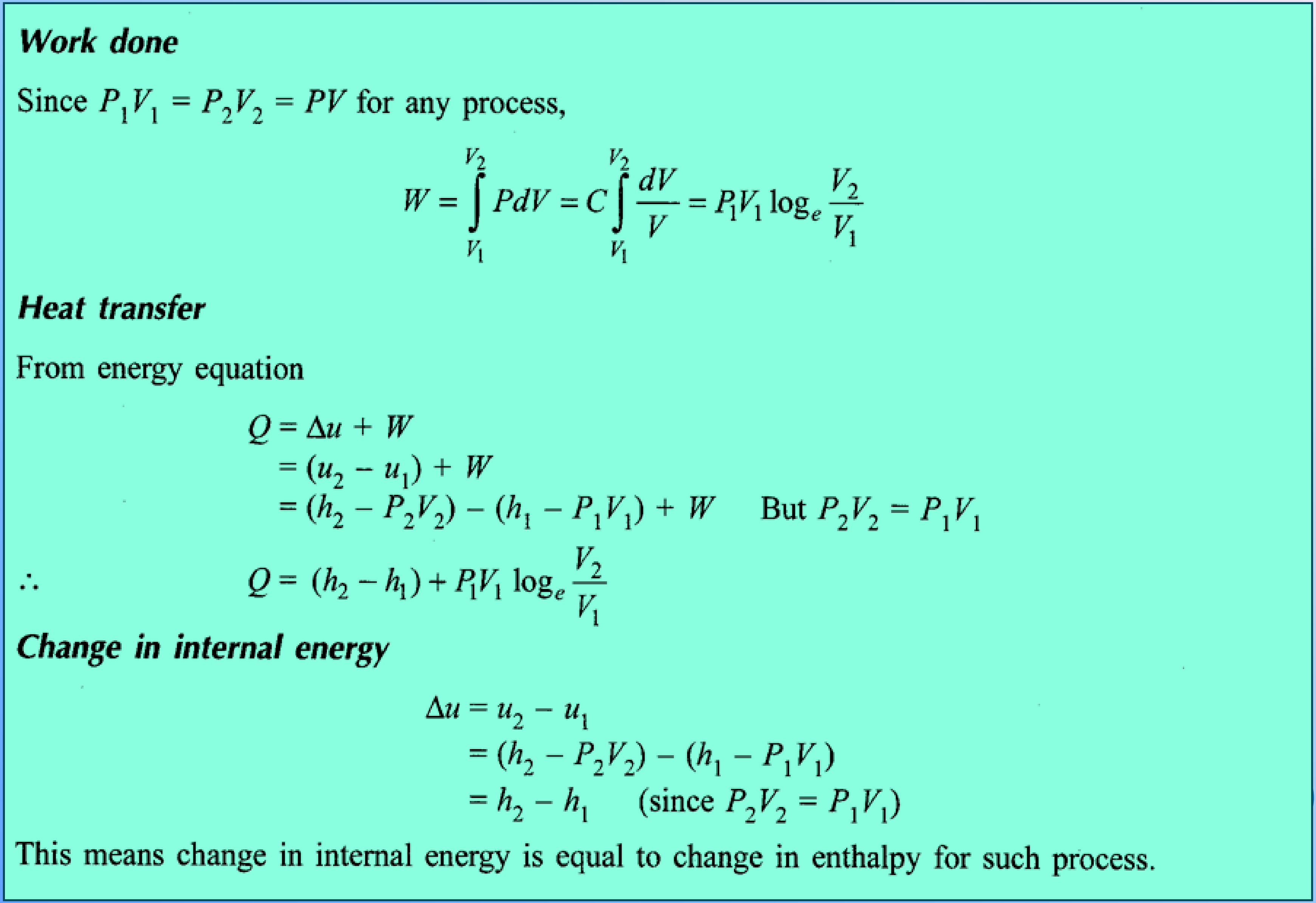
It needs to be estimated clearly for the superheated region as per each case.

HYPERBOLIC PROCESS



Hyperbolic process.

WORK DONE DURING HYPERBOLIC PROCESS



Work done

Since $P_1V_1 = P_2V_2 = PV$ for any process,

$$W = \int_{V_1}^{V_2} P\,dV = C\int_{V_1}^{V_2} \frac{dV}{V} = P_1V_1 \log_e \frac{V_2}{V_1}$$

Heat transfer

From energy equation

$$\begin{aligned} Q &= \Delta u + W \\ &= (u_2 - u_1) + W \\ &= (h_2 - P_2V_2) - (h_1 - P_1V_1) + W \qquad \text{But } P_2V_2 = P_1V_1 \end{aligned}$$

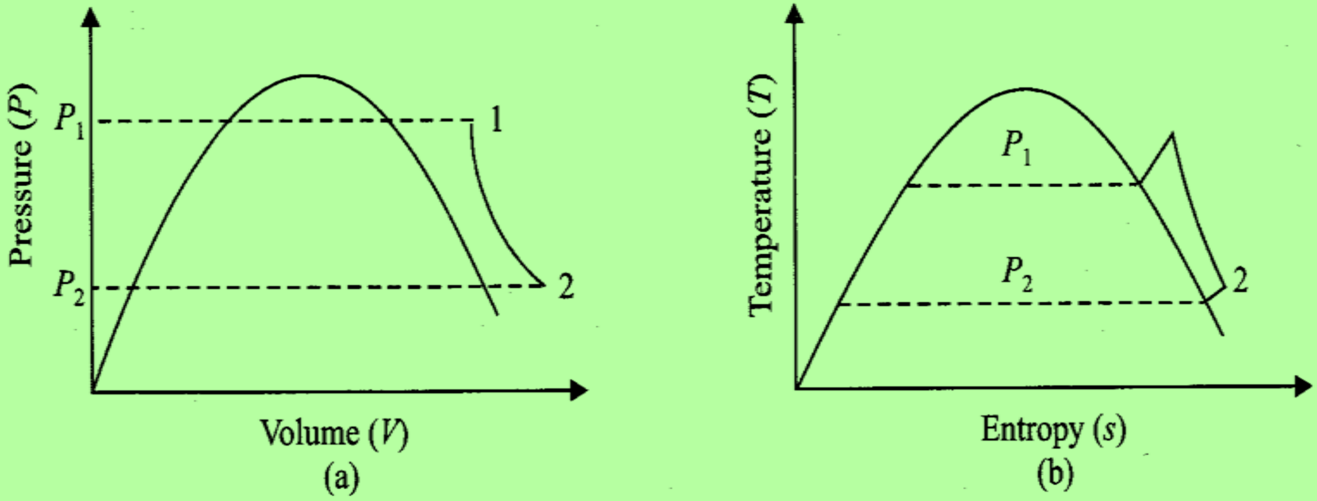
$$\therefore \qquad Q = (h_2 - h_1) + P_1V_1 \log_e \frac{V_2}{V_1}$$

Change in internal energy

$$\begin{aligned} \Delta u &= u_2 - u_1 \\ &= (h_2 - P_2V_2) - (h_1 - P_1V_1) \\ &= h_2 - h_1 \qquad (\text{since } P_2V_2 = P_1V_1) \end{aligned}$$

This means change in internal energy is equal to change in enthalpy for such process.

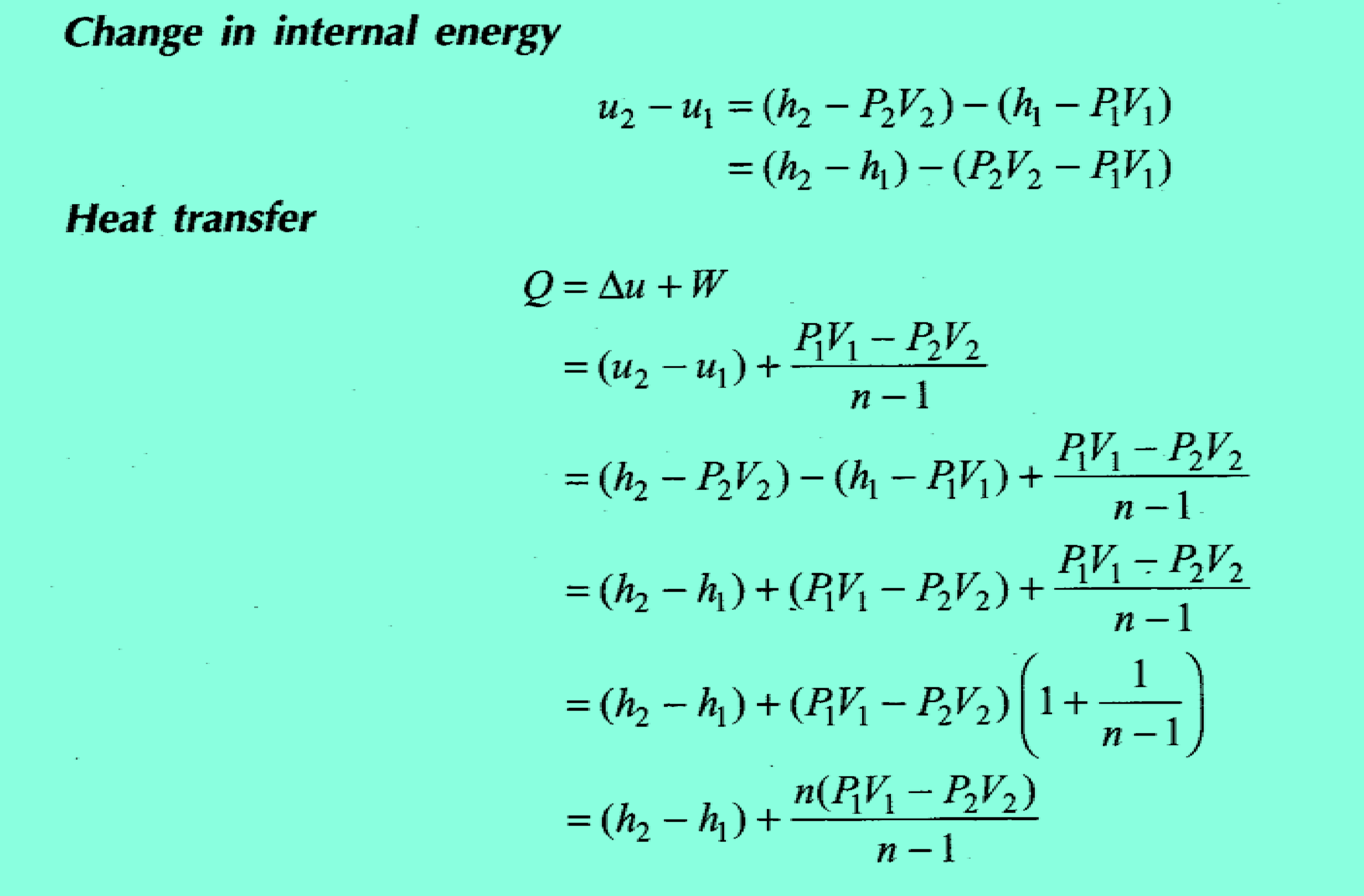
POLYTROPIC PROCES



Polytropic process.

Work Done = $(P_1 V_1 - P_2 V_2) / (n - 1)$

POLYTROPIC PROCESS



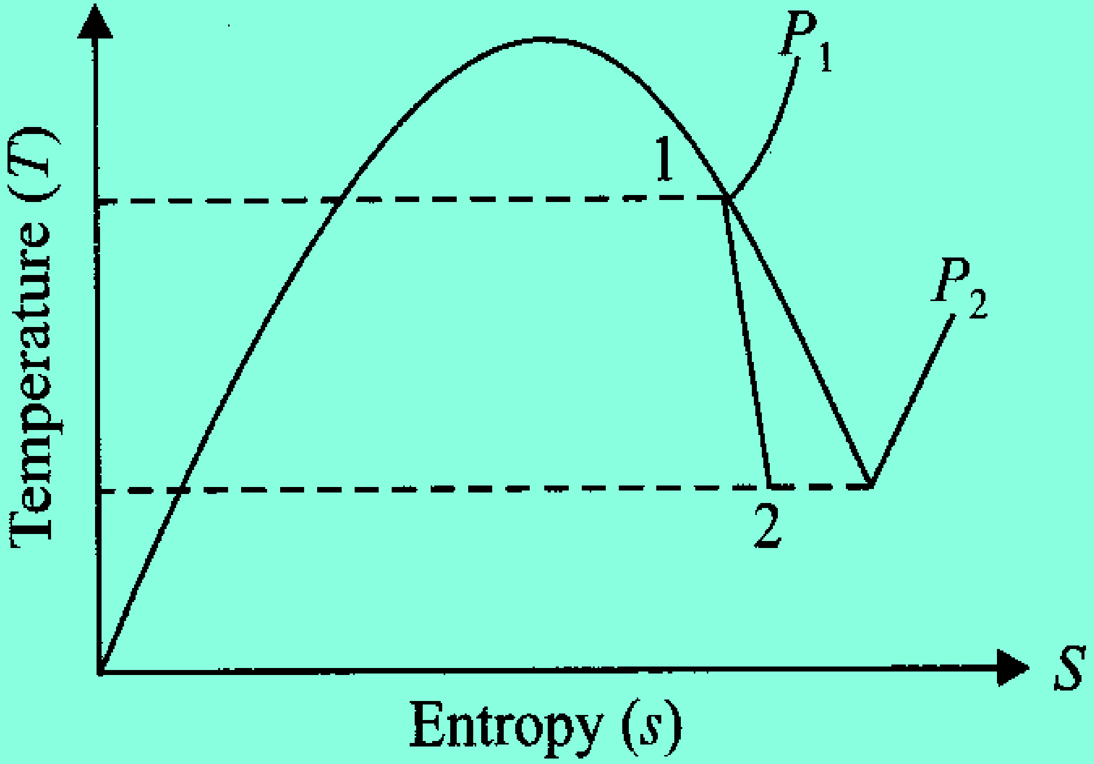
Change in internal energy

$$u_2 - u_1 = (h_2 - P_2V_2) - (h_1 - P_1V_1)$$
$$= (h_2 - h_1) - (P_2V_2 - P_1V_1)$$

Heat transfer

$$Q = \Delta u + W$$
$$= (u_2 - u_1) + \frac{P_1V_1 - P_2V_2}{n-1}$$
$$= (h_2 - P_2V_2) - (h_1 - P_1V_1) + \frac{P_1V_1 - P_2V_2}{n-1}$$
$$= (h_2 - h_1) + (P_1V_1 - P_2V_2) + \frac{P_1V_1 - P_2V_2}{n-1}$$
$$= (h_2 - h_1) + (P_1V_1 - P_2V_2)\left(1 + \frac{1}{n-1}\right)$$
$$= (h_2 - h_1) + \frac{n(P_1V_1 - P_2V_2)}{n-1}$$

ADIABATIC PROCESS



Adiabatic process.

ADIABATIC PROCESS

$dq = du + PdV$ But $dq = 0$

$\therefore$ $PdV = -du$ or work transfer $= u_1 - u_2$ or work done = change in internal energy

Since $dq = 0$, the change in entropy $ds = 0$.

Energy equation, $u_1 + P_1V_1 + \delta q = u_2 + P_2V_2 + \delta W \quad (\because \delta q = 0)$

$\therefore$ δW = work done $= (u_1 - u_2) + (P_1V_1 - P_2V_2) = h_1 - h_2$ kJ/kg

Since the change in entropy is zero, the entropy of the system remains constant. Therefore, the process is also called isentropic process. The steam table also gives the value of entropy and the value of entropy is provided at the end of the process. Such phenomena help in determining the initial and final states of the process.

The process line as shown in Figure 4.9 is vertical as $dq = 0$ and s = constant.

THROTTLING PROCESS

- The throttling process takes place when steam is allowed to pass through a restricted opening or through a valve.

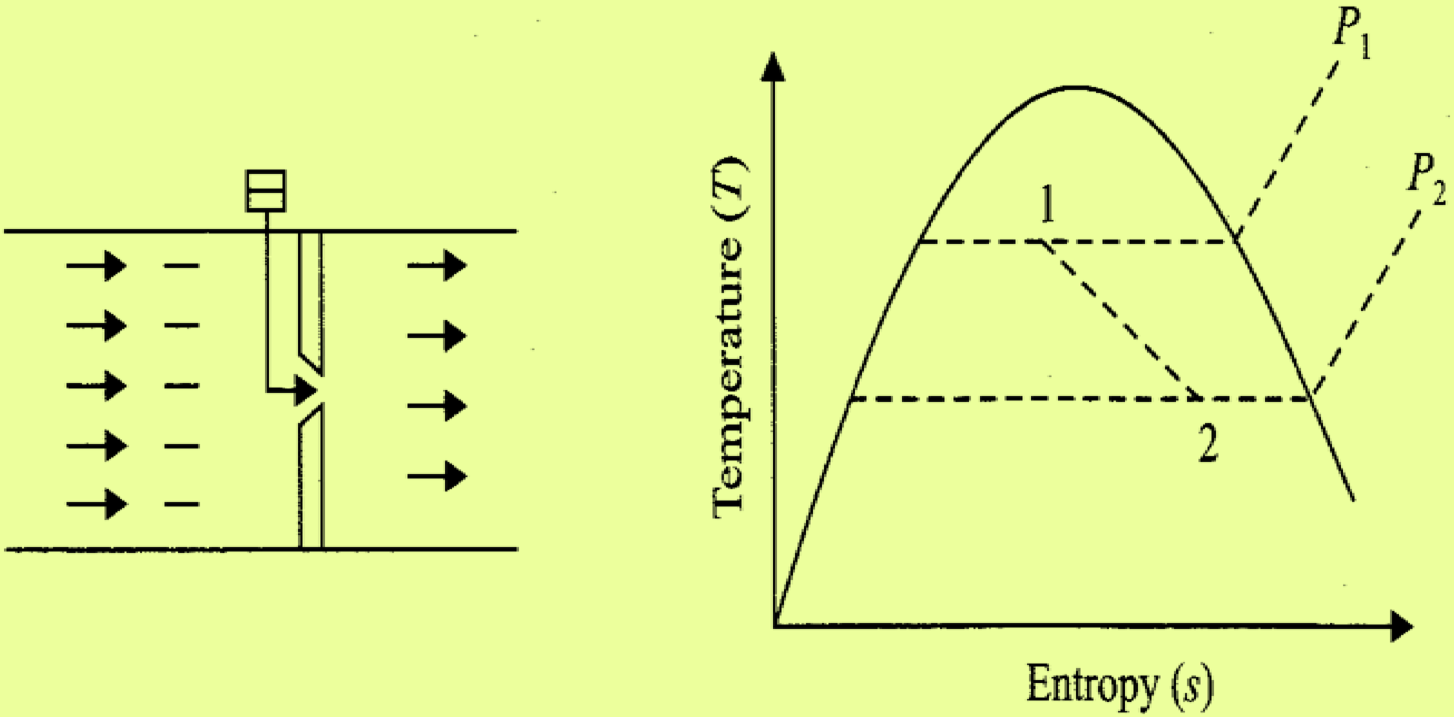
- It is an open system where the flow takes place due to the pressure difference between two sides of the wall.

- The process is in equilibrium at states 1 and 2 but intermediate states are not in equilibrium and therefore shown by the dotted lines.

- The process of throttling involves pressure drops but enthalpy remains constant and the process is also known as isenthalpic process.

- In such process, the steam after throttling may become superheated even if wet before throttling.

THROTTLING PROCESS:



Throttling process.

THROTTLING PROCESS (APPLICATIONS)

Applications of throttling process:

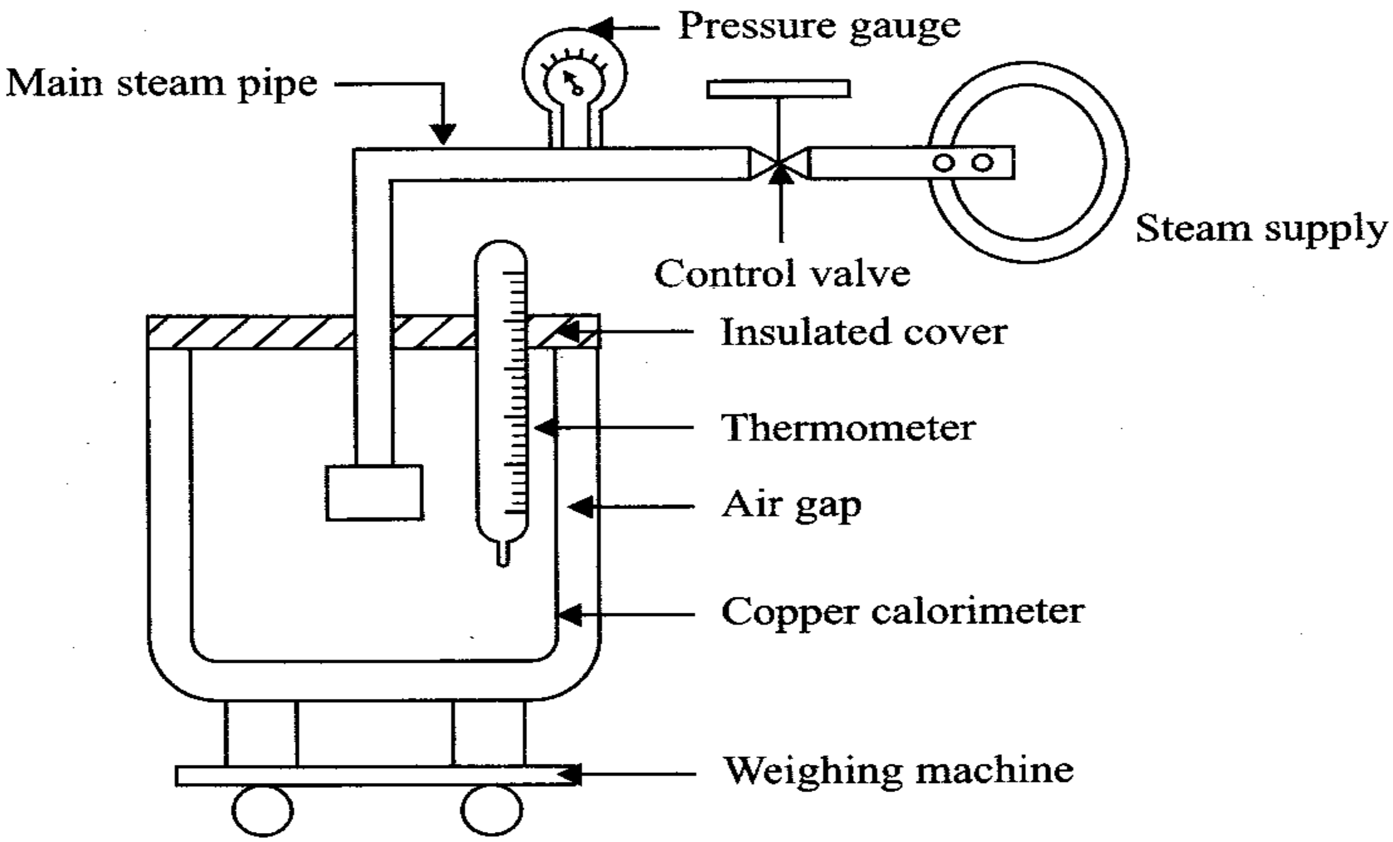
- Estimation of dryness fraction of steam.
- Cooling of refrigerants in refrigeration system.
- Speed control of IC engine and turbine.
- measurement of dryness fraction
- Wet steam at a given pressure has specific temperature for the entire range of dryness fractions from 0 to 1
- The pressure and temperature of wet steam are not the sufficient thermodynamic properties to specify the state of steam. It needs two independent properties such as temperature or pressure and dryness fraction to identify the state of steam.
- Wet steam contains water particles in suspension with the dry steam and the amount of these water particles needs to be estimated to find the dryness factor of the steam.
- The dryness fraction of steam can be determined with the help of steam calorimeter.

BARREL OR BUCKET CALORIMETER

Construction

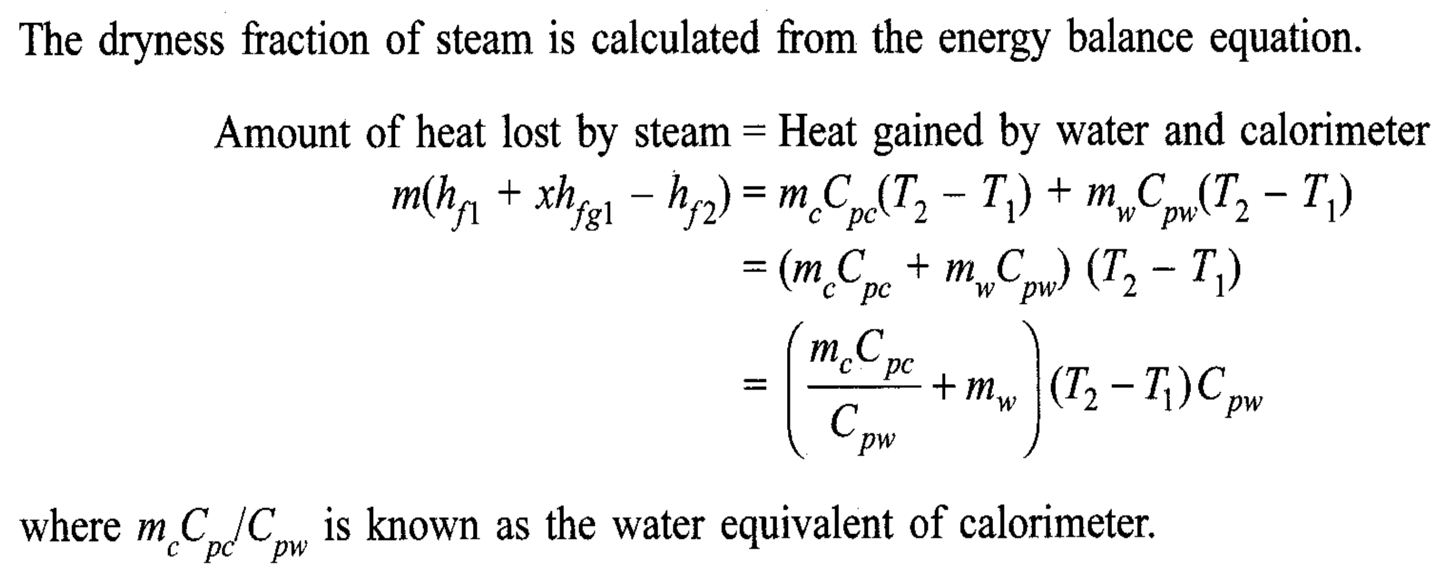
- It consists of an insulated cover with double wall copper calorimeter with air between the two walls of barrel calorimeter.
- The calorimeter is well insulated from all sides to eliminate heat transfer losses to surroundings.
- Steam from the supply tank is taken through the control valve and the main steam pipe leads to water in the calorimeter.
- Pressure gauge and thermometer are used to measure pressure and temperature.

BARREL OR BUCKET CALORIMETER



Barrel or bucket calorimeter.

BARREL OR BUCKET CALORIMETER



The dryness fraction of steam is calculated from the energy balance equation.

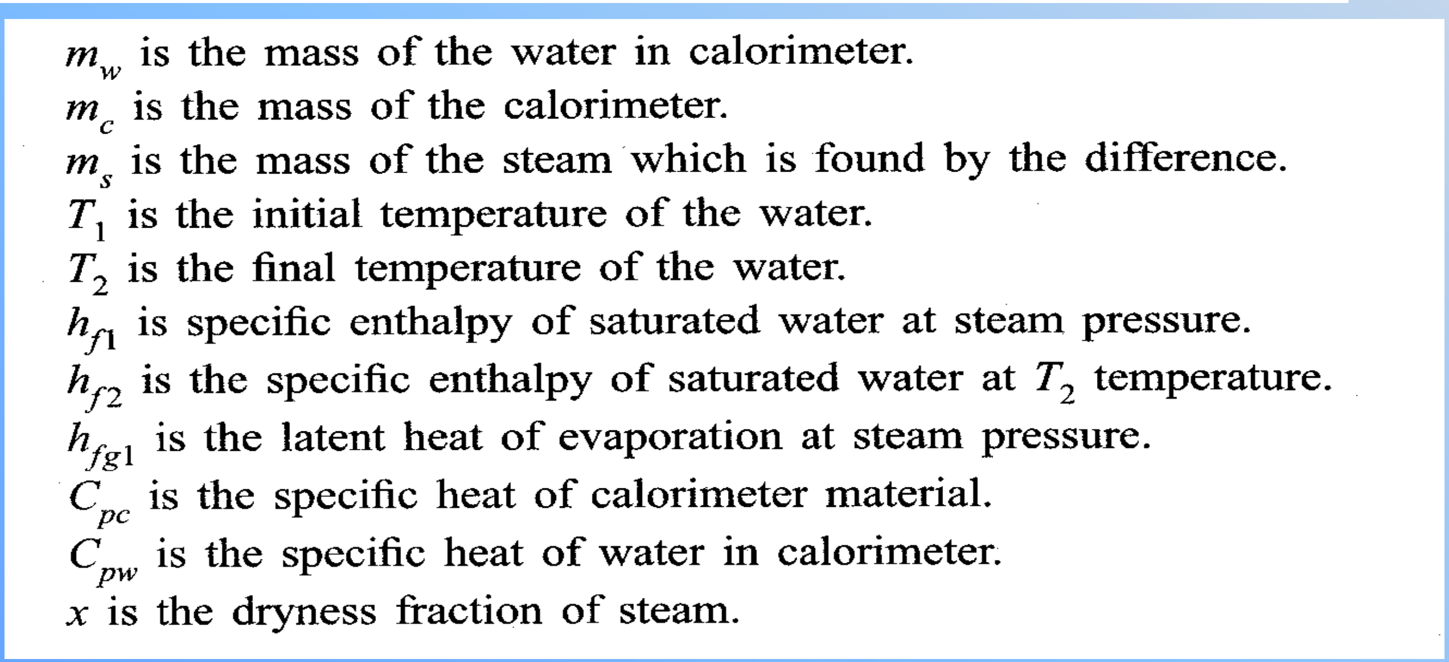
Amount of heat lost by steam = Heat gained by water and calorimeter

$$m(h_{f1} + xh_{fg1} - h_{f2}) = m_c C_{pc}(T_2 - T_1) + m_w C_{pw}(T_2 - T_1)$$

$$= (m_c C_{pc} + m_w C_{pw})\,(T_2 - T_1)$$

$$= \left(\frac{m_c C_{pc}}{C_{pw}} + m_w\right)(T_2 - T_1)C_{pw}$$

where $m_c C_{pc}/C_{pw}$ is known as the water equivalent of calorimeter.

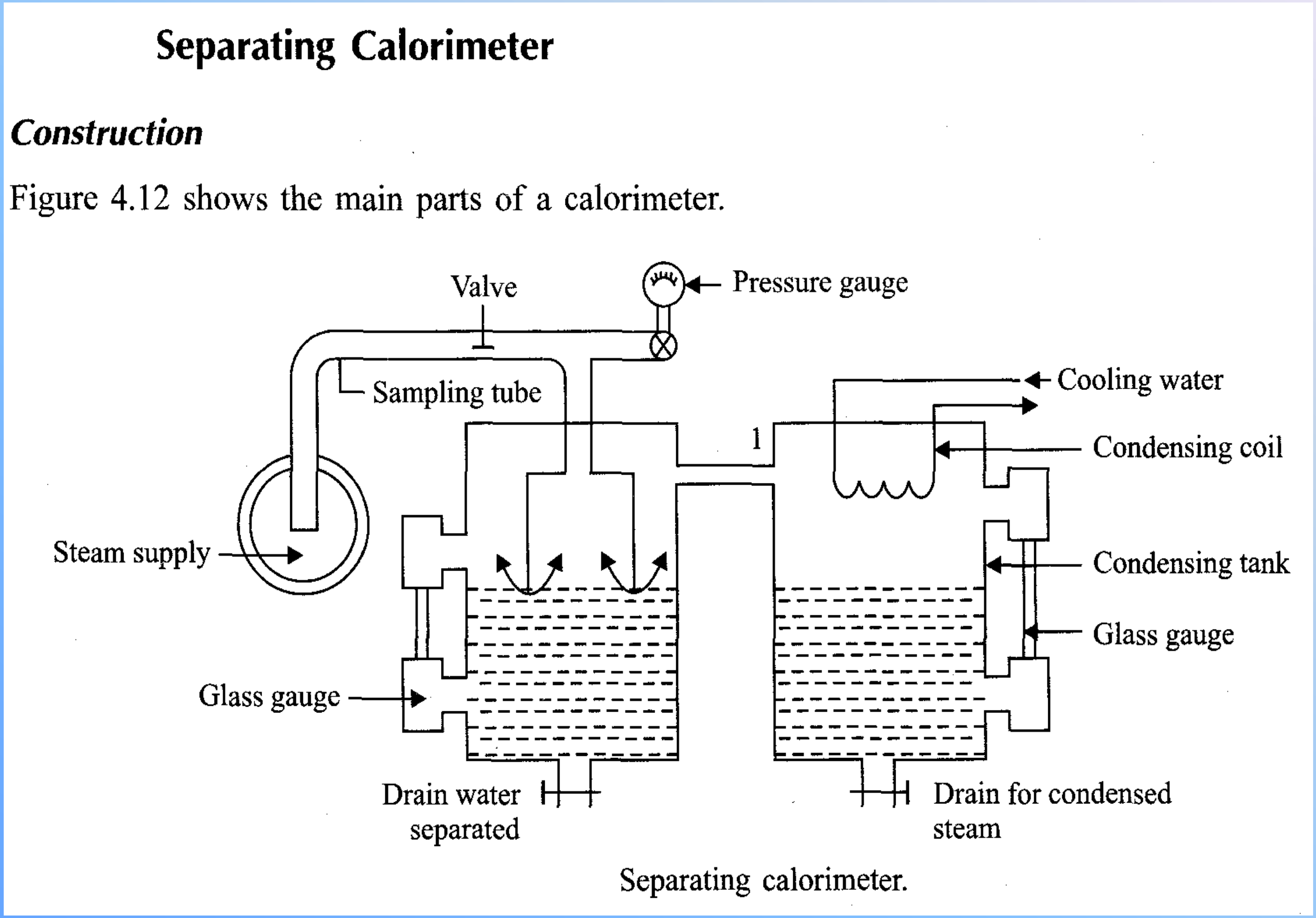


m_w is the mass of the water in calorimeter.
m_c is the mass of the calorimeter.
m_s is the mass of the steam which is found by the difference.
T_1 is the initial temperature of the water.
T_2 is the final temperature of the water.
h_{f1} is specific enthalpy of saturated water at steam pressure.
h_{f2} is the specific enthalpy of saturated water at T_2 temperature.
h_{fg1} is the latent heat of evaporation at steam pressure.
C_{pc} is the specific heat of calorimeter material.
C_{pw} is the specific heat of water in calorimeter.
x is the dryness fraction of steam.

LIMITATIONS OF BARREL OR BUCKET CALORIMETER

- At high temperature, heat losses are higher and therefore calculated values are lower than the actual values.
- The method is approximate as the heat losses are neglected.

SEPARATING CALORIMETER



Separating Calorimeter

Construction

Figure 4.12 shows the main parts of a calorimeter.

Separating calorimeter.

WORKING OF SEPARATING CALORIMETER

- It consists of two tanks, one is condensing tank and the other is separating tank. The condensing tank has gauge glass, drain for condensed steam and cooling water pipe.

- The collecting tank has gauge glass and is connected with sampling tube. This tube has pressure gauge and valve for controlling the steam. The sampling tube is connected to the steam supply line.

Working

- The calorimeter works on the principle of separating water particles from the sample of steam and finding the mass fraction in the sample. A sample of steam from the mains is taken through a sample tube where its pressure is measured and passed into the collector tank. Here the steam takes a complete `U' turn and therefore heavier water particles fall to the tank and their quantity is measured.

- The steam now goes to the condensing tank where cold water flows through a tube and the steam gets condensed as it comes in contact with the cold pipe. The mass of condensate is also measured.

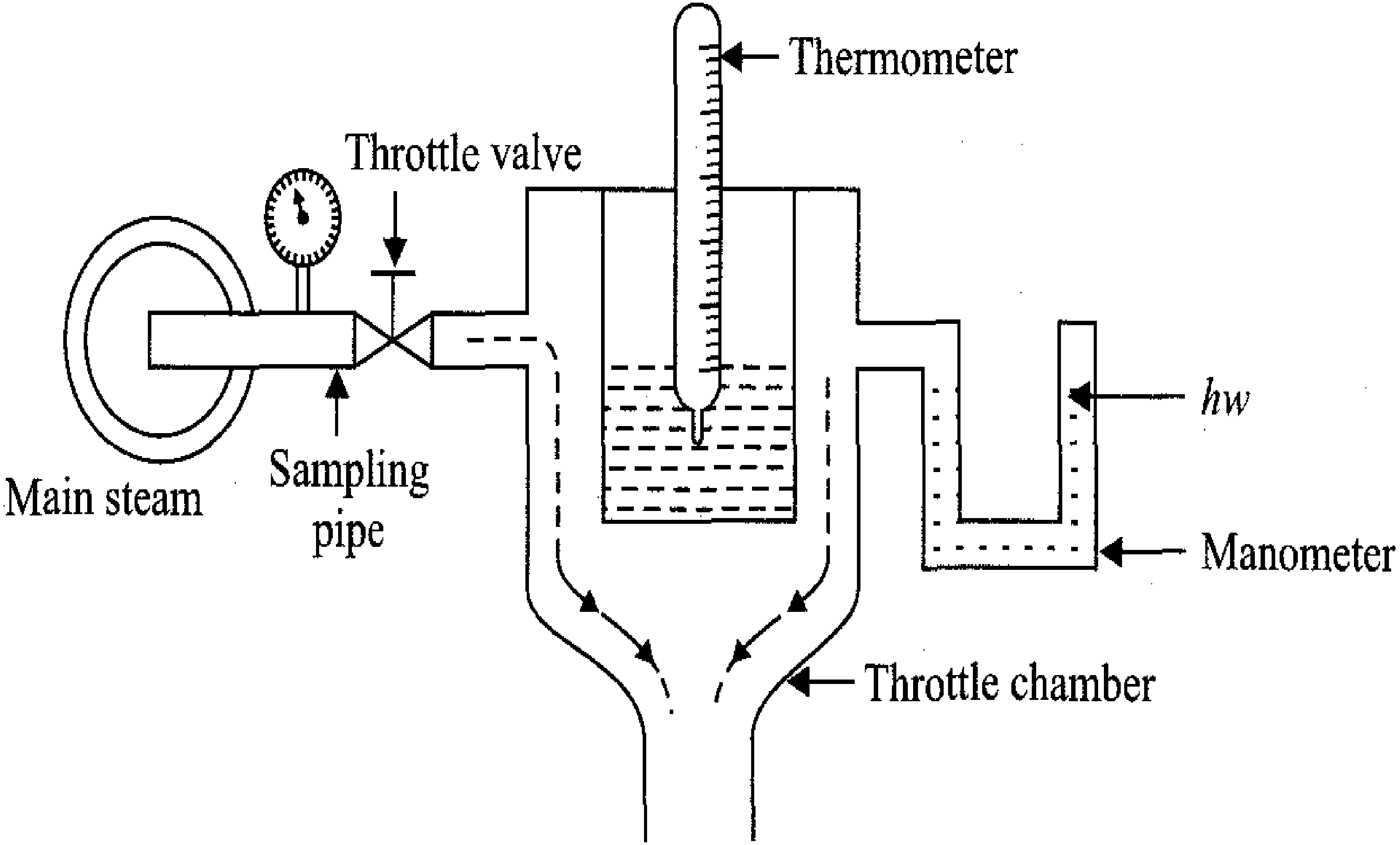
- The test should be performed with minimum of throttling to reduce conversion of water particles into the steam and for long time to improve the experimental result.

CALCULATIONS

- The measured quantity of water in the collector tank gives the amount of water present in the sample of steam denoted by m. The amount of water measured in the condensing tank gives the quantity of steam M. Therefore,

$$\text{Dryness fraction, } x = \frac{M}{M + m}$$

THROTTLING CALORIMETER



Throttling calorimeter.

THROTTLING CALORIMETER

- There is considerable pressure difference between the main supply of steam and throttling chamber which is separated by a valve used for throttling of steam.
- High pressure steam from the mains whose dryness is to be measured is taken from sampling pipe and throttled by a valve to near the atmospheric pressure in the throttled chamber.
- Such state continues till the steady-state conditions are reached.
- Steam from the mains should be of high dryness fraction such that it should become superheated after throttling.
- The values of pressure and temperature of the steam after throttling are measured with the help of manometer and thermometer kept in the throttling chamber.
- Since the pressure of the steam after throttling is close to the atmospheric pressure. the temperature of the steam should be more than 100°C to confirm it is in the superheated stage.

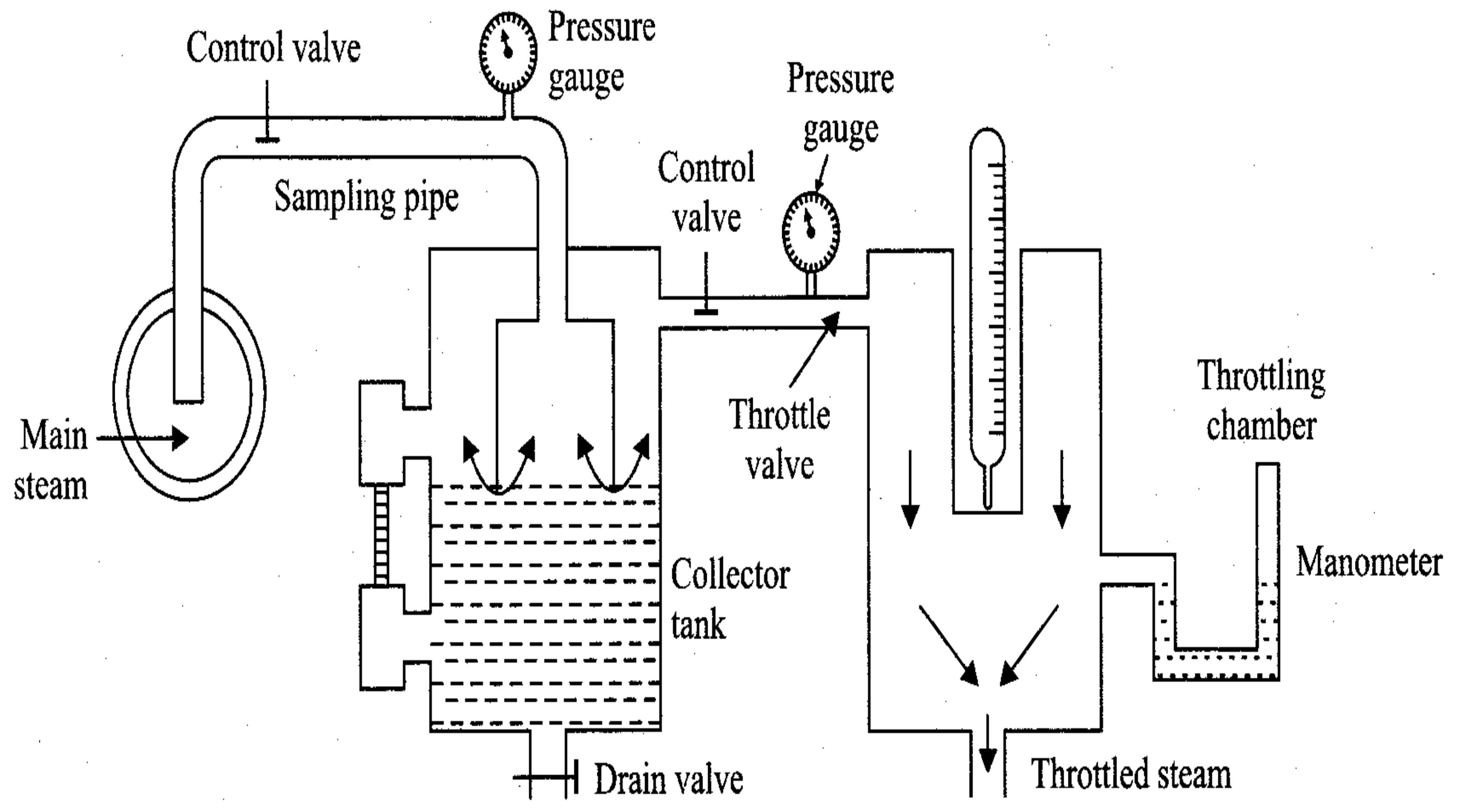
THROTTLING CALORIMETER

Calculations

- During the throttling process, the total enthalpy of the steam remains constant. This means enthalpy of the steam before and after throttling is the same and the steam has become superheated.

$$h_{f1} + xh_{fg1} = h_{g2} + C_{ps2}(T_{\text{sup}} - T_s)$$

COMBINED SEPARATING AND THROTTLING CALORIMETER



Combined separating and throttling calorimeter.

By: Mudit M. Saxena, Dept. of Mech. Engg

COMBINED SEPARATING AND THROTTLING CALORIMETER

Construction

- In this system, both the calorimeters which were described are combined in such a manner in series that the steam passes through the separating calorimeter and then goes to the throttling calorimeter.

Working

- The working of this calorimeter combines that of the two calorimeters. Steam is taken from the mains and some of the suspended water particles are separated in the collector tank and measured. Now the steam of the higher dryness fraction is throttled to the throttling chamber where temperature and pressure are measured and the principle of constant enthalpy is used here.

COMBINED SEPARATING AND THROTTLING CALORIMETER

Calculations

Let the mass of the steam measured after throttling be m_2 and m_1 be the mass of the water separated in the separating calorimeter.
Then

$$x_1 = \frac{m_2}{m_2 + m_1}$$

where x_1 is the dryness fraction of the steam entering into the separating calorimeter. m_2 is the mass of the steam and m_1 is the mass of the water separated.

Dryness fraction x_2 of the steam entering into the throttling calorimeter is estimated by equating the enthalpy of the steam before and after throttling.

$$\therefore \quad h_{f1} + x_2 h_{g1} = h_{g2} + C_{p\ \text{sup}}(T_{\text{sup}} - T_s)$$

Let x be the initial dryness fraction of the steam and that is to be estimated.
Then total water droplet quantity $= (1 - x)\,(m_1 + m_2)$
Mass of water particles removed in separating calorimeter $= (1 - x_1)\,(m_1 + m_2)$
Mass of water particles passed through throttling calorimeter $= (1 - x_2)m_2$

$$\therefore \quad (1 - x)\,(m_2 + m_1) = (1 - x_1)\,(m_2 + m_1) + (1 - x_2)m_2$$

or

$$1 - x = (1 - x_1) + (1 - x_2)\frac{m_2}{m_1 + m_2}$$

But $x_1 = m_2/(m_1 + m_2)$

$$\therefore \quad x_1 - x = (1 - x_2)x_1$$

or

$$-x = -x_1 \cdot x_2$$

or

$$x = x_1 \cdot x_2$$

The dryness fraction of the steam in the mains is a multiple of the dryness fraction of two calorimeters.