

MODULE III

3.1.0 Understand the principle of psychrometry and psychrometric processes

- 3.1.1 Define Psychrometry
- 3.1.2 Define dry air, moist air, saturated air, degree of saturation, specific humidity, absolute humidity, relative humidity, dry bulb temperature, wet bulb temperature, wet bulb depression, dew point temperature dew point depression.
- 3.1.3 State Dalton's law of partial pressure
- 3.1.4 Explain the enthalpy of moist air
- 3.1.5 Explain the construction and use of psychrometer
- 3.1.6 Explain the psychrometric chart and explain various lines in the chart.
- 3.1.7 Explain the use of psychrometric chart (Simple problems using tables and charts.)

3.2.0 Explain and represent psychrometric process such as sensible heating, sensible cooling, humidifying, dehumidifying, heating and humidifying, cooling and dehumidifying and adiabatic mixing of air streams on psychrometric charts

- 3.2.1 Explain by-pass factor of heating and cooling coil
- 3.2.2 Explain the concept of sensible heat factor
- 3.2.3 Derive efficiency of heating and cooling coils
- 3.2.4 Solve simple problems using psychrometric chart.

3.3.0 Understand the principle of Low temperature refrigeration

- 3.3.1 Define Cryogenics
- 3.3.2 List Advantages and applications of cryogenic refrigeration
- 3.3.3 Explain Cascade refrigeration
- 3.3.4 Explain Joule –Thomson effect
- 3.3.5 Explain Liquefaction of Nitrogen and Hydrogen.
- 3.3.6 Describe the adiabatic demagnetization of paramagnetic Salt for approaching Absolute zero.

Content Details

Psychrometry-Definition- Dry air- moist air- saturated- unsaturated -super saturated air- degree of saturation- dry bulb temperature- wet bulb temperature- dew point temperature- Dalton's law of partial pressures absolute humidity-relative humidity- specific humidity- Enthalpy of moist air –

Psychrometer psychrometric chart and tables- (Simple problems using tables and charts).

Psychrometric Processes Sensible heating - sensible cooling – by pass factor- humidifying- dehumidifying – sensible heat factor heating–humidifying- cooling –dehumidifying- efficiency of heating - cooling coil- Simple problems using psychrometric chart - tables.

Low temperature refrigeration (Cryogenics)

Definition for the term cryogenics.-advantages - –field of application-Cascade refrigeration system– Joule Thomson effect – (definition only) - liquefaction of Nitrogen -Hydrogen- absolute zero temperature –use Adiabatic demagnetization of paramagnetic salts

PSYCHROMETRY-Definition

Psychrometry is the science of studying the thermodynamic properties of moist air and the use of these properties to analyze conditions and processes involving moist air, (*Mixture of dry air and water vapour is known as moist air*) for example

- Air conditioning
- Drying processes
- Flue gas condensation

(Psychrometry is that branch of engineering science which deals with the study of mixture of dry air and water vapour)

PSYCHOMETRIC TERMS

Dry air. The dry air is a mixture of nitrogen and oxygen neglecting the small percentage of other gases such as carbon dioxide, hydrogen, argon, neon, helium etc. (78 % Nitrogen and 21% Oxygen) Dry air indicate water free air.

Moist air. It is a mixture of dry air and water vapour. The amount of water vapour present in the air depends upon the absolute pressure and temperature of the mixture. (Water vapour present in air is called as moisture.)

(Both dry air and water vapour can be considered as perfect gases because both exist in the atmosphere at low pressure. Thus all the perfect gas terms can be applied to them individually.)

Saturated air. It is mixture of dry air and water vapour, when the air has diffused the maximum amount of water vapour into it. The water vapours, usually, occur in the form of superheated steam as an invisible gas. However, when the saturated air is cooled, the water vapour in the air starts condensing, and the same may be visible in the form of moist, fog or condensation on cold surfaces.

Unsaturated air : If the water vapour present in the air less than the maximum quantity of water vapour it can hold for the same temperature and pressure, then that air is called unsaturated air

Degree of saturation. It is the ratio of mass of water vapour present in a 1 kg of dry air to the mass of water vapour present 1 kg of dry air when it is saturated at the same temperature. It is also known as percentage humidity. The degree of saturation is a measure of the capacity of air to absorb moisture.

Humidity. It is the mass of water vapour present in the moist air unit mass of dry air in a given volume, and is generally expressed in terms of gram of water vapour per kg of dry air (g / kg of dry air). It is also called specific humidity or humidity ratio.

Absolute humidity. It is the mass of water vapour present in unit volume of dry air, and is generally expressed in terms of gram of water vapor per cubic metre of dry air (g/m^3 of dry air). It is also expressed in terms of grains per cubic metre of dry air. Mathematically, one kg of water vapour is equal to 15 430 grains.

Relative humidity. It is defined as the ratio of actual moisture present in the air to the maximum moisture the air can hold at the same temperature and pressure. It is briefly written as RH or ϕ

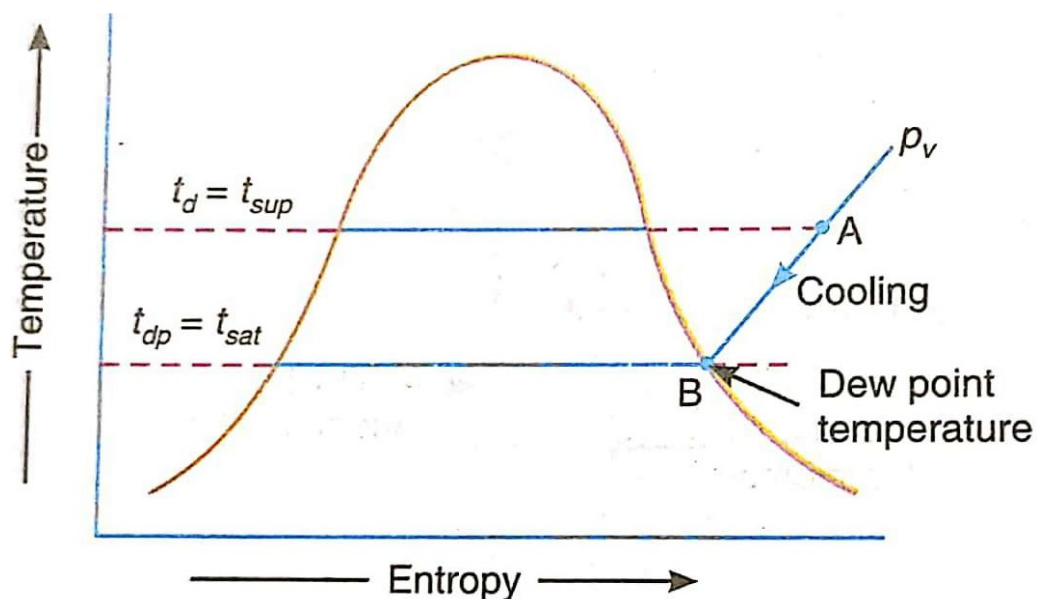
(It is the ratio of actual mass of water vapour in a given volume of moist air to the mass of water vapour in the same volume of saturated air at the same temperature and pressure.)

Dry bulb temperature (DBT). It is the temperature of air recorded by an ordinary thermometer, when it is not affected by the moisture present in the air. The dry bulb temperature is generally denoted by t_d or t_{db} .

Wet bulb temperature (WBT). It is the temperature of air recorded by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air. Such a thermometer is called *wet bulb thermometer. The wet bulb temperature is generally denoted by t_w or t_{wb} .

Wet bulb depression. It is the difference between dry bulb temperature and wet bulb temperature at any point. The wet bulb depression indicates relative humidity of the air.

Dew point temperature. It is the temperature of air recorded by a thermometer, when the moisture (water vapour) present in it begins to condense. It is, usually, denoted by t_{dp} . (In other words, the dew point temperature is the saturation temperature (t_{sat}), corresponding to the partial pressure of water vapour (P_v))



Dewpoint depression is the difference between the dry bulb temperature and the dewpoint temperature of air

DALTON'S LAW OF PARTIAL PRESSURES

It states, for a mixture of perfect gases, the total pressure exerted by the mixture is equal to the sum of partial pressures of the constituent gases.

(In other words, the total pressure exerted by air and water vapour mixture is equal to the barometric pressure.

*Mathematically, barometric pressure of the mixture, $P_b = P_a + P_v$,
where P_a = Partial pressure of dry air, and P_v = Partial pressure of water vapour.)*

Partial pressure: The individual pressure of a gas exerts in a mixture of gases is called its partial pressure

Enthalpy of Moist air

Enthalpy -h- (kJ/kg) of moist air is defined as the total enthalpy of the dry air and the water vapor mixture per kg of moist air, includes the

- Enthalpy of the dry air - the sensible heat – and
- Enthalpy of the evaporated water - the latent heat

- Enthalpy of moist air can be expressed as:

- $h = h_a + x h_w$

where

- h= specific enthalpy of moist air (kJ/kg)
- h_a = specific enthalpy of dry air (kJ/kg)
- x= humidity ratio
- h_w = specific enthalpy of water vapor (kJ/kg)

Psychrometer.

A psychrometer measures the relative humidity in the atmosphere through the use of two thermometers: a dry bulb thermometer is used to measure the temperature by being exposed to the air. A wet bulb thermometer, measures temperature by having the bulb dipped in a liquid.

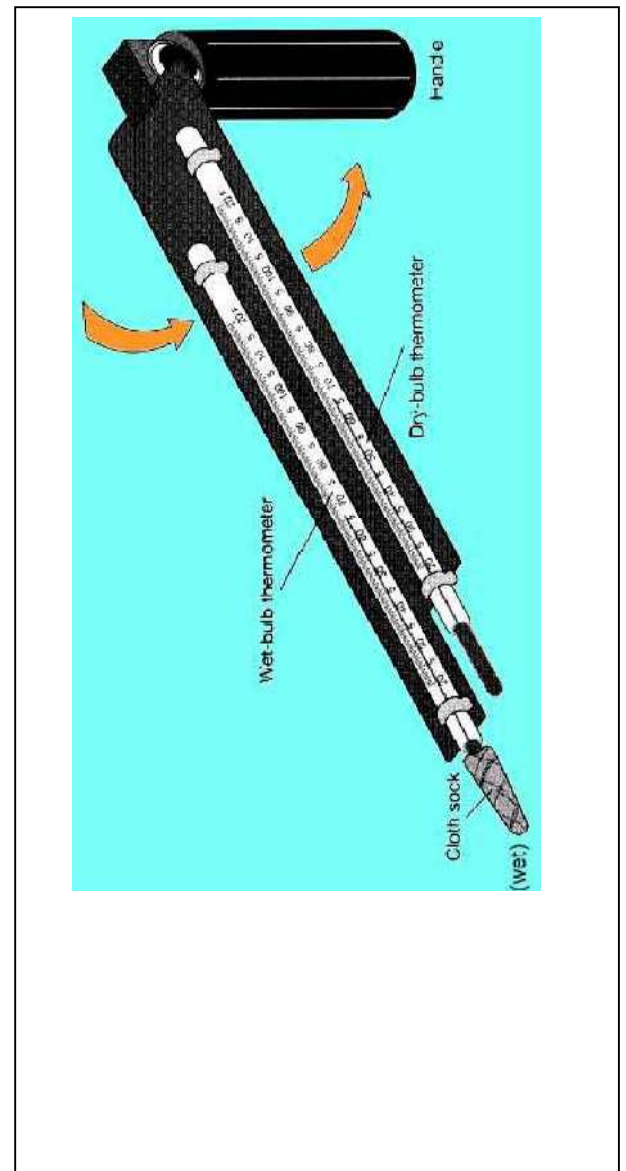
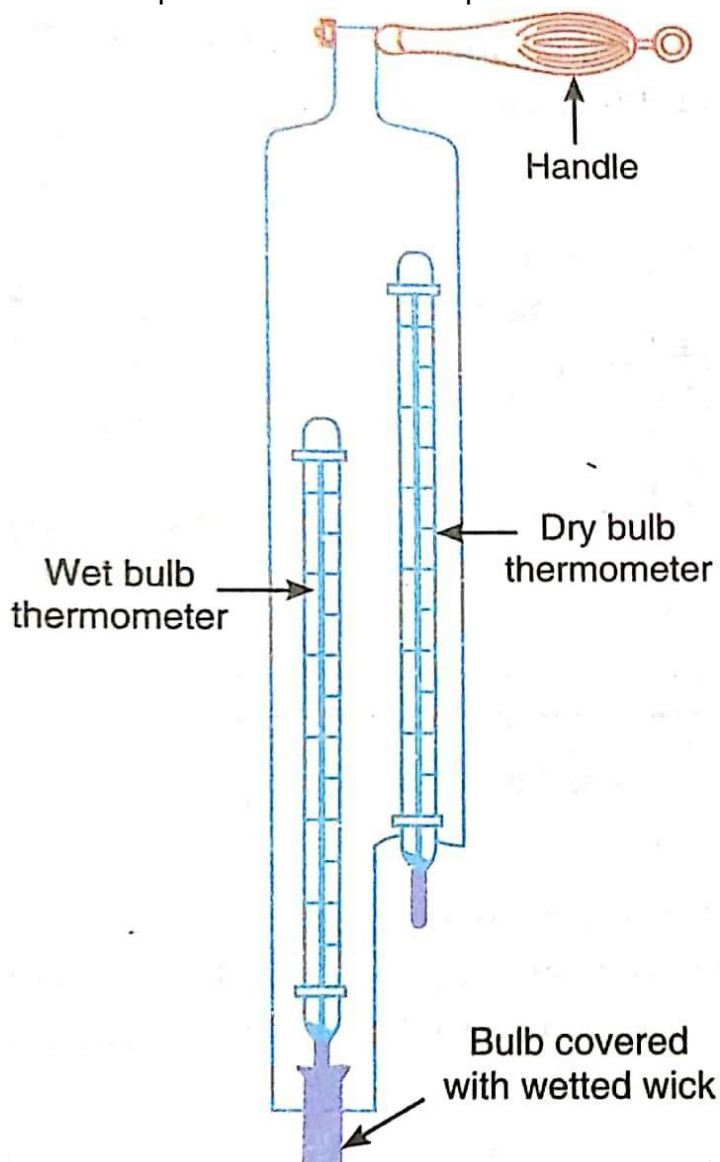
Different types of psychrometer generally used are

- Sling psychrometer
- Laboratory psychrometer
- Aspirating psychrometer
- Continuous recording psychrometer

The sling psychrometer, as shown in Fig, is widely used. It consists of a dry bulb thermometer and a wet bulb thermometer mounted side by side in a protective case that is attached to a handle by a swivel connection so that the case can be easily rotated. The dry bulb thermometer is directly exposed to air and measures the actual temperature of the air (DBT).

The bulb of the wet bulb thermometer is covered; by a wick thoroughly wetted by distilled water. The temperature measured by this wick covered bulb of a thermometer is the temperature of liquid water in the wick and is called wet bulb temperature.(WBT)

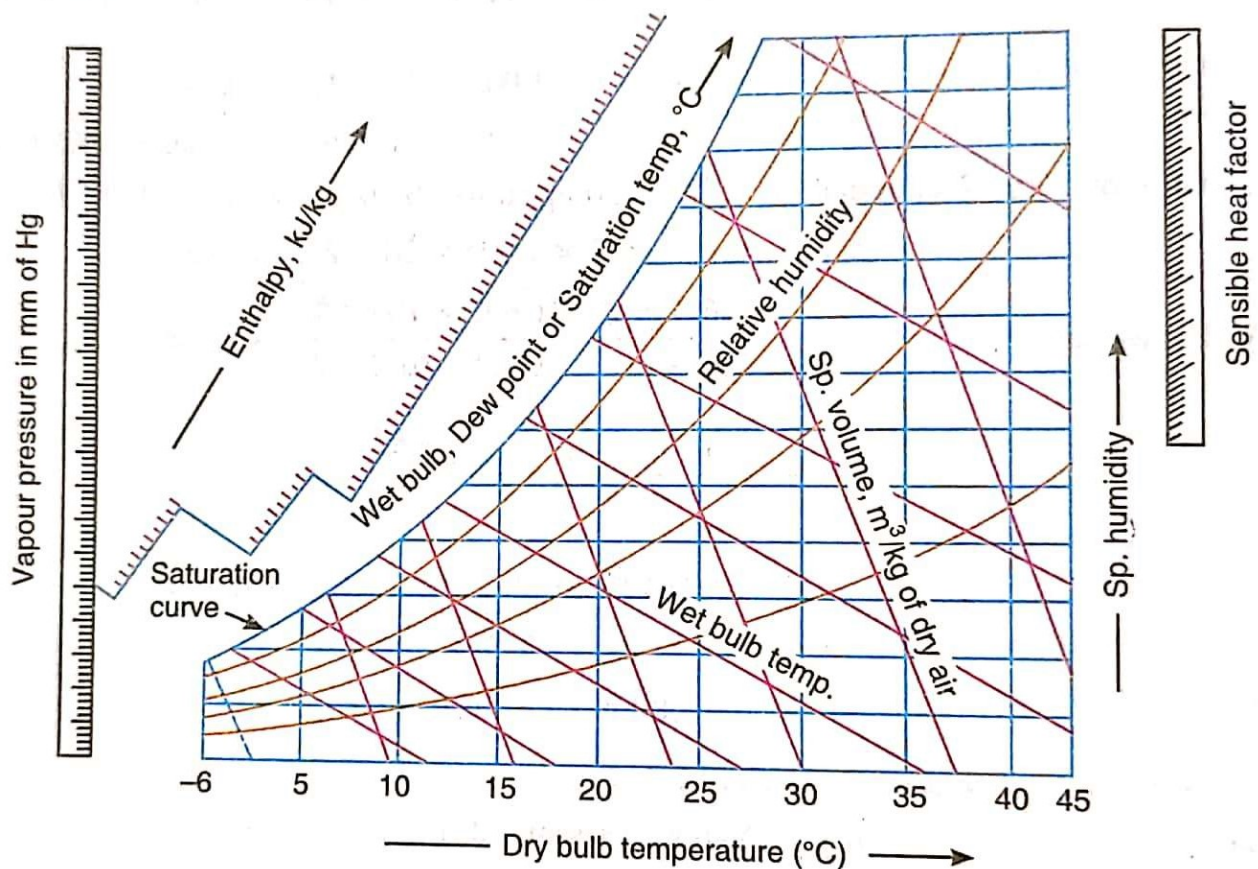
The sling psychrometer is rotated in the air for approximately one minute before which readings from both the thermometers are taken. This process is repeated several times to assure that the lowest possible wet bulb temperature is recorded.



PSYCHROMETRIC CHART

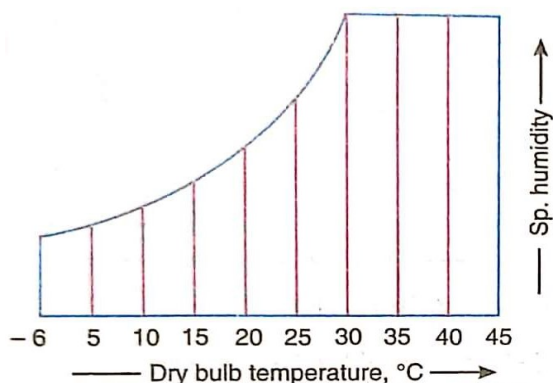
A Psychrometric chart graphically represents the thermodynamic properties of moist air. Standard psychrometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapour pressure or humidity ratio (ordinate). The Left Hand Side of the psychrometric chart is bounded by the saturation line. Figure shows the schematic of a psychrometric chart.

The psychrometric chart is very useful for finding out the properties of air (which are required in the field of air conditioning) and eliminate lot of calculations. There is a slight variation in the charts prepared by different air-conditioning manufactures but basically they are all alike. The psychrometric chart is normally drawn for standard atmospheric pressure of 760 mm of Hg (or 1.01325 bar).

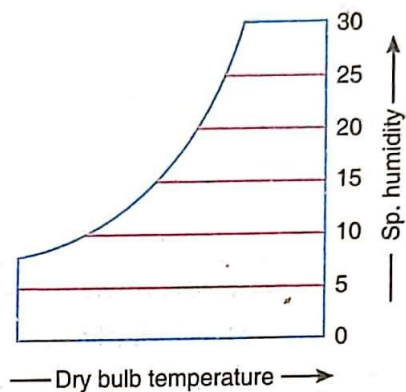


Dry bulb temperature lines. The dry bulb temperature lines are vertical i.e. parallel to the ordinate and uniformly spaced as shown in figure.

The dry bulb temperature lines are drawn with difference of every 5°C and up to the saturation curve as shown in the figure. The values of dry bulb temperatures are also shown on the saturation curve.



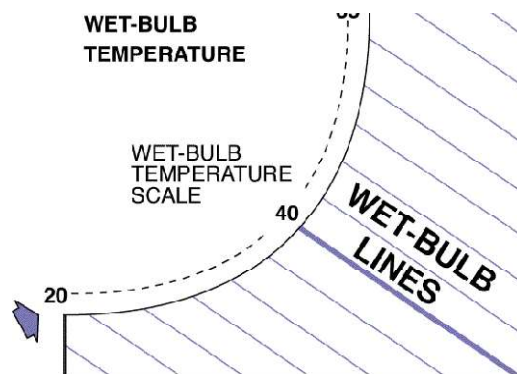
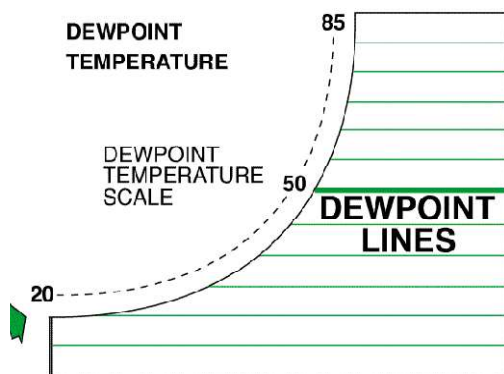
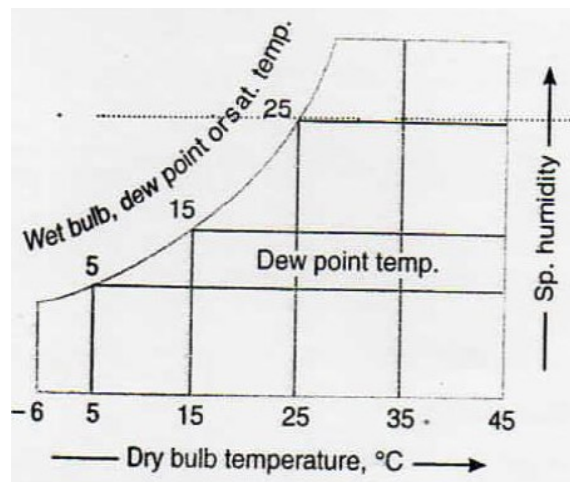
Specific humidity or moisture content lines. The specific humidity (moisture content) lines are horizontal i.e. parallel to the abscissa and are also uniformly spaced as shown in figure



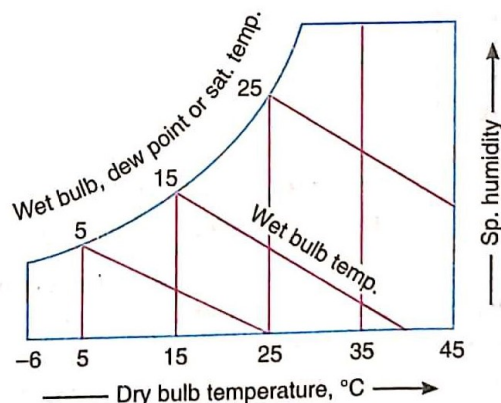
Dew point temperature lines. The dew point temperature lines are horizontal i.e. parallel to the abscissa and non-uniformly spaced as shown in figure.

At any point on the saturation curve, the dry bulb and dew point temperatures are equal.

The values of dew point temperatures are generally given along the saturation curve of the chart as shown in the figure

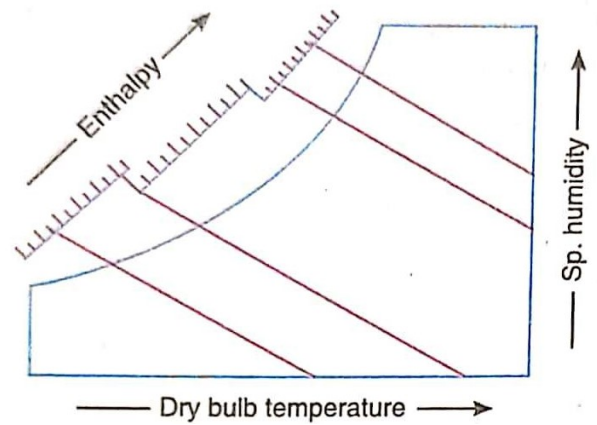


Wet bulb temperature lines. The wet bulb temperature lines are inclined straight lines and non-uniformly spaced as shown in figure. At any point on the saturation curve, the dry bulb and wet bulb temperatures are equal. The values of wet bulb temperatures are generally given along the saturation curve of the chart as shown in the figure

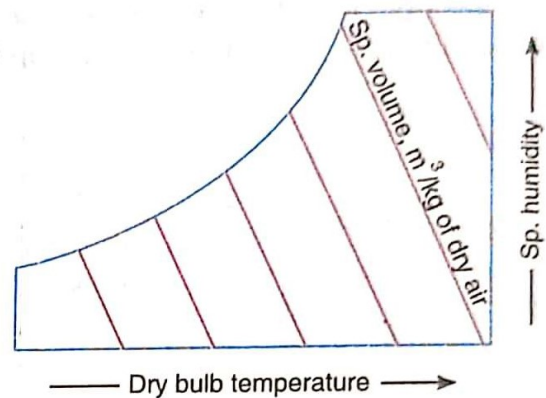


Constant Enthalpy (total heat) lines.

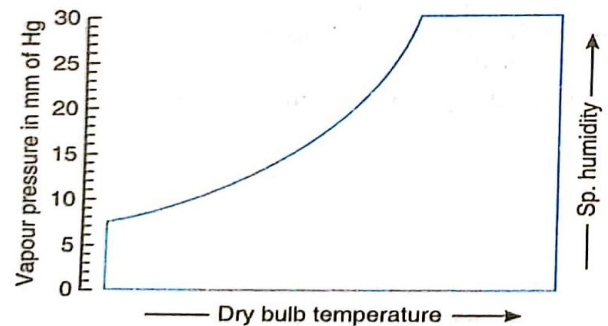
The enthalpy (or total heat) lines are inclined straight lines and uniformly spaced as shown in figure. These lines are parallel to the wet bulb temperature lines, and are drawn up to the saturation curve. Some of these lines coincide with the wet bulb temperature lines also. The values of total enthalpy are given on a scale above the saturation curve as shown in the figure



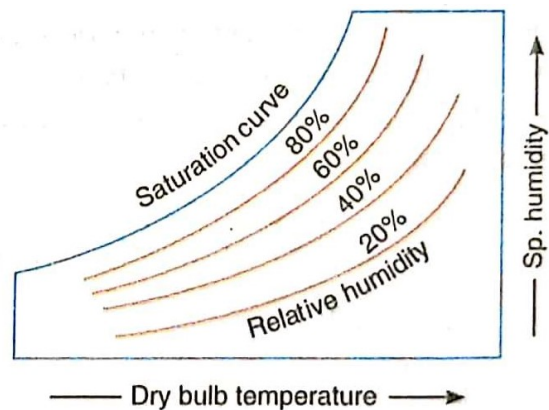
Specific volume lines. The specific volume lines are obliquely inclined straight lines and uniformly spaced as shown in figure. These lines are drawn up to the saturation curve. The values of volume lines are generally given at the base of the chart.



Vapour pressure lines. The vapour pressure lines are horizontal and uniformly spaced. Generally, the vapour pressure lines are not drawn in the main chart. But a scale showing vapour pressure in mm of Hg is given on the extreme left side of the chart as shown in figure



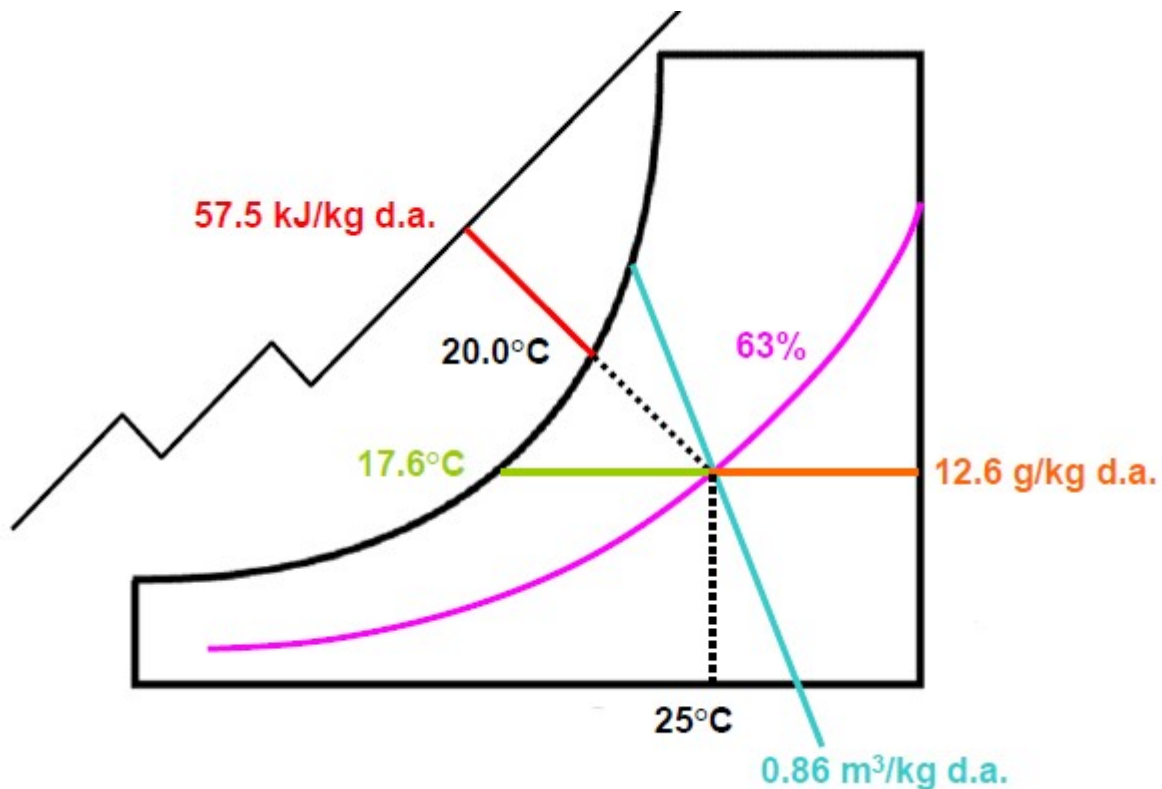
Relative humidity lines. The relative humidity lines are curved lines and follow the saturation curve. Generally, these lines are drawn with values 10%, 20%, 30% etc. and up to 100%. The saturation curve represents 100% relative humidity. The values of relative humidity lines are generally given along the lines themselves as shown in figure



Psychrometric chart: Example

Given: Find the following if Dry bulb temperature (DBT) = 25°C and Wet bulb temperature (WBT) = 20°C

- (a) Dew point temperature
- (b) Relative Humidity (RH)
- (c) Moisture Content,
- (d) Specific Volume
- (e) Enthalpy



- | | |
|----------------------------|---|
| (a) Dew point temperature | : 17.6°C |
| (b) Relative Humidity (RH) | : 63% |
| (c) Moisture Content, | : $12 \text{ g/kg of Dry Air}$ |
| (d) Specific Volume | : $0.86 \text{ m}^3/\text{kg of Dry Air}$ |
| (e) Enthalpy | : $57.5 \text{ kJ/kg of Dry Air}$ |

PSYCHROMETRIC PROCESSES

The various psychrometric processes involved in air conditioning to vary the psychrometric properties of air according to the requirement are as follows:

1. Sensible heating
2. Sensible cooling,
3. Humidification and dehumidification,
4. Cooling and adiabatic humidification,
5. Heating and humidification
6. Cooling and humidification by water injection,
7. Humidification by steam injection,
8. Adiabatic chemical dehumidification,
9. Adiabatic mixing of air streams.

Sensible Heating

a psychrometric process that involves the increase in the temperature of air without changing its humidity ratio

Let air at temperature t_{d1} , passes over a heating coil of temperature t_{d3} , as shown in figure (a). It may be noted that the temperature of air leaving the heating coil (t_{d2}) will be less than t_{d3} . The process of sensible heating, on the psychrometric chart, is shown by a horizontal line 1-2 extending from left to right as shown in figure (b). The point 3 represents the surface temperature of the heating coil.

The heat absorbed by the air during sensible heating may be obtained from the psychrometric chart by the enthalpy difference ($h_2 - h_1$) as shown in figure (b). It may be noted that the specific humidity during the sensible heating remains constant (i.e. $W_1 = W_2$).

The dry bulb temperature increases from t_{d1} , to t_{d2} and relative humidity reduces from ϕ_1 , to ϕ_2 as shown in figure (b).

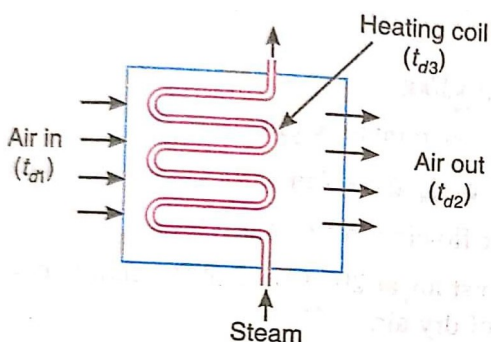
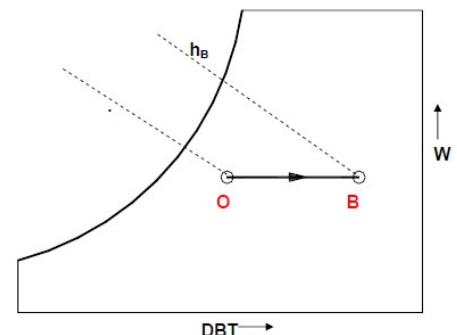
The amount of heat added during sensible heating may also be obtained from the relation:

$$\text{Heat Added } q = h_2 - h_1$$

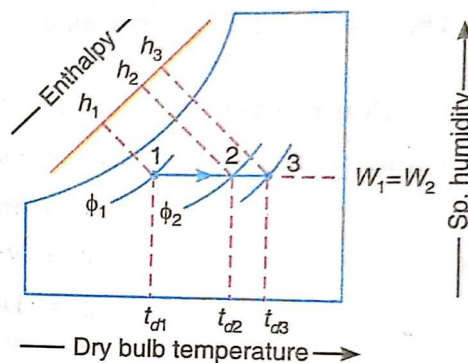
$$= C_{pm} (t_{d2} - t_{d1}) = 1.022 (t_{d2} - t_{d1}) \text{ kJ/kg}$$

The value of Humid Specific heat

C_{pm} is taken as $1.022 \text{ kJ/kg } ^\circ\text{K}$



(a) Psychrometric process.

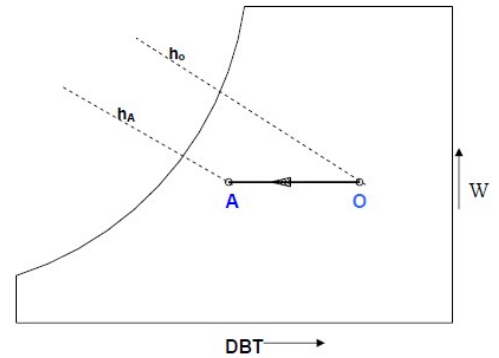


(b) Psychrometric chart.

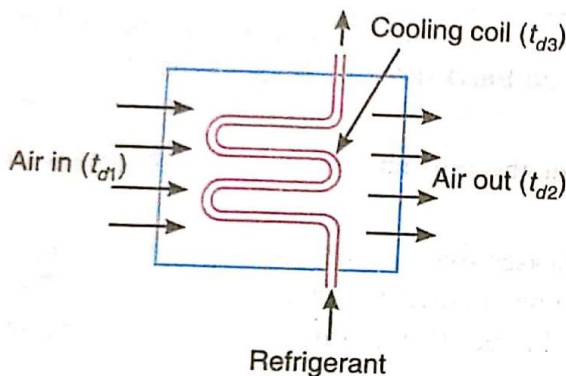
Sensible Cooling

Psychrometric process that involves the decrease in the temperature of air without changing its humidity ratio (The cooling of air without any change in its specific humidity, is known as sensible cooling.)

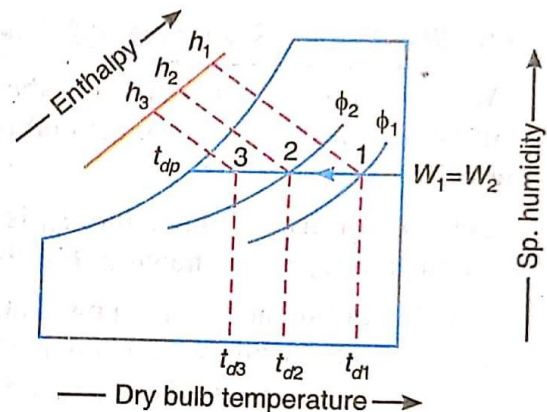
Let air at temperature t_{d1} , passes over a cooling coil of temperature t_{d3} as shown in figure (a). It may be noted that the temperature of air leaving the cooling coil (t_{d2}) will be more than t_{d3} . The process of sensible cooling, on the psychrometric chart, is shown by a horizontal line 1-2 extending from right to left as shown in figure



Sensible cooling process O-A



(a) Psychrometric process.



(b) Psychrometric chart.

Sensible cooling process

The heat rejected by air during sensible cooling may be obtained from the psychrometric chart by the enthalpy difference ($h_1 - h_2$) as shown in figure.

It may be noted that the specific humidity during the sensible cooling remains constant (i.e. $W_1 = W_2$).

The dry bulb temperature reduces from t_{d1} to t_{d2} and relative humidity increases from ϕ_1 to ϕ_2 as shown in figure (b).

The amount of heat rejected during sensible cooling may also be obtained from the relation:

$$\begin{aligned} \text{Heat rejected, } q &= h_1 - h_2 \\ &= C_{pa} (t_{d1} - t_{d2}) + W C_{ps} (t_{d1} - t_{d2}) \\ &= (C_{pa} + W C_{ps}) (t_{d1} - t_{d2}) = C_{pm} (t_{d1} - t_{d2}) \end{aligned}$$

The term $(C_{pa} + W C_{ps})$ is called humid specific heat (C_{pm}) and its value is taken as $1.022 \text{ kJ/kg } ^\circ\text{K}$.

$$\therefore \text{Heat rejected, } q = 1.022 (t_{d1} - t_{d2}) \text{ kJ/kg}$$

By Pass Factor

Under ideal conditions the dry bulb temperature of the air leaving the apparatus (t_{d2}) should be equal to that of the cooling coil (t_{d3}). But it is not so, because of the inefficiency of the coil. This phenomenon is known as by pass factor.

(Bye Pass Factor can also be defined as the ratio of air which is unaffected by the coil to the total quantity of air passing over the coil)

The temperature of the air coming out of the apparatus (t_{d2}) will be less than t_{d3} in case the coil is a heating coil and more than t_{d3} in case the coil is a cooling coil

The performance of a heating or cooling coil is measured in terms of a by-pass factor. A coil with low by-pass factor has better performance.

{A little consideration will show that when air passes over a coil, some of it (say x kg) just by-passes unaffected while the remaining $(1 - x)$ kg comes in direct contact with the coil. This by-pass process of air is measured in terms of a by-pass factor.

The amount of air that by-passes or the by-pass factor depends upon the following factors :

1. The number of fins provided in a unit length i.e. the pitch of the cooling coil fins ;
2. The number of rows in a coil in the direction of flow; and
3. The velocity of flow of air.

It may be noted that the by-pass factor of a cooling coil decreases with decrease in fin spacing and increase in number of rows}.

By-pass Factor of Heating Coil

$$\text{By Pass Factor} = \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}}$$

t_{d1} : Temperature of air passing over the heating coil

t_{d3} : Surface temperature of the heating coil

t_{d2} : Temperature of air leaving the heating coil

By-pass Factor of Cooling Coil

$$\text{By Pass Factor} = \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}}$$

The temperature of the air coming out of the apparatus (t_{d2}) will be less than t_{d3} in case the coil is a heating coil and more than t_{d3} in case the coil is a cooling coil

Sensible Heat Factor (SHF)

As a matter of fact, the heat added during a psychrometric process may be split up into sensible heat and latent heat. The ratio of the *sensible heat to the total heat is known as *sensible heat factor* (SHF) or *sensible heat ratio* (SHR).

Mathematically,

$$\text{Sensible Heat Factor} = \frac{\text{Sensible Heat}}{\text{Total Heat}} = \frac{SH}{SH + LH}$$

where SH = Sensible heat, and

LH = Latent heat.

The sensible heat factor scale is shown on the right hand side of the psychrometric chart.

Efficiency of Heating and Cooling Coils

The term $(1 - BPF)$ is known as efficiency of coil or contact factor.

∴ Efficiency of the heating coil,

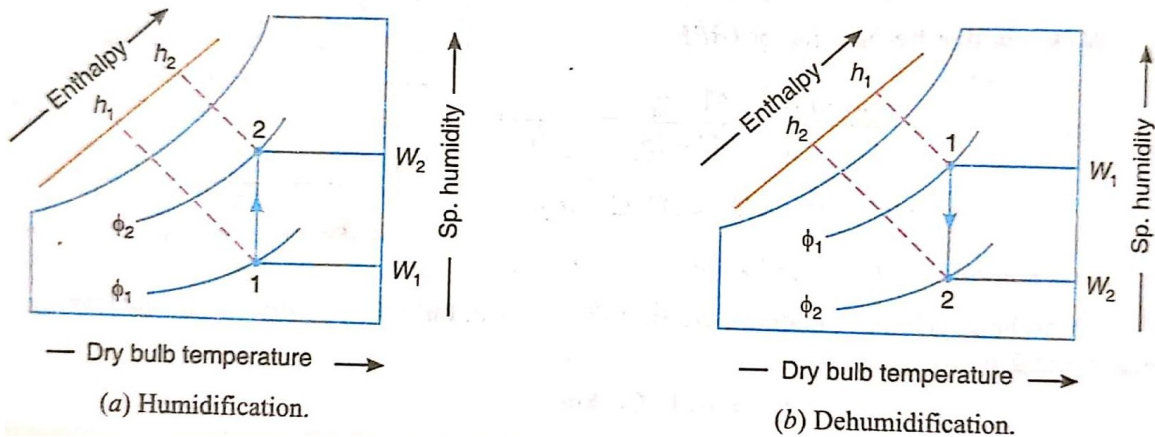
$$\begin{aligned}\eta_H &= 1 - BPF \\ &= \left[1 - \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}} \right] \\ &= \frac{t_{d2} - t_{d1}}{t_{d3} - t_{d1}}\end{aligned}$$

Efficiency of the Cooling coil

$$\begin{aligned}\eta_C &= 1 - BPF \\ &= \left[1 - \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}} \right] \\ &= \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}}\end{aligned}$$

Humidification and Dehumidification

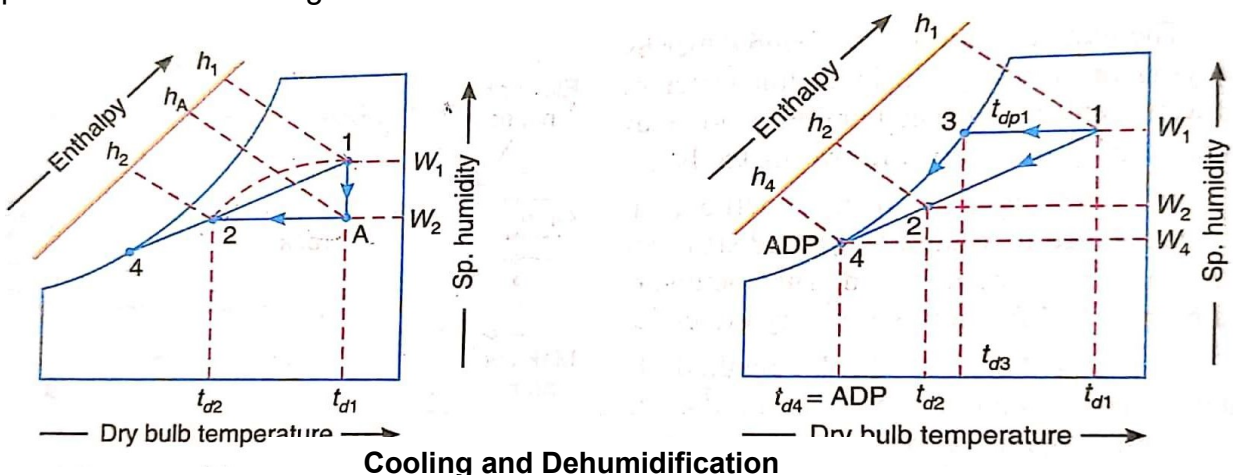
The addition of moisture to the air, without change in its dry bulb temperature, is known as *humidification*. Similarly, removal of moisture from the air, without change in its dry bulb temperature, is known as *dehumidification*. The heat added during humidification process and heat removed during dehumidification process is shown on the psychrometric chart in figure (a) and (b) respectively.



It may be noted that in humidification, the relative humidity increases from ϕ_1 to ϕ_2 and specific humidity also increases from W_1 to W_2 as shown in figure (a). Similarly, in dehumidification, the relative humidity decreases from ϕ_1 to ϕ_2 and specific humidity also decreases from W_1 to W_2 as shown in figure (b).

Cooling and Dehumidification

This process is generally used in summer air conditioning to cool and dehumidify the air. The air is passed over a cooling coil or through a cold water spray. In this process, the dry bulb temperature as well as the specific humidity of air decreases. The final relative humidity of the air is generally higher than that of the entering air. The dehumidification of air is only possible when the effective surface temperature of the cooling coil (i.e. t_{d4}) is less than the dew point temperature of the air entering the coil (i.e., t_{dp1}). The effective surface temperature of the coil is known as **apparatus dew point** (briefly written as ADP). The cooling and dehumidification process is shown in figure



t_{d1} = Dry bulb temperature of air entering the coil,
 t_{dp1} = Dew point temperature of the entering air = t_{d3}
 t_{d4} = Effective surface temperature or ADP of the coil.

Under ideal conditions, the dry bulb temperature of the air leaving the cooling coil (i.e. t_{d4}) should be equal to the surface temperature of the cooling coil (i.e. ADP), but it is never possible due to inefficiency of the cooling coil. Therefore, the resulting condition of air coming out of the coil is shown by a point 2 on the straight line joining the points 1 and 4. The by-pass factor in this case is given by

$$\text{By Pass Factor} = \frac{t_{d2} - t_{d4}}{t_{d1} - t_{d4}} = \frac{t_{d2} - \text{ADP}}{t_{d1} - \text{ADP}}$$

$$\text{By Pass Factor} = \frac{W_2 - W_4}{W_1 - W_4} = \frac{h_4 - h_2}{h_1 - h_2}$$

Actually, the cooling and dehumidification process follows the path as shown by a dotted curve in figure (a), but for the calculation of psychrometric properties, only end points are important. Thus the cooling and dehumidification process shown by a line 1-2 may be assumed to have followed a path 1-A (i.e. dehumidification) and A-2 (i.e. cooling) as shown in figure (a). We see that the total heat removed from the air during the cooling and dehumidification process is

$$q = h_1 - h_2 = (h_1 - h_A) + (h_A - h_2) = \text{LH} + \text{SH}$$

Where LH = $h_1 - h_A$ = Latent heat removed due to condensation of vapour of the reduced moisture content ($W_1 - W_2$), and
 SH = $h_A - h_2$ = Sensible heat removed.

We know that sensible heat factor,

$$\text{Sensible Heat Factor} = \frac{\text{Sensible Heat}}{\text{Total Heat}} = \frac{\text{SH}}{\text{SH} + \text{LH}} = \frac{h_A - h_2}{h_1 - h_2}$$

The line 1-4 (i.e. the line joining the point of entering air and the apparatus dew point) in figure (b) is known as sensible heat factor line.

Cooling With Adiabatic Humidification:

When the air is passed through an insulated chamber having sprays of water maintained at a temperature higher than the dew point temperature of entering air, but lower than its dry bulb temperature,

The air will be both cooled and humidified. From the spray chamber part of the water will be evaporated and is carried away with water thus air is humidified.

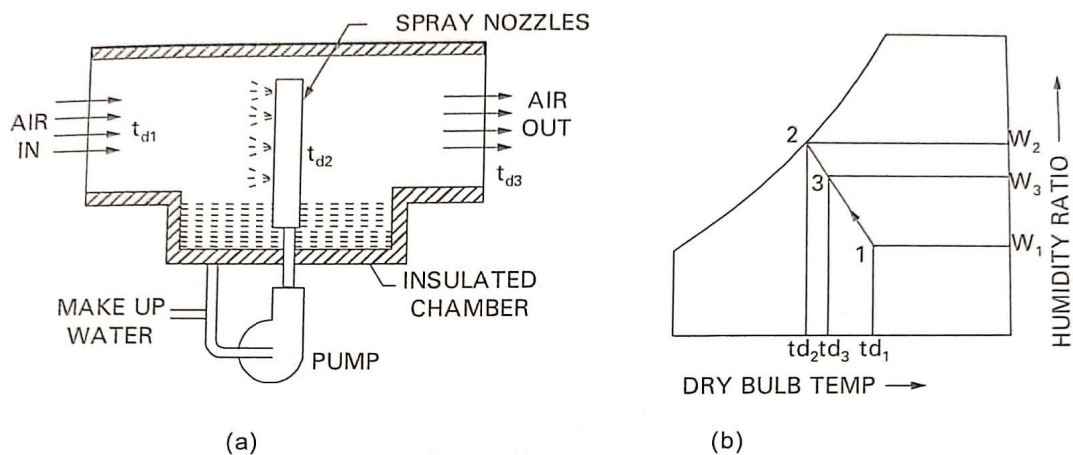
The heat required for evaporation of water carried with air is taken from the air itself by decreasing the temperature of the air.

Therefore the air is cooled. No heat is supplied or rejected from the spray water and the same water is re circulated again and again.

Therefore adiabatic saturation will be reached and the total enthalpy of air remains constant.

A condition of equilibrium is reached when the sensible heat drop in the entering air equals the heat of vapourisation of water.

The temperature of spray water will reach the thermodynamic wet bulb temperature of the air entering the spray water.



The air enters the spray chamber at Point 1. The air leaves the chamber at Point 3. Under ideal conditions it should have left at Point 2. The corresponding dry bulb temperature are t_{d1} , t_{d2} and t_{d3} at Points 1, 2 and 3 respectively.

$$\text{Effectiveness of Spray Chamber} = \frac{\text{Actual Drop in DBT}}{\text{Ideal Drop in DBT}} = \frac{t_{d1} - t_{d3}}{t_{d1} - t_{d2}}$$

Heating and Humidification

This process is generally used in winter air conditioning to warm and humidify the air. It is the reverse process of cooling and -- dehumidification.

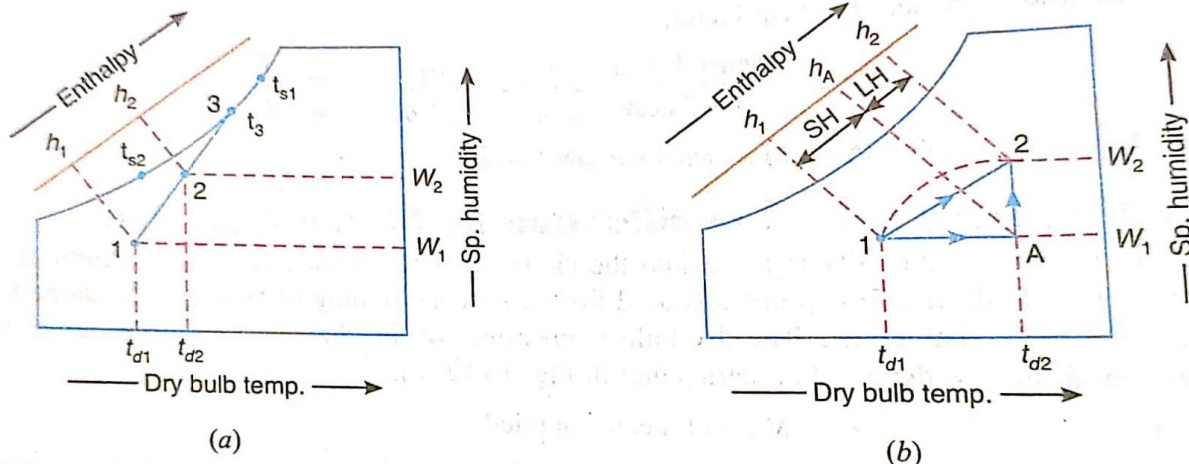
When air is passed through a humidifier having spray water temperature higher than the dry bulb temperature of the entering air, the unsaturated air will reach the condition of saturation and thus the air becomes hot.

The heat of vaporization of water is absorbed from the spray water itself and hence it gets cooled. In this way, the air becomes heated and humidified.

The process of heating and humidification is shown by line 1-2 on the psychrometric chart as shown in figure

The air enters at condition 1 and leaves at condition 2. In this process, the dry bulb temperature as well as specific humidity of air increases.

The final relative humidity of the air can be lower or higher than that of the entering air



Heating and Humidification

Let m_{w1} and m_{w2} = Mass of spray water entering and leaving the humidifier in kg,
 h_{fw1} and h_{fw2} = Enthalpy of spray water entering and leaving the humidifier in kJ/kg,
 W_1 and W_2 = Specific humidity of the entering and leaving air in kg/kg of dry
 h_1 and h_2 = Enthalpy of entering and leaving air in kJ/kg of dry air, and
 m_a = Mass of dry air entering in kg.

For mass balance of spray water,

$$(m_{w1} - m_{w2}) = m_a (W_2 - W_1)$$

$$m_{w2} = m_{w1} - m_a (W_2 - W_1) \dots (i)$$

or and for enthalpy balance,

$$m_{w1} h_{fw1} = m_{w2} h_{fw2} = m_a (h_2 - h_1) \dots (ii)$$

Substituting the value of m_{w2} from equation (i), we have

$$m_{w1} h_{fw1} - [m_{w1} - m_a (W_2 - W_1)] h_{fw2}$$

$$= m_a (h_2 - h_1)$$

$$h_2 - h_1 = \frac{m_{w1}}{m_a} (h_{fw1} - h_{fw2}) + (W_2 - W_1) h_{fw2}$$

The temperatures t_{s1} and t_{s2} shown in figure denote the temperatures of entering and leaving spray water respectively. The temperature t_3 is the mean temperature of the spray water which the entering air may be assumed to approach.

Actually, the heating and humidification process follows the path as shown by dotted curve in figure, but for the calculation of psychrometric properties, only the end points are important. Thus, the heating and humidification process shown by a line 1-2 on the psychrometric chart

may be assumed to have followed the path 1-A (i.e. heating) and A-2 (i.e. humidification), as shown in figure.

We see that the total heat added to the air during heating and humidification is

$$q = h_2 - h_1 = (h_2 - h_A) + (h_A - h_1) = q_L + q_s$$

Where $q_L = (h_2 - h_A) =$ Latent heat of vaporization of the increased moisture content ($W_2 - W_1$), and

$$q_s = (h_A - h_1) = \text{Sensible heat added}$$

We know that sensible heat factor,

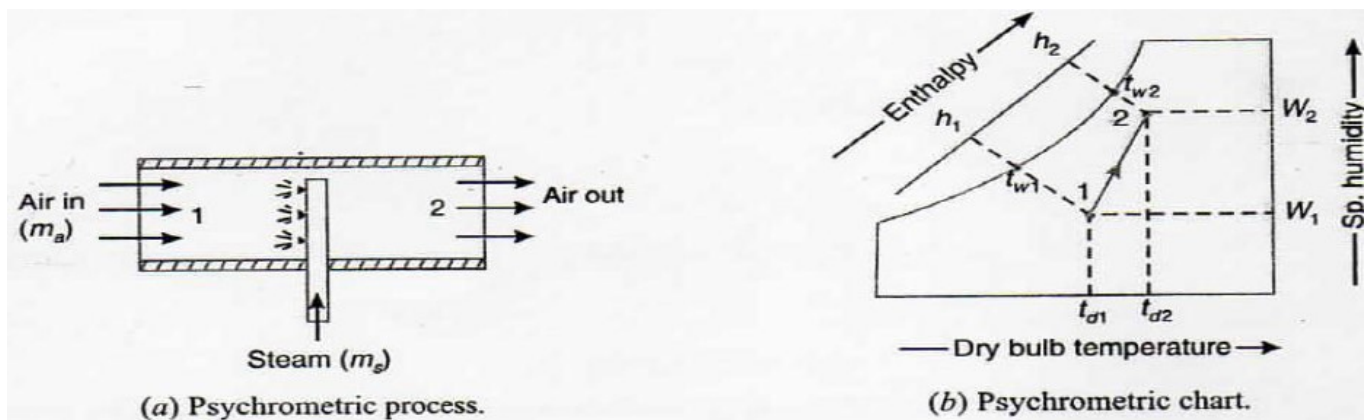
$$\text{Sensible Heat Factor} = \frac{\text{Sensible Heat}}{\text{Total Heat}} = \frac{SH}{SH + LH} = \frac{q_s}{q_s + q_L} = \frac{h_A - h_1}{h_2 - h_1}$$

Note: The line 1-2 in figure (b) is called sensible heat factor line.

Heating and Humidification by Steam Injection

The steam is normally injected into the air in order to increase its specific humidity as shown in figure (a). The dry bulb temperature of air changes very little during this process, as shown on the psychrometric chart in figure (b).

(This process is used for the air conditioning of textile mills where high humidity is to be maintained).



Heating and humidification by steam injection

Let

m_s = Mass of steam supplied,

m_a = Mass of dry air entering,

W_1 = Specific humidity of air entering,

W_2 = Specific humidity of air leaving,

h_1 = Enthalpy of air entering,

h_2 = Enthalpy of air leaving, and

h_s = Enthalpy of steam injected into the air.

Now for the mass balance,

$$W_2 = W_1 + \frac{m_s}{m_a}$$

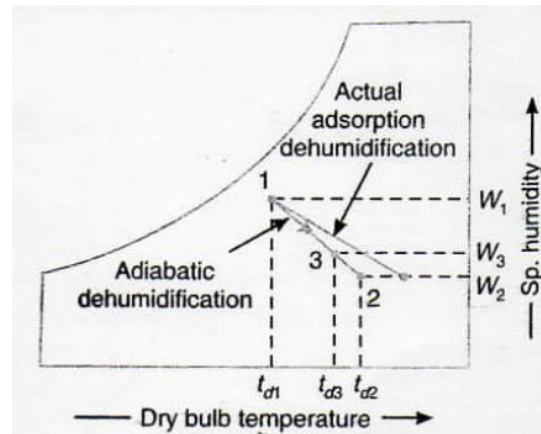
And for the heat balance

$$h_2 = h_1 + \left(\frac{m_s}{m_a} \right) h_s = h_1 + (W_2 - W_1) h_s$$

Heating and Dehumidification -Adiabatic Chemical Dehumidification

In this process, the air is passed over chemicals which have an affinity for moisture. As the air comes in contact with these chemicals, the moisture gets condensed out of the air and gives up its latent heat. Due to the condensation, the specific humidity decreases and the heat of condensation supplies sensible heat for heating the air and thus increasing its dry bulb temperature.

This process is mainly used in industrial air conditioning and can also be used for some comfort air conditioning installations requiring either a low relative humidity or low dew point temperature in the room.



The process, which is the reverse of adiabatic saturation process, is shown by the line 1-2 on the psychrometric chart as shown in figure. The path followed during the process is along the constant wet bulb temperature line or-constant enthalpy line.

The effectiveness or efficiency of the dehumidifier is given as

$$\eta_H = \frac{\text{Actual increase in DBT}}{\text{Ideal increase in DBT}} = \frac{t_{d3} - t_{d1}}{t_{d2} - t_{d1}}$$

Notes:

1. In actual practice, the process is accompanied with a release of heat called heat of adsorption, which is very large. Thus the sensible heat gain of air exceeds the loss of latent heat and the process is shown above the constant wet bulb temperature line in figure.
2. Two types of chemicals used for dehumidification are absorbents and adsorbents. The absorbents are substances which can take up moisture from air and during this process change it chemically, physically or in both respects. These include water solutions or brines of calcium chloride, lithium chloride, lithium bromide and ethylene glycol. These are used as air dehydrators by spraying or otherwise exposing a large surface of the solution in the air stream

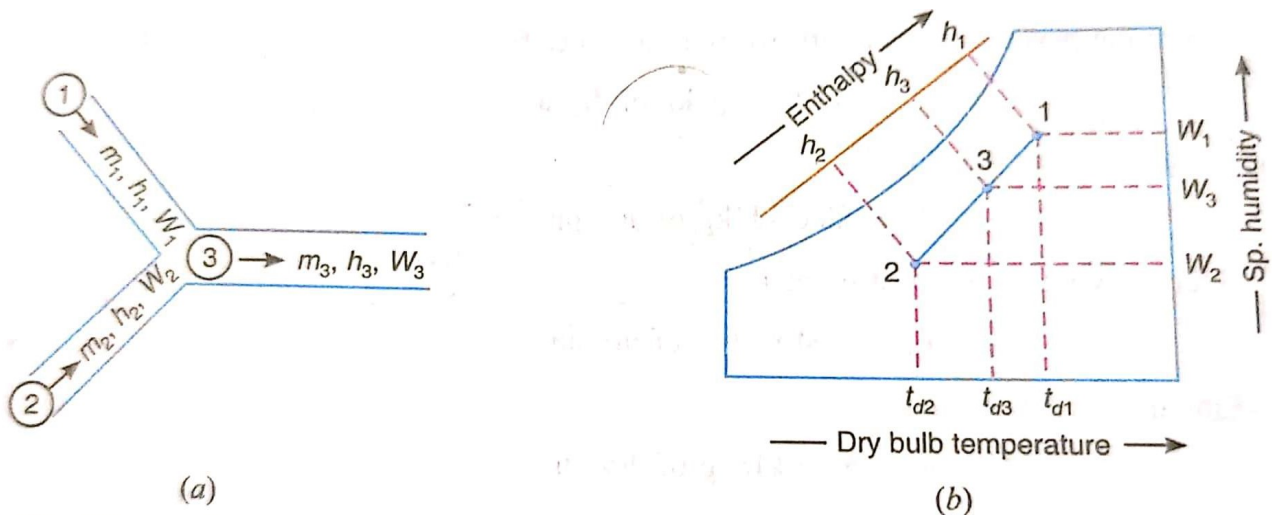
The adsorbents are substances in the solid state which can take up moisture from the air and during this process do not change it chemically or physically. These include silica gel (which is a form of silicon dioxide prepared by mixing fused sodium silicate and sulphuric acid) and activated alumina (which is a porous amorphous form of aluminum oxide).

Adiabatic Mixing of Two Air Streams

When two quantities of air having different enthalpies and different specific humidities are mixed, the final condition of the air mixture depends upon the masses involved, and on the enthalpy and specific humidity of each of the constituent masses which enter the mixture.

Now consider two air streams 1 and 2 mixing adiabatically as shown in figure (a).

Let m_1 = Mass of air entering at 1,
 h_1 = Enthalpy of air entering at 1,
 W_1 = Specific humidity of air entering at 1
 m_2, h_2, W_2 = Corresponding values of air entering at 2,
 m_3, h_3, W_3 = Corresponding values of the mixture leaving at 3.



Adiabatic mixing of two air streams.

Assuming no loss of enthalpy and specific humidity during the air mixing process, we have for the mass balance,

$$m_1 + m_2 = m_3 \quad (i)$$

For the energy balance,

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \quad (ii)$$

and for the mass balance of water vapour,

$$m_1 W_1 + m_2 W_2 = m_3 W_3 \quad (iii)$$

Substituting the value of m_3 from equation (i') in equation (ii)

$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} \quad (iv)$$

Similarly, substituting the value of m_3 from equation (i) in equation (iii), we have

$$\frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W_3} \quad (v)$$

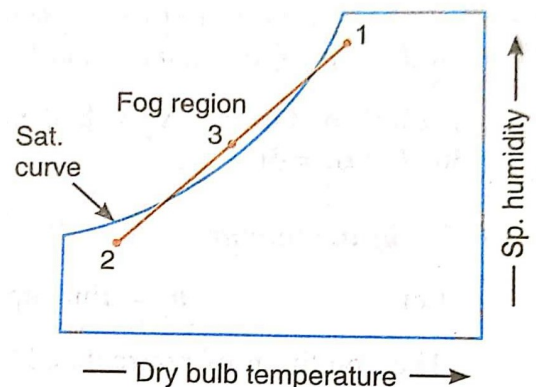
Now from equations (iv) and (v),

$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} = \frac{W_3 - W_2}{W_1 - W_3} = \frac{\text{Line 2 - 3}}{\text{Line 1 - 3}} \quad (vi)$$

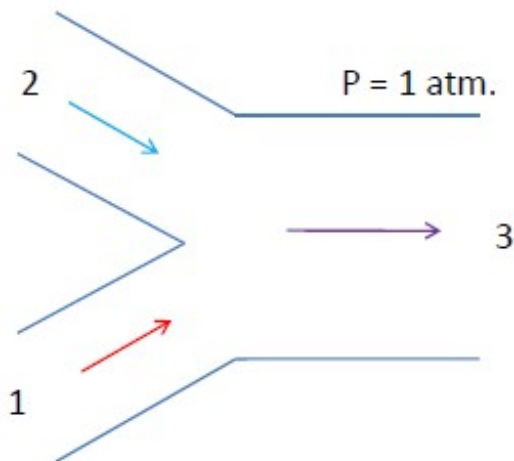
The adiabatic mixing process is represented on the psychrometric chart as shown in figure (b). The initial condition of the mixture (point 3) lies on the straight line 1-2. The point 3 divides the line 1-2 in the inverse ratio of the mixing masses. By calculating the value of W_3 from equation (vi), the point 3 is plotted on the line 1-2.

It may be noted that when warm and high humidity air is mixed with cold air, the resulting mixture will be a fog and the final condition (point 3) on the psychrometric chart will lie to the left or above the saturation curve which represents the fog region, as shown in figure (given in right side). The temperature of the fog is that of the extended wet bulb line passing through point 3

The fog may also result when steam or a very fine water spray is injected into air in a greater quantity than required to saturate the air. Even lesser quantity of steam, if not mixed properly, may result fog



Given: Adiabatic mixing of airstreams

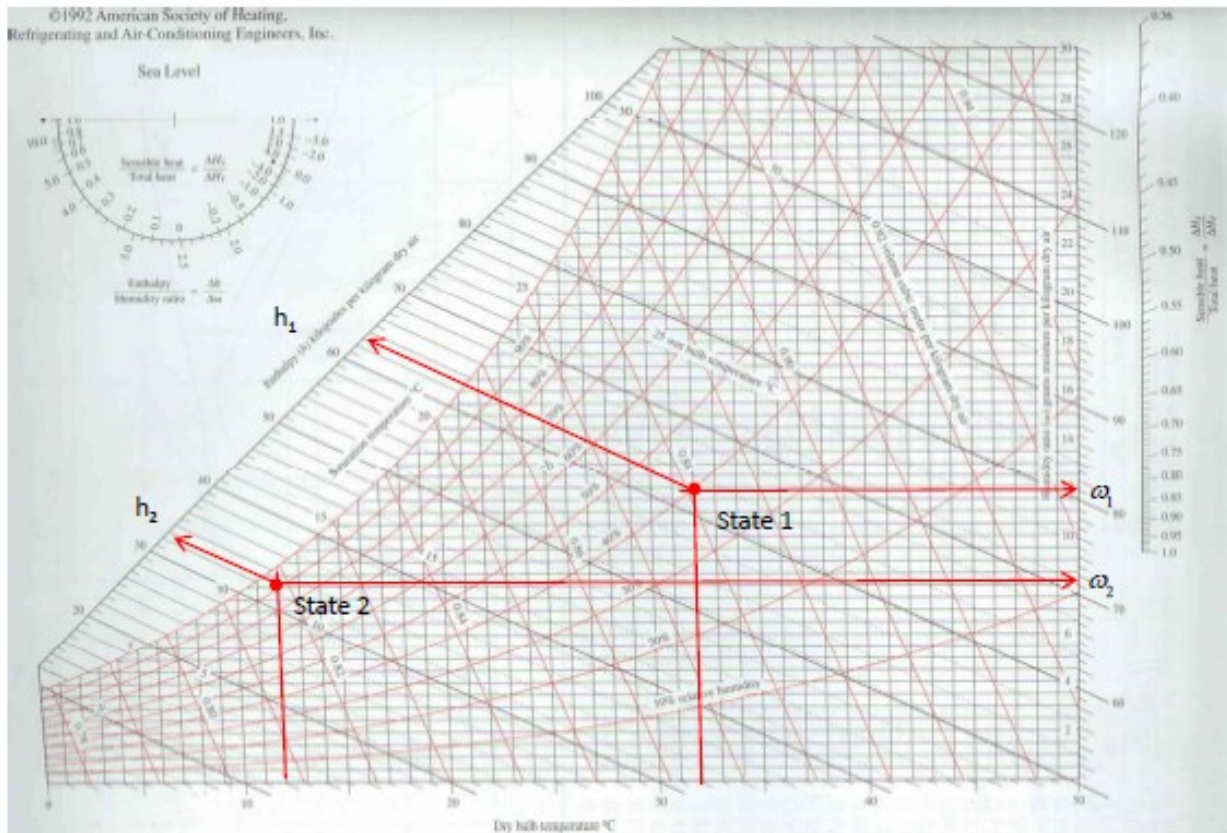


State 1
 $T_1 = 32^\circ\text{C}$
 $\phi_1 = 40\%$
 $\dot{V}_1 = 20\text{ m}^3/\text{min}$

State 2
 $T_2 = 12^\circ\text{C}$
 $\phi_2 = 90\%$
 $\dot{V}_2 = 25\text{ m}^3/\text{min}$

To Find: $\omega_3, \phi_3, T_3, \dot{V}_3$

Use psychrometric chart to determine states 1 and 2:



From the psychrometric chart, we find that:

$$h_1 = 63.0 \frac{kJ}{kg_{dry\ air}}$$

$$\omega_1 = 0.0119$$

$$v_1 = 0.882 \frac{m^3}{kg_{dry\ air}}$$

$$h_2 = 31.4 \frac{kJ}{kg_{dry\ air}}$$

$$\omega_2 = 0.0081$$

$$v_2 = 0.815 \frac{m^3}{kg_{dry\ air}}$$

Mass flow:

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{20 m^3/\min}{0.882 m^3/kg_{dry\ air}} = 22.7 \frac{kg}{\min}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{25 m^3/\min}{0.815 m^3/kg_{dry\ air}} = 30.6 \frac{kg}{\min}$$

$$\therefore \dot{m}_{a3} = \dot{m}_{a1} + \dot{m}_{a2} = (22.7 + 30.6) \frac{kg}{\min} = 53.3 \frac{kg}{\min}$$

Conservation of water mass:

$$\dot{m}_{v1} + \dot{m}_{v2} = \dot{m}_{v3}$$

$$\Rightarrow \omega_1 \times \dot{m}_{a1} + \omega_2 \times \dot{m}_{a2} = \omega_3 \times \dot{m}_{a3}$$

$$\Rightarrow \omega_1 \times \dot{m}_{a1} + \omega_2 \times \dot{m}_{a2} = \omega_3 \times (\dot{m}_{a1} + \dot{m}_{a2})$$

$$\Rightarrow \omega_3 = \frac{\omega_1 \times \dot{m}_{a1} + \omega_2 \times \dot{m}_{a2}}{\dot{m}_{a1} + \dot{m}_{a2}}$$

$$\Rightarrow \omega_3 = \frac{(0.0119 \times 22.7 + 0.0081 \times 30.6) kg/\min}{(22.7 + 30.6) kg/\min}$$

$$\Rightarrow \omega_3 = 0.0097 \leftarrow$$

Conservation of thermal energy:

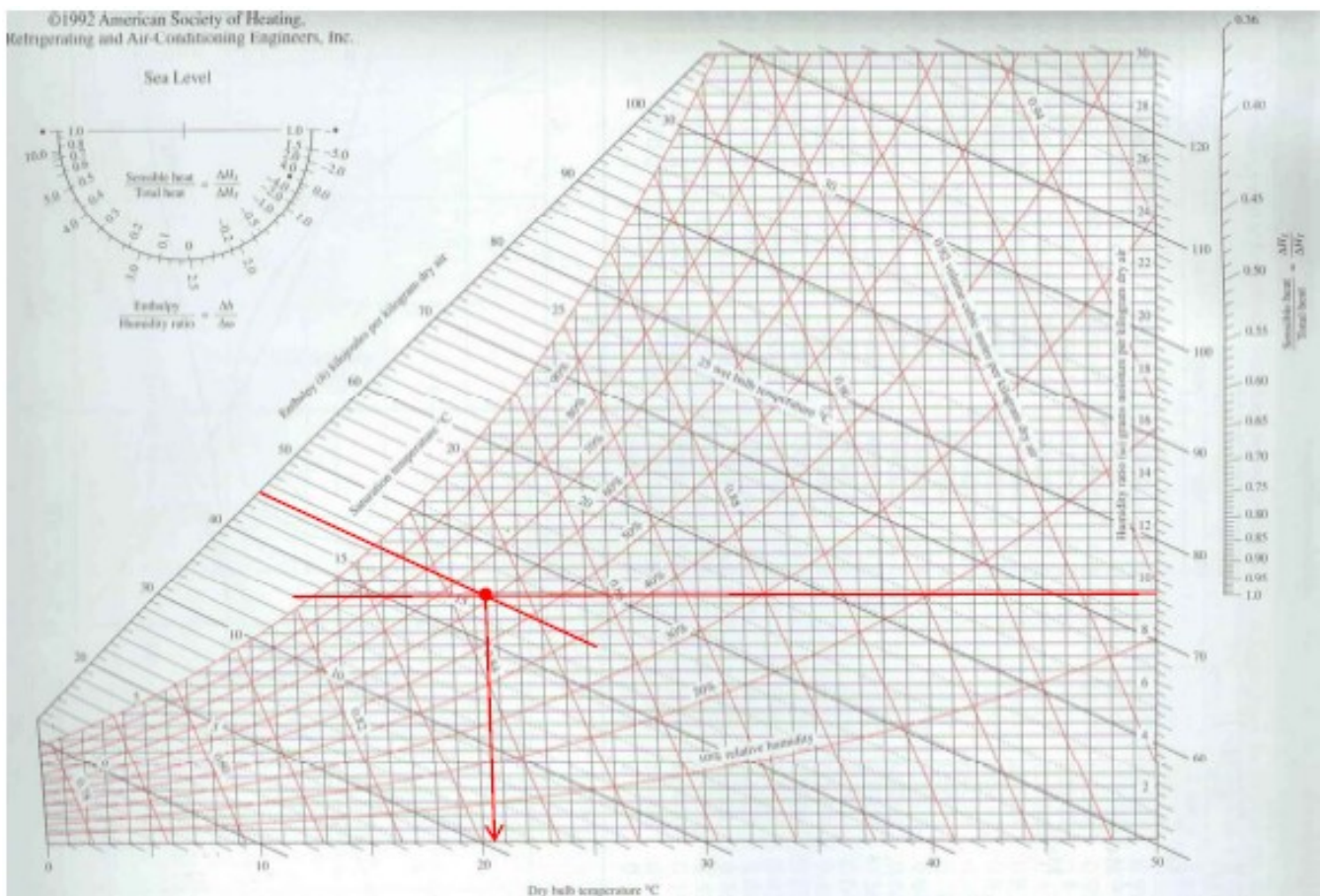
Substitute h for ω in the water mass conservation equation and use same logic.

$$\Rightarrow h_3 = \frac{h_1 \times \dot{m}_{a1} + h_2 \times \dot{m}_{a2}}{\dot{m}_{a1} + \dot{m}_{a2}}$$

$$\Rightarrow h_3 = \frac{(63.0 \times 22.7 + 31.4 \times 30.6) \text{ kJ/min}}{(22.7 + 30.6) \text{ kg/min}}$$

$$\Rightarrow h_3 = 44.6 \frac{\text{kJ}}{\text{kg}}$$

Using h_3 and ω_3 find state 3 and determine requested properties



From the psychrometric chart, we find:

$$T_3 = 20.6^\circ C \leftarrow$$

$$\phi_3 = 61\% \leftarrow$$

$$v_3 = 0.844 \frac{m^3}{kg_{dry air}} \leftarrow$$

3.3.0 Understand the principle of Low temperature refrigeration

- 3.3.1 Define Cryogenics
- 3.3.2 List Advantages and applications of cryogenic refrigeration
- 3.3.3 Explain Cascade refrigeration
- 3.3.4 Explain Joule –Thomson effect
- 3.3.5 Explain Liquefaction of Nitrogen and Hydrogen.
- 3.3.6 Describe the adiabatic demagnetization of paramagnetic Salt for approaching Absolute zero.

Content Details

Low temperature refrigeration (Cryogenics)

Definition for the term cryogenics.-advantages - –field of application-Cascade refrigeration system– Joule Thomson effect – (definition only) - liquefaction of Nitrogen -Hydrogen- absolute zero temperature –use Adiabatic demagnetization of paramagnetic salts

Low temperature refrigeration (Cryogenics)

Cryogenics is the science and technology associated with generation of low temperature below 123 K *{In refrigeration, the temperatures -100°C to -2730C (absolute zero) are treated as low temperatures.}*

In physics, cryogenics is the study of the production and behavior of materials at very low temperatures.

Cryogenics is defined as the branches of Physics and Engineering that involve the study of very low temperatures, how to produce them and how materials behave at those temperatures.

Cryogenics is also defined as a science that deals with how very low temperatures are produced and how they affect other things.

It is a science that deals with the production of very low temperatures and their effect on the properties of matter.

Advantages :

1. **High energy per unit mass** : Propellants like oxygen and hydrogen in liquid form give very high amounts of energy per unit mass due to which the amount of fuel to be carried aboard in the rockets decreases.
2. **Clean fuels** : Hydrogen and oxygen are extremely clean fuels. When they combine becomes water which can be thrown out in the form of hot vapour. Thus the rocket is nothing but a high burning steam engine.
3. **Economical** : The use of oxygen and hydrogen as fuels is very economical; as liquid oxygen costs less than gasoline.

Disadvantage. : The fuel tanks tend to be bulky.

Applications :

Space

- **Rocket propulsion**

Cryogenic engines are powered by cryogenic propellants

Liquid Hydrogen is used as a fuel to propel the rocket

Liquid Oxygen is used as an oxidizer

- **Cooling of Infra-Red (IR) sensor**

Cooling of IR detectors, Telescopes, Cold probes, etc. are some of the major applications of cryogenics.

- **Space simulation**

Space simulations chambers are realistic environment for space craft. The cold space is simulated at cryogenic temperatures by use of LN₂

The levels of vacuum required in space simulation chambers are very high

This is achieved by the use of cryo pumps and turbo molecular pumps.

Mechanical Applications

- **Magnetic Separation**

Magnetic separation technique is used in variety of applications like enhancing the brightness of kaolin, improving the quality of ultra-high purity quartz etc.-

- **Heat treatment**

The lives of the tools die castings & their dies, forgings, jigs & fixtures etc increase when subjected to cryogenic heat treatment.

- **Recycling**

Cryogenic recycling - turns the scrap into raw material by subjecting it to cryogenic temperatures. This is mostly used for PVC, rubbers

Medical applications

Cryosurgery is a novel technique in which the harmful tissues are destroyed by freezing them to cryogenic temperature. Cryosurgery has shorter hospital stay, less blood loss, and small recovery time.

Food preservation

Preserving food at low temperature is a well known technique. Cooling of sea foods, meat (sea export), Milk products for long time preservation is achieved by use of LN₂.

Cell preservation

Systems are developed to preserve blood cells, plasma cells, human organs and animal organs at cryogenic temperatures.

Gas industry applications

- **Liquefaction of gases**

The transportation of gases across the world is done in liquid state. This is done by storing the liquid at cryogenic temperature

Superconductivity

- **Super conducting transformers and generators**

Superconducting transformers and generators have coils (and cores sometimes) maintained at low temperature to minimize the I²R (copper) losses.

- **Maglev locomotion**

Maglev Train runs on the principle of Magnetic Levitation.

The train gets levitated from the guide way by using electromagnetic forces between superconducting magnets on the vehicle and coils on the ground.

This results in no contact motion and therefore no friction.

- **NMR and MRI**

The **NMR (Nuclear Magnetic Resonance)** is used by the pharmaceutical industry to study the molecular structure. (It has a super conducting magnet)

The **MRI (Magnetic Resonance Imaging)** machines are used for body scanning.

The super conducting magnets for both NMR and MRI machines are cooled by liquid Helium.

Disadvantages :

- a) Handling and storage of cryogenic gases can be dangerous.
- b) Low temperature hazards and oxygen enrichment.
- c) Explosion hazard near high nuclear radiation fuel: in the use of Liquid N₂.

Cascade Refrigeration System:

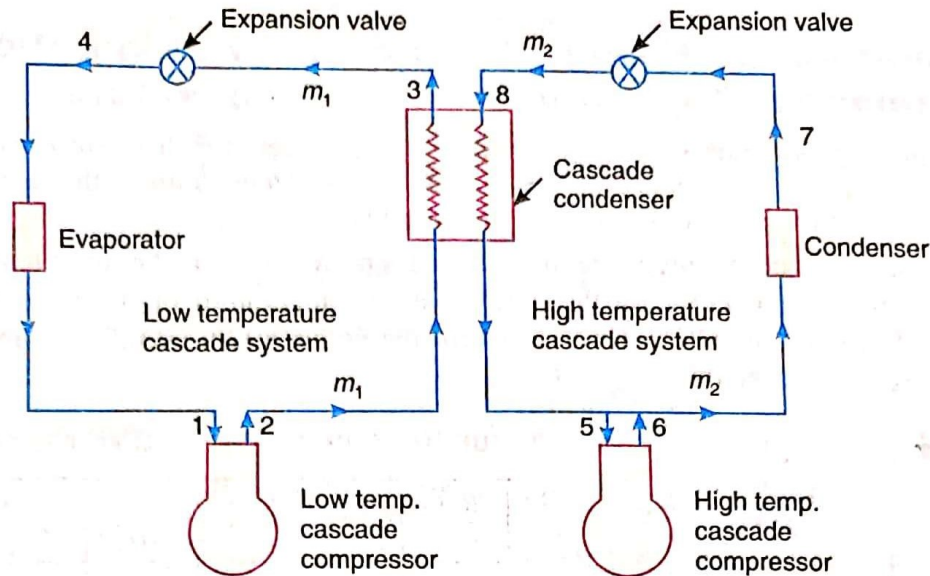
The single stage vapour compression refrigeration systems for different refrigerants are limited to an evaporator temperature of -40°C. Below this temperature, the use of vapour compression Systems has many drawbacks

- The use of vapour compression refrigeration system for the production of low temperatures is limited inherently by the solidification temperature of the refrigerants. The refrigerant used must have a freezing temperature well below the required temperature to be attained.
- The pressure in the evaporator is extremely low (below atmospheric) and the suction volume is very large when a refrigerant with high boiling temperature is used.
- The pressure in the condenser is extremely high when a refrigerant with low boiling temperature is used.
- The coefficient of performance is low because of very high pressure ratios.
- The difficulties encountered in the operation of any mechanical equipment at very low temperatures.

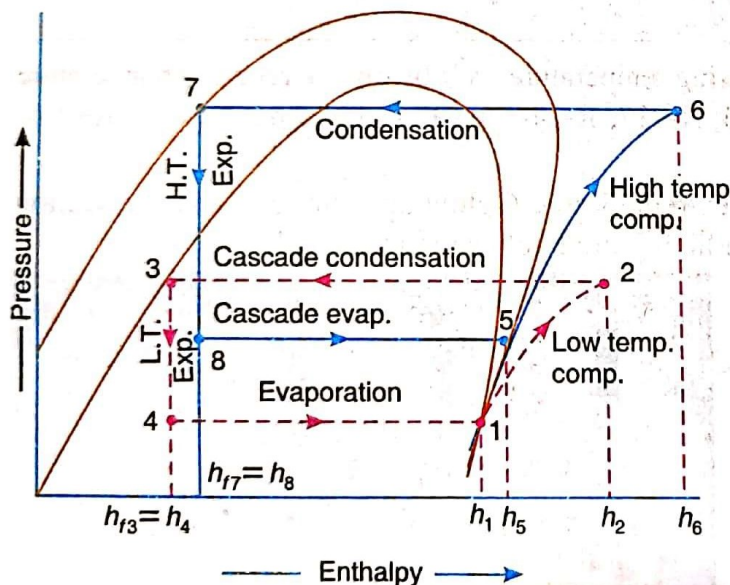
When the vapour compression system is to be used for the production of low temperature, We use cascade refrigeration system. In this system a series of refrigerants with progressively lower boiling temperatures is used in a series of single stage units (***The cascade refrigeration system consists of two or more vapour compression refrigeration systems in series***)

The two stage cascade system is explained below. These two stages work entirely independently. Two different refrigerants are used. Each cycle is analysed like a single unit.

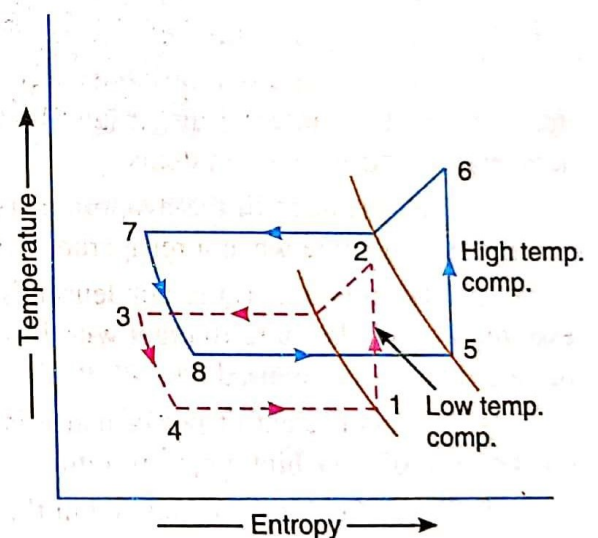
A cascade refrigerator system is equivalent to two independent simple vapour compressions system combined together. They are combined in such a way that the evaporator of the high-temperature system becomes the condenser of the low temperature system. But the working media of the two systems are separated from each other. The intermediate heat exchanger is also called a cascade heat exchanger or condenser. This arrangement is very useful for liquefaction of gases



(a) Schematic diagram of a two stage cascade system.



(b) p - h diagram.



(c) T - s diagram.

In this system, a cascade condenser serves as an evaporator for the high temperature cascade system and a condenser for the low temperature cascade system.

The only useful refrigerating effect is produced in the evaporator of the low temperature cascade system.

The principal advantage of the cascade system is that it permits the use of two different refrigerants.

The high temperature cascade system uses a refrigerant with high boiling temperature 'such as R-12 or R-22. The low temperature cascade system uses a refrigerant with low boiling temperature such as R-13 or R-13 B1.

These low boiling temperature refrigerants have extremely high pressure which ensures a smaller compressor displacement in the low temperature cascade system and a higher coefficient of performance.

- The difference in low temperature cascade *condenser temperature* and high temperature cascade *evaporator temperature* is called temperature over lap. This is necessary for heat transfer

Joule–Thomson effect

The **Joule–Thomson effect** (*also known as the Joule–Kelvin effect or Kelvin–Joule effect*) describes the temperature change of a *real* gas when it is forced through a valve or porous plug while keeping it insulated so that no heat is exchanged with the environment (*This procedure is called a throttling process or Joule–Thomson process*)

Definition of the Joule - Thomson effect:

The Joule - Thomson effect is the change in temperature of a fluid upon expansion (ie; pressure decrease) in a steady flow process involving neither heat transfer nor work (in constant enthalpy). This occurs in 'throttling' type processes such as adiabatic flow through a porous plug or an expansion valve.

Or in other words

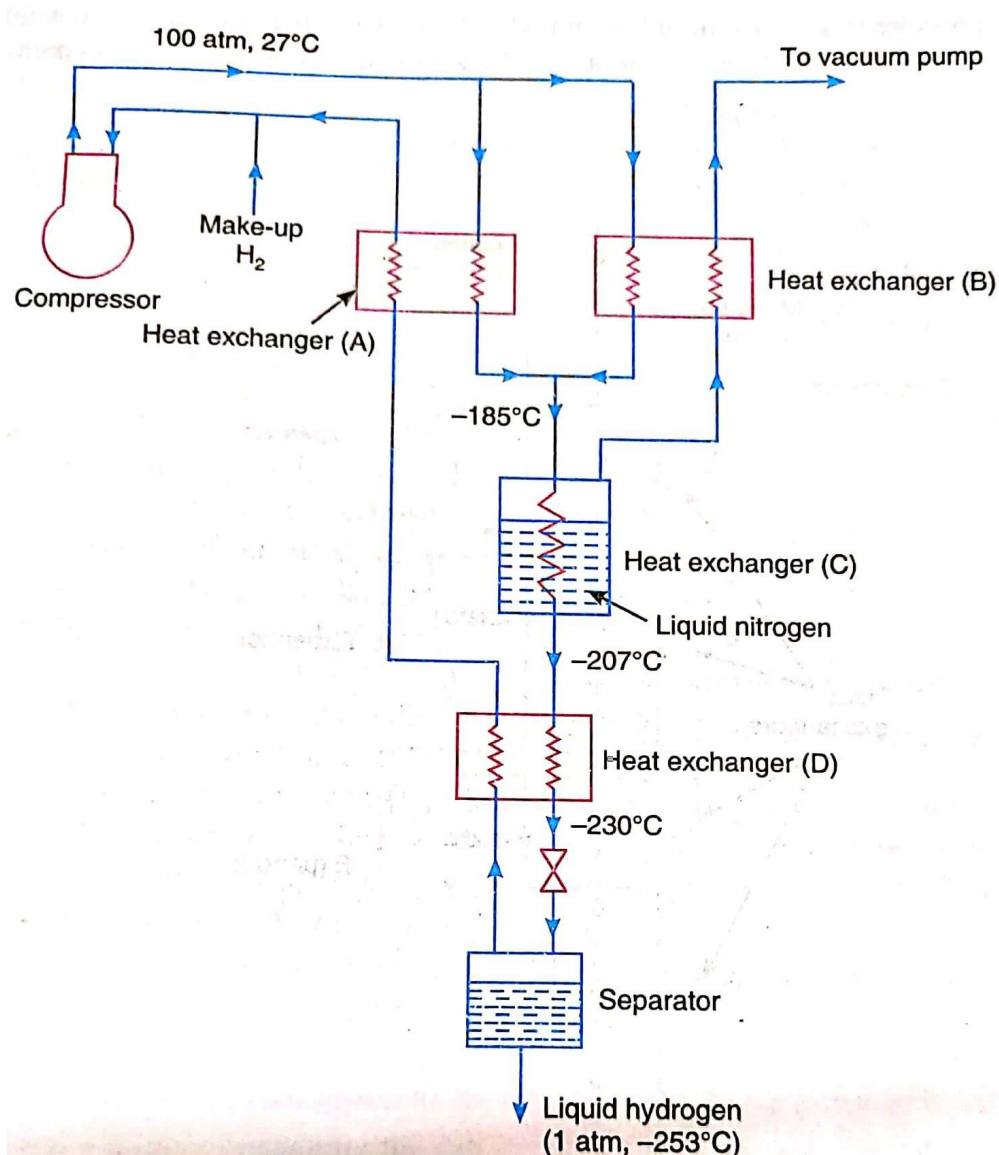
(Joule Thomson effect is the change in temperature that accompanies expansion of gas without production of work or transfer of heat. At ordinary temperatures and pressures, all real gases except hydrogen, helium and neon cool upon such expansion. This phenomenon is often utilised in liquefying gases.)

The gas-cooling throttling process is commonly exploited in refrigeration processes such as air conditioners, heat pumps, and liquefiers

Liquefaction of Hydrogen:

The hydrogen is the most difficult gas to liquefy because of its extremely low liquefaction temperature.

The schematic arrangement of equipment for liquefying hydrogen is shown in figure.



Schematic diagram Liquefaction of Hydrogen

In this system, pure hydrogen gas at a pressure about 100 atmospheres (101.325 kPa) and 27°C from the compressor is pre cooled in two heat exchangers A and B.

In heat exchanger A, the incoming high pressure hydrogen is cooled by the outgoing low pressure hydrogen while in heat exchanger B, it is cooled by nitrogen.

The high pressure hydrogen gas from both the heat exchangers is passed through a third heat exchanger C where the hydrogen gas is further cooled to about -207°C by nitrogen boiling under reduced pressure.

This hydrogen gas is further cooled to about -230°C, in the fourth heat exchanger by the low pressure hydrogen gas returning from the separator.

This liquid hydrogen is produced by throttling the hydrogen gas from the heat exchanger D to atmospheric pressure.

Liquefaction of Nitrogen

Liquid nitrogen is produced commercially from the cryogenic distillation of liquefied air or from the liquefaction of pure nitrogen derived from air using pressure swing adsorption.

An air compressor is used to compress filtered air to high pressure; the high-pressure gas is cooled back to ambient temperature, and allowed to expand to a low pressure. The expanding air cools greatly (the Joule–Thomson effect), and oxygen, nitrogen, and argon are separated by further stages of expansion and distillation. (*Small-scale production of liquid nitrogen is easily achieved using this principle*)

Liquid nitrogen may be produced for direct sale, or as a byproduct of manufacture of liquid oxygen used for industrial processes.

Adiabatic Demagnetisation of a Paramagnetic Salt

It is possible to attain a temperature of about 0.8 K (-272.2°C) through the lowering of pressure over liquid helium.

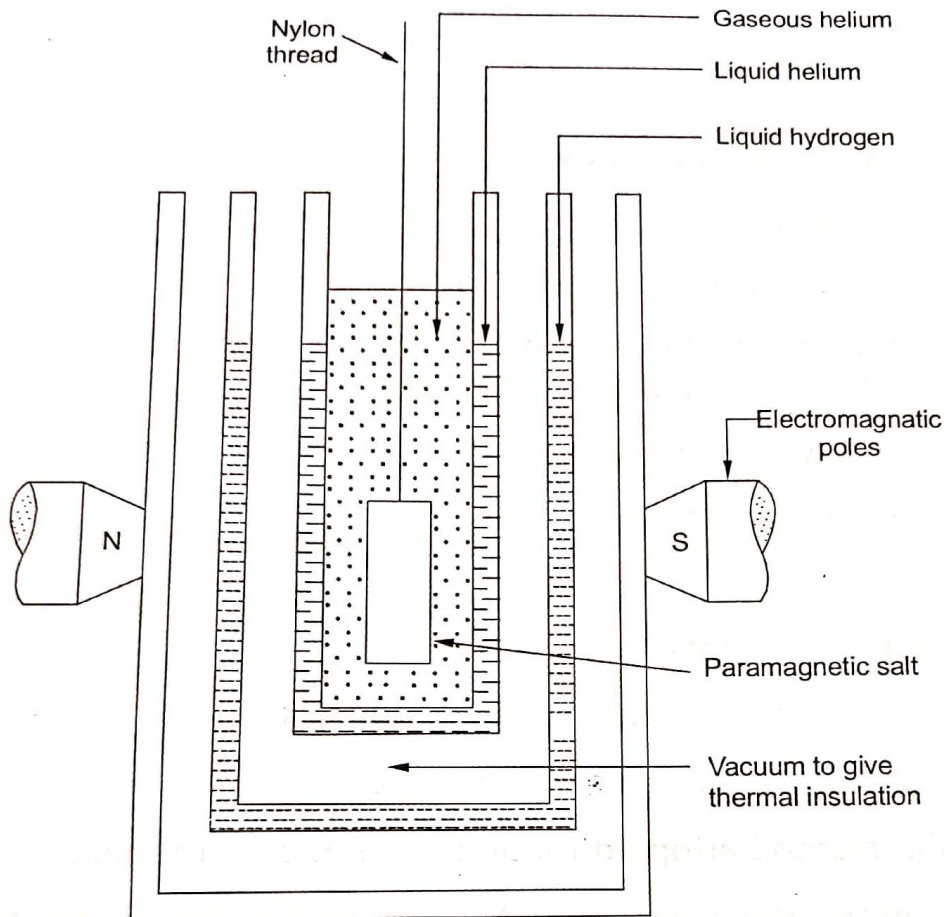
In 1933, Giauque and Debye proposed the adiabatic demagnetisation of magnetic salts for attaining the lower temperatures.

The lowest recorded temperature as low as 0.001 K (i.e. approaching to absolute zero) may be obtained by adiabatic demagnetisation of certain paramagnetic salts previously cooled by liquid helium and subjected to a strong magnetic field.

All substances may be divided into two classes with respect to their magnetic properties. Those substances which are ***repelled by a magnetic pole are called diamagnetic*** while those ***attracted by a magnetic pole (such as iron) are called paramagnetic***. Some of the paramagnetic salts such as gadolinium sulphate are found to be best suited for obtaining low temperatures by their adiabatic demagnetisation.

If such salts are pre cooled to a very low temperature so that any thermal motion of the molecules will be at a minimum, the molecules may be considered as tiny magnets. When the salt is not magnetised, the molecules are oriented in a random manner such that the magnetic forces are in balance. When such a substance is exposed to a strong magnetic field, the molecules attempt to align themselves in the direction of the magnetic field.

The realignment (or demagnetisation) of molecules require work. This work is converted into heat and causes a temperature rise unless the heat is removed by some form of cooling. When the magnetic field is removed, the molecules readjust their positions to the original random arrangement. Such readjustment requires that the salt perform work. In the absence of external heat exchange, the internal energy of the salt decreases. Consequently the salt must cool itself.



Adiabatic demagnetisation apparatus

Figure shows a schematic arrangement for adiabatic demagnetisation of a paramagnetic salt. The inner chamber containing the salt specimen suspended by a thread is initially filled with gaseous helium. This chamber is surrounded by a bath of liquid helium, which, in turn, is surrounded by a bath of liquid hydrogen. In actual practice, the procedure of cooling magnetically is accomplished in the following four steps:

1. First of all, the paramagnetic salt is cooled to about 0.8 K (-272.2°C) by surrounding it with liquid helium boiling under reduced pressure.
2. The salt is exposed to a strong magnetic field. The heat produced by magnetisation of the salt is transferred to the liquid helium without change in salt temperature.
3. The inner chamber containing the salt is evacuated of gaseous helium and the substance is thermally isolated at a temperature below 1 K under the stress of a strong magnetic field.
4. When the magnetic field is released, the salt temperature decreases in an almost perfectly isentropic way. The temperature of the salt as low as 0.001 K may be attained.

Such temperatures (ie; close to absolute zero) cannot be measured by ordinary means but can be calculated by measuring the magnetic susceptibility.