Psychrometry and Psychrometric Processes

Psychrometry – Content

1. Atmospheric air and its composition
2. Estimation of moist air properties
3. Important psychrometric properties and their relationship
4. Psychrometric chart
5. DBT WBT Temperatures
6. Psychrometric Processes
7. Air conditioning

Brief history of air conditioning

- Air conditioning developed from early works of cooling, cleaning, heating & ventilation.
- 15th century –Leonardo da Vinci built ventilation fan. Boyle in 1659 & Dalton in 1800 discovered laws. 1815 –book on heating & ventilation by Robertson Buchanan.
- 19th century –fans boilers & radiator invention. 1835 –generation of ice by Professor Alexander Twining with double acting vacuum & compression pump.
- 1834 –invention of vapour compression cycle by Jacob Perkins using sulphuric ether as refrigerant.

Brief history of air conditioning

- 19th century –development of air humidification for textile industry in England. Measurement device perfection in same period.

- 1904 –formation of American Society of Refrigerating Engineers(ASRE). W.H. Carrier(1876-1950) known as father of AC.

- Use of AC in cotton, silk, rayon, tobacco, paper, pharmaceuticals, candy & printing industries. 1920 –started AC in theaters.

Introduction

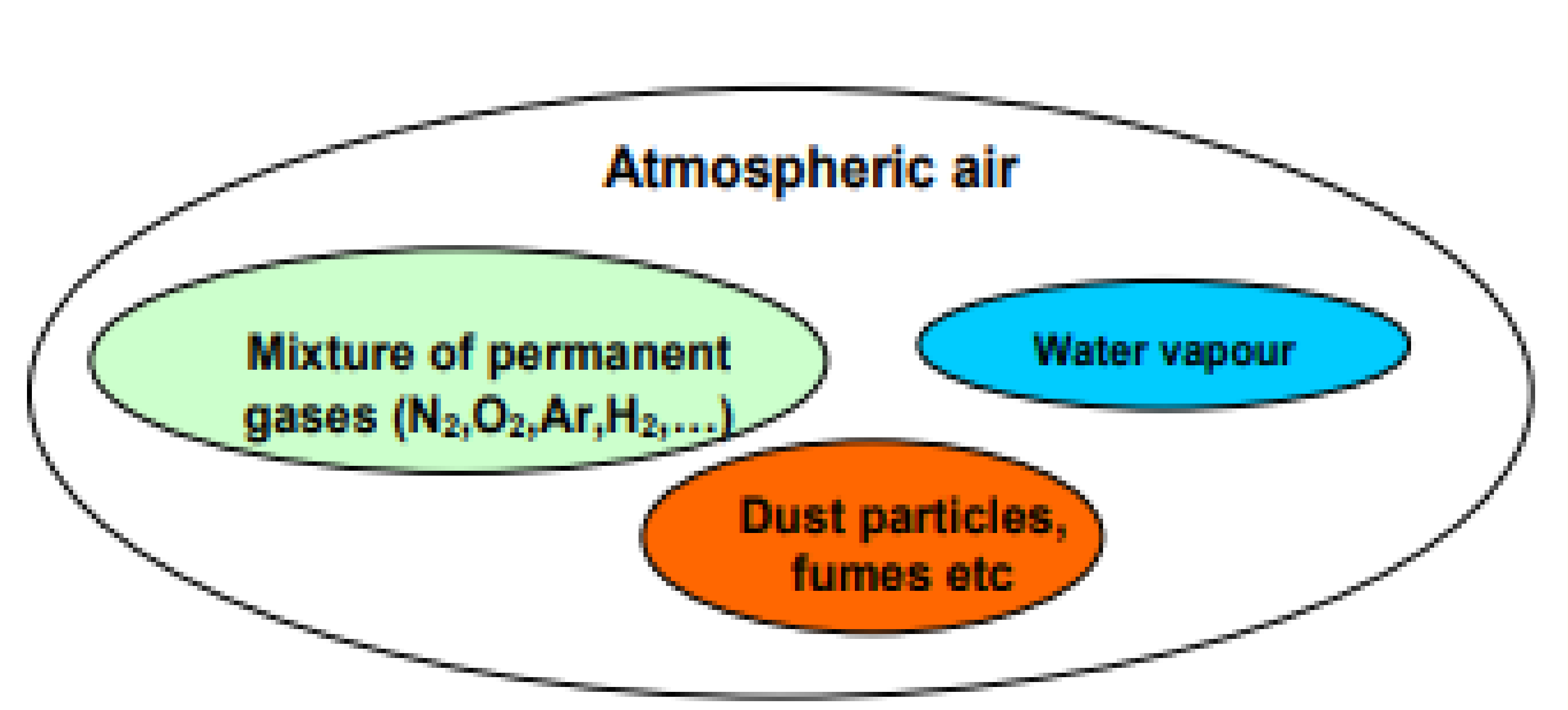
- **Atmospheric air** makes up the environment in almost every type of air conditioning system

- Understanding of the properties of atmospheric air – Analysis of various processes involving air is fundamental to air conditioning design

- **Psychrometry** is the study of the properties of mixtures of air and water vapour

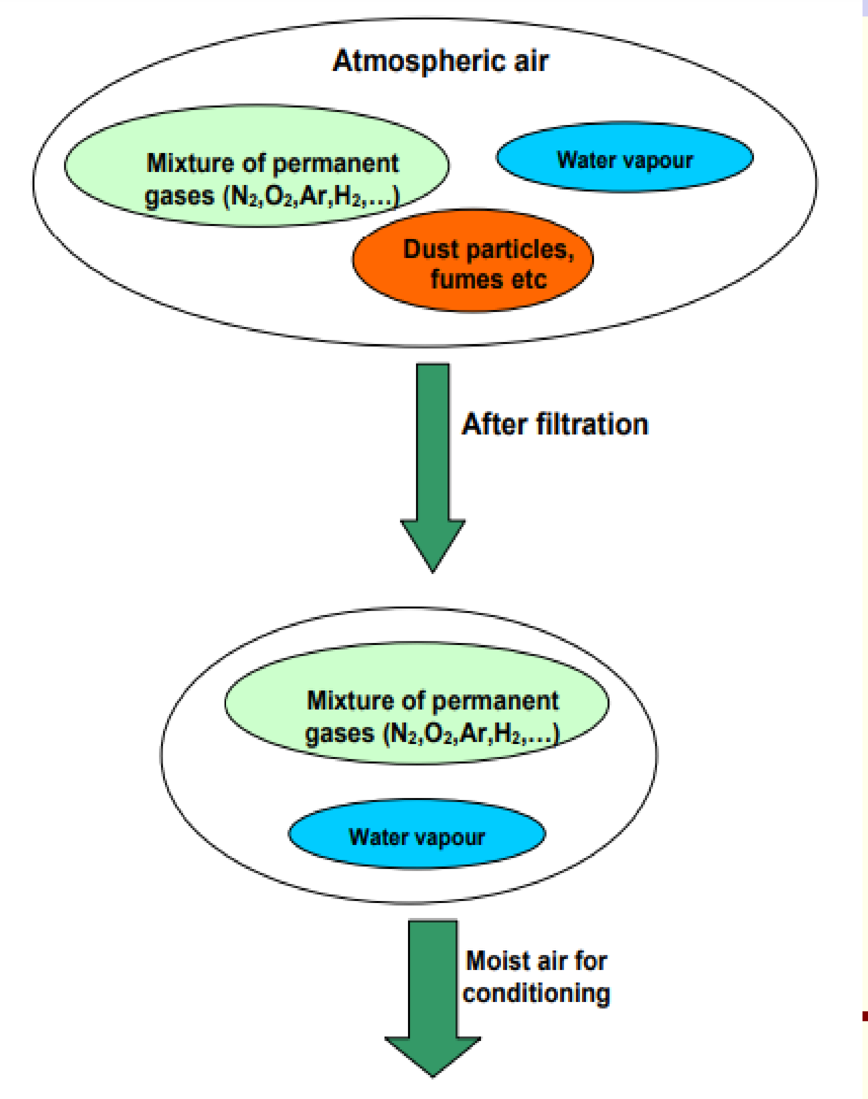
- **Atmospheric air is** a mixture of many gases plus water vapour and a number of pollutants

Atmospheric Air



Atmospheric Air

- Atmospheric air is a mixture of many gases plus water vapour and a number of pollutants.
- Above 10 km, atmospheric air consists of only dry air.
- The pollutants have to be filtered out before processing the air.
- Hence, what we process is essentially a mixture of various gases that constitute dry air and water vapour - Moist air



Atmospheric Air

- The moist air can be thought of as a mixture of dry air and moisture.
- For all practical purposes, the composition of dry air can be considered as constant.
- In 1949, a standard composition of dry air was fixed by the International Joint Committee on Psychrometric data.

Standard Composition of Dry Air

Constituent	Molecular weight	Mol fraction
Oxygen	32.000	0.2095
Nitrogen	28.016	0.7809
Argon	39.944	0.0093
Carbon dioxide	44.010	0.0003

- Based on this composition the molecular weight of dry air is found to be 28.966 and the gas constant R is 287.035 J/kgK

Psychrometry

- While the composition of dry air is constant, the amount of water vapour present in the air may vary from zero to a maximum value.
- When the moisture content is maximum, then the air is known as **saturated air**.
- The amount of saturated air is established by a neutral equilibrium between the moist air and the liquid or solid phases of water.
- For calculation purposes: Mol. wt of water vapour= 18.015
- Gas constant of water vapour = 461. 52 J/kgK

Psychrometry - Estimation of properties of moist air

- It is difficult to estimate the exact property values of moist air as it is a mixture of several permanent gases and water vapour.

- However, moist air upto 3 atm pressure obeys perfect gas laws with accuracy sufficient for engineering calculations.

- For very high accuracy, one has to consider the real gas behaviour of moist air by considering interaction between molecules of various gases and water vapour.

- This requires application of principles of statistical mechanics

Psychrometry

- Dry air may be assumed to be a perfect gas as its temperature is high relative to its saturation temperature

- Water vapour may be assumed to be a perfect gas because its pressure is low relative to its saturation pressure.

- These assumptions result in accuracies, that are, sufficient for engineering calculations (Less than 0.7 percent for total pressure below 3 atm)

Psychrometry

- Moist air is treated as a perfect gas mixture of dry air and water vapour

- According to the Gibbs-Dalton law for a mixture of perfect gases:

$$p_1 = \frac{n_1 R_u T}{V}; \quad p_2 = \frac{n_2 R_u T}{V}; \quad p_3 = \frac{n_3 R_u T}{V};$$

$$p_t = p_1 + p_2 + p_3 + \ldots\ldots.$$

- Applying this to moist air: $p = p_t = p_a + p_v$ *where,*

p_t =barometric pressure, p_a = pp of dry air, p_v = pp of water vapour

Psychrometry - Important psychrometric properties

- Dry bulb temperature (DBT),t: It is the temperature of the moist air as measured by a standard thermometer or other temperature measuring instruments.

- Saturated vapour pressure (p_{sat}): It is saturated partial pressure of water vapour at the dry bulb temperature.

- The saturated vapour pressures can be obtained from thermodynamic tables/charts.

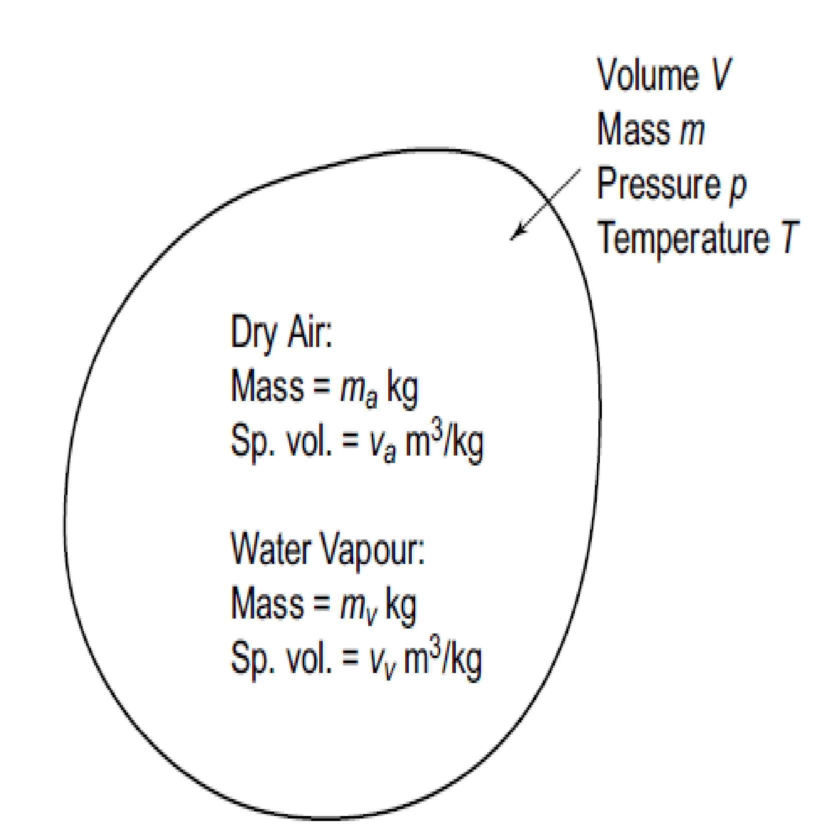
- ASHRAE suggested a regression equation for saturated vapour pressure of water, which is valid for 0 to 100°C

Psychrometric properties

- Air conditioning calculation are based on dry air as water vapour continuously variable.

- To define & calculation of psychrometric properties we consider volume v of moist air at p, T & contain mass of dry air mass of vapour.

- Moist air temp –**dry bulb temperature(DBT)** & total pressure –barometric pressure is constant.



Humidity Ratio (*w*)

- Ratio of mass of water vapor to mass of dry air in given vol of mixture.

$$p_v v_v = \frac{\bar{\boldsymbol{R}}}{M_v} T \quad , \quad p_v V = m_v \frac{\bar{\boldsymbol{R}}}{M_v} T$$

$$\omega = \frac{m_v}{m_a} = \frac{V/v_v}{V/v_a} = \frac{v_a}{v_v}$$

$$\omega = \frac{M_v p_v}{M_a p_a} = \frac{18.016}{28.966} \frac{p_v}{p_a}$$

$$p_a v_a = \frac{\bar{R}}{M_a} T \quad p_a V = m_a \frac{\bar{R}}{M_a} T$$

$$= 0.622 \frac{p_v}{p_a} \frac{kg. w. v}{kg\ d. a}$$

Humidity Ratio (*w*)

- The humidity ratio is the mass of water vapour associated with each kilogram of dry air
- Assuming both water vapour and dry air to be perfect gases, the humidity ratio is given by:

$$w = \frac{\text{kg of water vapour}}{\text{kg of dry air}} = \frac{p_v\, v/R_v\, T}{p_a\, v/R_a\, T} = \frac{p_v/Rv}{(p_t - p_v)/R_a}$$

- Substituting the values of gas constants:

$$w = 0.622\frac{p_v}{p_t - p_v}$$

Humidity Ratio

- From Dalton law : $p = p_a + p_v$

$$\omega = 0.622 \frac{p_v}{p - p_v}$$

- Considering total atmospheric pressure constant at particular locality : $\omega = f(p_v)$

- Specific humidity is function of partial pressure of water vapour only.

Humidity Ratio

- If we take 1 kg of d.a $m_a = 1kg$

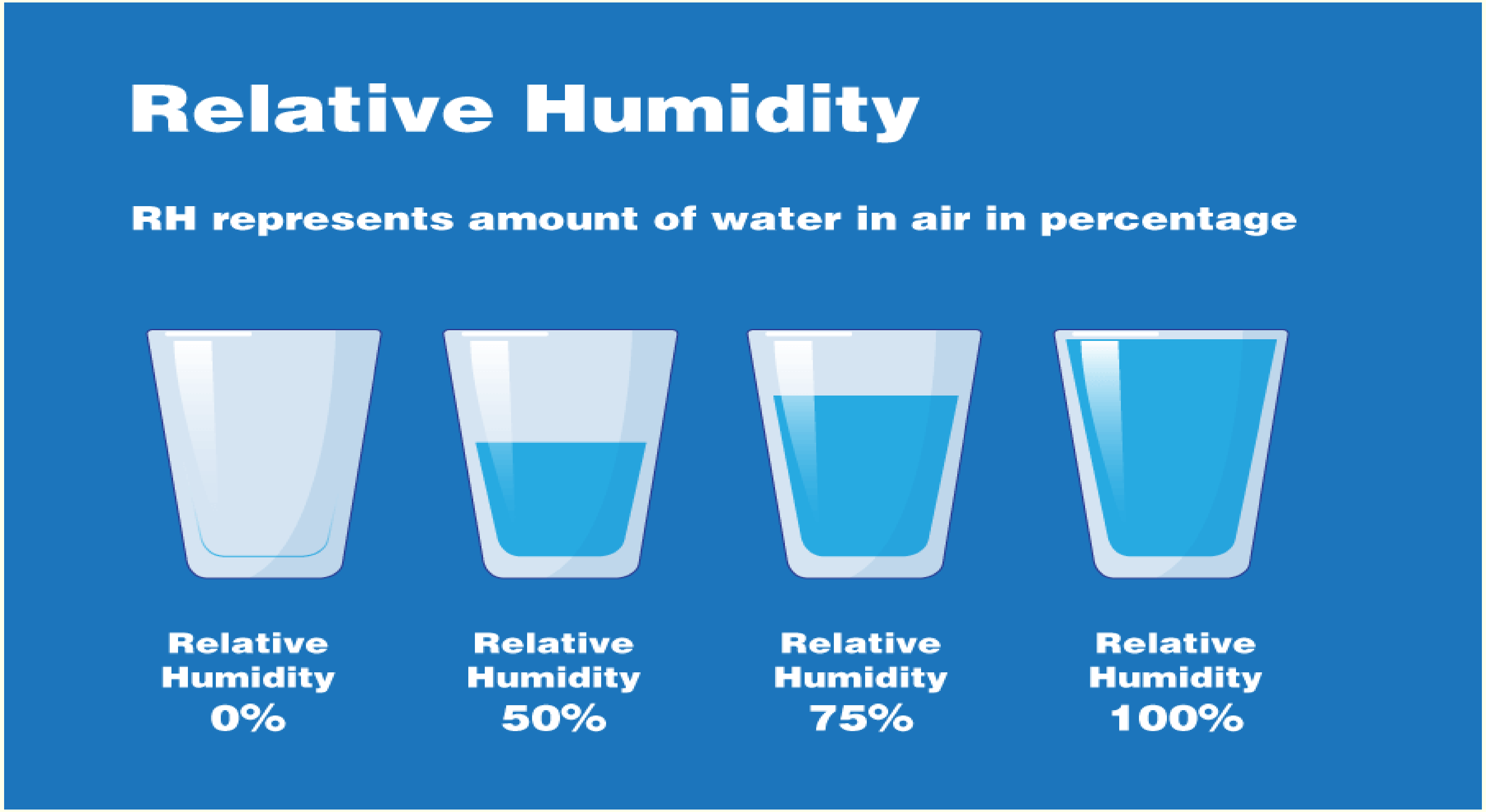
- Mass of water vapour associated with this dry air in same volume

$$m_v = \omega\ kg$$

- Total mass of this volume of moist air : $m = (1 + \omega)\ kg$

- It is to be noted that, *w* is a function of both total barometric pressure and vapor pressure of water.

Relative Humidity



Relative Humidity (Φ)

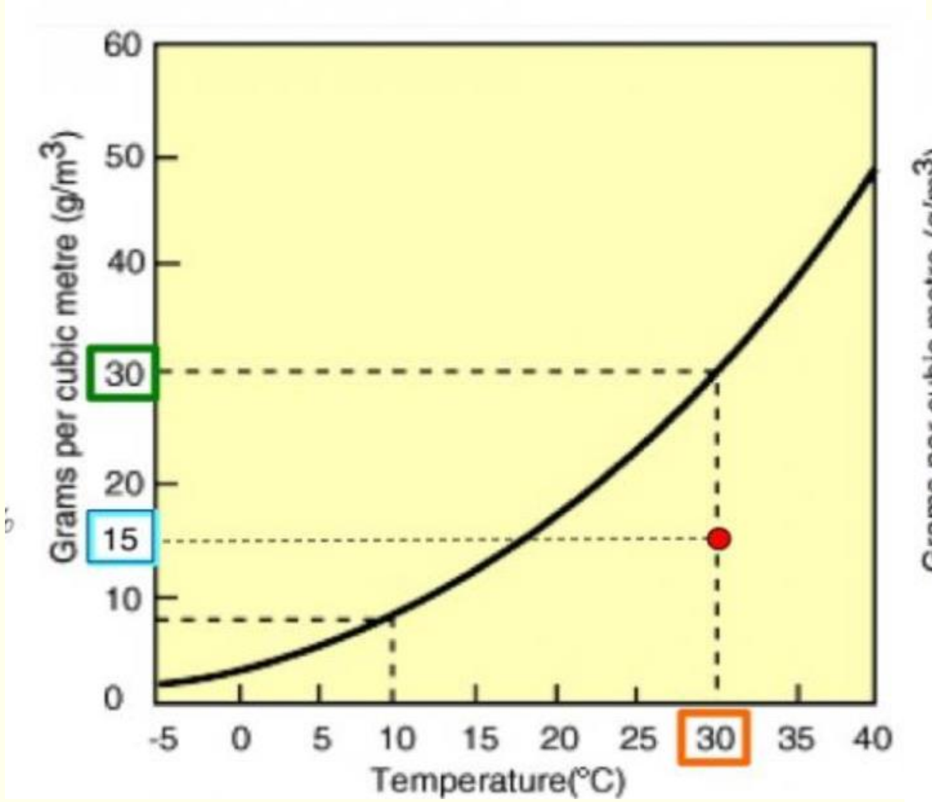
- It is defined as the ratio of the mole fraction of water vapour in moist air to mole fraction of water vapour in saturated air at the same temperature.

- Using perfect gas equation we can show that:

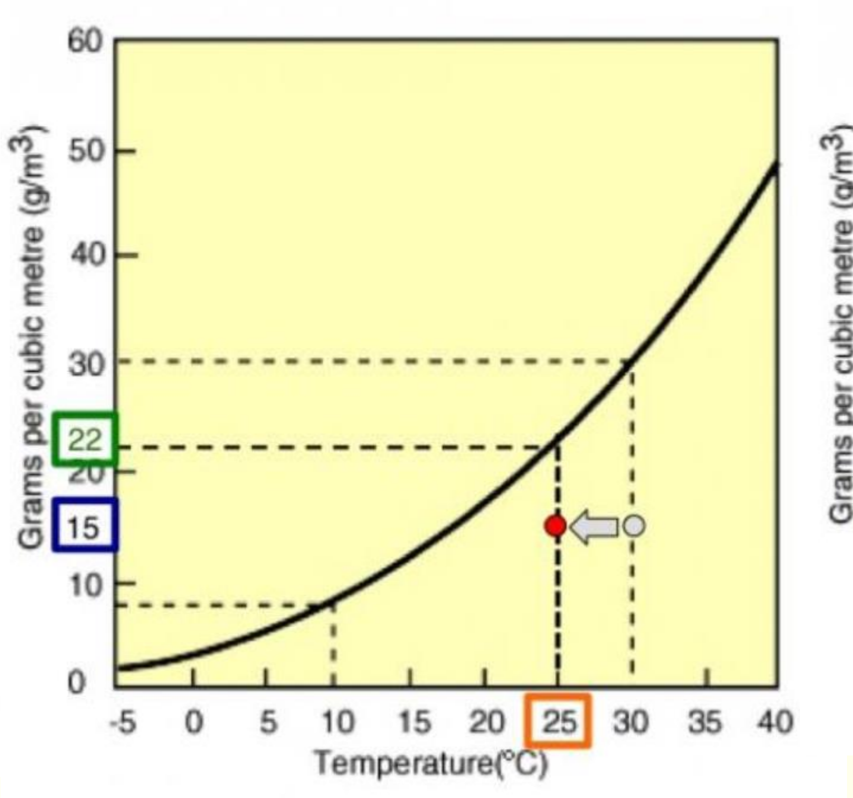
$$\Phi = \frac{\text{partial pressure of water vapour}}{\text{saturation pressure of pure water at same temperature}} = \frac{p_v}{p_{sat}}$$

- Normally it is expressed as a percent Φ is 100% implies saturated air

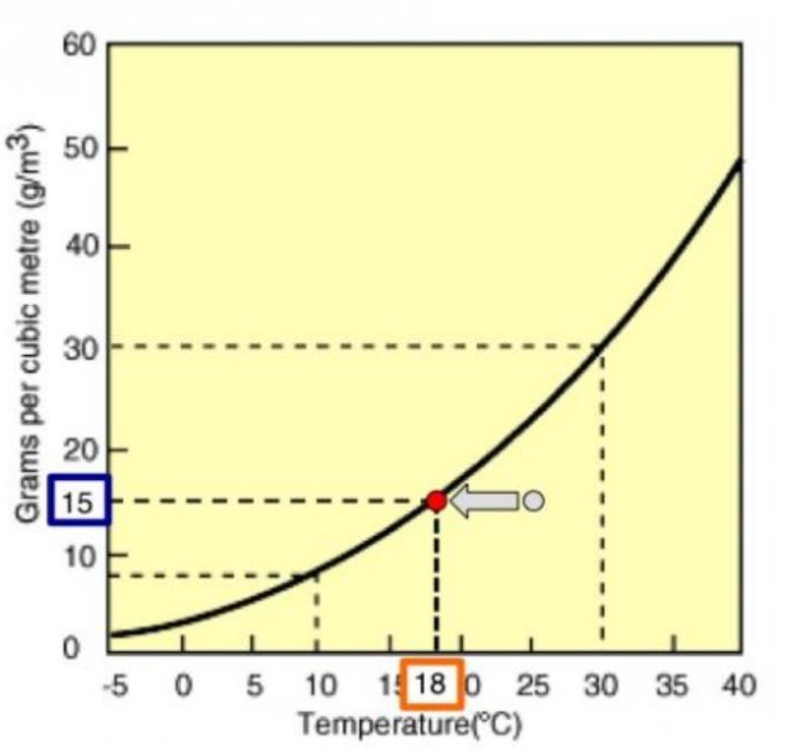
Relative Humidity (Φ)



RH = 50 %



RH = 67 %



RH = 100 %

Relative Humidity

- Ratio of mass of water vapour in certain vol of moist air to mass of water vapour in same vol of sat. air at same temperature.

$$\phi = \frac{m_v}{m_{v_s}} = \frac{\frac{p_v V}{\bar{R}T}}{\frac{p_s V}{\bar{R}T}} = \frac{p_v}{p_s}$$

- From perfect ideal gas

$$p_1 v_1 = p_2 v_2 \,; \quad p_v v_v = p_s v_s$$

$$\phi = \frac{p_v}{p_s} = \frac{v_s}{v_v}$$

- Relative humidity is measure of degree of saturation of air

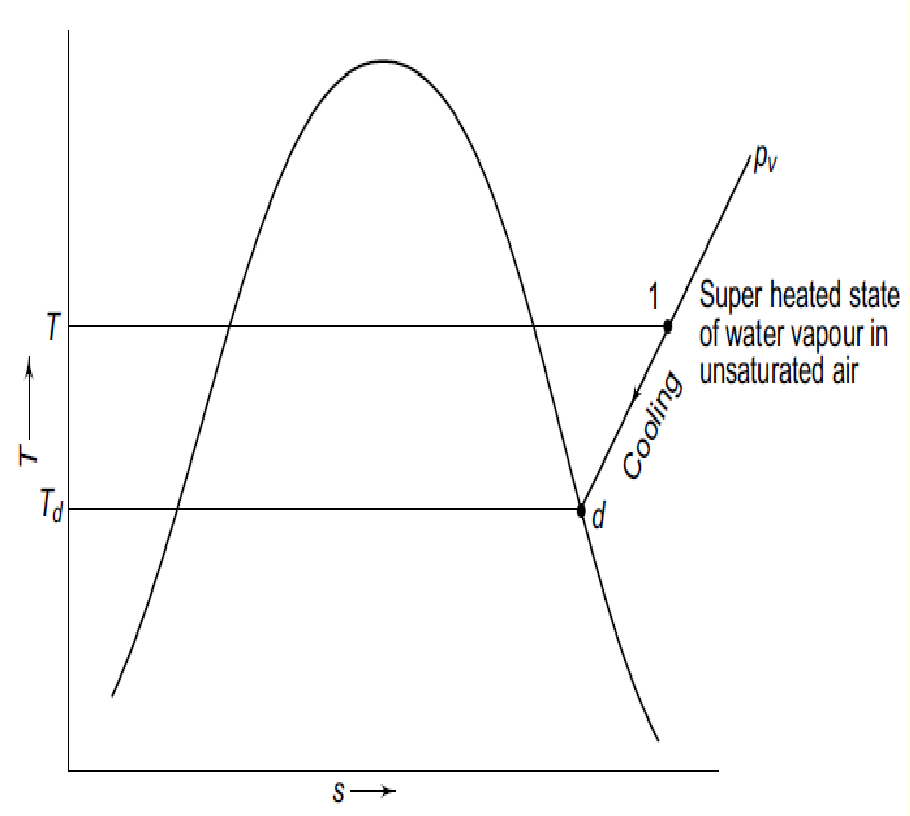
Degree of saturation, μ

- It is the capacity of air to absorb moisture.

- Max possible specific humidity at T

$$\omega_s = 0.622\frac{p_s}{p - p_s}$$

- **Degree of saturation** is ratio of actual specific humidity to specific humidity of sat. air at T : $\mu = \frac{\omega}{\omega_s} = \frac{p_v}{p_s}\left[\frac{1-\frac{p_s}{p}}{1-{p_v}/{p}}\right]$

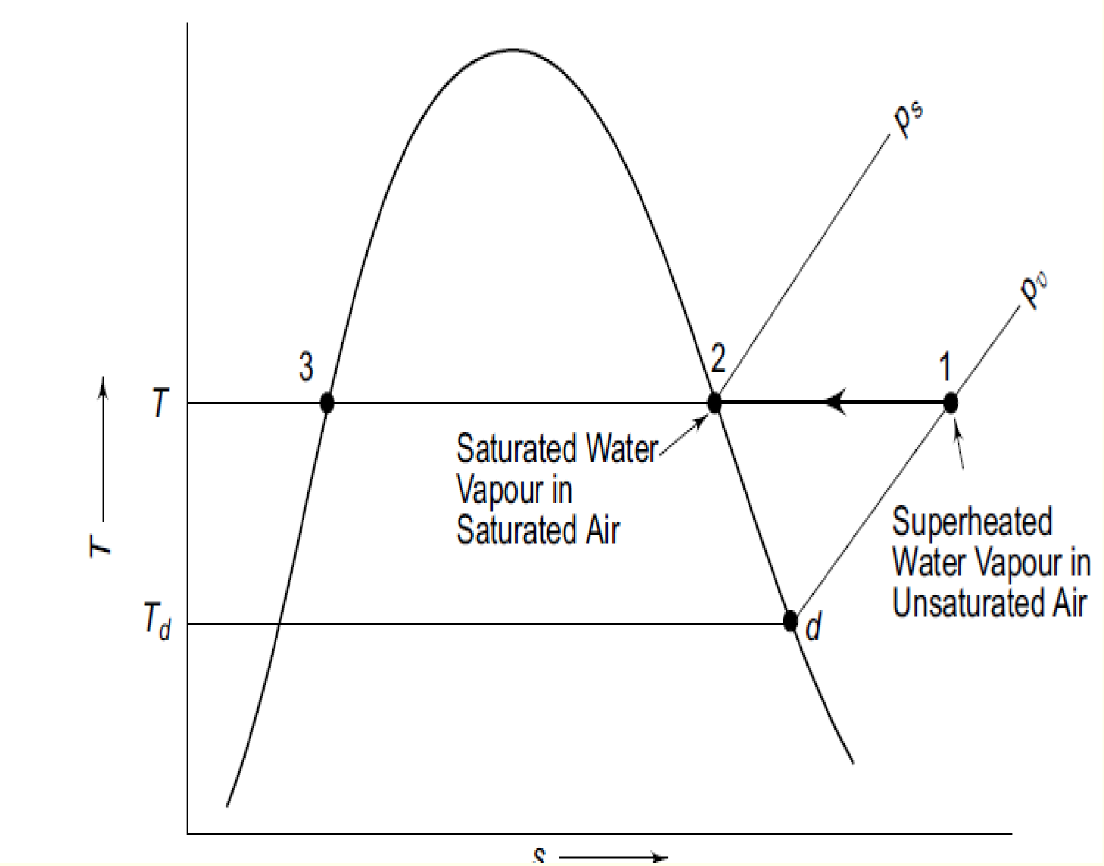


Degree of Saturation

- **Degree of saturation** : It is the ratio of the humidity ratio *w* to the humidity ratio of a saturated mixture w_s, at the same temperature and pressure, i.e.

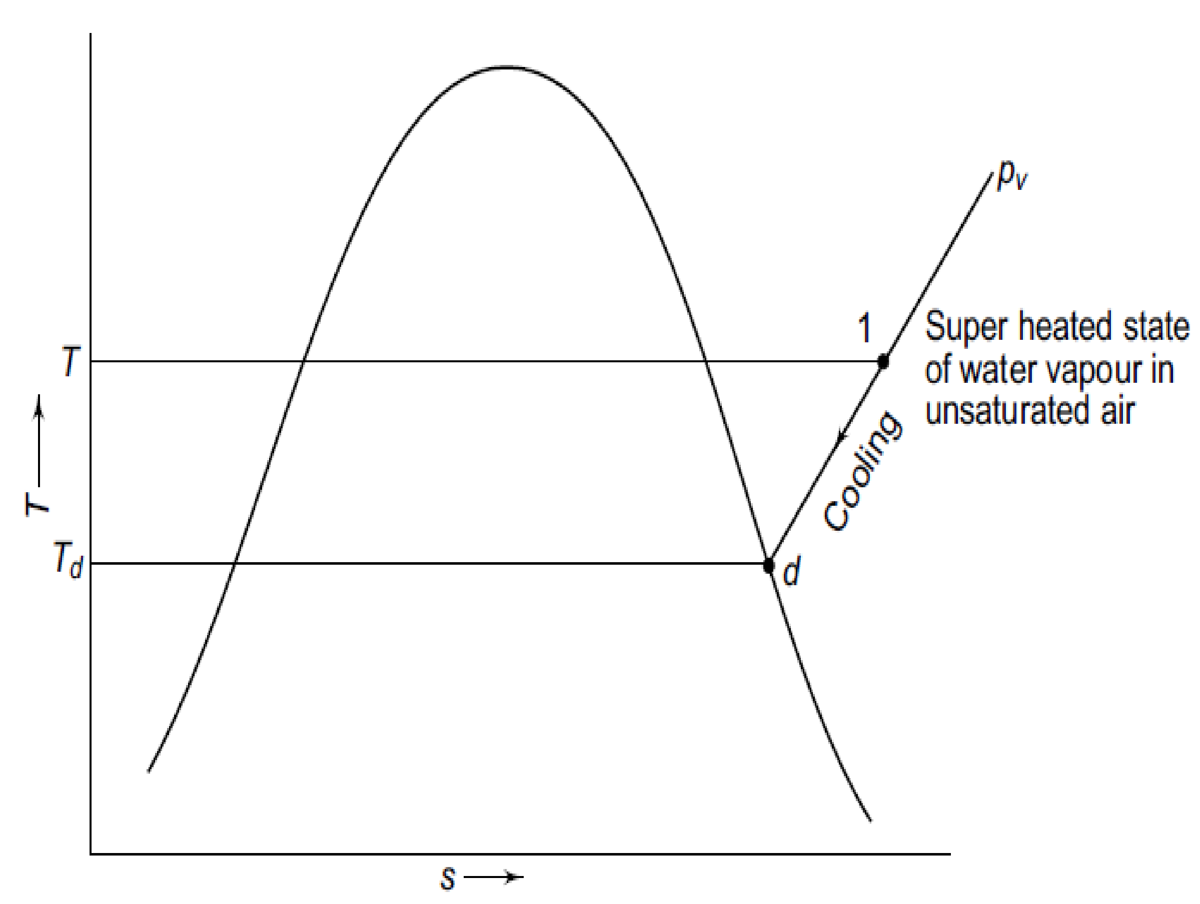
- Value of w_s can be obtained easily from barometric pressure and saturation pressure

$$\mu = \left|\frac{w}{w_s}\right|_{t,p}$$



Dew Point Temperature

- Moist air containing moisture in superheated state considered as unsaturated air.
- Such air cooled to saturation temperature at constant pressure, water vapour will condense in mixture.
- The temperature called dew point temperature(DPT).



Enthalpy

- Enthalpy, h: The enthalpy of moist air is the sum of the enthalpy of the dry air and the enthalpy of the water vapour.

- Reference: Enthalpy of dry air: 0 kJ/kg at 0°C enthalpy of sat.water(liq.): 0 kJ/kg at 0°C

- The enthalpy of moist air is given by: $h = h_a + wh_g = c_p t + w[h_{fg} + c_{pw} t]$

Where C_p and C_{pw} are the specific heats of dry air and water vapour, respectively, t is DBT, W is humidity ratio and h_{fg} latent heat of vaporization at 0°C (=2501 kJ/kg)

Psychrometry

- Substituting approximate values of Cp, Cpw and h_{fg}, we obtain:

$$h=1.005\,t+w(2501+1.88\,t)\ \text{kJ/kg}$$

- Humid specific heat, C_{pm}: From the equation for enthalpy of moist air, the humid specific heat of moist air can be written as:

$$C_{pm}=C_p+w.C_{pw}$$ Where C_{pm} is in kJ/kg dry air.K

- for all practical purposes, C_{pm} can be taken as 1.0216 kJ/kg dry air.K

Enthalpy of Moist Air

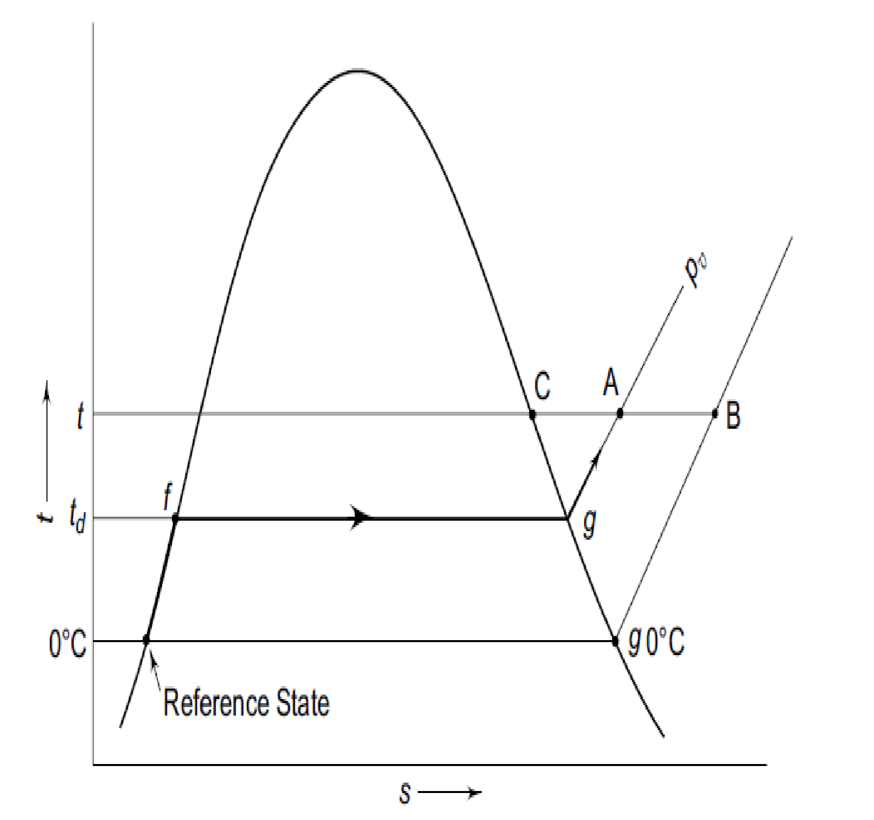
- Taking specific heat of liquid water & water vapour in range 0 to 60 °C

$$h_v = 4.1868\, t_d + \left(h_{fg}\right)_d + 1.88\,(t - t_d)$$

- Enthalpy of water vapour at A determined by two methods

$$h_A = h_C = \left(h_g\right)_t$$

$$h_A = h_B = \left(h_g\right)_{0\,°C} + C_{p_v}(t - 0)$$



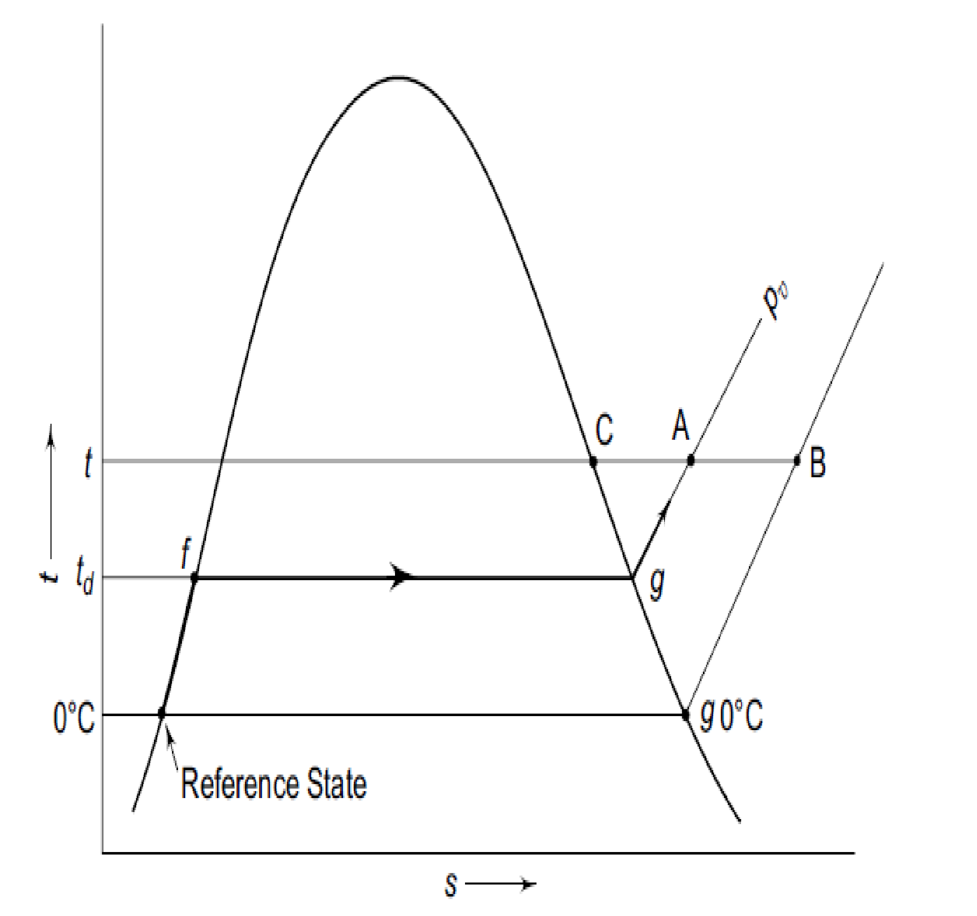
Enthalpy of Moist Air

- Empirical expression for water vapour part

$$h_v = 2501 + 1.88t \, \frac{kJ}{kg}$$

Thus enthalpy of moist air

$$h = 1.005t + \omega(2500 + 1.88t) \, \frac{kj}{kg\ d.a}$$



Humid Specific Heat

- Specific heat of moist air per kg of dry air
- Enthalpy of moist can also written as

$$h = \left(C_{p_a} + \omega C_{p_v}\right)t + \omega\left(h_{fg}\right)_{0\,^\circ C} = C_p t + \ \omega\left(h_{fg}\right)_{0\,^\circ C}$$

- Where $C_p = C_{p_a} + \omega C_{p_v} = (1.005 + 1.88\omega) \quad \frac{kJ}{kg\ d.a.K}$

Psychrometric Properties

From the ideal gas relations, relative humidity can be expressed as

$$\phi = \frac{x_w}{x_{w,sat}} = \frac{P_w}{P_{w,sat}}$$

x_w -- the mole fraction of the water vapor in moist air;

$x_{w,sat}$ -- mole fraction of water vapor in a saturated moist air at the same temperature;

5) Humidity ratio (Moisture Content) ω:

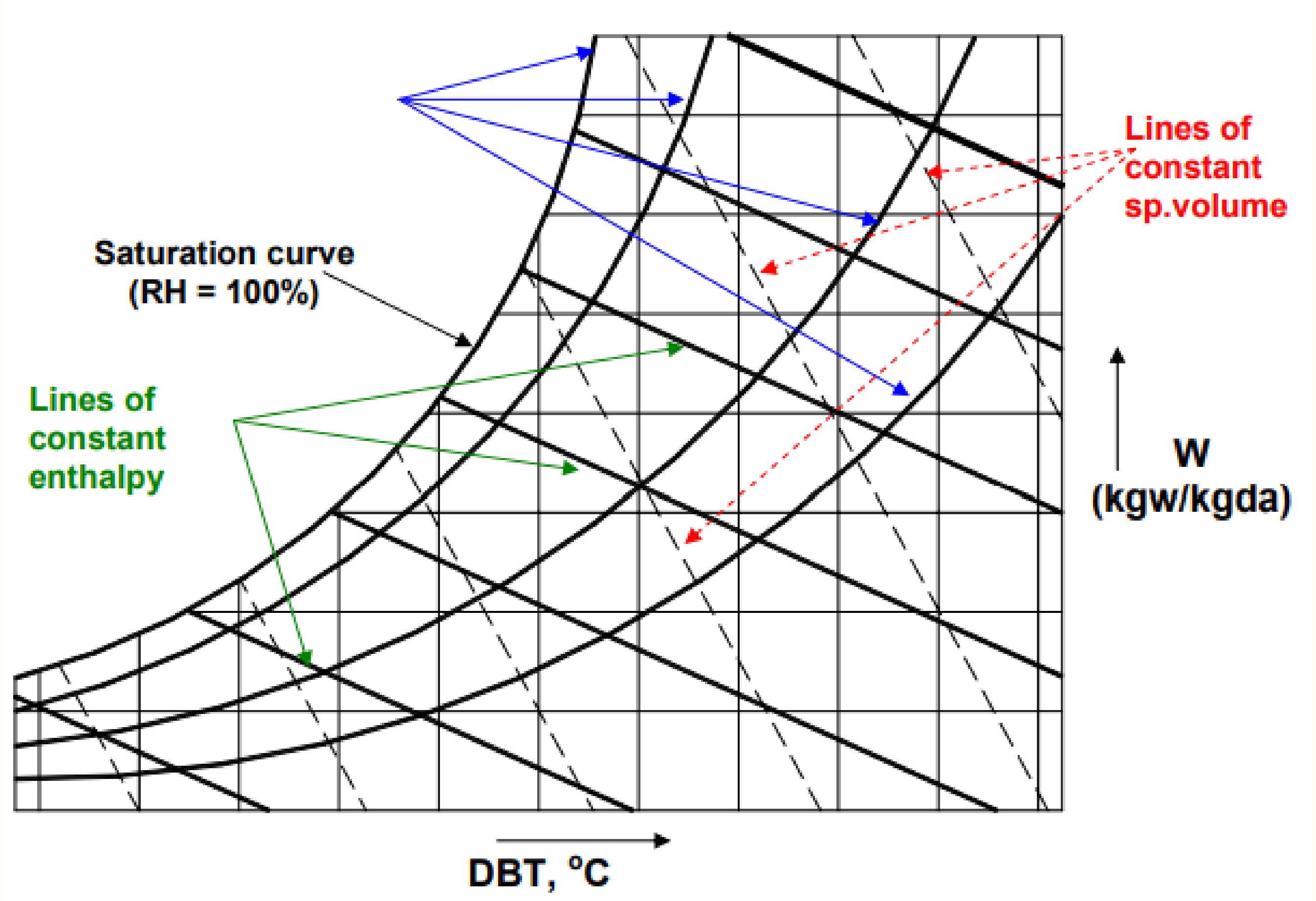
- The humidity ratio is the mass *kg* of water vapor interspersed in each *kg* of dry air.
- It should be noted that the mass of water refers only to the moisture in actual vapor state, and not to any moisture in the liquid state, such as dew, frost, fog or rain.
- The humididy ratio, like other several properties to be studied-enthalpy and specific volume-is based on 1 *kg* of dry air.

$$\omega = \frac{Kg \text{ of water}}{Kg \text{ of dry air}} = \frac{P_v V / R_v}{P_a V / R_a T}$$

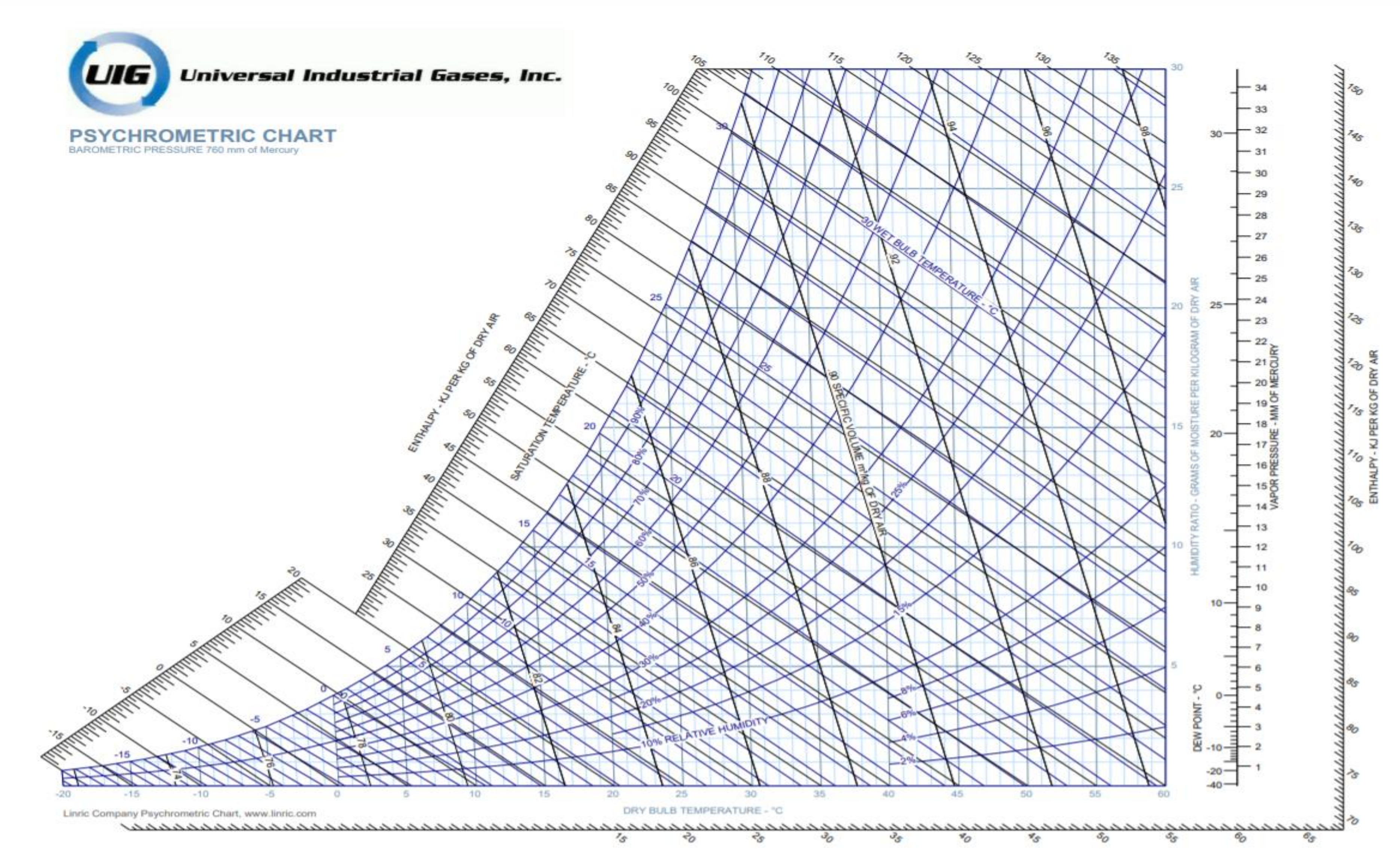
Psychrometric Chart

- A **Psychrometric chart** graphically represents the thermodynamic properties of moist air.
- Standard psychrometric charts are bounded by the DBT line (abscissa) and the vapour pressure or humidity ratio (ordinate).
- The Left Hand Side of the psychrometric chart is bounded by the saturation line.
- Using the psychrometric relations, one can construct psychrometric charts.
- Psychrometric charts are very useful in the analysis of air-conditioning systems.

Psychrometric Chart



Psychrometric chart for constant Barometric pressure


Universal Industrial Gases, Inc.
PSYCHROMETRIC CHART
BAROMETRIC PRESSURE 760 mm of Mercury
ENTHALPY - KJ PER KG OF DRY AIR
SATURATION TEMPERATURE - °C
WET BULB TEMPERATURE - °C
SPECIFIC VOLUME m³/kg OF DRY AIR
10% RELATIVE HUMIDITY
HUMIDITY RATIO - GRAMS OF MOISTURE PER KILOGRAM OF DRY AIR
VAPOR PRESSURE - MM OF MERCURY
DEW POINT - °C
DRY BULB TEMPERATURE - °C
Linric Company Psychrometric Chart, www.linric.com

DBT and WBT

- Based on Gibbs phase rule, the thermodynamic state for moist air is uniquely fixed if the barometric pressure and two other independent properties are known.

- At a given barometric pressure, the state of moist air can be determined by measuring any two independent properties.

- One of them could be the dry-bulb temperature, as the measurement of temperature is fairly simple and accurate.

DBT and WBT

- Accurate measurement of other independent parameters such as humidity ratio is very difficult in practice.

- Since measurement of temperatures is easier, would be convenient if the other independent parameter is also a temperature.

- Accurate measurement of dew-point temperature is difficult.

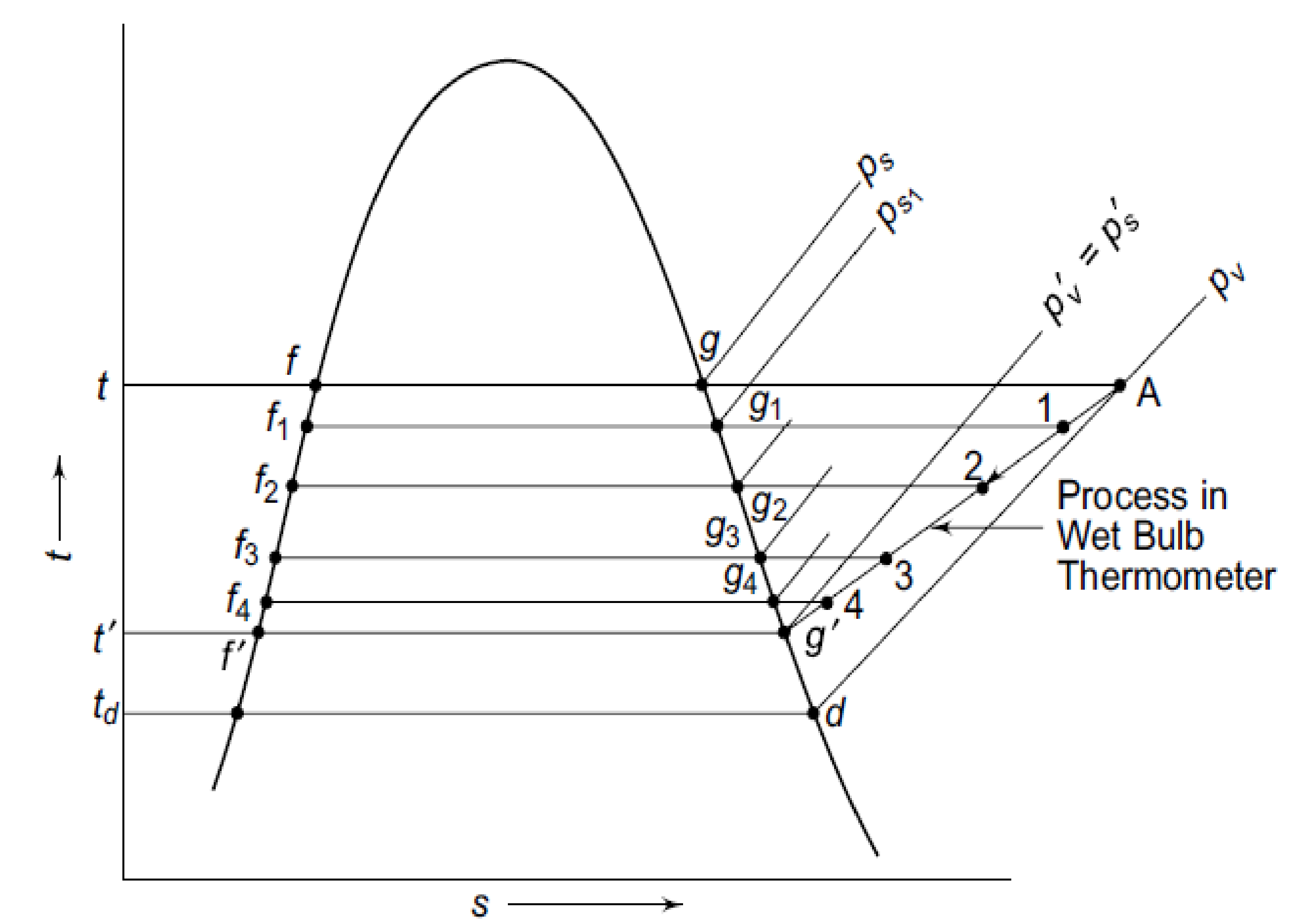
- Hence, a new independent temperature parameter, the wet-bulb temperature is conceptualized.

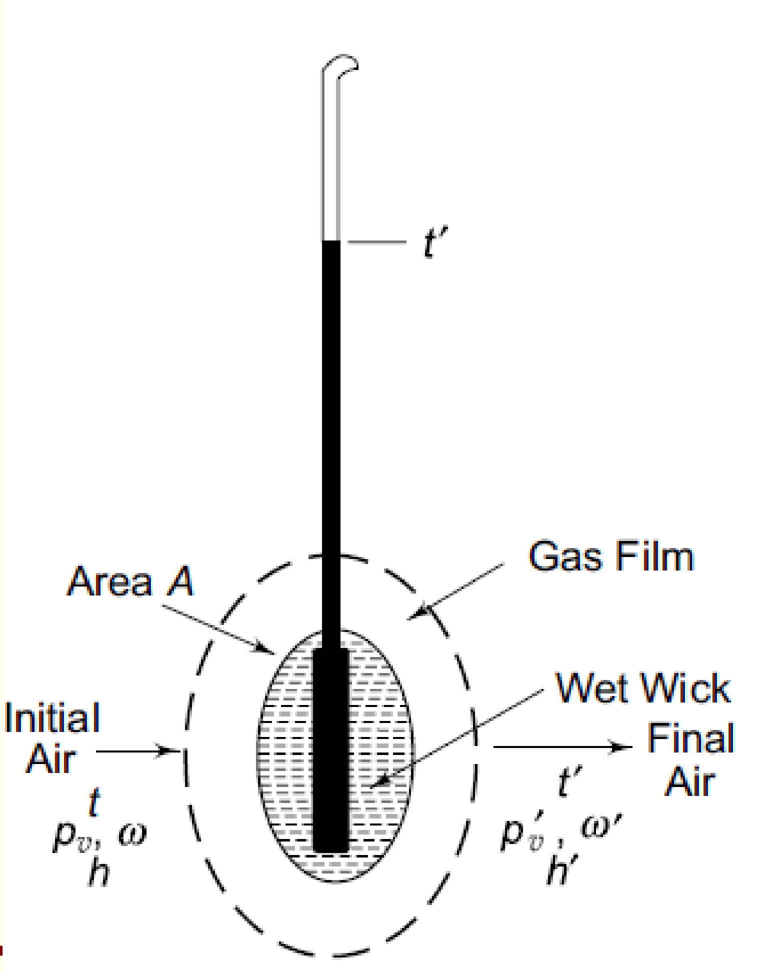
- Compared to DBT, it is easier to measure the wet-bulb temperature of moist air

Wet bulb temperature

- Psychrometer consists of dry bulb thermometer (DBT) & Wet bulb thermometer (WBT).
- Dry bulb thermometer directly exposed to air & measure actual temperature.
- Wet bulb thermometer – bulb covered with wick which wetted thoroughly.
- Temperature measured by wick indicates temperature of liquid-water in wick.
- This temperature called **wet bulb temperature.**

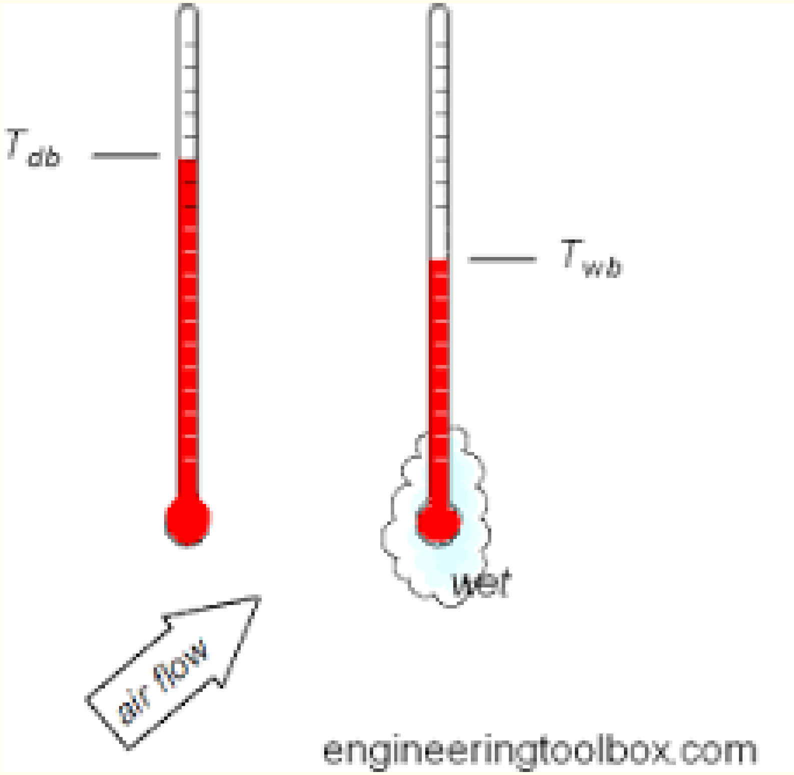
Wet bulb temperature





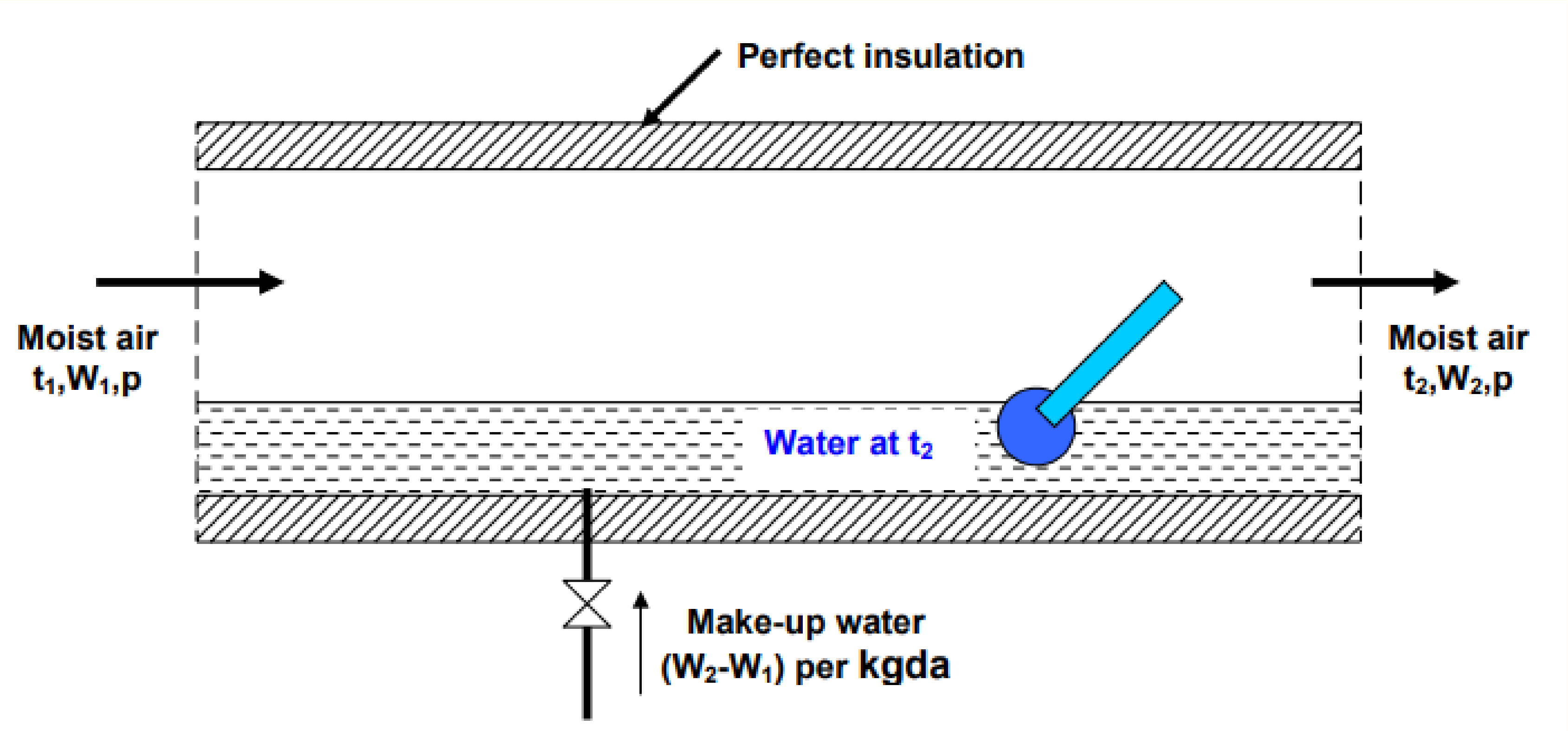
WBT

- Wet bulb temperature is the **lowest temperature to which air can be cooled** by the evaporation of water into the air at a constant pressure.



The warm air in contact with cold wetted surface cools and dehumidifies

Temperature of Adiabatic saturation



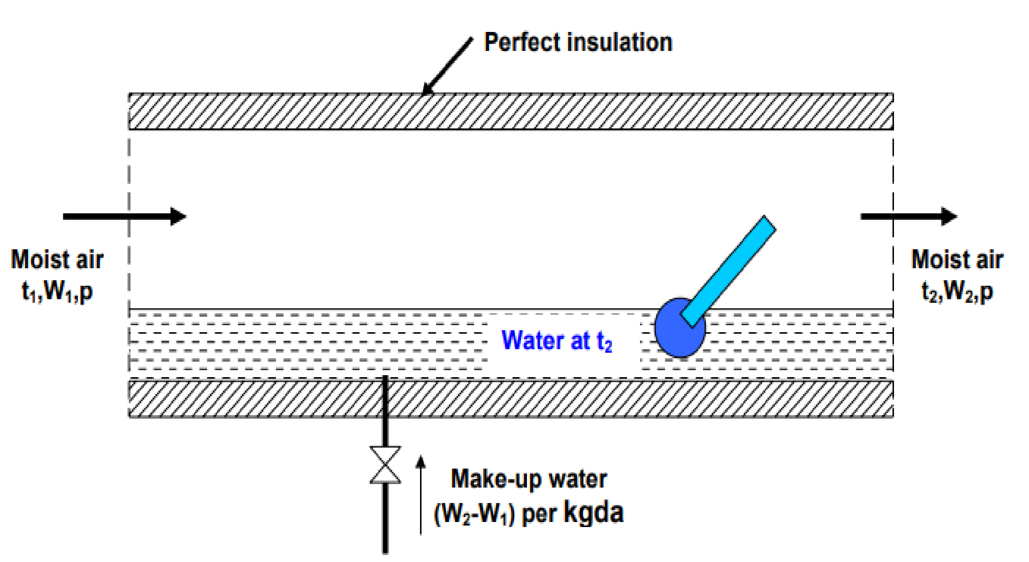
Adiabatic Saturator

Adiabatic saturation and Thermodynamic wet bulb temperature

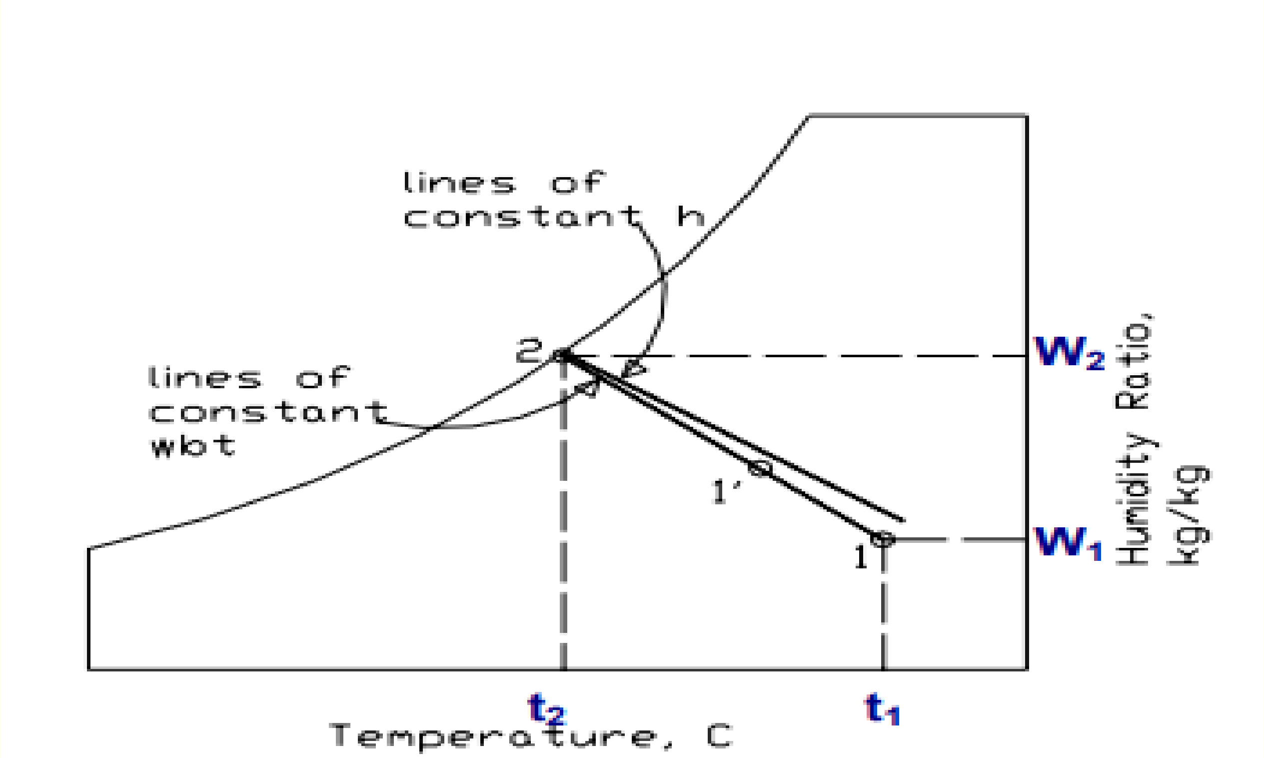
- Adiabatic saturation temperature is defined as that temperature at which water, by evaporating into air, can bring the air to saturation at the same temperature adiabatically.

- An adiabatic saturator is a device using which one can measure theoretically the adiabatic saturation temperature of air.

- At steady-state condition, the temperature indicated by the thermometer immersed in the sump is the thermodynamic wet-bulb temperature



Constant WBT line



The difference between actual enthalpy and the enthalpy obtained by following constant wet-bulb temperature is equal to $(W_2\text{-}W_1)h_f$

A line passing through all these points is a constant wet bulb temperature line. Thus all inlet conditions that result in the same sump temperature, for example point 1' have the same wet bulb temperature. The line is a straight line according to the straight-line law. The straight-line joining 1 and 2 represents the path of the air as it passes through the adiabatic saturator.

Normally lines of constant wet bulb temperature are shown on the psychrometric chart. The difference between actual enthalpy and the enthalpy obtained by following constant wet-bulb temperature is equal to $(\omega_2 - \omega_1)h_f$.

Psychrometry

- The thermodynamic wet bulb temperature will be less than the entering air DBT but greater than the dew point temperature.

- DBT, WBT and DPT will be same when the air is saturated.

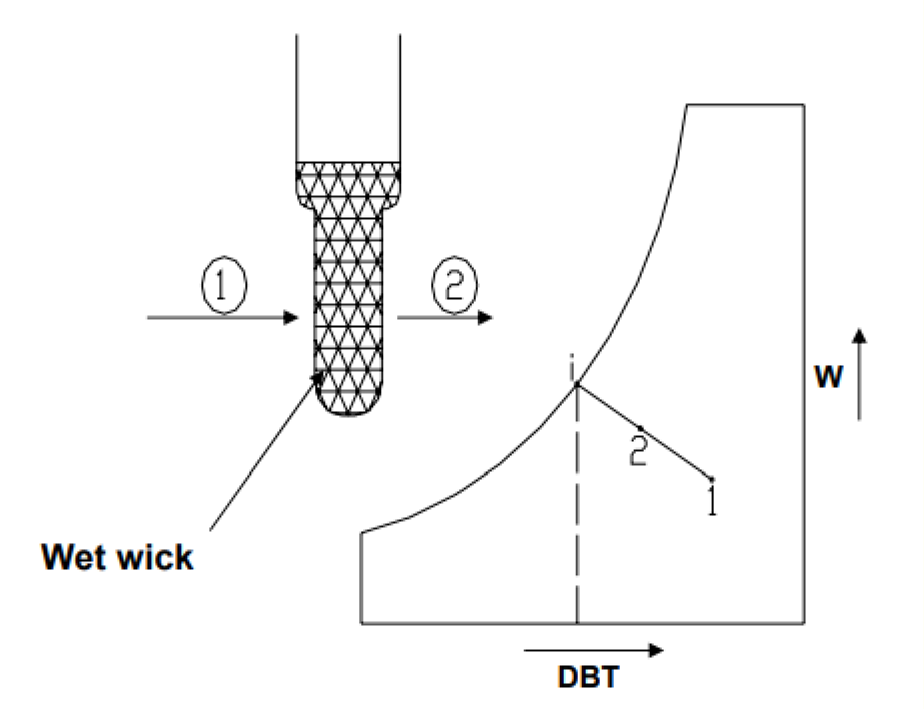
- Normally lines of constant wet bulb temperature are shown on the psychrometric chart.

- The difference between actual enthalpy and the enthalpy obtained by following constant wet-bulb temperature is equal to $(W_2-W_1)h_f$

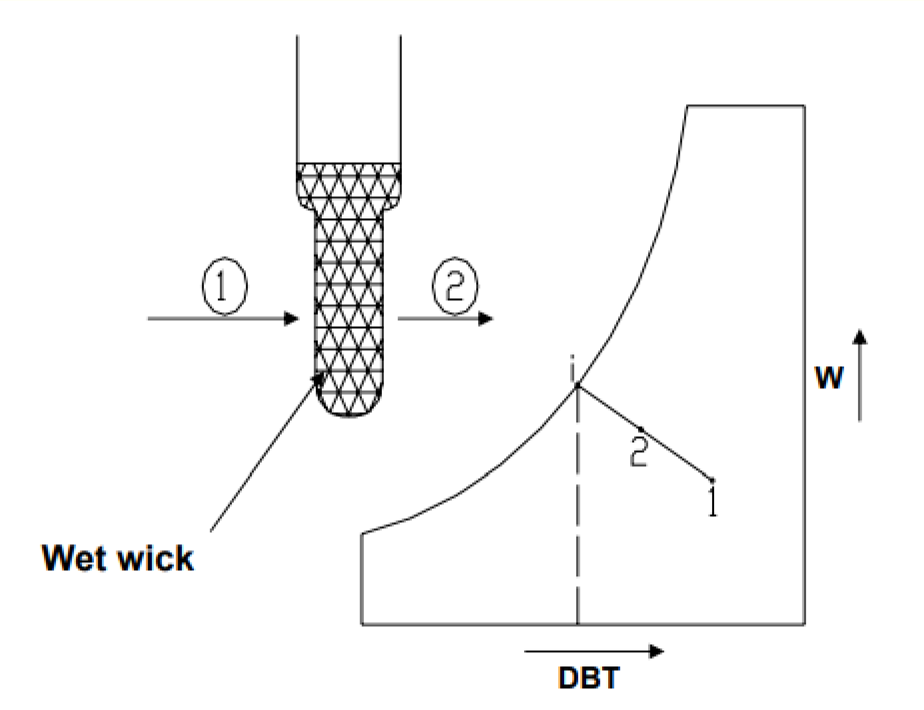
Wet-Bulb Thermometer

- In practice, it is not convenient to measure the wet-bulb temperature using an adiabatic saturator.

- In stead, a thermometer with a wetted wick is used to measure the wet bulb temperature.



Wet Bulb Thermometer



- It can be observed that since the area of the wet bulb is finite, the state of air at the exit of the wet bulb will not be saturated.
- Instead it will be point 2 on the straight line joining 1 and i, provided the temperature of water on the wet bulb is t1.

Temperature of Adiabatic Saturation

- $t_2 = f(t_1, W_1)$ is not a unique function, in the sense that there can be several combinations of t, and W, which can result in the same sump temperature in the adiabatic saturator.

- Thus all inlet conditions that result in the same sump temperature, have the same wet bulb temperature.

- A line passing through all these points is a constant wet bulb temperature line.

- The line 1-2 is a straight line as per the straight-line law, and represents the path of the air as it passes through the adiabatic saturator.

WBT

- From energy balance across the wet-bulb, the temperature measured by the wet-bulb thermometer is:

$$t_2 = t_1 - (k_w/h_c)h_{fg}(w_i - w);$$

- Where k_w is the mass transfer coefficient.
- From the expression for thermodynamic WBT; $t_2 = t_1 - \frac{h_{fg,2}}{C_{pm}}(w_2 - w_1)$
- For air-water mixtures, the ratio ($h_c/k_w C_{pm}$)= Lewis number is =1, hence, the wick temperature is approximately equal to the thermodynamic WBT

WBT

- It should be noted that, unlike thermodynamic WBT, the WBT of wet bulb thermometer is not a thermodynamic property as it depends upon the rates of heat and mass transfer between the wick and air.
- Precautions have to be taken while measuring WBT using wet bulb thermometer, for example:

1. The wick should always be clean and wet
2. Air around the bulb should not be stagnant.
3. Water used should have a temperature closer to WBT, or sufficient time must be allowed for steady state.
4. Radiation shields may be required to reduce errors due to radiation etc.

AST and WBT

- AST is the maximun limit upto which temperature of water can be lowered by evaporation at any given dry bulb temperature and pressure in adiabatic conditions.

- When AST is reached air becomes saturated with water while when WBT is reached there is no considerable change in the humidity of air.

- WBT is the maximum limit upto which the temperature of water can be lowered by evaporation in open.
- The wet bulb temperature is **always lower than the dry bulb temperature** but will be identical with 100% relative humidity (the air is at the saturation line).

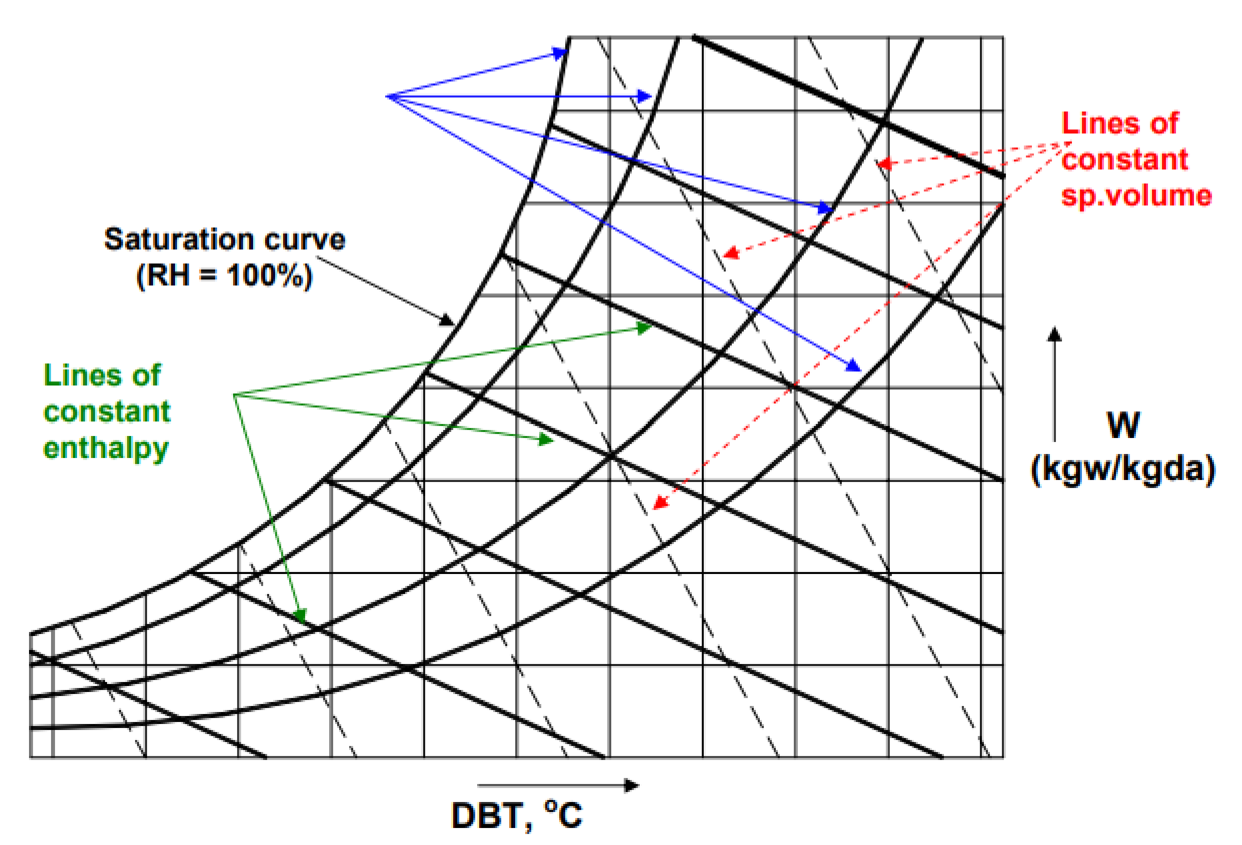
- AST is the equilibrium Temperature while the WBT is the steady state temperature.

- A wet-bulb temperature of 31°C is exceedingly harmful to humans, while a temperature of 35°C is unsurvivable for more than 6 hours.

Psychrometry

- It has been shown by Carrier, that this is a valid assumption for air-water mixtures.
- Hence for air-water mixtures, one can assume that the temperature measured by the wet bulb the thermometer is equal to the thermodynamic wet-bulb temperature.
- For other gas-vapor mixtures, there can be appreciable difference between thermodynamic and actual wet-bulb temperatures.
- An instrument used for measuring the psychrometric state of air is called a psychrometer.

Psychrometry Processes



Tutorial-1

Example 14.3 *A mixture of dry air and water vapour is at a temperature of 21°C under a total pressure of 736 mm Hg. The dew-point temperature is 15°C. Find:*

(i) *Partial pressure of water vapour.*
(ii) *Relative humidity.*
(iii) *Specific humidity.*
(iv) *Specific enthalpy of water vapour by the three methods of Fig. 14.5.*
(v) *Enthalpy of air per kg of dry air.*
(vi) *Specific volume of air per kg of dry air.*