UNIT – 2

Psychrometry

Contents

Important Repeated Questions:

1. **Explain Dalton's law of partial pressure.**
   (S25 - Q2a, 03 marks) (W22 - Q2a, 03 marks) (S22 - Q1a) (W23 - Q3b, 04 marks)
2. **Define/Explain the following: (i) Dew point temperature (ii) Relative humidity (iii) Wet bulb temperature.**
   (S25 - Q5a, 03 marks) (S24 - Q1c) (W24 - Q1c) (S23 - Q1b, 04 marks) (W22 - Q1a, 03 marks) (S22 - Q3b, 04 marks)
3. **What is Psychometric chart? Explain the measurement of different lines on it.**
   (S25 - Q4c, 07 marks) (W22 - Q1c)

Legends: W- Winter, S- Summer, Q- Question and 03/04/07- Marks of Question

2.1 Introduction to Psychrometry

The *atmospheric air* makes up the environment in almost every type of air conditioning system.

"Atmospheric air is a mixture of many gases plus water vapour and a number of pollutants."

The amount of water vapour and pollutants vary from place to place & the concentration of water vapour and pollutants decrease with altitude.

Hence a thorough understanding of the properties of atmospheric air and the ability to analyze various processes involving air is fundamental to air conditioning design.

Following terms are worthwhile to introduce psychrometry:

2.1.1 Psychrometry

▶ "The **psychrometry** is the branch of engineering science which deals with the study of the properties of mixtures of dry air and water vapour."

▶ It includes the study of behavior of dry air and water vapour mixture under various sets of conditions.

2.1.2 Dry Air

▶ "The **Dry air** is the mixture of a number of gases".

▶ The gases are nitrogen, oxygen, carbon dioxide, argon, neon, and helium etc."

▶ Above an altitude of about 10 km, atmospheric air consists of only dry air.

▶ In 1949, a standard composition of dry air was fixed by the International Joint Committee on Psychrometric data as given below:

Table 2.1 Composition of standard 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 the above composition; the molecular weight of dry air is **28.966** and the gas constant R is **287.035** J/kg K.

2.1.3 Moist Air

▶ "The **Moist air** is a mixture of dry air and water vapour."

▶ The pollutants have to be filtered out before processing the air; Hence, what we process is essentially a mixture of various gases that constitute air and water vapour.

▶ For all practical purposes, the composition of dry air is constant.

▶ But the amount of water vapour present in the air may vary from **zero to a maximum** depending upon the temperature and pressure of the mixture (dry air + water vapour).

2.1.4 Dalton's Law of Partial Pressures

▶ It states that, "The total pressure exerted by the mixture of air and water vapour is equal to the sum of the pressures, which each constituent would exert, if it alone occupied the same volume at same temperature."

▶ The **total pressure** exerted by air and water vapour mixture is equal to the barometric pressure.

▶ Mathematically, barometric pressure of the mixture is,

$$p_b = p_a + p_v \qquad \qquad Eq.\ (2.1)$$

Where p_a = Partial pressure of dry air

p_v = Partial pressure of water vapour

▶ Barometric pressure can be measured with the help of instrument called **barometer**; its value is 1.01325 bar (760 mm of Hg) at sea level.

2.1.5 Saturated Air

▶ "The saturated air is a mixture of dry air and water vapour, when the air holds the maximum amount of water vapour into it."

▶ When the partial pressure of water vapour (p_v) is equal to the saturation pressure (p_s) of the water vapour at dry bulb temperature of mixture; then the air will be saturated air.

▶ At a given temperature and pressure the dry air can only hold a certain maximum amount of moisture.

▶ When the moisture content is maximum, then the air becomes saturated, which is established by a neutral equilibrium between the moist air and the liquid or solid phases of water.

▶ For calculation purposes, the molecular weight of water vapour is taken as 18.015 and its gas constant is 461.52 J/kg K.

▶ The water vapour, usually, occur in the form superheated steam as an invisible gas.

▶ When the saturated air is cooled, the water vapor in the air starts condensing, and it is visible in the form of moist, fog or condensate on cold surfaces.

▶ For saturated air DBT, WBT and DPT are same and RH is 100%.

2.2 Psychrometric Properties

Various important psychrometric properties are discussed in detail as below:

2.2.1 Dry Bulb Temperature

▶ "It is the temperature of air measured by a thermometer, when it is not affected by the moisture present in the air."

▶ It is briefly written as DBT and denoted by t_d or t_{db}.

2.2.2 Wet Bulb Temperature

▶ "It is the temperature of air measured by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air."

▶ It is briefly written as WBT and denoted by t_w or t_{wb}.

2.2.3 Wet Bulb Depression

▶ "It is the difference between dry bulb temperature (t_d) and wet bulb temperature (t_w) of air".

▶ The wet bulb depression is useful to determine the relative humidity of the air.

2.2.4 Dew Point Temperature

▶ "It is the temperature of air measured by a thermometer, when the moisture (water vapour) present in it begins to condense."

▶ It is the saturation temperature (t_{sat}) corresponding to the partial pressure of water vapour (p_v).

▶ It is briefly written as DPT and denoted by t_{dp}.

2.2.5 Dew Point Depression

▶ "It is the difference between the dry bulb temperature (t_d) and dew point temperature of air (t_{dp})."

2.2.6 Pressure of Water Vapour

▶ According to Carrier's equation, the partial pressure of water vapour,

$$p_v = p_w - \frac{(p_b - p_w)(t_d - t_w)}{1544 - 1.44 t_w} \qquad Eq.\ (2.2)$$

Where, p_w = Saturation pressure corresponding to WBT (from steam table)

p_b = Barometric pressure (bar)

t_d = Dry bulb temperature (^{0}C)

t_w = Wet bulb temperature (^{0}C)

▶ The partial pressure of water vapour can be determine from psychrometric chart if any two properties of moist air are known.

2.2.7 Specific Humidity (Humidity Ratio OR Moisture Content)

▶ "It is the mass of water vapour present in 1 kg of dry air."

▶ It is expressed in terms g/kg of dry air & denoted by 'W'.

▶ Let p_a, v_a, T_a, m_a and R_a = Pressure, volume, temperature, mass and gas constant for dry air respectively, and

p_v, v_v, T_v, m_v and R_v = Corresponding values for the water vapour respectively.

▶ Assuming that the dry air and water vapour behave as perfect gases,

For dry air, $\quad p_a v_a = m_a R_a T_a \qquad$ Eq. (2.3)

For water vapour, $p_v v_v = m_v R_v T_v \qquad$ Eq. (2.4)

But $v_a = v_v$ and $T_a = T_v$ according to Dalton's law From

equation (2.3) and (2.4) we have,

$$\frac{p_v}{p_a} = \frac{m_v R_v}{m_a R_a}$$

Specific humidity, $\qquad W = \frac{m_v}{m_a} = \frac{R_a p_v}{R_v p_a}$

- By substituting $R_a \simeq 0.287 kJ/kgK$ and $R_v \simeq 0.461 kJ/kgK$ in above equation,

$$W \simeq \frac{0.287 \square p_v}{0.461 \square p_a} \simeq 0.622 \square \frac{p_v}{p_a}$$

$$W = 0.622 \frac{p_v}{p_b - p_v} \qquad \text{Eq. (2.5)}$$

- Consider **unsaturated air** containing superheated vapour at dry bulb temperature (t_d) and partial pressure (p_v) *as* shown by point '*A*' on the T-s diagram in Fig. 2.1.
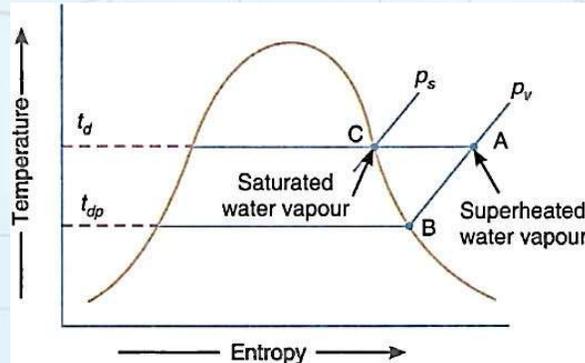

Fig.2.1 – T-s diagram

- If water is added into this unsaturated air, the water will evaporate & increase the moisture content of air and the partial pressure (p_v) also increases.

- This process will continue until the air becomes saturated at the same dry bulb temperature (t_d) as shown by point 'C' and there will be more evaporation of water.

- The partial pressure (p_v) increases to the saturation pressure (p_s) and it is maximum partial pressure of water vapour at temperature (t_d).

- The air containing moisture in at state of point 'C' is called saturated air.

- For saturated air; the maximum specific humidity is,

$$W_s \square W_{max} \square 0.622 \square \frac{p_s}{p_a} \square 0.622 \square \frac{p_s}{p_b \square p_s} \qquad \text{Eq. (2.6)}$$

Where, p_s = Partial pressure of air corresponding to saturation temperature or dry bulb temperature (t_d) obtained from steam table.

2.2.8 Degree of Saturation (% Humidity)

- "The Degree of Saturation is the ratio of actual mass of water vapour in a unit mass of dry air to the mass of water vapour in the same mass of dry air when it is saturated at the same dry bulb temperature."

OR

- "It is the ratio of the actual humidity ratio (W) to the humidity ratio of a saturated air (W_s) at the same dry bulb temperature."

- It is denoted by 'μ' and expressed in terms of percentage.

- Mathematically it is written as,

$$\frac{W}{W_s} = \frac{0.622 \dfrac{p_v}{p_b - p}}{0.622 \dfrac{p_s}{p_b - p_s}} = \frac{p_v}{p_s} \cdot \frac{p_b - p_s}{p_b - p_v} = \frac{p_v}{p_s} \cdot \frac{1 - \dfrac{p_s}{p_b}}{1 - \dfrac{p_v}{p_b}}$$

<div align="right">*Eq. (2.7)*</div>

2.2.9 Absolute Humidity (Vapour Density)

▶ "It is the mass of water vapour present in 1 m^3 of dry air"

▶ It is expressed in terms of g/m^3 of dry air and it is detonated by ρ_v.

▶ Let v_v = Volume of water vapour in m^3/kg of dry air at its partial pressure,

v_a = Volume of dry air in m^3/kg of dry air at its partial pressure,

ρ_v = Density of water vapour in kg/m^3 corresponding to its partial pressure and dry bulb temperature t$_d$, and

ρ_a = Density of dry air in kg/m^3 of dry air

▶ The mass of water vapour is given by,

$$m_v = v_v \cdot \rho_v$$

<div align="right">*Eq. (2.8)*</div>

And the mass of dry air is given by,

$$m_a = v_a \cdot \rho_a$$

<div align="right">*Eq. (2.9)*</div>

Dividing equation (2.8) by equation (2.9),

$$\frac{m_v}{m_a} = \frac{v_v \cdot \rho_v}{v_a \cdot \rho_a}$$

Since $v_a = v_v$; thus specific humidity,

$$W = \frac{m_v}{m_a} = \frac{\rho_v}{\rho_a}$$

$$\rho_v = W \cdot \rho_a$$

<div align="right">*Eq. (2.10)*</div>

We know that $p_a v_a = m_a R_a T_d$ $\left[\because v_a = \dfrac{1}{\rho_a} \text{ and } m_a = 1kg \right]$

$$p_a \cdot \frac{1}{\rho_a} = R_a T_d$$

$$\rho_a = \frac{p_a}{R_a T_d}$$

Substituting the value of ρ_a in equation (2.10), we get

$$R_a = \text{Gas constant for air} = 287 \text{ J/ kg K, and}$$

$$T_d = \text{Dry bulb temperature in K}$$

2.2.10 Relative Humidity

▶ "The Relative humidity 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 dry bulb temperature."

▶ It is briefly written as RH; denoted by 'φ' and expressed in terms of percentage.

▶ Let p_v, v_v, T_v, m_v and R_v ⬜ Pressure, volume, temperature, mass and gas constant for water vapour respectively in actual conditions,

p_s, v_s, T_s, m_s and R_s ⬜ Corresponding values for water vapour in saturated air Assuming that

the dry air and water vapour behave as perfect gases,

For water vapour in actual conditions,

$$p_v v_v \ \Box \ m_v R_v T_v \qquad\qquad Eq. (2.12)$$

Similarly, for water vapour in saturated conditions,

$$p_s v_s \ \Box \ m_s R_s T_s \qquad\qquad Eq. (2.13)$$

According to definition,

$$v_a \ \Box \ v_v \text{ and } T_a \ \Box \ T_v \ \Box \ T_d \text{ and } R_v \ \Box \ R_s \ \Box \ 0.461 kJ / kgK$$

From equation (2.12) and (2.13) we have,

$$Eq. (2.14)$$

$$\Box \ \Box \ \frac{m_v}{m_s} \ \Box \ \frac{p_v}{p_s}$$

▶ "The *relative humidity* is also the ratio of *actual partial pressure* of water vapour (p_v) in a given volume of moist air at a given temperature to the *saturation pressure* of water vapour (p_s) at the same temperature."

2.2.10.1 Relation Between Relative Humidity and Degree of Saturation

$$\Box \ \Box \ \frac{p_v}{p_s} \ \Box \ p_b \ \Box \ \frac{p_b}{p_v} \ \frac{s}{\Box} \ \Box \ \Box \ \Box \ \frac{1 \ \Box \ \frac{p_s}{p}}{1 \ \Box \ \Box \ \Box \ \frac{b}{p_b} p_s} \ \Box$$

$$\Box \ \Box \ \frac{\Box}{1 \ \Box \ \Box 1 \ \Box \ \Box \ \Box \ \frac{p_s}{p_b}} \qquad\qquad Eq. (2.15)$$

2.2.10.2 Psychrometers

▶ It is the instrument used to *determine the RH* of a moist air by measuring its DBT and WBT is known as psychrometer.

▶ There are two types of psychrometer are used: (i) sling type psychrometer (as shown in Fig. 2.2) and (ii) aspirator type psychrometer.
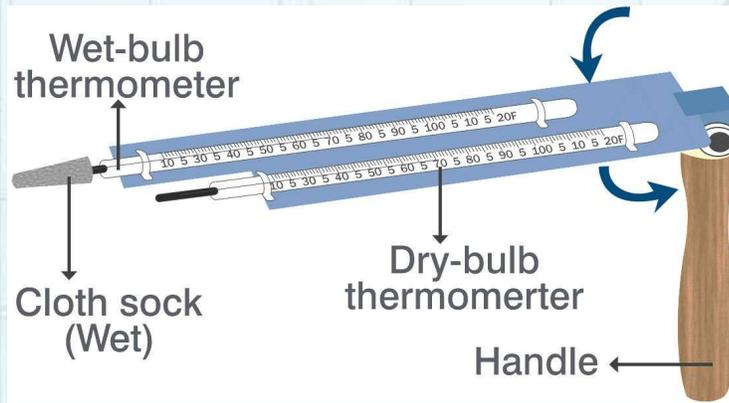
Fig.2.2 – Sling type psychrometer

▶ The Hygrometer is also use to measure relative humidity of air.

2.2.11 Specific Volume (Humid Volume)

▶ "The specific volume is defined as the m³ of moist air per kg of dry air".

▶ It is expressed in terms of **m³/kg of dry air** and it is detonated by 'v'.

▶ It can be determine by,

$$v = \frac{R_a T_d}{p_a} = \frac{R_a T_d}{p_b - p_v}; \frac{m^3}{kg}$$

Eq. (2.16)

2.2.12 Enthalpy of Moist Air

▶ "The enthalpy is the sum of the enthalpy of dry air and enthalpy of the water vapour in moist air."

▶ It is denoted by 'h' and expressed in terms of kJ/kg of most air

▶ Mathematically it is given by,

$$h = 1.005t_d + W[2500 + 1.9t_d]$$

Eq. (2.17)

Where W = Specific humidity (kg/kg of dry air)

        t_d = Dry bulb temperature (^{0}C)

2.3 Psychrometric Chart

▶ "It is a graphical representation of the various thermodynamic properties of moist air."

▶ It is very useful for finding out the properties of air in the field of air conditioning and eliminates lot of calculations.

▶ It is normally drawn for standard atmospheric pressure of 760 mm of Hg (or 1.01325 bar).

▶ In a psychrometric chart, dry bulb temperature is taken as abscissa and specific humidity as an ordinate, as shown in Fig. 2.3.

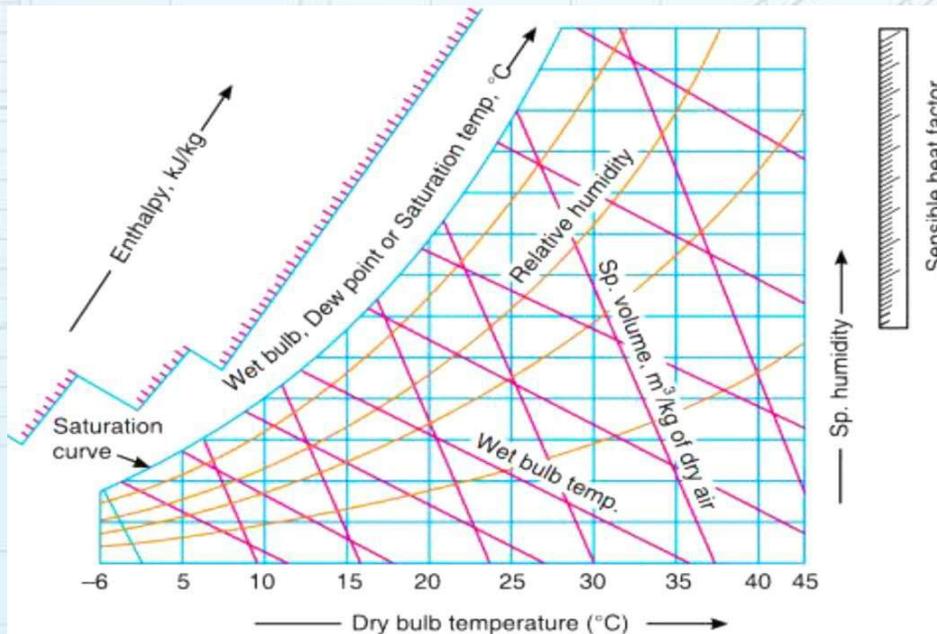▶ The saturation curve is drawn by plotting the various saturation points at corresponding dry bulb temperatures.

Fig.2.3 – Psychrometric chart

▶ Important lines on psychrometric chart are as under:

  ◻ Dry bulb temperature lines

  ◻ Specific humidity lines

  ◻ Dew point temperature lines

  ◻ Wet bulb temperature lines

  ◻ Enthalpy lines

  ◻ Specific volume lines

  ◻ Relative humidity curves

2.4 Psychrometric Processes

▶ The various psychrometric processes involved in air conditioning are as under:
  1) Sensible heating
  2) Sensible cooling
  3) Humidification
  4) Dehumidification
  5) Cooling and dehumidification
  6) Cooling and humidification (adiabatic saturation or evaporative cooling)
  7) Heating and humidification
  8) Heating and dehumidification (chemical dehumidification)

▶ Each psychrometric process is discussed in detail as below:

2.4.1 Sensible Heating

▶ "The heating of air, without any change in its specific humidity (moisture content) is known as sensible heating."

▶ Let,

t_{d1} = Dry bulb temperature of air entering the heating coil W_1 =

Specific humidity of air entering the heating coil

t_{d2} = Dry bulb temperature of air leaving the heating coil W_2 =

Specific humidity of air leaving the heating coil

t_{d3} = Surface temperature of the heating coil

▶ Let the air at temperature t_{d1} passes over a heating coil of temperature t_{d3} as shown in Fig. 2.4.

▶ The process of sensible heating on the psychrometric chart is shown by a **horizontal line 1-2** extending from left to right.
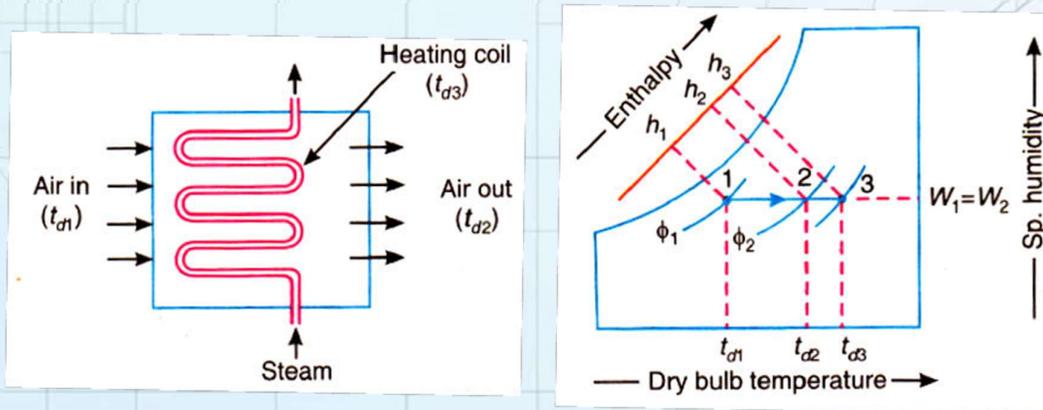
Fig.2.4 – Sensible heating process

▶ During sensible heating process (from psychrometric chart):

  ☐ Dry bulb temperature increases from t_{d1} to t_{d2}

  ☐ Dew point temperature remains constant

  ☐ Enthalpy increases from h_1 to h_2

  ☐ Specific humidity remains constant ($W_1 = W_2$)

  ☐ Relative humidity reduces from ϕ_1 to ϕ_2

▶ The amount of heat added to the air during sensible heating is equal to sum of heat supplied to dry air and water vapour. Mathematically;

$$q = c_{pa}\left[t_{d2} - t_{d1}\right] + \left[Wc_{ps}\left[t_{d2} - t_{d1}\right]\right]$$

$$q = \left[c_{pa} + Wc_{ps}\right]\left[t_{d2} - t_{d1}\right]$$

Where c_{pa} = Specific heat of dry air = $1.005\ kJ/kgK$

c_{ps} = Specific heat of superheated vapour = $1.9\ kJ/kgK$

c_{pm} = Humid Specific heat of moist air

$$q = c_{pm}\left[t_{d2} - t_{d1}\right]$$

$$q = 1.022\left[t_{d2} - t_{d1}\right]\ kJ/kg \qquad \text{Eq. (2.18)}$$

▶ The amount of heat added to the air during sensible heating may be obtained from the chart by enthalpy difference,

$$q = (h_2 - h_1); \, kJ/kg \qquad \qquad Eq. \,(2.19)$$

2.4.2 Sensible Cooling

▶ "The cooling of air without any change in its specific humidity (moisture content) is known as sensible cooling."

▶ Let,

t_{d1} = Dry bulb temperature of air entering the cooling coil W_1=

Specific humidity of air entering the cooling coil

t_{d2} = Dry bulb temperature of air leaving the cooling coil W_2=

Specific humidity of air leaving the cooling coil

t_{d3} = Surface temperature of the cooling coil

▶ The process of sensible cooling on the psychrometric chart is shown by a horizontal line 1-2 extending from right to left.

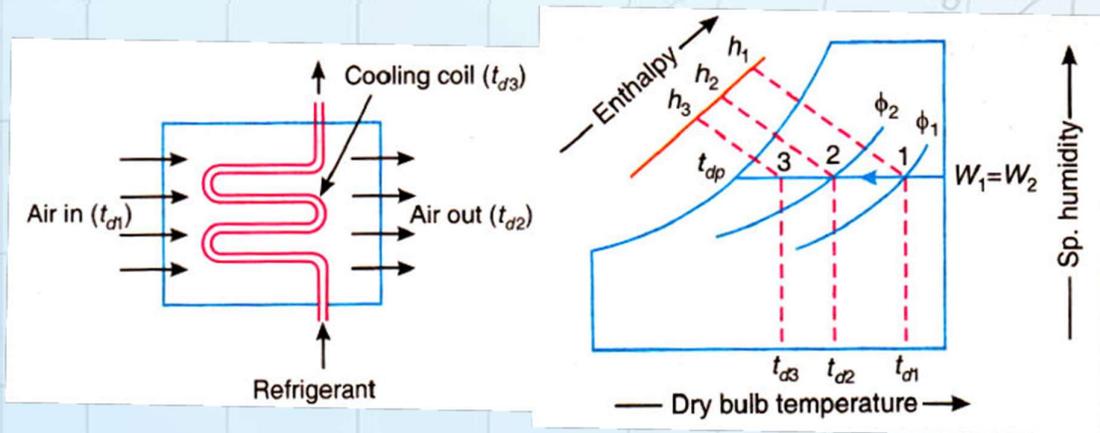▶ Let air at temperature t_{d1} passes over a cooling coil of temperature t_{d3} as shown in Fig. 2.5.

Fig.2.5 – Sensible cooling process

▶ During sensible heating (from psychrometric chart):

☐ Dry bulb temperature decreases from t_{d1} to t_{d2}

☐ Dew point temperature remains constant

☐ Enthalpy decreases from h_1 to h_2

☐ Specific humidity remains constant ($W_1 = W_2$)

☐ Relative humidity increases from $\varnothing_1$ to $\varnothing_2$

▶ The amount of heat rejected during sensible cooling is given by,

$$q = 1.022 \, [t_{d1} - t_{d2}] \; kJ/kg \qquad \qquad Eq. \,(2.20)$$

▶ The amount of heat rejected from the air can be obtained from the chart by the enthalpy difference is,

$$q = (h_1 - h_2); \, kJ/kg \qquad \qquad Eq. \,(2.21)$$

2.4.2.1 Bypass Factor (BPF)

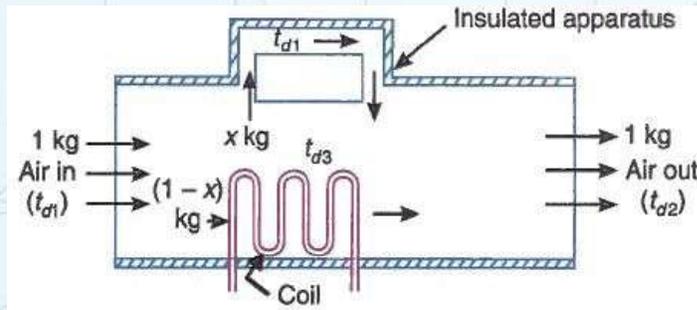▶ Let 1 kg of air at temperature t_{d1} is passed over the coil having temperature t_{d3} as shown in Fig. 2.6.

Fig.2.6 – Bypass factor of coil

▶ When the air passes over a coil, 'x' kg of air just by-passes while the remaining (1 - x) kg comes in direct contact with the coil. This bypass process of air is measured in terms of a Bypass factor (BPF).

▶ Balancing the enthalpies of air at inlet and outlet,

$$x c_{pm} t_{d1} + (1 - x) c_{pm} t_{d3} = 1 \times c_{pm} t_{d2}$$

$$x = BPF = \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}}$$

▶ Bypass factor of **cooling coil** is given by,

$$BPF = \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}} \qquad Eq. (2.22)$$

Similarly, Bypass factor of **heating coil** is given by,

$$BPF = \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}} \qquad Eq. (2.23)$$

▶ Efficiency of heating coil is given by,

$$\eta = 1 - BPF = 1 - \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}} = \frac{t_{d2} - t_{d1}}{t_{d3} - t_{d1}} \qquad Eq. (2.24)$$

▶ Similarly, Efficiency of cooling coil is given by,

$$\eta = 1 - BPF = 1 - \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}} = \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}} \qquad Eq. (2.25)$$

▶ Important conclusions from BPF are:

- If BPF is Zero → η =100 %; but if BPF is One → η = 0 %
- BPF is always between 0 to 1
- BPF should be as low as possible
- Lower the BPF → higher the η

2.4.2.2 Factors Affecting Bypass Factor

1. The number of fins provided in a unit length *i.e.* the pitch of the coil fins.
2. The number of rows in a coil in the direction of flow.
3. The velocity of flow of air.
4. BPF of a coil decreases with decrease in fin spacing and increase in number of rows.

2.4.3 Humidification

▶ "An addition of moisture to the air without change in its dry bulb temperature is known as humidification."

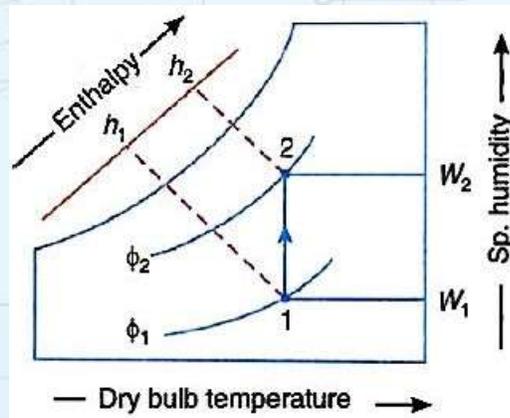▶ In this process only the latent heat **added** to the air. (Fig. 2.7)

Fig.2.7 – Humidification

▶ Let,

h_1 = Enthalpy of air entering the humidifier

W_1 = Specific humidity of air entering the humidifier h_2 =

Enthalpy of air leaving the humidifier

W_2 = Specific humidity of air leaving the humidifier

▶ The Latent heat (LH) transfer takes place to the air is given by,

$$LH \square \square h_2 \square h_1 \square \square h_{fg} \square W_2 \square W_1 \square \qquad Eq.\ (2.26)$$

▶ During humidification process (from psychrometric chart):

☐ Dry bulb temperature remains constant

☐ Enthalpy increases from h_1 to h_2

☐ Specific humidity increases from W_1 to W_2

☐ Relative humidity increases from $ø_1$ to $ø_2$

2.4.3.1 Methods of Humidification

▶ The humidification may be obtained by the following two methods:

1. Direct method and 2. indirect method

1. Direct Method

▶ Following three methods are used for humidification of air:

a) By *spraying of steam* directly into air before space being conditioned.

b) By injecting *highly atomised* hot water/cold water into air.

c) Forcing the air flow through a *wetted element* in which water evaporates.

▶ This method of obtaining humidification is not very effective.

2. Indirect Method (By Air Washer)

▶ In this method, the water is introduced into the air with the help of an air washer and the conditioned air is then supplied to the room to be air-conditioned.

▶ The air-washer humidification may be accomplished by following three ways:
   a) By using re-circulated spray water without prior heating of air.
   b) By pre-heating the air and then washing it with re-circulated water.
   c) By using heated spray water.

2.4.4 Dehumidification

▶ "The removal of moisture from the air without change in its dry bulb temperature is known as dehumidification."
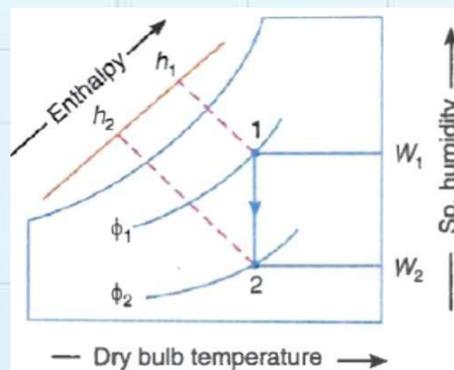

Fig.2.8 – Dehumidification

▶ In this process only the latent heat **removed** from the air. (Fig. 2.8)

▶ Let,

h_1 = Enthalpy of air entering the humidifier

W_1 = Specific humidity of air entering the humidifier h_2 =

Enthalpy of air leaving the humidifier

W_2 = Specific humidity of air leaving the humidifier

▶ The Latent heat transfer (LH) takes place from the air is given by,

$$\text{Latent heat} = LH \;\square\; \square h_1 \;\square\; h_2 \;\square\; \square\; h_{fg} \;\square\; W_1 \;\square\; W_2 \;\square \qquad Eq.\ (2.27)$$

▶ During dehumidification process (from psychrometric chart):

□ Dry bulb temperature remains constant

□ Enthalpy decreases from h_1 to h_2

□ Specific humidity decreases from W_1 to W_2

□ Relative humidity decreases from $\varnothing_1$ to $\varnothing_2$

2.4.4.1 Methods Of Dehumidification

▶ The dehumidification may be accomplished by following four methods:
   a) By cooling the air below DPT.
   b) By Absorption of moisture from air (i.e calcium chloride & aqueous lithium chloride solution spray over the cooling coil are used as absorbent).

c) By Adsorption of moisture from air (i.e silica gel & activated alumina are used as adsorbents).

d) By using Air washer.

2.4.5 Cooling and Dehumidification

▶ This process is used in *summer air conditioning* to cool and dehumidify the air.

▶ Let

t_{d1} = Dry bulb temperature of air entering the cooling coil W_1 =

Specific humidity of air entering the cooling coil

t_{dp1} = Dew point temperature of the entering air = t_{d3}

t_{d2} = Dry bulb temperature of air outlet from the cooling coil W_2 =

Specific humidity of air leaving the cooling coil

t_{d4} = Effective surface temperature or Apparatus Dew Point

temperature *(ADP)* of the cooling coil

▶ 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}) then air is *cooled and humidified*. ($t_{d4} < t_{dp1}$) as shown in Fig. 2.9.

▶ In this process; both *dry bulb temperature* (t_d) and the *specific humidity* (W) of air decreases but the relative humidity of the air is increases.
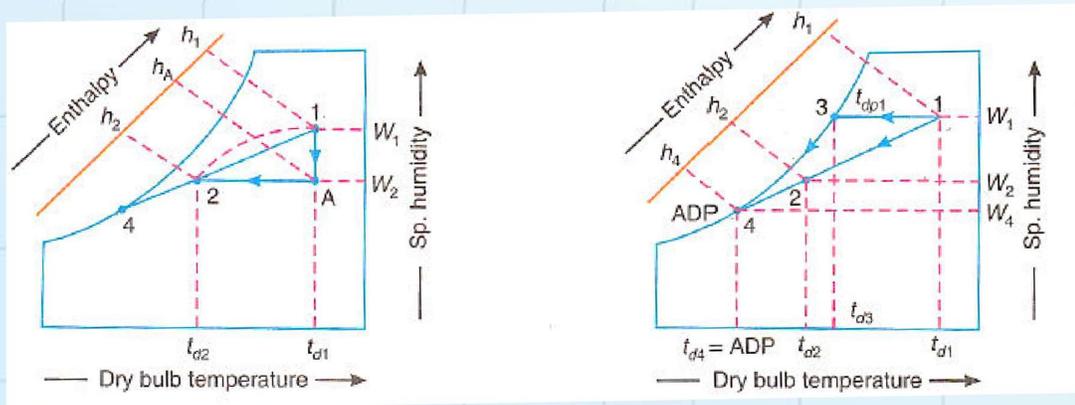

Fig.2.9 – Cooling and dehumidification

▶ Under *ideal conditions*, the dry bulb temperature of the air leaving the cooling coil (t_{d2}) should be *equal to* the surface temperature of the cooling coil (t_{d4}), but it is never possible due to *inefficiency* of the cooling coil.

▶ Therefore, the *actual condition* of air coming out of the coil is shown by a   *point 2* on the straight line joining the points 1 and 4 as shown in Fig. 2.7.

▶ The by-pass factor of this process from psychrometric chart is,

$$BPF = \frac{t_{d2} - t_{d4}}{t_{d1} - t_{d4}} = \frac{t_{d2} - ADP}{t_{d1} - ADP} = \frac{W_2 - W_4}{W_1 - W_4} = \frac{h_2 - h_4}{h_1 - h_4} \qquad Eq.\ (2.28)$$

▶ The cooling and dehumidification process shown by a *line 1-2* to be followed a *path 1-A* dehumidification and *path A-2* cooling as shown in Fig. 2.9.

▶ The total heat removed during process is,

$q = h_1 - h_2 = (h_1 - h_A) + (h_A - h_2) =$ Latent Heat + Sensible Heat
$LH + SH$

Where $h_1 - h_A$ = Latent heat removed due to condensation of vapour

$h_A - h_2$ = Sensible heat removed from the air

▸ The Sensible heat factor (SHF) is given by,

$$SHF = \frac{\text{Sensible Heat}}{\text{Total Heat}} = \frac{SH}{LH + SH} = \frac{h_A - h_2}{h_1 - h_2} \qquad \textit{Eq. (2.29)}$$

▸ Important conclusion from SHF:

☐ If SHF is "One" → No Latent heat transfer

☐ If SHF is "Zero" → No Sensible heat transfer

☐ Lower value of SHF (i.e 0.4) → high latent heat load in humid atm.

☐ Higher value of SHF (i.e 0.8) → high sensible heat load in dry atm.

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

2.4.6 Cooling and Humidification (Adiabatic Saturation OR Evaporative Cooling)

▸ The *insulated spray chamber* is used for the adiabatic saturation of air containing water with an arrangement for make-up water as shown in Fig. 2.10.

▸ Let,

t_{d1}, t_{w1} = Dry bulb & wet bulb temperature of entering air t_{dp1}

= Dew point temperature of entering air

t_{d2}, t_{w2} = Dry bulb & wet bulb temperature of air leaving the spray chamber W_1, W_2 =

Specific humidity of air entering & leaving the spray chamber
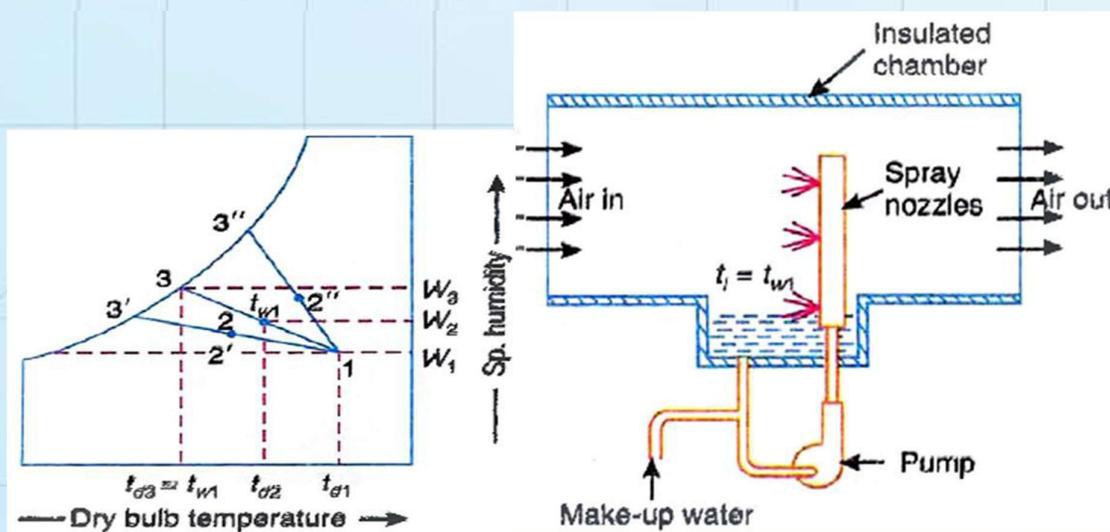
t_l = liquid water spray temperature

Fig.2.10 – Cooling and humidification

▸ When liquid water is spray into the flowing air stream by spray nozzle; some amount of water evaporates & increasing the water vapor content of the air.

▶ The condition of leaving air will depend on the amount of water evaporates.

▶ The temperature of the water should be lower than DBT of air but higher than DPT (i.e $t_l < t_{d1}$ but $t_l > t_{dp1}$) of air to avoid condensation of moisture.

▶ During evaporative cooling the heat required for evaporation of water is taken from air (sensible heat transfer from air to water), thus air is *cooled*.

▶ This evaporated water added into the air (latent heat transfer from water to air) thus air is *humidified*; thus both cooling & humidification of air takes place.

▶ The **total heat transfer** (from air to water & water to air) depends upon the temperature of water spray.

▶ If temperature of water spray is equal to WBT of air (i.e $t_l = t_{w1}$); then net heat transfer will be *zero*; because sensible heat transfer from *air to water* will be equal to latent heat transfers from water to air. *(process 1-3 in Fig. 2.8)*

▶ The spray water is *recirculated* and it is neither heated nor cooled prior to supply; hence WBT and enthalpy of air remains constant; finally, *adiabatic saturation* will occur.

▶ This process is shown by *line 1-3* on the psychrometric chart and follows the path along the constant wet bulb temperature line ($t_{w1} = t_{w2}$) or constant enthalpy line.

▶ In an ***ideal case,*** when the humidification is *perfect* (the humidifying efficiency is 100%), the final condition of the air will be at point 3 (i.e. at temperature t_{d3} and relative humidity 100%).

▶ But in *actual practice*, perfect humidification is never achieved; therefore, the final condition of air at outlet is represented by *point 2* on the *line 1-3*.

▶ Effectiveness or humidifying efficiency of the humidifier (spray chamber) is,

$$\eta_H = \frac{\text{Actual drop in DBT}}{\text{Ideal drop in DBT}}$$

$$= \frac{\text{Actual increase in sp. humidity}}{\text{Ideal increase in sp. humidity}}$$

$$\eta_H = \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}} = \frac{W_2 - W_1}{W_3 - W_1}$$

▶ The evaporative cooling is economical as well as effective in dry climate; therefore, it is some time referred as *"Desert Cooler"* also.

▶ If temperature of water spray is less than WBT of air *(i.e $t_l < t_{w1}$)*; then net heat transfers from air to water. **(process 1-3').** E.g. air cooler.

▶ If temperature of water spray is greater than WBT of air *(i.e $t_l > t_{w1}$)*; then net heat transfers from water to air. **(process 1-3'')** E.g. cooling tower.

2.4.7 Heating and Humidification

▶ This process is used in *Winter air conditioning* to heat and humidified the air.

▶ Let

t_{d1}, t_{d2} = Dry bulb temperature of air entering & leaving heating coil

W_1, W_2 = Specific humidity of air entering & leaving the heating coil

▶ In this process; both ***dry bulb temperature*** and the ***specific humidity*** of air ***increases*** but the relative humidity of the air is decreases.

- During heating & humidification process (from psychrometric chart):
  - ☐ Dry bulb temperature increases from t_{d1} to t_{d2}
  - ☐ Enthalpy increases from h_1 to h_2
  - ☐ Specific humidity increases from W_1 to W_2
  - ☐ Relative humidity decreases from ϕ_1 to ϕ_2

2.4.7.1 Methods of heating & humidification

- There are two methods:
  - a) By steam injection only and
  - b) By sensible heating & steam injection
- Each method will be discussed in detail as below.

(l) By Steam Injection Only

- In this method saturated steam injecting into the flowing stream of air. This process is represented by 1-2 on psychrometric chart (Fig. 2.11).
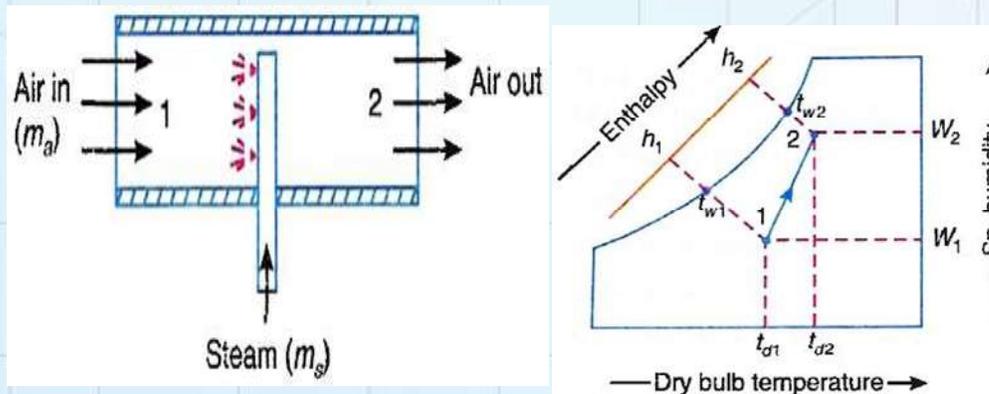
Fig.2.11 Heating & humidification by steam injection

- This method is used for conditioning of *textile mills* where high humidity is required to be maintain.

(Ii) By Sensible Heating & Steam Injection

- In this method *heating coil* is used for sensible heating of air and *steam injection* is applied for humidification of air.
- The heating and humidification process shown by a *line 1-2* to be followed by *path 1-A* heating and *path A-2* humidification as shown in Fig. 2.12..

Fig.2.12 – Heating and humidification by heating & steam injection

- The total heat supplied during process is,

$$q \square h_2 \square h_1 \square \square h_A \square h_1 \square \square \square h_2 \square h_A \square \square SH \square LH$$

Where, $h_A - h_1$ = Sensible heat added; kJ/kg

$h_2 - h_A$ = Latent heat added; kJ/kg

2.4.8 Heating and Dehumidification (Chemical or Adiabatic Dehumidification)

▸ This process is used for *air drying* process to heat and humidified the air.

▸ Let

t_{d1}, t_{d2} = Dry bulb temperature of air entering & leaving the hygroscopic material

W_1, W_2 = Specific humidity of air entering & leaving the hygroscopic material
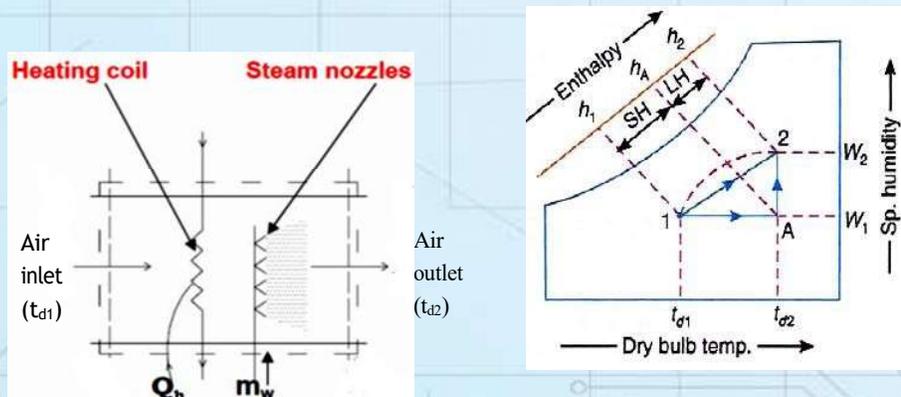

Fig.2.13 – Heating and dehumidification

▸ In this process air is passing over the **hygroscopic materials** which have affinity for moisture.

▸ When air is passing over the hygroscopic (i.e silica gel, activated alumina) material; it will adsorb the water vapor from air; thus **dehumidification** of air takes place as shown in Fig. 2.13.

▸ The heat released during condensation of vapour is added to air thus its *dry bulb temperature* also increases and **heating** also takes place.

▸ During heating & dehumidification (from psychrometric chart):

☐ Dry bulb temperature increases from t_{d1} to t_{d2}

☐ Wet bulb temperature remains constant ($t_{w1} = t_{w2}$)

☐ Enthalpy remains constant ($h_1 = h_2$)

☐ Specific humidity decreases from W_1 to W_2

☐ Relative humidity decreases from ϕ_1 to ϕ_2

▸ The process path followed during the *process 1-2* is along constant wet bulb temperature line or constant enthalpy line in psychrometric chart.

▸ It is the *reverse* of adiabatic saturation process.

2.5 Summary of Psychrometric Processes On Psychrometric Chart

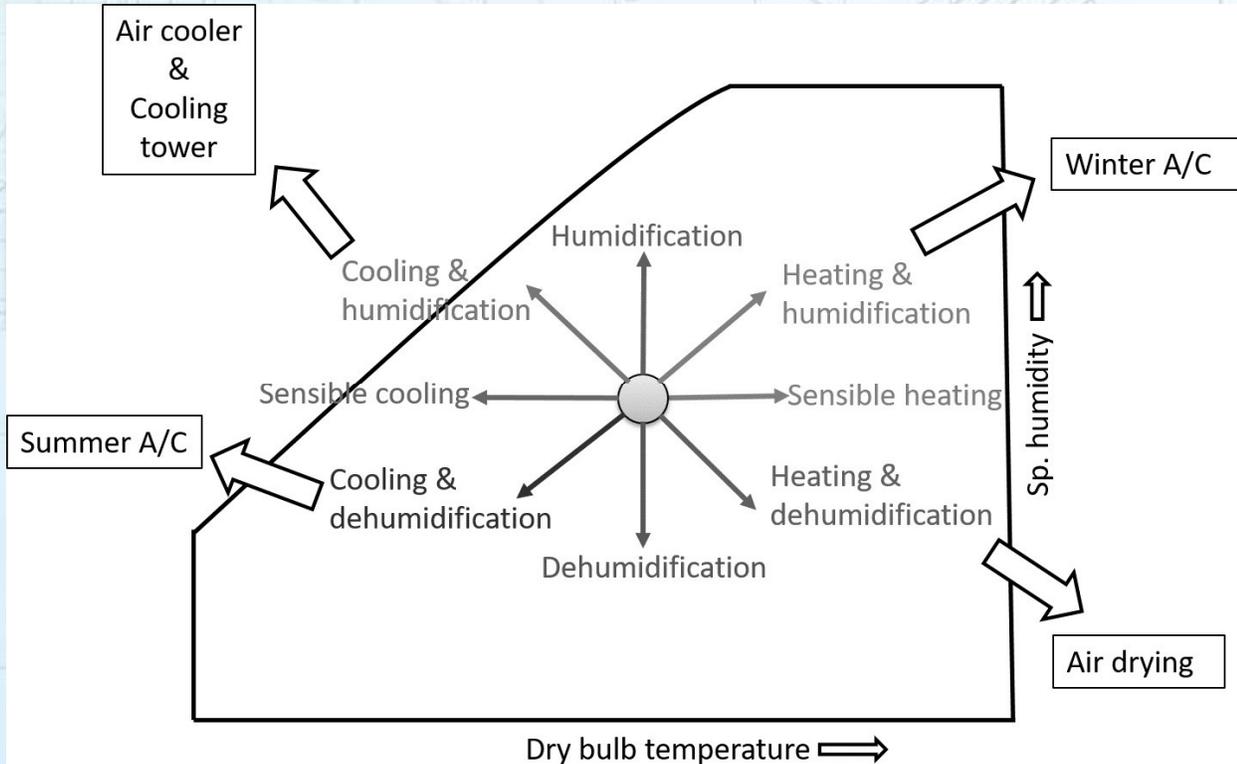▶ Representation of each of the psychrometric processes are on psychrometric chart Fig. 2.14.

Fig.2.14 – Summary of psychrometric processes on psychrometric chart

▶ The various psychrometric processes represented on chart are:

   ☐ Sensible heating (horizontally right to left '→')

   ☐ Sensible cooling (horizontally left to right '←')

   ☐ Humidification (vertically upwards '↑')

   ☐ Dehumidification (vertically downwards '↓')

   ☐ Cooling & dehumidification (inclined toward left downwards '↙')

   ☐ Cooling & humidification (inclined toward left upwards '↖')

   ☐ Heating & Humidification (inclined toward right upwards '↗')

   ☐ Heated & Dehumidification (inclined toward right downwards '↘')

▶ Other psychrometric processes used in air conditioning applications are:

   ☐ Cooling and dehumidification with reheat

   ☐ Preheat and humidification with reheat

   ☐ Mixing and adiabatic saturation with reheat

   ☐ Superstation

Table 2.2 Variation in psychrometric properties on psychrometric chart

Type of process	Variation in psychrometric properties								
	DBT	WBT	DPT	h	v	W	RH	μ	p_v
Sensible heating	↑	↑	Constant	↑	↑	Constant	↓	↓	Constant
Sensible cooling	↓	↓	Constant	↓	↓	Constant	↑	↑	Constant
Humidification	Constant	↑	↑	↑	↑	↑	↑	↑	↑
Dehumidification	Constant	↓	↓	↓	↓	↓	↓	↓	↓
Cooling & dehumidification	↓	↓	↓	↓	↓	↓	↑	↑	↓
Cooling & humidification (adiabatic saturation)	↓	Constant	↑	Constant	↓	↑	↑	↑	↑
Heating & humidification	↑	↑	↑	↑	↑	↑	↓	↓	↑
Heating & dehumidification	↑	Constant	↓	Constant	↑	↓	↓	↓	↓

2.6 References

1) Engineering Thermodynamics by P.K. Nag, McGraw-Hill Education

2) Refrigeration and Air Conditioning by C P Arora, McGraw-Hill India Publishing Ltd.

3) Principles of Refrigeration by Roy J. Dossat, Pearson Educations.