UNIT 4 PSYCHROMETRY

Structure

4.0 OBJECTIVES

After reading this unit, you should be able to:

- differentiate between wet basis and dry basis moisture content;
- define the important thermodynamic properties of humid air;
- understand psychrometric chart an its use;

- know the importance of equilibrium moisture content and water activity; and
- understand the water evoparation theory.

4.1 INTRODUCTION

In the field of grain drying, atmospheric air is used as a heat transfer medium. Normal atmospheric air is a mixture of dry air and water vapour, atmospheric air never being completly dry. Dry air at atmospheric pressure of 1.033 kg/cm^2 (14.7 *lb*/m^2) is considered composed of nitrogen and oxygen for all engineering purpose with following composition.

Composition of air at atmospheric pressure

	By volume	By mass	Molecular weight
Nitrogen	79 %	76.8%	28.02
Oxygen	21%	23.2%	32.00
	Dry air	28.97	

Even the amount of water vapour present in the atmospheric air is very less, the presence of water vapour greatly affects the drying process. It is essential to know the properties of dry air and vapour mixture to understand the drying theory. The clear understanding of the procedures involved in calculation of air-water vapour mixture properties can also be useful in solving the problems associated with heating, cooling, mixing of air masses, design of controlled atmosphere storage etc. In this chapter important physical and thermodynamical properties of air-water vapour mixture are defined. Psychrometric chart useful in calculation of these properties is explained.

4.2 WET BASIS AND DRY BASIS MOISTURE CONTENT AND DRIAGE

Moisture content is the amount of free, absorbed and adsorb water in the grain. Water in grain is present in inter granular spaces in the endosperm and seed coat, some water is bonded by weak hydrogen bonds to the molecules of starches and protein bodies and bulk of the water is present as free water adsorbed or absorbed on the surface, and in between the husk and kernels. Water in grain plays vital role in keeping the grain viable and controls all physical and biological functions of the grain. Therefore accurate measurement and control is the key, to successful preservation, processing and quality control of grain and its products.

4.2.1 Grain Moisture Content

Normally moisture content denotes the quantity of water in a unit mass of a grain sample. It is expressed in two different forms:

1. Moisture content wet basis
2. Moisture content dry basis

4.2.1.1 Moisture Content Wet Basis

It is the mass of water present per unit mass of undried grain sample i.e.

$$M_{wb} = \frac{m_w}{m_g} \times 100 = \frac{m_w}{m_d + m_w} \times 100 \qquad (1)$$

Where M_{wb} = present moisture content wet basis, %

m_w = mass of water in grain sample, g

m_d = mass of dry matter in grain sample, g

m_g = mass of grain sample = m_d - m_w, g

4.2.1.2 Moisture Content Dry Basis

It is the mass of water present per unit mass of dry matter in a grain sample.

$$M_{db} = \frac{m_w}{m_d} \times 100 = \frac{m_w}{m_g - m_w} \times 100 \qquad (2)$$

Where M_{db} = present moisture content dry basis other symbols remain same as in equation (1)

Wet basis moisture content is virtually universally used by the farmers, processors merchants and all agencies. Unless stated otherwise, all values of moisture content in grain mean representation of moisture on wet basis. Dry basis moisture content is mostly used in scientific work and is limited to research papers.

4.2.1.3 Relationship Between Wet Basis and Dry Basis Moisture Content:

The conversion of moisture content from wet basis to dry basis and vice versa is simple, and can be calculated from the given equations

$$M_{db} = \frac{100 \times M_{wb}}{100 - M_{wb}} \qquad (3)$$

and $$M_{wb} = \frac{100 \times M_{db}}{100 + M_{db}} \qquad (4)$$

where M_{db} and M_{wb} are respectively **percent moisture content** on dry basis and wet basis.

4.2.2 Determination of Driage

Driage is the loss in weight of grain consignment due to reduction in moisture. A grain consignment weighing W_1, kg was received in store at M_1 moisture content (wet basis) During storage its moisture reduced to M_2. We can determine the weight W_2 of the same consignment at M_2 moisture by following expression.

$$W_2 = \frac{100 - M_1}{100 - M_2} \text{ x } W_1 \qquad (5)$$

For example if 60 kg rice grain were stored at 20% moisture content (wb) and in store the moisture reduced to 16%. Mass of the grain at 16% moisture content

$$W_2 = \frac{100 - 20}{100 - 16} \text{ x 60 kg.}$$

$$= \frac{80}{84} \text{ x 60}$$

$$= 57 \text{ kg}$$

Therefore loss in weight of consignment due to reduction in moisture or driage = 60 - 57 = 3 kg.

4.3 AIR PROPERTIES

4.3.1 Dry-Bulb Temperature

Is the temperature given by an ordinary thermometer.

4.3.2 Wet-Bulb Temperature

Is the temperature given by a mercury thermometer when its bulb is covered with a wet wick and exposed to unsaturated airflow. The air flow passing over the wick should have a velocity of at least 4.6 m/s. When the wick is exposed to unsaturated air, the vapour pressure of water in wet wick is higher than the unsaturated air. Because of the vapour pressure difference water evaporates by using the latent heat from the wick, reducing the temperature of the covered bulb. As the temperature of the wick is less than the dry bulb temperature of air, a sensible heat flows from the air to wick. A steady state is achieved when the heat flow from air to wick is equal to the loss of heat by wick due to water evaporation. At this equilibrium state the temperature measured is called as wet bulb temperature. This is very useful in determining the relative humidity of air.

4.3.3 Absolute Humidity

The kg of moisture per kg of dry air is called the absolute humidity. The base (1 kg of dry air) is used since it is a constant for any change off conditions, thus facilitating calculations.

$$\mathrm{H} = \frac{1}{1.605} \times \frac{p_v}{p_{at} - p_v} \qquad (6)$$

$$\text{and } p_v = \frac{1.605\,H}{1.605\,H + 1}\; p_{at} \qquad (7)$$

where p_a = pressure exerted by the dry air, kg/cm²

p_{at} = pressure exerted by the atmosphere, kg/cm²

p_v = pressure exerted by the water vapor in the atmosphere, kg/cm²

4.3.4 Relative Humidity

Relative humidity is defined as the ratio of the actual pressure of the water vapor in the air to the pressure if the air were saturated with moisture at the same temperature.

$$\mathrm{R_h} = \frac{p_v}{p_s} \qquad (8)$$

Where $\mathrm{R_h}$ = relative humidity

p_s = saturation pressure kg/cm²

p_v = pressure exerted by the water vapor in the atmosphere, kg/cm²

4.3.5 Percentage Humidity

Percentage humidity is defined as the ratio of the absolute humidity at as state to the absolute humidity at the same temperature for a saturated condition.

$$\text{Percent Humidity} = \frac{H}{H_s} \times 100 \qquad (9)$$

Where H = absolute humidity, kg of water vapor/kg of dry air

H_s = saturated humidity, kg of water vapor/kg of dry air

4.3.6 Specific Volume

Is the volume of humid air containing 1kg of dry air at the given temperature and pressure. According to gas law humid volume of air is given by

$$\mathrm{V} = \frac{RT}{p_{at}} \left(\frac{1}{29} + \frac{H}{18} \right) \qquad (10)$$

Where V = humid volume m^3/kg

R = Universal gas constant = 0.0812 atm-m^3/kg.mole °k

T = temperature of air °K = (t °C+273)

H = absolute humidity of air kg of water vapor/kg of dry air

4.3.7 Dew Point Temperature

Is the temperature at which condensation occurs when the air is cooled at constant humidity ratio and constant atmospheric pressure. Thus, the dew point temperature can be considered as the saturation temperature corresponding to the humidity ratio and vapour pressure of the humid air.

4.3.8 Enthalpy

Is the total heat content of air water mixture at the given temperature and pressure and is given by

$$h_a = 0.24t + H.\,h_g \tag{11}$$

where h_a = heat content of humid air, kcal/kg of dry air

0.24t = average heat content of dry air, kcal/kg of dry air

H = absolute humidity

h_g = heat content of 1kg of water vapour at the given condition = h_{fg} + 0.45 t

h_{fg} = latent heat of evaporation at given temperature (as determined from steam table), kcal/kg

0.45 = specific heat of water vapour

Therefore $h_a = 0.24t + H\,(h_{fg} + 0.45t)$ (12)

4.3.9 Vapour Pressure of Water Vapour in Air

The water vapor in the atmosphere conforms to Dalton's law, and, thus, exerts a pressure independent of the dry air. Therefore, the vapor pressure for a space saturated with water vapor can be taken directly from any standard steam table

The total pressure of atmospheric air (p_{at}) is equal to the sum of partial pressure exerted by dry air (p_a) and partial pressure of exerted by water vapour (p_v).

$$p_{at} = p_a + p_w \quad (13)$$

4.4 PSYCHROMETRIC CHART

The psychrometric chart is graphic representation of the physical and thermal properties of atmospheric air. Instead of calculating from the equations, the properties of humid air can be obtained easily by using psychrometric chart. Figure 4.1 shows the psychrometric chart (ASHRAE Publishers) prepared for air at 101.325 kPa (1 atm pressure).

In the chart the horizontal axis gives dry bulb temperatures and the vertical axis gives humidity ratios. The horizontal lines represents the constant humidity ratios, where as the vertical lines represents constant dry bzulb lines.

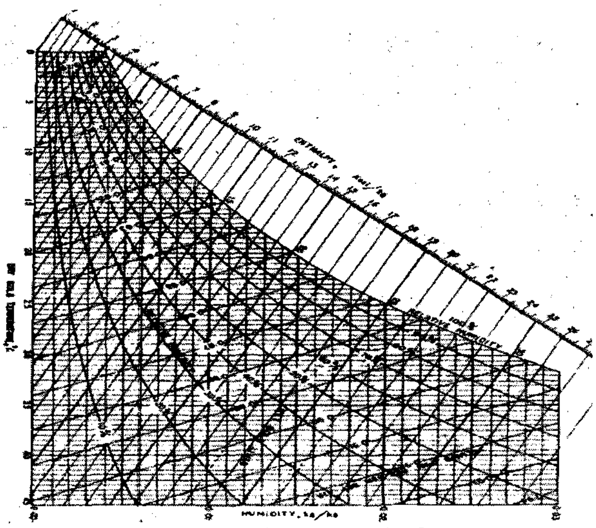


Fig. 4.1 : Pschrometric chart

The curves swinging upward give the relative humidity values. The extreme left curve is the 100% relative humidity curve, is also known as saturation curve. On this curve the values of dew point, wet-bulb and dry-bulb temperatures are equal. The curved lines below this saturation curve represents various percentage of relative humidities. The horizontal axis is the 0% relative humidity line, which represents complete dry air.

The wet bulb lines are straight and make sharp angle with the vertical axis. These lines are also called as adiabatic cooling lines, and having unequal magnitude of angles with vertical axis. The oblique straight lines having steeper slopes than wet bulb lines represents specific volume lines.

The enthalpy lines are inclined, parallel lines drawn in slightly different direction than the wet-bulb lines. The values of the enthalpy lines are indicated on a scale drawn upper left hand corner of the chart.

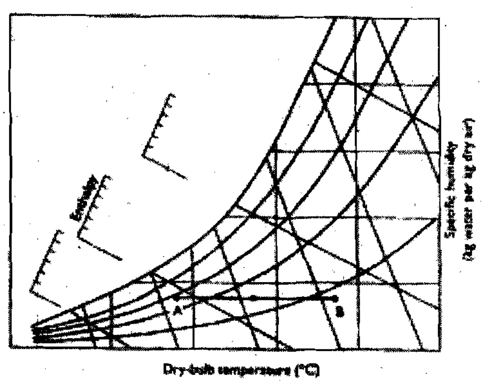
4.5 SOME APPLICATIONS OF PSYCHROMETRIC CHART

4.5.1 Determination of State Condition

Complete information about state condition of the air can be determined by Psychrometric chart by knowing any two conditions. For example by knowing dry bulb and wet bulb temperatures of the air, it is possible to determine relative humidity, absolute humidity, vapour pressure, humid volume and enthalpy of the air.

4.5.2 Cooling and Heating

Cooling or heating without changing the moisture content takes place horizontally, AB line as shown in figure 4.2, where there is no change in absolute humidity of the air. Line A to B indicates heating. Change in enthalpy (h_2 - h_1) gives the amount of heat required for heating the air from temperature t_1 to t_2. The line B to A indicates cooling process.



Courtesy : Paul Singh and Heldman (2001)

4.5.3 Drying

Drying in psychometric chart is represented by the constant wet bulb line and if the temperature of exhaust air is given, it is possible to determine the amount of water vapour removed per kg of dry air (Figure 4.3).

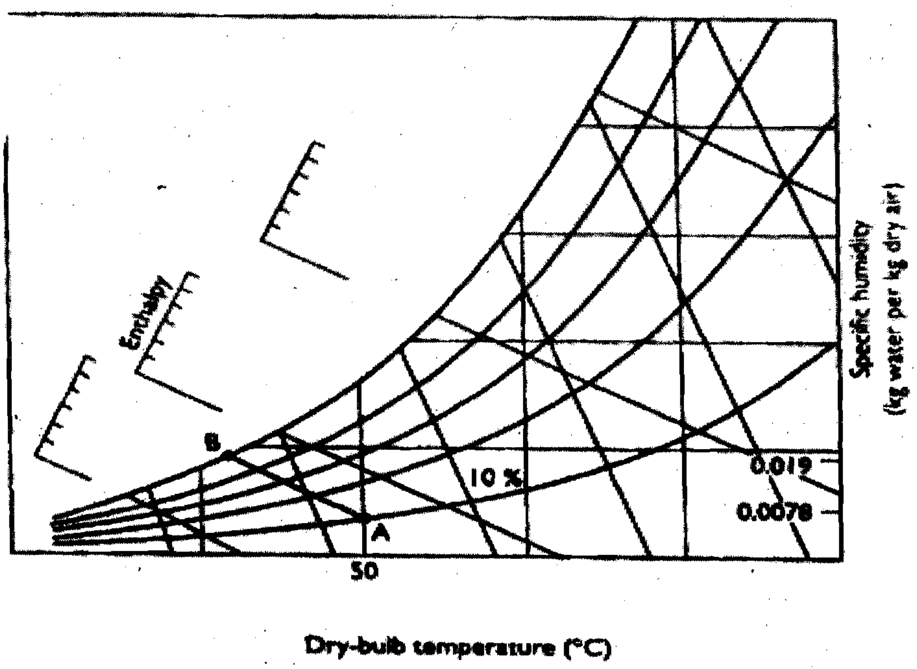


Fig. 4.3: Drying of humid air
Courtesy : Paul Singh and Heldman (2001)

4.5.4 Mixing of Air Masses

The state points of an air-vapour mixture resulting from mixing two volumes of air of different state points falls very nearly on a straight line connecting the two initial states. In figure 4.4, points A and B show two air masses. The line joining the points is divided in inverse proportion to the weights of individual air quantities. The point C (mid point of AB) in the figure 4.4 shows the air masses of two equal weights.

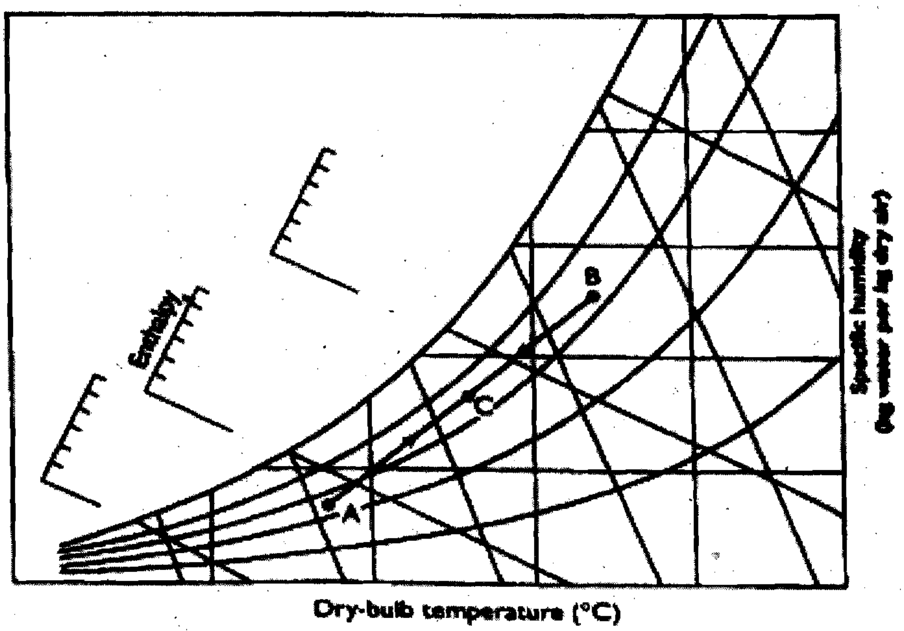


Fig. 4.4: Mixing of two air streams
Courtesy : Paul Singh and Heldman (2001)

Check Your Progress 1

Note: a) Use space given below for your answers.

b) Check your answers with those given at the end of the unit.

1. Give the composition of dry atmospheric air by volume.

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2. Express 20% wet basis moisture content in dry basis.

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3. Explain wet bulb temperature

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4. Calculate the specific volume of air at 70 °C, and a humidity ratio of 0.02 kg water/ kg of dry air, at 1 atm pressure. Check this value from the psychrometric chart

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5. What is dew point temperature?

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6. Which lines in psychrometric chart are considered as adiabatic cooling lines?

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7. An air –water vapour mixture is having 30 °C dry bulb temperature and 20°C wet bulb temperatures. Using the psychrometric chart determine the specific volume, humidity ratio, relative humidity, dew point temperature and enthalpy

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4.6 EQUILIBRIUM MOISTURE CONTNET AND WATERACTIVITY

4.6.1 Equilibrium Moisture Content

The equilibrium moisture content is useful to determine whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions. Product is in equilibrium with its environment when the rate of moisture loss from the product to the surrounding atmosphere is equal to the rate of moisture gain of the product from the surrounding atmosphere. The moisture content of the product when it is in equilibrium with the surrounding atmosphere is called the equilibrium moisture content or hygroscopic equilibrium. The relative humidity of the surrounding atmosphere is known as the equilibrium relative humidity at the particular temperature.elationship between the moisture content of a particular material and its equilibrium relative humidity, at the particular temperature can be expressed by means of equilibrium moisture curves. These curves are sometimes referred to as isotherms because the values plotted for each curve usually correspond to a specific temperature

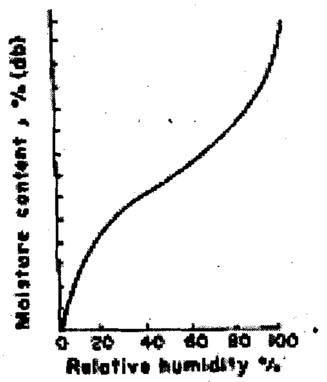

Fig. 4.5 : Equilibrium moisture content curve

An empirical equation (Henderson equation) is used to represent the equilibrium moisture content

$$1\text{-}RH = e^{-cTM_e^n} \qquad (14)$$

Where RH = the relative humidity, is represented as a decimal

T = the absolute temperature, deg K

M_e, the equilibrium moisture content, percent db.

c an n are constants varying with the materials.

From figure 4.5 and equation 14 it can be noted that

- the equilibrium moisture content is zero at *zero* relative humidity
- the equilibrium relative humidity approaches 100 percent as the moisture content approaches infinity.
- the slope of the curve approaches infinity as the moisture content approaches infinity and increases rapidly as the moisture content approaches zero.

The composition of the product determines the absorption of moisture. With feedstuffs, the relative amounts of soluble carbohydrate and protein largely determine the equilibrium moisture curve. At 63 percent relative humidity the water absorption varies directly with the carbohydrate content and inversely with the protein content and at 90 percent relative humidity the relationship is reversed.

4.6.2 Determination of Equilibrium Moisture Content

Two general methods are used for determining the equilibrium moisture content: The static method; in which atmosphere surrounding the product comes to equilibrium with the product without mechanical agitation of the air or product; and the dynamic method, in which the atmosphere surrounding the product or the product is mechanically moved. The dynamic method is quicker but presents problems in design and instrumentation. Therefore, the static method has been used more extensively. Several weeks may be required using the static method, where as, with the dynamic method the data may be obtained in a couple of days or less. The speed at which equilibrium is approached, of course, depends upon the amount of change which must take place in order to reach. equilibrium for a particular product. The usual procedure consists of using wet grain and drying to the equilibrium condition, in which case the term, desorption isotherm applies.

When using the static method for determining equilibrium moisture content a saturated salt solution or an acid solution may be used for maintaining the desired relative humidity at the temperature of storage. Another method is to permit, the product to come to equilibrium with an enclosed, surrounding, the relative humidity of which is then measured. In both cases the final moisture content of the product is determined by an accepted method. With the static method, because long periods are required for the product to come to equilibrium, mold is about to develop on most agricultural products at relative humidities above 80 percent. The moisture content obtained for relative humidities above 80 percent for the product is usually not a true one, because the moisture from the mold gives an apparent high equilibrium moisture content.

With the dynamic method air is bubbled through absorption towers containing an acid or saturated salt solution which controls the humidity around the product. Also, an air conditioning system can be used to obtain the desired conditions. In another method the air is moved around the product in closed container and the final relative humidity and temperature of the air determined to predefined level.

4.6.3 Water Activity

Water activity is an important parameter in analysis of storage stability of dehydrated food material. Water activity (a_w) is defined as the equilibrium relative humidity (ERH) of the product divided by 100. ERH is the percentage relative humidity of an atmosphere in contact with the product at an equilibrium water content. a_w is also expressed as the ratio of the partial pressure of water in the product to the vapour pressure of pure water at same temperature.

$$a_w = \frac{ERH}{100} = \frac{partial\ pressure of\ water\ in\ product}{vapour\ pressure\ in\ pure water} \tag{15}$$

Dehydrated foods are preserved by maintaining the water activity at a level, where no microbiological activity can occur and where deteriorative chemical and bio-chemical reaction rates reduced to a minimum. The relationship between the water activity and rate of deteriorative reactions are shown in figure 4.5. Reducing water activity less than 0.7 prevents microbiological spoilage including mold, yeast and bacterial growth. But to prevent all the spoilage reactions including non-enzymatic and enzymatic reactions along with microbiological reactions water activity should be reduced less than 0.3

Fig. 4.6 Relationship between water activity and deteriorative reactions in food
Courtesy: Toledo (2000)

4.7 WATER EVAPORATION PRINCIPLES

The phenomenon of adiabatic saturation of air is applicable to the convective drying of food materials. The unbound free moisture evaporates from the food material into the air by converting part of sensible heat of entering air into latent heat of vaporization. This process of water evaporation includes both heat transfer and mass transfer simultaneously.

To understand the principle of water evaporation under adiabatic saturation process let us consider the following experiment. As shown in figure 4.5 air is allowed to contact a large surface area of water in an well-insulated chamber. The insulated chamber is under adiabatic conditions, i.e. there is no heat gain from the surroundings to inside the chamber, and no heat loss from inside the chamber to the surrounding. In this conditions the evaporation of water takes places from the surface by converting the part of sensible heat of air into latent heat of vaporization. The process of evaporating water into the air results in saturation and is defined as adiabatic saturation.

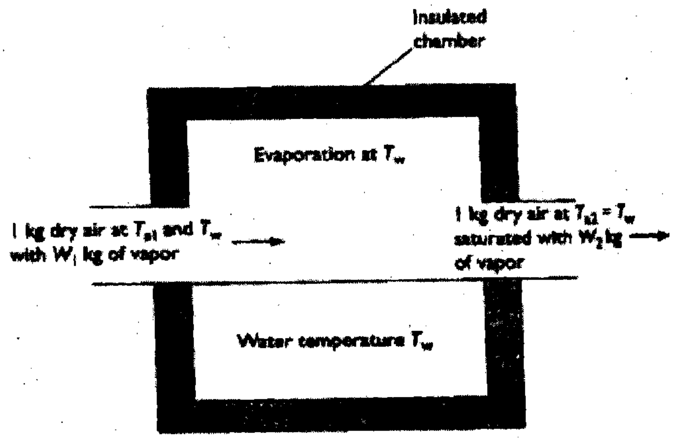

Fig. 4.7 Adiabatic saturation of air in insulated chamber

Courtesy : Paul Singh and Heldman (2001)

By applying energy balance at air-water surface, sensible heat transfer from air to water is equal to the latent heat of water vapour from the water to air, and for adiabatic saturation the equation can be written as

$$(T_{a1} - T_{a2}) = \lambda \frac{(W_2 - W_1)}{(1.005 + 1.88W_1)} \quad (16)$$

Where T_{a1} = Inlet air temperature

T_{a2} = Saturated air temperature

W_2 = Saturated air humidity

W_1 = Inlet air humidity

λ = Latent heat at wet bulb temperature (kJ/kg)

Check Your Progress 2

Note: a) Use space given below for your answers.

b) Check your answers with those given at the end of the unit.

1. Give Henderson equation and name the terms with units?

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2. Define and explain the importance of water activity?

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3. Air 50 °C dry bulb temperature with humidity ratio of 0.013 kg of water / kg of dry is adiabatically cooled and humidified to a humidity ratio of 0.02 kg of water / kg of dry. Find out the *temperature* of the final condition. Wet bulb temperature of air is given as 27 °C, and latent heat of vaporization is 2436 kJ/kg

   Hint: Use adiabatic saturation equation

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4.8 LET US SUM UP

Psychrometry is the study of properties of air-water vapour mixture. For the design and analysis of various food processing and storage systems air-water vapour mixture porperties are useful. The properties include absolute humidity, relative humidity, percentage humidity, dry bulb, wet bulb and dew point temperatures, enthalpy and specific volume. By knowing any two of these properties the remaining properties can be determined by using psychrometric chart. Equilibrium moisture content is useful to determine whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions. Water activity is an important parameter in analysis of storage stability of dehydrated food material.

4.9 KEY WORDS

Psychrometry : Study of properties of air-water vapour mixture.

Adiabatic condition : Where there is no heat transfer from the surroundings to the system and from the system to surroundings.

Equlibrium state : The state where the transfer from one condition to other is constant.

Water activity : It is the equilibrium relative humidity (ERH) of the product divided by 100.

Drying : It is process of removing the unbound moisture from the food products.

Moisture content : It is the quantity of water in a unit mass of a grain sample.

4.10 SOME USEFUL REFERENCES

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4.11 ANSWERS TO CHECK YOUR PROGRESS

Check Your Progress 1

Your answer should include the following points

1. Nitrogen 79%, oxygen 21%

2. Dry basis moisture content = (100 x 20)/(100-20) = 25%

3.
   - Wet bulb temperature is the temperature given by a mercury thermometer when its bulb is covered with a wet wick and exposed to unsaturated airflow.
   - The air flow passing over the wick should have a velocity of at least 4.6 m/s
   - Because of the vapour pressure difference water evaporates by using the latent heat from the wick, reducing the temperature of the covered bulb.
   - As the temperature of the wick is less than the dry bulb temperature of air, a sensible heat flows from the air to wick
   - A steady state is achieved when the heat flow from air to wick is equal to the loss of heat by wick due to water evaporation.

4. Specific vol = $\frac{0.0812(70+273)}{1}\left(\frac{1}{29}+\frac{0.02}{18}\right)$ = 0.9912 m^3/kg of dry air

5. The dew point temperature can be considered as the saturation temperature corresponding to the humidity ratio and vapour pressure of the humid air.

6. Wet bulb lines

7. Specific volume = 0.873 m^3/kg of dry air, humidity ratio = 0.0105 kg of water / kg of dry air, relative humidity = 40%, dew point temperature = 15 °C, enthalpy = 58kJ/kg of dry air

Check Your Progress 2

Your answer should include the following points

1. $1 - RH = e^{-cTM_e^n}$

   Where RH = the relative humidity, is represented as a decimal

   T = the absolute temperature, deg K

   M_e, the equilibrium moisture content, percent db.

   c an n are constants varying with the materials

2. - Water activity (a_w) is defined as the equilibrium relative humidity (ERH) of the product divided by 100. a_w is also expressed as the ratio of the partial pressure of water in the product to the vapour pressure of pure water at same temperature.
   - Water activity is an important parameter in analysis of storage stability of dehydrated food material.
   - Reducing water activity less than 0.7 prevents microbiological spoilage including mold, yeast and bacterial growth
   - Reducing water activity less than 0.3 prevents all the spoilage reactions including non-enzymatic and enzymatic reactions along with microbiological reactions.

3. Final temp = $50 - \dfrac{2436(0.02-0.013)}{1.005+1.88(0.013)} = 50\text{-}16.56 = 33.44\,^{\circ}C$