Paper No. : 04
Paper Title: Unit Operations in Food Processing
Module- 13: Introduction to Psychrometry

13.1 Introduction

Food processing operations, particularly drying operations use atmospheric air as the heating medium. To design and control such processes, it becomes inevitable to study the properties of atmospheric air. Air conditioning is another important area in food processing where the thermodynamic properties of moist air need to be judged thoroughly.

Psychrometry is the study of thermodynamic properties of air-water vapour mixture (moist air).

13.2 Properties of atmospheric Air

Atmospheric air consists of both the dry air and associated water vapour. Dry air is one which does not contain any water vapour. Dry air is composed of nitrogen (79% by volume and 77% by mass) and oxygen (21% by volume and 23% by mass). Other gases like carbon dioxide, hydrogen, argon, ozone etc. are present in trace amount. All the properties in psychrometry are derived with an assumption that, dry air behaves like an ideal gas. Since at normal temperature and pressure, these mixture of gases do not change their states, they can be considered as a single gas in the name of 'dry air'. The apparent molecular weight of dry air is 28.9645 and gas constant is 287.055 m^3Pa/kgK. The molecular weight of water is 18.01534.

Specific volume of Air and water vapour

Ideal gas law is followed to determine the specific volume of dry air. The specific volume (m^3/kg) can be expressed as $V_a = \frac{R_a T_a}{p_a}$

Where, R_a is the Gas constant (m^3Pa/kgK), T_a is the absolute temperature (K) and p_a is the partial pressure of dry air (kPa).

Specific volume of water vapour can also be determined following Gas law, since the superheated or saturated vapour behaves like an ideal gas below a temperature of 66^0C.

$V_w = \frac{R_w T_a}{p_w}$

Where, R_w and p_w are the gas constant and partial pressure of water vapour respectively.

Specific Heat of Air and water vapour

Specific heat is the heat required to raise the temperature to one unit of a unit mass of air. The average specific heat of dry air at one atmospheric temperature is c_{pa}=1.005 *kJ/kgK*. The specific heat of water vapour is c_{pw}=1.88 *kJ/kgK*.

Enthalpy of of Air and water vapour

Enthalpy is the amount of heat contained in air. The enthalpy of air at a reference temperature T_0 is given by,

$h_a = c_{pa}(T_a - T_0)$ or, $h_a = 1.005\ (T_a - T_0)$

The enthalpy of water vapour is associated with both the sensible heat and latent heat. So, the equation will be,

$$h_w = \lambda_w + 1.88\ (T_a - T_0)$$

In psychrometric calculations the reference temperature taken is 0^0C at one barometric pressure. The latent heat λ_w at this temperature is 2501.4 *kJ/kg*.

Dry bulb Temperature

The temperature sensed by an ordinary thermometer when in thermal equilibrium with air is called dry bulb temperature (DBT). DBT is the common reference for specifying normal air temperature.

13.3 Properties of air-water vapour mixture

The food engineers are more interested in the properties of air water vapour mixture rather to the independent properties. The important properties are discussed as follows.

Partial pressure

Air water vapour mixture does not follow perfect gas law. However, for up to 3 atmospheric pressure, Gas law can be used with sufficient accuracy.

Gibbs-Dalton law states that the total pressure exerted by a mixture of air water vapour is same as that exerted by the individual components independently.

$$p = p_a + p_v$$

Where, p is the total pressure, p_a and p_v are the partial pressure of dry air and water vapour respectively. If the mole fractions of air and vapour are x_a and x_v, the partial pressure can be represented as,

$$p_a = x_a p$$
$$p_v = x_v p$$

Saturated vapour pressure

With an increase in temperature of air, the water from liquid escapes to air as water vapour. After some time, the air is unable to take more vapour into it, i.e. the equilibrium between the air and liquid is maintained at a particular temperature. At this stage the partial pressure of water vapour is called saturated vapour pressure. So, saturated vapour pressure is the maximum vapour pressure that can occur at a given temperature.

Dew point temperature

Dew point is the temperature at which the water vapour at a particular pressure condenses to water at the same rate at which it evaporates. Condensation takes place when the temperature of air is same as the saturation temperature corresponding to the partial pressure exerted by the water vapour. This temperature is called dew point temperature. If the air water vapour cools at a fixed pressure and humidity ratio a temperature is reached when the mixture becomes saturated. Beyond this temperature if cooling continues, condensation takes place. In other words, dew point temperature is the temperature at which the vapour condenses out of air-vapour mixture. At dew point, the relative humidity is 100%.

Wet bulb temperature

Wet bulb temperature (WBT) is the temperature at which water gets evaporated and brings the air-water vapour to a state of saturation adiabatically at the same temperature. In other words, this is the minimum temperature an air-vapour mixture can achieve by addition of water to bring the relative humidity to 100%. WBT is often used to indicate how much of water can be added through evaporation to the air. WBT is also popularly known as *adiabatic saturation temperature*. WBT can be measured with a simple thermometer by wrapping the mercuric bulb of thermometer with a wet wick. One device that read the wet bulb and dry bulb temperature is **sling psychrometer**, where the thermometers are spun around in the air for a few minutes which are attached to a handle.

Two important interpretations we can make here in sling psychrometer.

- If the wet bulb temperature is *lower* than dry bulb temperature, the air-vapour mixture is said to be *unsaturated*, and
- If the wet bulb temperature is *same as* the dry bulb temperature, the air-vapour mixture is said to be *saturated*.

Humidity Ratio (H_a)

Humidity ratio is the actual amount of water present in air. It is expressed as the mass ratio of water vapour (m_v) and dry air (m_a). It is otherwise known as absolute humidity or specific humidity.

$$H_a(kg\,H_2O/kg\,dry\,air) = \frac{m_v}{m_a}$$

Addition of water vapour to dry air increases the humidity ratio of air. As we keep on adding the water, a stage will come when no more water can be contained by the air and the excess water gets condensed. This is the state of saturation of the air vapour mixture.

Humidity ratio can be expresses in terms of partial pressure of air and vapour as follows;

$$H_a = \frac{m_v}{m_a} = \frac{M_v p_v V/RT}{M_a p_a V/RT} = \frac{M_v p_v}{M_a p_a}$$

Putting the molecular weight of water and air and concerting p_a in terms of p_v we get

$$H_a = \frac{18}{29}\frac{p_v}{(p - p_v)}$$

Relative Humidity (RH)

Relative humidity is the ratio of actual vapour pressure of air to that of saturated air at the same temperature. If p_s is the partial pressure of saturated air, relative humidity can be expressed as

$$RH(\%) = \frac{p_v}{p_s} \times 100$$

Relative humidity is a relative expression of how much of water present in air to maximum amount of water can be added to air at the same temperature. So, if we go on adding water at a constant temperature, the RH will increase and eventually it will reach to 100%. Beyond this, if water is added, it will condense. Relative humidity is temperature dependent. Air can hold more water at higher temperature. That means air at 30^{0}C and 40% RH will have more water than at 20^{0}C and 40% RH. In other words, the humidity ratio at 30^{0}C will be more then that at 20^{0}C at 40%RH.

Humid Heat

Humid heat is the amount of heat required to raise the temperature of a unit mass of moist air by 1 K. Since the heat content of dry air is 1.005 kJ/kgK and that of water is 1.88 kJ/kgK, the humid heat (kJ/kg dry air K) can be represented as,

$$c_p = 1.005 + 1.88\,H_a$$

13.5 Psychrometric chart

The graphical representation of the thermodynamic properties of air-water vapour mixture is known as psychrometric chart. It is important to note here that the psychrometric charts are prepared at a single barometric pressure. The universal psychrometric charts are prepared at one barometric pressure (101.325kPa) or one atmosphere and normal temperature (0-50^{0}C). However, thermodynamic properties can be derived at different pressure and temperature profiles. ASHRAE has developed such psychrometric charts.

Chart is prepared taking absolute humidity and partial pressure as ***ordinate*** and dry bulb temperature as ***abscissa***. The thermodynamic properties appear in the chart are relative humidity, wet bulb temperature, specific volume and enthalpy. One can determine the whole state of moist air by knowing any two properties. The question arises here, which two properties are easier to determine. One obvious answer is the DBT which is in abscissa. The absolute humidity that is in coordinate is difficult to measure. Dew point temperature measurement is also not that easy. So DBT and WBT are two properties one can easily determine and other parameters can be derived from the chart. Since the enthalpy of an air-water vapour mixture remains constant during adiabatic saturation process, constant enthalpy line can be used as WBT line with approximation.

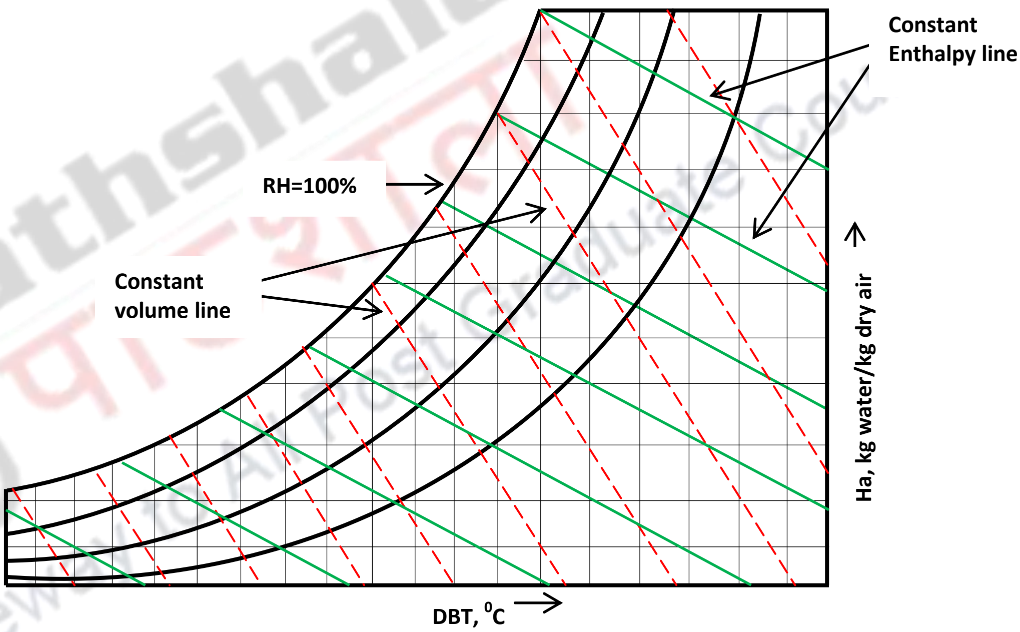


Fig.13.1: Psychrometric chart showing different properties

13.6 Use of psychrometric chart to evaluate processes

13.6.1 Sensible Heating and Cooling

This process involves only sensible heat transfer. In sensible heating or cooling the humidity ratio does not change. However, the enthalpy of the air changes which corresponds to the change in dry bulb temperature. The relative humidity increases with reduction in DBT and decreases with increase of DBT.

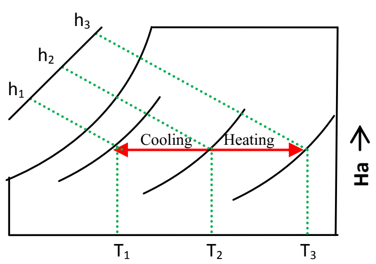


Fig.13.3: Sensible heating and cooling

Fig.13.3 depicts the process of sensible heating and cooling. With a reduction of temperature from T_2 to T_1 reduces the enthalpy from h_2 to h_1. So, the heat transfer will be

$q = h_2 - h_1$

With an increase of temperature from T_2 to T_3 increases the enthalpy from h_2 to h_3 and the corresponding heat transfer required for the change will be

$q = h_3 - h_2$

13.6.2 Cooling and Dehumidification

When the humidity ratio decreases, the process is said to be dehumidification and if the humidity ratio increases, the process is called humidification. Dehumidified air carries the advantage of higher rate of drying when used for drying food materials. Process 2 to 1 as shown in fig.13.4 represents the cooling and dehumidification. Air can be dehumidified by placing an evaporator coil across the air flow or by spraying chilled water to the air stream.

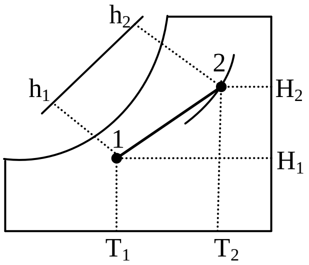


Fig.13.4 Cooling and Dehumidification

13.6.3 Drying (Evaporative cooling)

Drying of food materials involve the flow of hot air through a bed of moist food granules. This is an *adiabatic process* meaning no energy is transferred to or from the system. However, the energy is transferred from sensible heat to latent heat to evaporate the water from the food material. As shown in fig13.5, during adiabatic cooling process the enthalpy remains constant and DBT decreases. Constant enthalpy line gives a constant WBT. Since moisture gain occurs in course of time, the humidity ratio increases. Point 1 to 2 in fig 13.5 is an example of evaporative cooling.

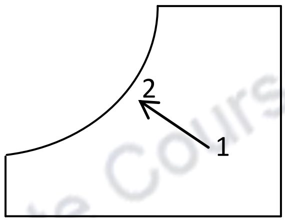


Fig.13.5 Evaporative cooling

13.6.4 Mixing of air

It is often seen in food processing that two air of different psychrometric properties are mixed. The mixed air properties will be different from the individual air properties. First we need to locate the positions of individual properties as shown here by points 1 and 2 (Fig.13.6). Let us assume, the two points meet at point 3 in a straight line. Doing a mass and energy balance we get

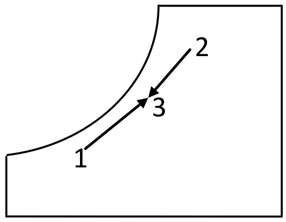


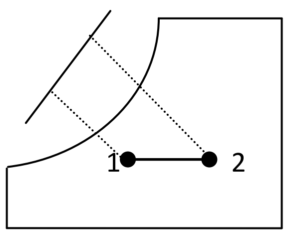
Fig.13.6 Mixing of air

$$\frac{m_1}{m_2} = \frac{H_2 - H_3}{H_3 - H_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

Point 3 can be traced by determining H_3 and h_3 from the above equation.

Numerical:

A food grain dryer operates at a temperature of 50^{0}C with an air flow rate of 350m^3/min. If the atmospheric air is at 25^{0}C and 65% RH, find out the power needed to heat the air to required temperature.



Solution:

The enthalpy of the hot air can be determined from the psychrometric chart (slanted line to left).

The condition of air at point 1 is: DBT=25^{0}C and RH=65%

The enthalpy at this point will be: h_1= 61 kJ/kg dry air

At point 2 (50^{0}C DBT), the enthalpy will be: h_2= 87 kJ/kg dry air

So, the excess heat requirement is: $h_2 - h_1$=26 kJ/kg dry air

The specific volume v_2= 1.025 m^3/kg dry air

The power requirement will be: $P = \frac{Change\ in\ enthalpy \times volumetric\ flow\ rate}{specific\ volume}$

So, $P = \frac{26\frac{kJ}{kg}}{\frac{1.025\ m^3}{kg}} \times \frac{350\ m^3}{min} \times \frac{1}{60\ s}$

P=147.96 kW

13.7 Conclusion

Study of thermodynamic properties is an important area for food engineers. This helps determine and correlate various psychrometric parameters at a given or fixed pressure level. Psychrometric chart is the graphical representation of the relationship between the various parameters like humidity ratio, dry bulb temperature, enthalpy, specific volume, relative humidity etc. drawn at 1 atmospheric pressure. Knowing ant two parameters, the other parameters can be found out from the psychrometric chart. Psychrometric chart also helps determine the properties in various processes like heating, cooling, dehumidifying, drying etc.

References:

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2. *Transport Processes and Unit Operations* (3rd Edition), C. J. Geankoplis, Prentice Hall nc. Publ., 1993.
3. *Food Process Engineering and Operations*, Z. Berk, Elsevier Publ. 2009.