Course Title	**ENGINEERING THERMODYNAMICS**
Course Code	**AMED07**
Class	**III SEM**
Section	**A**
Name of the Faculty	**Dr G.Hima Bindu**
Lecture hour and Date	
Course Outcome/s	
Topic covered	
Topic learning outcome	

OUTCOMES: Determine heat, work, internal energy, enthalpy for flow & non flow process using First Law of Thermodynamics.

Mixtures of perfect Gases:

A mixture, consisting of several pure substances, is referred to as a solution. Examples of pure substances are water, ethyl alcohol, nitrogen, ammonia, sodium chloride, and iron. Examples of mixtures are air, consisting of nitrogen, oxygen and a number of other gases, aqueous ammonia solutions, aqueous solutions of ethyl alcohol, various metal alloys. The pure substances making up a mixture are called components or constituents.

Mixture of ideal gases

Basic assumption is that the gases in the mixture do not interact with each other.

Consider a mixture with components $I = 1,2,3...$ with masses m_1, m_2, m_3 ...m_i and with $N_1, N_2, N_3, ... N_i, ...$ number of moles.

The total mixture occupies a volume V, has a total pressure P and temperature T (which is also the temperature of each of the component species)

The total mass

$$m = \sum m_i \qquad\qquad (4.1)$$

Total number of mole N

$$N = \sum N_i \qquad\qquad (4.2)$$

Mass fraction of species *i*

$$\phi_i = \frac{m_i}{m} \qquad\qquad (4.3)$$

Mole fraction of species *i*

$$Y_i = \frac{N_i}{N} \qquad\qquad (4.4)$$

The mass and number of moles of species *i* are related by

$$m_i = N_i M_i \qquad\qquad (4.5)$$

N_i is the number of moles of species i and M_i is the molar mass of species *i*

Also to be noted

$$\sum \phi_i = 1 \qquad \sum Y_i = 1$$

We can also define a molar mass of the mixture as

$$M = \frac{m}{N} = \frac{\sum N_i M_i}{N}$$ (4.7)

or,

$$M = \frac{\sum N_i}{N} M_i$$

or,

$$M = \sum Y_i M_i$$

Dalton 's Law of partial pressure

Total pressure of an ideal gas mixture is equal to the sum of the partial pressures of the constituent components, That is

$$P = \sum P_i$$ (4.9)

P is the total pressure of the mixture

P_i is the partial pressure of species i

= pressure of the species if it existed alone in the given temperature T and volume V

$$P_i = \frac{N_i \hat{R} T}{V}$$ (4.10)

$\hat{R}$ is the universal gas constant = 8.314 kJ/k mol K

Amagat's Law:

Volume of an ideal gas mixture is equal to the sum of the partial volumes

$$V = \sum V_i \qquad\qquad\qquad\qquad (4.11)$$

V = total volume of the mixture

V_i = partial volume of the species i

= volume of the species if it existed alone in the given temperature T and pressure

For an ideal gas

$$V_i = \frac{N_i \hat{R} T}{P}$$

$$V = \sum V_i = \frac{\sum N_i \hat{R} T}{P} = \frac{\hat{R} T}{P} \sum N_i = \frac{\hat{R} T}{P} N$$

$$V = \frac{N \hat{R} T}{P}$$

$$\frac{V_i}{V} = \frac{N_i \hat{R} T}{P} \frac{P}{N R T} \cdots = \frac{N_i}{N} = Y_i$$

$$\frac{V_i}{V} = Y_i$$

Volume fraction = Mole fraction

Mass based analysis is known as gravimetric analysisMole based analysis is known as molar

analysis

Mole Fraction:

The composition of a gas mixture can be described by the mole fractions of the gases present. The mole fraction (X) of any component of a mixture is the ratio of the number of moles of that component to the total number of moles of all the species present in the mixture (n_{tot}):

x_A=moles of A/total moles

   =na/ntot

=nA/(nA+nB+···)

The mole fraction is a dimensionless quantity between 0 and 1.

If $x_A=1.0$, then the sample is pure A , not a mixture.

If $x_A=0$, then no A is present in the mixture.

The sum of the mole fractions of all the components present must equal 1.

To see how mole fractions can help us understand the properties of gas mixtures, let's evaluate the ratio of the pressure of a gas A to the total pressure of a gas mixture that contains A . We can use the ideal gas law to describe the pressures of both gas A and the mixture: $P_A=n_ART/V$ and $P_{tot}=n_tRT/V$. The ratio of the two is thus

$P_A/P_{tot}= n_A/n_{tot}=x_A$

$P_A=X_AP_{tot}$

Mass Fraction:

the mass fraction of a substance within a mixture is the ratio of the mass of that substance to the total mass of the mixture.

Expressed as a formula, the mass fraction is

According to the conservation of mass, we have:

To change from a mass fraction analysis to a mole fraction analysis, we can show that

$$y_i = \frac{mf_i / M_i}{\sum_{i=1}^{k} mf_i / M_i}$$

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Psychrometric Properties:

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

Saturated vapour pressure (psat) is the saturated partial pressure of water vapour at the dry bulb temperature. This is readily available in thermodynamic tables and charts.
ASHRAE suggests the following regression equation for saturated vapour pressure of water, which is valid for 0 to 100°C.

Relative humidity (Φ) 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 and pressure. Using perfect gas equation we can show that:

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

Relative humidity is normally expressed as a percentage. When Φ is 100 percent, the air is saturated.

Humidity ratio (W): The humidity ratio (or specific humidity) W is the mass of water associated with each kilogram of dry air[1]. Assuming both water vapour and dry air to be perfect gases[2], the humidity ratio is given by:

$$W = \frac{\text{kg of water vapour}}{\text{kg of dry air}} = \frac{p_v V / R_v T}{p_a V / R_a T} = \frac{p_v / R_v}{(p_t - p_v)/R_a}$$

Substituting the values of gas constants of water vapour and air R_v and R_a in the above equation; the humidity ratio is given by:

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

For a given barometric pressure p_t, given the DBT, we can find the saturated vapour pressure p_{sat} from the thermodynamic property tables on steam. Then using the above equation, we can find the humidity ratio at saturated conditions, W_{sat}.

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

Dew-point temperature: If unsaturated moist air is cooled at constant pressure, then the temperature at which the moisture in the air begins to condense is known as _dew-point temperature (DPT)_ of air. An approximate equation for dew-point temperature is given by:

$$DPT = \frac{4030(DBT + 235)}{4030 - (DBT + 235)\ln\phi} - 235$$

where Φ is the relative humidity (in fraction). DBT & DPT are in °C. Of course, since from its definition, the dew point temperature is the saturation temperature corresponding to the vapour pressure of water vapour, it can be obtained from steam tables

Degree of saturation μ: The degree of saturation 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.,

$$\mu = \left.\frac{W}{W_s}\right|_{t,P}$$

Enthalpy: The enthalpy of moist air is the sum of the enthalpy of the dry air and the enthalpy of the water vapour. Enthalpy values are always based on some reference value. For moist air, the enthalpy of dry air is given a zero value at 0°C, and for water vapour the enthalpy of saturated water is taken as zero at 0°C.
The enthalpy of moist air is given by:

$$h = h_a + W h_g = c_p t + W(h_{fg} + c_{pw} t)$$

where
c_p = specific heat of dry air at constant pressure, kJ/kg.K
c_{pw} = specific heat of water vapor, kJ/kg.K
t = Dry-bulb temperature of air–vapor mixture, °C
W = Humidity ratio, kg of water vapor/kg of dry air
h_a = enthalpy of dry air at temperature t, kJ/kg
h_g = enthalpy of water vapor³ at temperature t, kJ/kg
h_{fg} = latent heat of vaporization at 0°C, kJ/kg

The unit of h is kJ/kg of dry air. Substituting the approximate values of c_p and h_g, we obtain:

$$h = 1.005\, t + W(2501 + 1.88t)$$

Humid specific heat: From the equation for enthalpy of moist air, the humid specific heat of moist air can be written as:

$$c_{pm} = c_p + W.c_{pw}$$

$$v = \frac{R_a T}{p_a} = \frac{R_a T}{p_t - p_v} \quad \text{m}^3 / \text{kg dry air}$$

where
c_{pm} = humid specific heat, kJ/kg.K
c_p = specific heat of dry air, kJ/kg.K
c_{pw} = specific heat of water vapor, kJ/kg
W = humidity ratio, kg of water vapor/kg of dry air

Since the second term in the above equation ($w.c_{pw}$) is very small compared to the first term, for all practical purposes, the humid specific heat of moist air, c_{pm} can be taken as 1.0216 kJ/kg dry air.K

Specific volume: The specific volume is defined as the number of cubic meters of moist air per kilogram of dry air. From perfect gas equation since the volumes occupied by the individual substances are the same, the specific volume is also equal to the number of cubic meters of dry air per kilogram of dry air, i.e.,

Psychrometric chart

A *Psychrometric chart* graphically represents the thermodynamic properties of moist air. Standard psychrometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapour pressure or humidity ratio (ordinate). The Left Hand Side of the psychrometric chart is bounded by the saturation line. Figure 27.2 shows the schematic of a psychrometric chart. Psychrometric charts are readily available for <u>standard barometric pressure of 101.325 kPa at sea level and for normal temperatures (0-50°C)</u>. ASHRAE has also developed psychrometric charts for other temperatures and barometric pressures (for low temperatures: -40 to 10°C, high temperatures 10 to 120°C and very high temperatures 100 to 120°C)
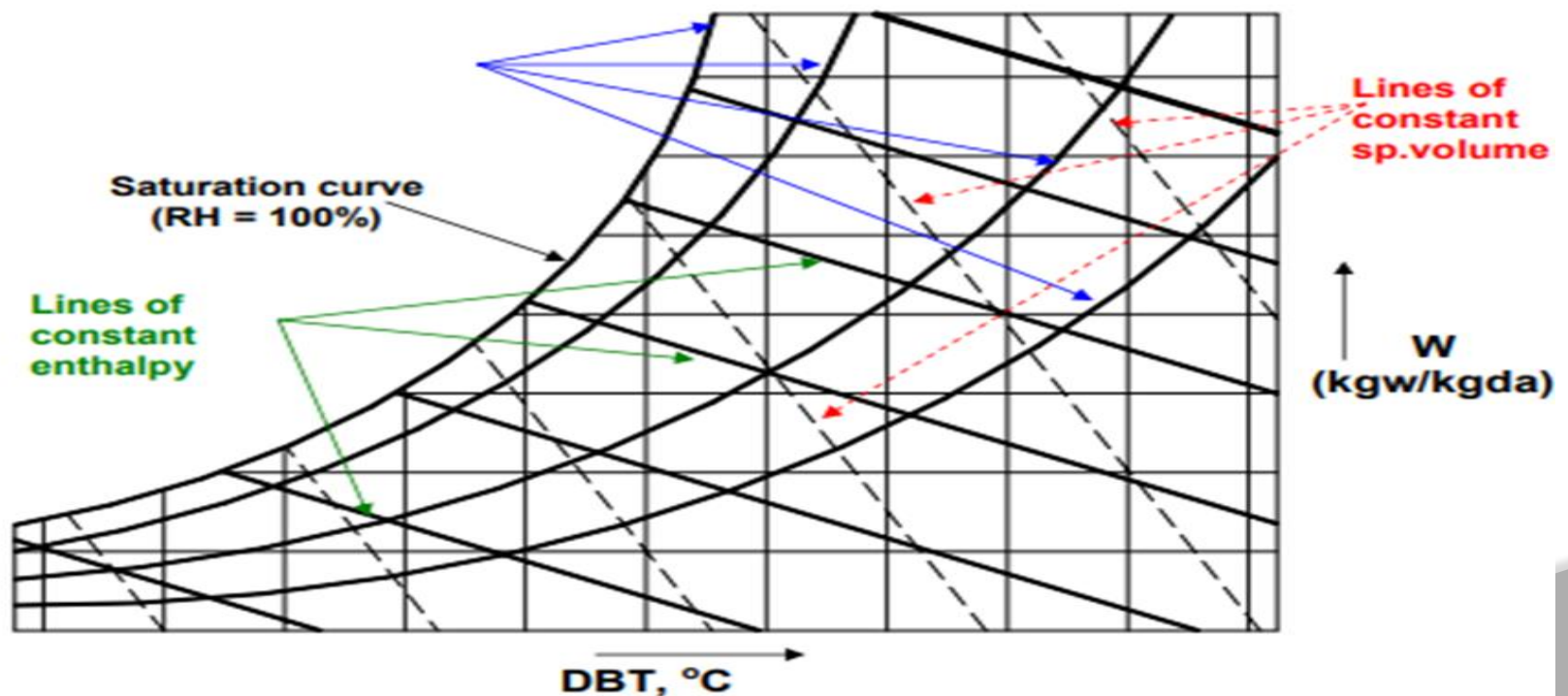
Schematic of a psychrometric chart for a given barometric pressure

Measurement of psychrometric properties:

Based on Gibbs' phase rule, the thermodynamic state of moist air is uniquely fixed if the barometric pressure and two other independent properties are known. This means that 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 (DBT), as the measurement of this temperature is fairly simple and accurate. The accurate measurement of other independent parameters such as humidity ratio is very difficult in practice. Since measurement of temperatures is easier, it would be convenient if the other independent parameter is also a temperature. Of course, this could be the dew-point temperature (DPT), but it is observed that accurate measurement of dew-point temperature is difficult. In this context, a new independent temperature parameter called the *wet-bulb temperature* (WBT) is defined. Compared to DPT, it is easier to measure the wet-bulb temperature of moist air. Thus knowing the dry-bulb and wet-bulb temperatures from measurements, it is possible to find the other properties of moist air.

To understand the concept of wet-bulb temperature, it is essential to understand the process of combined heat and mass transfer.

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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 as shown in Fig.27.6. 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, in stead it will be point 2 on the straight line joining 1 and i, provided the temperature of water on the wet bulb is i. 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 thermometer is equal to the thermodynamic wet-bulb temperature[4]. For other gas-vapor mixtures, there can be appreciable difference between the thermodynamic and actual wet-bulb temperatures.
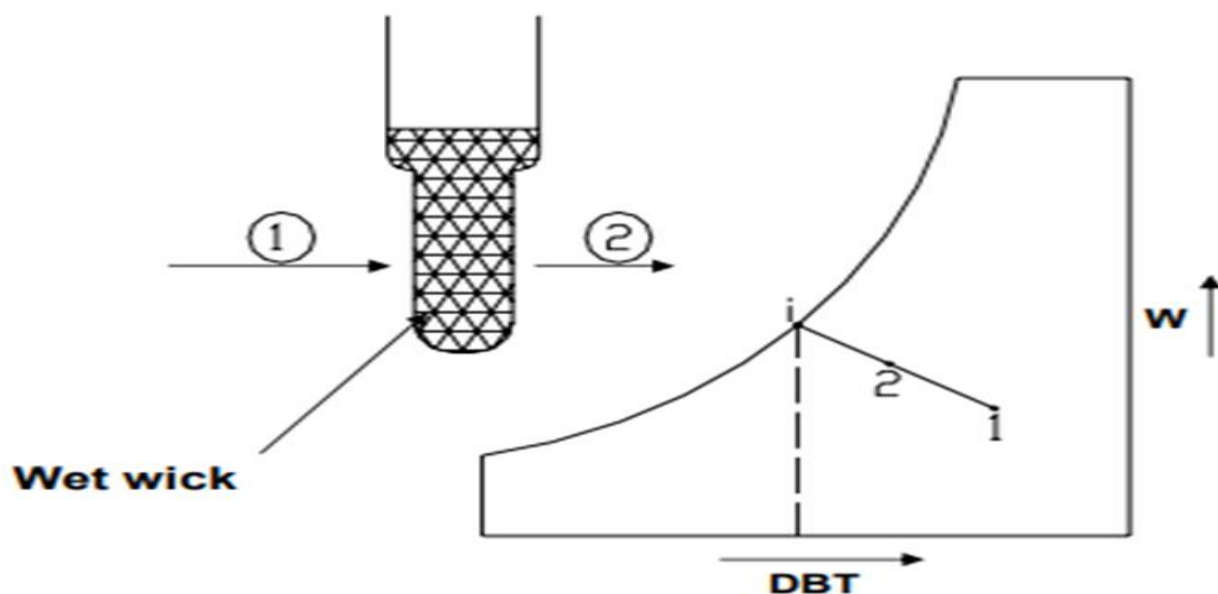
Schematic of a wet-bulb thermometer and the process
on psychrometric chart

Calculation of psychrometric properties from p, DBT and WBT:

As mentioned before, to fix the thermodynamic state of moist air, we need to know three independent properties. The properties that are relatively easier to measure, are: the barometric pressure, dry-bulb temperature and wet-bulb temperature. For a given barometric pressure, knowing the dry bulb and wet bulb temperatures, all other properties can be easily calculated from the psychrometric equations. The following are the empirical relations for the vapor pressure of water in moist air:

i) Modified Apjohn equation:

$$p_v = p_v' - \frac{1.8p(t - t')}{2700} \qquad (27.15)$$

ii) Modified Ferrel equation:

$$p_v = p_v' - 0.00066p(t - t')\left[1 + \frac{1.8t}{1571}\right] \qquad (27.16)$$

iii) Carrier equation:

$$p_v = p_v' - \frac{1.8(p - p_v')(t - t')}{2800 - 1.3(1.8t + 32)} \qquad (27.17)$$

where t = dry bulb temperature, °C
  t' = wet bulb temperature, °C
  p = barometric pressure
  p_v = vapor pressure
  p_v' = saturation vapor pressure at wet-bulb temperature

The units of all the pressures in the above equations should be consistent.

Once the vapor pressure is calculated, then all other properties such as relative humidity, humidity ratio, enthalpy, humid volume etc. can be calculated from the psychrometric equations presented earlier.

Psychrometer:

Any instrument capable of measuring the psychrometric state of air is called a psychrometer. As mentioned before, in order to measure the psychrometric state of air, it is required to measure three independent parameters. Generally two of these are the barometric pressure and air dry-bulb temperature as they can be measured easily and with good accuracy.

Two types of psychrometers are commonly used. Each comprises of two thermometers with the bulb of one covered by a moist wick. The two sensing bulbs are separated and shaded from each other so that the radiation heat transfer between them becomes negligible. Radiation shields may have to be used over the bulbs if the surrounding temperatures are considerably different from the air temperature.

5. On a particular day the weather forecast states that the dry bulb temperature is 37°C, while the relative humidity is 50% and the barometric pressure is 101.325 kPa. Find the humidity ratio, dew point temperature and enthalpy of moist air on this day.

Ans.:

At 37°C the saturation pressure (p_s) of water vapour is obtained from steam tables as **6.2795 kPa.**

Since the relative humidity is 50%, the vapour pressure of water in air (p_v) is:

$$p_v = 0.5 \times p_s = 0.5 \times 6.2795 = 3.13975 \text{ kPa}$$

the humidity ratio W is given by:

$$W = 0.622 \times p_v/(p_t - p_v) = 0.622 \times 3.13975/(101.325 - 3.13975) = 0.01989 \text{ kgw/kgda}$$

(Ans.)

The enthalpy of air (h) is given by the equation:

$$h = 1.005t + W(2501 + 1.88t) = 1.005 \times 37 + 0.01989(2501 + 1.88 \times 37) = 88.31 \text{ kJ/kgda}$$

(Ans.)

7. Moist air at 1 atm. pressure has a dry bulb temperature of 32°C and a wet bulb temperature of 26°C. Calculate a) the partial pressure of water vapour, b) humidity ratio, c) relative humidity, d) dew point temperature, e) density of dry air in the mixture, f) density of water vapour in the mixture and g) enthalpy of moist air using perfect gas law model and psychrometric equations.

Ans.:

a) Using modified Apjohn equation and the values of DBT, WBT and barometric pressure, the vapour pressure is found to be:

p_v = 2.956 kPa   (Ans.)

b) The humidity ratio W is given by:

W = 0.622 x 2.956/(101.325-2.956) = 0.0187 kgw/kgda   (Ans.)

c) Relative humidity RH is given by:

RH = (p_v/p_s) x 100 = (p_v/saturation pressure at 32°C) x 100

From steam tables, the saturation pressure of water at 32°C is **4.7552 kPa**, hence,

RH = (2.956/4.7552) x 100 = 62.16%   (Ans.)

d) Dew point temperature is the saturation temperature of steam at 2.956 kPa. Hence using steam tables we find that:

DPT = T_{sat}(2.956 kPa) = 23.8°C   (Ans.)

e) Density of dry air and water vapour

Applying perfect gas law to dry air:

Density of dry air $\rho_a = (p_a/R_aT) = (p_t - p_v)/R_aT = (101.325 - 2.956)/(287.035 \times 305) \times 10^3$

$$= 1.1236 \text{ kg/m}^3 \text{ of dry air} \qquad \text{(Ans.)}$$

f) Similarly the density of water vapour in air is obtained using perfect gas law as:

Density of water vapour $\rho v = (p_v/R_vT) = 2.956 \times 10^3/(461.52 \times 305) = 0.021 \text{ kg/m}^3$

$$\text{(Ans.)}$$

g) Enthalpy of moist air is found from the equation:

$$h = 1.005 \times t + W(2501 + 1.88 \times t) = 1.005 \times 32 + 0.0187(2501 + 1.88 \times 32)$$
$$h = 80.05 \text{ kJ/kg of dry air} \qquad \text{(Ans.)}$$