

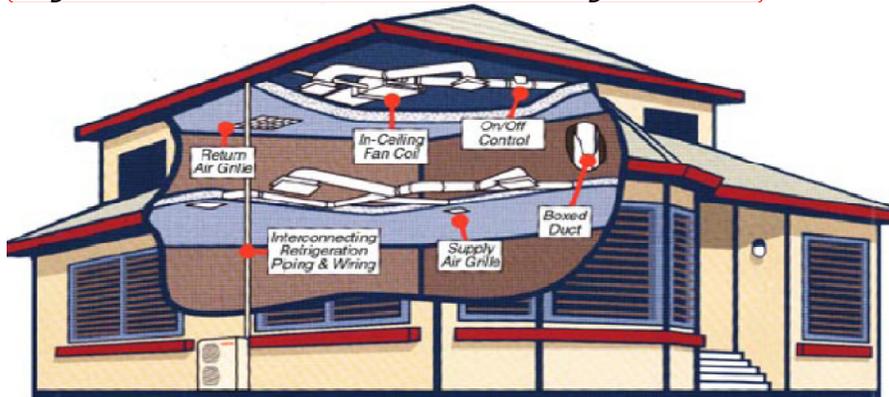
Fundamentals of Heating, Ventilating, and Air-Conditioning

The first chapters review HVAC system processes and equipment, control system types and equipment, and equipment-to-control interactions. The succeeding chapters cover specific control system functions including electrical interlock, motor starting, electrical and electronic control system diagrams, pneumatic control system diagrams, maintenance of electric and electronic control systems, maintenance of pneumatic control systems, testing direct digital control (DDC) systems, and training operating and maintenance personnel.

This book is to provide guidance in the operation and maintenance of all types of ATC (Automatic Temperature Control) systems. With the rapid increase in installations of DDC systems, it became necessary to include material that will provide basic coverage of DDC systems.

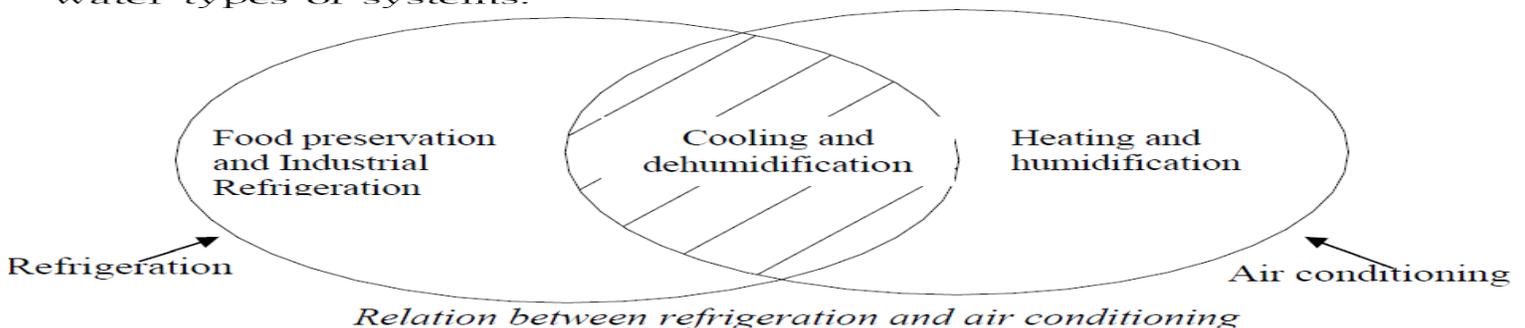
This book includes basic procedures in the operation and maintenance of DDC systems, particularly in the initial checkout and operator training on newly installed systems. Those procedures are also applicable to the recommissioning of existing DDC systems and in recurrent training of DDC system operators and maintenance technicians.

Basic Functions of HVAC Systems and Control Systems



The purpose of Heating, Ventilating, and Air Conditioning (HVAC) system is to provide and maintain comfortable environment within a building for the occupants or a suitable environment for the process being conducted.

This book covers basic HVAC systems of the all-air type, where all functions of heating, ventilating, and air conditioning are performed by an air handling system. Some functions for central hydronic cooling and heating distribution are included which also apply to air-water and all-water types of systems.



The principal functions of HVAC systems and control systems are:

- To maintain comfortable conditions in the space by providing the desired cooling and heating outputs, while factors which affect the cooling and heating outputs vary.
- To maintain comfortable conditions while using the least amount of energy.
- To operate the HVAC system so as to provide a healthy environment for occupants and safe conditions for equipment.

The ability of a system operator to diagnose and correct automatic temperature control (ATC) system operating problems requires a working knowledge of HVAC system types, the components of HVAC systems, the intended function of those components in the HVAC system, and the HVAC equipment-to-control interactions. Many problems which are considered to be HVAC system design problems are found to be ATC system operating problems.

In order to determine whether ATC system is functioning properly, it is necessary to determine how control sequence is intended to function.

Although HVAC systems must be designed to satisfy the maximum cooling and heating loads at design conditions, HVAC systems do not operate at full capacity very often. Systems seem to operate for most hours of the year at near half capacity, with variations due to changes in outside conditions for time-of-day and time-of-year and to changes in internal heat releases. The ATC system must be designed, set up, and operated to recognize changes and to maintain the space temperature at partial load.

Psychrometry

The specific objectives of this lecture are to:

1. Define psychrometry and the composition of moist air (*Section 27.1*)
2. Discuss the methods used for estimating properties of moist air (*Section 27.2*)
3. Present perfect gas law model for moist air (*Section 27.2.1*)
4. Define important psychrometric properties (*Section 27.2.2*)
5. Present graphical representation of psychrometric properties on a psychrometric chart (*Section 27.2.3*)
6. Discuss measurement of psychrometric properties (*Section 27.3*)
7. Discuss straight-line law as applied to air-water mixtures (*Section 27.3.1*)
8. Discuss the concept of adiabatic saturation and thermodynamic wet bulb temperature (*Section 27.3.2*)
9. Describe a wet-bulb thermometer (*Section 27.3.3*)
10. Discuss the procedure for calculating psychrometric properties from measured values of barometric pressure, dry bulb and wet bulb temperatures (*Section 27.4*)
11. Describe a psychrometer and the precautions to be taken while using psychrometers (*Section 27.5*)

ILO's :At the end of the lecture, the student should be able to:

1. Define psychrometry and atmospheric air
2. Use perfect gas law model and find the total pressure of air from partial pressures of dry air and water vapour
3. Define and estimate psychrometric properties
4. Draw the schematic of a psychrometric chart
5. Discuss the straight-line law and its usefulness in psychrometry
6. Explain concepts of adiabatic saturation and thermodynamic wet bulb temperature
7. Differentiate between thermodynamic WBT and WBT as measured by a wet bulb thermometer
8. Estimate various psychrometric properties given any three independent properties
9. Describe a psychrometer

27.1. Introduction:

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

Psychrometry is the study of the properties of mixtures of air and water vapour.

Atmospheric air is a mixture of many gases plus water vapour and a number of pollutants (Fig.27.1). The amount of water vapour and pollutants vary from place to place. The concentration of water vapour and pollutants decrease with altitude, and above an altitude of about 10 km, atmospheric air consists of only dry air. The pollutants have to be filtered out before processing the air. Hence, what we process is essentially a mixture of various gases that constitute air and water vapour. This mixture is known as *moist air*.

The moist air can be thought of as a mixture of dry air and moisture. For all practical purposes, the composition of dry air can be considered as constant. In 1949, a standard composition of dry air was fixed by the International Joint Committee on Psychrometric data. It is given in Table 27.1.

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

Table 27.1: Composition of standard air

Based on the above composition the *molecular weight of dry air is found to be 28.966 and the gas constant R is 287.035 J/kg.K.*

As mentioned before the air to be processed in air conditioning systems is a mixture of dry air and water vapour. While the composition of dry air is constant, the amount of water vapour present in the air may vary from zero to a maximum depending upon temperature and pressure of mixture (dry air + water vapour).

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 is known as saturated air, 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.

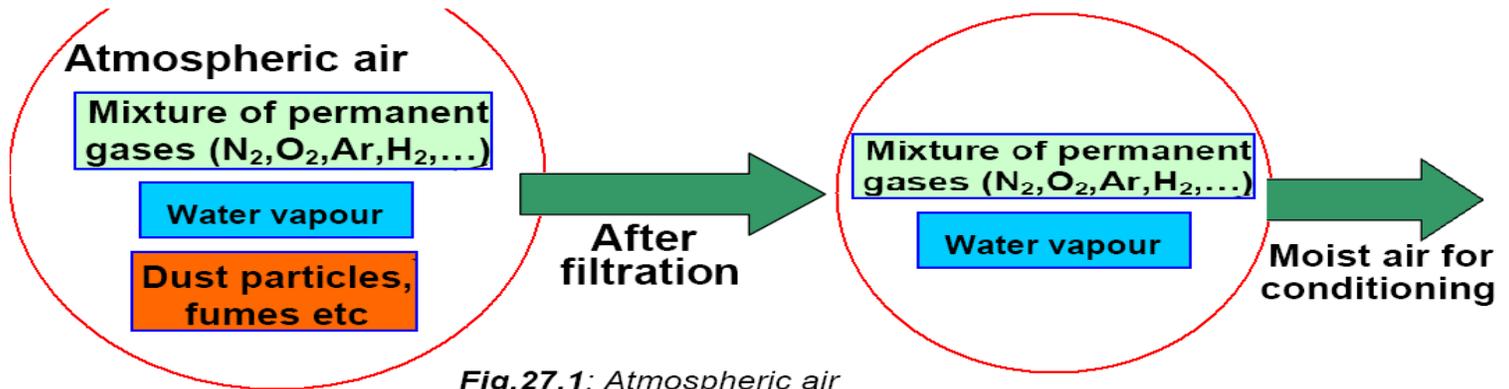


Fig.27.1: Atmospheric air

27.2. Methods for estimating properties of moist air:

In order to perform air conditioning calculations, it is essential first to estimate various properties of air. It is difficult to estimate the exact property values of moist air as it is a mixture of several permanent gases and water vapour. However, moist air upto 3 atm. pressure is found to obey perfect gas law with accuracy sufficient for engineering calculations. For higher accuracy Goff and Gratch tables can be used for estimating moist air properties. These tables are obtained using mixture models based on fundamental principles of statistical mechanics that take into account the real gas behaviour of dry air and water vapour. However, these tables are valid for a barometric pressure of 1 atm. only. Even though the calculation procedure is quite complex, using the mixture models it is possible to estimate moist air properties at other pressures also. However, since in most cases the pressures involved are low, one can apply the perfect gas model to estimate psychrometric properties.

27.2.1. Basic gas laws for moist air:

According to the Gibbs-Dalton law for a mixture of perfect gases, the total pressure exerted by the mixture is equal to the sum of partial pressures of the constituent gases. According to this law, for a homogeneous perfect gas mixture occupying a volume V and at temperature T , each constituent gas behaves as though the other gases are not present (i.e., there is no interaction between the gases). Each gas obeys perfect gas equation. Hence, the partial pressures exerted by each gas, $p_1, p_2, p_3 \dots$ and the total pressure p_t are given by:

$$p_1 = \frac{n_1 R_u T}{V}; p_2 = \frac{n_2 R_u T}{V}; p_3 = \frac{n_3 R_u T}{V} \dots \dots \quad (27.1)$$

$$p_t = p_1 + p_2 + p_3 + \dots \dots$$

where n_1, n_2, n_3, \dots are the number of moles of gases 1, 2, 3, ...

Applying this equation to moist air.

$$p = p_t = p_a + p_v \quad (27.2)$$

where $p = p_t =$ total barometric pressure **of the moist air**

$p_a =$ partial pressure of dry air

$p_v =$ partial pressure of water vapour

27.2.2. Important psychrometric properties:

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

درجة الحرارة الجافة **Dry Bulb Temperature (db)** الحرارة المقاسة بواسطة الترمومتر العادي.

Wet Bulb Temperature (wb) درجة الحرارة الرطبة

درجة الحرارة الرطبة عبارة عن أقل درجة حرارة يقيسها الترمومتر الرطب. الترمومتر الرطب عبارة عن ترمومتر زئبقي عادي بصيغته مغطاة بقطعة قماش مبللة. أحيانا تعرف درجة الحرارة الرطبة بدرجة حرارة التشبع الأدياباتية (adiabatic saturation temperature) وذلك لأن الحرارة اللازمة لتبخير الماء من قطعة القماش تؤخذ كلها من الهواء الجوي الذي يمر خلالها عندما تصل قراءة الترمومتر الرطب إلى أقل قيمة لها. وهي تعبر عن التأثير التبريدي لتبخير المياه.

درجة الحرارة الجافة (db) ودرجة الحرارة الرطبة (wb) تقاس في كثير من الأحيان بجهاز واحد يعرف بالمتلاع (sling psychrometer) كما في الشكل التالي:



شكل (٢ - ٣): المتلاع

Saturated vapour pressure (p_{sat}) 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.

$$\ln(p_{sat}) = \frac{c_1}{T} + c_2 + c_3 T + c_4 T^2 + c_5 T^3 + c_6 \ln(T) \quad (27.3)$$

where p_{sat} = saturated vapor pressure of water in kiloPascals

T = temperature in K

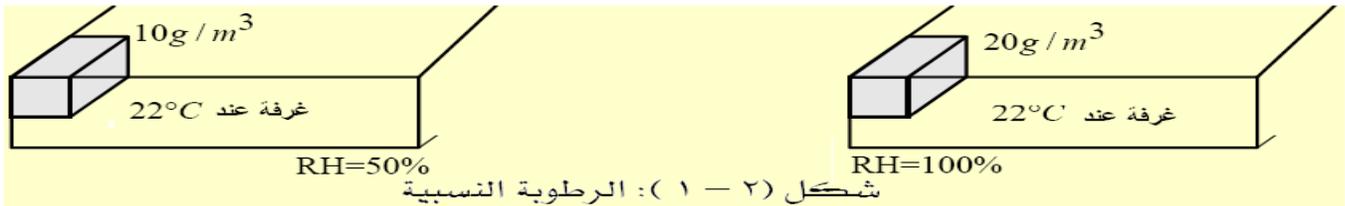
The regression coefficients c_1 to c_6 are given by:

$$c_1 = -5.80022006E+03, c_2 = -5.516256E+00, c_3 = -4.8640239E-02 \\ c_4 = 4.1764768E-05, c_5 = -1.4452093E-08, c_6 = 6.5459673E+00$$

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:

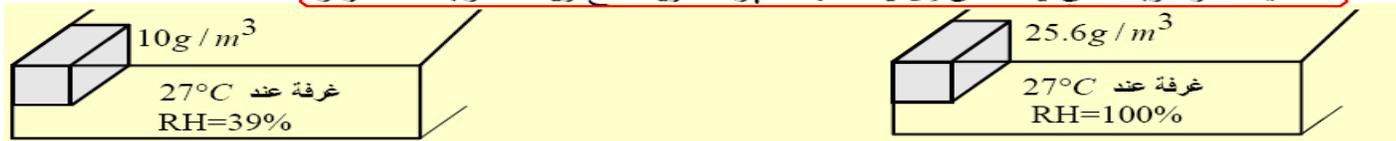
Relative Humidity (RH) الرطوبة النسبية

هي مقياس لنسبة كمية رطوبة الهواء إلى الكمية القصوى التي يمكن أن يحملها الهواء عند نفس درجة الحرارة. كمية الرطوبة التي يمكن أن يحملها الهواء تزيد مع درجة الحرارة. في الشكل التالي:



إذا كانت كمية الرطوبة الموجودة في غرفة تساوي $10g/m^3$ عند درجة حرارة $22^\circ C$. ثم أضيفت رطوبة إلى هواء الغرفة حتى وصل إلى درجة التشبع بحيث لا يتقبل أي زيادة في كمية الرطوبة. ووجد إن كمية الرطوبة بعد التشبع وعند نفس درجة الحرارة هي $20g/m^3$ عليه تكون الرطوبة النسبية للهواء هي: $RH = \frac{10}{20} = 0.50 = 50\%$

كمية الرطوبة التي يمكن أن يحملها الهواء تزيد مع زيادة درجة الحرارة



شكل (٢ - ٢): زيادة رطوبة الهواء مع درجة الحرارة

فمثلا عند $27^\circ C$ نجد إن كمية الرطوبة التي يمكن أن يتحملها الهواء تصل إلى $25.6g/m^3$ بدلا من $20g/m^3$ ، عليه إذا كانت كمية الرطوبة الموجودة في الحيز تساوي $10g/m^3$ فإن الرطوبة النسبية حينئذ تكون: $RH = \frac{10}{25.6} = 0.39 = 39\%$

ومن تعريف الرطوبة يمكن كتابتها كما يلي: $RH = \frac{m_v}{m_g}$

وباعتبار ضغط التشبع عند درجة الحرارة T هو P_g وضغط بخار الماء هو P_v ؛ وبالتالي

$$0 \leq RH \leq 1 \quad RH = \frac{P_v}{P_g}$$

أما الإنثالبي للهواء فهي $h = h_a + \omega h_{fg} = c_p T + \omega h_{fg}$

$$\phi = \frac{\text{partial pressure of water vapour}}{\text{saturation pressure of pure water vapour at same temperature}} = \frac{p_v}{p_{\text{sat}}} \quad (27.4)$$

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 air¹. Assuming both water vapour and dry air to be perfect gases², the humidity ratio is given by:

$$W = \frac{\text{kg of water vapour}}{\text{kg of dry air}} = \frac{p_v V / R_v T}{p_a V / R_a T} = \frac{p_v / R_v}{(p_t - p_v) / R_a} \quad (27.5)$$

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:

$$W = 0.622 \frac{p_v}{p_t - p_v} \quad (27.6)$$

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:

$$\text{DPT} = \frac{4030(\text{DBT} + 235)}{4030 - (\text{DBT} + 235) \ln \phi} - 235 \quad (27.7)$$

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 or using Eqn.(27.3).

¹ Properties such as humidity ratio, enthalpy and specific volume are based on 1 kg of dry air. This is useful as the total mass of moist air in a process varies by the addition/removal of water vapour, but the mass of dry air remains constant.

² Dry air is assumed to be a perfect gas as its temperature is high relative to its saturation temperature, and water vapour is assumed to be a perfect gas because its pressure is low relative to its saturation pressure. These assumptions result in accuracies, that are, sufficient for engineering calculations (less than 0.7 percent as shown by Threlkeld). However, more accurate results can be obtained by using the data developed by Goff and Gratch in 1945.

الرطوبة النوعية (Specific Humidity ω) الرطوبة النوعية (أو الرطوبة المطلقة) هي مقدار كمية الرطوبة في الهواء لكل 1 kg من الهواء الرطب (أو الهواء الجاف بإهمال وزن الماء بالمقارنة لوزن الهواء).

حيث: $\omega = \frac{m_v}{m_a}$ كمية الرطوبة في الهواء بوحدة kg. كتلة الهواء بوحدة kg

وباستعمال قانون الغازات العام: كتلة الرطوبة $m_v = \frac{p_v V_v}{R_v T_v}$ كتلة الهواء $m_a = \frac{p_a V_a}{R_a T_a}$ الرطوبة النوعية $\omega = \frac{m_v}{m_a} = \frac{p_v V_v}{R_v T_v} \times \frac{R_a T_a}{p_a V_a}$ لكن من قانون دالتون $T_{\text{mixture}} = T_a = T_v$ $V_{\text{mixture}} = V_a = V_v$

إذن عليه تكون الرطوبة النوعية $\omega = \frac{m_v}{m_a} = \frac{p_v}{p_a} \times \frac{R_a}{R_v}$

وبافتراض إن الضغط الجوي (p) يمكن كتابة الضغوط حسب قانون دالتون كالآتي: $p = p_a + p_v$ أو $p_a = p - p_v$ وبما أن: $\frac{R_a}{R_v} = \frac{R}{28.9} \times \frac{18}{R} = 0.622$

ومن ثم يمكن كتابة الرطوبة النوعية كالآتي: $\omega = \frac{m_v}{m_a} = 0.622 \frac{p_v}{p - p_v}$

ومن هنا يتضح إن الرطوبة النسبية تتناسب مع ضغط البخار (p_v).

عليه يتحمل الهواء قدر معين من بخار الماء، وأقصى حد يتحملة الهواء عندما تصل p_v إلى درجة التشبع عندئذ يكون الهواء مشبعاً، وزيادة أي رطوبة في الهواء تؤدي إلى التكثيف.

Degree of saturation μ : The degree of saturation is the ratio of the humidity ratio W to the humidity ratio of saturated mixture W_s at same temperature and pressure, i.e.,

$$\mu = \frac{W}{W_s} \bigg|_{t,P} \quad (27.8)$$

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:

$$h = h_a + Wh_g = c_p t + W(h_{fg} + c_{pw} t) \quad (27.9)$$

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, $^\circ\text{C}$

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

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

$$h = 1.005 t + W(2501 + 1.88t) \quad (27.10)$$

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

$$c_{pm} = c_p + W.c_{pw} \quad (27.11)$$

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.,

$$v = \frac{R_a T}{p_a} = \frac{R_a T}{p_t - p_v} \quad \text{m}^3 / \text{kg dry air} \quad (27.12)$$

³ Though the water vapor in moist air is likely to be superheated, no appreciable error results if we assume it to be saturated. This is because of the fact that the constant temperature lines in the superheated region on a Mollier chart (h vs s) are almost horizontal.

27.2.3. 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 standard barometric pressure of 101.325 kPa at sea level and for normal temperatures (0-50 $^\circ\text{C}$). 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)

الخريطة السيكرومترية:

الخريطة السيكرومترية هي أداة تسهل تحديد خصائص الهواء الرطب عند الضغط الجوي عند مختلف أحوال التبريد والتدفئة كما أنها تسهل وتوضح عمليات التكييف المختلفة.

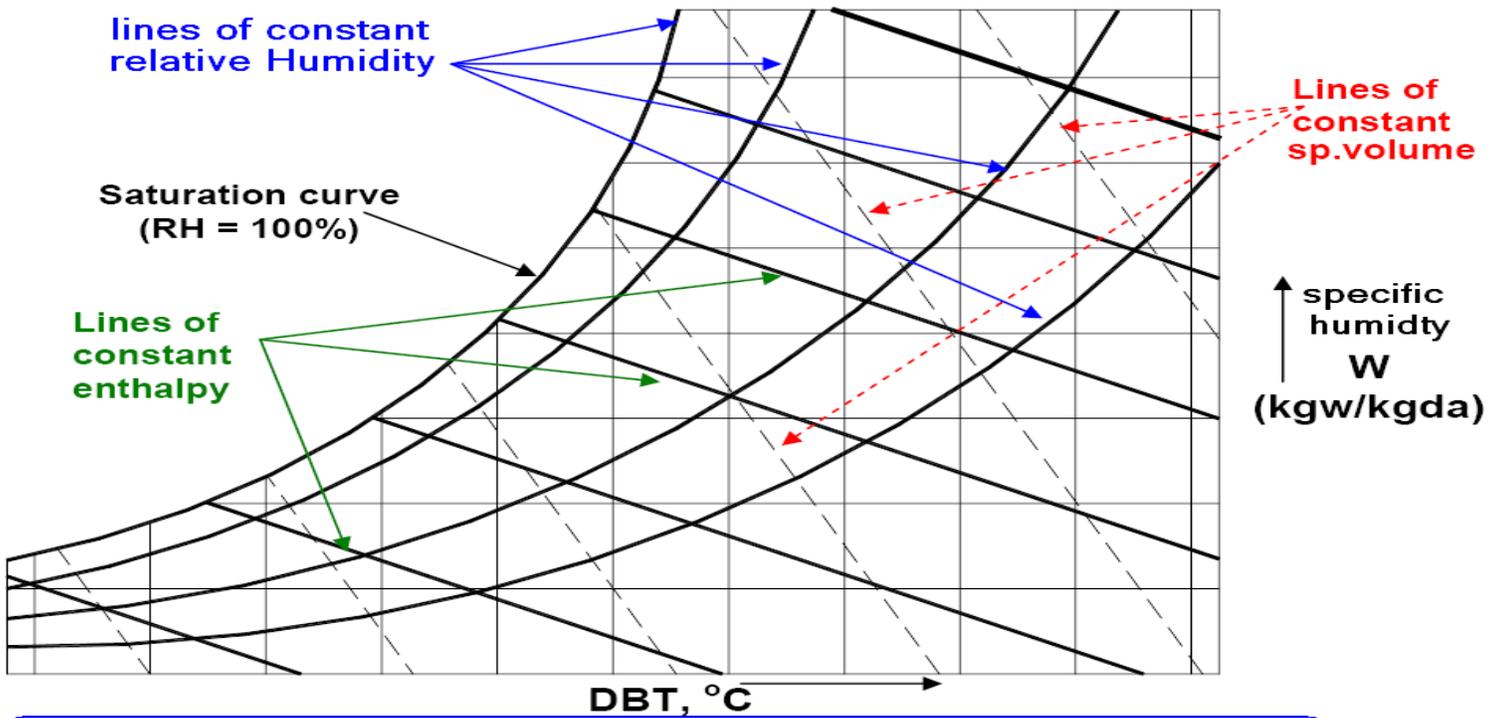
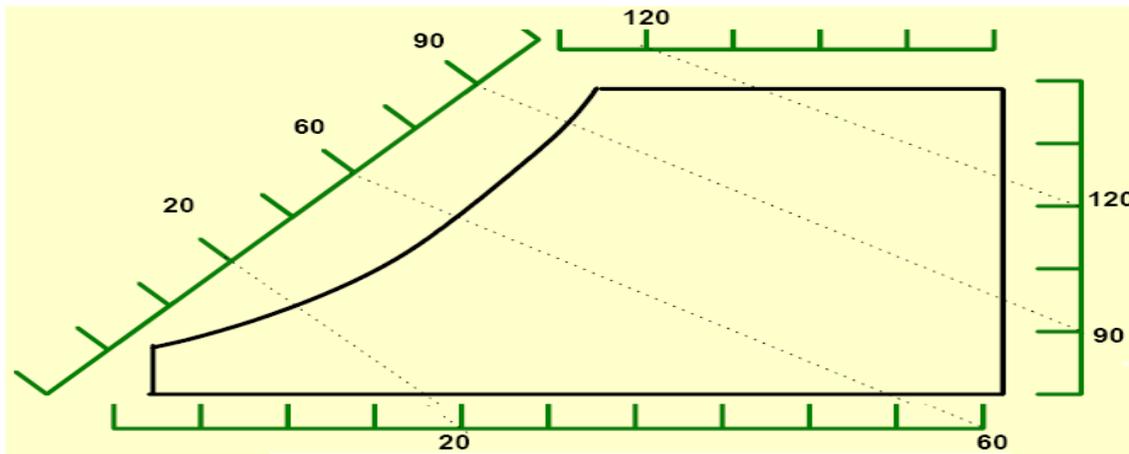


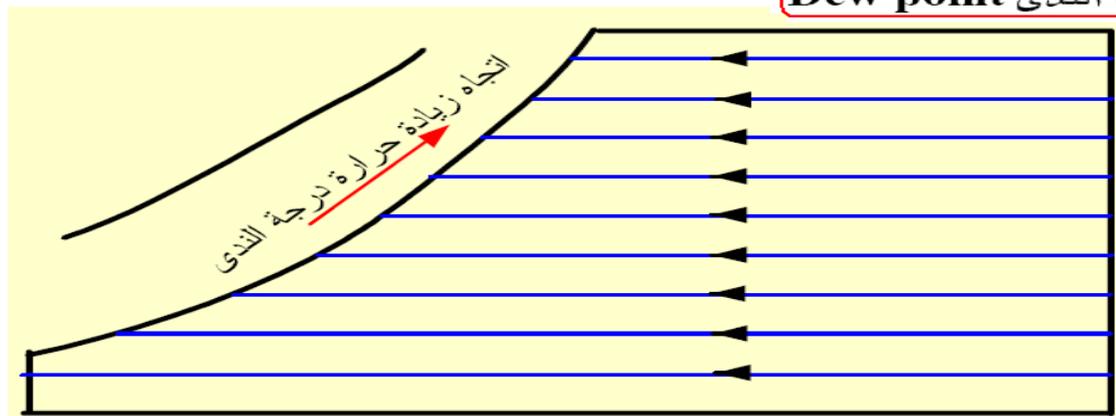
Fig.27.2: Schematic of a psychrometric chart for a given barometric pressure

- طاقة الإنثالبي (h) خطوط الإنثالبي توجد على أطراف الخريطة السيكمرومترية وفي كثير من الكتب تعتبر خطوط درجة الحرارة الرطوبة هي نفسها خطوط طاقة الإنثالبي. لتحديد قيمة الإنثالبي لنقطة ما في الخريطة السيكمرومترية يجب إن يتطابق رقمان لهما نفس القيمة عند القراءة كما يظهر في الرسم



شكل (٢ - ٩): خطوط ثبوت طاقة الإنثالبي.

درجة الندى Dew point -



شكل (٢ - ١٠): خطوط ثبوت درجة الندى

درجة الندى هي درجة الحرارة التي عندها يتكثف بخار الماء الموجود في الهواء، ويمكن قراءتها عند خط التشبع من قراءات درجة الحرارة الرطوبة أو الجافة. وهي تقع على اليسار أفقياً كما يشير السهم إلى ذلك.

27.3. 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 dry-bulb and wet-bulb temperatures from measurements, it is possible to find other properties of moist air. To understand concept of wet-bulb temperature, it is essential to understand process of combined heat and mass transfer.

27.3.1. Combined heat and mass transfer; the straight line law

The straight line law states that "when air is transferring heat and mass (water) to or from a wetted surface, the condition of air shown on a psychrometric chart drives towards the saturation line at the temperature of the wetted surface".

For example, as shown in Fig.27.3, when warm air passes over a wetted surface its temperature drops from 1 to 2. Also, since the vapor pressure of air at 1 is greater than the saturated vapor pressure at t_w , there will be moisture transfer from air to water, i.e., the warm air in contact with cold wetted surface cools and dehumidifies. According to the straight line law, the final condition of air (i.e., 2) lies on a straight line joining 1 with t_w on the saturation line. This is due to the value of unity of the Lewis number, that was discussed in an earlier chapter on analogy between heat and mass transfer.

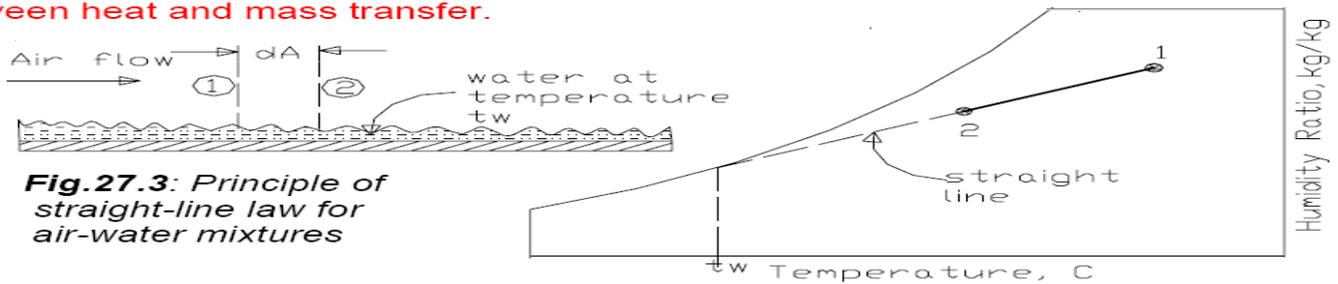


Fig.27.3: Principle of straight-line law for air-water mixtures

27.3.2. Adiabatic saturation and thermodynamic wet bulb temperature:

Adiabatic saturation temperature is defined as that temperature at which water, by evaporating into air, can bring the air to saturation at the same temperature adiabatically. An adiabatic saturator is a device using which one can measure theoretically the adiabatic saturation temperature of air.

As shown in Fig.27.4, an adiabatic saturator is a device in which air flows through an infinitely long duct containing water. As the air comes in contact with water in the duct, there will be heat and mass transfer between water and air. If the duct is infinitely long, then at the exit, there would exist perfect equilibrium between air and water at steady state. Air at the exit would be fully saturated and its temperature is equal to that of water temperature. The device is adiabatic as the walls of the chamber are thermally insulated. In order to continue the process, make-up water has to be provided to compensate for the amount of water evaporated into the air. The temperature of the make-up water is controlled so that it is the same as that in the duct.

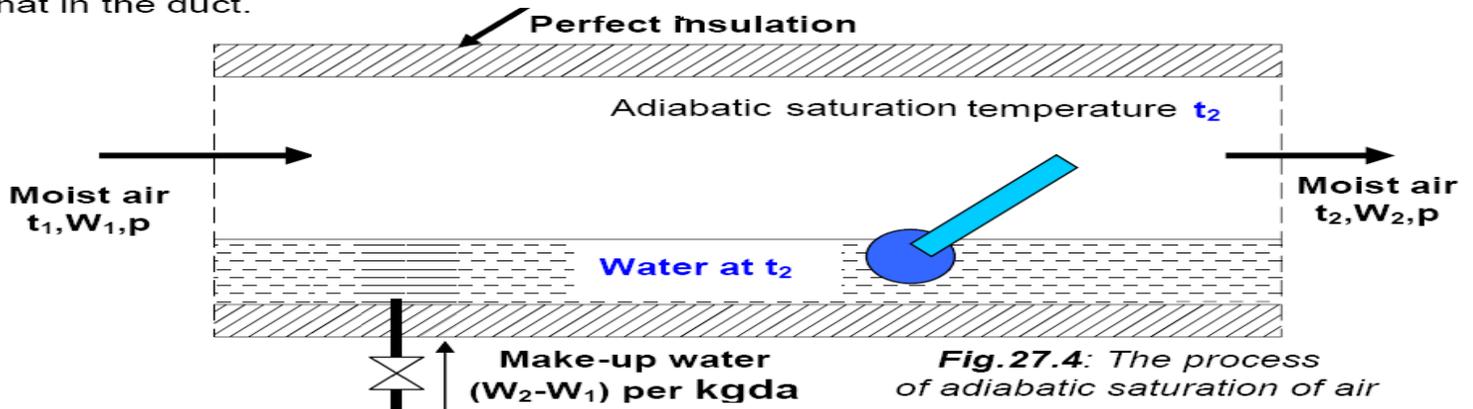


Fig.27.4: The process of adiabatic saturation of air

After the adiabatic saturator has achieved a steady-state condition, the temperature indicated by the thermometer immersed in the water is the thermodynamic wet-bulb temperature. The thermodynamic wet bulb temperature will be less than the entering air DBT but greater than the dew point temperature.

Certain combinations of air conditions will result in a given sump temperature, and this can be defined by writing the energy balance equation for the adiabatic saturator. Based on a unit mass flow rate of dry air, this is given by:

$$h_1 = h_2 - (W_2 - W_1)h_f \quad (27.13)$$

where h_f is the enthalpy of saturated liquid at the sump or thermodynamic wet-bulb temperature, h_1 and h_2 are the enthalpies of air at the inlet and exit of the adiabatic saturator, and W_1 and W_2 are the humidity ratio of air at the inlet and exit of the adiabatic saturator, respectively.

It is to be observed that the thermodynamic wet-bulb temperature is a thermodynamic property, and is independent of the path taken by air. Assuming the humid specific heat to be constant, from the enthalpy balance, the thermodynamic wet-bulb temperature can be written as:

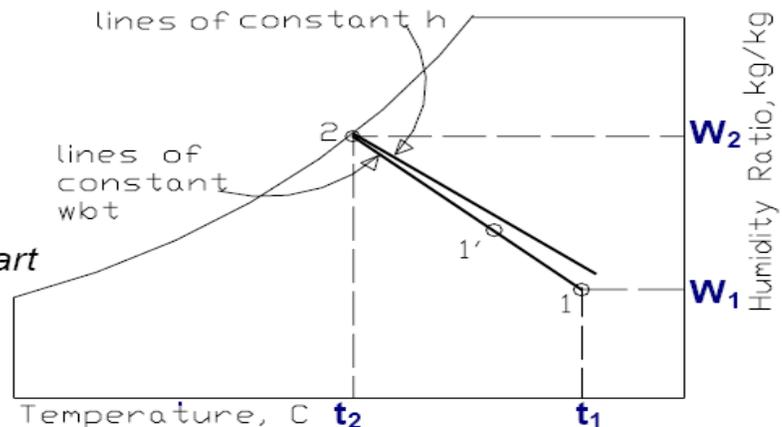
$$t_2 = t_1 - \frac{h_{fg,2}}{c_{pm}} (w_2 - w_1) \quad (27.14)$$

where $h_{fg,2}$ is the latent heat of vaporization at the saturated condition 2. Thus measuring the dry bulb (t_1) and wet bulb temperature (t_2) one can find the inlet humidity ratio (W_1) from the above expression as the outlet saturated humidity ratio (W_2) and latent heat of vaporizations are functions of t_2 alone (at fixed barometric pressure).

On the psychrometric chart as shown in Fig.27.4, point 1 lies below the line of constant enthalpy that passes through the saturation point 2. $t_2 = f(t_1, W_1)$ is not a unique function, in the sense that there can be several combinations of t_1 and W_1 which can result in the same sump temperature in the adiabatic saturator. A line passing through all these points is a constant wet bulb temperature line. Thus all inlet conditions that result in the same sump temperature, for example point 1' have the same wet bulb temperature. The line is a straight line according to the straight-line law. The straight-line joining 1 and 2 represents the path of the air as it passes through the adiabatic saturator.

Normally lines of constant wet bulb temperature are shown on the psychrometric chart. The difference between actual enthalpy and the enthalpy obtained by following constant wet-bulb temperature is equal to $(W_2 - W_1)h_f$.

Fig.27.5: Adiabatic saturation process 1-2 on psychrometric chart



27.3.3. 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 temperature⁴. For other gas-vapor mixtures, there can be appreciable difference between the thermodynamic and actual wet-bulb temperatures.

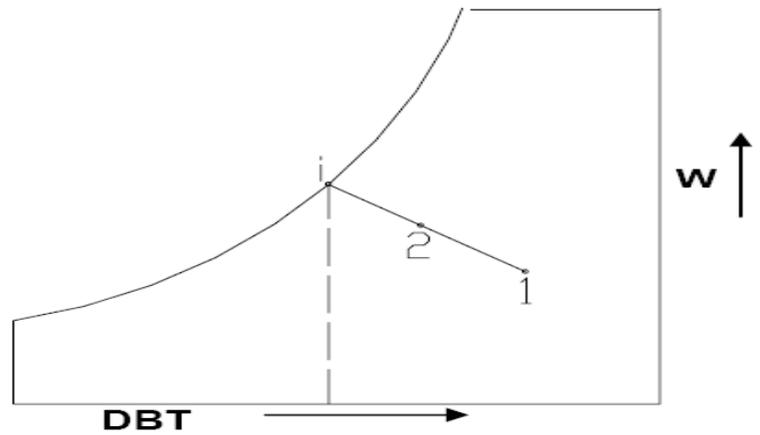
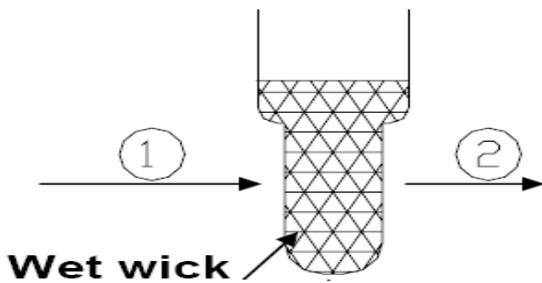


Fig.27.6: Schematic of a wet-bulb thermometer and the process on psychrometric chart

4 By performing energy balance across the wet-bulb, it can be shown that, the temperature measured by the wet-bulb thermometer is:

$t_2 = t_1 - (k_w / h_c) h_{fg} (w_i - w)$; where k_w is the mass transfer coefficient for air-water mixtures, the ratio $(h_c / k_w c_{pm}) = \text{Lewis number}$ is ≈ 1 , hence, the wick temperature is approximately equal to the thermodynamic wet-bulb temperature. It should be noted that, unlike thermodynamic WBT, the WBT of wet bulb thermometer is not a thermodynamic property as it depends upon the rates of heat and mass transfer between the wick and air.

27.4. Calculation of psychrometric properties from p, DBT, 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:
$$p_v = p_v' - \frac{1.8p(t - t')}{2700} \quad (27.15)$$

ii) Modified Ferrel equation:
$$p_v = p_v' - 0.00066p(t - t') \left[1 + \frac{1.8t}{1571} \right] \quad (27.16)$$

iii) Carrier equation:
$$p_v = p_v' - \frac{1.8(p - p_v')(t - t')}{2800 - 1.3(1.8t + 32)} \quad (27.17)$$

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.

27.5. 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 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 bulbs if surrounding temperatures are considerably different from air temperature.

The *sling psychrometer* is widely used for measurements involving room air or other applications where the air velocity inside the room is small. The sling psychrometer consists of two thermometers mounted side by side and fitted in a frame with a handle for whirling the device through air. The required air circulation (≈ 3 to 5 m/s) over the sensing bulbs is obtained by whirling the psychrometer (≈ 300 RPM). Readings are taken when both the thermometers show steady-state readings.

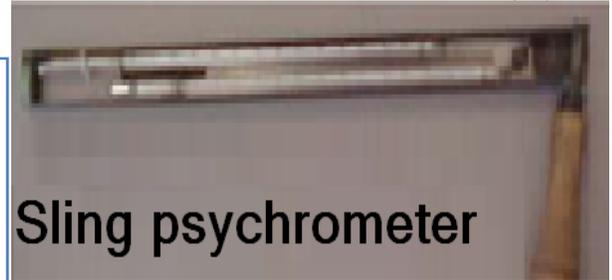
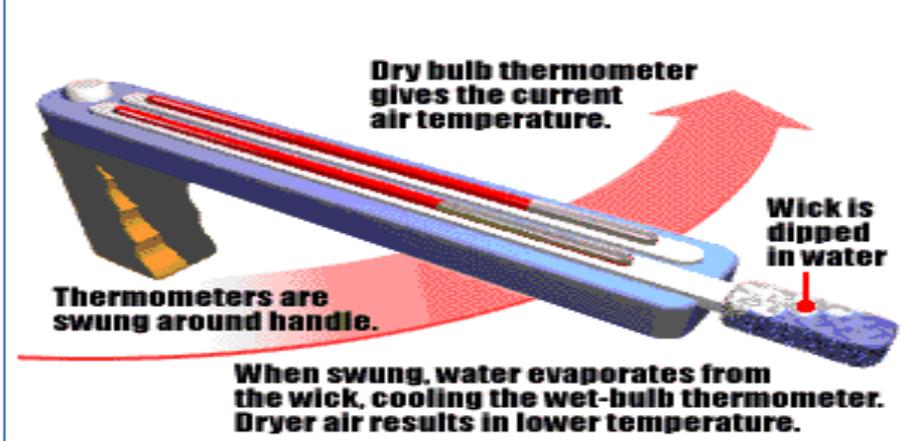
In the *aspirated psychrometer*, the thermometers remain stationary, and a small fan, blower or syringe moves the air across the thermometer bulbs.

The function of the wick on the wet-bulb thermometer is to provide a thin film of water on the sensing bulb. To prevent errors, there should be a continuous film of water on the wick. The wicks made of cotton or cloth should be replaced frequently, and only distilled water should be used for wetting it. The wick should extend beyond the bulb by 1 or 2 cms to minimize the heat conduction effects along the stem.

Other types of psychrometric instruments:

1. Dunmore Electric Hygrometer
2. DPT meter
3. Hygrometer (Using horse's or human hair)

How a sling psychrometer works



Sling psychrometer



Temperature and Humidity Measuring Relative Humidity and Temperature Pen



Temperature and Humidity Measuring

RH Meters and Thermohygrometers



Temperature and Humidity Measuring

RH Meters and Thermohygrometers



Handheld Psychrometer



Temp/RH Datalogger

Questions and answers:

1. Which of the following statements are TRUE?

- a) The maximum amount of moisture air can hold depends upon its temperature and barometric pressure
- b) Perfect gas model can be applied to air-water mixtures when total pressure is high
- c) The minimum number of independent properties to be specified for fixing the state of moist air is two
- d) The minimum number of independent properties to be specified for fixing the state of moist air is three

Ans.: a) and d)

2. Which of the following statements are TRUE?

- a) Straight-line law is applicable to any fluid-air mixtures
- b) Straight-line law is applicable to any water-air mixtures only
- c) Straight-line holds good as long as the Prandtl number is close to unity
- d) Straight-line holds good as long as the Lewis number is close to unity

Ans.: b) and d)

3. Which of the following statements are TRUE?

- a) When the dry bulb temperature is equal to dew point temperature, the relative humidity of air-water mixture is 1.0
- b) All specific psychrometric properties of moist air are based on unit mass of water vapour
- c) All specific psychrometric properties of moist air are based on unit mass of dry air
- d) All specific psychrometric properties of moist air are based on unit mass of moist air

Ans.: a) and d)

4. Which of the following statements are TRUE?

- a) Thermodynamic WBT is a property of moist air, while WBT as measured by wet bulb thermometer is not a property
- b) Both the thermodynamic WBT and WBT as measured by wet bulb thermometer are properties of moist air
- c) Under no circumstances, dry bulb and wet bulb temperatures are equal
- d) Wet bulb temperature is always lower than dry bulb temperature, but higher than dew point temperature

Ans.: a)

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:

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

From steam tables, the saturation temperature of water at 3.13975 Kpa is 24.8°C, hence moisture in air will condense when it comes in contact with the cold surface whose temperature is lower than the dew point temperature. **(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: **$p_v = 2.956 \text{ kPa}$ (Ans.)**

b) The humidity ratio W is given by:

$$W = 0.622 \times 2.956 / (101.325 - 2.956) = 0.0187 \text{ kgw/kgda (Ans.)}$$

c) Relative humidity RH is given by:

$$RH = (p_v / p_s) \times 100 = (p_v / \text{saturation pressure at } 32^\circ\text{C}) \times 100$$

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

$$RH = (2.956 / 4.7552) \times 100 = 62.16\% \quad \text{(Ans.)}$$

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

$$DPT = T_{\text{sat}}(2.956 \text{ kPa}) = 23.8^\circ\text{C} \quad \text{(Ans.)}$$

e) Density of dry air and water vapour

Applying perfect gas law to dry air:

$$\begin{aligned} \text{Density of dry air } \rho_a &= (p_a / R_a T) = (p_t - p_v) / R_a T = (101.325 - 2.956) / (287.035 \times 305) \times 10^3 \\ &= 1.1236 \text{ kg/m}^3 \text{ of dry air} \quad \text{(Ans.)} \end{aligned}$$

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

$$\text{Density of water vapour } \rho_v = (p_v / R_v T) = 2.956 \times 10^3 / (461.52 \times 305) = 0.021 \text{ kg/m}^3 \quad \text{(Ans.)}$$

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

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