ENGINEERING THERMODYNAMICS -II

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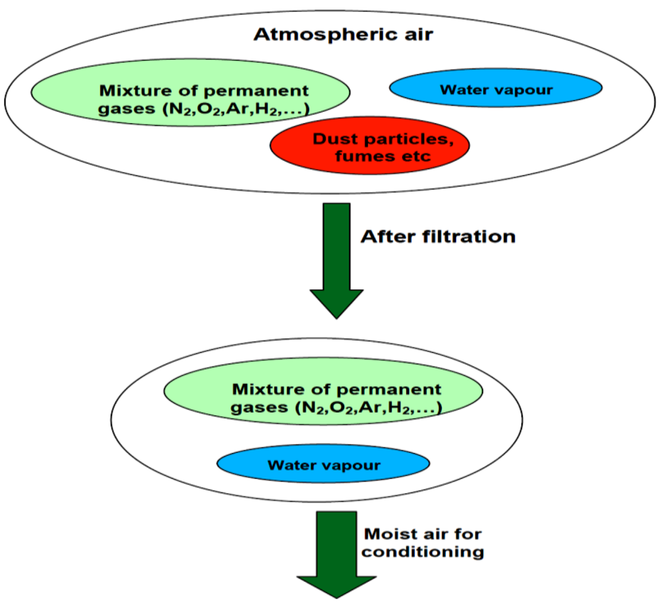

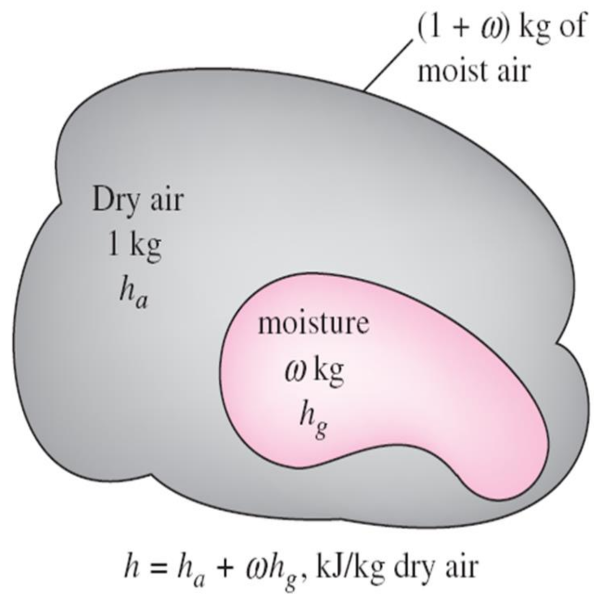

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2. Gas-steam mixtures and air conditioning process

Objectives

- ✓ Differentiate between dry air and atmospheric air.
- ✓ Define and calculate the specific and relative humidity of atmospheric air.
- ✓ Calculate the dew-point temperature of atmospheric air.
- ✓ Relate the adiabatic saturation temperature and wet-bulb temperatures of atmospheric air.
- ✓ Use the psychrometric chart as a tool to determine the properties of atmospheric air.
- ✓ Apply the principles of the conservation of mass and energy to various air-conditioning processes.

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 vapor.
- Atmospheric air is a mixture of many gases plus water vapor and a number of pollutants (Fig. below). The amount of water vapor and pollutants vary from place to place.
- The concentration of water vapor 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 vapor. This mixture is known as moist air.

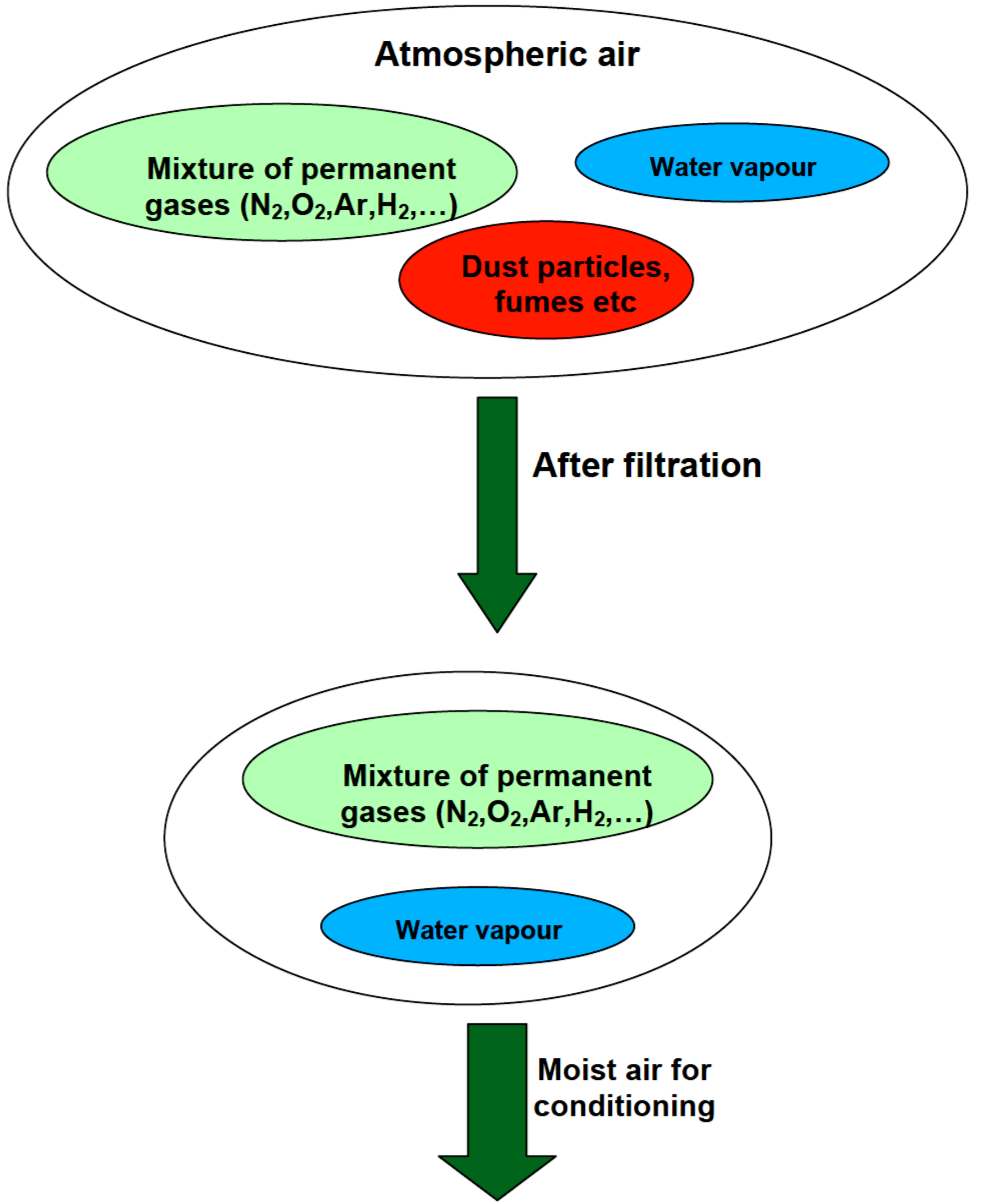


Fig. Atmospheric air

Introduction

- 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. The composition of dry air is given table below.

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

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

Introduction

- As mentioned before the air to be processed in air conditioning systems is a mixture of dry air and water vapor.
- While the composition of dry air is constant, the amount of water vapor present in the air may vary from zero to a maximum depending upon the temperature and pressure of the mixture (dry air + water vapor).
- 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 vapor is taken as 18.015 and its gas constant is 461.52 J/kg.K.

DRY AND ATMOSPHERIC AIR

Atmospheric air: Air in the atmosphere containing some water vapor (or *moisture*).

Dry air: Air that contains no water vapor.

Water vapor in the air plays a major role in human comfort. Therefore, it is an important consideration in air-conditioning applications.

$$h_{\text{dry air}} = c_p T = (1.005 \text{ kJ/kg} \cdot {}^\circ\text{C})T \qquad (\text{kJ/kg})$$

$$\Delta h_{\text{dry air}} = c_p \Delta T = (1.005 \text{ kJ/kg} \cdot {}^\circ\text{C})\, \Delta T \qquad (\text{kJ/kg})$$

Water vapor in air behaves as if it existed alone and obeys the ideal-gas relation $Pv = RT$. Then the atmospheric air can be treated as an ideal-gas mixture:

$$P = P_a + P_v \qquad (\text{kPa})$$

P_a Partial pressure of dry air

P_v Partial pressure of vapor (vapor pressure)

Dry air

T, °C	c_p, kJ/kg·°C
–10	1.0038
0	1.0041
10	1.0045
20	1.0049
30	1.0054
40	1.0059
50	1.0065

The c_p of air can be assumed to be constant at 1.005 kJ/kg·°C in the temperature range –10 to 50°C with an error under 0.2%.

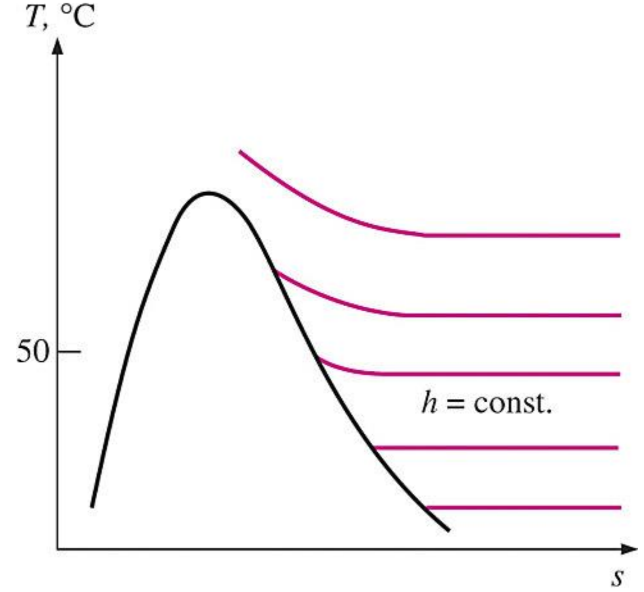
Dry and Atmospheric Air

- ❖ The assumption that the water vapor is an ideal gas is valid when the mixture temperature is below 50°C.
- ❖ This means that the saturation pressure of the water vapor in the air-vapor mixture is below 12.3 kPa.
- ✓ For these conditions, the enthalpy of the water vapor is approximated by $h_v(T) = hg$ at mixture temperature T.

The following T-s diagram for water illustrates the ideal-gas behavior at low vapor pressures.

- ➢ The saturated vapor value of the enthalpy is a function of temperature and can be expressed as

$$h_v = h_g(T) \cong 2501.3 + 1.82T \left(\frac{kJ}{kg_v}\right) \quad T \ in \ ^oC$$



Note: Average Cp value in range of -10 to 50°C is 1.82 KJ/kg-K and The enthalpy of vapor at 0°c is 2501.3KJ/kg.

Dry and Atmospheric Air

- Note: For the dry air-water vapor mixture, the partial pressure of the water vapor in the mixture is less that its saturation pressure at the temperature.

$$P_v \leq P_{sat\,@T_{mix}}$$

- Then the atmospheric air can be treated as an ideal-gas mixture whose pressure is the sum of the partial pressure of dry air Pa and that of water vapor P_v:

$$p = p_a + p_v$$

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

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

- 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

Specific and Relative Humidity of Air

- The amount of water vapor in the air can be specified in various ways.
- Probably the most logical way is to specify directly the mass of water vapor present in a unit mass of dry air.

This is called **absolute** or **specific humidity** (also called *humidity ratio*) and is denoted by ω:

$$\omega = \frac{Mass\ of\ water\ vapor\ in\ air}{Mass\ of\ dry\ air} = \frac{m_v}{m_a}$$

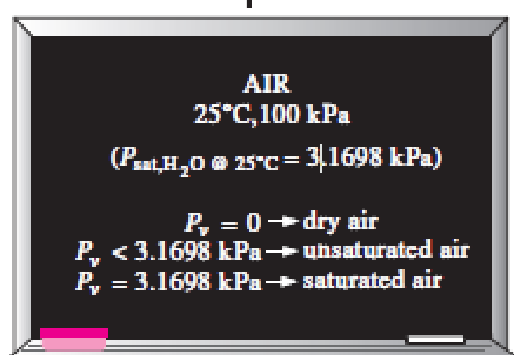
$$= \frac{P_v V M_v/(R_u T)}{P_a V M_a/(R_u T)} = \frac{P_v M_v}{P_a M_a}$$

$$= 0.622\frac{P_v}{P_a} = 0.622\frac{P_v}{P - P_v}$$

(kg water vapor/kg dry air)

Specific and Relative Humidity of Air

- Consider 1 kg of dry air. By definition, dry air contains no water vapor, and thus its specific humidity is zero.
- Now let us add some water vapor to this dry air. The specific humidity will increase. As more vapor or moisture is added, the specific humidity will keep increasing until the air can hold no more moisture.
- At this point, the air is said to be saturated with moisture, and it is called **saturated air.**
- Any moisture introduced into saturated air will condense.
- The amount of water vapor in saturated air at a specified temperature and pressure can be determined from above equation by replacing *Pv* by *Pg*, the saturation pressure of water at that temperature



Specific and Relative Humidity of Air

- The amount of moisture in the air has a definite effect on how comfortable we feel in an environment.
- However, the comfort level depends more on the amount of moisture the air holds (m_v) relative to the maximum amount of moisture the air can hold at the same temperature (m_g).

The ratio of these two quantities is called the relative humidity (ϕ)

$$\phi = \frac{Mass\ of\ \ vapor\ in\ air}{Mass\ of\ \ in\ saturated\ air} = \frac{m_v}{m_g}$$

$$= \frac{P_v}{P_g}$$

where: $p_g = p_{sat}$ @T

$$\phi = \frac{m_v}{m_g} = \frac{P_v V/(R_v T)}{P_g V/(R_v T)} = \frac{P_v}{P_g}$$

$$P_g \geq P_v,\ \phi \leq 1\ or\ 100\%,\ \phi = \frac{P_v}{P_g} = \frac{1.491\ kPa}{3.169\ kPa} = 0.47$$

Specific and Relative Humidity of Air

Using the definition of the specific humidity, the relative humidity may be expressed as

$$\phi = \frac{\omega P}{(0.622+\omega)\,P_g} \quad and \quad \omega = \frac{0.622\phi P_g}{P-\phi P_g}$$

Volume of mixture per mass of dry air, *v*

$$v = \frac{V}{m_a} = \frac{m_m R_m T_m \,/\, P_m}{m_a}$$

After several steps, we can show (you should try this)

$$v = \frac{V}{m_a} = v_a = \frac{R_a T_m}{P_a}$$

Specific and Relative Humidity of Air

So the volume of the mixture per unit mass of dry air is the specific volume of the dry air calculated at the mixture temperature and the partial pressure of the dry air.

Mass of mixture: $$m = m_a + m_v = m_a(1 + \frac{m_v}{m_a}) = m_a(1 + \omega)$$

Mass flow rate of dry air (m'$_a$):

Based on the volume flow rate of mixture at a given state, the mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}}{v} \qquad \frac{m^3/s}{m^3/kg_a} = \frac{kg_a}{s}$$

Enthalpy of mixture per mass dry air, *h*

$$h = \frac{H_m}{m_a} = \frac{H_a + H_v}{m_a} = \frac{m_a h_a + m_v h_v}{m_a}$$

$$= h_a + \omega h_v$$

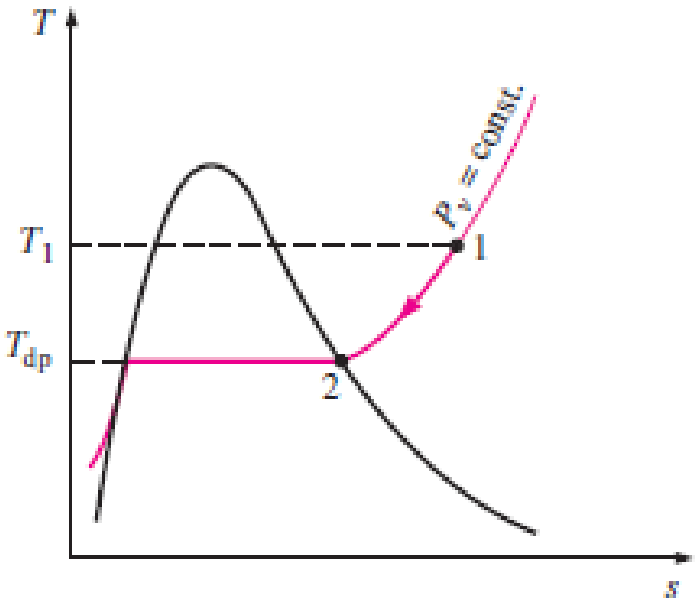
Dew-Point Temperature

- Dry Bulb Temperature Tdb: the temperature measured by a thermometer placed in a mixture of air and water-vapor.

Dew Point Temperature Tdp:

- Dew on the grass in morning !!! Water vapors on your car windscreen!!!
- is the temperature at which condensation begins when the air is cooled at constant pressure.
- Tdp is the saturation temperature of water corresponding to the vapor pressure:

$$T_{dp} = T_{sat@Pv}$$



EXAMPLE 2.1:

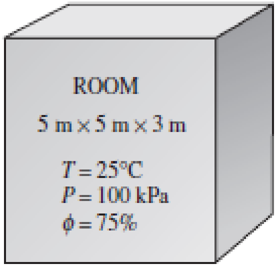
A 5m X 5m X 3m room shown in Fig. below contains air at 25°C and 100kPa at a relative humidity of 75 percent. Determine

(*a) the partial pressure* of dry air,

(*b) the specific humidity,*

(c) the enthalpy per unit mass of the dry air, and

(d) the masses of the dry air and water vapor in the room.



Assignment: 1

Atmospheric air is at 25^{o}C, 0.1MPa, 50 percent relative humidity. If the mixture is cooled at constant pressure to 10^{o}C, find ,

a) dew point temperature,

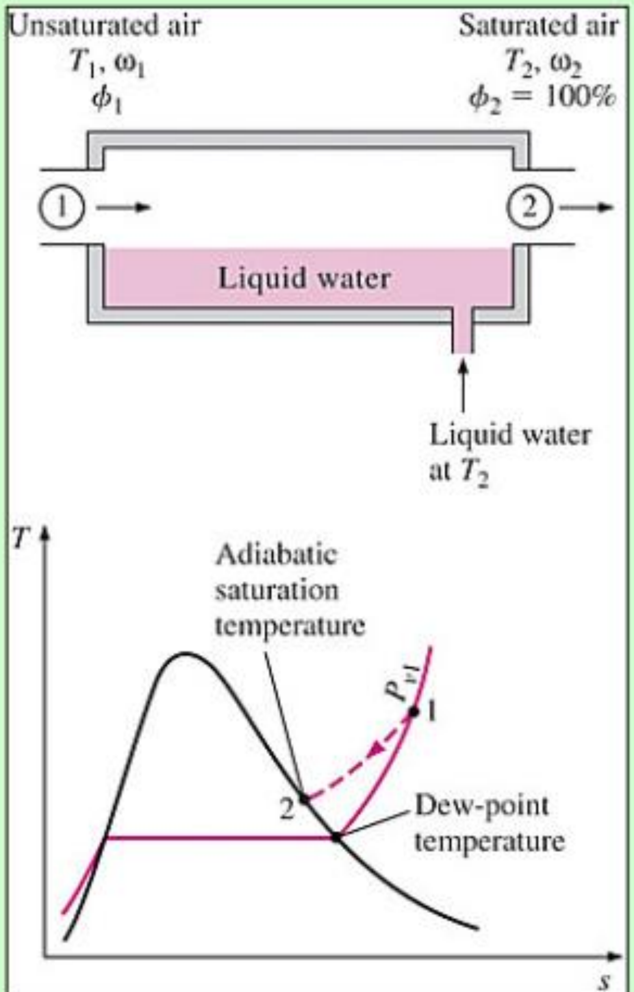
b) humidity ratio,

c) Enthalpy of the mixture per mass of dry air, and

d) the amount of water removed per mass of dry air.

The Adiabatic Saturation Process and Wet-Bulb Temperatures

- Air having a relative humidity less than 100 percent flows over water contained in a well-insulated duct.
- Since the air has ϕ < 100 percent, some of the water will evaporate and the temperature of the air-vapor mixture will decrease.



The system consists of a long insulated channel that contains a pool of water.

A steady stream of unsaturated air that has a specific humidity of ω_1 (unknown) and a temperature of T_1 is passed through this channel.

As the air flows over the water, some water evaporates and mixes with the airstream. The moisture content of air increases during this process, and its temperature decreases.

If the channel is long enough, the airstream exits as saturated air (ϕ = 100 percent) at temperature T_2, which is called the **adiabatic saturation temperature.**

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✓If the mixture leaving the duct is saturated and if the process is adiabatic, the temperature of the mixture on leaving the device is known as the **adiabatic saturation temperature**.

✓For this to be a steady-flow process, makeup water at the adiabatic saturation temperature is added at the same rate at which water is evaporated.

✓We assume that the total pressure is constant during the process.

❖Apply the conservation of energy to the steady-flow control volume

$$\dot{Q}_{net} + \sum_{inlets} \dot{m}_i \left(h + \frac{\vec{V}^2}{2} + gz\right)_i = \dot{W}_{net} + \sum_{exits} \dot{m}_e \left(h + \frac{\vec{V}^2}{2} + gz\right)_e$$

Neglecting the kinetic and potential energies and noting that the heat transfer and work are zero, we get

$$\dot{m}_{a1} h_{a1} + \dot{m}_{v1} h_{v1} + \dot{m}_{l2} h_{l2} = \dot{m}_{a2} h_{a2} + \dot{m}_{v2} h_{v2}$$

❖Conservation of mass for the steady-flow control volume is

$$\sum_{inlets} \dot{m}_i = \sum_{exits} \dot{m}_e$$

For the dry air:

$$\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$$

For the water vapor:

$$\dot{m}_{v1} + \dot{m}_{l2} = \dot{m}_{v2}$$

The mass flow rate water that must be supplied to maintain steady-flow is,

$$\dot{m}_{l2} = \dot{m}_{v2} - \dot{m}_{v1}$$

$$= \dot{m}_a(\omega_2 - \omega_1)$$

Divide the conservation of energy equation by $\dot{m}_a$, then

$$h_{a1} + \omega_1 h_{v1} + (\omega_2 - \omega_1)h_{l2} = h_{a2} + \omega_2 h_{v2}$$

What are the known's and unknowns in this equation?

Solving for ω_1

$$\omega_1 = \frac{h_{a2} - h_{a1} + \omega_2 (h_{v2} - h_{l2})}{(h_{v1} - h_{l2})}$$

$$= \frac{C_{pa}(T_2 - T_1) + \omega_2 h_{fg2}}{(h_{g1} - h_{f2})}$$

Since ω_1 is also defined by $$\omega_1 = 0.622 \frac{P_{v1}}{P_1 - P_{v1}}$$

We can solve for P_{v1}. $$P_{v1} = \frac{\omega_1 P_1}{0.622 + \omega_1}$$

Then, the relative humidity at state 1 is $$\phi_1 = \frac{P_{v1}}{P_{g1}}$$

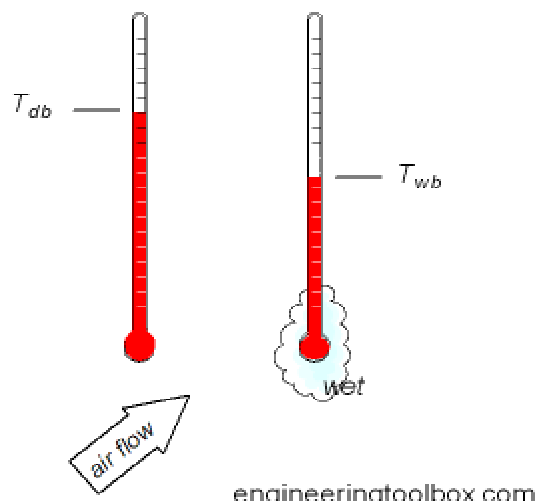
Wet-Bulb and Dry-Bulb Temperatures

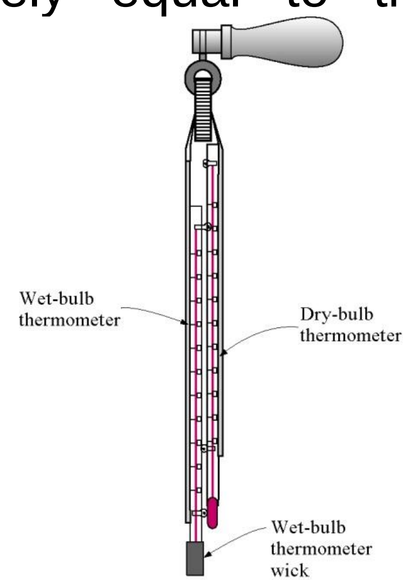
➢Any temperature you measure with thermometer is **dry bulb temperature.**

➢The **wet-bulb temperature is the** temperature a parcel of air would have if it were cooled to saturation by the evaporation of water into it, with the latent heat being supplied by the parcel.

✓These temperatures are measured by using a device called a psychrometer. The psychrometer is composed of two thermometers mounted on a sling. One thermometer is fitted with a wet gauze and reads the wet-bulb temperature. The other thermometer reads the dry-bulb, or ordinary, temperature. As the psychrometer is slung through the air, water vaporizes from the wet gauze, resulting in a lower temperature to be registered by the thermometer.

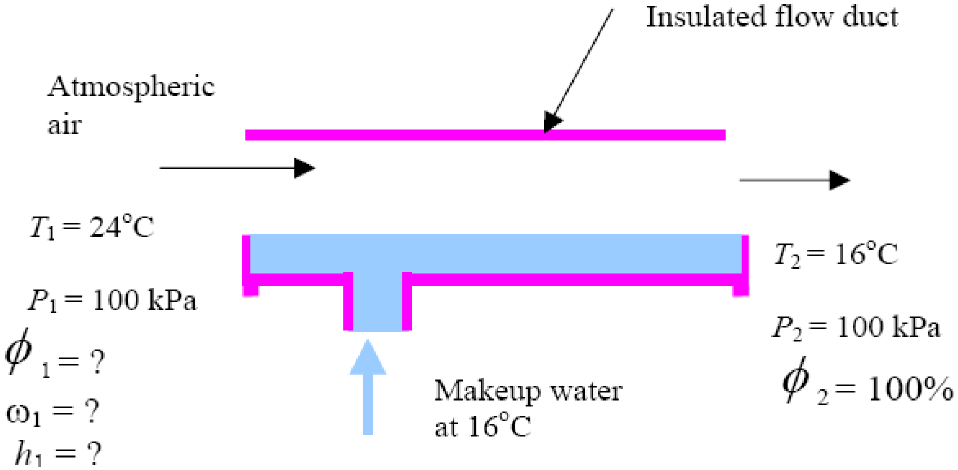
✓ The wet-bulb temperature is approximately equal to the adiabatic saturation temperature.



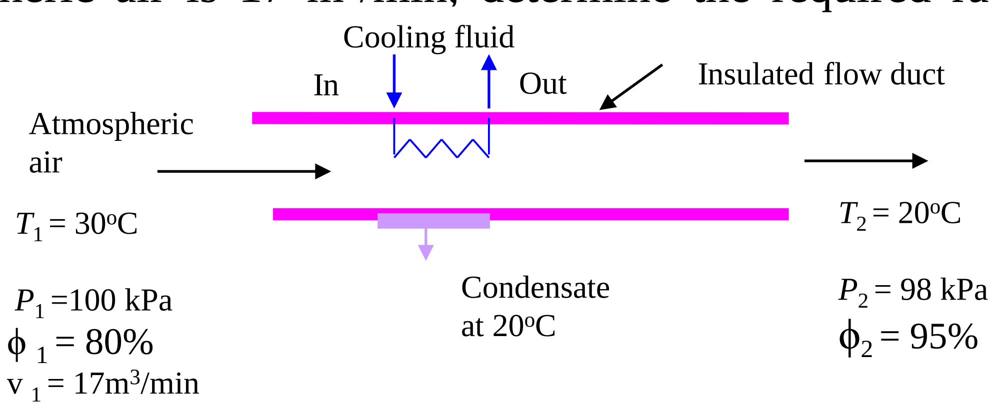


Example 2.2

For the adiabatic saturation process shown below, determine the relative humidity, humidity ratio (specific humidity), and enthalpy of the atmospheric air per mass of dry air at state 1.



Assignment:2 Given the inlet and exit conditions to an air conditioner shown below. What is the heat transfer to be removed per kg dry air flowing through the device? If the volume flow rate of the inlet atmospheric air is 17 m^3/min, determine the required rate of heat transfer.

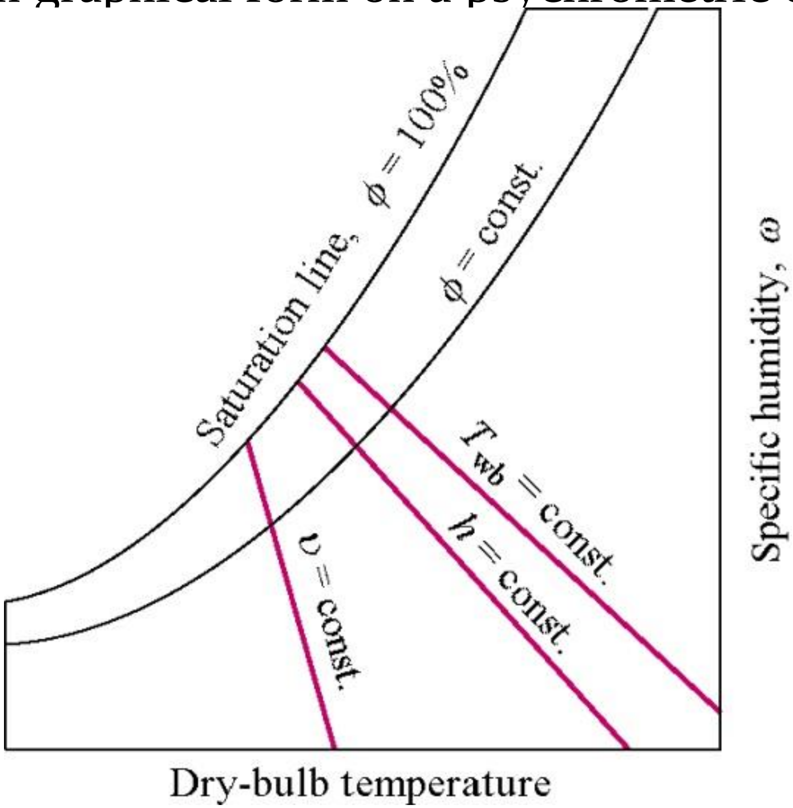


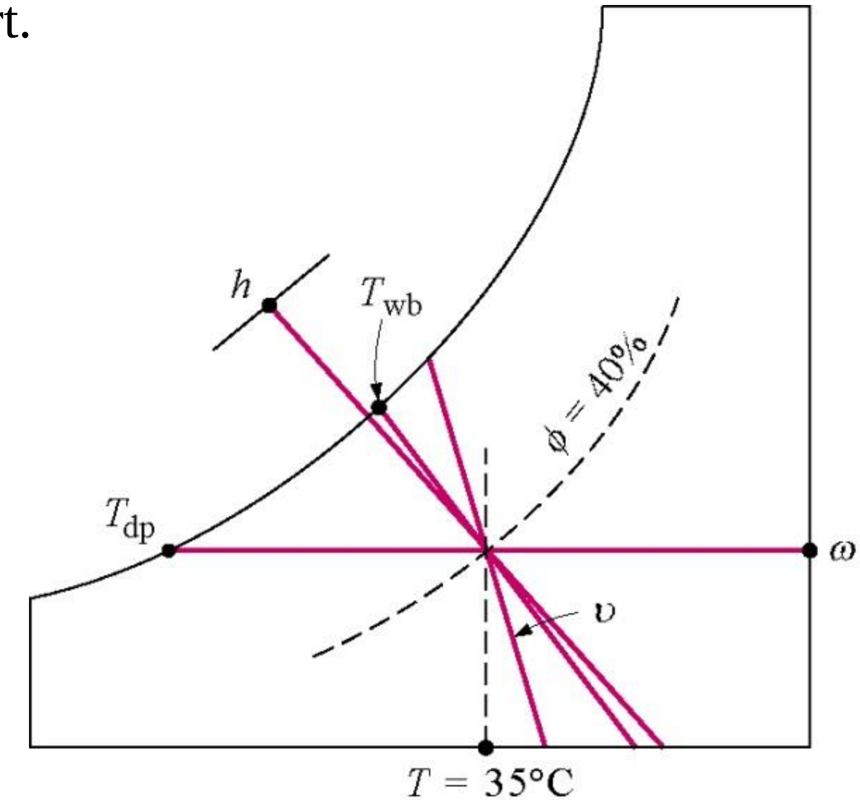
The Psychrometric Chart

❖The state of the atmospheric air at a specified pressure is completely specified by two independent intensive properties.

❖Psychrometric charts present the moist air properties; they are used extensively in air-conditioning applications.

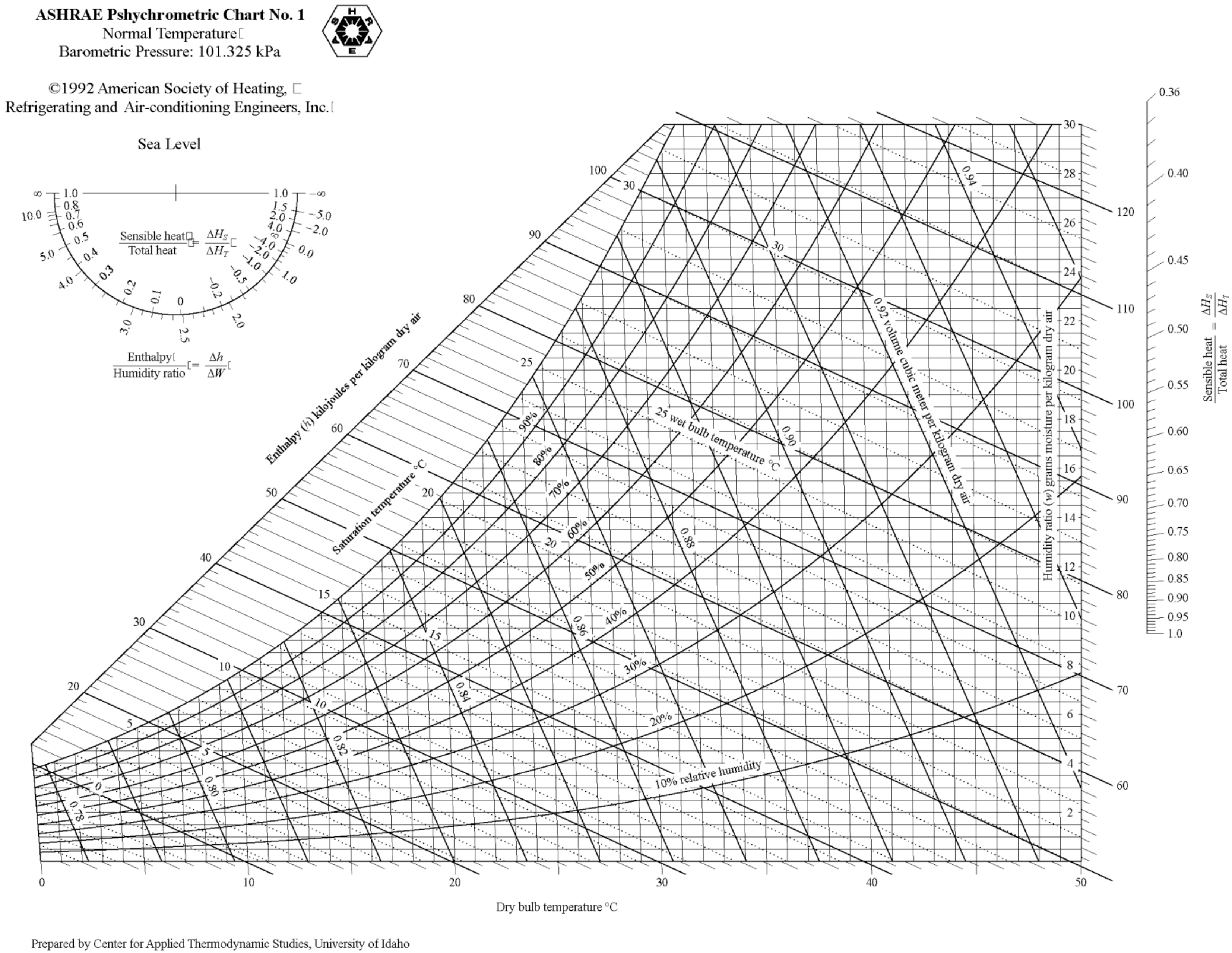
❖For a given, fixed, total air-vapor pressure, the properties of the mixture are given in graphical form on a psychrometric chart.





Basic features of psychrometric chart are:

- ✓ The dry bulb temperatures are shown on the horizontal axis.
- ✓ The specific humidity ω is shown on the vertical axis.
- ✓ The curved line at the left end of the chart is the saturation line. All the saturated air states are located on this curve. Thus, it also represents the curve of relative humidity 100%. Other constant relative humidity curves have the same general shape.
- ✓ Lines of constant wet-bulb temperature have a downhill appearance to the right.
- ✓ Lines of specific volume also have downhill appearance to the right with steeper slopes.
- ✓ Lines of constant enthalpy lie very near to the constant wet-bulb temperature, thus (in some charts) lines of constant wet-bulbs are used as constant-enthalpies.
- ✓ For saturated air, the dry-bulb, wet-bulb, and dew-point temperatures are identical.
- ✓ Thus the dew-point temperature of atmospheric air can be determined by drawing a horizontal line to the saturated curve.



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Example 2.3

Consider air at 1 atm, 35°C and 40% relative humidity. Using psychrometric chart, determine a) the specific humidity, b) the enthalpy, c) the wet-bulb temperature, d) the dew-point temperature and e) the specific volume of the air.

Assignment :3

The air in a room has a pressure of 1atm, a dry-bulb temperature of 24°C, and a wet-bulb temperature of 17°C. Using the psychrometric chart, determine (*a) the specific* humidity, (*b) the enthalpy (in kJ/kg dry air), (c) the relative* humidity, (*d) the dew-point temperature, and (e) the specific* volume of the air (in m3/kg dry air).

Human Comfort and Air-Conditioning

- ✓ Depending on the type of activity, part of the rejected body heat is dissipated through l*atent heat (sweating and breathing).*
- ✓ The comfort of human body depends on three factors:
- ❖ Temperature: most important index of comfort, most people feel comfortable when temperature is between 22 and 27°C.
- ❖ Relative humidity: it affects the amount of heat that body can dissipate through evaporation. Relative humidity is a measure of air's ability to absorb moisture. Most people prefer relative humidity of 40 to 60%.
- ❖ Air motion: it removes the warm, moist air that builds up around body and replaces it with fresh air. Most people feel comfortable at an airspeed of 15 m/min (0.25m/s).

Air-Conditioning processes

HVAC Processes:

Maintaining a living space or an industrial facility at the desired temperature and humidity requires some processes called air conditioning; including:

a) Simple heating: raising the air temperature.

b) Simple cooling: lowering the air temperature.

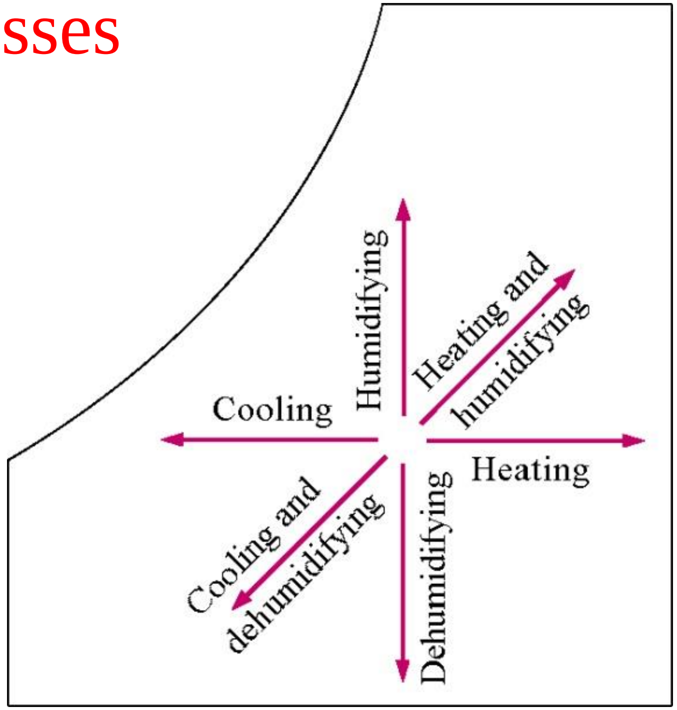
c) Humidifying: adding moisture.

d) Dehumidifying: removing moisture.

In many applications, a combination of these processes is needed to bring the air to a desired condition.

Air-Conditioning processes

The air-conditioning processes:



Most air-conditioning processes can be modeled as steady-flow processes; thus, one can write:

Mass balance for dry air: $\sum_{in} \dot{m}_a = \sum_{out} \dot{m}_a \quad (kg/s)$

Mass balance for water: $\sum_{in} \dot{m}_w = \sum_{out} \dot{m}_w \quad or \quad \sum_{in} \dot{m}_a \omega = \sum_{out} \dot{m}_a \omega$

Neglecting the potential and kinetic energy changes, the steady-state energy balance is:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}h = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}h$$

Air-Conditioning processes

1) Simple Heating and Cooling (ω = Constant)

The amount of moisture in the air remains constant during this process since no moisture is added or removed to or from the air.

Notice:

- ✓ the relative humidity of air decreases during a heating process and increases in a cooling process.
- ✓ This is because the relative humidity is the ratio of the moisture capacity of the air and it increases with increasing the air temperature.

Air-Conditioning processes

The conservation of mass reduces to:

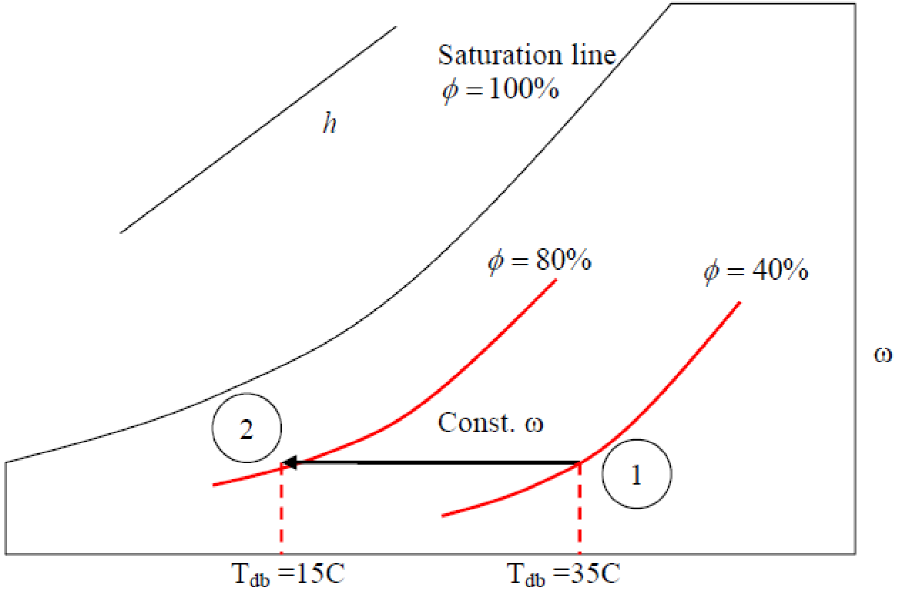
$$m_{a1} = m_{a2} = m_a$$

$$\omega_1 = \omega_2$$

Neglecting any fan work, the conservation of energy yields:

$$Q' = m' (h_2 - h_1) \quad \text{or } q = (h_2 - h_1)$$

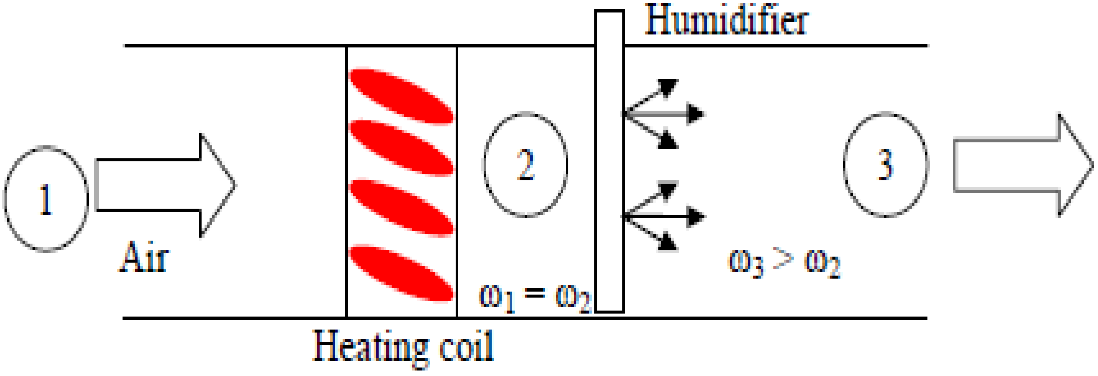
Where: *h_1 and h_2 are enthalpies per unit mass of dry air at the inlet and exit of the* heating/cooling section, respectively.



Air-Conditioning processes

2. Heating with Humidification

- To maintain comfortable relative humidity, simple heating is typically accompanied with humidification, Fig. below. That is accomplished by passing the air through a humidifying section.
- If steam is used in the humidifier, we will have additional heating; thus $T3 > T2$.
- If water is sprayed in the humidifier section, part of the latent heat of vaporization comes from the air which results in the cooling of the air; thus $T3 < T2$.



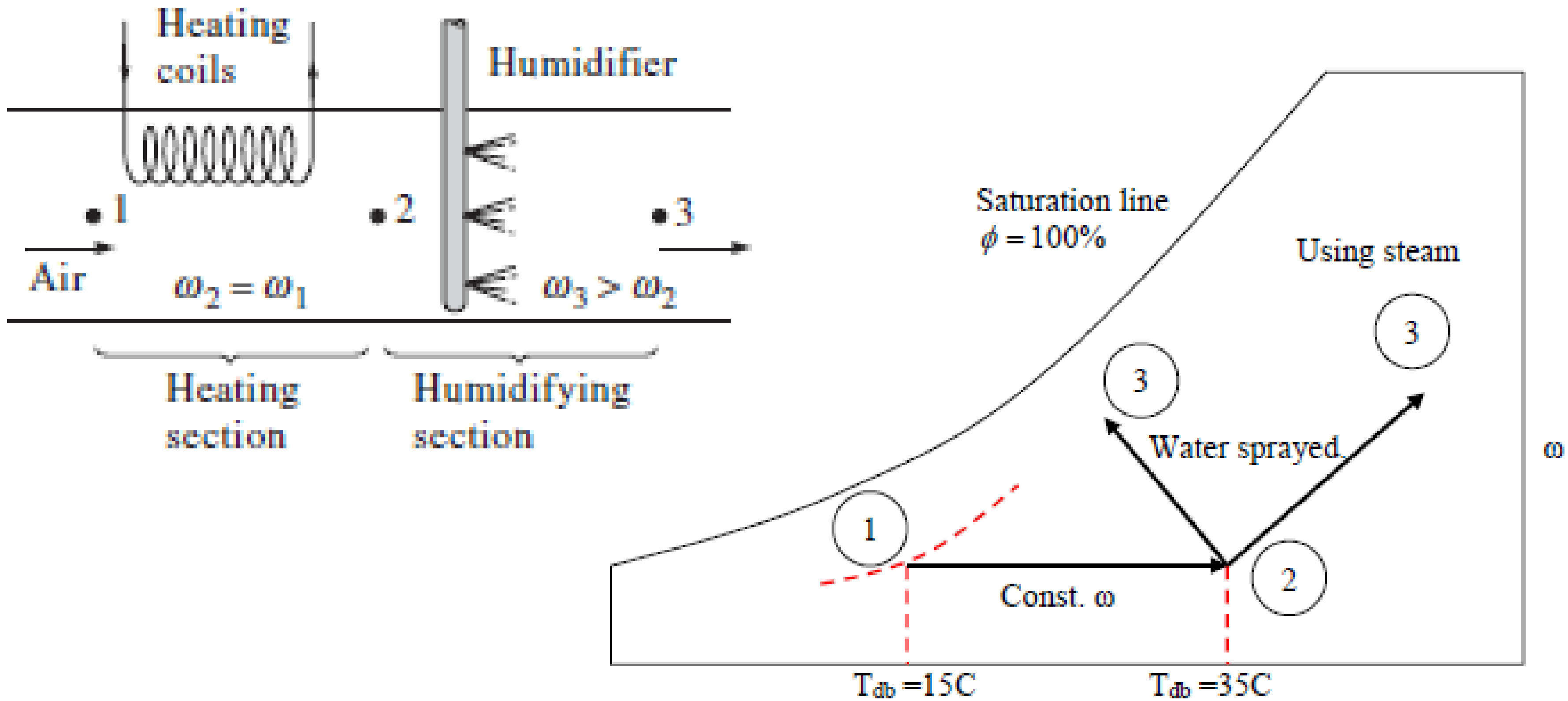
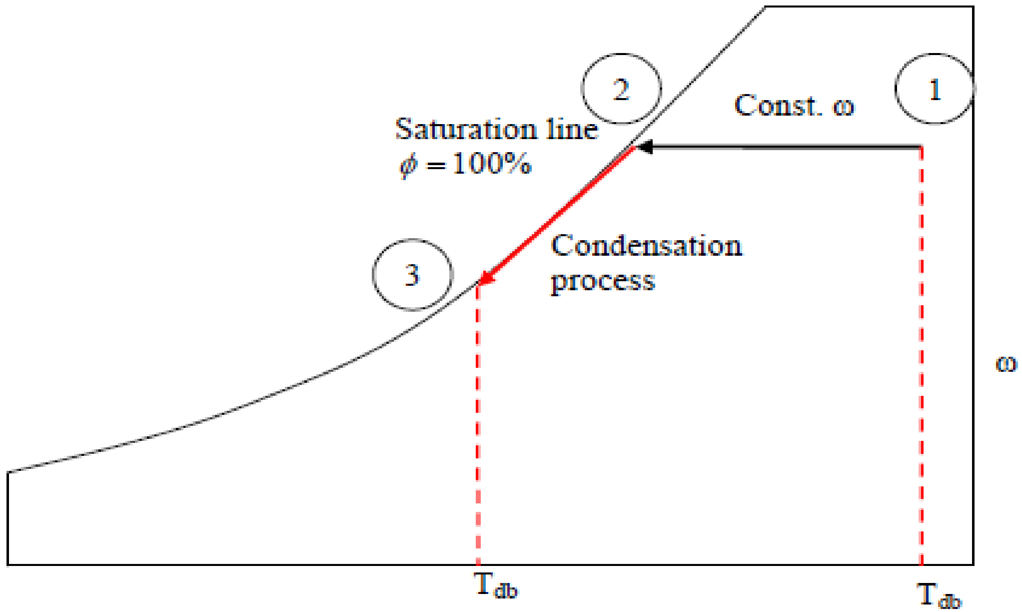


Fig.: Heating with humidification, using water spray or steam.

Air-Conditioning processes

3. Cooling with Dehumidification

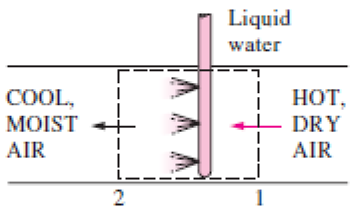
- ✓ To remove some moisture from the air, it should be cooled below its dew-point temperature.
- ✓ Passing through cooling coil, air temperature decreases and its relative humidity increases at constant specific humidity until air temperature reaches its dew point temperature.
- ✓ Any further cooling results in condensation of part of the moisture in the air.
- ✓ Note that air remains saturated during the entire condensation process.

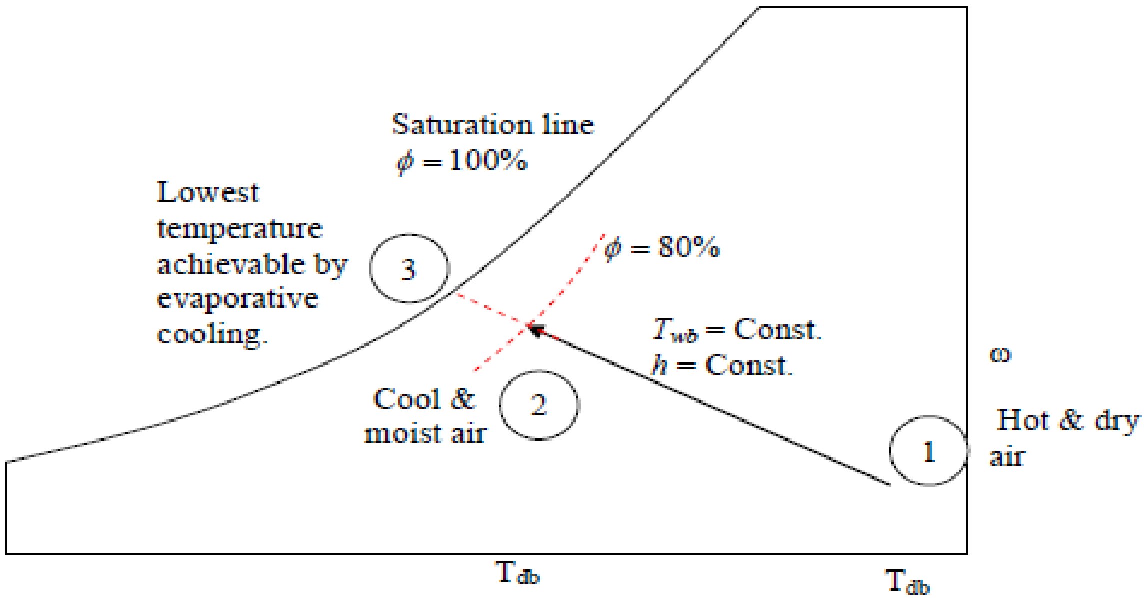


Air-Conditioning processes

4. Evaporative Cooling

- Evaporative cooling is based on a simple principle: as water evaporates, the latent heat of vaporization is absorbed from the water body and the surrounding air.
- As a result, both water and air are cooled.
- The evaporative cooling is essentially identical to the adiabatic saturation process. Thus the evaporative cooling process follows a line of constant wet-bulb temperature on the psychrometric chart.





Air-Conditioning processes

5. Adiabatic Mixing of Air streams

- ✓ Mixing processes normally involve no work interactions.
- ✓ Then the mass and energy balances for the adiabatic mixing of two airstreams reduce to:

Mass balance (dry air) $\dot{m}_{a1} + \dot{m}_{a2} = \dot{m}_{a3}$

Mass balance (water - vapor) $\omega_1 \dot{m}_{a1} + \omega_2 \dot{m}_{a2} = \omega_3 \dot{m}_{a3}$

Energy balance $\dot{m}_{a1} h_1 + \dot{m}_{a2} h_2 = \dot{m}_{a3} h_3$

Eliminating $\dot{m}_{a3}$, one obtains:

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

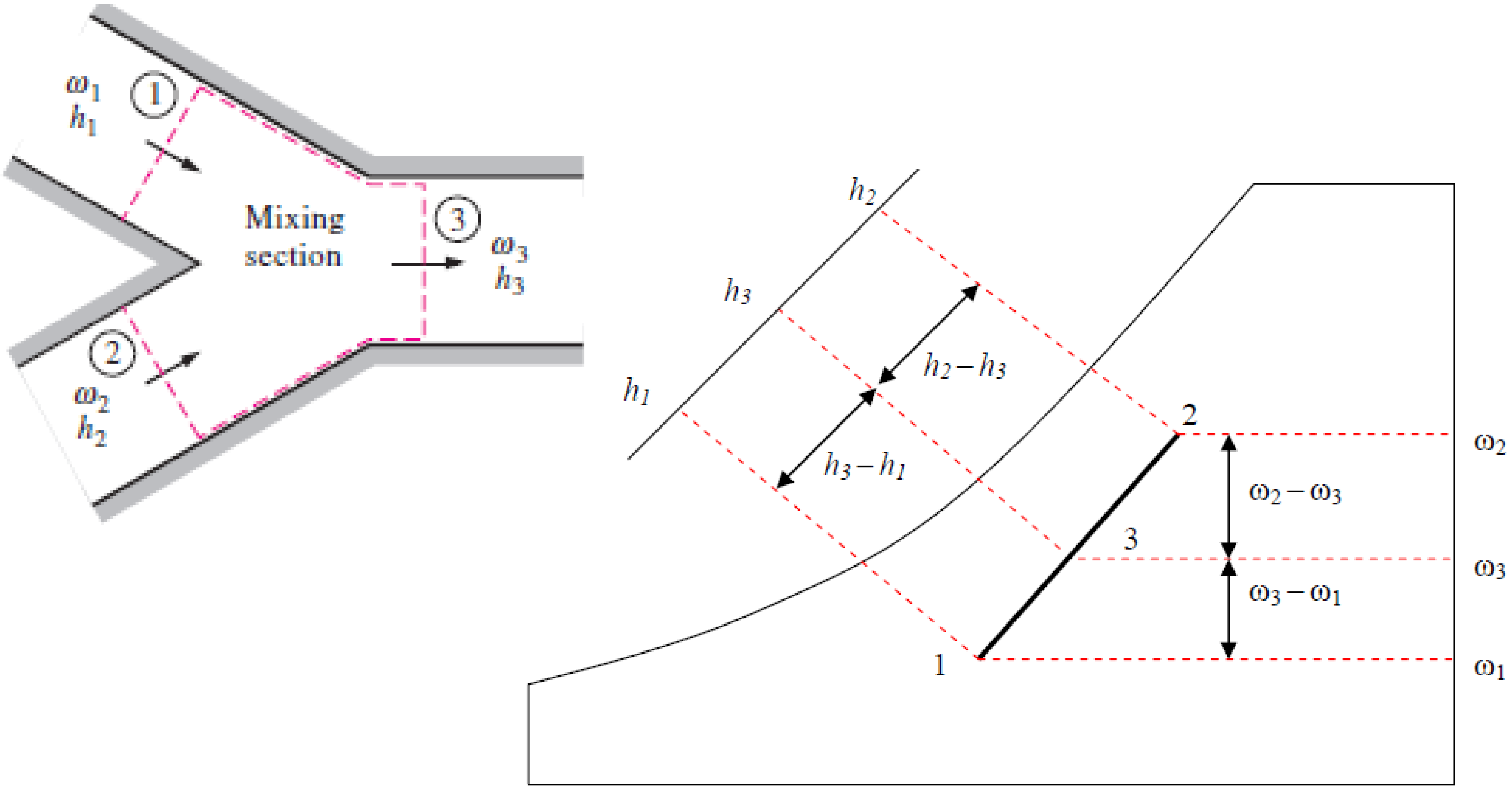


Fig: Adiabatic mixing of two streams

Example 2.4

An air-conditioning system is to take in outdoor air at 10°C and 30 percent relative humidity at a steady rate of 45 m3/min and to condition it to 25°C and 60 percent relative humidity. The outdoor air is first heated to 22°C in the heating section and then humidified by the injection of hot steam in the humidifying section. Assuming the entire process takes place at a pressure of 100 kPa, determine (*a) the rate of heat supply in the heating section and* (*b) the mass flow rate of the steam required in the humidifying section.*

Example 2.5

Saturated air at 14°C at a rate of 50 *m3/min is mixed adiabatically with the outside air at* 32°C and 60% relative humidity at a rate of 20 *m^3/min. Assuming that the mixing occurs* at 1atm, determine: a) The specific humidity, b) The relative humidity, c) The dry-bulb, and d) The wet-bulb of the mixture.

Assignment:4

For the air-conditioning system shown below in which atmospheric air is first heated and then humidified with a steam spray, determine the required heat transfer rate in the heating section and the required steam temperature in the humidification section when the steam pressure is 1MPa.