Fundamentals of Refrigeration and Air Conditioning

المرحلة الثانية

محاضرة رقم (4)

عمليات تكييف الهواء

Air Conditioning Processes

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2nd term – Lect. (**Air Conditioning Processes**)

Fundamentals of Refrigeration and Air Conditioning

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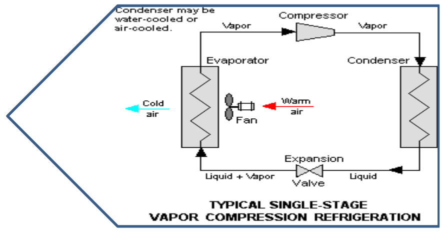
Lecture 4
Air-Conditioning Processes



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4. AIR-CONDITIONING PROCESSES

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

- These processes include:
- *sensible heating* (raising the temperature).
- *sensible cooling* (lowering the temperature).
- *humidifying* (adding moisture).
- *dehumidifying* (removing moisture).

Sometimes two or more of these processes are needed to bring the air to a desired temperature and humidity level.

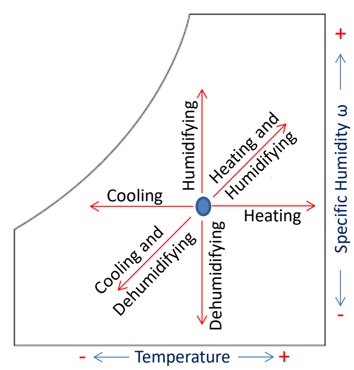

FIGURE 4–1
Various air-conditioning processes.

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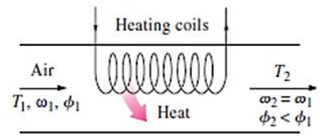
4-1 Sensible Heating and Cooling (ω = constant)

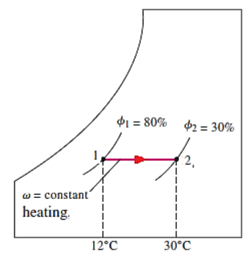
Sensible Heating

- Many residential heating systems consist of a stove, a heat pump, or an electric resistance heater.
- The air in these systems is heated by circulating it through a duct that contains the tubing for the hot gases or the electric resistance wires, as shown in Figure.
- No moisture is added to or removed from the air

$$\omega_1 = \omega_2 \quad , \quad \phi_2 < \phi_1$$

- Notice that the relative humidity of air decreases during a heating process even if the specific humidity **ω** remains constant.
- the relative humidity of heated air may be well below comfortable levels, causing dry skin, respiratory difficulties, and an increase in static electricity.





Sensible Cooling

- A cooling process at constant specific humidity is similar to the heating process discussed above, except the dry-bulb temperature decreases and the relative humidity increases during such a process, as shown in Figure.
- Cooling can be accomplished by passing the air over some coils through which a refrigerant or chilled water flows.
- The conservation of mass equations for a heating or cooling process that involves no humidification or dehumidification reduce to $m_{a1} = m_{a2} = ma$ for dry air and $\omega_1 = \omega_2$ for water.
- Neglecting any fan work that may be present, the conservation of energy equation in this case reduces to:

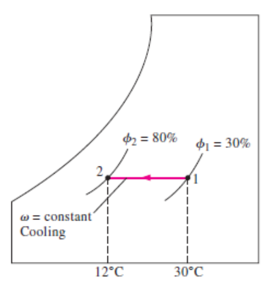


FIGURE 4–3
During simple cooling, specific humidity remains constant, but relative humidity increases.

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

where h_1 and h_2 are enthalpies per unit mass of dry air.

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4-2 Heating with Humidification

- Problems associated with the low relative humidity resulting from sensible heating can be eliminated by humidifying the heated air.
- This is accomplished by passing the air first through a heating section (process 1-2) and then through a humidifying section (process 2-3), as shown in Figure.
- The location of state 3 depends on how the humidification is accomplished.
- If steam is introduced in the humidification section, this will result in humidification with additional heating ($T3 > T2$).
- If humidification is accomplished by spraying water into the airstream instead, part of the latent heat of vaporization comes from the air, which results in the cooling of the heated airstream ($T3 < T2$). Air should be heated to a higher temperature in the heating section in this case to make up for the cooling effect during the humidification process.

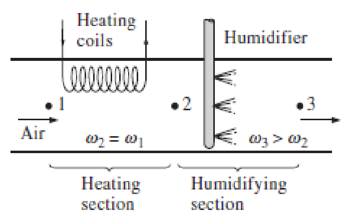
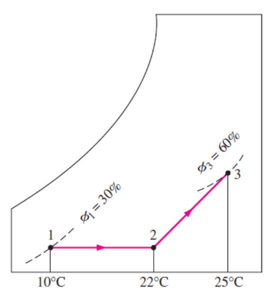


FIGURE 4– 4
Heating with humidification.

EXAMPLE 1 **Heating and Humidification of Air**

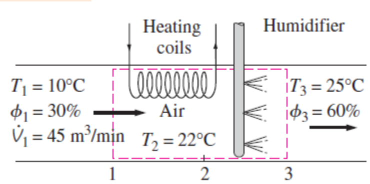
An air-conditioning system is to take in outdoor air at 10°C and 30 percent relative humidity at a steady rate of 45 m³/min and to condition it to 25°C and 60 percent relative humidity. The outdoor air is first heated to 22°C in the heating section and then humidified by the injection of hot steam in 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.



Solution

We note that the amount of water vapor in the air remains constant in the heating section ($\omega_1 = \omega_2$) but increases in the humidifying section ($\omega_3 > \omega_2$).



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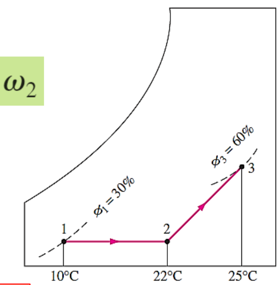
(a) Applying the mass and energy balances on the heating section gives

Dry air mass balance: $\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$

Water mass balance: $\dot{m}_{a_1}\omega_1 = \dot{m}_{a_2}\omega_2 \rightarrow \omega_1 = \omega_2$

Energy balance: $\dot{Q}_{in} + \dot{m}_a h_1 = \dot{m}_a h_2$

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1)$$



Note: At pressures other than 1 atm, either other charts for that pressure or the relations developed earlier should be used. In our case, the choice is clear:

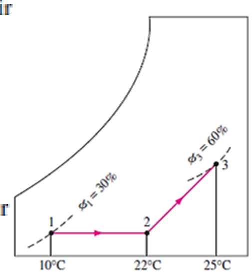
$$P_{v_1} = \phi_1 P_{g_1} = \phi P_{sat\ @\ 10°C} = (0.3)(1.2281\ kPa) = 0.368\ kPa$$

$$P_{a_1} = P_1 - P_{v_1} = (100 - 0.368)\ kPa = 99.632\ kPa$$

$$v_1 = \frac{R_a T_1}{P_a} = \frac{(0.287\ kPa \cdot m^3/kg \cdot K)(283\ K)}{99.632\ kPa} = 0.815\ m^3/kg\ dry\ air$$

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{45\ m^3/min}{0.815\ m^3/kg} = 55.2\ kg/min$$

$$\omega_1 = \frac{0.622 P_{v_1}}{P_1 - P_{v_1}} = \frac{0.622(0.368\ kPa)}{(100 - 0.368)\ kPa} = 0.0023\ kg\ H_2O/kg\ dry\ air$$



$$h_1 = c_p T_1 + \omega_1 h_{g_1} = (1.005\ kJ/kg \cdot °C)(10°C) + (0.0023)(2519.2\ kJ/kg)$$
$$= 15.8\ kJ/kg\ dry\ air$$

$$h_2 = c_p T_2 + \omega_2 h_{g_2} = (1.005\ kJ/kg \cdot °C)(22°C) + (0.0023)(2541.0\ kJ/kg)$$
$$= 28.0\ kJ/kg\ dry\ air$$

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (55.2\ kg/min)[(28.0 - 15.8)\ kJ/kg]$$
$$= 673\ kJ/min = 673\ \frac{1}{60} = 11.22\ kW$$

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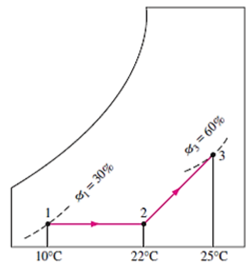
(*b*) The mass balance for water in the humidifying section can be expressed as

$$\dot{m}_{a_2}\omega_2 + \dot{m}_w = \dot{m}_{a_3}\omega_3$$

or

$$\dot{m}_w = \dot{m}_a(\omega_3 - \omega_2)$$



$P_{v3} = \phi_3 P_{sat@25^oC} = (0.6)(3.1698) = \mathbf{1.9019}$ kPa

$$\omega_3 = \frac{0.622\,P_{v3}}{P_3 - P_{v3}} = \frac{(0622)(1.9019)}{(100 - 1.9019)} = \mathbf{0.01206}\ kgH_{20}/kgdry_{\,air}$$

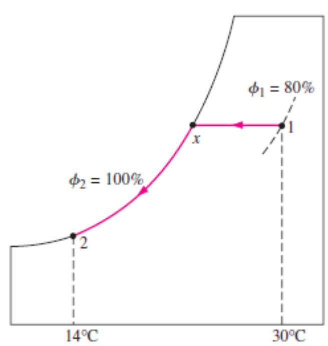
Notice $\omega_2 = \omega_1 = 0.0023\ kg_{H20}/kgdry_{\,air}$

Thus

$$m_w = (55.2)(0.01206 - \dot{0}.0023) = \mathbf{0.539\ kg/min}$$

4-3 Cooling with Dehumidification

- The specific humidity of air remains constant during a sensible (simple) cooling process, but its relative humidity increases.
- If the relative humidity reaches undesirably high levels, it may be necessary to remove some moisture from the air, that is, to dehumidify it. This requires cooling the air below its dew point temperature.
- Hot, moist air enters the cooling section at state 1. As it passes through the cooling coils, its temperature decreases and its relative humidity increases at constant specific humidity.
- If the cooling section is sufficiently long, air reaches its dew point (state *x*, saturated air). Further cooling of air results in the condensation of part of the moisture in the air.



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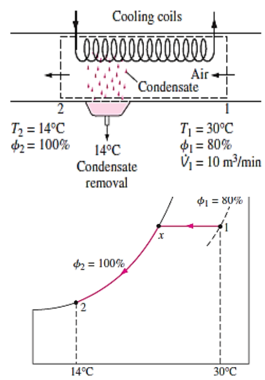
EXAMPLE 2 **Cooling and Dehumidification of Air**

Air enters a window air conditioner at 1 atm, 30°C, and 80 percent relative humidity at a rate of 10 m3/min, and it leaves as saturated air at 14°C. Part of the moisture in the air that condenses during the process is also removed at 14°C. Determine the rates of heat and moisture removal from the air.

Solution

The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. Therefore, we can determine the properties of the air at both states from the psychrometric chart to be



h_1=86.4 kJ/kg $_{dry\ air}$ h_2=39.4 kJ/kg $_{dry\ air}$

ω_1=0.022 kg $_{H2O}$/kg $_{dry\ air}$ ω_2=0.01 kg $_{H2O}$/kg $_{dry\ air}$

υ_1=0.889 m^3/kg $_{dry\ air}$

Dry air mass balance: $\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$

Water mass balance: $\dot{m}_{a1}\omega_1 = \dot{m}_{a2}\omega_2 + m_w$

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

Energy balance: $\sum_{in}\dot{m}h = \dot{Q}_{out} + \sum_{out}\dot{m}h \Longrightarrow \dot{Q}_{out} = \dot{m}(h_1 - h_2) - \dot{m}_w h_w$

Then,

$$\dot{m}a = \frac{\dot{V}_1}{\upsilon_1} = \frac{10}{0.889} = \mathbf{11.25\ kg/min}$$

$$\dot{m}_w = (11.25)(0.022 - 0.01) = \mathbf{0.135\ kg/min}$$

$$\dot{Q}_{out} = \dot{m}(h_1 - h_2) - \dot{m}_w h_w$$

$h_w = h_{f@14°C} = 58.8$ kJ/kg

$\dot{Q}_{out}$ = [(11.25)(86.4 – 39.4)] – (0.135)(58.8)
= **520.812 kJ/min** = 520.812 (1/60) = **8.68 kW**

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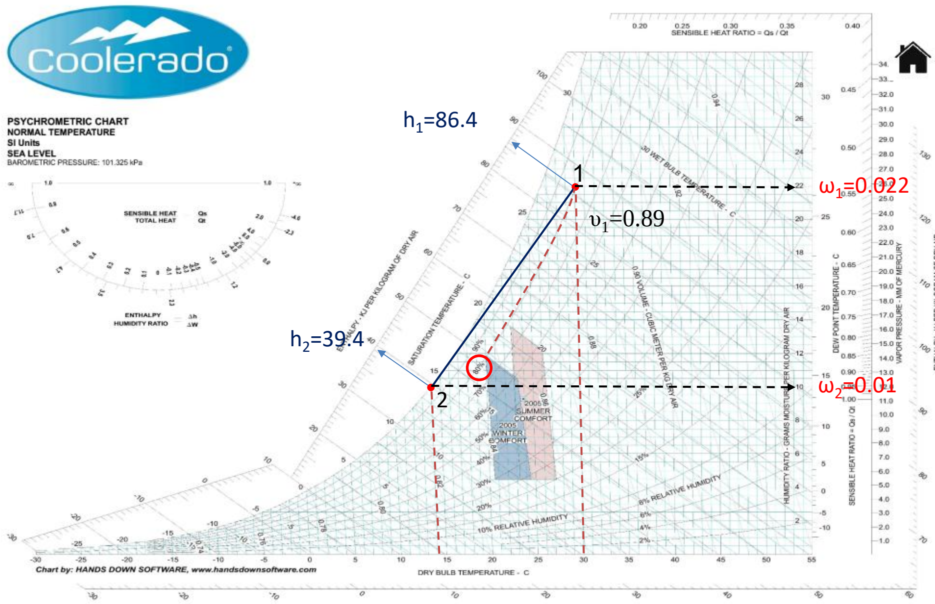
Lecture2. Air Properties



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27

Lecture4. Air-Conditioning Processes

4-4 Evaporative Cooling

- Conventional cooling systems operate on a refrigeration cycle, and they can be used in any part of the world. But they have a high initial and operating cost. In desert (hot and dry) climates, we can avoid the high cost of cooling by using ***evaporative coolers***, also known as ***swamp coolers*** ***or*** ***air washer***.
- 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 the water and the air are cooled during the process.

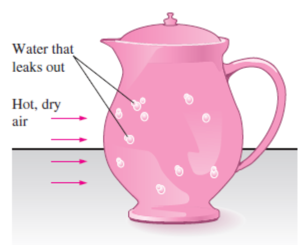

FIGURE 4–6
Water in a porous jug left in an open, breezy area cools as a result of evaporative cooling.

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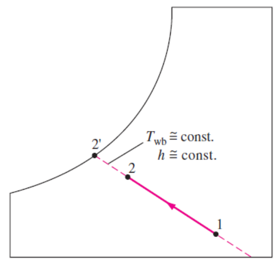
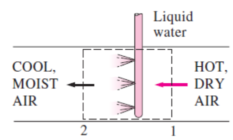
13

- Hot, dry air at state 1 enters the evaporative cooler, where it is sprayed with liquid water.
- Part of the water evaporates during this process by absorbing heat from the airstream. As a result, the temperature of the airstream decreases and its humidity increases (state 2).
- In the limiting case, the air leaves the evaporative cooler saturated at state 2'. This is the lowest temperature that can be achieved by this process.
- The evaporative cooling process is essentially identical to the adiabatic saturation process since the heat transfer between the airstream and the surroundings is usually negligible.
- the evaporative cooling process follows a line of constant wet-bulb temperature on the psychrometric chart. (Note that this will not exactly be the case if the liquid water is supplied at a temperature different from the exit temperature of the airstream.)





$$T_{wb} \cong \text{constant}$$
$$h \cong \text{constant}$$

EXAMPLE 3 **Evaporative Cooling of Air by a Swamp Cooler**

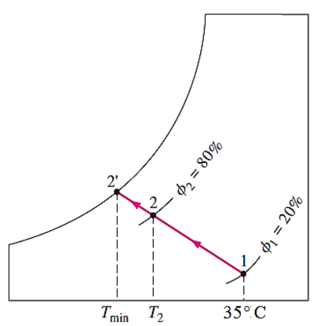
Air enters an evaporative (or swamp) cooler at 1 atm, 35°C, and 20 percent relative humidity, and it exits at 80 percent relative humidity. Determine
(a) The exit temperature of the air
(b) The lowest temperature to which the air can be cooled by this evaporative cooler.

Solution

The evaporative cooling process follows a line of constant wet-bulb temperature on the psychrometric chart.

T_2 = 21.3 °C

$T_{2'}$ = 18.8 °C



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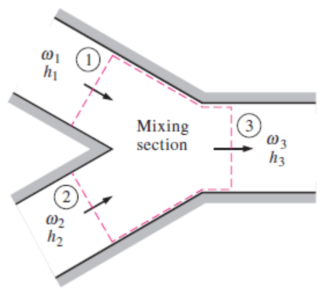
4-5 Adiabatic Mixing of Airstreams

- Many air-conditioning applications require the mixing of two airstreams. This is particularly true for large buildings, most production and process plants, and hospitals, which require that the conditioned air be mixed with a certain fraction of fresh outside air before it is routed into the living space.
- The mixing is accomplished by simply merging the two airstreams, as shown in Fig.



Lecture4. Air-Conditioning Processes

- The heat transfer with the surroundings is usually small, and thus the mixing processes can be assumed to be adiabatic.
- Mixing processes normally involve no work interactions, and the changes in kinetic and potential energies, if any, are negligible. Then the mass and energy balances for the adiabatic mixing of two airstreams reduce to:

Mass of dry air: $$\dot{m}_{a_1} + \dot{m}_{a_2} = \dot{m}_{a_3} \quad (4\text{–}21)$$

Mass of water vapor: $$\omega_1\dot{m}_{a_1} + \omega_2\dot{m}_{a_2} = \omega_3\dot{m}_{a_3} \quad (4\text{–}22)$$

Energy: $$\dot{m}_{a_1}h_1 + \dot{m}_{a_2}h_2 = \dot{m}_{a_3}h_3 \quad (4\text{–}23)$$

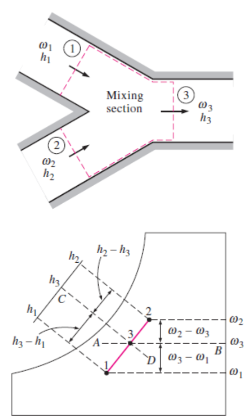


FIGURE 4–7
When two airstreams at states 1 and 2 are mixed adiabatically, the state of the mixture lies on the straight line connecting the two states.

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Eliminating $\dot{m}_{a_3}$ from the relations above, we obtain

$$\frac{\dot{m}_{a_1}}{\dot{m}_{a_2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1} \qquad (4\text{–}24)$$

- The concave nature of the saturation curve and the conclusion above lead to an interesting possibility. When states 1 and 2 are located close to the saturation curve, the straight line connecting the two states will cross the saturation curve, and state 3 may lie to the left of the saturation curve. In this case, some water will inevitably condense during the mixing process.

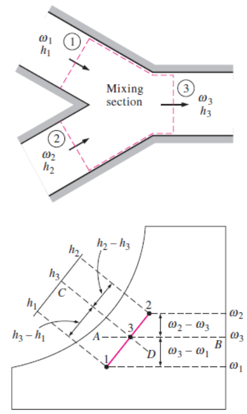

FIGURE 4–7
When two airstreams at states 1 and 2 are mixed adiabatically, the state of the mixture lies on the straight line connecting the two states.

EXAMPLE 4–4 Mixing of Conditioned Air with Outdoor Air

- Saturated air leaving the cooling section of an air-conditioning system at 14°C at a rate of 50 m³/min is mixed adiabatically with the outside air at 32°C and 60 percent relative humidity at a rate of 20 m³/min. Assuming that the mixing process occurs at a pressure of 1 atm, determine the specific humidity, the relative humidity, the dry-bulb temperature, and the volume flow rate of the mixture.
- ***Properties*** The properties of each inlet stream are determined from the psychrometric chart to be:

$$h_1 = 39.4 \text{ kJ/kg dry air} \qquad h_2 = 79.0 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.010 \text{ kg H}_2\text{O/kg dry air} \quad \text{and} \quad \omega_2 = 0.0182 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.826 \text{ m}^3\text{/kg dry air} \qquad v_2 = 0.889 \text{ m}^3\text{/kg dry air}$$

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The mass flow rates of dry air in each stream are

$$\dot{m}_{a_1} = \frac{\dot{V}_1}{v_1} = \frac{50\ \text{m}^3/\text{min}}{0.826\ \text{m}^3/\text{kg dry air}} = 60.5\ \text{kg/min}$$

$$\dot{m}_{a_2} = \frac{\dot{V}_2}{v_2} = \frac{20\ \text{m}^3/\text{min}}{0.889\ \text{m}^3/\text{kg dry air}} = 22.5\ \text{kg/min}$$

From the mass balance of dry air,

$$\dot{m}_{a_3} = \dot{m}_{a_1} + \dot{m}_{a_2} = (60.5 + 22.5)\ \text{kg/min} = 83\ \text{kg/min}$$

The specific humidity and the enthalpy of the mixture can be determined from Eq. 4–24,

$$\frac{\dot{m}_{a_1}}{\dot{m}_{a_2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\frac{60.5}{22.5} = \frac{0.0182 - \omega_3}{\omega_3 - 0.010} = \frac{79.0 - h_3}{h_3 - 39.4}$$

which yield

$$\omega_3 = \mathbf{0.0122\ kg\ H_2O/kg\ dry\ air}$$

$$h_3 = 50.1\ \text{kJ/kg dry air}$$

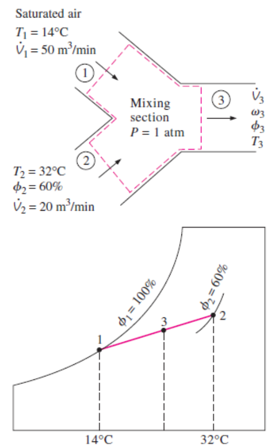

FIGURE 4–8
Schematic and psychrometric chart for Example 4–4

These two properties fix the state of the mixture. Other properties of the mixture are determined from the psychrometric chart:

T3 = **19.0°C**
ϕ = **89%**
V3 = 0.844 m^3/kg dry air

Finally, the volume flow rate of the mixture is determined from

$$\dot{V}_3 = \dot{m}_{a_3} v_3 = (83\ \text{kg/min})(0.844\ \text{m}^3/\text{kg}) = \mathbf{70.1\ m^3/min}$$

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