moisture), and *dehumidifying* (removing moisture). Sometimes two or more of these processes are needed to bring the air to a desired temperature and humidity level.

Various air conditioning processes are illustrated on the psychrometric chart in Fig. 13-20. Notice that simple heating and cooling processes appear as horizontal lines on this chart since the moisture content of the air remains constant (ω = constant) during these processes. Air is commonly heated and humidified in winter and cooled and dehumidfied in summer. Notice how these processes appear on the psychrometric chart.

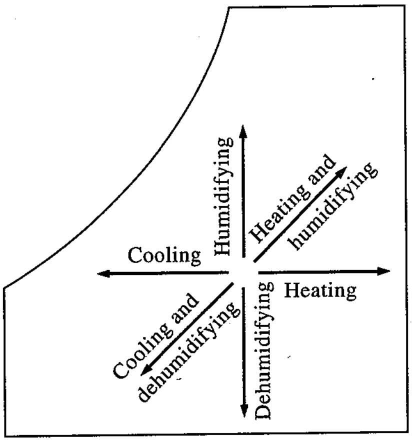

FIGURE 13-20
Various air conditioning processes.

Most air conditioning processes can be modeled as steady-flow processes, and therefore they can be analyzed by applying the steady-flow conservation of mass (for both dry air and water) and conservation of energy principles:

Dry air mass: $\sum \dot{m}_{a,i} = \sum \dot{m}_{a,e}$ (13-16)

Water mass: $\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e}$ or $\sum \dot{m}_{a,i}\omega_i = \sum \dot{m}_{a,e}\omega_e$ (13-17)

Energy: $\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$ (13-18)

Here subscripts i and e denote inlet and exit states, respectively. The changes in kinetic and potential energies are assumed to be negligible. The work term usually consists of the fan work, which is very small relative to the other terms in the energy equation. Next we examine some commonly encountered processes in air conditioning.

1 Simple Heating and Cooling (ω = constant)

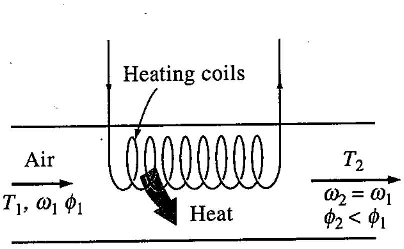

FIGURE 13-21
During simple heating, specific humidity remains constant, but relative humidity decreases.

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 Fig. 13-21. The amount of moisture in the air remains constant during this process since no moisture is added to or removed from the air. That is, the specific humidity of the air remains constant (ω = constant) during a heating (or cooling) process with no humidification or dehumidification. Such a heating process will proceed in the direction of increasing dry-bulb temperature following a line of constant specific humidity on the psychrometric chart, which appears as a horizontal line.

Notice that the relative humidity of air decreases during a heating process even if the specific humidity ω remains constant. This is because the relative humidity is the ratio of the moisture content to the moisture capacity of air at the same temperature, and moisture capacity increases with temperature. Therefore, the relative humidity of heated air may be well below comfortable levels, causing dry skin, respiratory difficulties, and an increase in static electricity.

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 Fig. 13-22. Cooling can be accomplished by passing the air over some coils through which a refrigerant or cool water flows.

The conservation of mass equations for a heating or cooling process which involves no humidification or dehumidification reduce to $\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$ 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 $\dot{Q} = \dot{m}_a(h_2 - h_1)$ or $q = h_2 - h_1$, where h_1 and h_2 are enthalpies per unit mass of dry air at the inlet and the exit of the heating or cooling section, respectively.

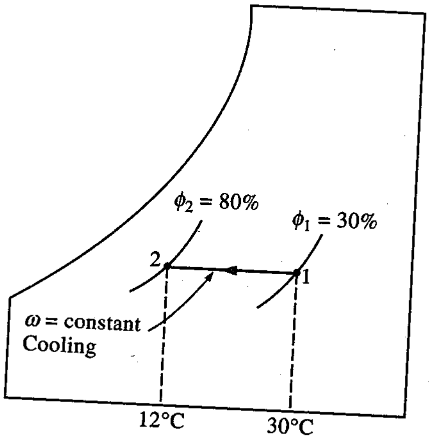

FIGURE 13-22
During simple cooling, specific humidity remains constant, but relative humidity increases.

2 Heating with Humidification

Problems associated with the low relative humidity resulting from simple 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 Fig. 13-23.

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 ($T_3 > T_2$). If humidification is accomplished by spraying water into the airstream instead, part of the latent heat of vaporization will come from the air, which will result in the cooling of the heated airstream ($T_3 < T_2$). Air should be heated to a higher temperature in the heating section in this case to make up for the cooling during the humidification process.

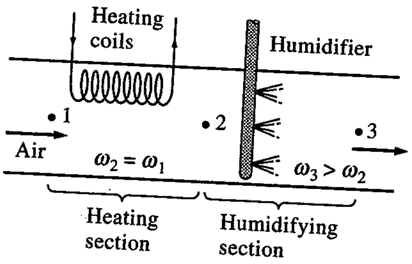

FIGURE 13-23
Heating and humidification.

EXAMPLE 13-5

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 The schematic of the system and the psychrometric chart of the process are shown in Fig. 13-24. The mass flow rate of the dry air remains constant during the entire process. The amount of moisture in the air remains constant as it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$).

(*a*) The conservation of mass and the conservation of energy equations for the heating section reduce to these:

Dry air mass: $\sum \dot{m}_{a,i} = \sum \dot{m}_{a,e} \longrightarrow \dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$

Water mass: $\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e} \longrightarrow \dot{m}_{a_1}\omega_1 = \dot{m}_{a_2}\omega_2 \quad \text{or} \quad \omega_1 = \omega_2$

Energy: $\dot{Q} - \cancel{\dot{W}}^{0} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \longrightarrow \dot{Q} = \dot{m}_a(h_2 - h_1)$

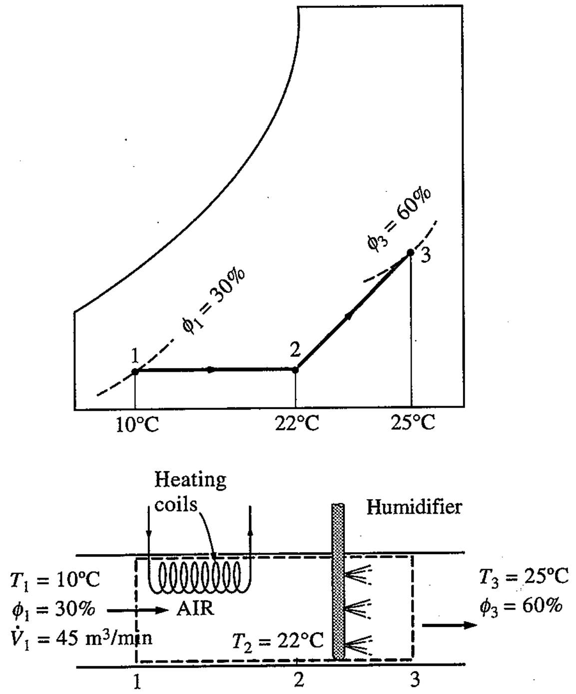

FIGURE 13-24
Schematic and psychrometric chart for Example 13-5.

The psychrometric chart offers great convenience in determining the properties of moist air. However, its use is limited to a specified pressure only, which is 1 atm (101.325 kPa) for the one given in the Appendix. 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:

$$P_{v_1} = \phi_1 P_{g_1} = \phi_1 P_{\text{sat @ 10°C}} = (0.3)(1.2276\ \text{kPa}) = 0.368\ \text{kPa}$$

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

$$v_1 = \frac{R_a T_1}{P_{a_1}} = \frac{[0.287\ \text{kPa}\cdot\text{m}^3/(\text{kg}\cdot\text{K})](283\ \text{K})}{99.632\ \text{kPa}} = 0.815\ \text{m}^3/\text{kg dry air}$$

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

$$\omega_1 = \frac{0.622 P_{v_1}}{P_1 - P_{v_1}} = \frac{0.622(0.368\ \text{kPa})}{(100 - 0.368)\ \text{kPa}} = 0.0023\ \text{kg H}_2\text{O/kg dry air}$$

$$\begin{aligned} h_1 &= C_p T_1 + \omega_1 h_{g_1} = [1.005\ \text{kJ/(kg}\cdot\text{°C)}](10\text{°C}) + (0.0023)(2519.8\ \text{kJ/kg}) \\ &= 15.8\ \text{kJ/kg dry air} \end{aligned}$$

$$\begin{aligned} h_2 &= C_p T_2 + \omega_2 h_{g_2} = [1.005\ \text{kJ/(kg}\cdot\text{°C)}](22\text{°C}) + (0.0023)(2541.7\ \text{kJ/kg}) \\ &= 28.0\ \text{kJ/kg dry air} \end{aligned}$$

since $\omega_2 = \omega_1$. Then the rate of heat transfer to the air in the heating section becomes

$$\begin{aligned} \dot{Q} &= \dot{m}_a(h_2 - h_1) = (55.2\ \text{kg/min})[(28.0 - 15.8)\ \text{kJ/kg}] \\ &= \mathbf{673.4\ kJ/min} \end{aligned}$$

the properties
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/ air

9.8 kJ/kg)

1.7 kJ/kg)

ting section

(*b*) The conservation of mass equation 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

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

where

$$\omega_3 = \frac{0.622\phi_3 P_{g_3}}{P_3 - \phi_3 P_{g_3}} = \frac{0.622(0.60)(3.169\text{ kPa})}{[100 - (0.60)(3.169)]\text{ kPa}}$$

$$= 0.01206\text{ kg H}_2\text{O/kg dry air}$$

Thus,

$$\dot{m}_w = (55.2\text{ kg/min})(0.01206 - 0.0023)$$

$$= \mathbf{0.539\ kg/min}$$

3 Cooling with Dehumidification

The specific humidity of air remains constant during a 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, i.e., to dehumidify it. This requires cooling the air below its dew-point temperature.

The cooling process with dehumidifying is illustrated schematically and on the psychrometric chart in Fig. 13-25 in conjunction with Example 13-6. 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 will reach its dew point (state 2, saturated air). Further cooling of air results in the condensation of part of the moisture in the air. Air remains saturated during the entire condensation process, which follows a line of 100 percent relative humidity until the final state (state 3) is reached. The water vapor that condenses out of the air during this process is removed from the cooling section through a separate channel. The condensate is usually assumed to leave the cooling section at T_3.

The cool, saturated air at state 3 is usually routed directly to the room, where it mixes with the room air. In some cases, however, the air at state 3 may be at the right specific humidity but at a very low temperature. In such cases, the air is passed through a heating section where its temperature is raised to a more comfortable level before it is routed to the room.

EXAMPLE 13-6

Air enters a window air conditioner at 1 atm, 30°C, and 80 percent relative humidity at a rate of 10 m^3/min, and it leaves as saturated air at 14°C. Part of the moisture in the air which condenses during the process is also removed at 14°C. Determine the rates of heat and moisture removal from the air.

Solution The schematic of the system and the psychrometric chart of the process are shown in Fig. 13-25. The mass flow rate of dry air remains constant during the entire process, but the amount of moisture in the air decreases due

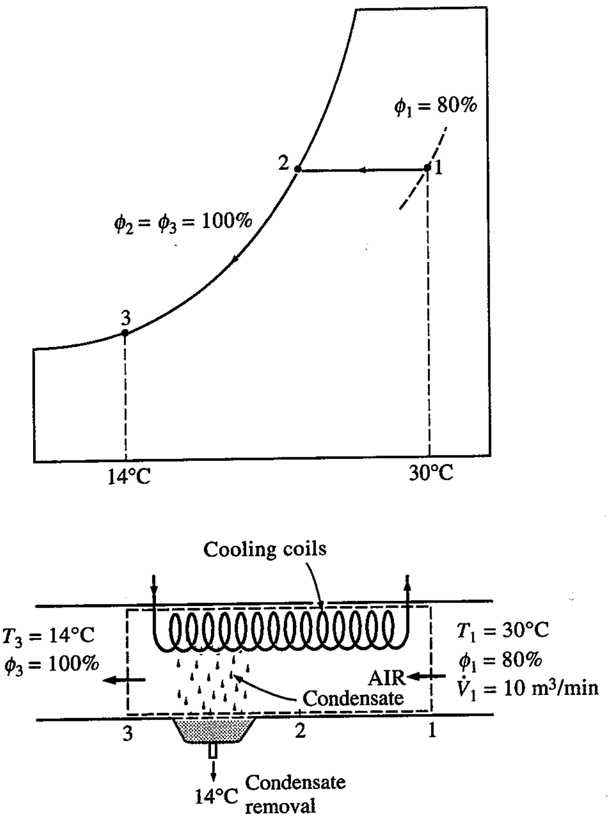

FIGURE 13-25
Schematic and psychrometric chart for Example 13-6.

to dehumidification ($\omega_2 < \omega_1$). The conservation of mass and the conservation of energy equations for the combined cooling and dehumidification section reduce to these:

Dry air mass: $\sum \dot m_{a,i} = \sum \dot m_{a,e} \longrightarrow \quad \dot m_{a_1} = \dot m_{a_2} = \dot m_a$

Water mass: $\sum \dot m_{w,i} = \sum \dot m_{w,e} \longrightarrow \dot m_{a_1}\omega_1 = \dot m_{a_2}\omega_2 + \dot m_w$

or $\dot m_w = \dot m_a(\omega_1 - \omega_2)$

Energy: $\dot Q - \cancel{\dot W}^{0} = \sum \dot m_e h_e - \sum \dot m_i h_i \longrightarrow \dot Q = \dot m_{a_2} h_2 - \dot m_{a_1} h_1 + \dot m_w h_w$
$= \dot m_a(h_2 - h_1) + \dot m_w h_w$

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:

$$h_1 = 85.4 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0216 \text{ kg } H_2O\text{/kg dry air}$$
$$v_1 = 0.889 \text{ m}^3\text{/kg dry air}$$

and
$$h_2 = 39.3 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0100 \text{ kg } H_2O\text{/kg dry air}$$

Also, $h_w = h_{f\,@\,14°C} = 58.8$ kJ/kg (Table A-4)

and the conservation
humidification section

$\dot m_w$

$\omega_2)$

$h_2 - \dot m_{a_1} h_1 + \dot m_w h_w$

$(h_2 - h_1) + \dot m_w h_w$

ecified, and the total
ties of the air at both

Then
$$\dot m_{a_1} = \frac{\dot V_1}{v_1} = \frac{10\ \text{m}^3/\text{min}}{0.889\ \text{m}^3/\text{kg dry air}} = 11.3\ \text{kg/min}$$

$$\dot m_w = (11.3\ \text{kg/min})(0.0216 - 0.0100) = 0.131\ \text{kg/min}$$

$$\dot Q = (11.3\ \text{kg/min})[(39.3 - 85.4)\ \text{kJ/kg}] + (0.131\ \text{kg/min})(58.8\ \text{kJ/kg})$$
$$= -513\ \text{kJ/min}$$

Therefore, this air conditioning unit removes moisture and heat from the air at rates of 0.131 kg/min and 513 kJ/min, respectively.

4 Evaporative Cooling

NO

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.*

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. This approach has been used for thousands of years to cool water. A porous jug or pitcher filled with water is left in an open, shaded area. A small amount of water leaks out through the porous holes, and the pitcher "sweats." In a dry environment, this water evaporates and cools the remaining water in the pitcher (Fig. 13-26).

You have probably noticed that on a hot, dry day the air feels a lot cooler when the yard is watered. This is because water absorbs heat from the air as it evaporates. An evaporative cooler works on the same principle. The evaporative cooling process is shown schematically and on a psychrometric chart in Fig. 13-27. 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 will leave the cooler saturated at state 2′. This is the lowest temperature which 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. Therefore, 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.) Since the constant-wet-bulb-temperature lines almost coincide with the constant-enthalpy lines, the enthalpy of the airstream can also be assumed to remain constant. That is,

$$T_{\text{wb}} \cong \text{constant} \tag{13-19}$$

and

$$h \cong \text{constant} \tag{13-20}$$

Air

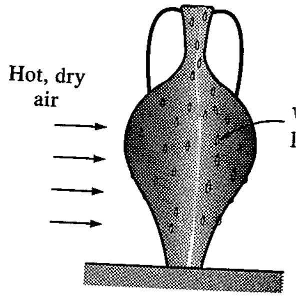

FIGURE
The water in a porous jug le
open, breezy area cools as a r
evaporative c