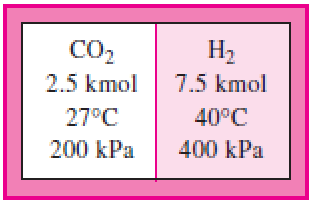
13–52 An insulated rigid tank is divided into two compartments by a partition. One compartment contains 2.5 kmol of CO_2 at 27°C and 200 kPa, and the other compartment contains 7.5 kmol of H_2 gas at 40°C and 400 kPa. Now the partition is removed, and the two gases are allowed to mix. Determine (*a*) the mixture temperature and (*b*) the mixture pressure after equilibrium has been established. Assume constant specific heats at room temperature for both gases.



13-52 The moles, temperatures, and pressures of two gases forming a mixture are given. The mixture temperature and pressure are to be determined.

Assumptions **1** Under specified conditions both CO_2 and H_2 can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** The tank is insulated and thus there is no heat transfer. **3** There are no other forms of work involved.

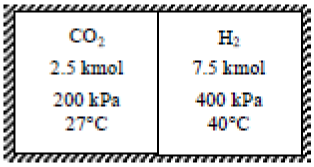
Properties The molar masses and specific heats of CO_2 and H_2 are 44.0 kg/kmol, 2.0 kg/kmol, 0.657 kJ/kg.°C, and 10.183 kJ/kg.°C, respectively. (Tables A-1 and A-2b).

Analysis (*a*) We take both gases as our system. No heat, work, or mass crosses the system boundary, therefore this is a closed system with $Q = 0$ and $W = 0$. Then the energy balance for this closed system reduces to

$$E_{in} - E_{out} = \Delta E_{system}$$

$$0 = \Delta U = \Delta U_{CO_2} + \Delta U_{H_2}$$

$$0 = [mc_v(T_m - T_1)]_{CO_2} + [mc_v(T_m - T_1)]_{H_2}$$



Using c_v values at room temperature and noting that $m = NM$, the final temperature of the mixture is determined to be

$$(2.5\times 44\text{ kg})(0.657\text{ kJ/kg}\cdot{}^\circ\text{C})(T_m - 27^\circ\text{C}) + (7.5\times 2\text{ kg})(10.183\text{ kJ/kg}\cdot{}^\circ\text{C})(T_m - 40^\circ\text{C}) = 0$$

$$T_m = \mathbf{35.8^\circ C} \quad (308.8\text{ K})$$

(*b*) The volume of each tank is determined from

$$V_{CO_2} = \left(\frac{NR_uT_1}{P_1}\right)_{CO_2} = \frac{(2.5\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(300\text{ K})}{200\text{ kPa}} = 31.18\text{ m}^3$$

$$V_{H_2} = \left(\frac{NR_uT_1}{P_1}\right)_{H_2} = \frac{(7.5\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(313\text{ K})}{400\text{ kPa}} = 48.79\text{ m}^3$$

Thus,

$$V_m = V_{CO_2} + V_{H_2} = 31.18\text{ m}^3 + 48.79\text{ m}^3 = 79.97\text{ m}^3$$

$$N_m = N_{CO_2} + N_{H_2} = 2.5\text{ kmol} + 7.5\text{ kmol} = 10.0\text{ kmol}$$

and $$P_m = \frac{N_mR_uT_m}{V_m} = \frac{(10.0\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(308.8\text{ K})}{79.97\text{ m}^3} = \mathbf{321\text{ kPa}}$$

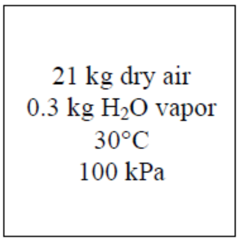
14–15 A tank contains 21 kg of dry air and 0.3 kg of water vapor at 30°C and 100 kPa total pressure. Determine (*a*) the specific humidity, (*b*) the relative humidity, and (*c*) the volume of the tank.

14-15 A tank contains dry air and water vapor at specified conditions. The specific humidity, the relative humidity, and the volume of the tank are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The specific humidity can be determined form its definition,

$$\omega = \frac{m_v}{m_a} = \frac{0.3\text{ kg}}{21\text{ kg}} = \mathbf{0.0143\ kg\ H_2O/kg\ dry\ air}$$



(*b*) The saturation pressure of water at 30°C is

$$P_g = P_{\text{sat @ 30°C}} = 4.2469\text{ kPa}$$

Then the relative humidity can be determined from

$$\phi = \frac{\omega P}{(0.622+\omega)P_g} = \frac{(0.0143)(100\text{ kPa})}{(0.622+0.0143)(4.2469\text{ kPa})} = \mathbf{52.9\%}$$

(*c*) The volume of the tank can be determined from the ideal gas relation for the dry air,

$$P_v = \phi P_g = (0.529)(4.2469\text{ kPa}) = 2.245\text{ kPa}$$

$$P_a = P - P_v = 100 - 2.245 = 97.755\text{ kPa}$$

$$V = \frac{m_a R_a T}{P_a} = \frac{(21\text{ kg})(0.287\text{ kJ/kg}\cdot\text{K})(303\text{ K})}{97.755\text{ kPa}} = \mathbf{18.7\ m^3}$$

14–17 A room contains air at 20°C and 98 kPa at a relative humidity of 85 percent. Determine (*a*) the partial pressure of dry air, (*b*) the specific humidity of the air, and (*c*) the enthalpy per unit mass of dry air.

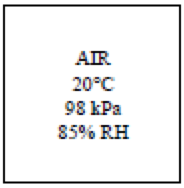
14-17 A room contains air at specified conditions and relative humidity. The partial pressure of air, the specific humidity, and the enthalpy per unit mass of dry air are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The partial pressure of dry air can be determined from

$$P_v = \phi P_g = \phi P_{\text{sat @ 20°C}} = (0.85)(2.3392\text{ kPa}) = 1.988\text{ kPa}$$

$$P_a = P - P_v = 98 - 1.988 = \mathbf{96.01\ kPa}$$



(*b*) The specific humidity of air is determined from

$$\omega = \frac{0.622 P_v}{P - P_v} = \frac{(0.622)(1.988\text{ kPa})}{(98-1.988)\text{ kPa}} = \mathbf{0.0129\ kg\ H_2O/kg\ dry\ air}$$

(*c*) The enthalpy of air per unit mass of dry air is determined from

$$h = h_a + \omega h_v \cong c_p T + \omega h_g$$

$$= (1.005\text{ kJ/kg}\cdot\text{°C})(20\text{°C}) + (0.0129)(2537.4\text{ kJ/kg}) = \mathbf{52.78\ kJ/kg\ dry\ air}$$

14–31 The dry- and wet-bulb temperatures of atmospheric air at 95 kPa are 25 and 17°C, respectively. Determine (*a*) the specific humidity, (*b*) the relative humidity, and (*c*) the enthalpy of the air, in kJ/kg dry air.

14-31 The dry- and wet-bulb temperatures of atmospheric air at a specified pressure are given. The specific humidity, the relative humidity, and the enthalpy of air are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) We obtain the properties of water vapor from EES. The specific humidity ω_1 is determined from

$$\omega_1 = \frac{c_p(T_2 - T_1) + \omega_2 h_{fg2}}{h_{g1} - h_{f2}}$$

95 kPa
25°C
T_{wb} = 17°C

where T_2 is the wet-bulb temperature, and ω_2 is determined from

$$\omega_2 = \frac{0.622 P_{g2}}{P_2 - P_{g2}} = \frac{(0.622)(1.938\text{ kPa})}{(95 - 1.938)\text{ kPa}} = 0.01295\text{ kg H}_2\text{O/kg dry air}$$

Thus, $$\omega_1 = \frac{(1.005\text{ kJ/kg}\cdot{}^\circ\text{C})(17-25)^\circ\text{C} + (0.01295)(2460.6\text{ kJ/kg})}{(2546.5 - 71.36)\text{ kJ/kg}} = \mathbf{0.00963\text{ kg H}_2\text{O/kg dry air}}$$

(*b*) The relative humidity ϕ_1 is determined from

$$\phi_1 = \frac{\omega_1 P_1}{(0.622 + \omega_1)P_{g1}} = \frac{(0.00963)(95\text{ kPa})}{(0.622 + 0.00963)(3.1698\text{ kPa})} = 0.457 \quad \text{or} \quad \mathbf{45.7\%}$$

(*c*) The enthalpy of air per unit mass of dry air is determined from

$$h_1 = h_{a1} + \omega_1 h_{v1} \cong c_p T_1 + \omega_1 h_{g1} = (1.005\text{ kJ/kg}\cdot{}^\circ\text{C})(25^\circ\text{C}) + (0.00963)(2546.5\text{ kJ/kg})$$
$$= \mathbf{49.65\text{ kJ/kg dry air}}$$

14–32 The air in a room has a dry-bulb temperature of 22°C and a wet-bulb temperature of 16°C. Assuming a pressure of 100 kPa, determine (*a*) the specific humidity, (*b*) the relative humidity, and (*c*) the dew-point temperature. *Answers:* (*a*) 0.0090 kg H_2O/kg dry air, (*b*) 54.1 percent, (*c*) 12.3°C

14-32 The dry- and wet-bulb temperatures of air in room at a specified pressure are given. The specific humidity, the relative humidity, and the dew-point temperature are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) We obtain the properties of water vapor from EES. The specific humidity ω_1 is determined from

$$\omega_1 = \frac{c_p(T_2 - T_1) + \omega_2 h_{fg2}}{h_{g1} - h_{f2}}$$

100 kPa
22°C
T_{wb} = 16°C

where T_2 is the wet-bulb temperature, and ω_2 is determined from

$$\omega_2 = \frac{0.622 P_{g2}}{P_2 - P_{g2}} = \frac{(0.622)(1.819\text{ kPa})}{(100 - 1.819)\text{ kPa}} = 0.01152\text{ kg H}_2\text{O/kg dry air}$$

Thus, $$\omega_1 = \frac{(1.005\text{ kJ/kg}\cdot°\text{C})(16-22)°\text{C} + (0.01152)(2463.0\text{ kJ/kg})}{(2541.1 - 67.17)\text{ kJ/kg}} = \mathbf{0.00903\ kg\ H_2O/kg\ dry\ air}$$

(*b*) The relative humidity ϕ_1 is determined from

$$\phi_1 = \frac{\omega_1 P_1}{(0.622 + \omega_1)P_{g1}} = \frac{(0.00903)(100\text{ kPa})}{(0.622 + 0.0091)(2.6452\text{ kPa})} = 0.541 \quad \text{or} \quad \mathbf{54.1\%}$$

(*c*) The vapor pressure at the inlet conditions is

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 22°C}} = (0.541)(2.6452\text{ kPa}) = 1.432\text{ kPa}$$

Thus the dew-point temperature of the air is

$$T_{dp} = T_{\text{sat @ }P_v} = T_{\text{sat @ 1.432 kPa}} = \mathbf{12.3°C}$$

14–35 Atmospheric air at 35°C flows steadily into an adiabatic saturation device and leaves as a saturated mixture at 25°C. Makeup water is supplied to the device at 25°C. Atmospheric pressure is 98 kPa. Determine the relative humidity and specific humidity of the air.

14-35 Atmospheric air flows steadily into an adiabatic saturation device and leaves as a saturated vapor. The relative humidity and specific humidity of air are to be determined.

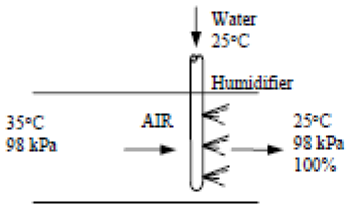
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis The exit state of the air is completely specified, and the total pressure is 98 kPa. The properties of the moist air at the exit state may be determined from EES to be

$$h_2 = 78.11\text{ kJ/kg dry air}$$
$$\omega_2 = 0.02079\text{ kg H}_2\text{O/kg dry air}$$

The enthalpy of makeup water is

$$h_{w2} = h_{f@25°\text{C}} = 104.83\text{ kJ/kg} \quad \text{(Table A-4)}$$



An energy balance on the control volume gives

$$h_1 + (\omega_2 - \omega_1)h_w = h_2$$
$$h_1 + (0.02079 - \omega_1)(104.83\text{ kJ/kg}) = 78.11\text{ kJ/kg}$$

Pressure and temperature are known for inlet air. Other properties may be determined from this equation using EES. A hand solution would require a trial-error approach. The results are

$$h_1 = 77.66\text{ kJ/kg dry air}$$
$$\omega_1 = \mathbf{0.01654\ kg\ H_2O/kg\ dry\ air}$$
$$\phi_1 = \mathbf{0.4511}$$

14–68 Air enters a heating section at 95 kPa, 12°C, and 30 percent relative humidity at a rate of 6 m^3/min, and it leaves at 25°C. Determine (*a*) the rate of heat transfer in the heating section and (*b*) the relative humidity of the air at the exit. *Answers:* (*a*) 91.1 kJ/min, (*b*) 13.3 percent

14-68 Air enters a heating section at a specified state and relative humidity. The rate of heat transfer in the heating section and the relative humidity of the air at the exit are to be determined.

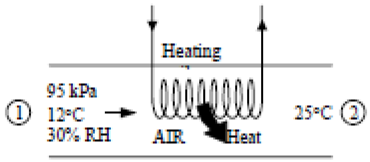
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (*a*) The amount of moisture in the air remains constant ($\omega_1 = \omega_2$) as it flows through the heating section since the process involves no humidification or dehumidification. The inlet state of the air is completely specified, and the total pressure is 95 kPa. The properties of the air are determined to be

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{sat\,@12°C} = (0.3)(1.403\text{ kPa}) = 0.421\text{ kPa}$$

$$P_{a1} = P_1 - P_{v1} = 95 - 0.421 = 94.58\text{ kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(285\text{ K})}{94.58\text{ kPa}} = 0.8648\text{ m}^3/\text{kg dry air}$$



$$\omega_1 = \frac{0.622 P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.421\text{ kPa})}{(95 - 0.421)\text{ kPa}} = 0.002768\text{ kg H}_2\text{O/kg dry air } (= \omega_2)$$

$$h_1 = c_p T_1 + \omega_1 h_{g1} = (1.005\text{ kJ/kg}\cdot°\text{C})(12°\text{C}) + (0.002768)(2522.9\text{ kJ/kg}) = 19.04\text{ kJ/kg dry air}$$

and

$$h_2 = c_p T_2 + \omega_2 h_{g2} = (1.005\text{ kJ/kg}\cdot°\text{C})(25°\text{C}) + (0.002768)(2546.5\text{ kJ/kg}) = 32.17\text{ kJ/kg dry air}$$

Also,

$$\dot m_{a1} = \frac{\dot V_1}{v_1} = \frac{6\text{ m}^3/\text{min}}{0.8648\text{ m}^3/\text{kg dry air}} = 6.938\text{ kg/min}$$

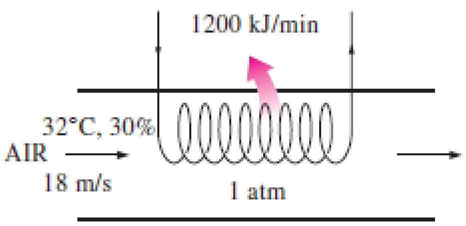
Then the rate of heat transfer to the air in the heating section is determined from an energy balance on air in the heating section to be

$$\dot Q_{in} = \dot m_a (h_2 - h_1) = (6.938\text{ kg/min})(32.17 - 19.04)\text{ kJ/kg} = \mathbf{91.1\text{ kJ/min}}$$

(*b*) Noting that the vapor pressure of air remains constant ($P_{v2} = P_{v1}$) during a simple heating process, the relative humidity of the air at leaving the heating section becomes

$$\phi_2 = \frac{P_{v2}}{P_{g2}} = \frac{P_{v2}}{P_{sat\,@25°C}} = \frac{0.421\text{ kPa}}{3.1698\text{ kPa}} = 0.133 \text{ or } \mathbf{13.3\%}$$

14–70 Air enters a 40-cm-diameter cooling section at 1 atm, 32°C, and 30 percent relative humidity at 18 m/s. Heat is removed from the air at a rate of 1200 kJ/min. Determine (*a*) the exit temperature, (*b*) the exit relative humidity of the air, and (*c*) the exit velocity. *Answers:* (*a*) 24.4°C, (*b*) 46.6 percent, (*c*) 17.6 m/s

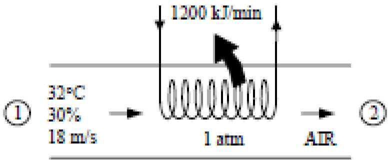


14-70 Air enters a cooling section at a specified pressure, temperature, velocity, and relative humidity. The exit temperature, the exit relative humidity of the air, and the exit velocity are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (*a*) The amount of moisture in the air remains constant ($\omega_1 = \omega_2$) as it flows through the cooling section since the process involves no humidification or dehumidification. The inlet state of the air is completely specified, and the total pressure is 1 atm. The properties of the air at the inlet state are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 55.0 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0089 \text{ kg H}_2\text{O/kg dry air } (= \omega_2)$$
$$v_1 = 0.877 \text{ m}^3/\text{kg dry air}$$



The mass flow rate of dry air through the cooling section is

$$\dot{m}_a = \frac{1}{v_1}V_1A_1$$
$$= \frac{1}{(0.877 \text{ m}^3/\text{kg})}(18 \text{ m/s})(\pi \times 0.4^2/4 \text{ m}^2) = 2.58 \text{ kg/s}$$

From the energy balance on air in the cooling section,

$$-\dot{Q}_{out} = \dot{m}_a(h_2 - h_1)$$
$$-1200/60 \text{ kJ/s} = (2.58 \text{ kg/s})(h_2 - 55.0) \text{ kJ/kg}$$
$$h_2 = 47.2 \text{ kJ/kg dry air}$$

The exit state of the air is fixed now since we know both h_2 and ω_2. From the psychrometric chart at this state we read

$$T_2 = \mathbf{24.4°C}$$
(*b*) $$\phi_2 = \mathbf{46.6\%}$$
$$v_2 = 0.856 \text{ m}^3/\text{kg dry air}$$

(*c*) The exit velocity is determined from the conservation of mass of dry air,

$$\dot{m}_{a1} = \dot{m}_{a2} \longrightarrow \frac{\dot{V}_1}{v_1} = \frac{\dot{V}_2}{v_2} \longrightarrow \frac{V_1A}{v_1} = \frac{V_2A}{v_2}$$
$$V_2 = \frac{v_2}{v_1}V_1 = \frac{0.856}{0.877}(18 \text{ m/s}) = \mathbf{17.6 \text{ m/s}}$$

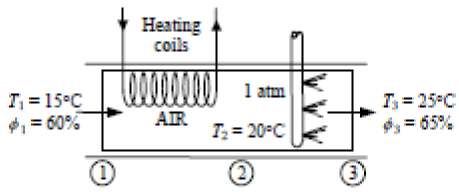
14–73 Air at 1 atm, 15°C, and 60 percent relative humidity is first heated to 20°C in a heating section and then humidified by introducing water vapor. The air leaves the humidifying section at 25°C and 65 percent relative humidity. Determine (*a*) the amount of steam added to the air, and (*b*) the amount of heat transfer to the air in the heating section. *Answers:* (*a*) 0.0065 kg H_2O/kg dry air, (*b*) 5.1 kJ/kg dry air

14-73 Air is first heated and then humidified by water vapor. The amount of steam added to the air and the amount of heat transfer to the air are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 31.1 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0064 \text{ kg H}_2\text{O / kg dry air } (= \omega_2)$$
$$h_2 = 36.2 \text{ kJ / kg dry air}$$
$$h_3 = 58.1 \text{ kJ / kg dry air}$$
$$\omega_3 = 0.0129 \text{ kg H}_2\text{O / kg dry air}$$



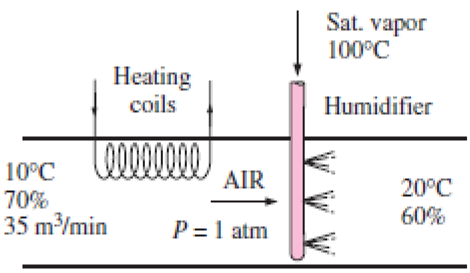
Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The amount of steam added to the air in the heating section is

$$\Delta\omega = \omega_3 - \omega_2 = 0.0129 - 0.0064 = \mathbf{0.0065 \text{ kg H}_2\text{O / kg dry air}}$$

(*b*) The heat transfer to the air in the heating section per unit mass of air is

$$q_{in} = h_2 - h_1 = 36.2 - 31.1 = \mathbf{5.1 \text{ kJ / kg dry air}}$$

14–75 An air-conditioning system operates at a total pressure of 1 atm and consists of a heating section and a humidifier that supplies wet steam (saturated water vapor) at 100°C. Air enters the heating section at 10°C and 70 percent relative humidity at a rate of 35 m³/min, and it leaves the humidifying section at 20°C and 60 percent relative humidity. Determine (*a*) the temperature and relative humidity of air when it leaves the heating section, (*b*) the rate of heat transfer in the heating section, and (*c*) the rate at which water is added to the air in the humidifying section.

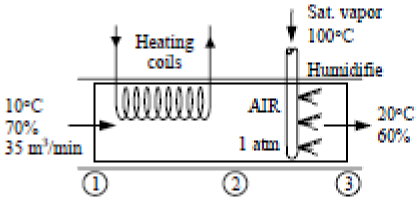


14-75 Air is first heated and then humidified by wet steam. The temperature and relative humidity of air at the exit of heating section, the rate of heat transfer, and the rate at which water is added to the air are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

$$h_1 = 23.5 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0053 \text{ kg H}_2\text{O/kg dry air } (= \omega_2)$$
$$v_1 = 0.809 \text{ m}^3\text{/kg dry air}$$
$$h_3 = 42.3 \text{ kJ/kg dry air}$$
$$\omega_3 = 0.0087 \text{ kg H}_2\text{O/kg dry air}$$



Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{35 \text{ m}^3/\text{min}}{0.809 \text{ m}^3/\text{kg}} = 43.3 \text{ kg/min}$$

Noting that $Q = W = 0$, the energy balance on the humidifying section can be expressed as

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \longrightarrow \dot{m}_w h_w + \dot{m}_{a2} h_2 = \dot{m}_a h_3$$
$$(\omega_3 - \omega_2) h_w + h_2 = h_3$$

Solving for h_2,

$$h_2 = h_3 - (\omega_3 - \omega_2) h_{g@100°C} = 42.3 - (0.0087 - 0.0053)(2675.6) = 33.2 \text{ kJ/kg dry air}$$

Thus at the exit of the heating section we have $\omega_2 = 0.0053$ kg H_2O dry air and $h_2 = 33.2$ kJ/kg dry air, which completely fixes the state. Then from the psychrometric chart we read

$$T_2 = \mathbf{19.5°C}$$
$$\phi_2 = \mathbf{37.8\%}$$

(*b*) The rate of heat transfer to the air in the heating section is

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (43.3 \text{ kg/min})(33.2 - 23.5) \text{ kJ/kg} = \mathbf{420 \text{ kJ/min}}$$

(*c*) The amount of water added to the air in the humidifying section is determined from the conservation of mass equation of water in the humidifying section,

$$\dot{m}_w = \dot{m}_a (\omega_3 - \omega_2) = (43.3 \text{ kg/min})(0.0087 - 0.0053) = \mathbf{0.15 \text{ kg/min}}$$

14–78 Air enters a window air conditioner at 1 atm, 32°C, and 70 percent relative humidity at a rate of 2 m^3/min, and it leaves as saturated air at 15°C. Part of the moisture in the air

that condenses during the process is also removed at 15°C. Determine the rates of heat and moisture removal from the air. *Answers:* 97.7 kJ/min, 0.023 kg/min

14-78 Air is cooled and dehumidified by a window air conditioner. The rates of heat and moisture removal from the air are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Properties The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The properties of the air at various states are determined from the psychrometric chart (Figure A-31) to be

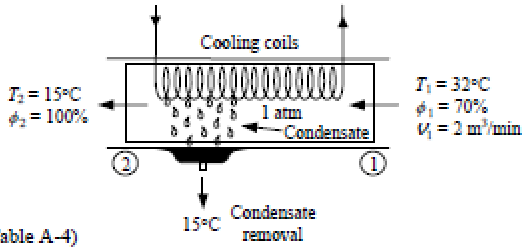
$$h_1 = 86.3 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0211 \text{ kg } H_2O\text{/kg dry air}$$
$$v_1 = 0.894 \text{ m}^3\text{/kg dry air}$$

and

$$h_2 = 42.0 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0107 \text{ kg } H_2O\text{/kg dry air}$$

Also,

$$h_w \cong h_{f@15°C} = 62.982 \text{ kJ/kg} \quad \text{(Table A-4)}$$



Analysis (a) The amount of moisture in the air decreases due to dehumidification ($\omega_2 < \omega_1$). The mass flow rate of air is

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{2 \text{ m}^3\text{/min}}{0.894 \text{ m}^3\text{/kg dry air}} = 2.238 \text{ kg/min}$$

Applying the water mass balance and energy balance equations to the combined cooling and dehumidification section,

Water Mass Balance:

$$\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e} \longrightarrow \dot{m}_{a1}\omega_1 = \dot{m}_{a2}\omega_2 + \dot{m}_w$$

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (2.238 \text{ kg/min})(0.0211 - 0.0107) = \mathbf{0.0233 \text{ kg/min}}$$

Energy Balance:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \dot{Q}_{out} + \sum \dot{m}_e h_e$$
$$\dot{Q}_{out} = \dot{m}_{a1}h_1 - (\dot{m}_{a2}h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$
$$\dot{Q}_{out} = (2.238 \text{ kg/min})(86.3 - 42.0)\text{kJ/kg} - (0.0233 \text{ kg/min})(62.982 \text{ kJ/kg})$$
$$= \mathbf{97.7 \text{ kJ/min}}$$

14–79 An air-conditioning system is to take in air at 1 atm, 34°C, and 70 percent relative humidity and deliver it at 22°C and 50 percent relative humidity. The air flows first over the cooling coils, where it is cooled and dehumidified, and then over the resistance heating wires, where it is heated to the desired temperature. Assuming that the condensate is removed from the cooling section at 10°C, determine (*a*) the temperature of air before it enters the heating section, (*b*) the amount of heat removed in the cooling section, and (*c*) the amount of heat transferred in the heating section, both in kJ/kg dry air.

14-79 Air is first cooled, then dehumidified, and finally heated. The temperature of air before it enters the heating section, the amount of heat removed in the cooling section, and the amount of heat supplied in the heating section are to be determined.

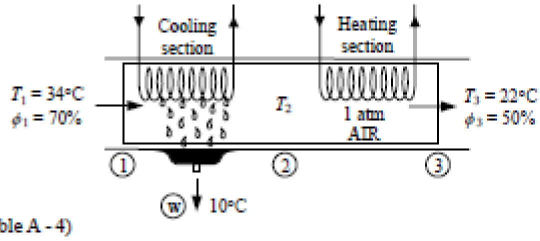
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (a) The amount of moisture in the air decreases due to dehumidification ($\omega_3 < \omega_1$), and remains constant during heating ($\omega_3 = \omega_2$). The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. The intermediate state (state 2) is also known since ϕ_2 = 100% and $\omega_2 = \omega_3$. Therefore, we can determined the properties of the air at all three states from the psychrometric chart (Fig. A-31) to be

$$h_1 = 95.2 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0238 \text{ kg H}_2\text{O / kg dry air}$$

and

$$h_3 = 43.1 \text{ kJ / kg dry air}$$
$$\omega_3 = 0.0082 \text{ kg H}_2\text{O / kg dry air } (= \omega_2)$$



Also,

$$h_w \cong h_{f@10°C} = 42.02 \text{ kJ/kg (Table A-4)}$$
$$h_2 = 31.8 \text{ kJ/kg dry air}$$
$$T_2 = \mathbf{11.1°C}$$

(b) The amount of heat removed in the cooling section is determined from the energy balance equation applied to the cooling section,

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e + \dot{Q}_{out,cooling}$$
$$\dot{Q}_{out,cooling} = \dot{m}_{a1} h_1 - (\dot{m}_{a2} h_2 + \dot{m}_w h_w) = \dot{m}_a (h_1 - h_2) - \dot{m}_w h_w$$

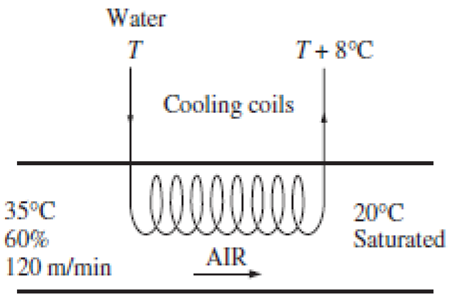
or, per unit mass of dry air,

$$q_{out,cooling} = (h_1 - h_2) - (\omega_1 - \omega_2) h_w$$
$$= (95.2 - 31.8) - (0.0238 - 0.0082)42.02$$
$$= \mathbf{62.7 \text{ kJ/kg dry air}}$$

(c) The amount of heat supplied in the heating section per unit mass of dry air is

$$q_{in,heating} = h_3 - h_2 = 43.1 - 31.8 = \mathbf{11.3 \text{ kJ / kg dry air}}$$

14–80 Air enters a 30-cm-diameter cooling section at 1 atm, 35°C, and 60 percent relative humidity at 120 m/min. The air is cooled by passing over a cooling coil through which cold water flows. The water experiences a temperature rise of 8°C. The air leaves the cooling section saturated at 20°C. Determine (*a*) the rate of heat transfer, (*b*) the mass flow rate of the water, and (*c*) the exit velocity of the airstream.



14-80 [*Also solved by EES on enclosed CD*] Air is cooled by passing it over a cooling coil through which chilled water flows. The rate of heat transfer, the mass flow rate of water, and the exit velocity of airstream are to be determined.

Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

Analysis (*a*) The saturation pressure of water at 35°C is 5. 6291 kPa (Table A-4). Then the dew point temperature of the incoming air stream at 35°C becomes

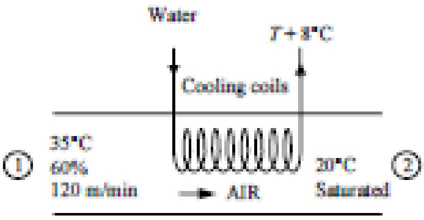
$$T_{dp} = T_{sat\,@\,P_v} = T_{sat\,@\,0.6\times 5.6291\,kPa} = 26°C \quad \text{(Table A-5)}$$

since air is cooled to 20°C, which is below its dew point temperature, some of the moisture in the air will condense. The amount of moisture in the air decreases due to dehumidification $(\omega_2 < \omega_1)$. The inlet and the exit states of the air are completely specified, and the total pressure is 1 atm. Then the properties of the air at both states are determined from the psychrometric chart (Fig. A-31) to be

$$h_1 = 90.3 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0215 \text{ kg } H_2O\text{/kg dry air}$$
$$v_1 = 0.904 \text{ m}^3\text{/kg dry air}$$

and

$$h_2 = 57.5 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0147 \text{ kg } H_2O\text{/kg dry air}$$
$$v_2 = 0.851 \text{ m}^3\text{/kg dry air}$$



Also, $h_w \cong h_{f\,@\,20°C} = 83.93 \text{ kJ/kg}$ (Table A-4)

Then,

$$\dot{V}_1 = V_1 A_1 = V_1 \frac{\pi D^2}{4} = (120 \text{ m/min})\left(\frac{\pi (0.3 \text{ m})^2}{4}\right) = 8.48 \text{ m}^3/\text{min}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{8.48 \text{ m}^3/\text{min}}{0.904 \text{ m}^3/\text{kg dry air}} = 9.38 \text{ kg/min}$$

Applying the water mass balance and the energy balance equations to the combined cooling and dehumidification section (excluding the water),

Water Mass Balance: $\quad \sum \dot{m}_{w,i} = \sum \dot{m}_{w,e} \longrightarrow \dot{m}_{a1}\omega_1 = \dot{m}_{a2}\omega_2 + \dot{m}_w$

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (9.38 \text{ kg/min})(0.0215 - 0.0147) = 0.064 \text{ kg/min}$$

Energy Balance:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}{}^{\nearrow 0\,(steady)} = 0 \longrightarrow \dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e + \dot{Q}_{out} \longrightarrow \dot{Q}_{out} = \dot{m}_{a1}h_1 - (\dot{m}_{a2}h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$

$$\dot{Q}_{out} = (9.38 \text{ kg/min})(90.3 - 57.5)\text{kJ/kg} - (0.064 \text{ kg/min})(83.93 \text{ kJ/kg}) = \mathbf{302.3 \text{ kJ/min}}$$

(*b*) Noting that the heat lost by the air is gained by the cooling water, the mass flow rate of the cooling water is determined from

$$\dot{Q}_{cooling\ water} = \dot{m}_{cooling\ water}\Delta h = \dot{m}_{cooling\ water} c_p \Delta T$$

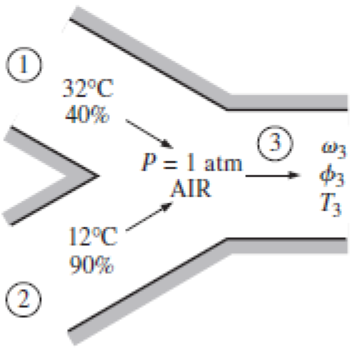
$$\dot{m}_{cooling\ water} = \frac{\dot{Q}_w}{c_p \Delta T} = \frac{302.3 \text{ kJ/min}}{(4.18 \text{ kJ/kg}\cdot°\text{C})(8°\text{C})} = \mathbf{9.04 \text{ kg/min}}$$

(*c*) The exit velocity is determined from the conservation of mass of dry air,

$$\dot{m}_{a1} = \dot{m}_{a2} \longrightarrow \frac{\dot{V}_1}{v_1} = \frac{\dot{V}_2}{v_2} \longrightarrow \frac{V_1 A}{v_1} = \frac{V_2 A}{v_2}$$

$$V_2 = \frac{v_2}{v_1}V_1 = \frac{0.851}{0.904}(120 \text{ m/min}) = \mathbf{113 \text{ m/min}}$$

14–102 Two airstreams are mixed steadily and adiabatically. The first stream enters at 32°C and 40 percent relative humidity at a rate of 20 m^3/min, while the second stream enters at 12°C and 90 percent relative humidity at a rate of 25 m^3/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. *Answers:* 0.0096 kg H_2O/kg dry air, 63.4 percent, 20.6°C, 45.0 m^3/min



14-102 Two airstreams are mixed steadily. The specific humidity, the relative humidity, the dry-bulb temperature, and the volume flow rate of the mixture are to be determined.

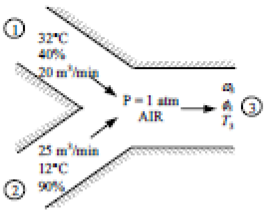
Assumptions 1 Steady operating conditions exist 2 Dry air and water vapor are ideal gases. 3 The kinetic and potential energy changes are negligible. 4 The mixing section is adiabatic.

Properties Properties of each inlet stream are determined from the psychrometric chart (Fig. A-31) to be

$h_1 = 62.7$ kJ/kg dry air $\qquad h_2 = 31.9$ kJ/kg dry air

$\omega_1 = 0.0119$ kg H_2O/kg dry air $\quad$ and $\quad \omega_2 = 0.0079$ kg H_2O/kg dry air

$v_1 = 0.882\ m^3$/kg dry air $\qquad v_2 = 0.819\ m^3$/kg dry air



Analysis The mass flow rate of dry air in each stream is

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{20\ m^3/min}{0.882\ m^3/kg\ dry\ air} = 22.7\ kg/min$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{25\ m^3/min}{0.819\ m^3/kg\ dry\ air} = 30.5\ kg/min$$

From the conservation of mass,

$$\dot{m}_{a3} = \dot{m}_{a1} + \dot{m}_{a2} = (22.7 + 30.5)\ kg/min = 53.2\ kg/min$$

The specific humidity and the enthalpy of the mixture can be determined from Eqs. 14-24, which are obtained by combining the conservation of mass and energy equations for the adiabatic mixing of two streams:

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

$$\frac{22.7}{30.5} = \frac{0.0079 - \omega_3}{\omega_3 - 0.0119} = \frac{31.9 - h_3}{h_3 - 62.7}$$

which yields,

$$\boldsymbol{\omega_3 = 0.0096\ kg\ H_2O/kg\ dry\ air}$$

$$h_3 = 45.0\ kJ/kg\ dry\ air$$

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

$$\boldsymbol{T_3 = 20.6°C}$$

$$\boldsymbol{\phi_3 = 63.4\%}$$

$$v_3 = 0.845\ m^3/kg\ dry\ air$$

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

$$\dot{V}_3 = \dot{m}_{a3} v_3 = (53.2\ kg/min)(0.845\ m^3/kg) = \boldsymbol{45.0\ m^3/min}$$

14–110 The cooling water from the condenser of a power plant enters a wet cooling tower at 40°C at a rate of 90 kg/s. The water is cooled to 25°C in the cooling tower by air that enters the tower at 1 atm, 23°C, and 60 percent relative humidity and leaves saturated at 32°C. Neglecting the power input to the fan, determine (*a*) the volume flow rate of air into the cooling tower and (*b*) the mass flow rate of the required makeup water.

14-110 Water is cooled by air in a cooling tower. The volume flow rate of air and the mass flow rate of the required makeup water are to be determined.

Assumptions **1** Steady operating conditions exist and thus mass flow rate of dry air remains constant during the entire process. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible. **4** The cooling tower is adiabatic.

Analysis (*a*) The mass flow rate of dry air through the tower remains constant $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$, but the mass flow rate of liquid water decreases by an amount equal to the amount of water that vaporizes in the tower during the cooling process. The water lost through evaporation must be made up later in the cycle to maintain steady operation. Applying the mass and energy balances yields

Dry Air Mass Balance:

$$\sum \dot{m}_{a,i} = \sum \dot{m}_{a,e} \longrightarrow \dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$$

Water Mass Balance:

$$\sum \dot{m}_{w,i} = \sum \dot{m}_{w,e} \longrightarrow \dot{m}_3 + \dot{m}_{a1}\omega_1 = \dot{m}_4 + \dot{m}_{a2}\omega_2$$

$$\dot{m}_3 - \dot{m}_4 = \dot{m}_a(\omega_2 - \omega_1) = \dot{m}_{\text{makeup}}$$

Energy Balance:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\nearrow 0\,(\text{steady})} = 0$$

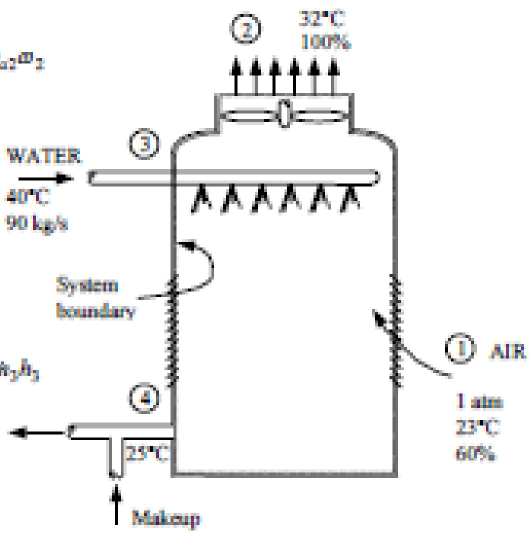
$$\dot{E}_{in} = \dot{E}_{out}$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \quad \text{since } \dot{Q} = \dot{W} = 0$$

$$0 = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$$

$$0 = \dot{m}_{a2}h_2 + \dot{m}_4 h_4 - \dot{m}_{a1}h_1 - \dot{m}_3 h_3$$

$$0 = \dot{m}_a(h_2 - h_1) + (\dot{m}_3 - \dot{m}_{\text{makeup}})h_4 - \dot{m}_3 h_3$$



Solving for $\dot{m}_a$,

$$\dot{m}_a = \frac{\dot{m}_3(h_3 - h_4)}{(h_2 - h_1) - (\omega_2 - \omega_1)h_4}$$

From the psychrometric chart (Fig. A-31),

$$h_1 = 49.9 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0105 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.853 \text{ m}^3\text{/kg dry air}$$

and

$$h_2 = 110.7 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0307 \text{ kg H}_2\text{O/kg dry air}$$

From Table A-4,

$$h_3 \cong h_{f@40°C} = 167.53 \text{ kJ/kg H}_2\text{O}$$
$$h_4 \cong h_{f@25°C} = 104.83 \text{ kJ/kg H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{(90\text{ kg/s})(167.53 - 104.83)\text{kJ/kg}}{(110.7 - 49.9)\text{ kJ/kg} - (0.0307 - 0.0105)(104.83)\text{ kJ/kg}} = 96.2 \text{ kg/s}$$

Then the volume flow rate of air into the cooling tower becomes

$$\dot{V}_1 = \dot{m}_a v_1 = (96.2\text{ kg/s})(0.854\text{ m}^3\text{/kg}) = 82.2\text{ m}^3\text{/s}$$

(*b*) The mass flow rate of the required makeup water is determined from

$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (96.2\text{ kg/s})(0.0307 - 0.0105) = 1.94\text{ kg/s}$$