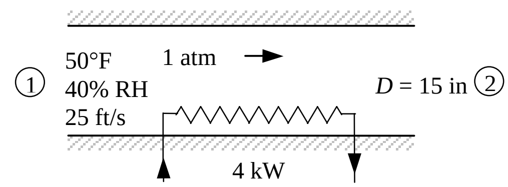
**14-69E** Air enters a heating section at a specified pressure, temperature, velocity, and relative humidity. The exit temperature of air, the exit relative humidity, and the exit velocity are to be determined.

***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 heating 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-31E) to be

$$h_1 = 15.3 \text{ Btu/lbm dry air}$$
$$\omega_1 = 0.0030 \text{ lbm H}_2\text{O/lbm dry air} (= \omega_2)$$
$$v_1 = 12.9 \text{ ft}^3/\text{lbm dry air}$$




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

$$\dot{m}_a = \frac{1}{v_1} V_1 A_1$$
$$= \frac{1}{(12.9 \text{ ft}^3/\text{lbm})}(25 \text{ ft/s})(\pi \times (15/12)^2/4 \text{ ft}^2) = 2.38 \text{ lbm/s}$$

From the energy balance on air in the heating section,

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1)$$
$$4 \text{ kW}\left(\frac{0.9478 \text{ Btu/s}}{1 \text{ kW}}\right) = (2.38 \text{ lbm/s})(h_2 - 15.3) \text{Btu/lbm}$$
$$h_2 = 16.9 \text{ Btu/lbm dry air}$$

The exit state of the air is fixed now since we know both $h_2$ and $\omega_2$. From the psychrometric chart at this state we read

$$T_2 = \mathbf{56.6°F}$$

(*b*) $$\phi_2 = \mathbf{31.4\%}$$

$$v_2 = 13.1 \text{ ft}^3/\text{lbm dry air}$$

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

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

Thus,

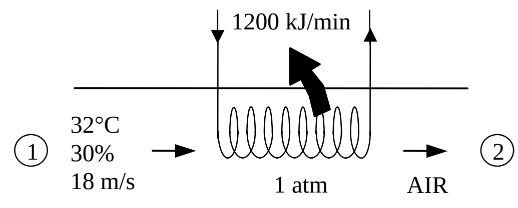
$$V_2 = \frac{v_2}{v_1} V_1 = \frac{13.1}{12.9}(25 \text{ ft/s}) = \mathbf{25.4 \text{ ft/s}}$$

**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

$$\begin{aligned} h_1 &= 55.0 \text{ kJ/kg dry air} \\ \omega_1 &= 0.0089 \text{ kg H}_2\text{O/kg dry air } (= \omega_2) \\ \boldsymbol{v}_1 &= 0.877 \text{ m}^3 / \text{kg dry air} \end{aligned}$$




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

$$\begin{aligned} \dot{m}_a &= \frac{1}{\boldsymbol{v}_1} V_1 A_1 \\ &= \frac{1}{(0.877 \text{ m}^3 / \text{kg})} (18 \text{ m/s})(\pi \times 0.4^2 / 4 \text{ m}^2) = 2.58 \text{ kg/s} \end{aligned}$$

From the energy balance on air in the cooling section,

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

The exit state of the air is fixed now since we know both $h_2$ and $\omega_2$. From the psychrometric chart at this state we read

$$T_2 = \mathbf{24.4°C}$$

(*b*) $$\phi_2 = \mathbf{46.6\%}$$

$$\boldsymbol{v}_2 = 0.856 \text{ m}^3 / \text{kg dry air}$$

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

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

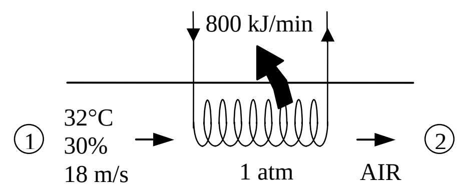
$$V_2 = \frac{\boldsymbol{v}_2}{\boldsymbol{v}_1} V_1 = \frac{0.856}{0.877}(18 \text{ m/s}) = \mathbf{17.6 \text{ m/s}}$$

**14-71** 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

$$\dot{m}_a = \frac{1}{v_1} V_1 A_1$$
$$= \frac{1}{(0.877 \text{ m}^3/\text{kg})}(18 \text{ m/s})(\pi \times 0.4^2/4 \text{ m}^2) = 2.58 \text{ kg/s}$$

From the energy balance on air in the cooling section,

$$-\dot{Q}_{\text{out}} = \dot{m}_a(h_2 - h_1)$$
$$-800/60 \text{ kJ/s} = (2.58 \text{ kg/s})(h_2 - 55.0) \text{ kJ/kg}$$
$$h_2 = 49.8 \text{ kJ/kg dry air}$$

The exit state of the air is fixed now since we know both $h_2$ and $\omega_2$. From the psychrometric chart at this state we read

$$T_2 = \mathbf{26.9°C}$$

(*b*) $$\phi_2 = \mathbf{40.0\%}$$

$$v_2 = 0.862 \text{ m}^3/\text{kg dry air}$$

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

$$\dot{m}_{a1} = \dot{m}_{a2} \longrightarrow \frac{\dot{V}_1}{v_1} = \frac{\dot{V}_2}{v_2} \longrightarrow \frac{V_1 A}{v_1} = \frac{V_2 A}{v_2}$$
$$V_2 = \frac{v_2}{v_1} V_1 = \frac{0.862}{0.877}(18 \text{ m/s}) = \mathbf{17.7 \text{ m/s}}$$

## Heating with Humidification

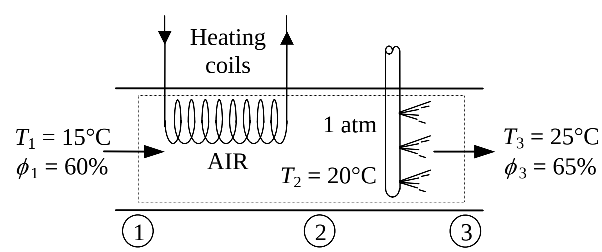
**14-72C** To achieve a higher level of comfort. Very dry air can cause dry skin, respiratory difficulties, and increased static electricity.

**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

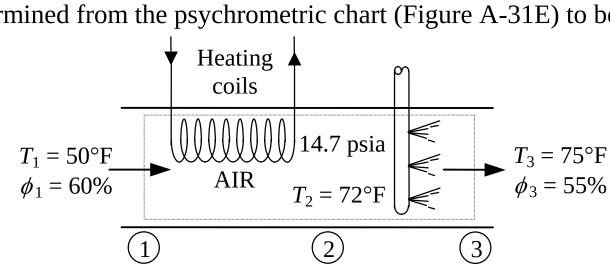
$$q_{\text{in}} = h_2 - h_1 = 36.2 - 31.1 = \mathbf{5.1 \text{ kJ / kg dry air}}$$

**14-74E** 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-31E) to be

$$h_1 = 17.0 \text{ Btu/lbm dry air}$$
$$\omega_1 = 0.0046 \text{ lbm H}_2\text{O/lbm dry air}$$
$$h_2 = 22.3 \text{ Btu/lbm dry air}$$
$$\omega_2 = \omega_1 = 0.0046 \text{ lbm H}_2\text{O/lbm dry air}$$
$$h_3 = 29.2 \text{ Btu/lbm dry air}$$
$$\omega_3 = 0.0102 \text{ lbm H}_2\text{O/lbm dry air}$$




***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

$$\Delta\omega = \omega_3 - \omega_2 = 0.0102 - 0.0046 = \mathbf{0.0056 \text{ lbm H}_2\text{O/lbm dry air}}$$

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

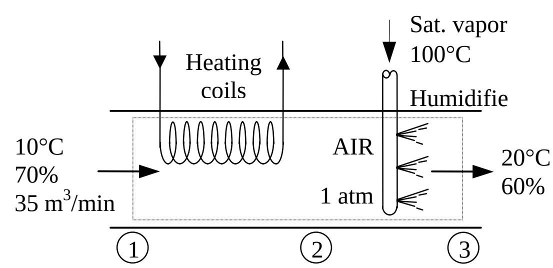
$$q_{\text{in}} = h_2 - h_1 = 22.3 - 17.0 = \mathbf{5.3 \text{ Btu/lbm dry air}}$$

**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

$$h_1 = 23.5 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0053 \text{ kg H}_2\text{O/kg dry air } (= \omega_2)$$
$$\boldsymbol{v}_1 = 0.809 \text{ m}^3\text{/kg dry air}$$
$$h_3 = 42.3 \text{ kJ/kg dry air}$$
$$\omega_3 = 0.0087 \text{ kg H}_2\text{O/kg dry air}$$




***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

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

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

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

Solving for $h_2$,

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

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

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

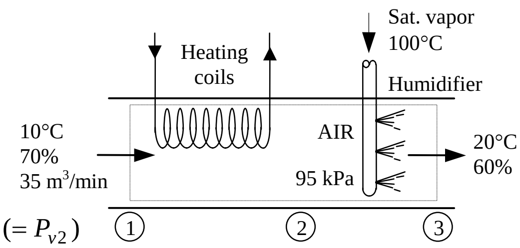
(*c*) The amount of water added to the air in the humidifying section is determined from the conservation of mass equation of water in the humidifying section,

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

**14-76** 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.

***Analysis*** (*a*) The amount of moisture in the air also remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The inlet and the exit states of the air are completely specified, and the total pressure is 95 kPa. The properties of the air at various states are determined to be




$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ }10°\text{C}} = (0.70)(1.2281\text{ kPa}) = 0.860\text{ kPa } (= P_{v2})$$

$$P_{a1} = P_1 - P_{v1} = 95 - 0.860 = 94.14\text{ kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(283\text{ K})}{94.14\text{ kPa}} = 0.863\text{ m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.86\text{ kPa})}{(95-0.86)\text{ kPa}} = 0.00568\text{ kg H}_2\text{O/kg dry air } (= \omega_2)$$

$$h_1 = c_p T_1 + \omega_1 h_{g1} = (1.005\text{ kJ/kg}\cdot°\text{C})(10°\text{C}) + (0.00568)(2519.2\text{ kJ/kg}) = 24.36\text{ kJ/kg dry air}$$

$$P_{v3} = \phi_3 P_{g3} = \phi_3 P_{\text{sat @ }20°\text{C}} = (0.60)(2.3392\text{ kPa}) = 1.40\text{ kPa}$$

$$\omega_3 = \frac{0.622\,P_{v3}}{P_3 - P_{v3}} = \frac{0.622(1.40\text{ kPa})}{(95-1.40)\text{ kPa}} = 0.00930\text{ kg H}_2\text{O/kg dry air}$$

$$h_3 = c_p T_3 + \omega_3 h_{g3} = (1.005\text{ kJ/kg}\cdot°\text{C})(20°\text{C}) + (0.0093)(2537.4\text{ kJ/kg}) = 43.70\text{ kJ/kg dry air}$$

Also, $$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{35\text{ m}^3/\text{min}}{0.863\text{ m}^3/\text{kg}} = 40.6\text{ kg/min}$$

Noting that $Q = W = 0$, the energy balance on the humidifying section gives

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

$$\sum \dot{m}_e h_e = \sum \dot{m}_i h_i \longrightarrow \dot{m}_w h_w + \dot{m}_{a2} h_2 = \dot{m}_a h_3 \longrightarrow (\omega_3 - \omega_2) h_w + h_2 = h_3$$

$$h_2 = h_3 - (\omega_3 - \omega_2) h_{g\text{ @ }100°\text{C}} = 43.7 - (0.0093 - 0.00568) \times 2675.6 = 34.0\text{ kJ/kg dry air}$$

Thus at the exit of the heating section we have $\omega = 0.00568$ kg $H_2O$ dry air and $h_2 = 34.0$ kJ/kg dry air, which completely fixes the state. The temperature of air at the exit of the heating section is determined from the definition of enthalpy,

$$h_2 = c_p T_2 + \omega_2 h_{g2} \cong c_p T_2 + \omega_2 (2500.9 + 1.82 T_2)$$

$$34.0 = (1.005) T_2 + (0.00568)(2500.9 + 1.82 T_2)$$

Solving for $h_2$, yields $T_2 = \mathbf{19.5°\,C}$

The relative humidity at this state is

$$\phi_2 = \frac{P_{v2}}{P_{g2}} = \frac{P_{v2}}{P_{\text{sat @ }19.5°\text{C}}} = \frac{0.859\text{ kPa}}{2.2759\text{ kPa}} = 0.377 \quad \text{or} \quad \mathbf{37.7\%}$$

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

$$\dot{Q}_{\text{in}} = \dot{m}_a (h_2 - h_1) = (40.6\text{ kg/min})(34.0 - 24.36)\text{ kJ/kg} = \mathbf{391\text{ kJ/min}}$$

(*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,

$$\dot{m}_w = \dot{m}_a (\omega_3 - \omega_2) = (40.6\text{ kg/min})(0.0093 - 0.00568) = \mathbf{0.147\text{ kg/min}}$$

## Cooling with Dehumidification

**14-77C** To drop its relative humidity to more desirable levels.

**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

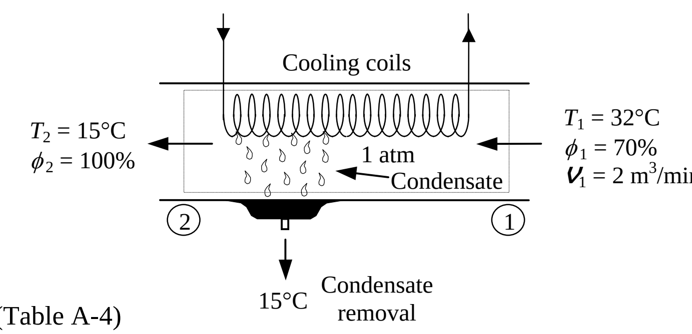
$$h_1 = 86.3\ \text{kJ/kg dry air}$$
$$\omega_1 = 0.0211\ \text{kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.894\ \text{m}^3\text{/kg dry air}$$

and

$$h_2 = 42.0\ \text{kJ/kg dry air}$$
$$\omega_2 = 0.0107\ \text{kg H}_2\text{O/kg dry air}$$

Also,

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




***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*:

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

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

*Energy Balance*:

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

$$\dot{Q}_{\text{out}} = (2.238\ \text{kg/min})(86.3 - 42.0)\text{kJ/kg} - (0.0233\ \text{kg/min})(62.982\ \text{kJ/kg})$$

$$= \mathbf{97.7\ \ kJ/min}$$

**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.

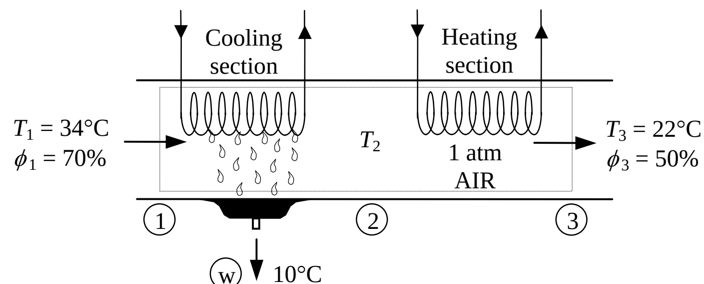
***Assumptions*** **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process $(\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a)$. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

***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 $\phi_2$ = 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,

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

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

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

or, per unit mass of dry air,

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

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

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

**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 35ºC is 5. 6291 kPa (Table A-4). Then the dew point temperature of the incoming air stream at 35°C becomes

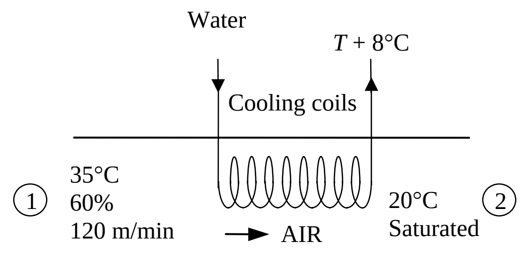
$$T_{\mathrm{dp}} = T_{\mathrm{sat}\,@\,P_v} = T_{\mathrm{sat}\,@\,0.6\times 5.6291\,\mathrm{kPa}} = 26°\mathrm{C} \quad \text{(Table A-5)}$$

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

$$h_1 = 90.3\ \mathrm{kJ/kg\ dry\ air}$$
$$\omega_1 = 0.0215\ \mathrm{kg\ H_2O/kg\ dry\ air}$$
$$\boldsymbol{v}_1 = 0.904\ \mathrm{m^3/kg\ dry\ air}$$

and

$$h_2 = 57.5\ \mathrm{kJ/kg\ dry\ air}$$
$$\omega_2 = 0.0147\ \mathrm{kg\ H_2O/kg\ dry\ air}$$
$$\boldsymbol{v}_2 = 0.851\ \mathrm{m^3/kg\ dry\ air}$$




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

Then,

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

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

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

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

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

*Energy Balance*:

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

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

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

(*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

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

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

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

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

$$V_2 = \frac{\boldsymbol{v}_2}{\boldsymbol{v}_1} V_1 = \frac{0.851}{0.904}(120\ \mathrm{m/min}) = \mathbf{113\ \ m/min}$$

**14-81 EES** Problem 14-80 is reconsidered. A general solution of the problem in which the input variables may be supplied and parametric studies performed is to be developed and the process is to be shown in the psychrometric chart for each set of input variables.

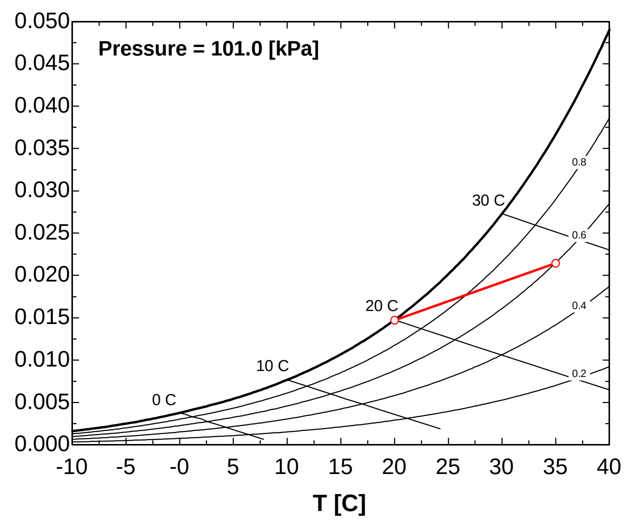
***Analysis*** The problem is solved using EES, and the solution is given below.

```
"Input Data from the Diagram Window"
{D=0.3
P[1] =101.32 [kPa]
T[1] = 35 [C]
RH[1] = 60/100   "%, relative humidity"
Vel[1] = 120/60 "[m/s]"
DELTAT_cw =8 [C]
P[2] = 101.32 [kPa]
T[2] = 20 [C]}
RH[2] = 100/100 "%"

"Dry air flow rate, m_dot_a, is constant"
Vol_dot[1]= (pi * D^2)/4*Vel[1]
v[1]=VOLUME(AirH2O,T=T[1],P=P[1],R=RH[1])
m_dot_a = Vol_dot[1]/v[1]

"Exit vleocity"
Vol_dot[2]= (pi * D^2)/4*Vel[2]
v[2]=VOLUME(AirH2O,T=T[2],P=P[2],R=RH[2])
m_dot_a = Vol_dot[2]/v[2]

"Mass flow rate of the condensed water"
m_dot_v[1]=m_dot_v[2]+m_dot_w
w[1]=HUMRAT(AirH2O,T=T[1],P=P[1],R=RH[1])
m_dot_v[1] = m_dot_a*w[1]
w[2]=HUMRAT(AirH2O,T=T[2],P=P[2],R=RH[2])
m_dot_v[2] = m_dot_a*w[2]
```




```
"SSSF conservation of energy for the air"
m_dot_a *(h[1] + (1+w[1])*Vel[1]^2/2*Convert(m^2/s^2, kJ/kg)) + Q_dot = m_dot_a*(h[2]
+(1+w[2])*Vel[2]^2/2*Convert(m^2/s^2, kJ/kg)) +m_dot_w*h_liq_2
h[1]=ENTHALPY(AirH2O,T=T[1],P=P[1],w=w[1])
h[2]=ENTHALPY(AirH2O,T=T[2],P=P[2],w=w[2])
h_liq_2=ENTHALPY(Water,T=T[2],P=P[2])

"SSSF conservation of energy for the cooling water"
-Q_dot =m_dot_cw*Cp_cw*DELTAT_cw  "Note: Q_netwater=-Q_netair"
Cp_cw = SpecHeat(water,T=10,P=P[2])"kJ/kg-K"
```

| $RH_1$ | ma | mw | mcw | Q [kW] | $Vel_1$ [m/s] | $Vel_2$ [m/s] | $T_1$ [C] | $T_2$ [C] | $w_1$ | $w_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.1574 | 0.0004834 | 0.1085 | -3.632 | 2 | 1.894 | 35 | 20 | 0.01777 | 0.0147 |
| 0.6 | 0.1565 | 0.001056 | 0.1505 | -5.039 | 2 | 1.883 | 35 | 20 | 0.02144 | 0.0147 |
| 0.7 | 0.1556 | 0.001629 | 0.1926 | -6.445 | 2 | 1.872 | 35 | 20 | 0.02516 | 0.0147 |
| 0.8 | 0.1547 | 0.002201 | 0.2346 | -7.852 | 2 | 1.861 | 35 | 20 | 0.02892 | 0.0147 |
| 0.9 | 0.1538 | 0.002774 | 0.2766 | -9.258 | 2 | 1.85 | 35 | 20 | 0.03273 | 0.0147 |

**14-82** Air is cooled by passing it over a cooling coil. The rate of heat transfer, the mass flow rate of water, and the exit velocity of airstream are to be determined.

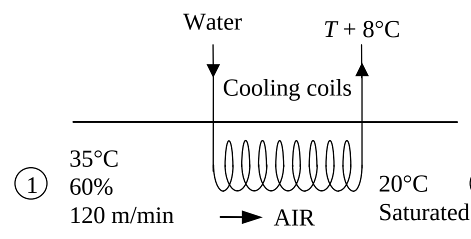
***Assumptions*** **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process. **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

***Analysis*** (*a*) The dew point temperature of the incoming air stream at 35°C is

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 35°C}} = (0.6)(5.6291\,\text{kPa}) = 3.38\,\text{kPa}$$

$$T_{\text{dp}} = T_{\text{sat @ }P_v} = T_{\text{sat @ 3.38 kPa}} = 25.9°\text{C}$$

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 95 kPa. Then the properties of the air at both states are determined to be

$$P_{a1} = P_1 - P_{v1} = 95 - 3.38 = 91.62\,\text{kPa}$$

$$\boldsymbol{v}_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\,\text{K})}{91.62\,\text{kPa}} = 0.965\,\text{m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(3.38\,\text{kPa})}{(95-3.38)\,\text{kPa}} = 0.0229\,\text{kg H}_2\text{O/kg dry air}$$

$$h_1 = c_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg}\cdot°\text{C})(35°\text{C}) + (0.0229)(2564.6\,\text{kJ/kg})$$
$$= 93.90\,\text{kJ/kg dry air}$$

and

$$P_{v2} = \phi_2 P_{g2} = (1.00) P_{\text{sat @ 20°C}} = 2.3392\,\text{kPa}$$

$$\boldsymbol{v}_2 = \frac{R_a T_2}{P_{a2}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\,\text{K})}{(95-2.339)\,\text{kPa}} = 0.908\,\text{m}^3/\text{kg dry air}$$

$$\omega_2 = \frac{0.622\,P_{v2}}{P_2 - P_{v2}} = \frac{0.622(2.339\,\text{kPa})}{(95-2.339)\,\text{kPa}} = 0.0157\,\text{kg H}_2\text{O/kg dry air}$$

$$h_2 = c_p T_2 + \omega_2 h_{g2} = (1.005\,\text{kJ/kg}\cdot°\text{C})(20°\text{C}) + (0.0157)(2537.4\,\text{kJ/kg})$$
$$= 59.95\,\text{kJ/kg dry air}$$

Also,

$$h_w \cong h_{f\text{ @ 20°C}} = 83.915\,\text{kJ/kg} \qquad \text{(Table A-4)}$$

Then,

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

$$\dot{m}_{a1} = \frac{\dot{\boldsymbol{V}}_1}{\boldsymbol{v}_1} = \frac{8.48\,\text{m}^3/\text{min}}{0.965\,\text{m}^3/\text{kg dry air}} = 8.79\,\text{kg/min}$$

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

*Water Mass Balance*:

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

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (8.79 \text{ kg/min})(0.0229 - 0.0157) = 0.0633 \text{ kg/min}$$

*Energy Balance*:

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

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

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

$$\dot{Q}_{\text{out}} = (8.79 \text{ kg/min})(93.90 - 59.94)\text{kJ/kg} - (0.0633 \text{ kg/min})(83.915 \text{ kJ/kg}) = \mathbf{293.2 \text{ kJ/min}}$$

(*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

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

$$\dot{m}_{\text{cooling water}} = \frac{\dot{Q}_w}{c_p \Delta T} = \frac{293.2 \text{ kJ/min}}{(4.18 \text{ kJ/kg}\cdot{}^\circ\text{C})(8^\circ\text{C})} = \mathbf{8.77 \text{ kg/min}}$$

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

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

$$V_2 = \frac{v_2}{v_1} V_1 = \frac{0.908}{0.965}(120 \text{ m/min}) = \mathbf{113 \text{ m/min}}$$