Adiabatic Mixing of Airstreams

14-100C This will occur when the straight line connecting the states of the two streams on the psychrometric chart crosses the saturation line.

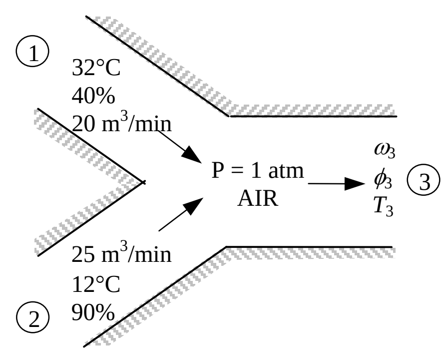
14-101C Yes.

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

$$h_1 = 62.7 \text{ kJ/kg dry air} \qquad h_2 = 31.9 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0119 \text{ kg H}_2\text{O/kg dry air} \quad \text{and} \quad \omega_2 = 0.0079 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.882 \text{ m}^3\text{/kg dry air} \qquad v_2 = 0.819 \text{ m}^3\text{/kg dry air}$$



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

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

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

From the conservation of mass,

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

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,

$$\omega_3 = \mathbf{0.0096 \text{ kg H}_2\text{O/kg dry air}}$$
$$h_3 = 45.0 \text{ kJ/kg dry air}$$

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

$$T_3 = \mathbf{20.6°C}$$
$$\phi_3 = \mathbf{63.4\%}$$
$$v_3 = 0.845 \text{ m}^3\text{/kg dry air}$$

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

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

14-103 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.

Analysis The properties of each inlet stream are determined to be

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 32°C}} = (0.40)(4.760\text{ kPa}) = 1.90\text{ kPa}$$

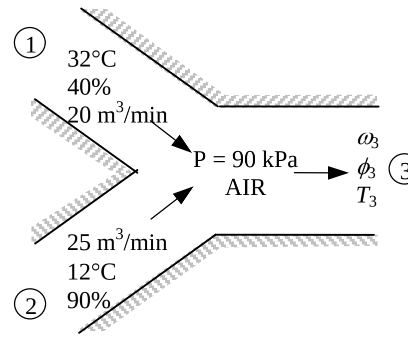
$$P_{a1} = P_1 - P_{v1} = 90 - 1.90 = 88.10\text{ kPa}$$

$$\boldsymbol{v}_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(305\text{ K})}{88.10\text{ kPa}} = 0.994\text{ m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(1.90\text{ kPa})}{(90-1.90)\text{ kPa}} = 0.0134\text{ kg H}_2\text{O/kg dry air}$$

$$h_1 = c_p T_1 + \omega_1 h_{g1} = (1.005\text{ kJ/kg}\cdot°\text{C})(32°\text{C}) + (0.0134)(2559.2\text{ kJ/kg})$$

$$= 66.45\text{ kJ/kg dry air}$$



and

$$P_{v2} = \phi_2 P_{g2} = \phi_2 P_{\text{sat@12°C}} = (0.90)(1.403\text{ kPa}) = 1.26\text{ kPa}$$

$$P_{a2} = P_2 - P_{v2} = 90 - 1.26 = 88.74\text{ kPa}$$

$$\boldsymbol{v}_2 = \frac{R_a T_2}{P_{a2}} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(285\text{ K})}{88.74\text{ kPa}} = 0.922\text{ m}^3/\text{kg dry air}$$

$$\omega_2 = \frac{0.622\,P_{v2}}{P_2 - P_{v2}} = \frac{0.622(1.26\text{ kPa})}{(90-1.26)\text{ kPa}} = 0.00883\text{ kg H}_2\text{O/kg dry air}$$

$$h_2 = c_p T_2 + \omega_2 h_{g2} = (1.005\text{ kJ/kg}\cdot°\text{C})(12°\text{C}) + (0.00883)(2522.9\text{ kJ/kg}) = 34.34\text{ kJ/kg dry air}$$

Then the mass flow rate of dry air in each stream is

$$\dot{m}_{a1} = \frac{\dot{\boldsymbol{V}}_1}{\boldsymbol{v}_1} = \frac{20\text{ m}^3/\text{min}}{0.994\text{ m}^3/\text{kg dry air}} = 20.12\text{ kg/min} \qquad \dot{m}_{a2} = \frac{\dot{\boldsymbol{V}}_2}{\boldsymbol{v}_2} = \frac{25\text{ m}^3/\text{min}}{0.922\text{ m}^3/\text{kg dry air}} = 27.11\text{ kg/min}$$

From the conservation of mass,

$$\dot{m}_{a3} = \dot{m}_{a1} + \dot{m}_{a2} = (20.12 + 27.11)\text{ kg/min} = 47.23\text{ kg/min}$$

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:

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1} \longrightarrow \frac{20.12}{27.11} = \frac{0.00883 - \omega_3}{\omega_3 - 0.0134} = \frac{34.34 - h_3}{h_3 - 66.45}$$

which yields $\quad \omega_3 = \mathbf{0.0108\ kg\ H_2O/kg\ dry\ air} \qquad h_3 = 48.02\text{ kJ/kg dry air}$

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

$$h_3 = c_p T_3 + \omega_3 h_{g3} \cong c_p T_3 + \omega_3(2501.3 + 1.82T_3)$$

$$48.02\text{ kJ/kg} = (1.005\text{ kJ/kg}\cdot°\text{C})T_3 + (0.0108)(2500.9 + 1.82T_3)\text{ kJ/kg} \longrightarrow T_3 = \mathbf{20.5°C}$$

$$\omega_3 = \frac{0.622\,P_{v3}}{P_3 - P_{v3}} \longrightarrow 0.0108 = \frac{0.622\,P_{v3}}{90 - P_{v3}} \longrightarrow P_{v3} = 1.54\text{ kPa}$$

$$\phi_3 = \frac{P_{v3}}{P_{g3}} = \frac{P_{v3}}{P_{\text{sat @}T_3}} = \frac{1.54\text{ kPa}}{2.41\text{ kPa}} = 0.639 \quad \text{or} \quad \mathbf{63.9\%}$$

Finally,

$$P_{a3} = P_3 - P_{v3} = 90 - 1.54 = 88.46\text{ kPa}$$

$$\boldsymbol{v}_3 = \frac{R_a T_3}{P_{a3}} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293.5\text{ K})}{88.46\text{ kPa}} = 0.952\text{ m}^3/\text{kg dry air}$$

$$\dot{\boldsymbol{V}}_3 = \dot{m}_{a3}\boldsymbol{v}_3 = (47.23\text{ kg/min})(0.952\text{ m}^3/\text{kg}) = \mathbf{45.0\ m^3/min}$$

14-104E Two airstreams are mixed steadily. The temperature, the specific humidity, and the relative humidity of the mixture are to be determined.

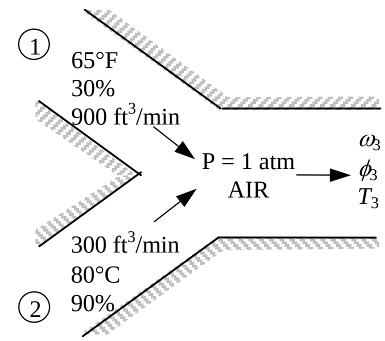
Assumptions **1** Steady operating conditions exist **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible. **4** The mixing section is adiabatic.

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

$$h_1 = 19.9 \text{ Btu/lbm dry air}$$
$$\omega_1 = 0.0039 \text{ lbm H}_2\text{O/lbm dry air}$$
$$v_1 = 13.30 \text{ ft}^3\text{/lbm dry air}$$

and

$$h_2 = 41.1 \text{ Btu/lbm dry air}$$
$$\omega_2 = 0.0200 \text{ lbm H}_2\text{O/lbm dry air}$$
$$v_2 = 14.04 \text{ ft}^3\text{/lbm dry air}$$



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

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{900 \text{ ft}^3 \text{ / min}}{13.30 \text{ ft}^3 \text{ / lbm dry air}} = 67.7 \text{ lbm/min}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{300 \text{ ft}^3 \text{ / min}}{14.04 \text{ ft}^3 \text{ / lbm dry air}} = 21.4 \text{ lbm/min}$$

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:

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

$$\frac{67.7}{21.4} = \frac{0.0200 - \omega_3}{\omega_3 - 0.0039} = \frac{41.1 - h_3}{h_3 - 19.9}$$

which yields,

(*a*) $\omega_3 =$ **0.0078 lbm H$_2$O / lbm dry air**

$$h_3 = 25.0 \text{ Btu / lbm dry air}$$

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

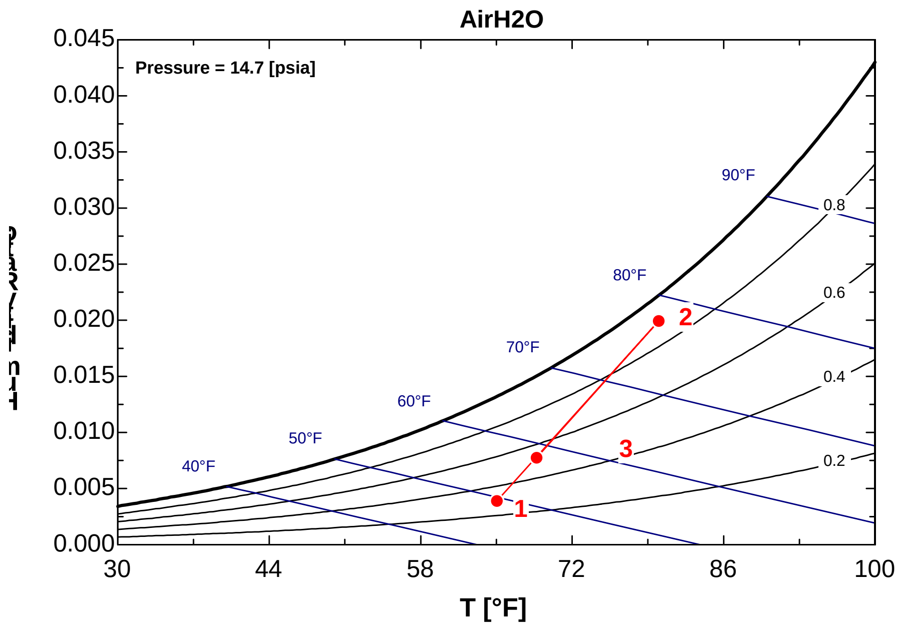
(*b*) $T_3 =$ **68.7°F**

(*c*) $\phi_3 =$ **52.1%**

14-105E EES Problem 14-104E 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 by Diagram Window:"
{P=14.696 [psia]
Tdb[1] =65 [F]
Rh[1] = 0.30
V_dot[1] = 900 [ft^3/min]
Tdb[2] =80 [F]
Rh[2] = 0.90
V_dot[2] = 300 [ft^3/min]}
P[1]=P
P[2]=P[1]
P[3]=P[1]

"Energy balance for the steady-flow mixing process:"
"We neglect the PE of the flow. Since we don't know the cross sectional area of the flow streams,
we also neglect theKE of the flow."
E_dot_in - E_dot_out = DELTAE_dot_sys
DELTAE_dot_sys = 0 [kW]
E_dot_in = m_dot[1]*h[1]+m_dot[2]*h[2]
E_dot_out = m_dot[3]*h[3]
"Conservation of mass of dry air during mixing:"
m_dot[1]+m_dot[2] = m_dot[3]
"Conservation of mass of water vapor during mixing:"
m_dot[1]*w[1]+m_dot[2]*w[2] = m_dot[3]*w[3]

m_dot[1]=V_dot[1]/v[1]*convert(1/min,1/s)
m_dot[2]=V_dot[2]/v[2]*convert(1/min,1/s)
h[1]=ENTHALPY(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])
v[1]=VOLUME(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])
w[1]=HUMRAT(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])

h[2]=ENTHALPY(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])
v[2]=VOLUME(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])
w[2]=HUMRAT(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])

Tdb[3]=TEMPERATURE(AirH2O,h=h[3],P=P[3],w=w[3])
Rh[3]=RELHUM(AirH2O,T=Tdb[3],P=P[3],w=w[3])
v[3]=VOLUME(AirH2O,T=Tdb[3],P=P[3],w=w[3])
m_dot[3]=V_dot[3]/v[3]*convert(1/min,1/s)
```



SOLUTION

DELTAE_dot_sys=0
E_dot_in=37.04 [kW]
E_dot_out=37.04 [kW]
h[1]=19.88 [Btu/lb_m]
h[2]=41.09 [Btu/lb_m]
h[3]=24.97 [Btu/lb_m]
m_dot[1]=1.127 [kga/s]
m_dot[2]=0.3561 [kga/s]
m_dot[3]=1.483 [kga/s]
P=14.7 [psia]
P[1]=14.7 [psia]
P[2]=14.7 [psia]
P[3]=14.7 [psia]
Rh[1]=0.3
Rh[2]=0.9
Rh[3]=0.5214
Tdb[1]=65 [F]
Tdb[2]=80 [F]
Tdb[3]=68.68 [F]
v[1]=13.31 [ft^3/lb_ma]
v[2]=14.04 [ft^3/lb_ma]
v[3]=13.49 [ft^3/lb_ma]
V_dot[1]=900 [ft^3/min]
V_dot[2]=300 [ft^3/min]
V_dot[3]=1200 [ft^3/min]
w[1]=0.003907 [lb_mv/lb_ma]
w[2]=0.01995 [lb_mv/lb_ma]
w[3]=0.007759 [lb_mv/lb_ma]

14-106 A stream of warm air is mixed with a stream of saturated cool air. The temperature, the specific humidity, and the relative humidity of the mixture are to be determined.

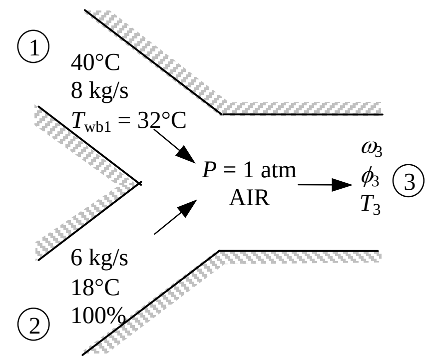
Assumptions **1** Steady operating conditions exist **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible. **4** The mixing section is adiabatic.

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

$$h_1 = 110.2 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0272 \text{ kg H}_2\text{O/kg dry air}$$

and

$$h_2 = 50.9 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0129 \text{ kg H}_2\text{O/kg dry air}$$



Analysis 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:

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

$$\frac{8.0}{6.0} = \frac{0.0129 - \omega_3}{\omega_3 - 0.0272} = \frac{50.9 - h_3}{h_3 - 110.2}$$

which yields,

(*b*) $\omega_3 = \mathbf{0.0211\ kg\ H_2O\,/\,kg\ dry\ air}$

$h_3 = 84.8 \text{ kJ / kg dry air}$

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

(*a*) $T_3 = \mathbf{30.7^\circ C}$

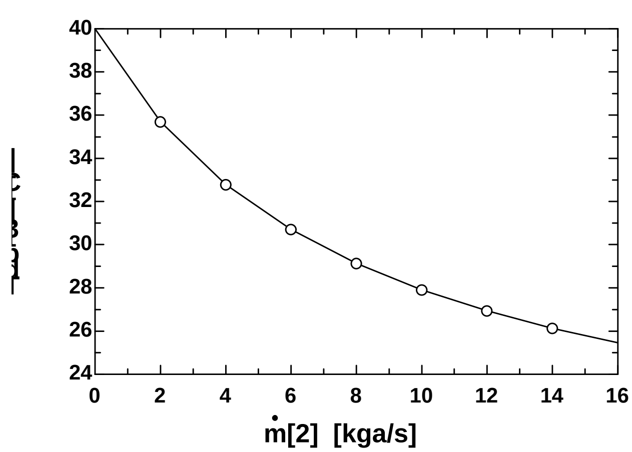
(*c*) $\phi_3 = \mathbf{75.1\%}$

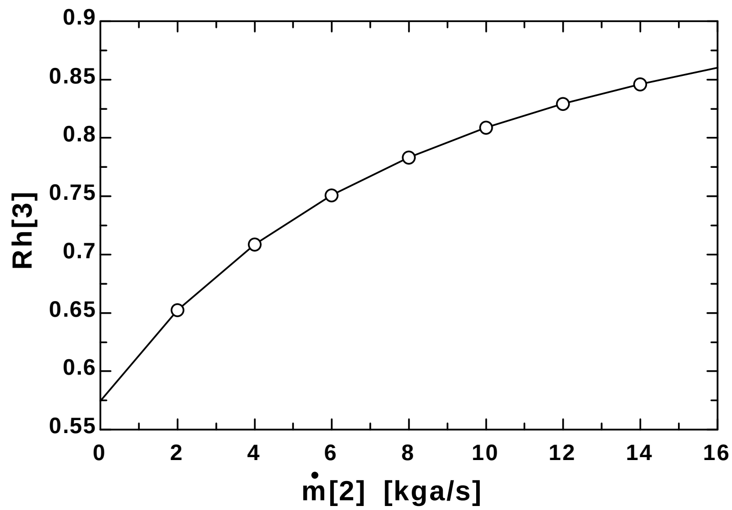
14-107 EES Problem 14-106 is reconsidered. The effect of the mass flow rate of saturated cool air stream on the mixture temperature, specific humidity, and relative humidity is to be investigated.

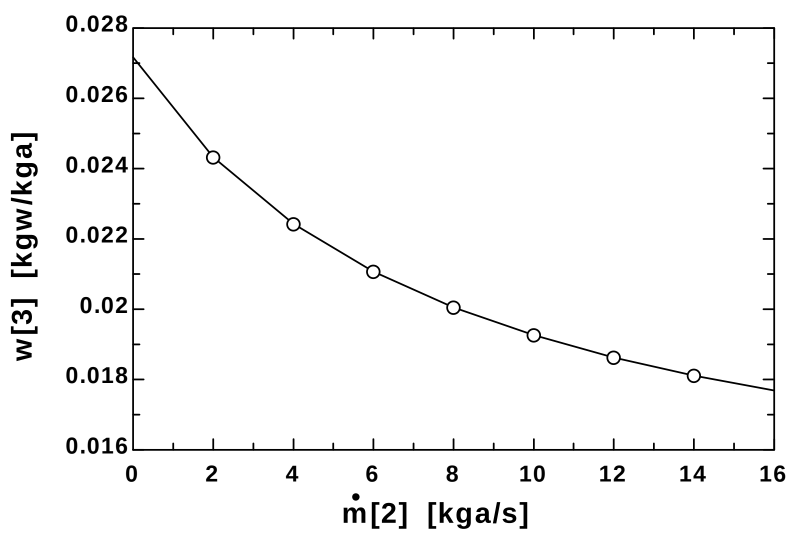
Analysis The problem is solved using EES, and the solution is given below.

```
P=101.325 [kPa]
Tdb[1] =40 [C]
Twb[1] =32 [C]
m_dot[1] = 8 [kg/s]
Tdb[2] =18 [C]
Rh[2] = 1.0
m_dot[2] = 6 [kg/s]
P[1]=P
P[2]=P[1]
P[3]=P[1]

"Energy balance for the steady-flow mixing process:"
"We neglect the PE of the flow. Since we don't know the cross sectional area of the flow streams, we also
neglect theKE of the flow."
E_dot_in - E_dot_out = DELTAE_dot_sys
DELTAE_dot_sys = 0 [kW]
E_dot_in = m_dot[1]*h[1]+m_dot[2]*h[2]
E_dot_out = m_dot[3]*h[3]
"Conservation of mass of dry air during mixing:"
m_dot[1]+m_dot[2] = m_dot[3]
"Conservation of mass of water vapor during mixing:"
m_dot[1]*w[1]+m_dot[2]*w[2] = m_dot[3]*w[3]

m_dot[1]=V_dot[1]/v[1]*convert(1/min,1/s)
m_dot[2]=V_dot[2]/v[2]*convert(1/min,1/s)
h[1]=ENTHALPY(AirH2O,T=Tdb[1],P=P[1],B=Twb[1])
Rh[1]=RELHUM(AirH2O,T=Tdb[1],P=P[1],B=Twb[1])
v[1]=VOLUME(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])
w[1]=HUMRAT(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])
h[2]=ENTHALPY(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])
v[2]=VOLUME(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])
w[2]=HUMRAT(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])
Tdb[3]=TEMPERATURE(AirH2O,h=h[3],P=P[3],w=w[3])
Rh[3]=RELHUM(AirH2O,T=Tdb[3],P=P[3],w=w[3])
v[3]=VOLUME(AirH2O,T=Tdb[3],P=P[3],w=w[3])
Twb[2]=WETBULB(AirH2O,T=Tdb[2],P=P[2],R=RH[2])
Twb[3]=WETBULB(AirH2O,T=Tdb[3],P=P[3],R=RH[3])
m_dot[3]=V_dot[3]/v[3]*convert(1/min,1/s)
```

m_2 [kga/s]	Tdb_3 [C]	Rh_3	w_3 [kgw/kga]
0	40	0.5743	0.02717
2	35.69	0.6524	0.02433
4	32.79	0.7088	0.02243
6	30.7	0.751	0.02107
8	29.13	0.7834	0.02005
10	27.91	0.8089	0.01926
12	26.93	0.8294	0.01863
14	26.13	0.8462	0.01811
16	25.45	0.8601	0.01768







Wet Cooling Towers

14-108C The working principle of a natural draft cooling tower is based on buoyancy. The air in the tower has a high moisture content, and thus is lighter than the outside air. This light moist air rises under the influence of buoyancy, inducing flow through the tower.

14-109C A spray pond cools the warm water by spraying it into the open atmosphere. They require 25 to 50 times the area of a wet cooling tower for the same cooling load.

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

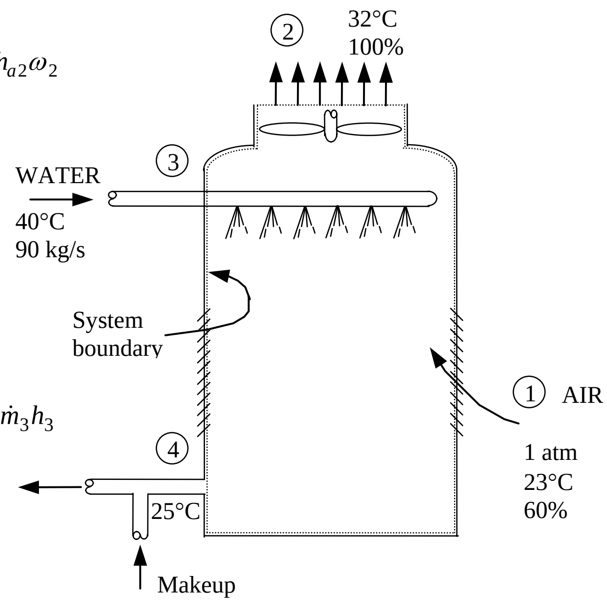
Dry Air Mass Balance:

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

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:

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

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

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

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

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

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

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),

$$h_1 = 49.9 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0105 \text{ kg H}_2\text{O/kg dry air}$$
$$\boldsymbol{v}_1 = 0.853 \text{ m}^3\text{/kg dry air}$$

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,

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

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

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

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

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

14-111E 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 balance and the energy balance equations yields

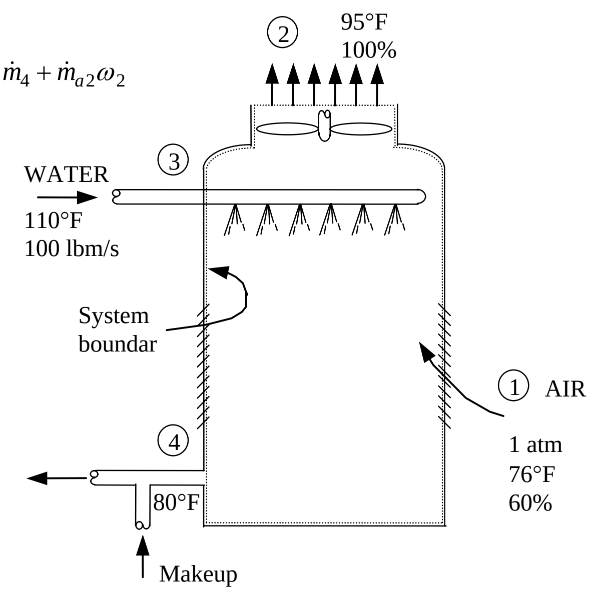
Dry Air Mass Balance:

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

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:

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

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

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

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

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

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

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),

$$h_1 = 30.9 \text{ Btu/lbm dry air}$$

$$\omega_1 = 0.0115 \text{ lbm H}_2\text{O/lbm dry air}$$

$$\boldsymbol{v}_1 = 13.76 \text{ ft}^3\text{/lbm dry air}$$

and

$$h_2 = 63.2 \text{ Btu / lbm dry air}$$

$$\omega_2 = 0.0366 \text{ lbm H}_2\text{O / lbm dry air}$$

From Table A-4E,

$$h_3 \cong h_{f\,@\,110°\text{F}} = 78.02 \text{ Btu/lbm H}_2\text{O}$$

$$h_4 \cong h_{f\,@\,80°\text{F}} = 48.07 \text{ Btu/lbm H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{(100 \text{ lbm/s})(78.02 - 48.07)\text{Btu/lbm}}{(63.2 - 30.9) \text{ Btu/lbm} - (0.0366 - 0.0115)(48.07) \text{ Btu/lbm}} = 96.3 \text{ lbm/s}$$

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

$$\dot{\boldsymbol{V}}_1 = \dot{m}_a \boldsymbol{v}_1 = (96.3 \text{ lbm/s})(13.76 \text{ ft}^3\text{/lbm}) = \mathbf{1325 \text{ ft}^3/s}$$

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

$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (96.3 \text{ lbm / s})(0.0366 - 0.0115) = \mathbf{2.42 \text{ lbm / s}}$$

14-112 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:

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

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

Energy Balance:

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

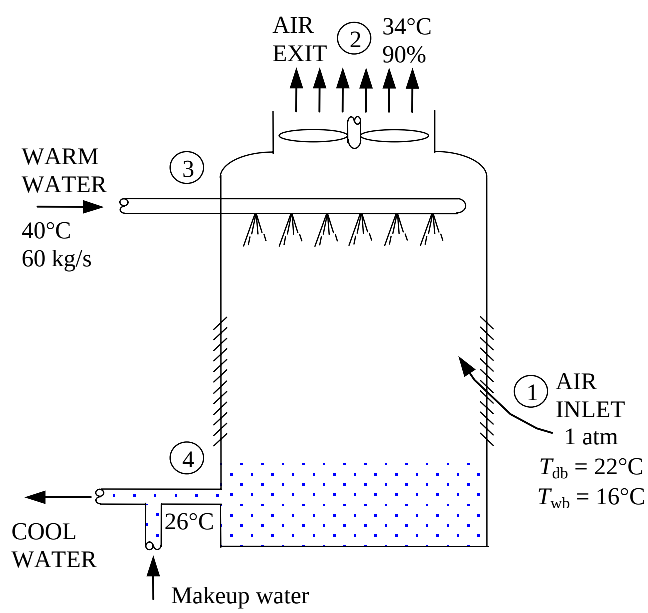
$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

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

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

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

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



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),

$$h_1 = 44.7 \text{ kJ/kg dry air}$$

$$\omega_1 = 0.0089 \text{ kg H}_2\text{O/kg dry air}$$

$$v_1 = 0.849 \text{ m}^3\text{/kg dry air}$$

and

$$h_2 = 113.5 \text{ kJ / kg dry air}$$

$$\omega_2 = 0.0309 \text{ kg H}_2\text{O / kg dry air}$$

From Table A-4,

$$h_3 \cong h_{f\,@\,40^\circ\text{C}} = 167.53 \text{ kJ/kg H}_2\text{O}$$

$$h_4 \cong h_{f\,@\,26^\circ\text{C}} = 109.01 \text{ kJ/kg H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{(60 \text{ kg/s})(167.53 - 109.01)\text{kJ/kg}}{(113.5 - 44.7) \text{ kJ/kg} - (0.0309 - 0.0089)(109.01) \text{ kJ/kg}} = 52.9 \text{ kg/s}$$

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

$$\dot{V}_1 = \dot{m}_a v_1 = (52.9 \text{ kg/s})(0.849 \text{ m}^3 \text{ / kg}) = \mathbf{44.9 \text{ m}^3\text{/s}}$$

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

$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (52.9 \text{ kg / s})(0.0309 - 0.0089) = \mathbf{1.16 \text{ kg / s}}$$

14-113 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:

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

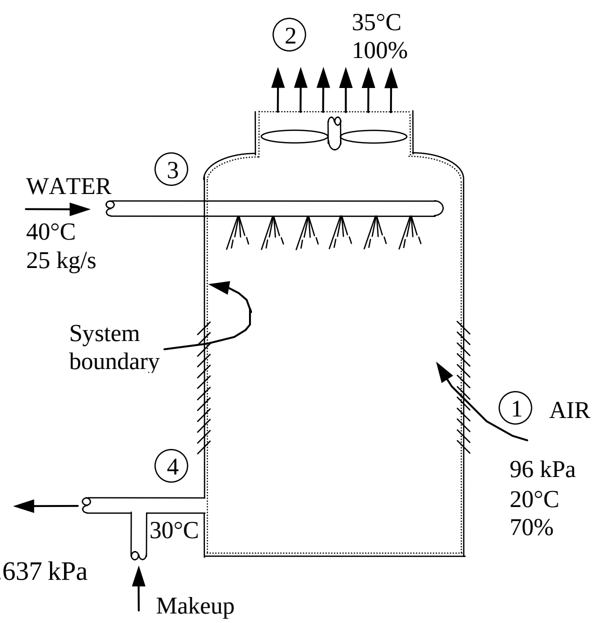
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \quad (\text{since } \dot{Q} = \dot{W} = 0)$$

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

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

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

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



The properties of air at the inlet and the exit are

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 20°C}} = (0.70)(2.3392\text{ kPa}) = 1.637\text{ kPa}$$

$$P_{a1} = P_1 - P_{v1} = 96 - 1.637 = 94.363\text{ kPa}$$

$$\boldsymbol{v}_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})}{94.363\text{ kPa}} = 0.891\text{ m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(1.637\text{ kPa})}{(96 - 1.637)\text{ kPa}} = 0.0108\text{ kg H}_2\text{O/kg dry air}$$

$$h_1 = c_p T_1 + \omega_1 h_{g1} = (1.005\text{ kJ/kg}\cdot°\text{C})(20°\text{C}) + (0.0108)(2537.4\text{ kJ/kg}) = 47.5\text{ kJ/kg dry air}$$

and $\quad P_{v2} = \phi_2 P_{g2} = \phi_2 P_{\text{sat @ 35°C}} = (1.00)(5.6291\text{ kPa}) = 5.6291\text{ kPa}$

$$\omega_2 = \frac{0.622\,P_{v2}}{P_2 - P_{v2}} = \frac{0.622(5.6291\text{ kPa})}{(96 - 5.6291)\text{ kPa}} = 0.0387\text{ kg H}_2\text{O/kg dry air}$$

$$h_2 = c_p T_2 + \omega_2 h_{g2} = (1.005\text{ kJ/kg}\cdot°\text{C})(35°\text{C}) + (0.0387)(2564.6\text{ kJ/kg}) = 134.4\text{ kJ/kg dry air}$$

From Table A-4,

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

$$h_4 \cong h_{f\text{ @ 30°C}} = 125.74\text{ kJ/kg H}_2\text{O}$$

Substituting, $\quad \dot{m}_a = \dfrac{(25\text{ kg/s})(167.53 - 125.74)\text{kJ/kg}}{(134.4 - 47.5)\text{ kJ/kg} - (0.0387 - 0.0108)(125.74)\text{ kJ/kg}} = 12.53\text{ kg/s}$

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

$$\dot{\boldsymbol{V}}_1 = \dot{m}_a \boldsymbol{v}_1 = (12.53\text{ kg/s})(0.891\text{ m}^3/\text{kg}) = \mathbf{11.2\ m^3/s}$$

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

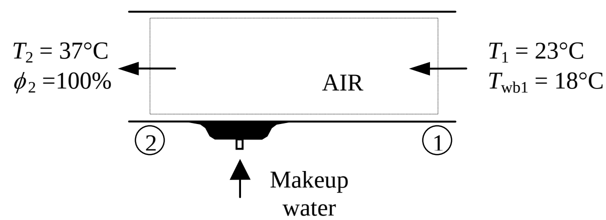
$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (12.53\text{ kg/s})(0.0387 - 0.0108) = \mathbf{0.35\ kg/s}$$

14-114 A natural-draft cooling tower is used to remove waste heat from the cooling water flowing through the condenser of a steam power plant. The mass flow rate of the cooling water, the volume flow rate of air into the cooling tower, and the mass flow rate of the required makeup water are to be determined.

Assumptions **1** All processes are steady-flow and 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 inlet and exit states of the moist air for the tower are completely specified. The properties may be determined from the psychrometric chart (Fig. A-31) or using EES psychrometric functions to be (we used EES)

$$h_1 = 50.74 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.01085 \text{ kg H}_2\text{O/kg dry air}$$
$$\boldsymbol{v}_1 = 0.8536 \text{ m}^3\text{/kg dry air}$$
$$h_2 = 142.83 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.04112 \text{ kg H}_2\text{O/kg dry air}$$



The enthalpies of cooling water at the inlet and exit of the condenser are (Table A-4)

$$h_{w3} = h_{f@\,40°C} = 167.53 \text{ kJ/kg}$$
$$h_{w4} = h_{f@\,26°C} = 109.01 \text{ kJ/kg}$$

The steam properties for the condenser are (Steam tables)

$$\left.\begin{array}{l} P_{s1} = 200 \text{ kPa} \\ x_{s1} = 0 \end{array}\right\} h_{s1} = 504.71 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{s2} = 10 \text{ kPa} \\ s_{s2} = 7.962 \text{ kJ/kg.K} \end{array}\right\} h_{s2} = 2524.3 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_{s3} = 10 \text{ kPa} \\ x_{s1} = 0 \end{array}\right\} h_{s3} = 191.81 \text{ kJ/kg}$$

The mass flow rate of dry air is given by

$$\dot{m}_a = \frac{\dot{\boldsymbol{V}}_1}{\boldsymbol{v}_1} = \frac{\dot{\boldsymbol{V}}_1}{0.8536 \text{ m}^3\text{/kg}}$$

The mass flow rates of vapor at the inlet and exit of the cooling tower are

$$\dot{m}_{v1} = \omega_1 \dot{m}_a = (0.01085)\frac{\dot{\boldsymbol{V}}_1}{0.8536} = 0.01271\dot{\boldsymbol{V}}_1$$

$$\dot{m}_{v2} = \omega_2 \dot{m}_a = (0.04112)\frac{\dot{\boldsymbol{V}}_1}{0.8536} = 0.04817\dot{\boldsymbol{V}}_1$$

Mass and energy balances on the cooling tower give

$$\dot{m}_{v1} + \dot{m}_{cw3} = \dot{m}_{v2} + \dot{m}_{cw4}$$
$$\dot{m}_a h_1 + \dot{m}_{cw3} h_{w3} = \dot{m}_a h_2 + \dot{m}_{cw4} h_{w4}$$

The mass flow rate of the makeup water is determined from

$$\dot{m}_{\text{makeup}} = \dot{m}_{v2} - \dot{m}_{v1} = \dot{m}_{cw3} - \dot{m}_{cw4}$$

An energy balance on the condenser gives

$$0.18\dot{m}_s h_{s1} + 0.82\dot{m}_s h_{s2} + \dot{m}_{cw4} h_{w4} + \dot{m}_{\text{makeup}} h_{w4} = \dot{m}_s h_{s3} + \dot{m}_{cw3} h_{w3}$$

Solving all the above equations simultaneously with known and determined values using EES, we obtain

$$\dot{m}_{cw3} = \mathbf{1413 \ kg/s}$$
$$\dot{\boldsymbol{V}}_1 = \mathbf{47{,}700 \ m^3/min}$$
$$\dot{m}_{\text{makeup}} = \mathbf{28.19 \ kg/s}$$