Chapter 9
GAS MIXTURES AND PSYCHROMETRICS

Composition of Gas Mixtures

9-1C It is the average or the equivalent gas constant of the gas mixture. No.

9-2C No. We can do this only when each gas has the same mole fraction.

9-3C It is the average or the equivalent molar mass of the gas mixture. No.

9-4C The mass fractions will be identical, but the mole fractions will not.

9-5C Yes.

9-6C The ratio of the mass of a component to the mass of the mixture is called the mass fraction (mf), and the ratio of the mole number of a component to the mole number of the mixture is called the mole fraction (y).

9-7C From the definition of mass fraction,

$$mf_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = y_i \left(\frac{M_i}{M_m} \right)$$

9-8C Yes, because both CO_2 and N_2O has the same molar mass, $M = 44$ kg/kmol.

9-9 A mixture consists of two gases. Relations for mole fractions when mass fractions are known are to be obtained .

Analysis The mass fractions of A and B are expressed as

$$mf_A = \frac{m_A}{m_m} = \frac{N_A M_A}{N_m M_m} = y_A \frac{M_A}{M_m} \qquad \text{and} \qquad mf_B = y_B \frac{M_B}{M_m}$$

Where m is mass, M is the molar mass, N is the number of moles, and y is the mole fraction. The apparent molar mass of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{N_A M_A + N_B M_B}{N_m} = y_A M_A + y_B M_B$$

Combining the two equation above and noting that $y_A + y_B = 1$ gives the following convenient relations for converting mass fractions to mole fractions,

$$y_A = \frac{M_B}{M_A (1 / mf_A - 1) + M_B} \qquad \text{and} \qquad y_B = 1 - y_A$$

which are the desired relations.

9-10 The molar fractions of the constituents of moist air are given. The mass fractions of the constituents are to be determined.

Assumptions The small amounts of gases in air are ignored, and dry air is assumed to consist of N_2 and O_2 only.

Properties The molar masses of N_2, O_2, and H_2O are 28.0, 32.0, and 18.0 kg/kmol, respectively (Table A-1).

Analysis The molar mass of moist air is

$$M = \sum y_i M_i = 0.78 \times 28.0 + 0.20 \times 32.0 + 0.02 \times 18 = 28.6 \text{ kg/kmol}$$

Then the mass fractions of constituent gases are determined to be

$$N_2: \qquad w_{N_2} = y_{N_2} \frac{M_{N_2}}{M} = (0.78)\frac{28.0}{28.6} = \mathbf{0.764}$$

$$O_2: \qquad w_{O_2} = y_{O_2} \frac{M_{O_2}}{M} = (0.20)\frac{32.0}{28.6} = \mathbf{0.224}$$

$$H_2O: \qquad w_{H_2O} = y_{H_2O} \frac{M_{H_2O}}{M} = (0.02)\frac{18.0}{28.6} = \mathbf{0.012}$$

Moist air
78% N_2
20% O_2
2% H_2O
(Mole fractions)

Therefore, the mass fractions of N_2, O_2, and H_2O in the air are 76.4%, 22.4%, and 1.2%, respectively.

9-11 The molar fractions of the constituents of a gas mixture are given. The gravimetric analysis of the mixture, its molar mass, and gas constant are to be determined.

Properties The molar masses of N_2, and CO_2 are 28.0 and 44.0 kg/kmol, respectively (Table A-1)

Analysis Consider 100 kmol of mixture. Then the mass of each component and the total mass are

$$N_{N_2} = 60 \text{kmol} \longrightarrow m_{N_2} = N_{N_2} M_{N_2} = (60\text{kmol})(28\text{kg/kmol}) = 1{,}680\text{kg}$$

$$N_{CO_2} = 40 \text{kmol} \longrightarrow m_{CO_2} = N_{CO_2} M_{CO_2} = (40\text{kmol})(44\text{kg/kmol}) = 1{,}760\text{kg}$$

$$m_m = m_{N_2} + m_{CO_2} = 1{,}680 \text{ kg} + 1{,}760 \text{ kg} = 3{,}440 \text{ kg}$$

Then the mass fraction of each component (gravimetric analysis) becomes

$$mf_{N_2} = \frac{m_{N_2}}{m_m} = \frac{1{,}680 \text{ kg}}{3{,}440 \text{ kg}} = 0.488 \quad \text{or} \quad \mathbf{48.8\%}$$

$$mf_{CO_2} = \frac{m_{CO_2}}{m_m} = \frac{1{,}760 \text{ kg}}{3{,}440 \text{ kg}} = 0.512 \quad \text{or} \quad \mathbf{51.2\%}$$

mole
60% N_2
40% CO_2

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{3{,}440 \text{ kg}}{100 \text{ kmol}} = \mathbf{34.40 \text{ kg/kmol}}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314 \text{ kJ/kmol} \cdot \text{K}}{34.4 \text{ kg/kmol}} = \mathbf{0.242 \text{ kJ/kg} \cdot \text{K}}$$

9-12 The molar fractions of the constituents of a gas mixture are given. The gravimetric analysis of the mixture, its molar mass, and gas constant are to be determined.

Properties The molar masses of O_2 and CO_2 are 32.0 and 44.0 kg/kmol, respectively (Table A-1)

Analysis Consider 100 kmol of mixture. Then the mass of each component and the total mass are

$$N_{O_2} = 60 \text{kmol} \longrightarrow m_{O_2} = N_{O_2} M_{O_2} = (60 \text{kmol})(32 \text{kg/kmol}) = 1{,}920 \text{kg}$$

$$N_{CO_2} = 40 \text{kmol} \longrightarrow m_{CO_2} = N_{CO_2} M_{CO_2} = (40 \text{kmol})(44 \text{kg/kmol}) = 1{,}760 \text{kg}$$

$$m_m = m_{O_2} + m_{CO_2} = 1{,}920 \text{kg} + 1{,}760 \text{kg} = 3{,}680 \text{kg}$$

Then the mass fraction of each component (gravimetric analysis) becomes

$$mf_{O_2} = \frac{m_{O_2}}{m_m} = \frac{1{,}920 \text{kg}}{3{,}680 \text{kg}} = 0.522 \text{ or } \textbf{52.2\%}$$

$$mf_{CO_2} = \frac{m_{CO_2}}{m_m} = \frac{1{,}760 \text{kg}}{3{,}680 \text{kg}} = 0.478 \text{ or } \textbf{47.8\%}$$

mole
60% O_2
40% CO_2

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{3{,}680 \text{kg}}{100 \text{kmol}} = \textbf{36.80 kg/kmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314 \text{kJ/kmol} \cdot \text{K}}{36.8 \text{kg/kmol}} = \textbf{0.226 kJ/kg} \cdot \textbf{K}$$

9-13 The masses of the constituents of a gas mixture are given. The mass fractions, the mole fractions, the average molar mass, and gas constant are to be determined.

Properties The molar masses of O_2, N_2, and CO_2 are 32.0, 28.0 and 44.0 kg/kmol, respectively (Table A-1)

Analysis (*a*) The total mass of the mixture is

$$m_m = m_{O_2} + m_{N_2} + m_{CO_2} = 5 \text{ kg} + 8 \text{ kg} + 10 \text{ kg} = 23 \text{ kg}$$

Then the mass fraction of each component becomes

$$mf_{O_2} = \frac{m_{O_2}}{m_m} = \frac{5 \text{ kg}}{23 \text{ kg}} = \textbf{0.217}$$

$$mf_{N_2} = \frac{m_{N_2}}{m_m} = \frac{8 \text{ kg}}{23 \text{ kg}} = \textbf{0.348}$$

$$mf_{CO_2} = \frac{m_{CO_2}}{m_m} = \frac{10 \text{ kg}}{23 \text{ kg}} = \textbf{0.435}$$

| 5 kg O_2 |
| 8 kg N_2 |
| 10 kg CO_2 |

(*b*) To find the mole fractions, we need to determine the mole numbers of each component first,

$$N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{5 \text{ kg}}{32 \text{ kg/kmol}} = 0.156 \text{ kmol}$$

$$N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{8 \text{ kg}}{28 \text{ kg/kmol}} = 0.286 \text{ kmol}$$

$$N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{10 \text{ kg}}{44 \text{ kg/kmol}} = 0.227 \text{ kmol}$$

Thus,

$$N_m = N_{O_2} + N_{N_2} + N_{CO_2} = 0.156 \text{ kmol} + 0.286 \text{ kmol} + 0.227 \text{ kmol} = 0.669 \text{ kmol}$$

and

$$y_{O_2} = \frac{N_{O_2}}{N_m} = \frac{0.156 \text{ kmol}}{0.699 \text{ kmol}} = \textbf{0.233}$$

$$y_{N_2} = \frac{N_{N_2}}{N_m} = \frac{0.286 \text{ kmol}}{0.669 \text{ kmol}} = \textbf{0.428}$$

$$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.227 \text{ kmol}}{0.669 \text{ kmol}} = \textbf{0.339}$$

(*c*) The average molar mass and gas constant of the mixture are determined from their definitions:

$$M_m = \frac{m_m}{N_m} = \frac{23 \text{ kg}}{0.669 \text{ kmol}} = \textbf{34.4 kg/kmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314 \text{ kJ/kmol·K}}{34.4 \text{ kg/kmol}} = \textbf{0.242 kJ/kg·K}$$

9-14 The mass fractions of the constituents of a gas mixture are given. The mole fractions of the gas and gas constant are to be determined.

Properties The molar masses of CH_4, and CO_2 are 16.0 and 44.0 kg/kmol, respectively (Table A-1)

Analysis For convenience, consider 100 kg of the mixture. Then the number of moles of each component and the total number of moles are

$$m_{CH_4} = 60\text{kg} \longrightarrow N_{CH_4} = \frac{m_{CH_4}}{M_{CH_4}} = \frac{60\text{kg}}{16\text{kg/kmol}} = 3.750\text{kmol}$$

$$m_{CO_2} = 40\text{kg} \longrightarrow N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{40\text{kg}}{44\text{kg/kmol}} = 0.909\text{kmol}$$

$$N_m = N_{CH_4} + N_{CO_2} = 3.750\text{kmol} + 0.909\text{kmol} = 4.659\text{kmol}$$

mass
60% CH_4
40% CO_2

Then the mole fraction of each component becomes

$$y_{CH_4} = \frac{N_{CH_4}}{N_m} = \frac{3.750\text{kmol}}{4.659\text{kmol}} = 0.804 \text{ or } \textbf{80.4\%}$$

$$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.909\text{kmol}}{4.659\text{kmol}} = 0.195 \text{ or } \textbf{19.5\%}$$

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{100\text{kg}}{4.659\text{kmol}} = 21.46\text{kg/kmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314\text{kJ/kmol}\cdot\text{K}}{21.46\text{kg/kmol}} = \textbf{0.387kJ/kg}\cdot\textbf{K}$$

9-15 The mole numbers of the constituents of a gas mixture are given. The mass of each gas and the apparent gas constant are to be determined.

Properties The molar masses of H_2, and N_2 are 2.0 and 28.0 kg/kmol, respectively (Table A-1)

Analysis The mass of each component is determined from

$$N_{H_2} = 8\text{kmol} \longrightarrow m_{H_2} = N_{H_2} M_{H_2} = (8\text{kmol})(2.0\text{kg/kmol}) = \mathbf{16kg}$$

$$N_{N_2} = 2\text{kmol} \longrightarrow m_{N_2} = N_{N_2} M_{N_2} = (2\text{kmol})(28\text{kg/kmol}) = \mathbf{56kg}$$

| 8 kmol H_2 |
| 2 kmol N_2 |

The total mass and the total number of moles are

$$m_m = m_{H_2} + m_{N_2} = 16 \text{ kg} + 56 \text{ kg} = 72 \text{ kg}$$

$$N_m = N_{H_2} + N_{N_2} = 8 \text{ kmol} + 2 \text{ kmol} = 10 \text{ kmol}$$

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{72\text{kg}}{10\text{kmol}} = 7.2\text{kg/kmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314\text{kJ/kmol} \cdot \text{K}}{7.2\text{kg/kmol}} = \mathbf{1.155kJ/kg \cdot K}$$

9-16E The mole numbers of the constituents of a gas mixture are given. The mass of each gas and the apparent gas constant are to be determined.

Properties The molar masses of H_2, and N_2 are 2.0 and 28.0 lbm/lbmol, respectively (Table A-1E).

Analysis The mass of each component is determined from

$$N_{H_2} = 5 \text{ lbmol} \longrightarrow m_{H_2} = N_{H_2} M_{H_2} = (5 \text{ lbmol})(2.0 \text{ lbm/lbmol}) = \mathbf{10\ lbm}$$

$$N_{N_2} = 3 \text{ lbmol} \longrightarrow m_{N_2} = N_{N_2} M_{N_2} = (3 \text{ lbmol})(28 \text{ lbm/lbmol}) = \mathbf{84\ lbm}$$

| 5 lbmol H_2 |
| 3 lbmol N_2 |

The total mass and the total number of moles are

$$m_m = m_{H_2} + m_{N_2} = 10 \text{ lbm} + 84 \text{ lbm} = 94 \text{ lbm}$$

$$N_m = N_{H_2} + N_{N_2} = 5 \text{ lbmol} + 3 \text{ lbmol} = 8 \text{ lbm}$$

The molar mass and the gas constant of the mixture are determined from their definitions,

$$M_m = \frac{m_m}{N_m} = \frac{94 \text{ lbm}}{8 \text{ lbmol}} = 11.75 \text{ lbm/lbmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{1.986 \text{ Btu/lbmol} \cdot \text{R}}{11.75 \text{ lbm/lbmol}} = \mathbf{0.169\ Btu/lbm \cdot R}$$

P-v-T Behavior of Gas Mixtures

9-17C Normally yes. Air, for example, behaves as an ideal gas in the range of temperatures and pressures at which oxygen and nitrogen behave as ideal gases.

9-18C The pressure of a gas mixture is equal to the sum of the pressures each gas would exert if existed alone at the mixture temperature and volume. This law holds exactly for ideal gas mixtures, but only approximately for real gas mixtures.

9-19C The volume of a gas mixture is equal to the sum of the volumes each gas would occupy if existed alone at the mixture temperature and pressure. This law holds exactly for ideal gas mixtures, but only approximately for real gas mixtures.

9-20C The P-v-T behavior of a component in an ideal gas mixture is expressed by the ideal gas equation of state using the properties of the individual component instead of the mixture, $P_i V_i = R_i T_i$. The *P-v-T* behavior of a component in a real gas mixture is expressed by more complex equations of state, or by $P_i V_i = Z_i R_i T_i$, where Z_i is the compressibility factor.

9-21C Component pressure is the pressure a component would exert if existed alone at the mixture temperature and volume. Partial pressure is the quantity $y_i P_m$, where y_i is the mole fraction of component i. These two are identical for ideal gases.

9-22C Component volume is the volume a component would occupy if existed alone at the mixture temperature and pressure. Partial volume is the quantity $y_i V_m$, where y_i is the mole fraction of component i. These two are identical for ideal gases.

9-23C The one with the highest mole number.

9-24C The partial pressures will decrease but the pressure fractions will remain the same.

9-25C The partial pressures will increase but the pressure fractions will remain the same.

9-26C No. The correct expression is "the volume of a gas mixture is equal to the sum of the volumes each gas would occupy if existed alone at the mixture temperature and pressure."

9-27C No. The correct expression is "the temperature of a gas mixture is equal to the temperature of the individual gas components."

9-28C Yes, it is correct.

9-29C With Kay's rule, a real-gas mixture is treated as a pure substance whose critical pressure and temperature are defined in terms of the critical pressures and temperatures of the mixture components as

$$P_{cr, m}' = \sum y_i P_{cr, i} \qquad \text{and} \qquad T_{cr, m}' = \sum y_i T_{cr, i}$$

The compressibility factor of the mixture (Z_m) is then easily determined using these pseudo-critical point values.

9-30 A tank contains a mixture of two gases of known masses at a specified pressure and temperature. The volume of the tank is to be determined.

Assumptions Under specified conditions both O_2 and CO_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Analysis The total number of moles is

$$N_m = N_{O_2} + N_{CO_2} = 8\text{kmol} + 10\text{kmol} = 18\text{kmol}$$

Then

$$V_m = \frac{N_m R_u T_m}{P_m} = \frac{(18\text{kmol})(8.314\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(290\text{K})}{150\text{kPa}} = \mathbf{289.3m^3}$$

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8 kmol O₂
10 kmol CO₂

290 K
150 kPa
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9-31 A tank contains a mixture of two gases of known masses at a specified pressure and temperature. The volume of the tank is to be determined.

Assumptions Under specified conditions both O_2 and CO_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Analysis The total number of moles is

$$N_m = N_{O_2} + N_{CO_2} = 8\text{kmol} + 10\text{kmol} = 18\text{kmol}$$

Then

$$V_m = \frac{N_m R_u T_m}{P_m} = \frac{(18\text{kmol})(8.314\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(350\text{K})}{150\text{kPa}} = \mathbf{349.2m^3}$$

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8 kmol O₂
10 kmol CO₂

350 K
150 kPa
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9-32 A tank contains a mixture of two gases of known masses at a specified pressure and temperature. The mixture is now heated to a specified temperature. The volume of the tank and the final pressure of the mixture are to be determined.

Assumptions Under specified conditions both Ar and N_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Analysis The total number of moles is

$$N_m = N_{Ar} + N_{N_2} = 0.5 \text{ kmol} + 2 \text{ kmol} = 2.5 \text{ kmol}$$

And

$$V_m = \frac{N_m R_u T_m}{P_m} = \frac{(2.5 \text{ kmol})(8.314 \text{ kPa} \cdot \text{m}^3 / \text{kmol} \cdot \text{K})(280 \text{ K})}{250 \text{ kPa}} = \mathbf{23.3 \text{ m}^3}$$

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0.5 kmol Ar
2 kmol N₂

280 K
250 kPa        Q
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Also,

$$\frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1} \longrightarrow P_2 = \frac{T_2}{T_1} P_1 = \frac{400 \text{ K}}{280 \text{ K}}(250 \text{ kPa}) = \mathbf{357.1 \text{ kPa}}$$

9-33 The masses of the constituents of a gas mixture at a specified pressure and temperature are given. The partial pressure of each gas and the apparent molar mass of the gas mixture are to be determined.

Assumptions Under specified conditions both CO_2 and CH_4 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Properties The molar masses of CO_2 and CH_4 are 44.0 and 16.0 kg/kmol, respectively (Table A-1)

Analysis The mole numbers of the constituents are

$$m_{CO_2} = 1\,kg \longrightarrow N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{1\,kg}{44\,kg/kmol} = 0.0227\,kmol$$

$$m_{CH_4} = 3\,kg \longrightarrow N_{CH_4} = \frac{m_{CH_4}}{M_{CH_4}} = \frac{3\,kg}{16\,kg/kmol} = 0.1875\,kmol$$

$$N_m = N_{CO_2} + N_{CH_4} = 0.0227\,kmol + 0.1875\,kmol = 0.2102\,kmol$$

$$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.0227\,kmol}{0.2102\,kmol} = 0.108$$

$$y_{CH_4} = \frac{N_{CH_4}}{N_m} = \frac{0.1875\,kmol}{0.2102\,kmol} = 0.892$$

| 1 kg CO_2 |
| 3 kg CH_4 |
| |
| 300 K |
| 200 kPa |

Then the partial pressures become

$$P_{CO_2} = y_{CO_2}\,P_m = (0.108)(200\,kPa) = \mathbf{21.6\ kPa}$$

$$P_{CH_4} = y_{CH_4}\,P_m = (0.892)(200\,kPa) = \mathbf{178.4\ kPa}$$

The apparent molar mass of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{4\,kg}{0.2102\,kmol} = \mathbf{19.03\ kg/kmol}$$

9-34E The masses of the constituents of a gas mixture at a specified pressure and temperature are given. The partial pressure of each gas and the apparent molar mass of the gas mixture are to be determined.

Assumptions Under specified conditions both CO_2 and CH_4 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Properties The molar masses of CO_2 and CH_4 are 44.0 and 16.0 lbm/lbmol, respectively (Table A-1E)

Analysis The mole numbers of gases are

$$m_{CO_2} = 1 \text{ lbm} \quad \longrightarrow \quad N_{CO_2} = \frac{m_{CO_2}}{M_{CO_2}} = \frac{1 \text{ lbm}}{44 \text{ lbm/lbmol}} = 0.0227 \text{ lbmol}$$

$$m_{CH_4} = 3 \text{ lbm} \quad \longrightarrow \quad N_{CH_4} = \frac{m_{CH_4}}{M_{CH_4}} = \frac{3 \text{ lbm}}{16 \text{ lbm/lbmol}} = 0.1875 \text{ lbmol}$$

$$N_m = N_{CO_2} + N_{CH_4} = 0.0227 \text{ lbmol} + 0.1875 \text{ lbmol} = 0.2102 \text{ lbmol}$$

$$y_{CO_2} = \frac{N_{CO_2}}{N_m} = \frac{0.0227 \text{ lbmol}}{0.2102 \text{ lbmol}} = 0.108$$

$$y_{CH_4} = \frac{N_{CH_4}}{N_m} = \frac{0.1875 \text{ lbmol}}{0.2102 \text{ lbmol}} = 0.892$$

1 lbm CO_2
3 lbm CH_4
600 R
20 psia

Then the partial pressures become

$$P_{CO_2} = y_{CO_2} P_m = (0.108)(20 \text{psia}) = \mathbf{2.16 \ psia}$$
$$P_{CH_4} = y_{CH_4} P_m = (0.892)(20 \text{psia}) = \mathbf{17.84 \ psia}$$

The apparent molar mass of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{4 \text{ lbm}}{0.2102 \text{ lbmol}} = \mathbf{19.03 \ lbm/lbmol}$$

9-35 The masses of the constituents of a gas mixture at a specified temperature are given. The partial pressure of each gas and the total pressure of the mixture are to be determined.

Assumptions Under specified conditions both N_2 and O_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Analysis The partial pressures of constituent gases are

$$P_{N_2} = \left(\frac{mRT}{V}\right)_{N_2} = \frac{(0.6\text{kg})(0.2968\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{K})}{0.3\text{m}^3} = \mathbf{178.1 \ kPa}$$

$$P_{O_2} = \left(\frac{mRT}{V}\right)_{O_2} = \frac{(0.4\text{kg})(0.2598\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{K})}{0.3\text{m}^3} = \mathbf{103.9 \ kPa}$$

0.3 m^3
0.6 kg N_2
0.4 kg O_2
300 K

and

$$P_m = P_{N_2} + P_{O_2} = 178.1 \text{ kPa} + 103.9 \text{ kPa} = \mathbf{282.0 \ kPa}$$

9-36 The volumetric fractions of the constituents of a gas mixture at a specified pressure and temperature are given. The mass fraction and partial pressure of each gas are to be determined.

Assumptions Under specified conditions all N_2, O_2 and CO_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Properties The molar masses of N_2, O_2 and CO_2 are 28.0, 32.0, and 44.0 kg/kmol, respectively (Table A-1)

Analysis For convenience, consider 100 kmol of mixture. Then the mass of each component and the total mass are

$$N_{N_2} = 65 \text{ kmol} \longrightarrow m_{N_2} = N_{N_2} M_{N_2} = (65 \text{ kmol})(28 \text{ kg/kmol}) = 1820 \text{ kg}$$

$$N_{O_2} = 20 \text{ kmol} \longrightarrow m_{O_2} = N_{O_2} M_{O_2} = (20 \text{ kmol})(32 \text{ kg/kmol}) = 640 \text{ kg}$$

$$N_{CO_2} = 15 \text{ kmol} \longrightarrow m_{CO_2} = N_{CO_2} M_{CO_2} = (15 \text{ kmol})(44 \text{ kg/kmol}) = 660 \text{ kg}$$

$$m_m = m_{N_2} + m_{O_2} + m_{CO_2} = 1{,}820 \text{ kg} + 640 \text{ kg} + 660 \text{ kg} = 3{,}120 \text{ kg}$$

65% N_2
20% O_2
15% CO_2
350 K
300 kPa

Then the mass fraction of each component (gravimetric analysis) becomes

$$mf_{N_2} = \frac{m_{N_2}}{m_m} = \frac{1{,}820 \text{ kg}}{3{,}120 \text{ kg}} = 0.583 \text{ or } \mathbf{58.3\%}$$

$$mf_{O_2} = \frac{m_{O_2}}{m_m} = \frac{640 \text{ kg}}{3{,}120 \text{ kg}} = 0.205 \text{ or } \mathbf{20.5\%}$$

$$mf_{CO_2} = \frac{m_{CO_2}}{m_m} = \frac{660 \text{ kg}}{3{,}120 \text{ kg}} = 0.212 \text{ or } \mathbf{21.2\%}$$

For ideal gases, the partial pressure is proportional to the mole fraction, and is determined from

$$P_{N_2} = y_{N_2} P_m = (0.65)(300 \text{ kPa}) = \mathbf{195 \ kPa}$$

$$P_{O_2} = y_{O_2} P_m = (0.20)(300 \text{ kPa}) = \mathbf{60 \ kPa}$$

$$P_{CO_2} = y_{CO_2} P_m = (0.15)(300 \text{ kPa}) = \mathbf{45 \ kPa}$$

9-37 The masses, temperatures, and pressures of two gases contained in two tanks connected to each other are given. The valve connecting the tanks is opened and the final temperature is measured. The volume of each tank and the final pressure are to be determined.

Assumptions Under specified conditions both N_2 and O_2 can be treated as ideal gases, and the mixture as an ideal gas mixture

Properties The molar masses of N_2 and O_2 are 28.0 and 32.0 kg/kmol, respectively (Table A-1)

Analysis The volumes of the tanks are

$$V_{N_2} = \left(\frac{mRT}{P}\right)_{N_2} = \frac{(2\text{kg})(0.2968\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{K})}{200\text{kPa}} = \mathbf{0.884\ m^3}$$

$$V_{O_2} = \left(\frac{mRT}{P}\right)_{O_2} = \frac{(3\text{kg})(0.2598\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{K})}{500\text{kPa}} = \mathbf{0.465\ m^3}$$

2 kg N_2		3 kg O_2
25°C		25°C
200 kPa		500 kPa
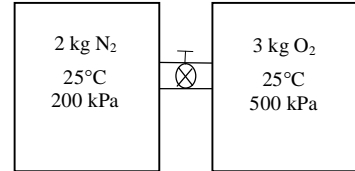
$$V_{total} = V_{N_2} + V_{O_2} = 0.884\text{ m}^3 + 0.465\text{ m}^3 = 1.349\text{ m}^3$$

Also,

$$m_{N_2} = 2\text{ kg} \longrightarrow N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{2\text{ kg}}{28\text{ kg/kmol}} = 0.0714\text{ kmol}$$

$$m_{O_2} = 3\text{ kg} \longrightarrow N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{3\text{ kg}}{32\text{ kg/kmol}} = 0.0938\text{ kmol}$$

$$N_m = N_{N_2} + N_{O_2} = 0.0714\text{ kmol} + 0.0938\text{ kmol} = 0.1652\text{ kmol}$$

Thus,

$$P_m = \left(\frac{NR_uT}{V}\right)_m = \frac{(0.1652\text{kmol})(8.314\text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(298\text{K})}{1.349\text{m}^3} = \mathbf{303.4\ kPa}$$

Properties of Gas Mixtures

9-38C Yes. Yes (extensive property).

9-39C No (intensive property).

9-40C The answers are the same for entropy.

9-41C Yes. Yes (conservation of energy).

9-42C We have to use the partial pressure.

9-43C No, this is an approximate approach. It assumes a component behaves as if it existed alone at the mixture temperature and pressure (i.e., it disregards the influence of dissimilar molecules on each other.)

9-44 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

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

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

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

CO₂	H₂
0.5 kmol	7.5 kmol
200 kPa	400 kPa
27°C	40°C

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

$$(0.5 \times 44\,\text{kg})(0.657\,\text{kJ/kg} \cdot °\text{C})(T_m - 27°\text{C}) + (7.5 \times 2\,\text{kg})(10.183\,\text{kJ/kg} \cdot °\text{C})(T_m - 40°\text{C}) = 0$$

$$T_m = \textbf{38.9°C} \quad (311.9\text{K})$$

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

$$V_{CO_2} = \left(\frac{NR_u T_1}{P_1}\right)_{CO_2} = \frac{(0.5\,\text{kmol})(8.314\,\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(300\text{K})}{200\,\text{kPa}} = 6.24\,\text{m}^3$$

$$V_{H_2} = \left(\frac{NR_u T_1}{P_1}\right)_{H_2} = \frac{(7.5\,\text{kmol})(8.314\,\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(313\text{K})}{400\,\text{kPa}} = 48.79\,\text{m}^3$$

Thus,

$$V_m = V_{CO_2} + V_{H_2} = 6.24\,\text{m}^3 + 48.79\,\text{m}^3 = 55.03\,\text{m}^3$$

$$N_m = N_{CO_2} + N_{H_2} = 0.5\,\text{kmol} + 7.5\,\text{kmol} = 8.0\,\text{kmol}$$

and

$$P_m = \frac{N_m R_u T_m}{V_m} = \frac{(8.0\,\text{kmol})(8.314\,\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(311.9\text{K})}{55.03\,\text{m}^3} = \textbf{377kPa}$$

9-45 The temperatures and pressures of two gases forming a mixture are given. The final mixture temperature and pressure are to be determined.
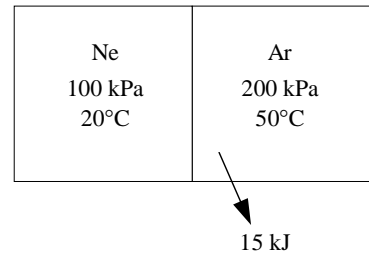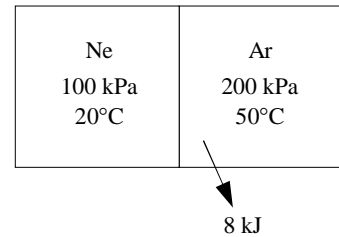
Assumptions **1** Under specified conditions both Ne and Ar can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** There are no other forms of work involved.

Properties The molar masses and specific heats of Ne and Ar are 20.18 kg/kmol, 39.95 kg/kmol, 0.6179 kJ/kg.°C, and 0.3122 kJ/kg.°C, respectively. (Tables A-1 and A-2b).

Analysis The mole number of each gas is

$$N_{Ne} = \left(\frac{P_1 V_1}{R_u T_1}\right)_{Ne} = \frac{(100\text{kPa})(0.45\text{m}^3)}{(8.314\text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(293\text{K})} = 0.0185\text{kmol}$$

$$N_{Ar} = \left(\frac{P_1 V_1}{R_u T_1}\right)_{Ar} = \frac{(200\text{kPa})(0.45\text{m}^3)}{(8.314\text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(323\text{K})} = 0.0335\text{kmol}$$

Ne	Ar
100 kPa	200 kPa
20°C	50°C

15 kJ

Thus,

$$N_m = N_{Ne} + N_{Ar} = 0.0185 \text{ kmol} + 0.0335 \text{ kmol} = 0.0520 \text{ kmol}$$

(*a*) We take both gases as the system. No work or mass crosses the system boundary, therefore this is a closed system with $W = 0$. Then the conservation of energy equation for this closed system reduces to

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

$$-Q_{out} = \Delta U = \Delta U_{Ne} + \Delta U_{Ar} \longrightarrow -Q_{out} = \left[mC_v(T_m - T_1)\right]_{Ne} + \left[mC_v(T_m - T_1)\right]_{Ar}$$

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

$$-15\text{kJ} = (0.0185 \times 20.18\text{kg})(0.6179\text{kJ/kg}\cdot\text{°C})(T_m - 20\text{°C})$$
$$+ (0.0335 \times 39.95\text{kg})(0.3122\text{kJ/kg}\cdot\text{°C})(T_m - 50\text{°C})$$
$$T_m = \textbf{16.2°C} \ (289.2\text{K})$$

(*b*) The final pressure in the tank is determined from

$$P_m = \frac{N_m R_u T_m}{V_m} = \frac{(0.052 \text{ kmol})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(289.2 \text{ K})}{0.9 \text{ m}^3} = \textbf{138.9 kPa}$$

9-46 The temperatures and pressures of two gases forming a mixture are given. The final mixture temperature and pressure are to be determined.

Assumptions **1** Under specified conditions both Ne and Ar can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** There are no other forms of work involved.

Properties The molar masses and specific heats of Ne and Ar are 20.18 kg/kmol, 39.95 kg/kmol, 0.6179 kJ/kg.°C, and 0.3122 kJ/kg.°C, respectively. (Tables A-1 and A-2b).

Analysis The mole number of each gas is

$$N_{Ne} = \left(\frac{P_1 V_1}{R_u T_1}\right)_{Ne} = \frac{(100\text{kPa})(0.45\text{m}^3)}{(8.314\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(293\text{K})} = 0.0185\text{kmol}$$

$$N_{Ar} = \left(\frac{P_1 V_1}{R_u T_1}\right)_{Ar} = \frac{(200\text{kPa})(0.45\text{m}^3)}{(8.314\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(323\text{K})} = 0.0335\text{kmol}$$

Ne	Ar
100 kPa	200 kPa
20°C	50°C

8 kJ

Thus,

$$N_m = N_{Ne} + N_{Ar} = 0.0185 \text{ kmol} + 0.0335 \text{ kmol} = 0.0520 \text{ kmol}$$

(*a*) We take both gases as the system. No work or mass crosses the system boundary, therefore this is a closed system with $W = 0$. Then the conservation of energy equation for this closed system reduces to

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

$$-Q_{out} = \Delta U = \Delta U_{Ne} + \Delta U_{Ar} \longrightarrow -Q_{out} = [mC_v(T_m - T_1)]_{Ne} + [mC_v(T_m - T_1)]_{Ar}$$

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

$$-8\text{kJ} = (0.0185 \times 20.18\text{kg})(0.6179\text{kJ/kg} \cdot °\text{C})(T_m - 20°\text{C})$$
$$+ (0.0335 \times 39.95\text{kg})(0.3122\text{kJ/kg} \cdot °\text{C})(T_m - 50°\text{C})$$
$$T_m = \textbf{27.0°C} \quad (300.0\text{K})$$

(*b*) The final pressure in the tank is determined from

$$P_m = \frac{N_m R_u T_m}{V_m} = \frac{(0.052\text{kmol})(8.314\text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(300.0\text{K})}{0.9\text{m}^3} = \textbf{144.1kPa}$$

9-47 An equimolar mixture of helium and argon gases expands in a turbine. The isentropic work output of the turbine is to be determined.

***Assumptions* 1** Under specified conditions both He and Ar can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** The turbine is insulated and thus there is no heat transfer. **3** This is a steady-flow process. **4** The kinetic and potential energy changes are negligible.

Properties The molar masses and specific heats of He and Ar are 4.0 kg/kmol, 40.0 kg/kmol, 5.1926 kJ/kg.°C, and 0.5203 kJ/kg.°C, respectively. (Table A-1 and Table A-2b).

Analysis The C_p and k values of this equimolar mixture are determined from

1.2 MPa
1300 K

He-Ar turbine

200 kPa

$$M_m = \sum y_i M_i = y_{He} M_{He} + y_{Ar} M_{Ar} = 0.5 \times 4 + 0.5 \times 40 = 22 \text{ kg/kmol}$$

$$mf_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = \frac{y_i M_i}{M_m}$$

$$C_{p,m} = \sum mf_i C_{p,i} = \frac{y_{He} M_{He}}{M_m} C_{p,He} + \frac{y_{Ar} M_{Ar}}{M_m} C_{p,Ar}$$

$$= \frac{0.5 \times 4 \text{ kg/kmol}}{22 \text{ kg/kmol}} (5.1926 \text{ kJ/kg} \cdot \text{K}) + \frac{0.5 \times 40 \text{ kg/kmol}}{22 \text{ kg/kmol}} (0.5203 \text{ kJ/kg} \cdot \text{K})$$

$$= 0.945 \text{ kJ/kg} \cdot \text{K}$$

and

$$k_m = 1.667 \quad \text{since } k = 1.667 \text{ for both gases.}$$

Therefore, the He-Ar mixture can be treated as a single ideal gas with the properties above. For isentropic processes,

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (1200\text{K}) \left(\frac{200\text{kPa}}{1300\text{kPa}}\right)^{0.667/1.667} = 567.4\text{K}$$

From an energy balance on the turbine,

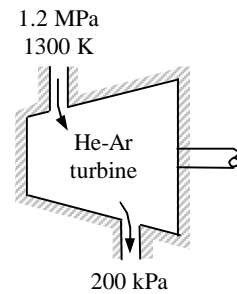$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\bar{A}0 \text{ (steady)}} = 0$$

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

$$h_1 = h_2 + w_{out}$$

$$w_{out} = h_1 - h_2$$

$$w_{out} = C_p(T_1 - T_2) = (0.945\text{kJ/kg} \cdot \text{K})(1200 - 567.4)\text{K} = \textbf{597.8 kJ/kg}$$
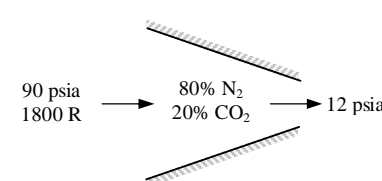
9-48E [*Also solved by EES on enclosed CD*] A gas mixture with known mass fractions is accelerated through a nozzle from a specified state to a specified pressure. For a specified isentropic efficiency, the exit temperature and the exit velocity of the mixture are to be determined.

Assumptions **1** Under specified conditions both N_2 and CO_2 can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** The nozzle is adiabatic and thus heat transfer is negligible. **3** This is a steady-flow process. **4** Potential energy changes are negligible.

Properties The specific heats of N_2 and CO_2 are $C_{p,N2} = 0.248$ Btu/lbm.R, $C_{v,N2} = 0.177$ Btu/lbm.R, $C_{p,CO2} = 0.203$ Btu/lbm.R, and $C_{v,CO2} = 0.158$ Btu/lbm.R. (Table A-2Eb).

Analysis (*a*) Under specified conditions both N_2 and CO_2 can be treated as ideal gases, and the mixture as an ideal gas mixture. The C_p, C_v, and k values of this mixture are determined from

$$C_{p,m} = \sum mf_i C_{p,i} = mf_{N_2} C_{p,N_2} + mf_{CO_2} C_{p,CO_2}$$
$$= (0.8)(0.248) + (0.2)(0.203) = 0.239 \, \text{Btu/lbm} \cdot \text{R}$$

$$C_{v,m} = \sum mf_i C_{v,i} = mf_{N_2} C_{v,N_2} + mf_{CO_2} C_{v,CO_2}$$
$$= (0.8)(0.177) + (0.2)(0.158) = 0.173 \, \text{Btu/lbm} \cdot \text{R}$$

$$k_m = \frac{C_{p,m}}{C_{v,m}} = \frac{0.239 \, \text{Btu/lbm} \cdot \text{R}}{0.173 \, \text{Btu/lbm} \cdot \text{R}} = 1.382$$

90 psia
1800 R → 80% N_2
20% CO_2 → 12 psia

Therefore, the N_2-CO_2 mixture can be treated as a single ideal gas with above properties. Then the isentropic exit temperature can be determined from

$$T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (1,800 \, \text{R})\left(\frac{12 \, \text{psia}}{90 \, \text{psia}}\right)^{0.382/1.382} = 1031.3 \, \text{R}$$

From the definition of adiabatic efficiency,

$$\eta_N = \frac{h_1 - h_2}{h_1 - h_{2s}} = \frac{C_p(T_1 - T_2)}{C_p(T_1 - T_{2s})} \longrightarrow 0.92 = \frac{1,800 - T_2}{1,800 - 1031.3} \longrightarrow T_2 = \mathbf{1092.8 \ R}$$

(*b*) Noting that, $q = w = 0$, from the steady-flow energy balance relation,

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

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

$$h_1 + \mathbf{V}_1^2 / 2 = h_2 + \mathbf{V}_2^2 / 2$$

$$0 = C_p(T_2 - T_1) + \frac{\mathbf{V}_2^2 - \mathbf{V}_1^{2\,\nearrow 0}}{2}$$

$$\mathbf{V}_2 = \sqrt{2 C_p(T_1 - T_2)} = \sqrt{2(0.239 \, \text{Btu/lbm} \cdot \text{R})(1,800 - 1,092.8) \text{R}\left(\frac{25,037 \, \text{ft}^2/\text{s}^2}{1 \, \text{Btu/lbm}}\right)} = \mathbf{2,909 \ ft/s}$$

9-49E Problem 9-48E is reconsidered. The problem is to be solved using EES (or other) software, and for all other conditions being the same, the problem is to be solved again to determine the composition of the nitrogen and carbon dioxide that is required to have an exit velocity of 2000 ft/s at the nozzle exit.

"Input Data"
"To solve 12-55E, place {} around the next two equations"
mf_N2 = 0.8   "Mass fraction for the nitrogen, lbm_N2/lbm_mix"
mf_CO2 = 0.2   "Mass fraction for the carbon dioxide, lbm_CO2/lbm_mix"
{mf_CO2=1- mf_N2}"To solve 12-55E, remove the {} here"

T[1] = 1800"R"
P[1] = 90 "psia"
Vel[1] = 0"ft/s"
P[2] = 12 "psia"
Eta_N =0.92   "Nozzle adiabatic efficiency"

"Enthalpy property data per unit mass of mixture:"

" Note: EES calculates the enthalpy of ideal gases referenced to
the enthalpy of formation as h = h_f + (h_T - h_537) where h_f is the
enthalpy of formation such that the enthalpy of the elements or their
stable compounds is zero at 77 F or 537 R, see Chapter 14. The enthalpy
of formation is often negative; thus, the enthalpy of ideal gases can
be negative at a given temperature. This is true for CO2 in this problem."

h[1]= mf_N2* enthalpy(N2, T=T[1]) + mf_CO2* enthalpy(CO2, T=T[1])
h[2]= mf_N2* enthalpy(N2, T=T[2]) + mf_CO2* enthalpy(CO2, T=T[2])

"Conservation of Energy for a unit mass flow of mixture:"
"E_in - E_out = DELTAE_cv Where DELTAE_cv = 0 for SSSF"
h[1]+Vel[1]^2/2*convert(ft^2/s^2,Btu/lbm) - h[2] - Vel[2]^2/2*convert(ft^2/s^2,Btu/lbm) =0
"SSSF energy balance"

"Nozzle Efficiency Calculation:"
Eta_N=(h[1]-h[2])/(h[1]-h_s2)
h_s2= mf_N2* enthalpy(N2, T=T_s2) + mf_CO2* enthalpy(CO2, T=T_s2)

"The mixture isentropic exit temperature, T_s2, is calculated from setting the
entropy change per unit mass of mixture equal to zero."

DELTAs_mix=mf_N2 * DELTAs_N2 + mf_CO2 * DELTAs_CO2
DELTAs_N2 = entropy(N2, T=T_s2, P=P_2_N2) - entropy(N2, T=T[1], P=P_1_N2)
DELTAs_CO2 = entropy(CO2, T=T_s2, P=P_2_CO2) - entropy(CO2, T=T[1], P=P_1_CO2)
DELTAs_mix=0

"By Dalton's Law the partial pressures are:"
P_1_N2 = y_N2 * P[1]; P_1_CO2 = y_CO2 * P[1]
P_2_N2 = y_N2 * P[2]; P_2_CO2 = y_CO2 * P[2]

"mass fractions, mf, and mole fractions, y, are related by:"
M_N2 = molarmass(N2)
M_CO2=molarmass(CO2)
y_N2=mf_N2/M_N2/(mf_N2/M_N2 + mf_CO2/M_CO2)
y_CO2=mf_CO2/M_CO2/(mf_N2/M_N2 + mf_CO2/M_CO2)

{Vel[2] = 2600"[ft/s]"}"To solve 12-55E, remove the {} here."

SOLUTION
Variables in Main
DELTAs_CO2=-0.04486 [Btu/lbm-R]   DELTAs_mix=0 [Btu/lbm-R]
DELTAs_N2=0.01122 [Btu/lbm-R]   Eta_N=0.92
h[1]=-439.7 [Btu/lbm]   h[2]=-613.7 [Btu/lbm]
h_s2=-628.8 [Btu/lbm]   mf_CO2=0.2 [lbm_CO2/lbm_mix]
mf_N2=0.8 [lbm_N2/lbm_mix]   M_CO2=44.01 [lbm/lbmol]
M_N2=28.01 [lbm/lbmol]   P[1]=90 [psia]
P[2]=12 [psia]   P_1_CO2=12.36 [psia]
P_1_N2=77.64 [psia]   P_2_CO2=1.647 [psia]
P_2_N2=10.35 [psia]   T[1]=1800 [R]
T[2]=1160 [R]   T_s2=1102 [R]
Vel[1]=0 [ft/s]   Vel[2]=2952 [ft/s]
y_CO2=0.1373 [ft/s]   y_N2=0.8627 [lbmol_N2/lbmol_mix]

mf_{CO2} [lbm$_{CO2}$/lbm$_{mix}$]	mf_{N2} [lbm$_{CO2}$/lbm$_{mix}$]	Vel$_2$ [ft/s]
0.9	0.1	2601
0.8	0.2	2658
0.7	0.3	2712
0.6	0.4	2764
0.5	0.5	2814
0.4	0.6	2862
0.3	0.7	2907
0.2	0.8	2952
0.1	0.9	2994

9-50 A piston-cylinder device contains a gas mixture at a given state. Heat is transferred to the mixture. The amount of heat transfer and the entropy change of the mixture are to be determined.

Assumptions **1** Under specified conditions both H_2 and N_2 can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** Kinetic and potential energy changes are negligible.
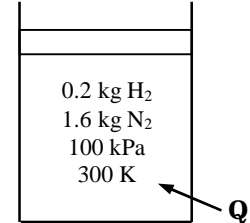
Properties The constant pressure specific heats of H_2 and N_2 at 450 K are 14.501 kJ/kg.K and 1.039 kJ/kg.K, respectively. (Table A-2b).

Analysis (*a*) Noting that $P_2 = P_1$ and $V_2 = 2V_1$,

$$\frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1} \longrightarrow T_2 = \frac{2V_1}{V_1} T_1 = 2T_1 = (2)(300\text{K}) = 600\text{K}$$

Also P = constant. Then from the closed system energy balance relation,

$$E_{in} - E_{out} = \Delta E_{system}$$
$$Q_{in} - W_{b,out} = \Delta U \ \rightarrow \ Q_{in} = \Delta H$$

0.2 kg H_2
1.6 kg N_2
100 kPa
300 K

Q

since W_b and ΔU combine into ΔH for quasi-equilibrium constant pressure processes.

$$Q_{in} = \Delta H = \Delta H_{H_2} + \Delta H_{N_2} = \left[m C_{p,ave} \left(T_2 - T_1 \right) \right]_{H_2} + \left[m C_{p,ave} \left(T_2 - T_1 \right) \right]_{N_2}$$
$$= (0.2\text{kg})(14.501\text{kJ/kg} \cdot \text{K})(600-300)\text{K} + (1.6\text{kg})(1.049\text{kJ/kg} \cdot \text{K})(600-300)\text{K}$$
$$= \mathbf{1{,}374 \ kJ}$$

(*b*) Noting that the total mixture pressure, and thus the partial pressure of each gas, remains constant, the entropy change of the mixture during this process is

$$\Delta S_{H_2} = \left[m(s_2 - s_1) \right]_{H_2} = m_{H_2} \left(C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}^{\bar{A}0} \right)_{H_2} = \left(C_p \ln \frac{T_2}{T_1} \right)_{H_2}$$
$$= (0.2\text{kg})(14.501\text{kJ/kg} \cdot \text{K}) \ln \frac{600\text{K}}{300\text{K}}$$
$$= 2.01\text{kJ/K}$$

$$\Delta S_{N_2} = \left[m(s_2 - s_1) \right]_{N_2} = m_{N_2} \left(C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}^{\bar{A}0} \right)_{N_2} = \left(C_p \ln \frac{T_2}{T_1} \right)_{N_2}$$
$$= (1.6\text{kg})(1.049\text{kJ/kg} \cdot \text{K}) \ln \frac{600\text{K}}{300\text{K}}$$
$$= 1.160\text{kJ/K}$$

$$\Delta S_{total} = \Delta S_{H_2} + \Delta S_{N_2} = 2.01\text{kJ/K} + 1.16\text{kJ/K} = \mathbf{3.17 \ kJ/K}$$

9-51 The states of two gases contained in two tanks are given. The gases are allowed to mix to form a homogeneous mixture. The final pressure and the heat transfer are to be determined.

Assumptions **1** Under specified conditions both O_2 and N_2 can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** The tank containing oxygen is insulated. **3** There are no other forms of work involved.

Properties The constant volume specific heats of O_2 and N_2 are 0.658 kJ/kg.°C and 0.743 kJ/kg.°C, respectively. (Table A-2b).

Analysis (*a*) The volume of the O_2 tank and mass of the nitrogen are

$$V_{1,O_2} = \left(\frac{mRT_1}{P_1}\right)_{O_2} = \frac{(1\ \text{kg})(0.2598\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(288\ \text{K})}{300\ \text{kPa}} = 0.25\ \text{m}^3$$

$$m_{N_2} = \left(\frac{P_1V_1}{RT_1}\right)_{N_2} = \frac{(500\ \text{kPa})(2\ \text{m}^3)}{(0.2968\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(323\ \text{K})} = 10.43\ \text{kg}$$

$$V_{total} = V_{1,O_2} + V_{1,N_2} = 0.25\ \text{m}^3 + 2.0\ \text{m}^3 = 2.25\ \text{m}^3$$

Also,

$$m_{O_2} = 1\ \text{kg} \qquad\longrightarrow\qquad N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{1\ \text{kg}}{32\ \text{kg/kmol}} = 0.03125\ \text{kmol}$$

$$m_{N_2} = 10.43\ \text{kg} \qquad\longrightarrow\qquad N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{10.43\ \text{kg}}{28\ \text{kg/kmol}} = 0.3725\ \text{kmol}$$

$$N_m = N_{N_2} + N_{O_2} = 0.3725\ \text{kmol} + 0.03125\ \text{kmol} = 0.40375\ \text{kmol}$$

Thus,

$$P_m = \left(\frac{NR_uT}{V}\right)_m = \frac{(0.40375\ \text{kmol})(8.314\ \text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(298\ \text{K})}{2.25\ \text{m}^3} = \textbf{444.6 kPa}$$

(*b*) We take both gases as the system. No work or mass crosses the system boundary, and thus this is a closed system with $W = 0$. Taking the direction of heat transfer to be from the system (will be verified), the energy balance for this closed system reduces to

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

$$-Q_{out} = \Delta U = \Delta U_{O_2} + \Delta U_{N_2} \longrightarrow Q_{out} = \left[mC_v(T_1 - T_m)\right]_{O_2} + \left[mC_v(T_1 - T_m)\right]_{N_2}$$

Using C_v values at room temperature (Table A-2b), the heat transfer is determined to be

$$Q_{out} = (1\ \text{kg})(0.658\ \text{kJ/kg}\cdot°\text{C})(15-25)°\text{C} + (10.43\ \text{kg})(0.743\ \text{kJ/kg}\cdot°\text{C})(50-25)°\text{C}$$
$$= \textbf{187.2 kJ} \ (\text{from the system})$$
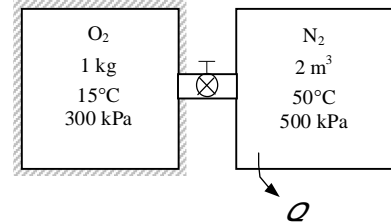
9-52 Problem 9-51 is reconsidered. Using EES (or other) software, the results obtained assuming ideal gas behavior with constant specific heats at the average temperature are to be compared to those obtained using real gas data from EES by assuming variable specific heats over the temperature range.

"Input Data:"
T_O2[1] =15"[C]"
T_N2[1] =50"[C]"
T[2] =25"[C]"
T_o = 25"[C]"
m_O2 = 1"[kg]"
P_O2[1]=300"[kPa]"
V_N2[1]=2"[m^3]"
P_N2[1]=500"[kPa]"
R_u=8.314"[kJ/kmol-K]"
MM_O2=molarmass(O2)"[kg/kmol]"
MM_N2=molarmass(N2)"[kg/kmol]"
P_O2[1]*V_O2[1]=m_O2*R_u/MM_O2*(T_O2[1]+273)
P_N2[1]*V_N2[1]=m_N2*R_u/MM_N2*(T_N2[1]+273)
V_total=V_O2[1]+V_N2[1]"[m^3/kg]"
N_O2=m_O2/MM_O2
N_N2=m_N2/MM_N2
N_total=N_O2+N_N2
P[2]*V_total=N_total*R_u*(T[2]+273)
P_Final =P[2]"[kPa]"

"Conservation of energy for the combined system:"
E_in - E_out = DELTAE_sys
E_in = 0 "[kJ]"
E_out = Q"[kJ]"
DELTAE_sys=m_O2*(intenergy(O2,T=T[2]) - intenergy(O2,T=T_O2[1])) +
m_N2*(intenergy(N2,T=T[2]) - intenergy(N2,T=T_N2[1]))"[kJ]"
P_O2[2]=P[2]*N_O2/N_total
P_N2[2]=P[2]*N_N2/N_total

"Entropy generation:"
 - Q/(T_o+273) + S_gen = DELTAS_O2 + DELTAS_N2
DELTAS_O2 = m_O2*(entropy(O2,T=T[2],P=P_O2[2]) -
entropy(O2,T=T_O2[1],P=P_O2[1]))
DELTAS_N2 = m_N2*(entropy(N2,T=T[2],P=P_N2[2]) -
entropy(N2,T=T_N2[1],P=P_N2[1]))

"Constant Property (ConstP) Solution:"
-Q_ConstP=m_O2*Cv_O2*(T[2]-T_O2[1])+m_N2*Cv_N2*(T[2]-T_N2[1])
Tav_O2 =(T[2]+T_O2[1])/2
Cv_O2 = SPECHEAT(O2,T=Tav_O2) - R_u/MM_O2
Tav_N2 =(T[2]+T_N2[1])/2
Cv_N2 = SPECHEAT(N2,T=Tav_N2) - R_u/MM_N2
 - Q_ConstP/(T_o+273) + S_gen_ConstP = DELTAS_O2_ConstP + DELTAS_N2_ConstP
DELTAS_O2_ConstP = m_O2*(
SPECHEAT(O2,T=Tav_O2)*LN((T[2]+273)/(T_O2[1]+273))-
R_u/MM_O2*LN(P_O2[2]/P_O2[1]))
DELTAS_N2_ConstP = m_N2*(
SPECHEAT(N2,T=Tav_N2)*LN((T[2]+273)/(T_N2[1]+273))-
R_u/MM_N2*LN(P_N2[2]/P_N2[1]))

SOLUTION
Variables in Main
Cv_N2=0.7454 [kJ/kg-K]   Cv_O2=0.6627 [kJ/kg-K]
DELTAE_sys=-187.7 [kJ]   DELTAS_N2=-0.262 [kJ/K]
DELTAS_N2_ConstP=-0.2625 [kJ/K]   DELTAS_O2=0.594 [kJ/K]
DELTAS_O2_ConstP=0.594 [kJ/K]   E_in=0 [kJ]
E_out=187.7 [kJ]   MM_N2=28.01 [kg/kmol]
MM_O2=32 [kg/kmol]   m_N2=10.43 [kg]
m_O2=1 [kg]   N_N2=0.3724 [kmol]
N_O2=0.03125 [kmol]   N_total=0.4036 [kmol]
P[2]=444.6 [kPa]   P_Final=444.6 [kPa]
P_N2[1]=500 [kPa]   P_N2[2]=410.1 [kPa]
P_O2[1]=300 [kPa]   P_O2[2]=34.42 [kPa]
Q=187.7 [kJ]   Q_ConstP=187.8 [kJ]
R_u=8.314 [kJ/kmol-K]   S_gen=0.962 [kJ]
S_gen_ConstP=0.9616 [kJ]   Tav_N2=37.5 [C]
Tav_O2=20 [C]   T[2]=25 [C]
T_N2[1]=50 [C]   T_o=25 [C]
T_O2[1]=15 [C]   V_N2[1]=2 [m^3]
V_O2[1]=0.2494 [m^3]   V_total=2.249 [m^3/kg]

Dry and Atmospheric Air, Specific and Relative Humidity

9-53C Yes; by cooling the air at constant pressure.

9-54C Yes.

9-55C Specific humidity will decrease but relative humidity will increase.

9-56C Dry air does not contain any water vapor, but atmospheric air does.

9-57C Yes, the water vapor in the air can be treated as an ideal gas because of its very low partial pressure.

9-58C The partial pressure of the water vapor in atmospheric air is called vapor pressure.

9-59C The same. This is because water vapor behaves as an ideal gas at low pressures, and the enthalpy of an ideal gas depends on temperature only.

9-60C Specific humidity is the amount of water vapor present in a unit mass of dry air. Relative humidity is the ratio of the actual amount of vapor in the air at a given temperature to the maximum amount of vapor air can hold at that temperature.

9-61C The specific humidity will remain constant, but the relative humidity will decrease as the temperature rises in a well-sealed room.

9-62C The specific humidity will remain constant, but the relative humidity will decrease as the temperature drops in a well-sealed room.

9-63C A tank that contains moist air at 3 atm is located in moist air that is at 1 atm. The driving force for moisture transfer is the vapor pressure difference, and thus it is possible for the water vapor to flow into the tank from surroundings if the vapor pressure in the surroundings is greater than the vapor pressure in the tank.

9-64C Insulations on *chilled water lines* are always wrapped with *vapor barrier jackets* to eliminate the possibility of vapor entering the insulation. This is because moisture that migrates through the insulation to the cold surface will condense and remain there indefinitely with no possibility of vaporizing and moving back to the outside.

9-65C When the temperature, total pressure, and the relative humidity are given, the vapor pressure can be determined from the psychrometric chart or the relation $P_v = \phi P_{sat}$ where P_{sat} is the saturation (or boiling) pressure of water at the specified temperature and ϕ is the relative humidity.

9-66 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,

$$\omega = \frac{m_v}{m_a} = \frac{0.3 \text{ kg}}{21 \text{ kg}} = \textbf{0.0143 kg H}_2\textbf{O / kg dry air}$$

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

$$P_g = P_{\text{sat @ 30°C}} = 4.246 \text{ kPa}$$

21 kg dry air
0.3 kg H$_2$O vapor
30°C
100 kPa

Then the relative humidity can be determined from

$$\phi = \frac{\omega P}{(0.622 + \omega) P_g} = \frac{(0.0143)(100 \text{ kPa})}{(0.622 + 0.0143)4.246 \text{ kPa}} = \textbf{52.9\%}$$

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

$$P_v = \phi P_g = (0.529)(4.246 \text{ kPa}) = 2.246 \text{ kPa}$$
$$P_a = P - P_v = 100 - 2.246 = 97.754 \text{ kPa}$$
$$V = \frac{m_a R_a T}{P_a} = \frac{(21 \text{ kg})(0.287 \text{ kJ / kg} \cdot \text{K})(303 \text{ K})}{97.754 \text{ kPa}} = \textbf{18.7 m}^3$$

9-67 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,

$$\omega = \frac{m_v}{m_a} = \frac{0.3 \text{ kg}}{21 \text{ kg}} = \textbf{0.0143 kg H}_2\textbf{O / kg dry air}$$

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

$$P_g = P_{\text{sat @ 35°C}} = 5.628 \text{ kPa}$$

21 kg dry air
0.3 kg H$_2$O vapor
35°C
100 kPa

Then the relative humidity can be determined from

$$\phi = \frac{\omega P}{(0.622 + \omega) P_g} = \frac{(0.0143)(100 \text{ kPa})}{(0.622 + 0.0143)5.628 \text{ kPa}} = \textbf{39.9\%}$$

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

$$P_v = \phi P_g = (0.399)(5.628 \text{ kPa}) = 2.246 \text{ kPa}$$
$$P_a = P - P_v = 100 - 2.246 = 97.754 \text{ kPa}$$
$$V = \frac{m_a R_a T}{P_a} = \frac{(21 \text{ kg})(0.287 \text{ kJ/kg} \cdot \text{K})(308 \text{ K})}{97.754 \text{ kPa}} = \textbf{19.0 m}^3$$

9-68 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

$$P_v = \phi P_g = \phi P_{\text{sat @ 20°C}} = (0.85)(2.339\text{ kPa}) = 1.99\text{ kPa}$$
$$P_a = P - P_v = 98 - 1.99 = \mathbf{96.01\ kPa}$$

┌─────────────┐
│   │
│   AIR   │
│   20°C   │
│   98 kPa   │
│   85% RH   │
│   │
└─────────────┘

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

$$\omega = \frac{0.622\, P_v}{P - P_v} = \frac{(0.622)(1.99\text{ kPa})}{(98 - 1.99)\text{ kPa}} = \mathbf{0.0129\ kg\ H_2O\ /\ kg\ dry\ air}$$

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

$$h = h_a + \omega h_v \cong C_p T + \omega h_g$$
$$= (1.005\text{ kJ / kg·°C})(20°\text{C}) + (0.0129)(2538.1\text{ kJ / kg}) = \mathbf{52.84\ kJ\ /\ kg\ dry\ air}$$

9-69 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

$$P_v = \phi P_g = \phi P_{\text{sat @ 20°C}} = (0.85)(2.339\text{ kPa}) = 1.99\text{ kPa}$$
$$P_a = P - P_v = 85 - 1.99 = \mathbf{83.01\ kPa}$$

┌─────────────┐
│   │
│   AIR   │
│   20°C   │
│   85 kPa   │
│   85% RH   │
│   │
└─────────────┘

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

$$\omega = \frac{0.622\, P_v}{P - P_v} = \frac{(0.622)(1.99\text{ kPa})}{(85 - 1.99)\text{ kPa}} = \mathbf{0.0149\ kg\ H_2O/kg\ dry\ air}$$

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

$$h = h_a + \omega h_v \cong C_p T + \omega h_g$$
$$= (1.005\text{ kJ/kg·°C})(20°\text{C}) + (0.0149)(2538.1\text{ kJ/kg}) = \mathbf{57.95\ kJ/kg\ dry\ air}$$

9-70E 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

$$P_v = \phi P_g = \phi P_{\text{sat @ 70°F}} = (0.85)(0.3632 \text{ psia}) = 0.309 \text{ psia}$$

$$P_a = P - P_v = 14.6 - 0.309 = \textbf{14.291 psia}$$

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

$$\omega = \frac{0.622\, P_v}{P - P_v} = \frac{(0.622)(0.309 \text{ psia})}{(14.6 - 0.309) \text{ psia}} = \textbf{0.0134 lbm H}_2\textbf{O / lbm dry air}$$

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

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

$$= (0.24 \text{ Btu / lbm·°F})(70°\text{F}) + (0.0134)(1092 \text{ Btu / lbm}) = \textbf{31.43 Btu / lbm dry air}$$

```
AIR
70°F
14.6 psia
85% RH
```

9-71 The masses of dry air and the water vapor contained in a room at specified conditions and relative humidity are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis The partial pressure of water vapor and dry air are determined to be

$$P_v = \phi P_g = \phi P_{\text{sat @ 23°C}} = (0.50)(2.837 \text{ kPa}) = 1.42 \text{ kPa}$$

$$P_a = P - P_v = 98 - 1.42 = 96.58 \text{ kPa}$$

The masses are determined to be

$$m_a = \frac{P_a V}{R_a T} = \frac{(96.58 \text{ kPa})(240 \text{ m}^3)}{(0.287 \text{ kPa·m}^3\text{/kg·K})(296 \text{ K})} = \textbf{272.9 kg}$$

$$m_v = \frac{P_v V}{R_v T} = \frac{(1.42 \text{ kPa})(240 \text{ m}^3)}{(0.4615 \text{ kPa·m}^3\text{/kg·K})(296 \text{ K})} = \textbf{2.49 kg}$$

```
ROOM
240 m³
23°C
98 kPa
50% RH
```

Dew-point, Adiabatic Saturation, and Wet-bulb Temperatures

9-72C Dew-point temperature is the temperature at which condensation begins when air is cooled at constant pressure.

9-73C Andy's. The temperature of his glasses may be below the dew-point temperature of the room, causing condensation on the surface of the glasses.

9-74C The outer surface temperature of the glass may drop below the dew-point temperature of the surrounding air, causing the moisture in the vicinity of the glass to condense. After a while, the condensate may start dripping down because of gravity.

9-75C When the temperature falls below the dew-point temperature, dew forms on the outer surfaces of the car. If the temperature is below 0°C, the dew will freeze. At very low temperatures, the moisture in the air will freeze directly on the car windows.

9-76C When the air is saturated (100% relative humidity).

9-77C These two are approximately equal at atmospheric temperatures and pressure.

9-78 A house contains air at a specified temperature and relative humidity. It is to be determined whether any moisture will condense on the inner surfaces of the windows when the temperature of the window drops to a specified value.

Assumptions The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v is uniform throughout the house, and its value can be determined from

$$P_v = \phi\, P_{g@25°C} = (0.65)(3.169 \text{ kPa}) = 2.06 \text{ kPa}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ 2.06 kPa}} = \mathbf{17.9°C}$$
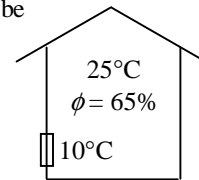
That is, the moisture in the house air will start condensing when the temperature drops below 17.9°C. Since the windows are at a lower temperature than the dew-point temperature, some moisture **will condense** on the window surfaces.

25°C
$\phi = 65\%$
10°C

9-79 A person wearing glasses enters a warm room at a specified temperature and relative humidity from the cold outdoors. It is to be determined whether the glasses will get fogged.

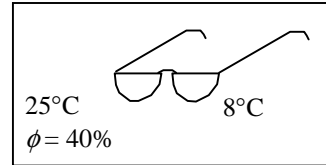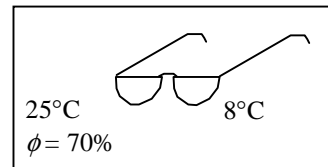*Assumptions* The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v of the air in the house is uniform throughout, and its value can be determined from

$$P_v = \phi P_{g\,@\,25°C} = (0.40)(3.169\,\text{kPa}) = 1.268\,\text{kPa}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{\text{sat}\,@\,P_v} = T_{\text{sat}\,@\,1.268\,\text{kPa}} = \mathbf{10.2°C}$$

That is, the moisture in the house air will start condensing when the air temperature drops below 10.2°C. Since the glasses are at a lower temperature than the dew-point temperature, some moisture will condense on the glasses, and thus they **will get fogged**.

25°C   8°C
$\phi = 40\%$

9-80 A person wearing glasses enters a warm room at a specified temperature and relative humidity from the cold outdoors. It is to be determined whether the glasses will get fogged.

Assumptions The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v of the air in the house is uniform throughout, and its value can be determined from

$$P_v = \phi P_{g\,@\,25°C} = (0.70)(3.169\,\text{kPa}) = 2.22\,\text{kPa}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{\text{sat}\,@\,P_v} = T_{\text{sat}\,@\,2.22\,\text{kPa}} = \mathbf{19.1°C}$$

25°C   8°C
$\phi = 70\%$

That is, the moisture in the house air will start condensing when the air temperature drops below 19.1°C. Since the glasses are at a lower temperature than the dew-point temperature, some moisture will condense on the glasses, and thus they **will get fogged**.

9-81E A woman drinks a cool canned soda in a room at a specified temperature and relative humidity. It is to be determined whether the can will sweat.

*Assumptions* The air and the water vapor are ideal gases.

Analysis The vapor pressure P_v of the air in the house is uniform throughout, and its value can be determined from

$$P_v = \phi P_{g\,@\,80°F} = (0.50)(0.5073\,\text{psia}) = 0.254\,\text{psia}$$

The dew-point temperature of the air in the house is

$$T_{dp} = T_{\text{sat}\,@\,P_v} = T_{\text{sat}\,@\,0.254\,\text{psia}} = \mathbf{59.7°F}$$

80°F
50% RH

Cola
40°F

That is, the moisture in the house air will start condensing when the air temperature drops below 59.7°C. Since the canned drink is at a lower temperature than the dew-point temperature, some moisture will condense on the can, and thus it **will sweat.**
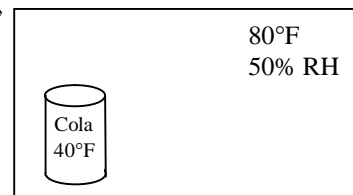
9-82 The dry- and wet-bulb temperatures of atmospheric air at a specified pressure are given. The specific humidity, the relative humidity, and the enthalpy of air are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The specific humidity ω_1 is determined from

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

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

$$\omega_2 = \frac{0.622\, P_{g2}}{P_2 - P_{g2}} = \frac{(0.622)(2.339\ \text{kPa})}{(95 - 2.339)\ \text{kPa}} = 0.0157\ \text{kg H}_2\text{O / kg dry air}$$

Thus,

$$\omega_1 = \frac{(1.005\ \text{kJ / kg·°C})(20 - 25)°\text{C} + (0.0157)(2454.1\ \text{kJ / kg})}{(2547.2 - 83.96)\ \text{kJ / kg}} = \mathbf{0.0136\ \text{kg H}_2\text{O / kg dry air}}$$

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

$$\phi_1 = \frac{\omega_1 P_1}{(0.622 + \omega_1) P_{g1}} = \frac{(0.0136)(95\ \text{kPa})}{(0.622 + 0.0136)(3.169\ \text{kPa})} = 0.641 \quad \text{or} \quad \mathbf{64.1\%}$$

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

$$h_1 = h_{a1} + \omega_1 h_{v1} \cong C_p T_1 + \omega_1 h_{g1} = (1.005\ \text{kJ / kg·°C})(25°\text{C}) + (0.0136)(2547.2\ \text{kJ / kg})$$

$$= \mathbf{59.8\ \text{kJ / kg dry air}}$$

> 95 kPa
> 25°C
> $T_{wb} = 20$°C

9-83 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*) The specific humidity ω_1 is determined from

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

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

$$\omega_2 = \frac{0.622\, P_{g2}}{P_2 - P_{g2}} = \frac{(0.622)(1.83\ \text{kPa})}{(100 - 1.83)\ \text{kPa}} = 0.0116\ \text{kg}\ H_2O\,/\,\text{kg dry air}$$

Thus,

$$\omega_1 = \frac{(1.005\ \text{kJ}\,/\,\text{kg·°C})(16 - 22)°\text{C} + (0.0116)(2463.5\ \text{kJ}\,/\,\text{kg})}{(2541.7 - 67.18)\ \text{kJ}\,/\,\text{kg}}$$

$$= \mathbf{0.0091\ kg\ H_2O\,/\,kg\ dry\ air}$$

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

$$\phi_1 = \frac{\omega_1 P_1}{(0.622 + \omega_1)P_{g1}} = \frac{(0.0091)(100\ \text{kPa})}{(0.622 + 0.0091)(2.67\ \text{kPa})} = 0.540 \quad \text{or} \quad \mathbf{54.0\%}$$

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

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 22°C}} = (0.540)(2.67\ \text{kPa}) = 1.442\ \text{kPa}$$

Thus the dew-point temperature of the air is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ 1.442 kPa}} = \mathbf{12.3°C}$$

100 kPa
22°C
$T_{wb} = 16°C$

9-84 Problem 9-83 is reconsidered. The required properties are to be determined using EES (or other) software. The property values are also to be determined at a pressure of 300 kPa.

Tdb=22"[C]"
Twb=16"[C]"
P1=100"[kPa]"
P2=300"[kPa]"
    h1=enthalpy(AirH2O,T=Tdb,P=P1,B=Twb)
       v1=volume(AirH2O,T=Tdb,P=P1,B=Twb)
       Tdp1=dewpoint(AirH2O,T=Tdb,P=P1,B=Twb)
       w1=humrat(AirH2O,T=Tdb,P=P1,B=Twb)
       Rh1=relhum(AirH2O,T=Tdb,P=P1,B=Twb)

h2=enthalpy(AirH2O,T=Tdb,P=P2,B=Twb)
       v2=volume(AirH2O,T=Tdb,P=P2,B=Twb)
       Tdp2=dewpoint(AirH2O,T=Tdb,P=P2,B=Twb)
       w2=humrat(AirH2O,T=Tdb,P=P2,B=Twb)
       Rh2=relhum(AirH2O,T=Tdb,P=P2,B=Twb)

SOLUTION
Variables in Main
h1=45.09 [kJ/kga]
h2=25.54 [kJ/kga]
P1=100 [kPa]
P2=300 [kPa]
Rh1=0.541
Rh2=0.243
Tdb=22 [C]
Tdp1=12.3 [C]
Tdp2=0.6964 [C]
Twb=16 [C]
v1=0.8595 [m^3/kga]
v2=0.283 [m^3/kga]
w1=0.009029 [kgv/kga]
w2=0.001336 [kgv/kga]

9-85E 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*) The specific humidity ω_1 is determined from

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

```
┌─────────────────┐
│   14.7 psia     │
│     70°F        │
│  T_wb = 60°F    │
└─────────────────┘
```

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

$$\omega_2 = \frac{0.622\, P_{g2}}{P_2 - P_{g2}} = \frac{(0.622)(0.2563\text{ psia})}{(14.7 - 0.2563)\text{ psia}} = 0.0110 \text{ lbm H}_2\text{O / lbm dry air}$$

Thus,

$$\omega_1 = \frac{(0.24\text{ Btu / lbm·°F})(60 - 70)°\text{F} + (0.0110)(1059.6\text{ Btu / lbm})}{(1092.0 - 28.08)\text{ Btu / lbm}}$$

$$= \mathbf{0.0087 \text{ lbm H}_2\text{O / lbm dry air}}$$

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

$$\phi_1 = \frac{\omega_1 P_1}{(0.622 + \omega_1)\, P_{g1}} = \frac{(0.0087)(14.7\text{ psia})}{(0.622 + 0.0087)(0.3632\text{ psia})} = 0.558 \quad \text{or} \quad \mathbf{55.8\%}$$

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

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 70°F}} = (0.558)(0.3632\text{ psia}) = 0.2027 \text{ psia}$$

Thus the dew-point temperature of the air is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ 0.2027 psia}} = \mathbf{53.2°F}$$

Psychometric Chart

9-86C They are very nearly parallel to each other.

9-87C The saturation states (located on the saturation curve).

9-88C By drawing a horizontal line until it intersects with the saturation curve. The corresponding temperature is the dew-point temperature.

9-89C No, they cannot. The enthalpy of moist air depends on ω, which depends on the total pressure.

9-90 [*Also solved by EES on enclosed CD***]** The pressure, temperature, and relative humidity of air in a room are specified. Using the psychrometric chart, the specific humidity, the enthalpy, the wet-bulb temperature, the dew-point temperature, and the specific volume of the air are to be determined.

Analysis From the psychometric chart we read

(*a*) $\omega = 0.0181$ kg H_2 / kg dry air

(*b*) $h = 78.4$ kJ / kg dry air

(*c*) $T_{wb} = 25.5°C$

(*d*) $T_{dp} = 23.3°C$

(*e*) $v = 0.890$ m^3 / kg dry air

9-91 Problem 9-90 is reconsidered. The required properties are to be determined using EES (or other) software instead of the psychrometric chart. The property values are also to be determined at a location at 1500 m altitude.

Procedure
Find(Prop1$,Prop2$,Value1,Value2,Pinput$,PorAltitude:P,Z,Tdb,Twb,Tdp,h,v,Rh,w,pl)

"Due to the very general nature of this problem, a large number of 'if-then-else' statements are necessary."

If Pinput$ = 'Atmospheric Pressure, kPa' Then
P = PorAltitude
Z = (1- (P/101.325)^(1/5.256))/0.02256*1000"[m]"
Else
Z=PorAltitude
P=101.325*(1-0.02256*Z/1000)^5.256"[kPa]"
Endif
If Prop1$='Dry-bulb Temperature, C' Then
    Tdb=Value1
    pl=1
    If Prop2$='Dry-bulbTemperature, C' then Call Error('Both properties cannot be Dry-bulb Temperature, Tdb=xxxF2',Tdb)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=2
        h=enthalpy(AirH2O,T=Tdb,P=P,R=Rh)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,R=Rh)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Wet-bulb Temperature, C' then
        Twb=value2
        pl=3
        if Twb>Tdb then Call Error('These values of Dry-bulb Temperature and Wet-bulb Temperature are incompatible, Tdb=xxxF2',Tdb)
        h=enthalpy(AirH2O,T=Tdb,P=P,B=Twb)
        v=volume(AirH2O,T=Tdb,P=P,B=Twb)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,B=Twb)
        w=humrat(AirH2O,T=Tdb,P=P,B=Twb)
        Rh=relhum(AirH2O,T=Tdb,P=P,B=Twb)
    endif
    if Prop2$='Dew Point Temperature, C' then
        Tdp=value2
        pl=4
        if Tdp>Tdb then Call Error('These values of Dry-bulb Temperature and Dew Point Temperature are incompatible, Tdb=xxxF2',Tdb)
        h=enthalpy(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
    if Prop2$='Enthalpy, kJ/kga' then
        h=value2
        pl=5
        Twb=wetbulb(AirH2O,T=Tdb,P=P,H=h)
        w=humrat(AirH2O,T=Tdb,P=P,H=h)

```
        Rh=relhum(AirH2O,T=Tdb,P=P,H=h)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, kgv/kga' then
        w=value2
        pI=6
        h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
        v=volume(AirH2O,T=Tdb,P=P,W=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        Rh=relhum(AirH2O,T=Tdb,P=P,w=w)
    endif
Endif
If Prop1$='Dew Point Temperature, C' Then
    Tdp=Value1
    pI=7
    If Prop2$='Dew Point Temperature, C' then Call Error('Both properties cannot be Dew
Point Temperature, Tdp=xxxF2',Tdp)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pI=8
        h=enthalpy(AirH2O,D=Tdp,P=P,R=Rh)
        Tdb=temperature(AirH2O,h=h,P=P,R=RH)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,B=Twb,P=P,R=Rh)
    endif
    if Prop2$='Wet-bulb Temperature, C' then
        Twb=value2
        pI=9
          if Tdp>Twb then Call Error('These values of Dew Point Temperature and Wet-
bulb Temperature are incompatible, Tdp=xxxF3',Tdp)
        Pw=pressure(steam,T=Twb ,x=1)
        Pv=pressure(steam,T=Tdp ,x=1)
   "Pv=Pw-(P-Pw)*(Tdb-Twb)*1.8/(2800 -1.3*(1.8*Twb+32))  Carrier Equation"
        Tdb=Twb+(Pw-Pv)/(P-Pw)*(2800-1.3*(1.8*Twb+32))/1.8
        h=enthalpy(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
        if Prop2$='Enthalpy, kJ/kga' then
        h=value2
        pI=10
        Tdptest=temperature(AirH2O,h=h,P=P,R=1)
        if Tdp>Tdptest then Call Error('These values of Dew Point Temperature and
Enthalpy are incompatible, Tdp=xxxF3',Tdp)
        Pv = pressure(steam, T=Tdp, x=1)
        w=molarmass(steam)/molarmass(air)*Pv/(P-Pv)
        Tdb=temperature(airH2O,h=h,P=P,w=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, kgv/kga' then
    w=Value2
    pI=11
```

Call Error('The properties cannot be Dew Point Temperature and Humidity Ratio, Tdp=xxxF3',Tdp)
    endif
Endif
If Prop1$='Wet-bulb Temperature, C' Then
    Twb=Value1
    pl=12
    If Prop2$='Wet-bulbTemperature, C' then Call Error('Both properties cannot be Wet-bulb Temperature, Twb=xxxF2',Twb)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=13
        Tdb=temperature(AirH2O,B=Twb,P=P,R=RH)
        h=enthalpy(AirH2O,T=Tdb,P=P,R=Rh)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,B=Twb,P=P,R=Rh)
    endif
    if Prop2$='Dew Point Temperature, C' then
        Tdp=value2
        pl=14
        if Tdp>Twb then Call Error('These values of Wet-bulb Temperature and Dew Point Temperature are incompatible, Twb=xxxF3',Twb)
      Pw=pressure(steam,T=Twb ,x=1)
      Pv=pressure(steam,T=Tdp ,x=1)
  "Pv=Pw-(P-Pw)*(Tdb-Twb)*1.8/(2800 -1.3*(1.8*Twb+32)) Carrier Equation"
        Tdb=Twb+(Pw-Pv)/(P-Pw)*(2800-1.3*(1.8*Twb+32))/1.8
        h=enthalpy(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
    if Prop2$='Enthalpy, kJ/kga' then
    pl=15
    Call Error('The properties cannot be Wet-bulb Temperature and Enthalpy, Twb=xxxF3',Twb)
    endif
    if Prop2$='Humidity Ratio, kgv/kga' then
        w=value2
        pl=16
        Tdb=temperature(AirH2O,B=Twb,P=P,w=w)
        h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
        v=volume(AirH2O,T=Tdb,P=P,W=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        Rh=relhum(AirH2O,T=Tdb,P=P,w=w)
    endif
Endif
If Prop1$='Relative Humidity, 0 to 1' Then
    Rh=Value1
    pl=17
    If Prop2$='Relative Humidity, 0 to 1' then Call Error('Both properties cannot be Relative Humidity, Rh=xxxF2',Rh)
    if Prop2$='Wet-bulb Temperature, C' then
        Twb=value2
        pl=18
        Tdb=temperature(AirH2O,B=Twb,P=P,R=RH)
        h=enthalpy(AirH2O,T=Tdb,P=P,B=Twb)

```
         v=volume(AirH2O,T=Tdb,P=P,B=Twb)
         Tdp=dewpoint(AirH2O,T=Tdb,P=P,B=Twb)
         w=humrat(AirH2O,T=Tdb,P=P,B=Twb)
    endif
    if Prop2$='Dew Point Temperature, C' then
         Tdp=value2
         pl=19
         h=enthalpy(AirH2O,R=Rh,P=P,D=Tdp)
         Tdb=temperature(AirH2O,h=h,P=P,R=Rh)
         v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
         Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
         w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
    if Prop2$='Enthalpy, kJ/kga' then
         h=value2
         pl=20
         Tdb=temperature(AirH2O,h=h,P=P,R=Rh)
         w=humrat(AirH2O,h=h,P=P,R=Rh)
         Twb=wetbulb(AirH2O,T=Tdb,P=P,H=h)
         Tdp=dewpoint(AirH2O,T=Tdb,P=P,w= w)
         v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, kgv/kga' then
         w=value2
         pl=21
         Tdb=temperature(AirH2O,R=Rh,P=P,w=w)
         h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
         v=volume(AirH2O,T=Tdb,P=P,W=w)
         Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
         Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
    endif
Endif
If Prop1$='Enthalpy, kJ/kga' Then
    h=Value1
    pl=22
    If Prop2$='Enthalpy, kJ/kga' then Call Error('Both properties cannot be  Enthalpy,
h=xxxF2',h)
    if Prop2$='Relative Humidity, 0 to 1' then
         Rh=Value2
         pl=23
         Tdb=temperature(AirH2O,h=h, P=P,R=Rh)
         v=volume(AirH2O,T=Tdb,P=P,R=Rh)
         Twb=wetbulb(AirH2O,T=Tdb,P=P,R=Rh)
         Tdp=dewpoint(AirH2O,T=Tdb,P=P,R=Rh)
         w=humrat(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Wet-bulb Temperature, C' then
    pl=24
    Call Error('The properties cannot be Wet-bulb Temperature and Enthalpy, h=xxxF2',h)
    endif
    if Prop2$='Dew Point Temperature, C' then
         Tdp=value2
         pl=25
         Tdptest=temperature(AirH2O,h=h,P=P,R=1)
         if Tdp>Tdptest then Call Error('These values of Dew Point Temperature and
Enthalpy are incompatible h=xxxF2', h)
         Pv = pressure(steam, T=Tdp, x=1)
         w=molarmass(steam)/molarmass(air)*Pv/(P-Pv)
```

```
          Tdb=temperature(airH2O,h=h,P=P,w=w)
          Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
          Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
          v=volume(AirH2O,T=Tdb,P=P,R=Rh)
      endif
      if Prop2$='Humidity Ratio, kgv/kga' then
          w=value2
          pl=26
          wtest=humrat(AirH2O,h=h,P=P,R=1)
          If w>wtest then Call Error('These values of Humidity Ratio and Enthalpy are
incompatible, h=xxxF2', h)
          Tdb=temperature(airH2O,h=h,P=P,w=w)
          Twb=wetbulb(AirH2O,T=Tdb,P=P,w=w)
          Rh=relhum(AirH2O,T=Tdb,P=P,H=h)
          Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
          v=volume(AirH2O,T=Tdb,P=P,R=Rh)
      endif
Endif
If Prop1$='Humidity Ratio, kgv/kga' Then
      w=Value1
      pl=27
      If Prop2$='Humidity Ratio, kgv/kga' then Call Error('Both properties cannot be  Humidity
Ratio, kgv/kga, w=xxxF3',w)
      if Prop2$='Relative Humidity, 0 to 1' then
          Rh=Value2
          pl=28
          Tdb=temperature(AirH2O,R=Rh,P=P,w=w)
          h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
          v=volume(AirH2O,T=Tdb,P=P,W=w)
          Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
          Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
      endif
      if Prop2$='Wet-bulb Temperature, C' then
          Twb=value2
          pl=29
          wtest=humrat(airH2O,B=Twb,P=P,R=1)
      If w>wtest then Call Error('These values of  Wet-bulb Temperature and Humidity Ratio
are incompatible, w=xxxF3',w)
          Tdb=temperature(airH2O,B=Twb,P=P,w=w)
          h=enthalpy(AirH2O,T=Tdb,P=P,w=w)
          v=volume(AirH2O,T=Tdb,P=P,B=Twb)
          Tdp=dewpoint(AirH2O,T=Tdb,P=P,B=Twb)
          Rh=relhum(AirH2O,T=Tdb,P=P,B=Twb)
      endif
      if Prop2$='Dew Point Temperature, C' then
      pl=30
      Call Error('The properties Humidity Ratio and Dew Point Temperature are incompatible,
w=xxxF3',w)
      endif
      if Prop2$='Enthalpy, kJ/kga' then
          h=value2
          pl=31
          wtest=humrat(AirH2O,h=h,P=P,R=1)
          If w>wtest then Call Error('These values of Humidity Ratio and Enthalpy are
incompatible, w=xxxF3',w)
          Tdb=temperature(airH2O,h=h,P=P,w=w)
          Twb=wetbulb(AirH2O,T=Tdb,P=P,w=w)
          Rh=relhum(AirH2O,T=Tdb,P=P,H=h)
```

```
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
Endif
end
```

"Input from the diagram window"
{P=101.3"kPa"
Prop1$='Dry-bulb Temperature, C'
Prop2$='Relative Humidity, 0 to 1'
Value1=24
Value1=0.5}
"For debuging, the variable pl gives the procedure location."

Call Find(Prop1$,Prop2$,Value1,Value2, Pinput$,PorAltitude:P,Z,Tdb,Twb,Tdp,h,v,Rh,w,pl)
T[1] = Tdb; w[1] =w

SOLUTION
Variables in Main

h=87.85 [kJ/kga]	P=84.554 [kPa]
Pinput$='Altitude Above Sea Level, m'	pl=2 [Procedure Location]
PorAltitude=1500.000	Prop1$='Dry-bulb Temperature, C'
Prop2$='Relative Humidity, 0 to 1'	Rh=0.6
Tdb=32 [C]	Tdp=23.26 [C]
Twb=25.27 [C]	T[1]=32 [C]
v=1.072 [m^3 / kga]	Value1=32
Value2=0.6	w=0.02174 [kgv/kga]
w[1]=0.02174 [kgv/kga]	Z=1500.00 [m]
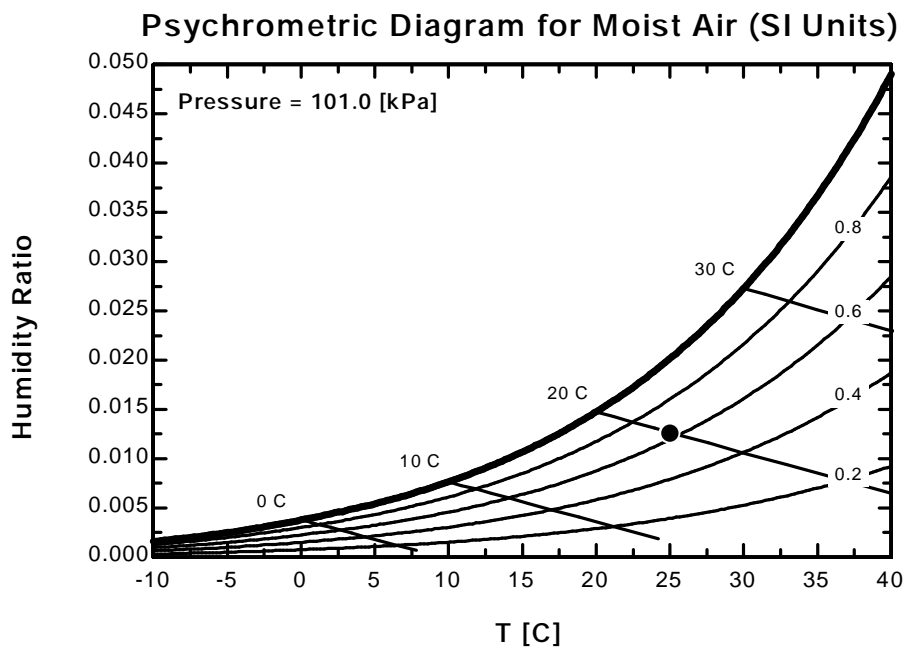
Psychrometric Diagram for Moist Air (SI Units)

9-92 The pressure, temperature, and relative humidity of air in a room are specified. Using the psychrometric chart, the specific humidity, the enthalpy, the wet-bulb temperature, the dew-point temperature, and the specific volume of the air are to be determined.

Analysis From the psychometric chart we read

(*a*) $\omega = 0.0148$ kg H_2 / kg dry air

(*b*) $h = 63.9$ kJ / kg dry air

(*c*) $T_{wb} = 21.9°$C

(*d*) $T_{dp} = 20.1°$C

(*e*) $v = 0.868$ m^3 / kg dry air

9-93 Problem 9-92 is reconsidered. The required properties are to be determined using EES (or other) software instead of the psychrometric chart. Property values are also to be determined at 2000 m altitude.

Tdb=22"[C]"
Twb=16"[C]"
P1=101.325"[kPa]"
Z = 2000"[m]"
P2=101.325*(1-0.02256*Z*convert(m,km))^5.256"[kPa]"   "Relation giving P as function of altitude"
    h1=enthalpy(AirH2O,T=Tdb,P=P1,B=Twb)
      v1=volume(AirH2O,T=Tdb,P=P1,B=Twb)
      Tdp1=dewpoint(AirH2O,T=Tdb,P=P1,B=Twb)
      w1=humrat(AirH2O,T=Tdb,P=P1,B=Twb)
      Rh1=relhum(AirH2O,T=Tdb,P=P1,B=Twb)

h2=enthalpy(AirH2O,T=Tdb,P=P2,B=Twb)
      v2=volume(AirH2O,T=Tdb,P=P2,B=Twb)
      Tdp2=dewpoint(AirH2O,T=Tdb,P=P2,B=Twb)
      w2=humrat(AirH2O,T=Tdb,P=P2,B=Twb)
      Rh2=relhum(AirH2O,T=Tdb,P=P2,B=Twb)

SOLUTION
Variables in Main
h1=44.7 [kJ/kga]
h2=52.78 [kJ/kga]
P1=101.3 [kPa]
P2=79.49 [kPa]
Rh1=0.539
Rh2=0.5715
Tdb=22 [C]
Tdp1=12.25 [C]
Tdp2=13.14 [C]
Twb=16 [C]
v1=0.848 [m^3/kga]
v2=1.086 [m^3/kga]
w1=0.008877 [kgv/kga]
w2=0.01206 [kgv/kga]
Z=2000 [m]

9-94E The pressure, temperature, and relative humidity of air in a room are specified. Using the psychrometric chart, the specific humidity, the enthalpy, the wet-bulb temperature, the dew-point temperature, and the specific volume of the air are to be determined.

Analysis From the psychometric chart we read

(*a*) $\omega = 0.0165$ lbm H_2O / lbm dry air

(*b*) $h = 37.8$ Btu / lbm dry air

(*c*) $T_{wb} = 74.3°$ F

(*d*) $T_{dp} = 71.3°$ F

(*e*) $v = 14.0$ ft^3 / lbm dry air

9-95 Problem 9-94 is reconsidered. The required properties are to be determined using EES (or other) software instead of the psychrometric chart. The property values are also to be determined at a location at 5000 ft altitude.

This problem is an exercise in determining the properties of atmospheric air given the atmospheric pressure and any other two compatible independent intensive properties from the following list: relative humidity, dry-bulb temperature, wet-bulb temperature, specific humidity (humidity ratio), and dew point temperature."

"After specifying the atmospheric pressure on the diagram window, we select two independent intensive properties, and EES determines the other properties."

Procedure
Find(Prop1$,Prop2$,Value1,Value2,Pinput$,PorAltitude:P,Z,Tdb,Twb,Tdp,h,v,Rh,w,pl)

"Due to the very general nature of this problem, a large number of 'if-then-else' statements are necessary."

```
If Pinput$ = 'Atmospheric Pressure, psia' Then
P = PorAltitude
Peq=P*convert(psia,kPa)
Z = (1- (Peq/101.325)^(1/5.256))/0.02256*1000*convert(m,ft)+0.1
Else
Z=PorAltitude
Zeq=Z*convert(ft,m)
P=101.325*(1-0.02256*Zeq/1000)^5.256*convert(kPa,psia)"[psia]"
Endif
If Prop1$='Dry-bulb Temperature, F' Then
    Tdb=Value1
    pl=1
    If Prop2$='Dry-bulbTemperature, F' then Call Error('Both properties cannot be Dry-bulb
Temperature, Tdb=xxxF2',Tdb)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=2
        h=enthalpy(AirH2O,T=Tdb,P=P,R=Rh)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,R=Rh)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Wet-bulb Temperature, F' then
        Twb=value2
        pl=3
        if Twb>Tdb then Call Error('These values of Dry-bulb Temperature and Wet-bulb
Temperature are incompatible, Tdb=xxxF2',Tdb)
        h=enthalpy(AirH2O,T=Tdb,P=P,B=Twb)
        v=volume(AirH2O,T=Tdb,P=P,B=Twb)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,B=Twb)
        w=humrat(AirH2O,T=Tdb,P=P,B=Twb)
        Rh=relhum(AirH2O,T=Tdb,P=P,B=Twb)
    endif
    if Prop2$='Dew Point Temperature, F' then
        Tdp=value2
        pl=4
        if Tdp>Tdb then Call Error('These values of Dry-bulb Temperature and Dew Point
Temperature are incompatible, Tdb=xxxF2',Tdb)
        h=enthalpy(AirH2O,T=Tdb,P=P,D=Tdp)
```

```
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
    if Prop2$='Enthalpy, Btu/lbma' then
        h=value2
        pl=5
        Twb=wetbulb(AirH2O,T=Tdb,P=P,H=h)
        w=humrat(AirH2O,T=Tdb,P=P,H=h)
        Rh=relhum(AirH2O,T=Tdb,P=P,H=h)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, lbmv/lbma' then
        w=value2
        pl=6
        h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
        v=volume(AirH2O,T=Tdb,P=P,W=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        Rh=relhum(AirH2O,T=Tdb,P=P,w=w)
    endif
Endif
If Prop1$='Dew Point Temperature, F' Then
    Tdp=Value1
    pl=7
    If Prop2$='Dew Point Temperature, F' then Call Error('Both properties cannot be Dew
Point Temperature, Tdp=xxxF2',Tdp)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=8
        h=enthalpy(AirH2O,D=Tdp,P=P,R=Rh)
        Tdb=temperature(AirH2O,h=h,P=P,R=RH)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,B=Twb,P=P,R=Rh)
    endif
    if Prop2$='Wet-bulb Temperature, F' then
        Twb=value2
        pl=9
          if Tdp>Twb then Call Error('These values of Dew Point Temperature and Wet-
bulb Temperature are incompatible, Tdp=xxxF3',Tdp)
        Pw=pressure(steam,T=Twb ,x=1)
        Pv=pressure(steam,T=Tdp ,x=1)
     "Pv=Pw-(P-Pw)*(Tdb-Twb)/(2800 -1.3*Twb)  Carrier Equation"
        Tdb=Twb+(Pw-Pv)/(P-Pw)*(2800-1.3*Twb)
        h=enthalpy(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
        if Prop2$='Enthalpy, Btu/lbma' then
        h=value2
        pl=10
        Tdptest=temperature(AirH2O,h=h,P=P,R=1)
        if Tdp>Tdptest then Call Error('These values of Dew Point Temperature and
Enthalpy are incompatible, Tdp=xxxF3',Tdp)
```

```
        Pv = pressure(steam, T=Tdp, x=1)
        w=molarmass(steam)/molarmass(air)*Pv/(P-Pv)
        Tdb=temperature(airH2O,h=h,P=P,w=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, lbmv/lbma' then
    w=Value2
    pl=11
    Call Error('The properties cannot be Dew Point Temperature and Humidity Ratio,
Tdp=xxxF3',Tdp)
    endif
Endif
If Prop1$='Wet-bulb Temperature, F' Then
    Twb=Value1
    pl=12
    If Prop2$='Wet-bulbTemperature, F' then Call Error('Both properties cannot be Wet-
bulb Temperature, Twb=xxxF2',Twb)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=13
        Tdb=temperature(AirH2O,B=Twb,P=P,R=RH)
        h=enthalpy(AirH2O,T=Tdb,P=P,R=Rh)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,B=Twb,P=P,R=Rh)
    endif
    if Prop2$='Dew Point Temperature, F' then
        Tdp=value2
        pl=14
            if Tdp>Twb then Call Error('These values of Wet-bulb Temperature and Dew
Point Temperature are incompatible, Twb=xxxF3',Twb)
        Pw=pressure(steam,T=Twb ,x=1)
        Pv=pressure(steam,T=Tdp ,x=1)
    "Pv=Pw-(P-Pw)*(Tdb-Twb)*1.8/(2800 -1.3*Twb)  Carrier Equation"
        Tdb=Twb+(Pw-Pv)/(P-Pw)*(2800-1.3*Twb)
        h=enthalpy(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
    if Prop2$='Enthalpy, Btu/lbma' then
    pl=15
    Call Error('The properties cannot be Wet-bulb Temperature and Enthalpy,
Twb=xxxF3',Twb)
    endif
    if Prop2$='Humidity Ratio, lbmv/lbma' then
        w=value2
        pl=16
        Tdb=temperature(AirH2O,B=Twb,P=P,w=w)
        h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
        v=volume(AirH2O,T=Tdb,P=P,W=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        Rh=relhum(AirH2O,T=Tdb,P=P,w=w)
    endif
Endif
```

```
If Prop1$='Relative Humidity, 0 to 1' Then
    Rh=Value1
    pl=17
    If Prop2$='Relative Humidity, 0 to 1' then Call Error('Both properties cannot be Relative
Humidity, Rh=xxxF2',Rh)
    if Prop2$='Wet-bulb Temperature, F' then
        Twb=value2
        pl=18
        Tdb=temperature(AirH2O,B=Twb,P=P,R=RH)
        h=enthalpy(AirH2O,T=Tdb,P=P,B=Twb)
        v=volume(AirH2O,T=Tdb,P=P,B=Twb)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,B=Twb)
        w=humrat(AirH2O,T=Tdb,P=P,B=Twb)
    endif
    if Prop2$='Dew Point Temperature, F' then
        Tdp=value2
        pl=19
        h=enthalpy(AirH2O,R=Rh,P=P,D=Tdp)
        Tdb=temperature(AirH2O,h=h,P=P,R=Rh)
        v=volume(AirH2O,T=Tdb,P=P,D=Tdp)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
        w=humrat(AirH2O,T=Tdb,P=P,D=Tdp)
    endif
    if Prop2$='Enthalpy, Btu/lbma' then
        h=value2
        pl=20
        Tdb=temperature(AirH2O,h=h,P=P,R=Rh)
        w=humrat(AirH2O,h=h,P=P,R=Rh)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,H=h)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w= w)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, lbmv/lbma' then
        w=value2
        pl=21
        Tdb=temperature(AirH2O,R=Rh,P=P,w=w)
        h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
        v=volume(AirH2O,T=Tdb,P=P,W=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
    endif
Endif
If Prop1$='Enthalpy, Btu/lbma' Then
    h=Value1
    pl=22
    If Prop2$='Enthalpy, Btu/lbma' then Call Error('Both properties cannot be  Enthalpy,
h=xxxF2',h)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=23
        Tdb=temperature(AirH2O,h=h, P=P,R=Rh)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,R=Rh)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,R=Rh)
        w=humrat(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Wet-bulb Temperature, F' then
    pl=24
```

```
        Call Error('The properties cannot be Wet-bulb Temperature and Enthalpy, h=xxxF2',h)
    endif
    if Prop2$='Dew Point Temperature, F' then
        Tdp=value2
        pl=25
        Tdptest=temperature(AirH2O,h=h,P=P,R=1)
        if Tdp>Tdptest then Call Error('These values of Dew Point Temperature and
Enthalpy are incompatible h=xxxF2', h)
        Pv = pressure(steam, T=Tdp, x=1)
        w=molarmass(steam)/molarmass(air)*Pv/(P-Pv)
        Tdb=temperature(airH2O,h=h,P=P,w=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,D=Tdp)
        Rh=relhum(AirH2O,T=Tdb,P=P,D=Tdp)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
    if Prop2$='Humidity Ratio, lbmv/lbma' then
        w=value2
        pl=26
        wtest=humrat(AirH2O,h=h,P=P,R=1)
        If w>wtest then Call Error('These values of Humidity Ratio and Enthalpy are
incompatible, h=xxxF2', h)
        Tdb=temperature(airH2O,h=h,P=P,w=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,w=w)
        Rh=relhum(AirH2O,T=Tdb,P=P,H=h)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
        v=volume(AirH2O,T=Tdb,P=P,R=Rh)
    endif
Endif
If Prop1$='Humidity Ratio, lbmv/lbma' Then
    w=Value1
    pl=27
    If Prop2$='Humidity Ratio, lbmv/lbma' then Call Error('Both properties cannot be
Humidity Ratio, lbmv/lbma, w=xxxF3',w)
    if Prop2$='Relative Humidity, 0 to 1' then
        Rh=Value2
        pl=28
        Tdb=temperature(AirH2O,R=Rh,P=P,w=w)
        h=enthalpy(AirH2O,T=Tdb,P=P,W=w)
        v=volume(AirH2O,T=Tdb,P=P,W=w)
        Twb=wetbulb(AirH2O,T=Tdb,P=P,W=w)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
    endif
    if Prop2$='Wet-bulb Temperature, F' then
        Twb=value2
        pl=29
        wtest=humrat(airH2O,B=Twb,P=P,R=1)
If w>wtest then Call Error('These values of  Wet-bulb Temperature and Humidity Ratio are
incompatible, w=xxxF3',w)
        Tdb=temperature(airH2O,B=Twb,P=P,w=w)
        h=enthalpy(AirH2O,T=Tdb,P=P,w=w)
        v=volume(AirH2O,T=Tdb,P=P,B=Twb)
        Tdp=dewpoint(AirH2O,T=Tdb,P=P,B=Twb)
        Rh=relhum(AirH2O,T=Tdb,P=P,B=Twb)
    endif
    if Prop2$='Dew Point Temperature, F' then
    pl=30
    Call Error('The properties Humidity Ratio and Dew Point Temperature are incompatible,
w=xxxF3',w)
```

```
        endif
        if Prop2$='Enthalpy, Btu/lbma' then
            h=value2
            pl=31
            wtest=humrat(AirH2O,h=h,P=P,R=1)
            If w>wtest then Call Error('These values of Humidity Ratio and Enthalpy are
incompatible, w=xxxF3',w)
            Tdb=temperature(airH2O,h=h,P=P,w=w)
            Twb=wetbulb(AirH2O,T=Tdb,P=P,w=w)
            Rh=relhum(AirH2O,T=Tdb,P=P,H=h)
            Tdp=dewpoint(AirH2O,T=Tdb,P=P,w=w)
            v=volume(AirH2O,T=Tdb,P=P,R=Rh)
        endif
Endif
end

"Input from the diagram window"
{P=101.3"psia"
Prop1$='Dry-bulb Temperature, F'
Prop2$='Relative Humidity, 0 to 1'
Value1=24
Value1=0.5}
"For debuging, the variable pl gives the procedure location."
Call Find(Prop1$,Prop2$,Value1,Value2, Pinput$,PorAltitude:P,Z,Tdb,Twb,Tdp,h,v,Rh,w,pl)
T[1] = Tdb; w[1] =w
```

SOLUTION
Variables in Main
h=41.54 [Btu/lbma]
P=12.227 [psia]
Pinput$='Altitude Above Sea Level, ft'
pl=2 [Procedure Location]
PorAltitude=5000.000
Prop1$='Dry-bulb Temperature, F'
Prop2$='Relative Humidity, 0 to 1'
Rh=0.7
Tdb=82 [F]
Tdp=71.25 [F]
Twb=73.89 [F]
T[1]=82 [F]
v=16.94 [ft^3 / lbma]
Value1=82
Value2=0.7
w=0.0199 [lbmv/lbma]
w[1]=0.0199 [lbmv/lbma]
Z=5000.00 [ft]

AirH2O
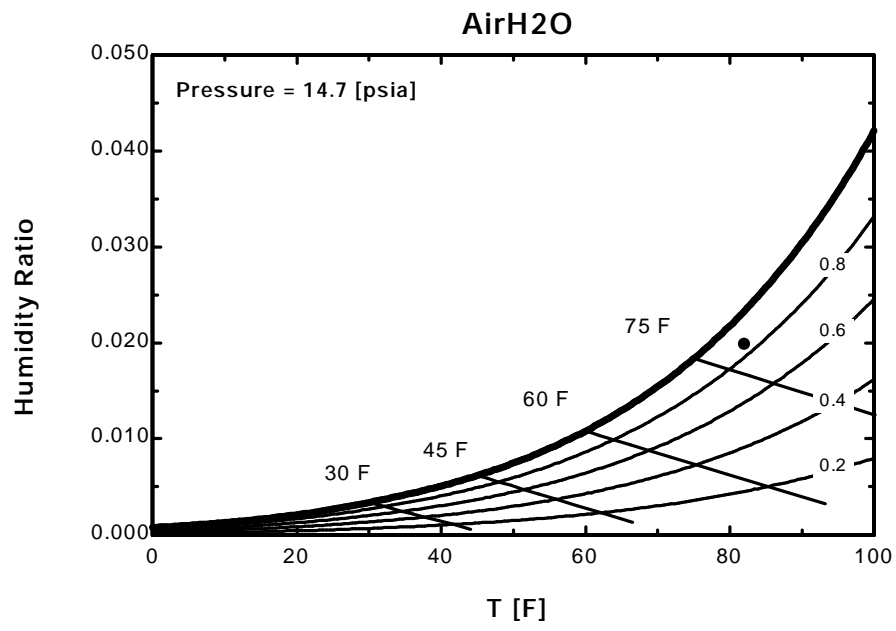
9-96 The pressure and the dry- and wet-bulb temperatures of air in a room are specified. Using the psychrometric chart, the specific humidity, the enthalpy, the relative humidity, the dew-point temperature, and the specific volume of the air are to be determined.

Analysis From the psychometric chart we read

        (*a*) $\omega = 0.0092$ kg H_2 / kg dry air

        (*b*) $h = 47.6$ kJ / kg dry air

        (*c*) $\phi = 49.6\%$

        (*d*) $T_{dp} = 12.8°\text{C}$

        (*e*) $v = 0.855$ m^3 / kg dry air

9-97 Problem 9-96 is reconsidered. The required properties are to be determined using EES (or other) software instead of the psychrometric chart. The property values are also to be determined at a location at 5000 m altitude.

"Prob. 13-44 The air in a room has a pressure of 1 atm, a dry-bulb temperature of 24°C, and a wet-bulb temperature of 17°C. Using the psychrometric chart, determine (a) the specific humidity, (b) the enthalpy (in kJ/kg dry air), (c) the relative humidity, (d) the dew-point temperature, and (e) the specific volume of the air (in m3/kg dry air)."

"See the solution to Problem 13-39 for a more general solution."

Tdb=24"[C]"
Twb=17"[C]"
P1=101.325"[kPa]"
Z = 5000"[m]"
P2=101.325*(1-0.02256*Z*convert(m,km))^5.256"[kPa]" "Relation giving P as function of altitude"
    h1=enthalpy(AirH2O,T=Tdb,P=P1,B=Twb)
        v1=volume(AirH2O,T=Tdb,P=P1,B=Twb)
        Tdp1=dewpoint(AirH2O,T=Tdb,P=P1,B=Twb)
        w1=humrat(AirH2O,T=Tdb,P=P1,B=Twb)
        Rh1=relhum(AirH2O,T=Tdb,P=P1,B=Twb)

h2=enthalpy(AirH2O,T=Tdb,P=P2,B=Twb)
        v2=volume(AirH2O,T=Tdb,P=P2,B=Twb)
        Tdp2=dewpoint(AirH2O,T=Tdb,P=P2,B=Twb)
        w2=humrat(AirH2O,T=Tdb,P=P2,B=Twb)
        Rh2=relhum(AirH2O,T=Tdb,P=P2,B=Twb)

SOLUTION
Variables in Main
h1=47.61 [kJ/kga]
h2=75.51 [kJ/kga]
P1=101.3 [kPa]
P2=54.02 [kPa]
Rh1=0.4956
Rh2=0.5686
Tdb=24 [C]
Tdp1=12.81 [C]
Tdp2=14.93 [C]
Twb=17 [C]
v1=0.8542 [m^3/kga]
v2=1.63 [m^3/kga]
w1=0.009219 [kgv/kga]
w2=0.02018 [kgv/kga]
Z=5000 [m]

Human Comfort and Air-Conditioning

9-98C It humidifies, dehumidifies, cleans and even deodorizes the air.

9-99C (*a*) Perspires more, (*b*) cuts the blood circulation near the skin, and (*c*) sweats excessively.

9-100C It is the direct heat exchange between the body and the surrounding surfaces. It can make a person feel chilly in winter, and hot in summer.

9-101C It affects by removing the warm, moist air that builds up around the body and replacing it with fresh air.

9-102C The spectators. Because they have a lower level of activity, and thus a lower level of heat generation within their bodies.

9-103C Because they have a large skin area to volume ratio. That is, they have a smaller volume to generate heat but a larger area to lose it from.

9-104C It affects a body's ability to perspire, and thus the amount of heat a body can dissipate through evaporation.

9-105C Humidification is to add moisture into an environment, dehumidification is to remove it.

9-106C The metabolism refers to the burning of foods such as carbohydrates, fat, and protein in order to perform the necessary bodily functions. The metabolic rate for an average man ranges from 108 W while reading, writing, typing, or listening to a lecture in a classroom in a seated position to 1250 W at age 20 (730 at age 70) during strenuous exercise. The corresponding rates for women are about 30 percent lower. Maximum metabolic rates of trained athletes can exceed 2000 W. We are interested in metabolic rate of the occupants of a building when we deal with heating and air conditioning because the metabolic rate represents the rate at which a body generates heat and dissipates it to the room. This body heat contributes to the heating in winter, but it adds to the cooling load of the building in summer.

9-107C The metabolic rate is proportional to the size of the body, and the metabolic rate of women, in general, is lower than that of men because of their smaller size. Clothing serves as insulation, and the thicker the clothing, the lower the environmental temperature that feels comfortable.

9-108C Sensible heat is the energy associated with a temperature change. The sensible heat loss from a human body increases as (*a*) the skin temperature increases, (*b*) the environment temperature decreases, and (*c*) the air motion (and thus the convection heat transfer coefficient) increases.

9-109C Latent heat is the energy released as water vapor condenses on cold surfaces, or the energy absorbed from a warm surface as liquid water evaporates. The latent heat loss from a human body increases as (*a*) the skin wetness increases and (*b*) the relative humidity of the environment decreases. The rate of evaporation from the body is related to the rate of latent heat loss by $\dot{Q}_{latent} = \dot{m}_{vapor} h_{fg}$ where h_{fg} is the latent heat of vaporization of water at the skin temperature.

9-110 An average person produces 0.25 kg of moisture while taking a shower. The contribution of showers of a family of four to the latent heat load of the air-conditioner per day is to be determined.

Assumptions All the water vapor from the shower is condensed by the air-conditioning system.

Properties The latent heat of vaporization of water is given to be 2450 kJ/kg.

Analysis The amount of moisture produced per day is

$$\dot{m}_{vapor} = (\text{Moisture produced per person})(\text{No. of persons})$$
$$= (0.25 \text{ kg / person})(4 \text{ persons / day}) = 1 \text{ kg / day}$$

Then the latent heat load due to showers becomes

$$\dot{Q}_{latent} = \dot{m}_{vapor} h_{fg} = (1 \text{ kg / day})(2450 \text{ kJ / kg}) = \textbf{2450 kJ / day}$$

9-111 There are 100 chickens in a breeding room. The rate of total heat generation and the rate of moisture production in the room are to be determined.

Assumptions All the moisture from the chickens is condensed by the air-conditioning system.

Properties The latent heat of vaporization of water is given to be 2430 kJ/kg. The average metabolic rate of chicken during normal activity is 10.2 W (3.78 W sensible and 6.42 W latent).

Analysis The total rate of heat generation of the chickens in the breeding room is

$$\dot{Q}_{gen, total} = \dot{q}_{gen, total}(\text{No. of chickens}) = (10.2 \text{ W / chicken})(100 \text{ chickens}) = \textbf{1020 W}$$

The latent heat generated by the chicken and the rate of moisture production are

$$\dot{Q}_{gen, latent} = \dot{q}_{gen, latent}(\text{No. of chickens})$$
$$= (6.42 \text{ W/chicken})(100 \text{ chickens}) = 642 \text{ W}$$
$$= 0.642 \text{ kW}$$

$$\dot{m}_{moisture} = \frac{\dot{Q}_{gen, latent}}{h_{fg}} = \frac{0.642 \text{ kJ / s}}{2430 \text{ kJ / kg}} = 0.000264 \text{ kg / s} = \textbf{0.264 g / s}$$

9-112 A department store expects to have a specified number of people at peak times in summer. The contribution of people to the sensible, latent, and total cooling load of the store is to be determined.

Assumptions There is a mix of men, women, and children in the classroom.

Properties The average rate of heat generation from people doing light work is 115 W, and 70% of is in sensible form (see Sec. 9-6).

Analysis The contribution of people to the sensible, latent, and total cooling load of the store are

$$\dot{Q}_{people,\,total} = (No.\,of\ people) \times \dot{Q}_{person,\,total} = 135 \times (115\,W) = \mathbf{15,525\,W}$$

$$\dot{Q}_{people,\,sensible} = (No.\,of\ people) \times \dot{Q}_{person,\,sensible} = 135 \times (0.7 \times 115\,W) = \mathbf{10,868\,W}$$

$$\dot{Q}_{people,\,latent} = (No.\,of\ people) \times \dot{Q}_{person,\,latent} = 135 \times (0.3 \times 115\,W) = \mathbf{4658\,W}$$

9-113E There are a specified number of people in a movie theater in winter. It is to be determined if the theater needs to be heated or cooled.

Assumptions There is a mix of men, women, and children in the classroom.

Properties The average rate of heat generation from people in a movie theater is 105 W, and 70 W of it is in sensible form and 35 W in latent form (Table 12-8).

Analysis Noting that only the sensible heat from a person contributes to the heating load of a building, the contribution of people to the heating of the building is

$$\dot{Q}_{people,\,sensible} = (No.\,of\ people) \times \dot{Q}_{person,\,sensible} = 500 \times (70\,W) = 35,000\,W = \mathbf{119,420\,Btu/h}$$

since 1 W = 3.412 Btu/h. The building needs to be heated since the heat gain from people is less than the rate of heat loss of 120,000 Btu/h from the building.

9-114 The infiltration rate of a building is estimated to be 1.2 ACH. The sensible, latent, and total infiltration heat loads of the building at sea level are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air infiltrates at the outdoor conditions, and exfiltrates at the indoor conditions. **3** Excess moisture condenses at 5°C. **4** The effect of water vapor on air density is negligible.

Properties The gas constant and the specific heat of air are $R = 0.287$ kPa.m^3/kg.K and $C_p = 1.0$ kJ/kg·°C (Tables A-1 and A-3). The heat of vaporization of water at 5°C is $h_{fg} = h_{fg\,@5°C} = 2490$ kJ/kg (Table A-4).

The properties of the ambient and room air are determined from the psychrometric chart (Fig. A-33) to be

$$\left.\begin{array}{l} T_{ambient} = 32° \text{C} \\ \phi_{ambient} = 50\% \end{array}\right\} \; w_{ambient} = 0.0150 \text{ kg/kg dry air}$$

$$\left.\begin{array}{l} T_{room} = 24° \text{C} \\ \phi_{room} = 50\% \end{array}\right\} \; w_{room} = 0.0093 \text{ kg/kg dry air}$$

Analysis Noting that the infiltration of ambient air will cause the air in the cold storage room to be changed 0.8 times every hour, the air will enter the room at a mass flow rate of

$$\rho_{ambient} = \frac{P_0}{RT_0} = \frac{101.325 \text{ kPa}}{(0.287 \text{ kPa.m}^3/\text{kg.K})(32 + 273 \text{ K})} = 1.16 \text{ kg/m}^3$$

$$\dot{m}_{air} = \rho_{ambient} \, V_{room} \text{ ACH} = (1.16 \text{ kg/m}^3)(20 \times 13 \times 3 \text{ m}^3)(1.2 \text{ h}^{-1}) = 1086 \text{ kg/h} = 0.3016 \text{ kg/s}$$

Then the sensible, latent, and total infiltration heat loads of the room are determined to be

$$\dot{Q}_{infiltration,\,sensible} = \dot{m}_{air} \, C_p (T_{ambient} - T_{room}) = (0.3016 \text{ kg/s})(1.0 \text{ kJ/kg.°C})(32 - 24)°\text{C} = \mathbf{2.41\,kW}$$

$$\dot{Q}_{infiltration,\,latent} = \dot{m}_{air} (w_{ambient} - w_{room}) h_{fg} = (0.3016 \text{ kg/s})(0.0150 - 0.0093)(2490 \text{ kJ/kg}) = \mathbf{4.28\,kW}$$

$$\dot{Q}_{infiltration,\,total} = \dot{Q}_{infiltration,\,sensible} + \dot{Q}_{infiltration,\,latent} = 2.41 + 4.28 = \mathbf{6.69\,kW}$$

Discussion The specific volume of the dry air at the ambient conditions could also be determined from the psychrometric chart at ambient conditions.

9-115 The infiltration rate of a building is estimated to be 1.8 ACH. The sensible, latent, and total infiltration heat loads of the building at sea level are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air infiltrates at the outdoor conditions, and exfiltrates at the indoor conditions. **3** Excess moisture condenses at 5°C. **4** The effect of water vapor on air density is negligible.

Properties The gas constant and the specific heat of air are $R = 0.287$ kPa.m^3/kg.K and $C_p = 1.0$ kJ/kg·°C (Tables A-1 and A-3). The heat of vaporization of water at 5°C is $h_{fg} = h_{fg@5°C} = 2490$ kJ/kg (Table A-4).

The properties of the ambient and room air are determined from the psychrometric chart (Fig. A-33) to be

$$\left.\begin{array}{l} T_{ambient} = 32°C \\ \phi_{ambient} = 50\% \end{array}\right\} w_{ambient} = 0.0150 \text{ kg/kg dryair}$$

$$\left.\begin{array}{l} T_{room} = 24°C \\ \phi_{room} = 50\% \end{array}\right\} w_{room} = 0.0093 \text{ kg/kg dryair}$$

Analysis Noting that the infiltration of ambient air will cause the air in the cold storage room to be changed 1.8 times every hour, the air will enter the room at a mass flow rate of

$$\rho_{ambient} = \frac{P_0}{RT_0} = \frac{101.325 \text{ kPa}}{(0.287 \text{ kPa.m}^3/\text{kg.K})(32+273\text{ K})} = 1.16 \text{ kg/m}^3$$

$$\dot{m}_{air} = \rho_{ambient} V_{room} \text{ACH} = (1.16 \text{ kg/m}^3)(20\times13\times3\text{ m}^3)(1.8\text{ h}^{-1}) = 1629 \text{ kg/h} = 0.4524 \text{ kg/s}$$

Then the sensible, latent, and total infiltration heat loads of the room are determined to be

$$\dot{Q}_{infiltration, sensible} = \dot{m}_{air} C_p (T_{ambient} - T_{room}) = (0.4524 \text{ kg/s})(1.0 \text{ kJ/kg.°C})(32-24)°C = \textbf{3.62 kW}$$

$$\dot{Q}_{infiltration, latent} = \dot{m}_{air}(w_{ambient} - w_{room})h_{fg} = (0.4524 \text{ kg/s})(0.0150-0.0093)(2490 \text{ kJ/kg}) = \textbf{6.42 kW}$$

$$\dot{Q}_{infiltration, total} = \dot{Q}_{infiltration, sensible} + \dot{Q}_{infiltration, latent} = 3.62 + 6.42 = \textbf{10.04 kW}$$

Discussion The specific volume of the dry air at the ambient conditions could also be determined from the psychrometric chart at ambient conditions.

Simple Heating and cooling

9-116C Relative humidity decreases during a simple heating process and increases during a simple cooling process. Specific humidity, on the other hand, remains constant in both cases.

9-117C Because a horizontal line on the psychometric chart represents a ω = constant process, and the moisture content ω of air remains constant during these processes.

9-118 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

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{sat\,@\,15°C} = (0.3)(1.7051\,\text{kPa}) = 0.51\,\text{kPa}$$

$$P_{a1} = P_1 - P_{v1} = 95 - 0.51 = 94.49\,\text{kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(288\,\text{K})}{94.49\,\text{kPa}}$$

$$= 0.875\,\text{m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.51\,\text{kPa})}{(95 - 0.51)\,\text{kPa}} = 0.00336\,\text{kg H}_2\text{O/kg dry air}\;(= \omega_2)$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg}\cdot°\text{C})(15°\text{C}) + (0.00336)(2528.9\,\text{kJ/kg})$$
$$= 23.57\,\text{kJ/kg dry air}$$

and

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (1.005\,\text{kJ/kg}\cdot°\text{C})(25°\text{C}) + (0.00336)(2547.2\,\text{kJ/kg})$$
$$= 33.68\,\text{kJ/kg dry air}$$

Also,

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{4\,\text{m}^3/\text{min}}{0.875\,\text{m}^3/\text{kg dry air}} = 4.571\,\text{kg/min}$$

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

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (4.571\,\text{kg/min})(33.68 - 23.57)\,\text{kJ/kg} = \mathbf{46.2\,kJ/min}$$

(*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

$$\phi_2 = \frac{P_{v2}}{P_{g2}} = \frac{P_{v2}}{P_{sat\,@\,25°C}} = \frac{0.51\,\text{kPa}}{3.169\,\text{kPa}} = 0.161 \quad\text{or}\quad \mathbf{16.1\%}$$

Heating coils

95 kPa
15°C
30% RH
①

AIR   Heat

25°C ②
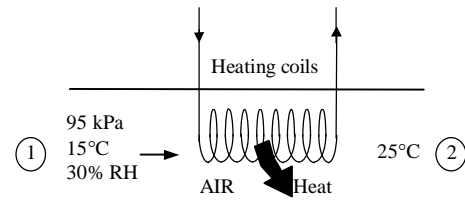
9-119E Air enters a heating section at a specified pressure, temperature, velocity, and relative humidity. The exit temperature of air, the exit relative humidity, and the exit velocity are to be determined.
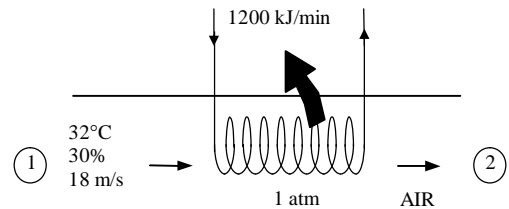
Assumptions **1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process ($\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$). **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

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 psychometric chart (Figure A-33) 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

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

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 ω_2. From the psychometric chart at this state we read

$$T_2 = \textbf{56.8}°\textbf{F}$$

(*b*) $\phi_2 = \textbf{30.8\%}$

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

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

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

Thus,

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

9-120 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.
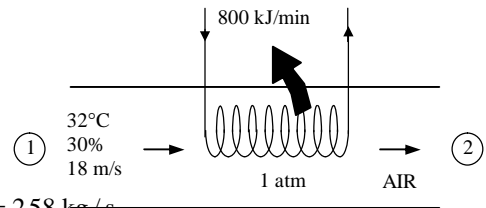
***Assumptions* 1** This is a steady-flow process and thus the mass flow rate of dry air remains constant during the entire process ($\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$). **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible.

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 psychometric chart (Figure A-33) 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,

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

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

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

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

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

9-121 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 psychometric chart (Figure A-33) 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

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

From the energy balance on air in the cooling section,

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

$$-800 / 60 \text{ kJ/s} = (2.58 \text{ kg/s})(h_2 - 55.0) \text{ kJ/kg}$$

$$h_2 = 49.8 \text{ kJ/kg dry air}$$

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

$$T_2 = \mathbf{26.9°C}$$

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

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

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

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

$$V_2 = \frac{v_2}{v_1} V_1 = \frac{0.862}{0.877}(18 \text{ m/s}) = \mathbf{17.7 \, m/s}$$

Heating with Humidification

9-122C To achieve a higher level of comfort. Very dry air can cause dry skin, respiratory difficulties, and increased static electricity.

9-123 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 psychometric chart (Figure A-33) to be

$h_1 = 31.1 \text{ kJ / kg dry air}$

$\omega_1 = 0.0064 \text{ kg H}_2\text{O / kg dry air} \, (= \omega_2)$

$h_2 = 36.2 \text{ kJ / kg dry air}$

$h_3 = 58.1 \text{ kJ / kg dry air}$

$\omega_3 = 0.0129 \text{ kg H}_2\text{O / kg dry air}$
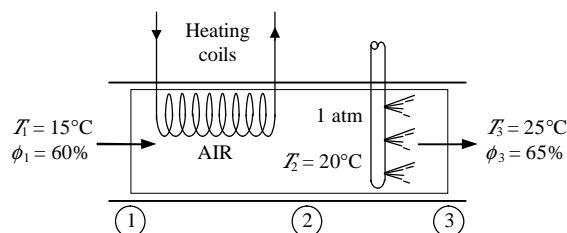
Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The amount of steam added to the air in the heating section is

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

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

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

9-124E 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 psychometric chart (Figure A-33E) to be

$h_1 = 19.2$ Btu / lbm dry air

$\omega_1 = 0.0055$ lbm H_2O / lbm dry air

$h_2 = 23.3$ Btu / lbm dry air

$\omega_2 = \omega_1 = 0.0055$ lbm H_2O / lbm dry air

$h_3 = 31.2$ Btu / lbm dry air

$\omega_3 = 0.0121$ lbm H_2O / lbm dry air
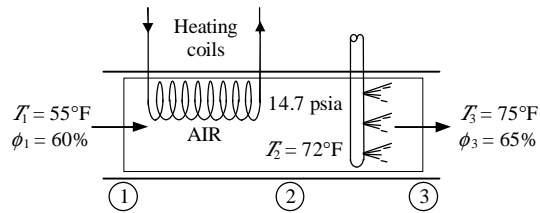
Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The amount of steam added to the air in the heating section is

$$\Delta\omega = \omega_3 - \omega_2 = 0.0121 - 0.0055 = \textbf{0.0066 lbm H}_2\textbf{O / lbm dry air}$$

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

$$q_{in} = h_2 - h_1 = 23.3 - 19.2 = \textbf{4.1 Btu/lbm dry air}$$

9-125 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 psychometric chart (Figure A-33) to be

$h_1 = 23.5$ kJ/kg dry air

$\omega_1 = 0.0053$ kg H_2O/kg dry air $(= \omega_2)$

$v_1 = 0.809$ m^3/kg dry air

$h_3 = 42.3$ kJ / kg dry air

$\omega_3 = 0.0088$ kg H_2O / kg dry air
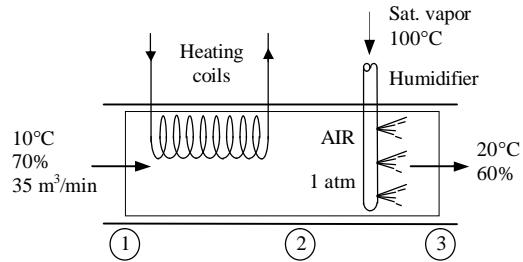
Analysis (*a*) The amount of moisture in the air remains constant it flows through the heating section ($\omega_1 = \omega_2$), but increases in the humidifying section ($\omega_3 > \omega_2$). The mass flow rate of dry air is

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

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

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

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

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e \quad \longrightarrow \quad \dot{m}_w h_w + \dot{m}_{a2} h_2 = \dot{m}_a h_3$$

$$(\omega_3 - \omega_2)h_w + h_2 = h_3$$

Solving for h₂,

$$h_2 = h_3 - (\omega_3 - \omega_2)h_{g@100°C} = 42.3 - (0.0088 - 0.0053)(2676.1) = 32.9 \text{ kJ / kg dry air}$$

Thus at the exit of the heating section we have $\omega = 0.0053$ kg H_2O dry air and $h_2 = 32.9$ kJ/kg dry air, which completely fixes the state. Then from the psychometric chart we read

$T_2 = \mathbf{19.4° C}$

$\phi_2 = \mathbf{37.8\%}$

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

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (43.3 \text{ kg/min})(32.9 - 23.5) \text{ kJ/kg} = \mathbf{407 \, kJ/min}$$

(*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,

$$\dot{m}_w = \dot{m}_a (\omega_3 - \omega_2) = (43.3 \text{ kg/min})(0.0088 - 0.0053) = \mathbf{0.15 \, kg/min}$$

9-126 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

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 10°C}} = (0.70)(1.2276\,\text{kPa}) = 0.859\,\text{kPa}\,(= P_{v2})$$

$$P_{a1} = P_1 - P_{v1} = 95 - 0.859 = 94.141\,\text{kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa} \cdot \text{m}^3\,/\,\text{kg} \cdot \text{K})(283\,\text{K})}{94.141\,\text{kPa}}$$

$$= 0.863\,\text{m}^3\,/\,\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.859\,\text{kPa})}{(95 - 0.859)\,\text{kPa}}$$

$$= 0.00568\,\text{kg H}_2\text{O/kg dry air}\,(= \omega_2)$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg} \cdot °\text{C})(10°\text{C}) + (0.00568)(2519.8\,\text{kJ/kg})$$
$$= 24.36\,\text{kJ/kg dry air}$$

Heating coils — Sat. vapor 100°C — Humidifier — AIR — 10°C 70% 35 m³/min — 20°C 60% — 95 kPa — 1 2 3

$$P_{v3} = \phi_3 P_{g3} = \phi_3 P_{\text{sat @ 20°C}} = (0.60)(2.339\,\text{kPa}) = 1.40\,\text{kPa}$$

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

$$h_3 = C_p T_3 + \omega_3 h_{g3} = (1.005\,\text{kJ/kg} \cdot °\text{C})(20°\text{C}) + (0.0093)(2538.1\,\text{kJ/kg})$$
$$= 43.70\,\text{kJ/kg dry air}$$

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 $\dot{Q} = \dot{W} = 0$, the energy balance on the humidifying section can be expressed as

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

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

$$\sum \dot{m}_e h_e = \sum \dot{m}_i h_i \quad \longrightarrow \quad \dot{m}_w h_w + \dot{m}_{a2} h_2 = \dot{m}_a h_3$$

$$(\omega_3 - \omega_2) h_w + h_2 = h_3$$

Solving for h_2,

$$h_2 = h_3 - (\omega_3 - \omega_2) h_{g@100°C} = 43.7 - (0.0093 - 0.00568) \times 2676.1 = 34.0\,\text{kJ}\,/\,\text{kg dry air}$$
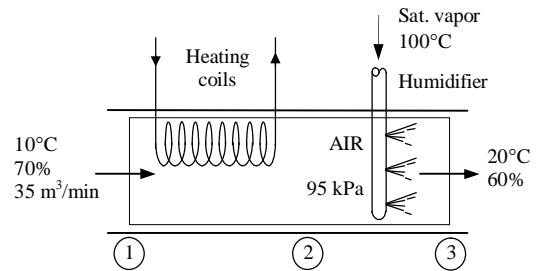
Thus at the exit of the heating section we have $\omega = 0.00568$ kg H$_2$O dry air and $h_2 = 34.0$ kJ/kg dry air, which completely fixes the state. The temperature of air at the exit of the heating section is determined from the definition of enthalpy,

$$h_2 = C_p T_2 + \omega_2 h_{g2} \cong C_p T_2 + \omega_2 (2501.3 + 1.82\, T_2)$$
$$34.0 = (1.005)\, T_2 + (0.00568)(2501.3 + 1.82\, T_2)$$

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

The relative humidity at this state is

$$\phi_2 = \frac{P_{v2}}{P_{g2}} = \frac{P_{v2}}{P_{sat\ @\ 19.5°C}} = \frac{0.859\,\text{kPa}}{2.276\,\text{kPa}} = 0.377 \quad \text{or} \quad \mathbf{37.7\%}$$

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

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

(*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,

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

Cooling with Dehumidification

9-127C To drop its relative humidity to more desirable levels.

9-128 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 psychometric chart (Figure A-33) to be

$$h_1 = 86.4 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0212 \text{ kg } H_2O \text{ / kg dry air}$$
$$v_1 = 0.894 \text{ m}^3 \text{ / kg dry air}$$

and

$$h_2 = 34.1 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0087 \text{ kg } H_2O \text{ / kg dry air}$$

Also,

$$h_w \cong h_{f@12°C} = 50.4 \text{ kJ / kg}$$

Cooling coils

$T_2 = 12°C$
$\phi_2 = 100\%$

1 atm AIR

Condensate

$T_1 = 32°C$
$\phi_1 = 70\%$
$V_1 = 3 \text{ m}^3/\text{min}$

② ①

12°C Condensate removal
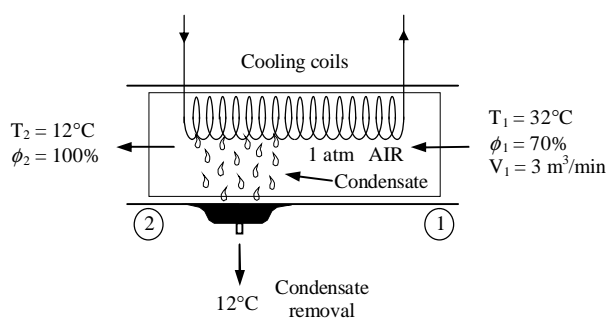
Analysis (a) The amount of moisture in the air decreases due to dehumidification ($\omega_2 < \omega_1$). The mass flow rate of air is

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{3 \text{ m}^3 \text{ / min}}{0.894 \text{ m}^3 \text{ / kg dry air}} = 3.356 \text{ kg/min}$$

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

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

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (8.95 \text{ kg/min})(0.0212 - 0.0087) = \textbf{0.112 kg/min}$$

Energy Balance.

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \dot{Q}_{out} + \sum \dot{m}_e h_e$$
$$\dot{Q}_{out} = \dot{m}_{a1} h_1 - (\dot{m}_{a2} h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$
$$\dot{Q}_{out} = (3.356 \text{ kg/min})(86.4 - 34.1)\text{kJ/kg} - (0.112 \text{ kg/min})(50.4 \text{ kJ/kg})$$
$$= \textbf{170 kJ/min}$$

9-129 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 psychometric chart (Figure A-33) to be

$$h_1 = 95.2 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0238 \text{ kg } H_2O \text{ / kg dry air}$$

and

$$h_3 = 43.1 \text{ kJ / kg dry air}$$
$$\omega_3 = 0.0082 \text{ kg } H_2O \text{ / kg dry air} (= \omega_2)$$

Also,

$$h_w \cong h_{f@10°C} = 42.0 \text{ kJ / kg}$$
$$h_2 = 31.8 \text{ kJ / kg dry air}$$
$$T_2 = \mathbf{11.1° C}$$
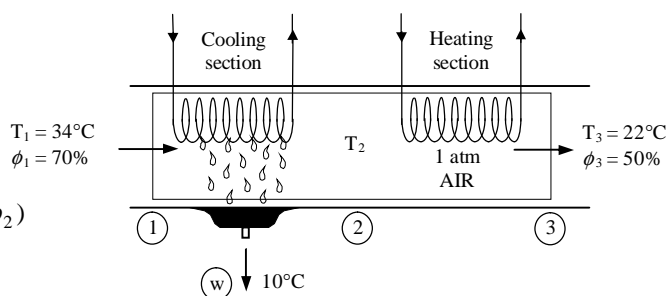
(b) The amount of heat removed in the cooling section is determined from the energy balance equation applied to the cooling section,

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

or, per unit mass of dry air,

$$q_{out,cooling} = (h_1 - h_2) - (\omega_1 - \omega_2) h_w$$
$$= (95.2 - 31.8) - (0.0238 - 0.0082)42.0$$
$$= \mathbf{62.7 \text{ kJ / kg dry air}}$$

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

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

9-130 [*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 dew point temperature of the incoming air stream at 35°C is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ } 0.6 \times 5.628 \text{ kPa}} = 25.9°\text{C}$$

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 1 atm. Then the properties of the air at both states are determined from the psychometric chart (Figure A-33) to be

$$h_1 = 90.3 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0215 \text{ kg H}_2\text{O / kg dry air}$$
$$v_1 = 0.904 \text{ m}^3 / \text{kg dry air}$$

and

$$h_2 = 57.5 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0147 \text{ kg H}_2\text{O / kg dry air}$$
$$v_2 = 0.851 \text{ m}^3 / \text{kg dry air}$$

Also,

$$h_w \cong h_{f@20°C} = 83.96 \text{ kJ / kg} \qquad \text{(Table A-4)}$$

Then,

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

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{8.48 \text{ m}^3 / \text{min}}{0.904 \text{ m}^3 / \text{kg dry air}} = 9.38 \text{ kg/min}$$
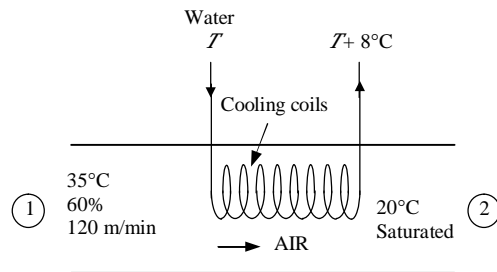
Applying the water mass balance and the energy balance equations to the combined cooling and dehumidification section (excluding the water),

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

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

Energy Balance:

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

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

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

$$\dot{Q}_{out} = (9.38 \text{ kg/min})(90.3 - 57.5)\text{kJ/kg} - (0.064 \text{ kg/min})(83.96 \text{ kJ/kg})$$
$$= \mathbf{302.3 \text{ kJ/min}}$$

(*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

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

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

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

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

$$\mathbf{V}_2 = \frac{v_2}{v_1} \mathbf{V}_1 = \frac{0.851}{0.904}(120 \text{ m/min}) = \mathbf{113 \text{ m/min}}$$

9-70

9-131 Problem 9-130 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 results are to be plotted on the psychrometric chart.

"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*1000)) + Q_dot = m_dot_a*(h[2]
+(1+w[2])*Vel[2]^2/(2*1000)) +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"

SOLUTION
Variables in Main
Cp_cw=4.188 [kJ/kg-K]   D=0.3 [m]
DELTAT_cw=8 [C]   h[1]=90.25 [kJ/kg]
h[2]=57.43 [kJ/kg]   h_liq_2=83.93 [kJ/kg]
m_dot_a=0.1565 [kg/s]   m_dot_cw=0.1506 [kg/s]
m_dot_v[1]=0.003358 [kg/s]   m_dot_v[2]=0.002301 [kg/s]
m_dot_w=0.001057 [kg/s]   P[1]=101.3 [kPa]
P[2]=101.3 [kPa]   Q_dot=-5.047 [kW]
RH[1]=0.6   RH[2]=1
T[1]=35 [C]   T[2]=20 [C]
v[1]=0.9033 [m^3/kg]   v[2]=0.8503 [m^3/kg]
Vel[1]=2 [m/s]   Vel[2]=1.883 [m/s]
Vol_dot[1]=0.1414 [m^3/s]   Vol_dot[2]=0.1331 [m^3/s]
w[1]=0.02145 [kg_w / kg_air]   w[2]=0.0147 [kg_w / kg_air]

RH₁	ma	mw	mcw	Q [kW]	Vel₁ [m/s]	Vel₂ [m/s]	T₁ [C]	T₂ [C]	w₁	w₂
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
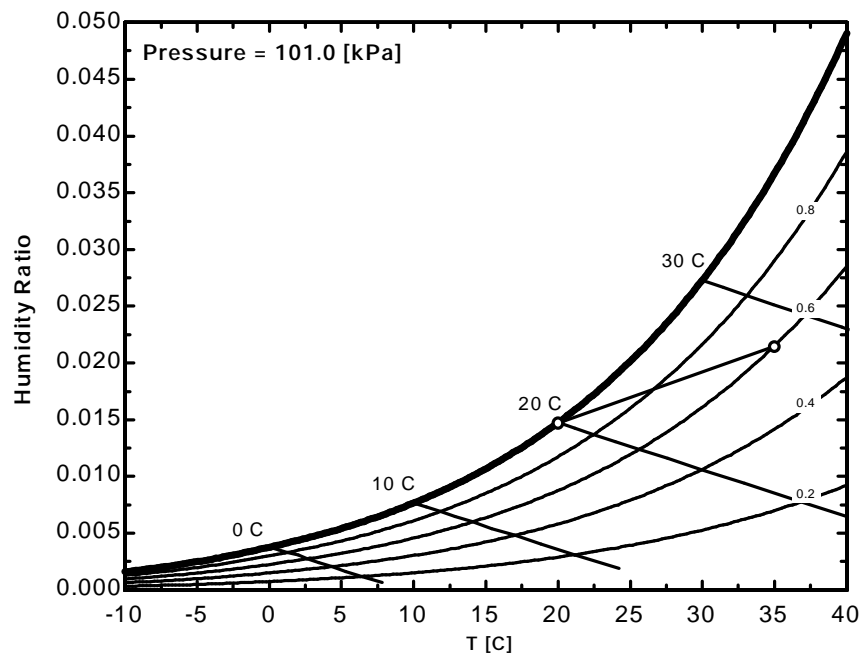
9-132 Air is cooled by passing it over a cooling coil. The rate of heat transfer, the mass flow rate of water, and the exit velocity of airstream are to be determined.

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

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 35°C}} = (0.6)(5.628\,\text{kPa}) = 3.38\,\text{kPa}$$
$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ 3.38 kPa}} = 25.9°\text{C}$$

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

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

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\,\text{K})}{91.62\,\text{kPa}} = 0.965\,\text{m}^3/\text{kg dry air}$$

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

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ}/\text{kg}\cdot°\text{C})(35°\text{C}) + (0.0229)(2565.3\,\text{kJ}/\text{kg})$$
$$= 93.92\,\text{kJ}/\text{kg dry air}$$

and

$$P_{v2} = \phi_2 P_{g2} = (1.00) P_{\text{sat @ 20°C}} = 2.339\,\text{kPa}$$

$$v_2 = \frac{R_a T_2}{P_{a2}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\,\text{K})}{(95 - 2.339)\,\text{kPa}} = 0.908\,\text{m}^3/\text{kg dry air}$$

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

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (1.005\,\text{kJ}/\text{kg}\cdot°\text{C})(20°\text{C}) + (0.0157)(2538.1\,\text{kJ}/\text{kg})$$
$$= 59.95\,\text{kJ}/\text{kg dry air}$$

Also,

$$h_w \cong h_{f@20°C} = 83.96\,\text{kJ}/\text{kg} \qquad \text{(Table A-4)}$$

Then,

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

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{8.48\,\text{m}^3/\text{min}}{0.965\,\text{m}^3/\text{kg dry air}} = 8.79\,\text{kg/min}$$

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

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

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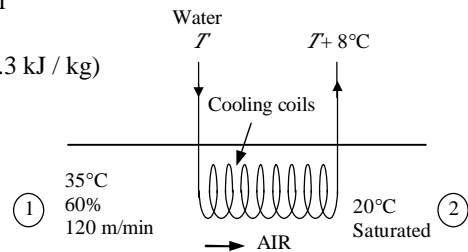
Energy Balance:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\,\ä0 \,(steady)} = 0$$

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

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

$$\dot{Q}_{out} = (8.79\,\text{kg/min})(93.92 - 59.95)\text{kJ/kg} - (0.0633\,\text{kg/min})(83.96\,\text{kJ/kg}) = \mathbf{293.3\,kJ/min}$$

(*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

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

$$\dot{m}_{cooling\ water} = \frac{\dot{Q}_w}{C_p \Delta T} = \frac{293.3\,\text{kJ/min}}{(4.18\,\text{kJ/kg} \cdot °\text{C})(8°\text{C})} = \mathbf{8.77\,kg/min}$$

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

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

$$\mathbf{V}_2 = \frac{v_2}{v_1} \mathbf{V}_1 = \frac{0.908}{0.965}(120\,\text{m/min}) = \mathbf{113\,m/min}$$

9-133E 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 dew point temperature of the incoming air stream at 90°F is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ } 0.6 \times 0.6988 \text{ psia}} = 74°\text{F}$$

Since air is cooled to 70°F, 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 14.7 psia. Then the properties of the air at both states are determined from the psychometric chart (Figure A-33E) to be
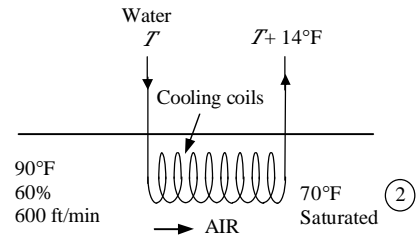
$$h_1 = 41.8 \text{ Btu/lbm dry air}$$
$$\omega_1 = 0.0183 \text{ lbm H}_2\text{O/lbm dry air}$$
$$v_1 = 14.26 \text{ ft}^3/\text{lbm dry air}$$

and

$$h_2 = 34.1 \text{ Btu/lbm dry air}$$
$$\omega_2 = 0.0158 \text{ lbm H}_2\text{O/lbm dry air}$$
$$v_2 = 13.68 \text{ ft}^3/\text{lbm dry air}$$

Also,

$$h_w \cong h_{f@70°\text{F}} = 38.09 \text{ Btu / lbm} \qquad \text{(Table A-4E)}$$

Then,

$$\dot{V}_1 = \mathbf{V}_1 A_1 = \mathbf{V}_1 \frac{\pi D^2}{4} = (600 \text{ ft/min})\left(\frac{\pi (1 \text{ ft})^2}{4}\right) = 471 \text{ ft}^3 / \text{min}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{471 \text{ ft}^3 / \text{min}}{14.26 \text{ ft}^3 / \text{lbm dry air}} = 33.0 \text{ lbm/min}$$

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

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

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (33.0 \text{ lbm/min})(0.0183 - 0.0158) = 0.083 \text{ lbm/min}$$

Energy Balance:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\ä0 \text{ (steady)}} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e + \dot{Q}_{out} \quad \rightarrow \quad Q_{out} = \dot{m}_{a1} h_1 - (\dot{m}_{a2} h_2 + \dot{m}_w h_w) = \dot{m}_a(h_1 - h_2) - \dot{m}_w h_w$$

$$\dot{Q}_{out} = (33.0 \text{ lbm/min})(41.8 - 34.1)\text{Btu/lbm} - (0.083 \text{ lbm/min})(38.09 \text{ Btu/lbm})$$
$$= \mathbf{250.9 \, Btu/min}$$

(*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
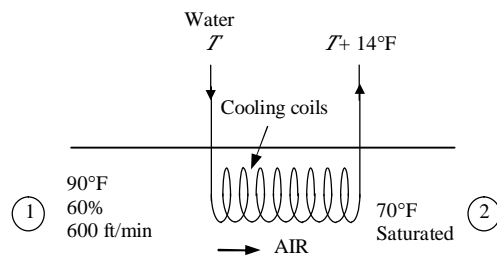
$$\dot{Q}_{\text{cooling water}} = \dot{m}_{\text{cooling water}} \Delta h = \dot{m}_{\text{cooling water}} C_p \Delta T$$

$$\dot{m}_{\text{cooling water}} = \frac{\dot{Q}_w}{C_p \Delta T} = \frac{250.9 \, \text{Btu/min}}{(1.0 \, \text{Btu/lbm} \cdot {}^{\circ}\text{F})(14 {}^{\circ}\text{F})} = \mathbf{17.9 \, lbm/min}$$

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

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

$$\mathbf{V}_2 = \frac{v_2}{v_1} \mathbf{V}_1 = \frac{13.68}{14.26} (600 \, \text{ft/min}) = \mathbf{576 \, ft/min}$$

9-134E Problem 9-133E is reconsidered. The effect of the total pressure of the air over the range 14.3 to 15.2 psia on the required results is to be investigated, and the required results are to be plotted as functions of air total pressure.

"Input Data from the Diagram Window"
{D=1.0"[ft]"
P[1] =14.7 "[psia]"
T[1] = 90"[F]"
RH[1] = 60/100   "%, relative humidity"
Vel[1] = 600"[ft/min]"
DELTAT_cw =14"[F]"
P[2] = 14.7"[psia]"
T[2] = 70"[F]"}
{P[1]=P
P[2]=P}
Tdp_1=DEWPOINT(AirH2O,T=T[1],P=P[1],w=w[1])
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(ft^2/min^2,Btu/lbm)) = Q_dot+ m_dot_a*(h[2]
+(1+w[2])*Vel[2]^2/2*convert(ft^2/min^2,Btu/lbm)) +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=60,P=P[2])"kJ/kg-K"

m_{CW} [lb$_{mw}$/min]	P [psia]	Q [Btu/min]	Vel$_2$ [ft/min]
17.65	14.3	247	575.8
17.81	14.5	249.2	575.9
18.05	14.8	252.5	575.9
18.2	15	254.6	576
18.36	15.2	256.8	576

AirH2O
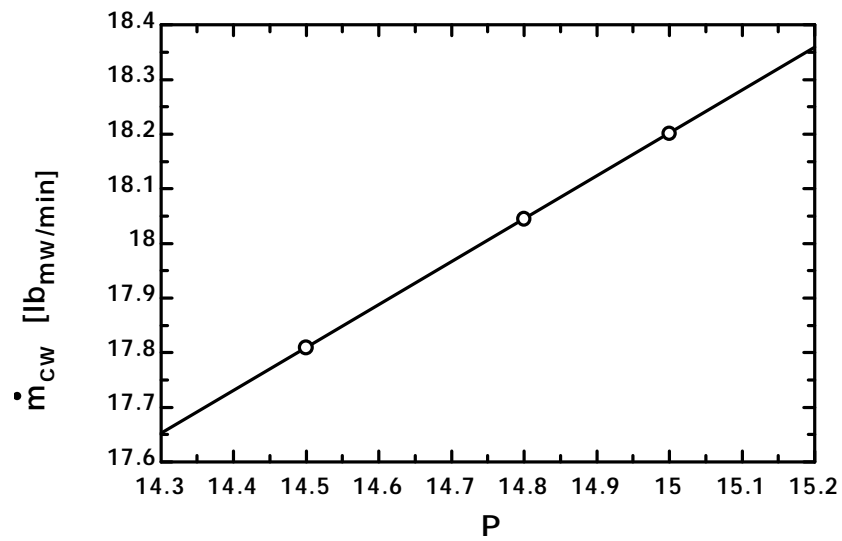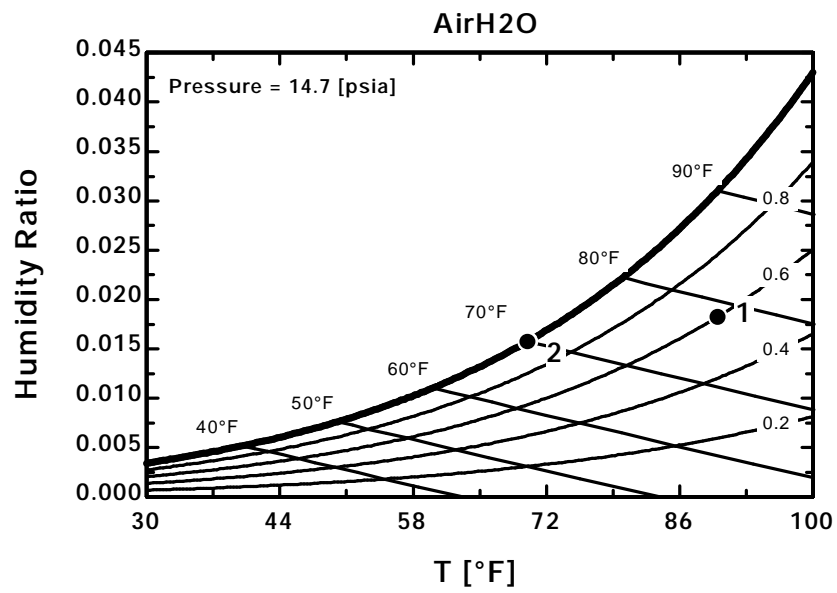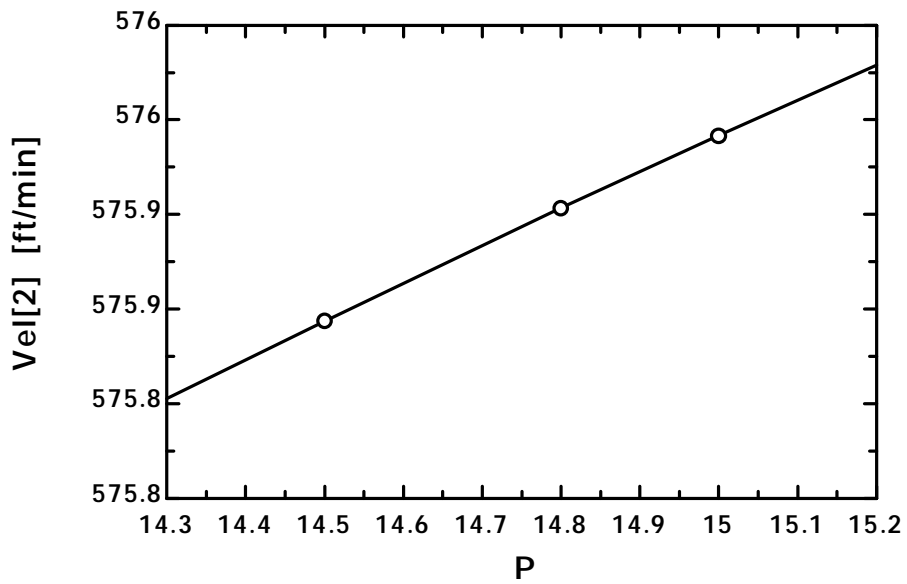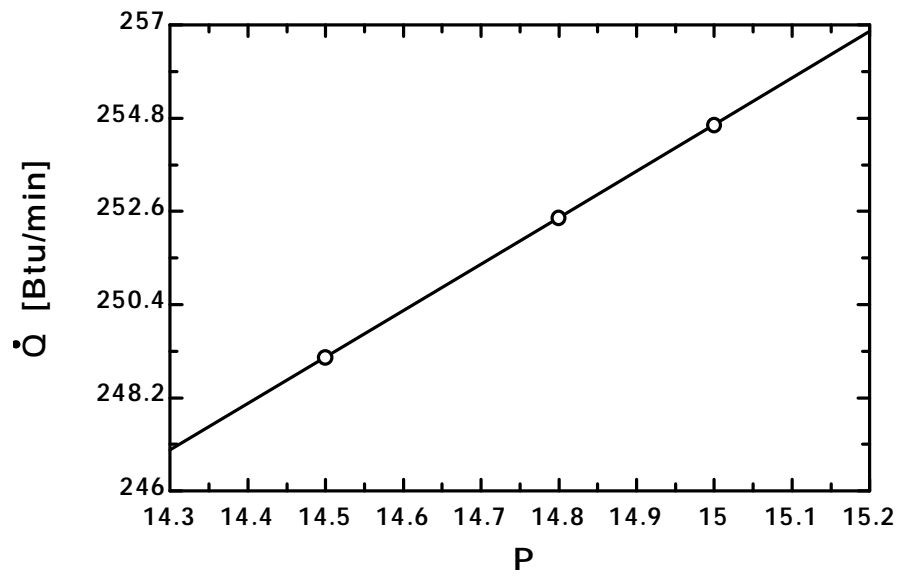
9-135E Air is cooled by passing it over a cooling coil through which chilled water flows. The rate of heat transfer, the mass flow rate of water, and the exit velocity of airstream are to be determined.

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 dew point temperature of the incoming air stream at 90°F is

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{sat\,@\,90°F} = (0.6)(0.6988\,\text{psia}) = 0.42\,\text{psia}$$

$$T_{dp} = T_{sat\,@\,P_v} = T_{sat\,@\,0.42\,\text{psia}} = 74°F$$

Since air is cooled to 70°F, which is below its dew point temperature, some of the moisture in the air will condense.

The mass flow rate of dry air remains constant during the entire process ($\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a$), but 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 14.4 psia. Then the properties of the air at both states are determined to be

$$P_{a1} = P_1 - P_{v1} = 14.4 - 0.42 = 13.98\,\text{psia}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.3704\,\text{psia}\cdot\text{ft}^3\,/\,\text{lbm}\cdot\text{R})(550\,\text{R})}{13.98\,\text{psia}} = 14.57\,\text{ft}^3\,/\,\text{lbm dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.42\,\text{psia})}{(14.4 - 0.42)\,\text{psia}} = 0.0187\,\text{lbm H}_2\text{O/lbm dry air}$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (0.24\,\text{Btu/lbm}\cdot°F)(90°F) + (0.0187)(1100.7\,\text{Btu/lbm})$$
$$= 42.18\,\text{Btu/lbm dry air}$$

and

$$P_{v2} = \phi_2 P_{g2} = (1.00)P_{sat\,@\,70°F} = 0.36\,\text{psia}$$

$$P_{a2} = P_2 - P_{v2} = 14.4 - 0.36 = 14.04\,\text{psia}$$

$$v_2 = \frac{R_a T_2}{P_{a2}} = \frac{(0.3704\,\text{psia}\cdot\text{ft}^3\,/\,\text{lbm}\cdot\text{R})(530\,\text{R})}{14.04\,\text{psia}} = 14.0\,\text{ft}^3\,/\,\text{lbm dry air}$$

$$\omega_2 = \frac{0.622\,P_{v2}}{P_2 - P_{v2}} = \frac{0.622(0.36\,\text{psia})}{(14.4 - 0.36)\,\text{psia}} = 0.0159\,\text{lbm H}_2\text{O/lbm dry air}$$

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (0.24\,\text{Btu/lbm}\cdot°F)(70°F) + (0.0159)(1092.0\,\text{Btu/lbm})$$
$$= 34.16\,\text{Btu/lbm dry air}$$

Also,

$$h_w \cong h_{f\,@\,70°F} = 38.09\,\text{Btu/lbm} \qquad \text{(Table A-4E)}$$

Then,

$$\dot{V}_1 = \mathbf{V}_1 A_1 = \mathbf{V}_1 \frac{\pi D^2}{4} = (600\,\text{ft/min})\left(\frac{\pi(1\,\text{ft})^2}{4}\right) = 471\,\text{ft}^3\,/\,\text{min}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{471\,\text{ft}^3\,/\,\text{min}}{14.57\,\text{ft}^3\,/\,\text{lbm dry air}} = 32.3\,\text{lbm/min}$$

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

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

9-80

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (32.3\,\text{lbm/min})(0.0187 - 0.0159) = 0.0904\,\text{lbm/min}$$

Energy balance.

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

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

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

$$\dot{Q}_{out} = (32.3\,\text{lbm/min})(42.18 - 34.16)\text{Btu/lbm} - (0.0904\,\text{lbm/min})(38.09\,\text{Btu/lbm})$$

$$= \mathbf{255.6\,Btu/min}$$

(*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

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

$$\dot{m}_{\text{cooling water}} = \frac{\dot{Q}_w}{C_p\Delta T} = \frac{255.6\,\text{Btu/min}}{(1.0\,\text{Btu/lbm}\cdot\text{°F})(14\text{°F})} = \mathbf{18.3\,lbm/min}$$

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

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

$$\mathbf{V}_2 = \frac{v_2}{v_1}\mathbf{V}_1 = \frac{14.0}{14.57}(600\,\text{ft/s}) = \mathbf{577\,ft/min}$$

Evaporative Cooling

9-136C In steady operation, the mass transfer process does not have to involve heat transfer. However, a mass transfer process that involves phase change (evaporation, sublimation, condensation, melting etc.) must involve heat transfer. For example, the evaporation of water from a lake into air (mass transfer) requires the transfer of latent heat of water at a specified temperature to the liquid water at the surface (heat transfer).

9-137C During evaporation from a water body to air, the latent heat of vaporization will be equal to *convection* heat transfer from the air when *conduction* from the lower parts of the water body to the surface is negligible, and temperature of the surrounding surfaces is at about the temperature of the water surface so that the *radiation* heat transfer is negligible.

9-138C Evaporative cooling is the cooling achieved when water evaporates in dry air. It will not work on humid climates.

9-139 Air is cooled by an evaporative cooler. The exit temperature of the air and the required rate of water supply are to be determined.

Analysis (*a*) From the psychometric chart (Figure A-33) at 36°C and 20% relative humidity we read

$$T_{wb1} = 19.5°C$$
$$\omega_1 = 0.0074 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.887 \text{ m}^3/\text{kg dry air}$$

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature. That is,

$$T_{wb2} \cong T_{wb1} = 19.5°C$$

At this wet-bulb temperature and 90% relative humidity we read

$$T_2 = \mathbf{20.5°\, C}$$
$$\omega_2 = 0.0137 \text{ kg H}_2\text{O / kg dry air}$$

Thus air will be cooled to 20.5°C in this evaporative cooler.

(*b*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{4 \text{ m}^3/\text{min}}{0.887 \text{ m}^3/\text{kg dry air}} = 4.51 \text{ kg/min}$$

Then the required rate of water supply to the evaporative cooler is determined from

$$\dot{m}_{\text{supply}} = \dot{m}_{w2} - \dot{m}_{w1} = \dot{m}_a(\omega_2 - \omega_1)$$
$$= (4.51 \text{ kg/min})(0.0137 - 0.0074)$$
$$= \mathbf{0.028 \text{ kg/min}}$$
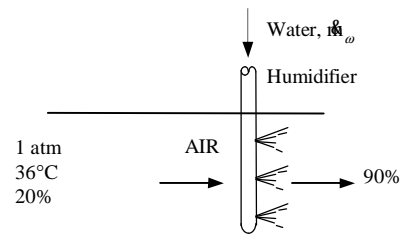
9-140E Air is cooled by an evaporative cooler. The exit temperature of the air and the required rate of water supply are to be determined.

Analysis (*a*) From the psychometric chart (Figure A-33E) at 90°F and 20% relative humidity we read

$$T_{wb1} = 62.8°F$$
$$\omega_1 = 0.0060 \, \text{lbm H}_2\text{O/lbm dry air}$$
$$v_1 = 14.0 \, \text{ft}^3/\text{lbm dry air}$$

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature. That is,

$$T_{wb2} \cong T_{wb1} = 62.8° \, F$$

At this wet-bulb temperature and 90% relative humidity we read

$$T_2 = \mathbf{64° \, F}$$
$$\omega_2 = 0.0116 \, \text{lbm H}_2\text{O / lbm dry air}$$

Thus air will be cooled to 64°F in this evaporative cooler.

(*b*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{150 \, \text{ft}^3 / \text{min}}{14.0 \, \text{ft}^3 / \text{lbm dry air}} = 10.7 \, \text{lbm/min}$$

Then the required rate of water supply to the evaporative cooler is determined from

$$\dot{m}_{\text{supply}} = \dot{m}_{w2} - \dot{m}_{w1} = \dot{m}_a(\omega_2 - \omega_1)$$
$$= (10.7 \, \text{lbm/min})(0.0116 - 0.0060)$$
$$= \mathbf{0.06 \, lbm/min}$$

Water, $\dot{m}_\omega$

Humidifier

1 atm
90°F
20%

AIR

90%
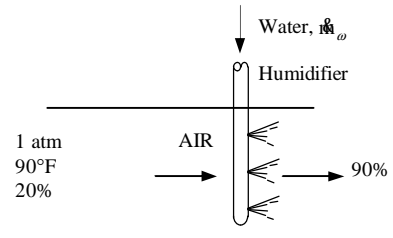
9-141 Air is cooled by an evaporative cooler. The exit temperature of the air is to be determined.

Analysis The enthalpy of air at the inlet is determined from

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 35°C}} = (0.30)(5.628\,\text{kPa}) = 1.69\,\text{kPa}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(1.69\,\text{kPa})}{(95 - 1.69)\,\text{kPa}} = 0.0113\,\text{kg H}_2\text{O/kg dry air}$$

$$h_1 = C_p T_1 + \omega_1 h_{g1}$$

$$= (1.005\,\text{kJ/kg} \cdot \text{°C})(35\text{°C}) + (0.0113)(2565.3\,\text{kJ/kg}) = 64.2\,\text{kJ/kg dry air}$$
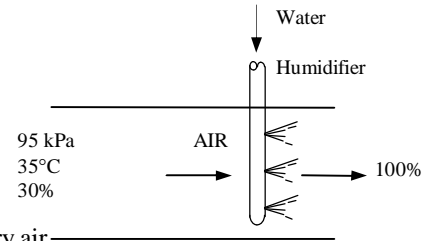
Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature, which is almost parallel to the constant enthalpy lines. That is,

$$h_2 \cong h_1 = 64.2\,\text{kJ / kg dry air}$$

Also,

$$\omega_2 = \frac{0.622\,P_{v2}}{P_2 - P_{v2}} = \frac{0.622\,P_{g2}}{95 - P_{g2}}$$

since air leaves the evaporative cooler saturated. Substituting this into the definition of enthalpy, we obtain

$$h_2 = C_p T_2 + \omega_2 h_{g2} \cong C_p T_2 + \omega_2 (2501.3 + 1.82\,T_2)$$

$$64.2\,\text{kJ / kg} = (1.005\,\text{kJ / kg} \cdot \text{°C})\,T_2 + \frac{0.622\,P_{g2}}{95 - P_{g2}}(2501.3 + 1.82\,T_2)\,\text{kJ / kg}$$

By trial and error, the exit temperature is determined to be $T_2 = \mathbf{21.1°C}$.

9-142E Air is cooled by an evaporative cooler. The exit temperature of the air is to be determined.

Analysis The enthalpy of air at the inlet is determined from

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 93°F}} = (0.30)(0.774 \text{ psia}) = 0.232 \text{ psia}$$

$$\omega_1 = \frac{0.622\, P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.232 \text{ psia})}{(14.5 - 0.232) \text{ psia}}$$

$$= 0.0101 \text{ lbm } H_2O/\text{lbm dry air}$$

$$h_1 = C_p T_1 + \omega_1 h_{g1}$$

$$= (0.24 \text{ Btu/lbm} \cdot °F)(93°F) + (0.0101)(1102.0 \text{ Btu/lbm})$$

$$= 33.45 \text{ Btu/lbm dry air}$$
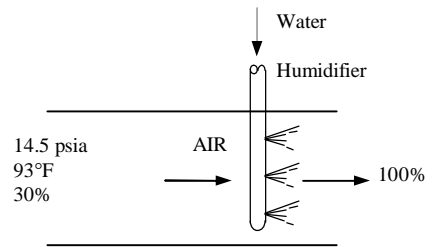
Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature, which is almost parallel to the constant enthalpy lines. That is,

$$h_2 \cong h_1 = 33.45 \text{ Btu / lbm dry air}$$

Also,

$$\omega_2 = \frac{0.622\, P_{v2}}{P_2 - P_{v2}} = \frac{0.622\, P_{g2}}{14.5 - P_{g2}}$$

since air leaves the evaporative cooler saturated. Substituting this into the definition of enthalpy, we obtain

$$h_2 = C_p T_2 + \omega_2 h_{g2} \cong C_p T_2 + \omega_2 (1061.5 + 0.435\, T_2)$$

$$33.45 \text{ Btu / lbm} = (0.24 \text{ Btu / lbm} \cdot °F)\, T_2 + \frac{0.622\, P_{g2}}{14.5 - P_{g2}}(1061.5 + 0.435\, T_2)$$

By trial and error, the exit temperature is determined to be $T_2 = \mathbf{69.0° F}$.

9-143 Air is cooled by an evaporative cooler. The final relative humidity and the amount of water added are to be determined.

Analysis (*a*) From the psychometric chart (Figure A-33) at 32°C and 30% relative humidity we read

$$T_{wb1} = 19.4°C$$
$$\omega_1 = 0.0089 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.877 \text{ m}^3\text{/kg dry air}$$

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature. That is,

$$T_{wb2} \cong T_{wb1} = 19.4°C$$

At this wet-bulb temperature and 22°C temperature we read

$$\phi_2 = \textbf{77\%}$$
$$\omega_2 = 0.0130 \text{ kg H}_2\text{O/kg dry air}$$

(*b*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{2 \text{ m}^3 / \text{min}}{0.877 \text{ m}^3 / \text{kg dry air}} = 2.28 \text{ kg/min}$$

Then the required rate of water supply to the evaporative cooler is determined from

$$\dot{m}_{\text{supply}} = \dot{m}_{w2} - \dot{m}_{w1} = \dot{m}_a(\omega_2 - \omega_1)$$
$$= (2.28 \text{ kg/min})(0.0130 - 0.0089)$$
$$= \textbf{0.0094 kg/min}$$
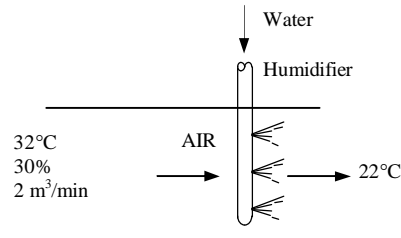
9-144 Air enters an evaporative cooler at a specified state and relative humidity. The lowest temperature that air can attain is to be determined.

Analysis From the psychometric chart (Figure A-33) at 29°C and 40% relative humidity we read

$$T_{wb1} = 19.3°C$$

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature, which is the lowest temperature that can be obtained in an evaporative cooler. That is,

$$T_{\text{min}} = T_{wb1} = \textbf{19.3°C}$$
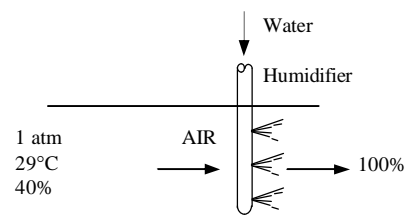
9-145 Air is first heated in a heating section and then passed through an evaporative cooler. The exit relative humidity and the amount of water added are to be determined.

Analysis (*a*) From the psychometric chart (Figure A-33) at 15°C and 60% relative humidity we read

$\omega_1 = 0.00635$ kg H_2O / kg dry air

The specific humidity ω remains constant during the heating process. Therefore, $\omega_2 = \omega_1 = 0.00635$ kg H_2O / kg dry air. At this ω value and 30°C we read $T_{wb2} = 16.6$°C.

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature. That is, $T_{wb3} \cong T_{wb2} = 16.6$°C. At this T_{wb} value and 25°C we read

$\phi_3 = $ **42.3%**

$\omega_3 = 0.00836$ kg H_2O / kg dry air

(*b*) The amount of water added to the air per unit mass of air is

$\Delta\omega_{23} = \omega_3 - \omega_2 = 0.00836 - 0.00635 = $ **0.00201 kg H_2O / kg dry air**
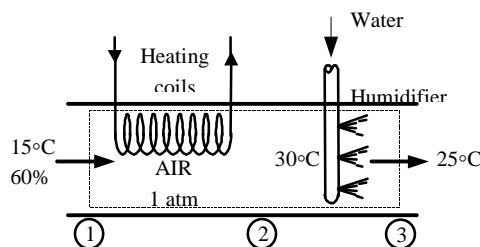
Adiabatic Mixing of Airstreams

9-146C This will occur when the straight line connecting the states of the two streams on the psychometric chart crosses the saturation line.

9-147C Yes.

9-148 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 psychometric chart (Figure A-33) to be

$$h_1 = 62.7 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0119 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.882 \text{ m}^3/\text{kg dry air}$$

and

$$h_2 = 31.9 \text{ kJ/kg dry air}$$
$$\omega_2 = 0.0079 \text{ kg H}_2\text{O/kg dry air}$$
$$v_2 = 0.819 \text{ m}^3/\text{kg dry air}$$

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,

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

Specific humidity and the enthalpy of the mixture can be determined from Eqs. 9-24, 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,

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

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

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

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

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

9-149 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.
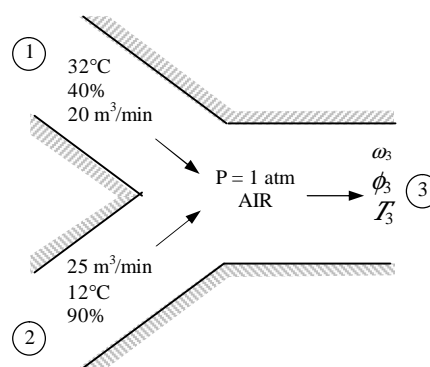
Assumptions **1** Steady operating conditions exist **2** Dry air and water vapor are ideal gases. **3** The kinetic and potential energy changes are negligible. **4** The mixing section is adiabatic.

Analysis The properties of each inlet stream are determined to be

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 32°C}} = (0.40)(4.800\,\text{kPa}) = 1.92\,\text{kPa}$$

$$P_{a1} = P_1 - P_{v1} = 95 - 1.92 = 93.08\,\text{kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(305\,\text{K})}{93.08\,\text{kPa}}$$
$$= 0.940\,\text{m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(1.92\,\text{kPa})}{(95-1.92)\,\text{kPa}} = 0.0128\,\text{kg H}_2\text{O/kg dry air}$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg}\cdot\text{°C})(32\text{°C}) + (0.0128)(2559.9\,\text{kJ/kg})$$
$$= 64.9\,\text{kJ/kg dry air}$$
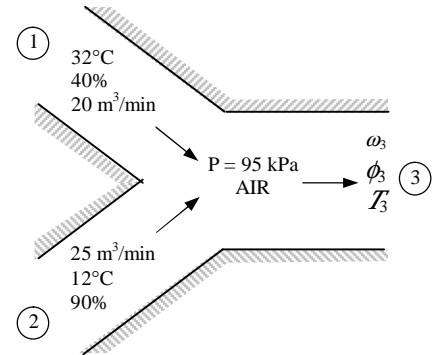
and

$$P_{v2} = \phi_2 P_{g2} = \phi_2 P_{\text{sat @ 12°C}} = (0.90)(1.4186\,\text{kPa}) = 1.277\,\text{kPa}$$

$$P_{a2} = P_2 - P_{v2} = 95 - 1.277 = 93.723\,\text{kPa}$$

$$v_2 = \frac{R_a T_2}{P_{a2}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(285\,\text{K})}{93.723\,\text{kPa}} = 0.873\,\text{m}^3/\text{kg dry air}$$

$$\omega_2 = \frac{0.622\,P_{v2}}{P_2 - P_{v2}} = \frac{0.622(1.277\,\text{kPa})}{(95-1.277)\,\text{kPa}} = 0.0085\,\text{kg H}_2\text{O/kg dry air}$$

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (1.005\,\text{kJ/kg}\cdot\text{°C})(12\text{°C}) + (0.0085)(2523.4\,\text{kJ/kg}) = 33.5\,\text{kJ/kg dry air}$$

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

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{20\,\text{m}^3/\text{min}}{0.940\,\text{m}^3/\text{kg dry air}} = 21.3\,\text{kg/min}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{25\,\text{m}^3/\text{min}}{0.873\,\text{m}^3/\text{kg dry air}} = 28.6\,\text{kg/min}$$

From the conservation of mass,

$$\dot{m}_{a3} = \dot{m}_{a1} + \dot{m}_{a2} = (21.3 + 28.6)\,\text{kg/min} = 49.9\,\text{kg/min}$$

The specific humidity and the enthalpy of the mixture can be determined from Eqs. 9-24, which are obtained by combining the conservation of mass and energy equations for the adiabatic mixing of two streams:

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

$$\frac{21.3}{28.6} = \frac{0.0085 - \omega_3}{\omega_3 - 0.0128} = \frac{33.5 - h_3}{h_3 - 64.9}$$

which yields,

$$\omega_3 = \textbf{0.0103 kg H}_2\textbf{O / kg dry air}$$

$$h_3 = 46.9\,\text{kJ/kg dry air}$$

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

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

$$46.9\,\text{kJ/kg} = (1.005\,\text{kJ/kg}\cdot\text{°C})\,T_3 + (0.0103)(2501.3 + 1.82\,T_3)\,\text{kJ/kg}$$

$$T_3 = \textbf{20.6° C}$$

$$\omega_3 = \frac{0.622 P_{v3}}{P_3 - P_{v3}} \longrightarrow 0.0103 = \frac{0.622 P_{v3}}{95 - P_{v3}} \longrightarrow P_{v3} = 1.55 \text{ kPa}$$

$$\phi_3 = \frac{P_{v3}}{P_{g3}} = \frac{P_{v3}}{P_{\text{sat @ } T_3}} = \frac{1.55 \text{ kPa}}{2.44 \text{ kPa}} = 0.635 \quad \text{or} \quad \mathbf{63.5\%}$$

Finally,

$$P_{a3} = P_3 - P_{v3} = 95 - 1.55 = 93.45 \text{ kPa}$$

$$v_3 = \frac{R_a T_3}{P_{a3}} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3 / \text{kg} \cdot \text{K})(293.6 \text{ K})}{93.45 \text{ kPa}} = 0.902 \text{ m}^3/\text{kg dry air}$$

$$\dot{V}_3 = \dot{m}_{a3} v_3 = (49.9 \text{ kg/min})(0.902 \text{ m}^3 / \text{kg}) = \mathbf{45.0 \text{ m}^3/\text{min}}$$

9-150E 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 psychometric chart (Figure A-33E) to be

$$h_1 = 19.9 \text{ Btu/lbm dry air}$$
$$\omega_1 = 0.0039 \text{ lbm } H_2O/\text{lbm dry air}$$
$$v_1 = 13.30 \text{ ft}^3/\text{lbm dry air}$$

and

$$h_2 = 41.1 \text{ Btu/lbm dry air}$$
$$\omega_2 = 0.0200 \text{ lbm } H_2O/\text{lbm dry air}$$
$$v_2 = 14.03 \text{ ft}^3/\text{lbm dry air}$$

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

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

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{300 \text{ ft}^3/\text{min}}{14.03 \text{ ft}^3/\text{lbm dry air}} = 21.4 \text{ lbm/min}$$

The specific humidity and the enthalpy of the mixture can be determined from Eqs. 9-24, 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*)　　$\omega_3 = \textbf{0.0078 lbm } H_2O/\textbf{lbm dry air}$

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

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

(*b*)　　$T_3 = \textbf{69.5}° \textbf{F}$

(*c*)　　$\phi_3 = \textbf{49.0\%}$
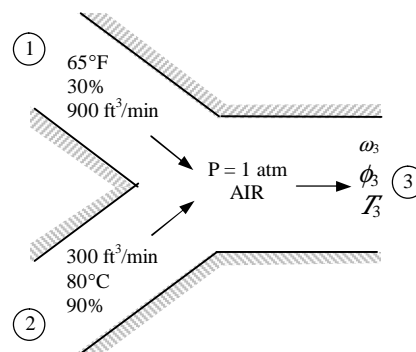
9-151E Problem 9-159E is reconsidered. A general solution of the problem in which the input variables may be supplied and parametric studies performed is to be developed. For each set of input variables for which the pressure is atmospheric, the process is to be shown on the psychrometric chart.

"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"[psia]"
P[2]=P[1]"[psia]"
P[3]=P[1]"[psia]"

"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 the KE 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)"[kga/s]"
m_dot[2]=V_dot[2]/v[2]*convert(1/min,1/s)"[kga/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)"[kga/s]"
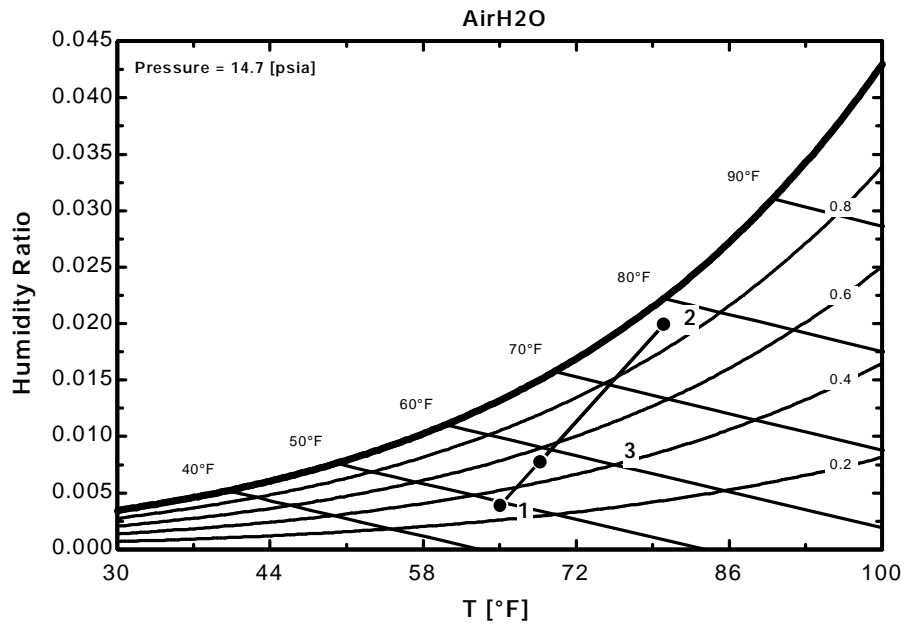
SOLUTION
Variables in Main
DELTAE_dot_sys=0
E_dot_in=37.04 [kW]
E_dot_out=37.04 [kW]
h[1]=19.88 [Btu/lb_m]
h[2]=41.09 [Btu/lb_m]
h[3]=24.97 [Btu/lb_m]
m_dot[1]=1.127 [kga/s]
m_dot[2]=0.3561 [kga/s]
m_dot[3]=1.483 [kga/s]
P=14.7 [psia]
P[1]=14.7 [psia]
P[2]=14.7 [psia]
P[3]=14.7 [psia]
Rh[1]=0.3
Rh[2]=0.9
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]

9-152 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 psychometric chart (Figure A-33) to be

$$h_1 = 110.3 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0272 \text{ kg } H_2O \text{ / kg dry air}$$

and

$$h_2 = 50.9 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0130 \text{ kg } H_2O \text{ / kg dry air}$$

Analysis The specific humidity and the enthalpy of the mixture can be determined from Eqs. 9-24, which are obtained by combining the conservation of mass and energy equations for the adiabatic mixing of two streams:

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

$$\frac{8.0}{6.0} = \frac{0.0130 - \omega_3}{\omega_3 - 0.0272} = \frac{50.9 - h_3}{h_3 - 110.3}$$

which yields,

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

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

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

(*a*) $T_3 = \mathbf{30.7° C}$

(*c*) $\phi_3 = \mathbf{75.1\%}$
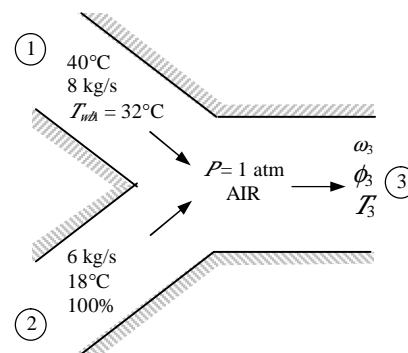
9-153 Problem 9-152 is reconsidered. The effect of the mass flow rate of saturated cool air stream on the mixture temperature, specific humidity, and relative humidity is to be determined. The mass flow rate of saturated cool air is to be varied from 0 to 16 kg/s while maintaining the mass flow rate of warm air constant at 8 kg/s. The mixture temperature, specific humidity, and relative humidity are to be plotted as functions of the mass flow rate of cool air, and discuss the results.

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"[kPa]"
P[2]=P[1]"[kPa]"
P[3]=P[1]"[kPa]"

"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 the KE 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)"[kga/s]"
m_dot[2]=V_dot[2]/v[2]*convert(1/min,1/s)"[kga/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)"[kga/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
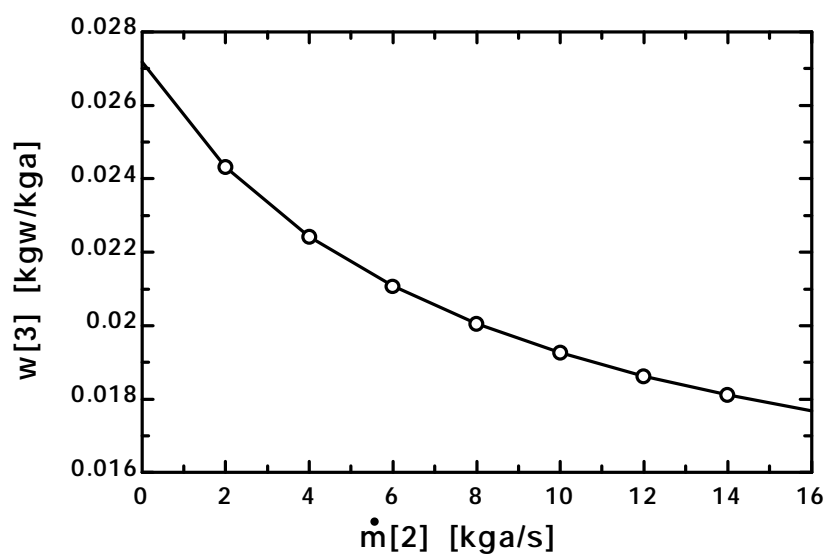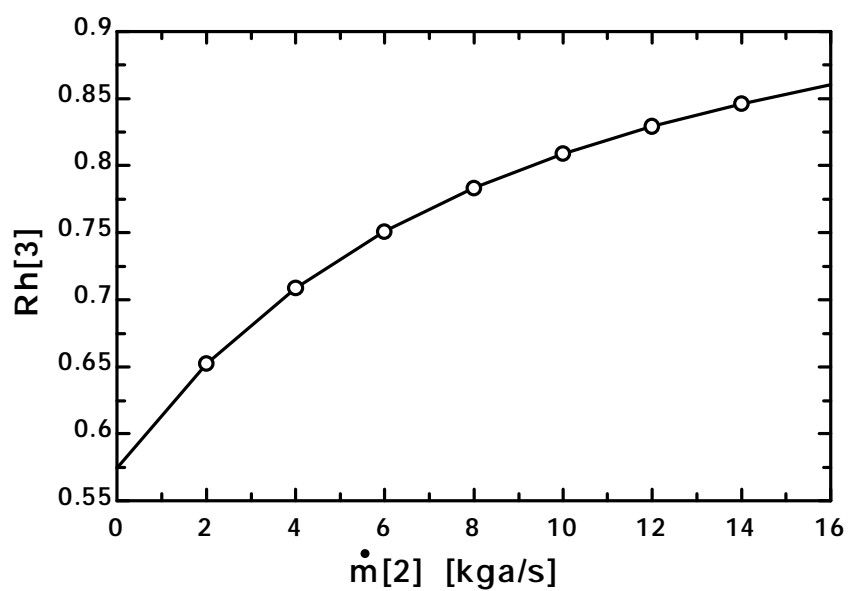
Wet Cooling Towers

9-154C 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.

9-155C 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.

9-156 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:

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

Water Mass Balance:

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

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

Energy Balance:

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

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

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

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

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

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

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 psychometric chart (Figure A-33),

$$h_1 = 50.3 \text{ kJ/kg dry air}$$
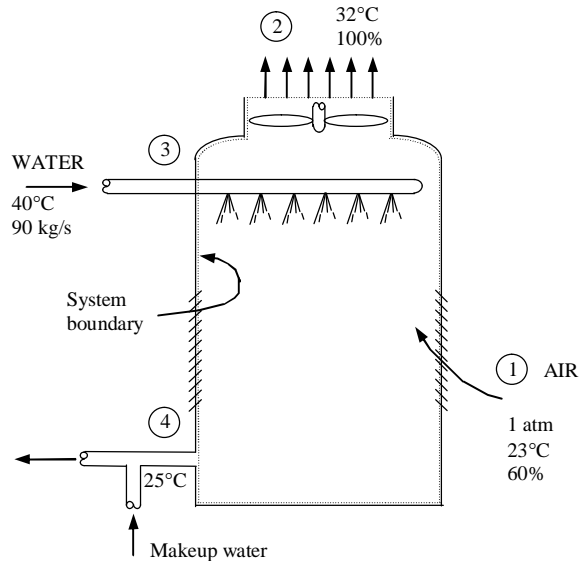$$\omega_1 = 0.0106 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.854 \text{ m}^3/\text{kg dry air}$$

and

$$h_2 = 110.8 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0307 \text{ kg H}_2\text{O / kg dry air}$$

From Table A-4,

$$h_3 \cong h_{f@40°C} = 167.57 \text{ kJ / kg H}_2\text{O}$$

$$h_4 \cong h_{f@25°C} = 104.89 \text{ kJ / kg H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{(90 \text{ kg/s})(167.57 - 104.89)\text{kJ/kg}}{(110.8 - 50.3) \text{ kJ/kg} - (0.0307 - 0.0106)(104.89) \text{ kJ/kg}} = 96.6 \text{ kg/s}$$

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

$$\dot{V}_1 = \dot{m}_a v_1 = (96.6 \text{ kg/s})(0.854 \text{ m}^3 \text{ /kg}) = \mathbf{82.5\,m^3/s}$$

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

$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (96.6 \text{ kg/s})(0.0307 - 0.0106) = \mathbf{1.942\,kg/s}$$

9-157E 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:

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

Water Mass Balance:

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

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

Energy Balance:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \Delta \dot{E}_{\text{system}}^{\ä0 \text{ (steady)}} = 0$$

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

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

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

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

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

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 psychometric chart (Figure A-33),

$$h_1 = 30.9 \text{ Btu/lbm dry air}$$
$$\omega_1 = 0.0115 \text{ lbm H}_2\text{O/lbm dry air}$$
$$v_1 = 13.76 \text{ ft}^3/\text{lbm dry air}$$

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,

$$h_3 \cong h_{f@110°F} = 78.02 \text{ Btu / lbm H}_2\text{O}$$
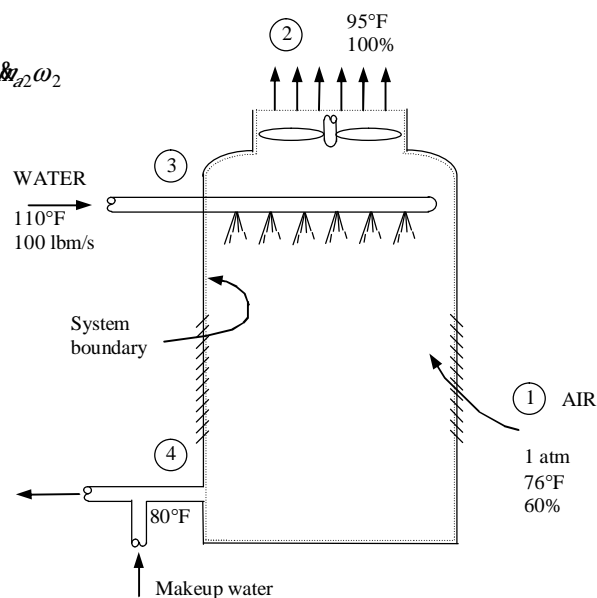$$h_4 \cong h_{f@80°F} = 48.09 \text{ Btu / lbm H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{(100 \text{ lbm/s})(78.02 - 48.09)\text{Btu/lbm}}{(63.2 - 30.9) \text{ Btu/lbm} - (0.0366 - 0.0115)(48.09) \text{ Btu/lbm}} = 96.3 \text{ lbm/s}$$

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

$$\dot{V}_1 = \dot{m}_a v_1 = (96.3 \text{ lbm/s})(13.76 \text{ ft}^3/\text{lbm}) = \mathbf{1325\,ft^3/s}$$

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

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

9-158 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:

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

Water Mass Balance:

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

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

Energy Balance:

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

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

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

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

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

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

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 psychometric chart (Figure A-33),

$$h_1 = 44.7 \text{ kJ/kg dry air}$$
$$\omega_1 = 0.0089 \text{ kg H}_2\text{O/kg dry air}$$
$$v_1 = 0.849 \text{ m}^3/\text{kg dry air}$$

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,

$$h_3 \cong h_{f@40°C} = 167.57 \text{ kJ/kg H}_2\text{O}$$
$$h_4 \cong h_{f@26°C} = 109.07 \text{ kJ/kg H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{(60 \text{ kg/s})(167.57 - 109.07)\text{kJ/kg}}{(113.5 - 44.7) \text{ kJ/kg} - (0.0309 - 0.0089)(109.07) \text{ kJ/kg}} = 52.9 \text{ kg/s}$$
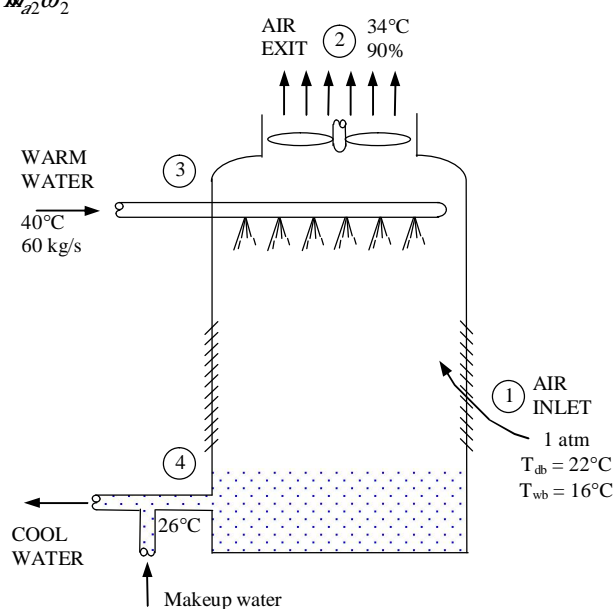
Then the volume flow rate of air into the cooling tower becomes

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

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

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

9-159 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.

Diagram labels (right side):
AIR EXIT — 2 — 34°C 90%
WARM WATER — 3 — 40°C 60 kg/s
AIR INLET — 1 — 1 atm, $T_{db} = 22°C$, $T_{wb} = 16°C$
COOL WATER — 4 — 26°C
Makeup water

Chapter 9 *Gas Mixtures and Psychrometrics*

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:

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

Water Mass Balance:

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

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

Energy Balance:

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

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

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

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

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

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

Solving for $\dot{m}_a$,

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

The properties of air at the inlet and the exit of the tower are calculated to be

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{sat\ @\ 20°C} = (0.70)(2.339\,\text{kPa}) = 1.637\,\text{kPa}$$

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

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\,\text{K})}{94.363\,\text{kPa}} = 0.891\,\text{m}^3/\text{kg dry air}$$

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

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg}\cdot°\text{C})(20°\text{C}) + (0.0108)(2538.1\,\text{kJ/kg})$$
$$= 47.5\,\text{kJ/kg dry air}$$

and

$$P_{v2} = \phi_2 P_{g2} = \phi_2 P_{sat\ @\ 35°C} = (1.00)(5.628\,\text{kPa}) = 5.628\,\text{kPa}$$
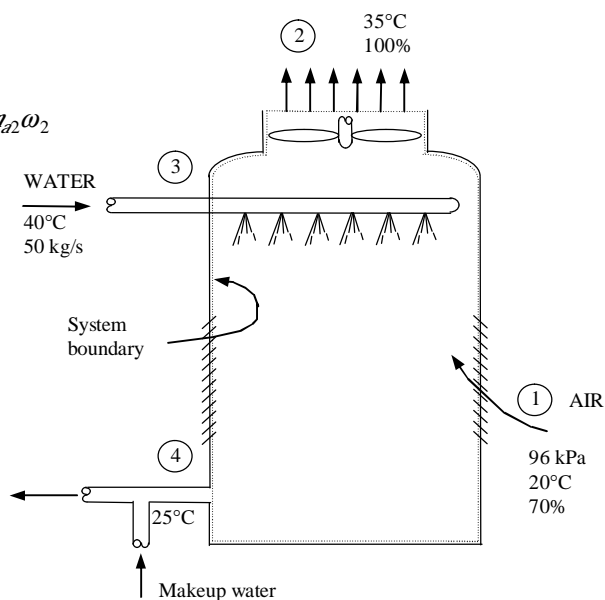
$$\omega_2 = \frac{0.622 P_{v2}}{P_2 - P_{v2}} = \frac{0.622(5.628\,\text{kPa})}{(96 - 5.628)\,\text{kPa}} = 0.0387\,\text{kg H}_2\text{O/kg dry air}$$

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (1.005\,\text{kJ/kg}\cdot°\text{C})(35°\text{C}) + (0.0387)(2565.3\,\text{kJ/kg})$$
$$= 134.5\,\text{kJ/kg dry air}$$

From Table A-4,

$$h_3 \cong h_{f\ @\ 40°C} = 167.57\,\text{kJ/kg H}_2\text{O}$$

$$h_4 \cong h_{f\ @\ 25°C} = 104.89\,\text{kJ/kg H}_2\text{O}$$

9-101

Substituting,

$$\dot{m}_a = \frac{(50\,\text{kg/s})(167.57 - 104.89)\text{kJ/kg}}{(134.5 - 47.5)\,\text{kJ/kg} - (0.0387 - 0.0108)(104.89)\,\text{kJ/kg}} = 37.3\,\text{kg/s}$$

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

$$\dot{V}_1 = \dot{m}_a v_1 = (37.3\,\text{kg/s})(0.891\,\text{m}^3/\text{kg}) = \mathbf{33.2\,m^3/s}$$

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

$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (33.2\,\text{kg/s})(0.0387 - 0.0108) = \mathbf{1.04\,kg/s}$$

Review Problems

9-160 The molar fractions of constituents of air are given. The gravimetric analysis of air and its molar mass are to be determined.

Assumptions All the constituent gases and their mixture are ideal gases.

Properties The molar masses of O_2, N_2, and Ar are 32.0, 28.0, and 40.0 kg/kmol. (Table A-1).

Analysis For convenience, consider 100 kmol of air. Then the mass of each component and the total mass are

$$N_{O_2} = 21 \text{kmol} \longrightarrow m_{O_2} = N_{O_2} M_{O_2} = (21\text{kmol})(32\text{kg/kmol}) = 672\text{kg}$$

$$N_{N_2} = 78\text{kmol} \longrightarrow m_{N_2} = N_{N_2} M_{N_2} = (78\text{kmol})(28\text{kg/kmol}) = 2,184\text{kg}$$

$$N_{Ar} = 1\text{kmol} \longrightarrow m_{Ar} = N_{Ar} M_{Ar} = (1\text{kmol})(40\text{kg/kmol}) = 40\text{kg}$$

$$m_m = m_{O_2} + m_{N_2} + m_{Ar} = 672 \text{ kg} + 2,184 \text{ kg} + 40 \text{ kg} = 2,896 \text{ kg}$$

AIR
21% O_2
78% N_2
1% Ar

Then the mass fraction of each component (gravimetric analysis) becomes

$$mf_{O_2} = \frac{m_{O_2}}{m_m} = \frac{672 \text{ kg}}{2,896 \text{ kg}} = 0.232 \quad \text{or} \quad \textbf{23.2\%}$$

$$mf_{N_2} = \frac{m_{N_2}}{m_m} = \frac{2,184 \text{ kg}}{2,896 \text{ kg}} = 0.754 \quad \text{or} \quad \textbf{75.4\%}$$

$$mf_{Ar} = \frac{m_{Ar}}{m_m} = \frac{40 \text{ kg}}{2,896 \text{ kg}} = 0.014 \quad \text{or} \quad \textbf{1.4\%}$$

The molar mass of the mixture is determined from its definitions,

$$M_m = \frac{m_m}{N_m} = \frac{2,896 \text{ kg}}{100 \text{ kmol}} = \textbf{28.96 kg / kmol}$$

9-161 Using EES (or other) software, a program is to be written to determine the mole fractions of

the components of a mixture of 3 gases with known molar masses when the mass
fractions are given, and to determine the mass fractions of the components when
the mole fractions are given. The program is to be run for a sample case, and the results
are to be listed.

Procedure Fractions(Type$,A$,B$,C$,A,B,C:mf_A,mf_B,mf_C,y_A,y_B,y_C)
{If Type$ <> ('mass fraction' OR 'mole fraction') then
Call ERROR('Type$ must be set equal to "mass fraction" or "mole fraction".')
GOTO 10
endif}
Sum = A+B+C
If ABS(Sum - 1) > 0 then goto 20
MM_A = molarmass(A$)
MM_B = molarmass(B$)
MM_C = molarmass(C$)

If Type$ = 'mass fraction' then

mf_A = A
mf_B = B
mf_C = C
sumM_mix = mf_A/MM_A+ mf_B/MM_B+ mf_C/MM_C"[kJ/kmol]"
y_A = mf_A/MM_A/sumM_mix
y_B = mf_B/MM_B/sumM_mix
y_C = mf_C/MM_C/sumM_mix
GOTO 10
endif
if Type$ = 'mole fraction' then

y_A = A
y_B = B
y_C = C
MM_mix = y_A*MM_A+ y_B*MM_B+ y_C*MM_C"[kJ/kmol]"
mf_A = y_A*MM_A/MM_mix
mf_B = y_B*MM_B/MM_mix
mf_C = y_C*MM_C/MM_mix
GOTO 10

Endif
Call ERROR('Type$ must be either mass fraction or mole fraction.')
GOTO 10

20:
Call ERROR('The sum of the mass or mole fractions must be 1')
10:

END

"Either the mole fraction y_i or the mass fraction mf_i may be given by setting the parameter
Type$='mole fraction' when the mole fractions are given or Type$='mass fraction' is given"

{Input Data in the Diagram Window}
{Type$='mole fraction'
A$ = 'N2'
B$ = 'O2'
C$ = 'Argon'

A = 0.71 "When Type$='mole fraction' A, B, C are the mole fractions"
B = 0.28 "When Type$='mass fraction' A, B, C are the mass fractions"
C = 0.01}
Call Fractions(Type$,A$,B$,C$,A,B,C:mf_A,mf_B,mf_C,y_A,y_B,y_C)

SOLUTION
Variables in Main
A=0.71
A$='N2'
B=0.28
B$='O2'
C=0.01
C$='Argon'
mf_A=0.680
mf_B=0.306
mf_C=0.014
Type$='mole fraction'
y_A=0.710
y_B=0.280
y_C=0.010

9-162 Using EES (or other) software, a program is to be written to determine the apparent gas constant, constant volume specific heat, and internal energy of a mixture of 3 ideal gases when the mass fractions and other properties of the constituent gases are given. The program is to be run for a sample case, and the results are to be listed.

T=300"[K]"
A$ = 'N2'
B$ = 'O2'
C$ = 'CO2'
mf_A = 0.71
mf_B = 0.28
mf_C = 0.01
R_u = 8.314"[kJ/kmol-K]"
MM_A = molarmass(A$)"[kg/kmol]"
MM_B = molarmass(B$)"[kg/kmol]"
MM_C = molarmass(C$)"[kg/kmol]"
SumM_mix = mf_A/MM_A+ mf_B/MM_B+ mf_C/MM_C
y_A = mf_A/MM_A/SumM_mix
y_B = mf_B/MM_B/SumM_mix
y_C = mf_C/MM_C/SumM_mix
MM_mix = y_A*MM_A+ y_B*MM_B+ y_C*MM_C"[kg/kmol]"
R_mix = R_u/MM_mix"[kJ/kg-K]"
C_P_mix=mf_A*specheat(A$,T=T)+mf_B*specheat(B$,T=T)+mf_C*specheat(C$,T=T)"[kJ/kg-K]"
C_V_mix=C_P_mix - R_mix"[kJ/kg-K]"
u_mix=C_V_mix*T"[kJ/kg]"
h_mix=C_P_mix*T"[kJ/kg]"

SOLUTION
Variables in Main
A$='N2'
B$='O2'
C$='CO2'
C_P_mix=1.006 [kJ/kg-K]
C_V_mix=0.7206 [kJ/kg-K]
h_mix=301.8 [kJ/kg]
mf_A=0.71
mf_B=0.28
mf_C=0.01
MM_A=28.01 [kg/kmol]
MM_B=32 [kg/kmol]
MM_C=44.01 [kg/kmol]
MM_mix=29.14 [kg/kmol]
R_mix=0.2854 [kJ/kg-K]
R_u=8.314 [kJ/kmol-K]
SumM_mix=0.03432
T=300 [K]
u_mix=216.2 [kJ/kg]
y_A=0.7384
y_B=0.2549
y_C=0.00662

9-163 Air is compressed by a compressor and then cooled to the ambient temperature at high pressure. It is to be determined if there will be any condensation in the compressed air lines.

Assumptions The air and the water vapor are ideal gases.

Properties The saturation pressure of water at 25°C is 3.169 kPa (Table A-4)..

Analysis The vapor pressure of air before compression is

$$P_{v1} = \phi_1 P_g = \phi_1 P_{\text{sat @ 25°C}} = (0.40)(3.169 \text{ kPa}) = 1.27 \text{ kPa}$$

The pressure ratio during the compression process is (800 kPa)/(92 kPa) = 8.70. That is, the pressure of air and any of its components increases by 8.70 times. Then the vapor pressure of air after compression becomes

$$P_{v2} = P_{v1} \times (\text{Pressure ratio}) = (1.27 \text{ kPa})(8.70) = 11.0 \text{ kPa}$$

The dew-point temperature of the air at this vapor pressure is

$$T_{dp} = T_{\text{sat @ } P_{v2}} = T_{\text{sat @ 11.0 kPa}} = 47.4°\text{C}$$

which is greater than 25°C. Therefore, part of the moisture in the compressed air will **condense** when air is cooled to 25°C.

9-164E The error involved in assuming the density of air to remain constant during a humidification process is to be determined.

Properties The density of moist air before and after the humidification process is determined from the psychrometric chart (Figure A-33E) to be

$$\left. \begin{array}{l} T_1 = 80°\text{F} \\ \phi_1 = 30\% \end{array} \right\} \rho_{\text{air},1} = 0.0727 \, \text{lbm/ft}^3 \qquad \text{and} \qquad \left. \begin{array}{l} T_1 = 80°\text{F} \\ \phi_1 = 90\% \end{array} \right\} \rho_{\text{air},2} = 0.07117 \, \text{lbm/ft}^3$$

Analysis The error involved as a result of assuming constant air density is then determined to be

$$\% \, \text{Error} = \frac{\Delta \rho_{\text{air}}}{\rho_{\text{air},1}} \times 100 = \frac{0.0727 - 0.0712 \, \text{lbm/ft}^3}{0.0727 \, \text{lbm/ft}^3} \times 100 = \mathbf{2.1\%}$$

which is acceptable for most engineering purposes.

9-165 Dry air flows over a water body at constant pressure and temperature until it is saturated. The molar analysis of the saturated air and the density of air before and after the process are to be determined.

Assumptions The air and the water vapor are ideal gases.

Properties The molar masses of N_2, O_2, Ar, and H_2O are 28.0, 32.0, 39.9 and 18 kg / kmol, respectively (Table A-1). The molar analysis of dry air is given to be 78.1 percent N_2, 20.9 percent O_2, and 1 percent Ar. The saturation pressure of water at 25°C is 3.169 kPa (Table A-4). Also, 1 atm = 101.325 kPa.

Analysis (*a*) Noting that the total pressure remains constant at 101.32 kPa during this process, the partial pressure of air becomes

$$P = P_{air} + P_{vapor} \rightarrow P_{air} = P - P_{vapor} = 101.325 - 3.169 = 98.156 \text{ kPa}$$

Then the molar analysis of the saturated air becomes

$$y_{H_2O} = \frac{P_{H_2O}}{P} = \frac{3.169}{101.325} = \mathbf{0.0313}$$

$$y_{N_2} = \frac{P_{N_2}}{P} = \frac{y_{N_2,dry} P_{dry\,air}}{P} = \frac{0.781(98.156 \text{ kPa})}{101.325} = \mathbf{0.7566}$$

$$y_{O_2} = \frac{P_{O_2}}{P} = \frac{y_{O_2,dry} P_{dry\,air}}{P} = \frac{0.209(98.156 \text{ kPa})}{101.325} = \mathbf{0.2025}$$

$$y_{Ar} = \frac{P_{Ar}}{P} = \frac{y_{Ar,dry} P_{dry\,air}}{P} = \frac{0.01(98.156 \text{ kPa})}{101.325} = \mathbf{0.0097}$$

Air
1 atm
25°C

Lake
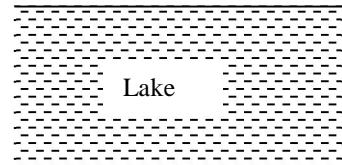
(*b*) The molar masses of dry and saturated air are

$$M_{dry\,air} = \sum y_i M_i = 0.781 \times 28.0 + 0.209 \times 32.0 + 0.01 \times 39.9 = 29.0 \text{ kg / kmol}$$

$$M_{sat.\,air} = \sum y_i M_i = 0.7566 \times 28.0 + 0.2025 \times 32.0 + 0.0097 \times 39.9 + 0.0313 \times 18 = 28.62 \text{ kg/kmol}$$

Then the densities of dry and saturated air are determined from the ideal gas relation to be

$$\rho_{dry\,air} = \frac{P}{(R_u / M_{dry\,air})T} = \frac{101.325 \text{kPa}}{[(8.314 \text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K}) / 29.0 \text{kg/kmol}](25 + 273)\text{K}} = \mathbf{1.186 \ kg/m^3}$$

$$\rho_{sat.\,air} = \frac{P}{(R_u / M_{sat\,air})T} = \frac{101.325 \text{kPa}}{[(8.314 \text{kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K}) / 28.62 \text{kg/kmol}](25 + 273)\text{K}} = \mathbf{1.170 \ kg/m^3}$$

Discussion We conclude that the density of saturated air is less than that of the dry air, as expected. This is due to the molar mass of water being less than that of dry air.

9-166E A room is cooled adequately by a 7500 Btu/h air-conditioning unit. If the room is to be cooled by an evaporative cooler, the amount of water that needs to be supplied to the cooler is to be determined.

Assumptions **1** The evaporative cooler removes heat at the same rate as the air conditioning unit. **2** Water evaporates at an average temperature of 70°F.

Properties The enthalpy of vaporization of water at 70°F is 1054 Btu/lbm (Table A-4E).

Analysis Noting that 1 lbm of water removes 1054 Btu of heat as it evaporates, the amount of water that needs to evaporate to remove heat at a rate of 5000 Btu/h is determined from $\dot{Q} = \dot{m}_{water} h_{fg}$ to be

$$\dot{m}_{water} = \frac{\dot{Q}}{h_{fg}} = \frac{7500 \text{ Btu/h}}{1054 \text{ Btu/lbm}} = \mathbf{7.12 \, lbm/h}$$

9-167E The required size of an evaporative cooler in cfm (ft³/min) for an 8-ft high house is determined by multiplying the floor area of the house by 4. An equivalent rule is to be obtained in SI units.

Analysis Noting that 1 ft = 0.3048 m and thus 1 ft² = 0.0929 m² and 1 ft³ = 0.0283 m³, and noting that a flow rate of 4 ft³/min is required per ft² of floor area, the required flow rate in SI units per m² of floor area is determined to

$$1 \text{ ft}^2 \leftrightarrow 4 \text{ ft}^3/\min$$
$$0.0929 \text{ m}^2 \leftrightarrow 4 \times 0.0283 \text{ m}^3/\min$$
$$1 \text{ m}^2 \leftrightarrow 1.22 \text{ m}^3/\min$$

Therefore, a flow rate of **1.22 m³/min** is required per m² of floor area.

9-168 A cooling tower with a cooling capacity of 440 kW is claimed to evaporate 15,800 kg of water per day. It is to be determined if this is a reasonable claim.

Assumptions **1** Water evaporates at an average temperature of 30°C. **2** The coefficient of performance of the air-conditioning unit is COP = 3.

Properties The enthalpy of vaporization of water at 30°C is 2430.5 kJ/kg (Table A-4).

Analysis Using the definition of COP, the electric power consumed by the air conditioning unit when running is

$$\dot{W}_{in} = \frac{\dot{Q}_{cooling}}{COP} = \frac{440 \text{ kW}}{3} = 146.7 \text{ kW}$$

Then the rate of heat rejected at the cooling tower becomes

$$\dot{Q}_{rejected} = \dot{Q}_{cooling} + \dot{W}_{in} = 440 + 146.7 = 586.7 \text{ kW}$$

Noting that 1 kg of water removes 2430.5 kJ of heat as it evaporates, the amount of water that needs to evaporate to remove heat at a rate of 586.7 kW is determined from $\dot{Q}_{rejected} = \dot{m}_{water} h_{fg}$ to be

$$\dot{m}_{water} = \frac{\dot{Q}_{rejected}}{h_{fg}} = \frac{586.7 \text{ kJ/s}}{2430.5 \text{ kJ/kg}} = 0.241 \text{ kg/s} = 869 \text{ kg/h} = 20,856 \text{ kg/day}$$

In practice, the air-conditioner will run intermittently rather than continuously at the rated power, and thus the water use will be less. Therefore, the claim amount of 15,800 kg per day is **reasonable**.

9-169 It is estimated that 190,000 barrels of oil would be saved per day if the thermostat setting in residences in summer were raised by 6°F (3.3°C). The amount of money that would be saved per year is to be determined.

Assumptions The average cooling season is given to be 120 days, and the cost of oil to be $20/barrel.

Analysis The amount of money that would be saved per year is determined directly from

$$(190,000 \text{ barrel}/\text{day})(120 \text{ days}/\text{year})(\$20/\text{barrel}) = \textbf{\$456,000,000}$$

Therefore, the proposed measure will save about half-a-billion dollars a year.

9-170E Wearing heavy long-sleeved sweaters and reducing the thermostat setting 1°F reduces the heating cost of a house by 4 percent at a particular location. The amount of money saved per year by lowering the thermostat setting by 4°F is to be determined.

Assumptions The household is willing to wear heavy long-sleeved sweaters in the house, and the annual heating cost is given to be $600 a year.

Analysis The amount of money that would be saved per year is determined directly from

$$(\$600/\text{year})(0.04/°\text{F})(4°\text{F}) = \textbf{\$96/year}$$

Therefore, the proposed measure will save the homeowner about $100 during a heating season..

9-171 Shading the condenser can reduce the air-conditioning costs by up to 10 percent. The amount of money shading can save a homeowner per year during its lifetime is to be determined.

Assumptions It is given that the annual air-conditioning cost is $500 a year, and the life of the air-conditioning system is 20 years.

Analysis The amount of money that would be saved per year is determined directly from

$$(\$500/\text{year})(20 \text{ years})(0.10) = \textbf{\$1000}$$

Therefore, the proposed measure will save about $1000 during the lifetime of the system.

9-172 A tank contains saturated air at a specified state. The mass of the dry air, the specific humidity, and the enthalpy of the air are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The air is saturated, thus the partial pressure of water vapor is equal to the saturation pressure at the given temperature,

$$P_v = P_g = P_{\text{sat @ } 25°C} = 3.169\,\text{kPa}$$
$$P_a = P - P_v = 97 - 3.169 = 93.831\,\text{kPa}$$

Treating air as an ideal gas,

$$m_a = \frac{P_a V}{R_a T} = \frac{(93.831\,\text{kPa})(5\,\text{m}^3)}{(0.287\,\text{kPa}\cdot\text{m}^3 / \text{kg}\cdot\text{K})(298\,\text{K})} = \mathbf{5.49\,kg}$$

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

$$\omega = \frac{0.622 P_v}{P - P_v} = \frac{(0.622)(3.169\,\text{kPa})}{(97 - 3.169)\,\text{kPa}} = \mathbf{0.0210\,kg\,H_2O/kg\,dry\,air}$$

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

$$h = h_a + \omega h_v \cong C_p T + \omega h_g = (1.005\,\text{kJ} / \text{kg}\cdot°\text{C})(25°\text{C}) + (0.0210)(2547.2\,\text{kJ} / \text{kg})$$
$$= \mathbf{78.62\,kJ / kg\,dry\,air}$$

Box:
```
5 m³
25°C
97 kPa
```

9-111

9-173 Problem 9-172 is reconsidered. The properties of the air at the initial state are to be determined. The effects of heating the air at constant volume until the pressure is 110 kPa are to be investigated. The required heat transfer is to be plotted as a function of pressure.

"Input Data:"
Tdb[1] = 25"[C]"
P[1]=97"[kPa]"
Rh[1]=1.0
P[2]=110"[kPa]"
Vol = 5"[m^3]"

w[1]=HUMRAT(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])
v[1]=VOLUME(AirH2O,T=Tdb[1],P=P[1],R=Rh[1])
m_a=Vol/v[1]"[kga]"
h[1]=ENTHALPY(AirH2O,T=Tdb[1],P=P[1],w=w[1])
"Energy Balance for the constant volume tank:"
E_in - E_out = DELTAE_tank"[kJ]"
DELTAE_tank=m_a*(u[2] -u[1])"[kJ]"
E_in = Q_in"[kJ]"
E_out = 0"[kJ]"
u[1]=INTENERGY(AirH2O,T=Tdb[1],P=P[1],w=w[1])"[kJ/kga]"
u[2]=INTENERGY(AirH2O,T=Tdb[2],P=P[2],w=w[2])"[kJ/kga]"
"The ideal gas mixture assumption applied to the constant volume process yields:"
P[1]/(Tdb[1]+273)=P[2]/(Tdb[2]+273)
"The mass of the water vapor and dry air are constant, thus:"
w[2]=w[1]
Rh[2]=RELHUM(AirH2O,T=Tdb[2],P=P[2],w=w[2])
h[2]=ENTHALPY(AirH2O,T=Tdb[2],P=P[2],w=w[2])
v[2]=VOLUME(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])

P_2 [kPa]	Q_{in} [kJ]
97	-0.0000022
99	25.2
101	50.39
103	75.57
105	100.7
107	125.9
109	151.1
110	163.7
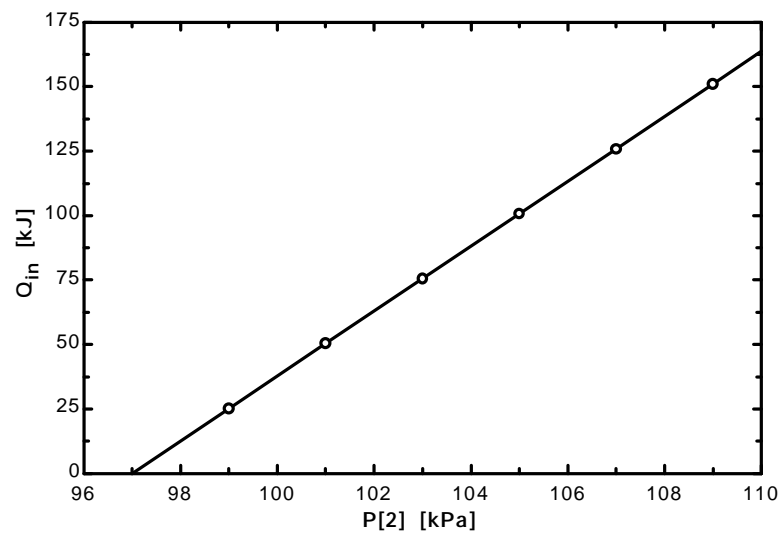
9-174E Air at a specified state and relative humidity flows through a circular duct. The dew-point temperature, the volume flow rate of air, and the mass flow rate of dry air are to be determined.

Assumptions The air and the water vapor are ideal gases.

Analysis (*a*) The vapor pressure of air is

$$P_v = \phi P_g = \phi P_{\text{sat @ 60°F}} = (0.50)(0.2563\,\text{psia}) = 0.128\,\text{psia}$$

Thus the dew-point temperature of the air is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ 0.128 psia}} = \mathbf{41.2°F}$$
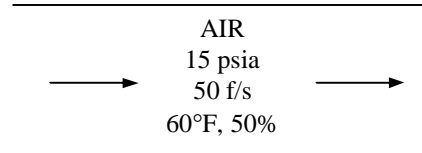
(*b*) The volume flow rate is determined from

$$\dot{V} = \mathbf{V}A = \mathbf{V}\frac{\pi D^2}{4} = (50\,\text{ft/s})\left(\frac{\pi \times (8/12\,\text{ft})^2}{4}\right) = \mathbf{17.45\ ft^3/s}$$

(*c*) To determine the mass flow rate of dry air, we first need to calculate its specific volume,

$$P_a = P - P_v = 15 - 0.128 = 14.872\,\text{psia}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.3704\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(520\,\text{R})}{14.872\,\text{psia}} = 12.95\,\text{ft}^3/\text{lbm dry air}$$

Thus, $$\dot{m}_{a1} = \frac{\dot{V}}{v_1} = \frac{17.45\,\text{ft}^3/\text{s}}{12.95\,\text{ft}^3/\text{lbm dry air}} = \mathbf{1.35\ lbm/s}$$

AIR
15 psia
50 f/s
60°F, 50%

9-175 Air enters a cooling section at a specified pressure, temperature, and relative humidity. The temperature of the air at the exit and the rate of heat transfer 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 ($\omega_1 = \omega_2$) as it flows through the cooling section since the process involves no humidification or dehumidification. The total pressure is 97 kPa. The properties of the air at the inlet state are

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{\text{sat @ 35°C}} = (0.2)(5.628\,\text{kPa}) = 1.13\,\text{kPa}$$

$$P_{a1} = P_1 - P_{v1} = 97 - 1.13 = 95.87\,\text{kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\,\text{K})}{95.87\,\text{kPa}}$$

$$= 0.922\,\text{m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(1.13\,\text{kPa})}{(97-1.13)\,\text{kPa}} = 0.0073\,\text{kg H}_2\text{O/kg dry air} \,(= \omega_2)$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg°C})(35°\text{C}) + (0.0073)(2565.3\,\text{kJ/kg})$$

$$= 53.90\,\text{kJ/kg dry air}$$
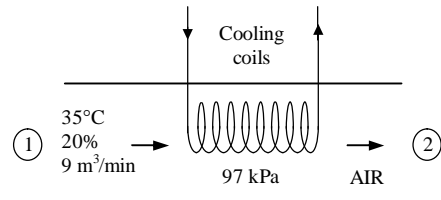
The air at the final state is saturated and the vapor pressure during this process remains constant. Therefore, the exit temperature of the air must be the dew-point temperature,

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ 1.13 kPa}} = \mathbf{8.6°C}$$

(*b*) The enthalpy of the air at the exit is

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (1.005\,\text{kJ/kg}\cdot°\text{C})(8.6°\text{C}) + (0.0073)(2517.1\,\text{kJ/kg})$$

$$= 27.02\,\text{kJ/kg dry air}$$

Also,

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{9\,\text{m}^3/\text{s}}{0.922\,\text{m}^3/\text{kg dry air}} = 9.76\,\text{kg/min}$$

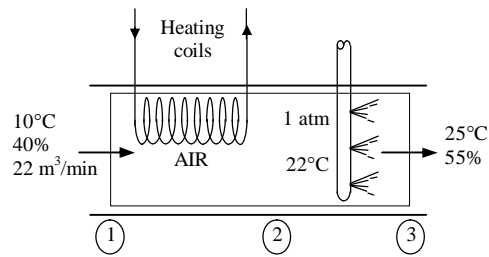Then the rate of heat transfer from the air in the cooling section becomes

$$\dot{Q}_{\text{out}} = \dot{m}_a(h_1 - h_2) = (9.76\,\text{kg/min})(53.90 - 27.02)\,\text{kJ/kg} = \mathbf{262.4\,kJ/min}$$

9-176 The outdoor air is first heated and then humidified by hot steam in an air-conditioning system. The rate of heat supply in the heating section and the mass flow rate of the steam required in the humidifying 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.

Properties The amount of moisture in the air also remains constants 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 1 atm. The properties of the air at various states are determined from the psychometric chart to be

$h_1 = 17.7 \text{ kJ/kg dry air}$

$\omega_1 = 0.0030 \text{ kg H}_2\text{O/kg dry air} (= \omega_2)$

$v_1 = 0.807 \text{ m}^3/\text{kg dry air}$

$h_2 = 29.8 \text{ kJ / kg dry air}$

$\omega_2 = \omega_1 = 0.0030 \text{ kg H}_2\text{O / kg dry air}$

$h_3 = 52.9 \text{ kJ / kg dry air}$

$\omega_3 = 0.0109 \text{ kg H}_2\text{O / kg dry air}$

Analysis (*a*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{22 \text{ m}^3 / \text{min}}{0.807 \text{ m}^3 / \text{kg}} = 27.3 \text{ kg/min}$$

Then the rate of heat transfer to the air in the heating section becomes

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (27.3 \text{ kg/min})(29.8 - 17.7) \text{kJ/kg} = \textbf{330.3kJ/min}$$

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

$$\dot{m}_{a2}\omega_2 + \dot{m}_w = \dot{m}_{a3}\omega_3 \quad \text{or} \quad \dot{m}_w = \dot{m}_a(\omega_3 - \omega_2)$$

Thus,

$$\dot{m}_w = (27.3 \text{ kg/min})(0.0109 - 0.0030) = \textbf{0.216kg/min}$$

9-177 Air is cooled and dehumidified in an air-conditioning system. The rate of dehumidification, the rate of heat transfer, and the mass flow rate of the refrigerant 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 dew point temperature of the incoming air stream at 30°C is

$$T_{dp} = T_{\text{sat @ } P_v} = T_{\text{sat @ } 0.7 \times 4.246 \text{ kPa}} = 24°C$$

Since air is cooled to 20°C, which is below its dew point temperature, some of the moisture in the air will condense.

The mass flow rate of dry air remains constant during the entire process, but 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 psychometric chart (Figure A-33) to be

$$h_1 = 78.3 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0188 \text{ kg H}_2\text{O / kg dry air}$$
$$v_1 = 0.885 \text{ m}^3 \text{ / kg dry air}$$

and

$$h_2 = 57.5 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0147 \text{ kg H}_2\text{O / kg dry air}$$

Also,

$$h_w \cong h_{f@20°C} = 83.96 \text{ kJ / kg}$$

Then,

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{4 \text{ m}^3 \text{ / min}}{0.885 \text{ m}^3 \text{ / kg dry air}} = 4.52 \text{ kg / min}$$

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

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

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (4.52 \text{ kg / min})(0.0188 - 0.0147) = \textbf{0.0185 kg / min}$$

(*b*) *Energy Balance:*

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

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

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

$$\dot{Q}_{\text{out}} = (4.52 \text{ kg/min})(78.3 - 57.5)\text{kJ/kg} - (0.0185 \text{ kg/min})(83.96 \text{ kJ/kg}) = \textbf{92.5 kJ/min}$$
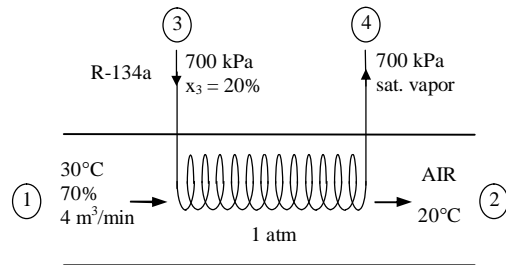
(*c*) The inlet and exit enthalpies of the refrigerant are

$$h_3 = h_g + x_3 h_{fg} = 86.78 + 0.2 \times 175.07 = 121.79 \text{ kJ/kg}$$
$$h_4 = h_{g@700 \text{ kPa}} = 261.85 \text{ kJ/kg}$$

Noting that the heat lost by the air is gained by the refrigerant, the mass flow rate of the refrigerant becomes

$$\dot{Q}_R = \dot{m}_R(h_4 - h_3) \;\rightarrow\; \dot{m}_R = \frac{\dot{Q}_R}{h_4 - h_3} = \frac{92.5 \text{ kJ/min}}{(261.85 - 121.79) \text{ kJ/kg}} = \textbf{0.66 kg/min}$$

9-178 Air is cooled and dehumidified in an air-conditioning system. The rate of dehumidification, the rate of heat transfer, and the mass flow rate of the refrigerant 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 30°C is

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{sat\,@\,30°C} = (0.7)(4.246\ kPa) = 2.97\ kPa$$

$$T_{dp} = T_{sat\,@\,P_v} = T_{sat\,@\,2.97\ kPa} = 24°C$$

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. The properties of the air at both states are determined to be

$$P_{a1} = P_1 - P_{v1} = 95 - 2.97 = 92.03\ kPa$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\ kPa \cdot m^3/kg \cdot K)(303\ K)}{92.03\ kPa} = 0.945\ m^3/kg\ dry\ air$$

$$\omega_1 = \frac{0.622\ P_{v1}}{P_1 - P_{v1}} = \frac{0.622(2.97\ kPa)}{(95 - 2.97)\ kPa} = 0.0201\ kg\ H_2O/kg\ dry\ air$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\ kJ/kg\cdot°C)(30°C) + (0.0201)(2556.3\ kJ/kg)$$
$$= 81.53\ kJ/kg\ dry\ air$$

and

$$P_{v2} = \phi_2 P_{g2} = (1.00)P_{sat\,@\,20°C} = 2.339\ kPa$$

$$\omega_2 = \frac{0.622\ P_{v2}}{P_2 - P_{v2}} = \frac{0.622(2.339\ kPa)}{(95 - 2.339)\ kPa} = 0.0157\ kg\ H_2O/kg\ dry\ air$$

$$h_2 = C_p T_2 + \omega_2 h_{g2} = (1.005\ kJ/kg \cdot °C)(20°C) + (0.0157)(2538.1\ kJ/kg)$$
$$= 59.95\ kJ/kg\ dry\ air$$

Also,

$$h_w \cong h_{f@20°C} = 83.96\ kJ/kg \qquad \text{(Table A-4)}$$

Then,

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{4\ m^3/min}{0.945\ m^3/kg\ dry\ air} = 4.23\ kg/min$$

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

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

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (4.23\ kg/min)(0.0201 - 0.0157) = \mathbf{0.0186\ kg/min}$$

(*b*) *Energy Balance:*
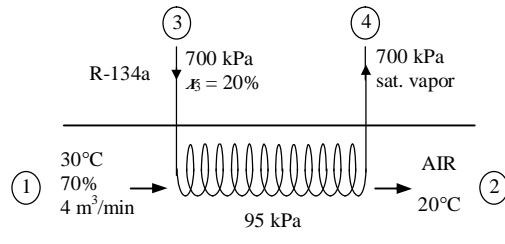
$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}^{\ddot{a}0 \text{ (steady)}} = 0$$

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

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

$$\dot{Q}_{out} = (4.23 \text{ kg/min})(81.53 - 59.95)\text{kJ/kg} - (0.0186 \text{ kg/min})(83.96 \text{ kJ/kg}) = \mathbf{89.7\,kJ/min}$$

(*c*) The inlet and exit enthalpies of the refrigerant are

$$h_3 = h_g + x_3 h_{fg} = 86.78 + 0.2 \times 175.07 = 121.79 \text{ kJ/kg}$$

$$h_4 = h_{g @ 700 \text{ kPa}} = 261.85 \text{ kJ/kg}$$

Noting that the heat lost by the air is gained by the refrigerant, the mass flow rate of the refrigerant is determined from

$$\dot{Q}_R = \dot{m}_R (h_4 - h_3)$$

$$\dot{m}_R = \frac{\dot{Q}_R}{h_4 - h_3} = \frac{89.7 \text{ kJ/min}}{(261.85 - 121.79) \text{ kJ/kg}} = \mathbf{0.640\,kg/min}$$

9-179 Air is heated and dehumidified in an air-conditioning system consisting of a heating section and an evaporative cooler. The temperature and relative humidity of the air when it leaves the heating section, the rate of heat transfer in the heating section, and the rate of water added to the air in the evaporative cooler 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*) Assuming the wet-bulb temperature of the air remains constant during the evaporative cooling process, the properties of air at various states are determined from the psychrometric chart (Figure A-33) to be

$$\left.\begin{array}{l} T_1 = 10°C \\ \phi_1 = 70\% \end{array}\right\} \begin{array}{l} h_1 = 23.5 \text{ kJ/kg dry air} \\ \omega_1 = 0.00532 \text{ kg/ } H_2O/\text{kg dry air} \\ v_1 = 0.810 \text{ m}^3 / \text{kg} \end{array}$$

$$\left.\begin{array}{l} \omega_2 = \omega_1 \\ T_{wb2} = T_{wb3} \end{array}\right\} \begin{array}{l} T_2 = \mathbf{28.3°C} \\ \phi_2 = \mathbf{23.0\%} \\ h_2 \cong h_3 = 42.3 \text{ kJ / kg dry air} \end{array}$$

$$\left.\begin{array}{l} T_3 = 20°C \\ \phi_3 = 60\% \end{array}\right\} \begin{array}{l} h_3 = 42.3 \text{ kJ/kg dry air} \\ \omega_3 = 0.00875 \text{ kg/ } H_2O/\text{kg dry air} \\ T_{wb3} = 15.1°C \end{array}$$
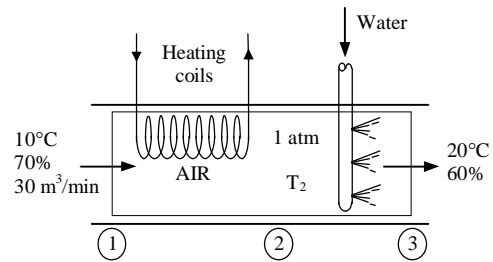
(*b*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{30 \text{ m}^3 / \text{min}}{0.810 \text{ m}^3 / \text{kg dry air}} = 37.0 \text{ kg/min}$$

Then the rate of heat transfer to air in the heating section becomes

$$\dot{Q}_{in} = \dot{m}_a (h_2 - h_1) = (37.0 \text{ kg/min})(42.3 - 23.5)\text{kJ/kg} = \mathbf{696 \text{ kJ/min}}$$

(*c*) The rate of water added to the air in evaporative cooler is

$$\begin{aligned} \dot{m}_{w, added} &= \dot{m}_{w3} - \dot{m}_{w2} = \dot{m}_a (\omega_3 - \omega_2) \\ &= (37.0 \text{ kg/min})(0.00875 - 0.00532) \\ &= \mathbf{0.127 \text{ kg/min}} \end{aligned}$$

9-180 Problem 9-179 is reconsidered. The effect of total pressure in the range 94 to 104 kPa on the desored results in the problem is to be investigated, and the results are to be plotted as functions of total pressure.

P=101.325"[kPa]"
Tdb[1] =10"[C]"
Rh[1] = 0.70
Vol_dot[1]= 50"[m^3/min]"
Tdb[3] = 20"[C]"
Rh[3] = 0.60
P[1]=P"[kPa]"
P[2]=P[1]"[kPa]"
P[3]=P[1]"[kPa]"

"Energy balance for the steady-flow heating process 1 to 2:"
"We neglect the PE of the flow. Since we don't know the cross sectional area of the flow streams, we also neglect the KE of the flow."
E_dot_in - E_dot_out = DELTAE_dot_sys
DELTAE_dot_sys = 0"[kJ/min]"
E_dot_in = m_dot_a*h[1]+Q_dot_in"[kJ/min]"
E_dot_out = m_dot_a*h[2]"[kJ/min]"
"Conservation of mass of dry air during mixing: m_dot_a = constant"
m_dot_a = Vol_dot[1]/v[1] "[kga/in]"
"Conservation of mass of water vapor during the heating process:"
m_dot_a*w[1] = m_dot_a*w[2]
"Conservation of mass of water vapor during the evaporative cooler process:"
m_dot_a*w[2]+m_dot_w = m_dot_a*w[3]

"During the evaporative cooler process:"
Twb[2] = Twb[3]
Twb[3] =WETBULB(AirH2O,T=Tdb[3],P=P[3],R=Rh[3])
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],B=Twb[2])}
h[2]=h[3]
Tdb[2]=TEMPERATURE(AirH2O,h=h[2],P=P[2],w=w[2])
w[2]=HUMRAT(AirH2O,T=Tdb[2],P=P[2],R=Rh[2])
h[3]=ENTHALPY(AirH2O,T=Tdb[3],P=P[3],R=Rh[3])
w[3]=HUMRAT(AirH2O,T=Tdb[3],P=P[3],R=Rh[3])

m_w [kg/min]	Q_{in} [kJ/min]	Rh_2	Tdb_2 [C]	P [kPa]
0.2112	1119	0.212	29.2	94
0.2112	1131	0.2144	29	96
0.2111	1143	0.2167	28.82	98
0.2111	1155	0.219	28.64	100
0.211	1168	0.2212	28.47	102
0.2109	1180	0.2233	28.3	104
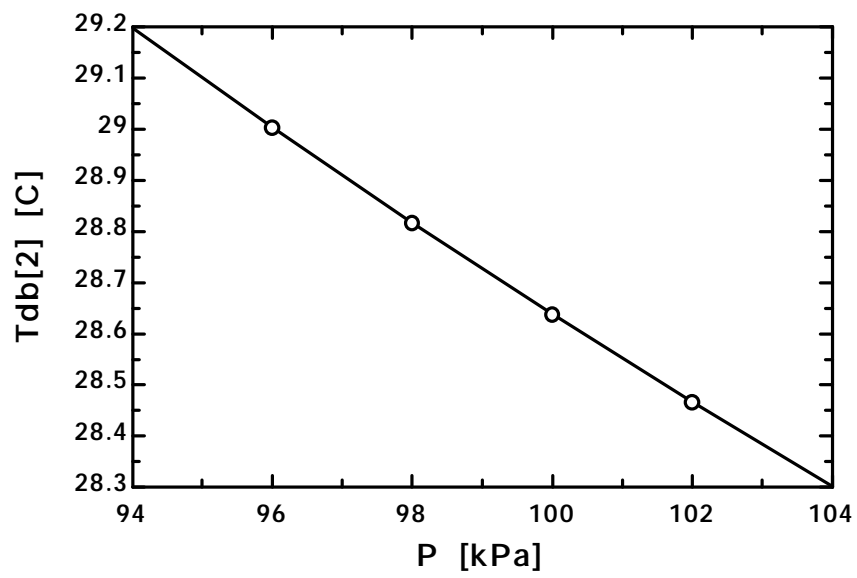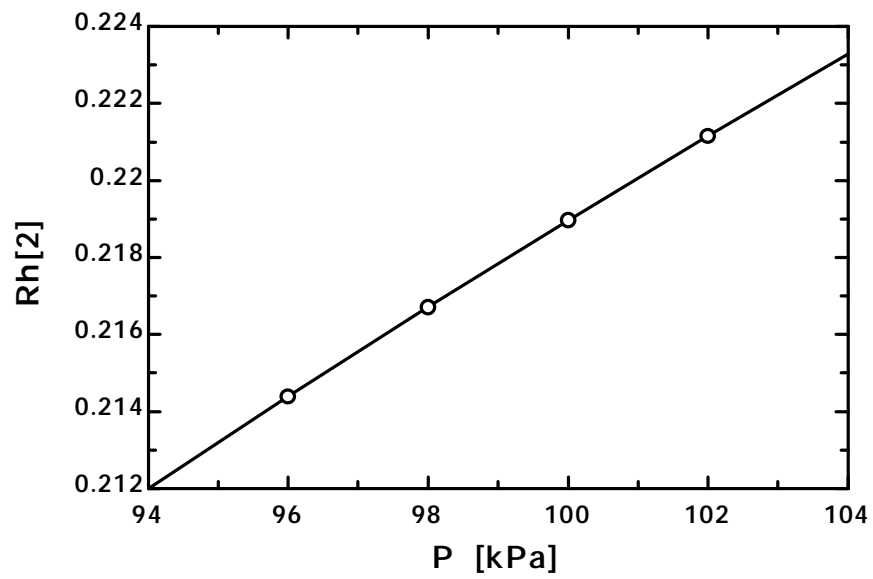
9-181 Air is heated and dehumidified in an air-conditioning system consisting of a heating section and an evaporative cooler. The temperature and relative humidity of the air when it leaves the heating section, the rate of heat transfer in the heating section, and the rate at which water is added to the air in the evaporative cooler 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*) Assuming the wet-bulb temperature of the air remains constant during the evaporative cooling process, the properties of air at various states are determined to be

$$P_{v1} = \phi_1 P_{g1} = \phi_1 P_{sat\,@\,10°C} = (0.70)(1.2276\,\text{kPa}) = 0.86\,\text{kPa}$$

$$P_{a1} = P_1 - P_{v1} = 96 - 0.86 = 95.14\,\text{kPa}$$

$$v_1 = \frac{R_a T_1}{P_{a1}} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(283\,\text{K})}{95.14\,\text{kPa}}$$

$$= 0.854\,\text{m}^3/\text{kg dry air}$$

$$\omega_1 = \frac{0.622\,P_{v1}}{P_1 - P_{v1}} = \frac{0.622(0.86\,\text{kPa})}{(96-0.86)\,\text{kPa}} = 0.00562\,\text{kg H}_2\text{O/kg dry air}$$

$$h_1 = C_p T_1 + \omega_1 h_{g1} = (1.005\,\text{kJ/kg}\cdot°\text{C})(10°\text{C}) + (0.00562)(2519.8\,\text{kJ/kg})$$

$$= 24.21\,\text{kJ/kg dry air}$$
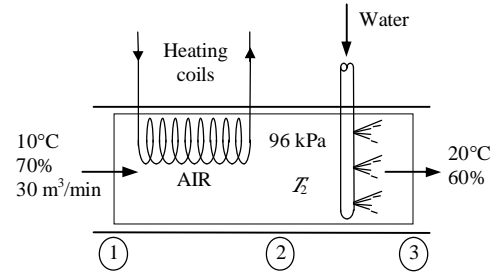
and

$$P_{v3} = \phi_3 P_{g3} = \phi_3 P_{sat\,@\,20°C} = (0.60)(2.339\,\text{kPa}) = 1.40\,\text{kPa}$$

$$P_{a3} = P_3 - P_{v3} = 96 - 1.40 = 94.60\,\text{kPa}$$

$$\omega_3 = \frac{0.622\,P_{v3}}{P_3 - P_{v3}} = \frac{0.622(1.40\,\text{kPa})}{(96-1.40)\,\text{kPa}} = 0.00921\,\text{kg H}_2\text{O/kg dry air}$$

$$h_3 = C_p T_3 + \omega_3 h_{g3} = (1.005\,\text{kJ/kg}\cdot°\text{C})(20°\text{C}) + (0.00921)(2538.1\,\text{kJ/kg})$$

$$= 43.48\,\text{kJ/kg dry air}$$

Also,

$$h_2 \cong h_3 = 43.48\,\text{kJ/kg}$$

$$\omega_2 = \omega_1 = 0.00562\,\text{kg H}_2\text{O/kg dry air}$$

Thus,

$$h_2 = C_p T_2 + \omega_2 h_{g2} \cong C_p T_2 + \omega_2(2501.3 + 1.82\,T_2) 43.48\,\text{kJ/kg}$$

$$= (1.005\,\text{kJ/kg}\cdot°\text{C})\,T_2 + (0.00562)(2501.3 + 1.82\,T_2)\,\text{kJ/kg}$$

Solving for T_2,

$$T_2 = \mathbf{29.0°C} \quad\longrightarrow\quad P_{g2} = P_{sat\,@\,29°C} = 4.031\,\text{kPa}$$

Thus,

$$\phi_2 = \frac{\omega_2 P_2}{(0.622 + \omega_2) P_{g2}} = \frac{(0.00562)(96)}{(0.622 + 0.00562)(4.031)} = 0.213 \text{ or } \mathbf{21.3\%}$$

(*b*) The mass flow rate of dry air is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{30 \, \text{m}^3 / \text{min}}{0.854 \, \text{m}^3 / \text{kg dry air}} = 35.1 \, \text{kg/min}$$

Then the rate of heat transfer to air in the heating section becomes

$$\dot{Q}_{\text{in}} = \dot{m}_a (h_2 - h_1) = (35.1 \, \text{kg/min})(43.48 - 24.21) \text{kJ/kg} = \mathbf{676 \, kJ/min}$$

(*c*) The rate of water addition to the air in evaporative cooler is

$$\begin{aligned}
\dot{m}_{w,\text{added}} &= \dot{m}_{w3} - \dot{m}_{w2} = \dot{m}_a (\omega_3 - \omega_2) \\
&= (35.1 \, \text{kg/min})(0.00921 - 0.00562) \\
&= \mathbf{0.126 \, kg/min}
\end{aligned}$$

9-182 Conditioned air is to be mixed with outside air. The ratio of the dry air mass flow rates of the conditioned- to-outside air, and the temperature 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 chamber is adiabatic.

Properties The properties of each inlet stream are determined from the psychometric chart (Figure A-33) to be

$$h_1 = 34.3 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0084 \text{ kg } H_2O \text{ / kg dry air}$$

and

$$h_2 = 68.5 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0134 \text{ kg } H_2O \text{ / kg dry air}$$

Analysis The ratio of the dry air mass flow rates of the Conditioned air to the outside air can be determined from

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$
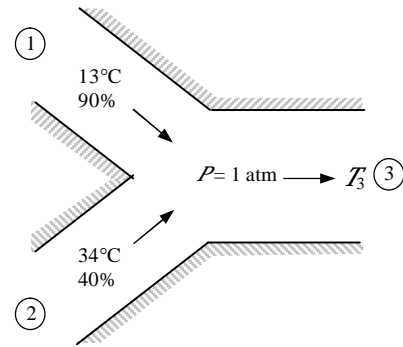
But state 3 is not completely specified. However, we know that state 3 is on the straight line connecting states 1 and 2 on the psychometric chart. At the intersection point of this line and $\phi = 60\%$ line we read

(*b*) $T_3 = \mathbf{23.5° C}$

$$\omega_3 = 0.0109 \text{ kg } H_2O/\text{kg dry air}$$
$$h_3 = 51.3 \text{ kJ/kg dry air}$$

Therefore, the mixture will leave at 23.5°C. The $\dot{m}_{a1} / \dot{m}_{a2}$ ratio is determined by substituting the specific humidity (or enthalpy) values into the above relation,
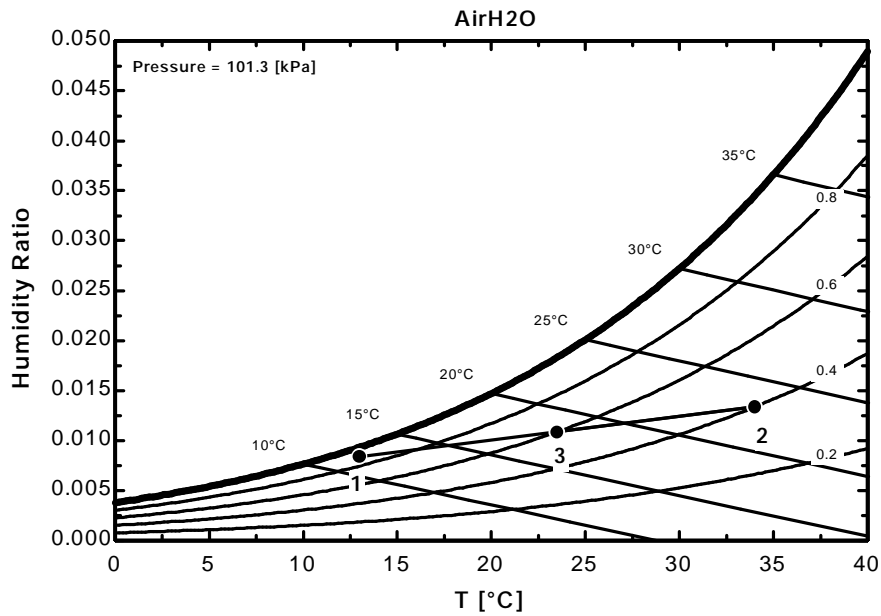
(*a*) $$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{0.0134 - 0.0109}{0.0109 - 0.0084} = \mathbf{1.00}$$

Therefore, the mass flow rate of each stream must be the same.

9-183 Problem 9-182 is reconsidered. The desired quantities are to be determined using EES (or other) software instead of the psychrometric chart. The results are also to be determined for a

location at an atmospheric pressure of 80 kPa.

"Without loss of generality assume the mass flow rate of the outside air is m_dot[2] = 1 kg/s."
{P=14.696"[psia]"
Tdb[1] =13"[C]" "State 1 is the conditioned air"
Rh[1] = 0.90
Tdb[2] =34"[C]" "State 2 is the outside air"
Rh[2] = 0.40
Rh[3] = 0.60}
P[1]=P"[kPa]"
P[2]=P[1]"[kPa]"
P[3]=P[1]"[kPa]"
m_dot[2] = 1"[kga/s]"
MassRatio = m_dot[1]/m_dot[2]
"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]

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],R=Rh[3])
w[3]=HUMRAT(AirH2O,T=Tdb[3],P=P[3],R=Rh[3])
v[3]=VOLUME(AirH2O,T=Tdb[3],P=P[3],w=w[3])

SOLUTION
Variables in Main
DELTAE_dot_sys=0
E_dot_in=118.2 [kW]
E_dot_out=118.2 [kW]
h[1]=40 [kJ/kga]
h[2]=77.82 [kJ/kga]
h[3]=58.82 [kJ/kga]
MassRatio=1.009
m_dot[1]=1.009 [kga/s]
m_dot[2]=1 [kga/s]
m_dot[3]=2.009 [kga/s]
P=80 [kPa]
P[1]=80 [kPa]
P[2]=80 [kPa]
P[3]=80 [kPa]
Rh[1]=0.9
Rh[2]=0.4
Rh[3]=0.6
Tdb[1]=13 [C]
Tdb[2]=34 [C]
Tdb[3]=23.51 [C]
v[1]=1.044 [m^3/kga]
v[2]=1.132 [m^3/kga]
v[3]=1.088 [m^3/kga]
w[1]=0.01066 [kgw/kga]
w[2]=0.01701 [kgw/kga]
w[3]=0.01382 [kgw/kga]

9-184 [_Also solved by EES on enclosed CD_**]** Waste heat from the cooling water is rejected to air in a natural-draft cooling tower. The mass flow rate of the cooling water, 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. **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 is made up later in the cycle using water at 27°C. 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:

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

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

Energy Balance:

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

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

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

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

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

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

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 (Figure A-33),

$$h_1 = 50.8 \text{ kJ / kg dry air}$$
$$\omega_1 = 0.0109 \text{ kg H}_2\text{O / kg dry air}$$
$$v_1 = 0.854 \text{ m}^3 \text{ / kg dry air}$$

and

$$h_2 = 143.0 \text{ kJ / kg dry air}$$
$$\omega_2 = 0.0412 \text{ kg H}_2\text{O / kg dry air}$$

From Table A-4,

$$h_3 \cong h_{f@42°C} = 175.92 \text{ kJ / kg H}_2\text{O}$$
$$h_4 \cong h_{f@27°C} = 113.25 \text{ kJ / kg H}_2\text{O}$$

Substituting,

$$\dot{m}_a = \frac{\dot{m}_3(175.92 - 113.25)\text{kJ / kg}}{(143.0 - 50.8) \text{ kJ / kg} - (0.0412 - 0.0109)(113.25) \text{ kJ / kg}} = 0.706 \dot{m}_3$$

The mass flow rate of the cooling water is determined by applying the steady flow energy balance equation on the cooling water,
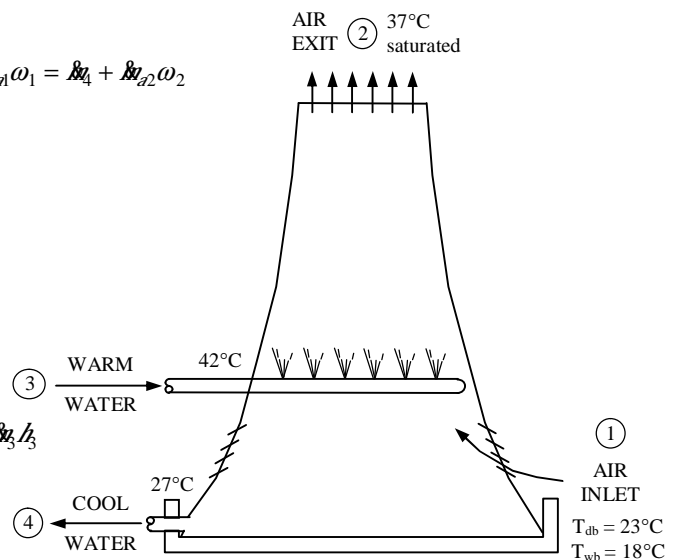
$$\dot{Q}_{\text{waste}} = \dot{m}_3 h_3 - (\dot{m}_3 - \dot{m}_{\text{makeup}}) h_4 = \dot{m}_3 h_3 - [\dot{m}_3 - \dot{m}_a(\omega_2 - \omega_1)] h_4$$

$$= \dot{m}_3 h_3 - \dot{m}_3[1 - 0.706(0.0412 - 0.0109)] h_4 = \dot{m}_3(h_3 - 0.9786 h_4)$$

$$50{,}000\,\text{kJ/s} = \dot{m}_3(175.92 - 0.9786 \times 113.25)\,\text{kJ/kg}$$

$$\dot{m}_3 = \mathbf{768.1\,kg/s}$$

and

$$\dot{m}_a = 0.706 \dot{m}_3 = (0.706)(768.1\,\text{kg/s}) = 542.3\,\text{kg/s}$$

(*b*) Then the volume flow rate of air into the cooling tower becomes

$$\dot{V}_1 = \dot{m}_a v_1 = (542.3\,\text{kg/s})(0.854\,\text{m}^3/\text{kg}) = \mathbf{463.1\,m^3/s}$$

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

$$\dot{m}_{\text{makeup}} = \dot{m}_a(\omega_2 - \omega_1) = (542.3\,\text{kg/s})(0.0412 - 0.0109) = \mathbf{16.4\,kg/s}$$

9-185 Problem 9-184 is reconsidered. The effect of air inlet wet-bulb temperature on the required air volume flow rate and the makeup water flow rate when the other input data are the stated values are to be investigated. The results are to be plotted as functions of wet-bulb temperature.

"Plot Window 1 shows the effect of air inlet wet-bulb temperature on
the required air volume flow rate and the makeup water flow rate.
All other input data were the stated values. To generate the data
for these plots, place '{ }' about the line T_wb_1 = 18'C'. Then press
F3 or select Solve Table from the Calculate menu."

"Input Data"

P_atm =101.32 "kPa"
T_db_1 = 23"C"
T_wb_1 = 18"C"
T_db_2 = 37"C"
RH_2 = 100/100"%. relative humidity at state 2, saturated condition"
Q_dot_waste = 50"Mw"*1000"kJ/s/MW"
T_cw_3 = 42"C" "Cooling water temperature at state 3"
T_cw_4 = 27"C" "Cooling water temperature at state 4"

"Dry air mass flow rates:"
"RH_1 is the relative humidity at state 1 on a decimal basis"

v_1=VOLUME(AirH2O,T=T_db_1,P=P_atm,R=RH_1)
T_wb_1 = WETBULB(AirH2O,T=T_db_1,P=P_atm,R=RH_1)
m_dot_a_1 = Vol_dot_1/v_1

"Conservation of mass for the dry air (ma) in the SSSF mixing device:"

m_dot_a_in - m_dot_a_out = DELTAm_dot_a_cv
m_dot_a_in = m_dot_a_1
m_dot_a_out = m_dot_a_2
DELTAm_dot_a_cv = 0   "Stead flow requirement"

"Conservation of mass for the water vapor (mv) and cooling water for the SSSF process:"

m_dot_w_in - m_dot_w_out = DELTAm_dot_w_cv
m_dot_w_in = m_dot_v_1 + m_dot_cw_3
m_dot_w_out = m_dot_v_2+m_dot_cw_4
DELTAm_dot_w_cv = 0   "Stead flow requirement"
w_1=HUMRAT(AirH2O,T=T_db_1,P=P_atm,R=RH_1)
m_dot_v_1 = m_dot_a_1*w_1
w_2=HUMRAT(AirH2O,T=T_db_2,P=P_atm,R=RH_2)
m_dot_v_2 = m_dot_a_2*w_2

"Conservation of energy for the SSSF cooling tower process:"
"The process is adiabatic and has no work done, neglect ke and pe"

E_dot_in_tower - E_dot_out_tower = DELTAE_dot_tower_cv
E_dot_in_tower= m_dot_a_1 *h[1] + m_dot_cw_3*h_w[3]
E_dot_out_tower = m_dot_a_2*h[2] + m_dot_cw_4*h_w[4]
DELTAE_dot_tower_cv = 0   "Steady flow requirement"
h[1]=ENTHALPY(AirH2O,T=T_db_1,P=P_atm,w=w_1)
h[2]=ENTHALPY(AirH2O,T=T_db_2,P=P_atm,w=w_2)
h_w[3]=ENTHALPY(steam,T=T_cw_3,x=0)
h_w[4]=ENTHALPY(steam,T=T_cw_4,x=0)

"Energy balance on the external heater determines the cooling water flow rate:"
"Assume the makeup water is supplied at a temperature equal to T_cw_4."

E_dot_in_heater - E_dot_out_heater = DELTAE_dot_heater_cv
E_dot_in_heater = Q_dot_waste + m_dot_cw_4*h_w[4]+ m_dot_makeup * h_w[4]
E_dot_out_heater = m_dot_cw_3 * h_w[3]
DELTAE_dot_heater_cv = 0   "Steady flow requirement"

"Conservation of mass on the external heater gives the makeup water flow rate."
"Note: The makeup water flow rate equals the amount of water vaporized in the cooling tower."

m_dot_cw_in - m_dot_cw_out = DELTAm_dot_cw_cv
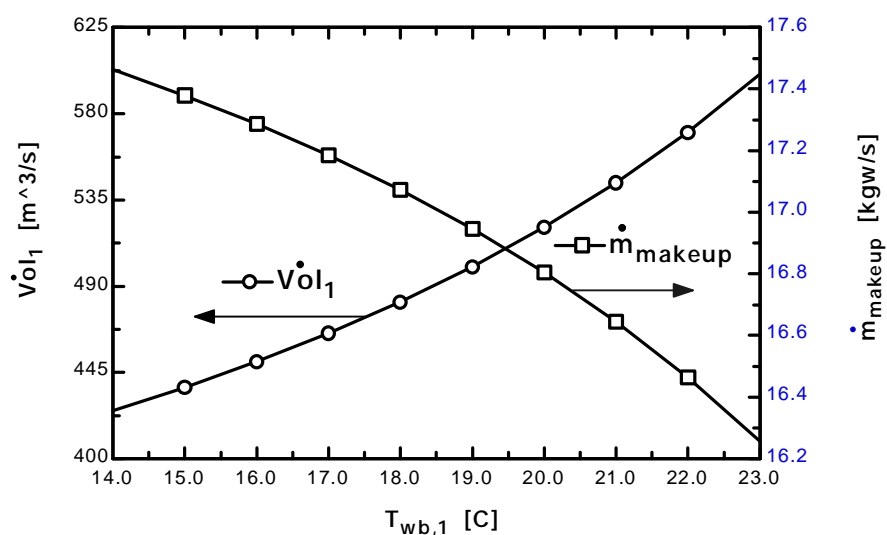m_dot_cw_in = m_dot_cw_4 + m_dot_makeup
m_dot_cw_out = m_dot_cw_3
DELTAm_dot_cw_cv = 0   "Stead flow requirement"

Vol_1 [m³/s]	m_{makeup} [kgw/s]	m_{cw3} [kgw/s]	m_{a1} [kga/s]	T_{wb1} [C]
424.9	17.46	798.5	501.3	14
437.1	17.38	798.5	514.8	15
450.6	17.29	798.5	529.7	16
465.4	17.19	798.5	546.1	17
481.8	17.07	798.5	564.3	18
500.2	16.95	798.5	584.6	19
520.7	16.8	798.5	607.4	20
543.9	16.64	798.5	633.1	21
570.3	16.46	798.5	662.3	22
600.6	16.26	798.5	695.8	23

Effect of $T_{wb,1}$ on inlet volume flow rate and makeup water flow rate

9-186 ··· 9-191 Design and Essay Problems

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