Chapter 12

GAS MIXTURES

Composition of Gas Mixtures

12-1C It is the average or the equivalent gas constant of the gas mixture. No.

12-2C No. We can do this only when each gas has the same mole fraction.

12-3C It is the average or the equivalent molar mass of the gas mixture. No.

12-4C The mass fractions will be identical, but the mole fractions will not.

12-5C Yes.

12-6C 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*).

12-7C From the definition of mass fraction,

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

12-8C Yes, because both CO_2 and N_2O has the same molar mass, M = 44 kg/kmol.

12-9 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.

12-13 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

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

5 kg O_2
8 kg N_2
10 kg CO_2

Then the mass fraction of each component becomes

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

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

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

(*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

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

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

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

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

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

and

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

P-v-T Behavior of Gas Mixtures

12-17C 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.

12-18C 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.

12-19C 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.

12-20C 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.

12-21C 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.

12-22C 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.

12-23C The one with the highest mole number.

12-24C The partial pressures will decrease but the pressure fractions will remain the same.

12-25C The partial pressures will increase but the pressure fractions will remain the same.

12-26C 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."

12-27C No. The correct expression is "the temperature of a gas mixture is equal to the temperature of the individual gas components."

12-28C Yes, it is correct.

12-29C 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.

12-33 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

1 kg CO_2 3 kg CH_4 300 K 200 kPa

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

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

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

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

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

Then the partial pressures become

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

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

The apparent molar mass of the mixture is

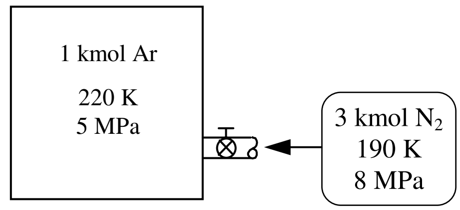
$$M_m = \frac{m_m}{N_m} = \frac{4\text{ kg}}{0.2102\text{ kmol}} = \mathbf{19.03\ kg/kmol}$$

12-39 [*Also solved by EES on enclosed CD*] The mole numbers, temperatures, and pressures of two gases forming a mixture are given. The final temperature is also given. The pressure of the mixture is to be determined using two methods.

Analysis (*a*) Under specified conditions both Ar and N_2 will considerably deviate from the ideal gas behavior. Treating the mixture as an ideal gas,

$$\left.\begin{array}{l}\text{Initial state}: P_1V_1 = N_1R_uT_1 \\ \text{Final state}: P_2V_2 = N_2R_uT_2\end{array}\right\} P_2 = \frac{N_2T_2}{N_1T_1}P_1 = \frac{(4)(200\text{ K})}{(1)(220\text{ K})}(5\text{ MPa}) = \mathbf{18.2\ MPa}$$

(*b*) Initially,



$$\left.\begin{array}{l} T_R = \dfrac{T_1}{T_{cr,\text{Ar}}} = \dfrac{220\text{K}}{151.0\text{K}} = 1.457 \\ P_R = \dfrac{P_1}{P_{cr,\text{Ar}}} = \dfrac{5\text{MPa}}{4.86\text{MPa}} = 1.0278 \end{array}\right\} Z_{\text{Ar}} = 0.90$$

Then the volume of the tank is

$$V = \frac{ZNR_uT}{P} = \frac{(0.90)(1\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(220\text{ K})}{5000\text{ kPa}} = 0.33\text{ m}^3$$

After mixing,

$$\text{Ar:}\quad \left.\begin{array}{l} T_{R,\text{Ar}} = \dfrac{T_m}{T_{cr,\text{Ar}}} = \dfrac{200\text{K}}{151.0\text{K}} = 1.325 \\ \text{v}_{R,\text{Ar}} = \dfrac{\text{v}_{\text{Ar}}}{R_uT_{cr,\text{Ar}}/P_{cr,\text{Ar}}} = \dfrac{V_m/N_{\text{Ar}}}{R_uT_{cr,\text{Ar}}/P_{cr,\text{Ar}}} \\ \quad = \dfrac{(0.33\text{m}^3)/(1\text{kmol})}{(8.314\text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(151.0\text{K})/(4860\text{kPa})} = 1.278 \end{array}\right\} P_R = 0.90$$

$$\text{N}_2\text{:}\quad \left.\begin{array}{l} T_{R,\text{N}_2} = \dfrac{T_m}{T_{cr,\text{N}_2}} = \dfrac{200\text{K}}{126.2\text{K}} = 1.585 \\ \text{v}_{R,\text{N}_2} = \dfrac{\text{v}_{\text{N}_2}}{R_uT_{cr,\text{N}_2}/P_{cr,\text{N}_2}} = \dfrac{V_m/N_{\text{N}_2}}{R_uT_{cr,\text{N}_2}/P_{cr,\text{N}_2}} \\ \quad = \dfrac{(0.33\text{m}^3)/(3\text{kmol})}{(8.314\text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(126.2\text{K})/(3390\text{kPa})} = 0.355 \end{array}\right\} P_R = 3.75$$

Thus,

$$P_{\text{Ar}} = (P_RP_{cr})_{\text{Ar}} = (0.90)(4.86\text{ MPa}) = 4.37\text{ MPa}$$
$$P_{\text{N}_2} = (P_RP_{cr})_{\text{N}_2} = (3.75)(3.39\text{ MPa}) = 12.7\text{ MPa}$$

and $\quad P_m = P_{\text{Ar}} + P_{\text{N}_2} = 4.37\text{ MPa} + 12.7\text{ MPa} = \mathbf{17.1\ MPa}$

12-40 EES solution of this (and other comprehensive problems designated with the *computer icon*) is available to instructors at the *Instructor Manual* section of the *Online Learning Center* (OLC) at www.mhhe.com/cengel-boles. See the Preface for access information.

Properties of Gas Mixtures

12-42C Yes. Yes (extensive property).

12-43C No (intensive property).

12-44C The answers are the same for entropy.

12-45C Yes. Yes (conservation of energy).

12-46C We have to use the partial pressure.

12-47C 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.)

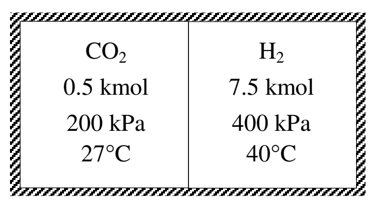
12-48 The moles, temperatures, and pressures of two gases forming a mixture are given. The mixture temperature and pressure are to be determined.

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

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$
$$0 = \Delta U = \Delta U_{CO_2} + \Delta U_{H_2}$$
$$0 = [mC_v(T_m - T_1)]_{CO_2} + [mC_v(T_m - T_1)]_{H_2}$$



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

$$(0.5\times 44\text{kg})(0.657\text{kJ/kg}\cdot{}^\circ\text{C})(T_m - 27^\circ\text{C}) + (7.5\times 2\text{kg})(10.183\text{kJ/kg}\cdot{}^\circ\text{C})(T_m - 40^\circ\text{C}) = 0$$
$$T_m = \mathbf{38.9^\circ C} \quad (311.9\text{K})$$

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

$$V_{CO_2} = \left(\frac{NR_uT_1}{P_1}\right)_{CO_2} = \frac{(0.5\text{kmol})(8.314\text{kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(300\text{K})}{200\text{kPa}} = 6.24\text{m}^3$$

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

Thus,

$$V_m = V_{CO_2} + V_{H_2} = 6.24\text{ m}^3 + 48.79\text{ m}^3 = 55.03\text{ m}^3$$
$$N_m = N_{CO_2} + N_{H_2} = 0.5\text{ kmol} + 7.5\text{ kmol} = 8.0\text{ kmol}$$

and

$$P_m = \frac{N_mR_uT_m}{V_m} = \frac{(8.0\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(311.9\text{ K})}{55.03\text{ m}^3} = \mathbf{377\ kPa}$$