Chapter 13

GAS MIXTURES

Composition of Gas Mixtures

13-1C It is the average or the equivalent gas constant of the gas mixture. No.

13-2C No. We can do this only when each gas has the same mole fraction.

13-3C It is the average or the equivalent molar mass of the gas mixture. No.

13-4C The mass fractions will be identical, but the mole fractions will not.

13-5C Yes.

13-6C 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*).

13-7C From the definition of mass fraction,

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

13-8C Yes, because both CO_2 and N_2O has the same molar mass, M = 44 kg/kmol.

13-9 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

$$\mathrm{mf}_A = \frac{m_A}{m_m} = \frac{N_A M_A}{N_m M_m} = y_A \frac{M_A}{M_m} \qquad \text{and} \qquad \mathrm{mf}_B = y_B \frac{M_B}{M_m}$$

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,

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

which are the desired relations.

13-10 The definitions for the mass fraction, weight, and the weight fractions are

$$(\mathrm{mf})_i = \frac{m_i}{m_{\text{total}}}$$

$$W = mg$$

$$(\mathrm{wf})_i = \frac{W_i}{W_{\text{total}}}$$

Since the total system consists of one mass unit, the mass of the ith component in this mixture is xi. The weight of this one component is then

$$W_i = g(\mathrm{mf})_i$$

Hence, the weight fraction for this one component is

$$(\mathrm{wf})_i = \frac{g(\mathrm{mf})_i}{\sum g(\mathrm{mf})_i} = (\mathrm{mf})_i$$

13-11 The moles of components of a gas mixture are given. The mole fractions and the apparent molecular weight are to be determined.

Properties The molar masses of He, O_2, N_2, and H_2O are 4.0, 32.0, 28.0 and 18.0 lbm/lbmol, respectively (Table A-1).

Analysis The total mole number of the mixture is

$$N_m = N_{\mathrm{He}} + N_{\mathrm{O2}} + N_{\mathrm{H2O}} + N_{\mathrm{N2}} = 1 + 2 + 0.1 + 1.5 = 4.6\,\mathrm{lbmol}$$

and the mole fractions are

$$y_{\mathrm{He}} = \frac{N_{\mathrm{He}}}{N_m} = \frac{1\,\mathrm{lbmol}}{4.6\,\mathrm{lbmol}} = \mathbf{0.217}$$

$$y_{\mathrm{O2}} = \frac{N_{\mathrm{O2}}}{N_m} = \frac{2\,\mathrm{lbmol}}{4.6\,\mathrm{lbmol}} = \mathbf{0.435}$$

$$y_{\mathrm{H2O}} = \frac{N_{\mathrm{H2O}}}{N_m} = \frac{0.1\,\mathrm{lbmol}}{4.6\,\mathrm{lbmol}} = \mathbf{0.0217}$$

$$y_{\mathrm{N2}} = \frac{N_{\mathrm{N2}}}{N_m} = \frac{1.5\,\mathrm{lbmol}}{4.6\,\mathrm{lbmol}} = \mathbf{0.326}$$

1 lbmol He
2 lbmol O_2
0.1 lbmol H_2O
1.5 lbmol N_2

The total mass of the mixture is

$$\begin{aligned} m_m &= m_{\mathrm{He}} + m_{\mathrm{O2}} + m_{\mathrm{H2O}} + + m_{\mathrm{N2}} \\ &= N_{\mathrm{He}} M_{\mathrm{He}} + N_{\mathrm{O2}} M_{\mathrm{O2}} + N_{\mathrm{H2O}} M_{\mathrm{H2O}} + N_{\mathrm{N2}} M_{\mathrm{N2}} \\ &= (1\,\mathrm{lbm})(4\,\mathrm{lbm/lbmol}) + (2\,\mathrm{lbm})(32\,\mathrm{lbm/lbmol}) + (0.1\,\mathrm{lbm})(18\,\mathrm{lbm/lbmol}) + (1.5\,\mathrm{lbm})(28\,\mathrm{lbm/lbmol}) \\ &= 111.8\,\mathrm{kg} \end{aligned}$$

Then the apparent molecular weight of the mixture becomes

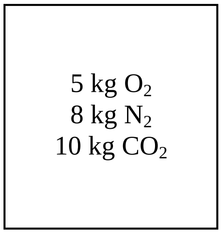
$$M_m = \frac{m_m}{N_m} = \frac{111.8\,\mathrm{lbm}}{4.6\,\mathrm{lbmol}} = \mathbf{24.3\ lbm/lbmol}$$

13-12 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

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

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

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

(*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

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

13-13 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

$$m_{\mathrm{CH_4}} = 75\ \mathrm{kg} \longrightarrow N_{\mathrm{CH_4}} = \frac{m_{\mathrm{CH_4}}}{M_{\mathrm{CH_4}}} = \frac{75\ \mathrm{kg}}{16\ \mathrm{kg/kmol}} = 4.688\ \mathrm{kmol}$$

$$m_{\mathrm{CO_2}} = 25\ \mathrm{kg} \longrightarrow N_{\mathrm{CO_2}} = \frac{m_{\mathrm{CO_2}}}{M_{\mathrm{CO_2}}} = \frac{25\ \mathrm{kg}}{44\ \mathrm{kg/kmol}} = 0.568\ \mathrm{kmol}$$

$$N_m = N_{\mathrm{CH_4}} + N_{\mathrm{CO_2}} = 4.688\ \mathrm{kmol} + 0.568\ \mathrm{kmol} = 5.256\ \mathrm{kmol}$$

mass

75% CH_4
25% CO_2

Then the mole fraction of each component becomes

$$y_{\mathrm{CH_4}} = \frac{N_{\mathrm{CH_4}}}{N_m} = \frac{4.688\ \mathrm{kmol}}{5.256\ \mathrm{kmol}} = 0.892 \text{ or } \mathbf{89.2\%}$$

$$y_{\mathrm{CO_2}} = \frac{N_{\mathrm{CO_2}}}{N_m} = \frac{0.568\ \mathrm{kmol}}{5.256\ \mathrm{kmol}} = 0.108 \text{ or } \mathbf{10.8\%}$$

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

$$M_m = \frac{m_m}{N_m} = \frac{100\ \mathrm{kg}}{5.256\ \mathrm{kmol}} = 19.03\ \mathrm{kg/kmol}$$

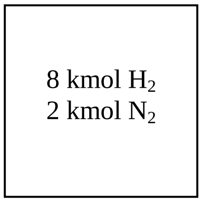
and

$$R_m = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol\cdot K}}{19.03\ \mathrm{kg/kmol}} = \mathbf{0.437\ kJ/kg\cdot K}$$

13-14 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



$$N_{H_2} = 8\text{ kmol} \longrightarrow m_{H_2} = N_{H_2}M_{H_2} = (8\text{ kmol})(2.0\text{ kg/kmol}) = \mathbf{16\text{ kg}}$$
$$N_{N_2} = 2\text{ kmol} \longrightarrow m_{N_2} = N_{N_2}M_{N_2} = (2\text{ kmol})(28\text{ kg/kmol}) = \mathbf{56\text{ kg}}$$

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,

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

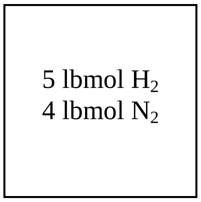
and

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

13-15E 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



$$N_{H_2} = 5\text{ lbmol} \longrightarrow m_{H_2} = N_{H_2}M_{H_2} = (5\text{ lbmol})(2.0\text{ lbm/lbmol}) = \mathbf{10\text{ lbm}}$$
$$N_{N_2} = 4\text{ lbmol} \longrightarrow m_{N_2} = N_{N_2}M_{N_2} = (4\text{ lbmol})(28\text{ lbm/lbmol}) = \mathbf{112\text{ lbm}}$$

The total mass and the total number of moles are

$$m_m = m_{H_2} + m_{N_2} = 10\text{ lbm} + 112\text{ lbm} = 122\text{ lbm}$$
$$N_m = N_{H_2} + N_{N_2} = 5\text{ lbmol} + 4\text{ lbmol} = 9\text{ lbmol}$$

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

$$M_m = \frac{m_m}{N_m} = \frac{122\text{ lbm}}{9\text{ lbmol}} = 13.56\text{ lbm/lbmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{1.986\text{ Btu/lbmol}\cdot\text{R}}{13.56\text{ lbm/lbmol}} = \mathbf{0.1465\text{ Btu/lbm}\cdot\text{R}}$$

13-16 The mass fractions of the constituents of a gas mixture are given. The volumetric analysis of the mixture and the apparent gas constant are to be determined.

Properties The molar masses of O_2, N_2 and CO_2 are 32.0, 28, 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

$$m_{\mathrm{O_2}} = 20\ \mathrm{kg} \longrightarrow N_{\mathrm{O_2}} = \frac{m_{\mathrm{O_2}}}{M_{\mathrm{O_2}}} = \frac{20\ \mathrm{kg}}{32\ \mathrm{kg/kmol}} = 0.625\ \mathrm{kmol}$$

$$m_{\mathrm{N_2}} = 20\ \mathrm{kg} \longrightarrow N_{\mathrm{N_2}} = \frac{m_{\mathrm{N_2}}}{M_{\mathrm{N_2}}} = \frac{30\ \mathrm{kg}}{28\ \mathrm{kg/kmol}} = 1.071\ \mathrm{kmol}$$

$$m_{\mathrm{CO_2}} = 50\ \mathrm{kg} \longrightarrow N_{\mathrm{CO_2}} = \frac{m_{\mathrm{CO_2}}}{M_{\mathrm{CO_2}}} = \frac{50\ \mathrm{kg}}{44\ \mathrm{kg/kmol}} = 1.136\ \mathrm{kmol}$$

$$N_m = N_{\mathrm{O_2}} + N_{\mathrm{N_2}} + N_{\mathrm{CO_2}} = 0.625 + 1.071 + 1.136 = 2.832\ \mathrm{kmol}$$

mass

20% O_2
30% N_2
50% CO_2

Noting that the volume fractions are same as the mole fractions, the volume fraction of each component becomes

$$y_{\mathrm{O_2}} = \frac{N_{\mathrm{O_2}}}{N_m} = \frac{0.625\ \mathrm{kmol}}{2.832\ \mathrm{kmol}} = 0.221 \text{ or } \mathbf{22.1\%}$$

$$y_{\mathrm{N_2}} = \frac{N_{\mathrm{N_2}}}{N_m} = \frac{1.071\ \mathrm{kmol}}{2.832\ \mathrm{kmol}} = 0.378 \text{ or } \mathbf{37.8\%}$$

$$y_{\mathrm{CO_2}} = \frac{N_{\mathrm{CO_2}}}{N_m} = \frac{1.136\ \mathrm{kmol}}{2.832\ \mathrm{kmol}} = 0.401 \text{ or } \mathbf{40.1\%}$$

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

$$M_m = \frac{m_m}{N_m} = \frac{100\ \mathrm{kg}}{2.832\ \mathrm{kmol}} = 35.31\ \mathrm{kg/kmol}$$

and

$$R_m = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol\cdot K}}{35.31\ \mathrm{kg/kmol}} = \mathbf{0.235\ \ kJ/kg\cdot K}$$

P-v-T Behavior of Gas Mixtures

13-17C 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.

13-18C 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.

13-19C 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.

13-20C 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.

13-21C 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.

13-22C 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.

13-23C The one with the highest mole number.

13-24C The partial pressures will decrease but the pressure fractions will remain the same.

13-25C The partial pressures will increase but the pressure fractions will remain the same.

13-26C 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."

13-27C No. The correct expression is "the temperature of a gas mixture is equal to the temperature of the individual gas components."

13-28C Yes, it is correct.

13-29C 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

$$P'_{\mathrm{cr},m} = \sum y_i P_{\mathrm{cr},i} \quad \text{and} \quad T'_{\mathrm{cr},m} = \sum y_i T_{\mathrm{cr},i}$$

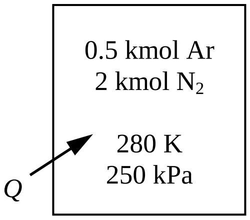
The compressibility factor of the mixture (Z_m) is then easily determined using these pseudo-critical point values.

13-30 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

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



and

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

Also,

$$\frac{P_2 \mathbf{V}_2}{T_2} = \frac{P_1 \mathbf{V}_1}{T_1} \longrightarrow P_2 = \frac{T_2}{T_1} P_1 = \frac{400\,\mathrm{K}}{280\,\mathrm{K}}(250\,\mathrm{kPa}) = \mathbf{357.1\,kPa}$$

13-31 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

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

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

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

1 kg CO_2
3 kg CH_4

300 K
200 kPa

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

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

Then the partial pressures become

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

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

The apparent molar mass of the mixture is

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

13-32 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

0.3 m^3

0.6 kg N_2
0.4 kg O_2

300 K

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

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

and

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

13-33 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.

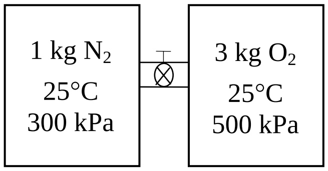
Assumptions Under specified conditions both N_2 and O_2 can be treated as ideal gases, and the mixture as an ideal gas mixture

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

$$\mathcal{V}_{N_2} = \left(\frac{mRT}{P}\right)_{N_2} = \frac{(1\text{ kg})(0.2968\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{ K})}{300\text{ kPa}} = \mathbf{0.295\ m^3}$$

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



$$\mathcal{V}_{\text{total}} = \mathcal{V}_{N_2} + \mathcal{V}_{O_2} = 0.295\text{ m}^3 + 0.465\text{ m}^3 = 0.76\text{ m}^3$$

Also,

$$m_{N_2} = 1\text{ kg} \longrightarrow N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{1\text{ kg}}{28\text{ kg/kmol}} = 0.03571\text{ kmol}$$

$$m_{O_2} = 3\text{ kg} \longrightarrow N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{3\text{ kg}}{32\text{ kg/kmol}} = 0.09375\text{ kmol}$$

$$N_m = N_{N_2} + N_{O_2} = 0.03571\text{ kmol} + 0.09375\text{ kmol} = 0.1295\text{ kmol}$$

Thus,

$$P_m = \left(\frac{NR_uT}{\mathcal{V}}\right)_m = \frac{(0.1295\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(298\text{ K})}{0.76\text{ m}^3} = \mathbf{422.2\ \ kPa}$$

13-34 A container contains a mixture of two fluids whose volumes are given. The density of the mixture is to be determined.

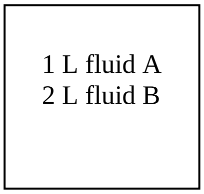
Assumptions The volume of the mixture is the sum of the volumes of the two constituents.

Properties The specific volumes of the two fluids are given to be 0.0003 m^3/kg and 0.00023 m^3/kg.

Analysis The mass of the two fluids are

$$m_A = \frac{\mathcal{V}_A}{v_A} = \frac{0.001\,\text{m}^3}{0.0003\,\text{m}^3/\text{kg}} = 3.333\,\text{kg}$$

$$m_B = \frac{\mathcal{V}_B}{v_B} = \frac{0.002\,\text{m}^3}{0.00023\,\text{m}^3/\text{kg}} = 8.696\,\text{kg}$$



The density of the mixture is then

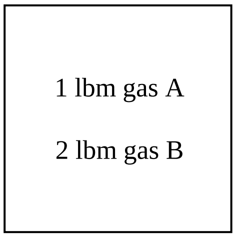
$$\rho = \frac{m_A + m_B}{\mathcal{V}_A + \mathcal{V}_B} = \frac{(3.333 + 8.696)\text{ lbf}}{(0.001 + 0.002)\text{ ft}^3} = \mathbf{4010\ kg/m^3}$$

13-35E A mixture is obtained by mixing two gases at constant pressure and temperature. The volume and specific volume of the mixture are to be determined.

Properties The densities of two gases are given in the problem statement.

Analysis The volume of constituent gas A is

$$V_A = \frac{m_A}{\rho_A} = \frac{1\,\text{lbm}}{0.001\,\text{lbm/ft}^3} = 1000\,\text{ft}^3$$



and the volume of constituent gas B is

$$V_B = \frac{m_B}{\rho_B} = \frac{2\,\text{lbm}}{0.002\,\text{lbm/ft}^3} = 1000\,\text{ft}^3$$

Hence, the volume of the mixture is

$$V = V_A + V_B = 1000 + 1000 = \mathbf{2000\ ft^3}$$

The specific volume of the mixture will then be

$$v = \frac{V}{m} = \frac{2000\,\text{ft}^3}{(1+2)\,\text{lbm}} = \mathbf{666.7\ ft^3/lbm}$$

13-36 The masses of components of a gas mixture are given. The apparent molecular weight of this mixture, the volume it occupies, the partial volume of the oxygen, and the partial pressure of the helium are to be determined.

Properties The molar masses of O_2, CO_2, and He are 32.0, 44.0, and 4.0 kg/kmol, respectively (Table A-1).

Analysis The total mass of the mixture is

$$m_m = m_{\mathrm{O2}} + m_{\mathrm{CO2}} + m_{\mathrm{He}} = 0.1 + 1 + 0.5 = 1.6\ \mathrm{kg}$$

The mole numbers of each component are

0.1 kg O_2
1 kg CO_2
0.5 kg He

$$N_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{M_{\mathrm{O2}}} = \frac{0.1\ \mathrm{kg}}{32\ \mathrm{kg/kmol}} = 0.003125\ \mathrm{kmol}$$

$$N_{\mathrm{CO2}} = \frac{m_{\mathrm{CO2}}}{M_{\mathrm{CO2}}} = \frac{1\ \mathrm{kg}}{44\ \mathrm{kg/kmol}} = 0.02273\ \mathrm{kmol}$$

$$N_{\mathrm{He}} = \frac{m_{\mathrm{He}}}{M_{\mathrm{He}}} = \frac{0.5\ \mathrm{kg}}{4\ \mathrm{kg/kmol}} = 0.125\ \mathrm{kmol}$$

The mole number of the mixture is

$$N_m = N_{\mathrm{O2}} + N_{\mathrm{CO2}} + N_{\mathrm{He}} = 0.003125 + 0.02273 + 0.125 = 0.15086\ \mathrm{kmol}$$

Then the apparent molecular weight of the mixture becomes

$$M_m = \frac{m_m}{N_m} = \frac{1.6\ \mathrm{kg}}{0.15086\ \mathrm{kmol}} = \mathbf{10.61\ kg/kmol}$$

The volume of this ideal gas mixture is

$$\boldsymbol{V}_m = \frac{N_m R_u T}{P} = \frac{(0.1509\ \mathrm{kmol})(8.314\ \mathrm{kPa\cdot m^3/kmol\cdot K})(300\ \mathrm{K})}{100\ \mathrm{kPa}} = \mathbf{3.764\ m^3}$$

The partial volume of oxygen in the mixture is

$$\boldsymbol{V}_{\mathrm{O2}} = y_{\mathrm{O2}}\boldsymbol{V}_m = \frac{N_{\mathrm{O2}}}{N_m}\boldsymbol{V}_m = \frac{0.003125\ \mathrm{kmol}}{0.1509\ \mathrm{kmol}}(3.764\ \mathrm{m^3}) = \mathbf{0.07795\ m^3}$$

The partial pressure of helium in the mixture is

$$P_{\mathrm{He}} = y_{\mathrm{He}} P_m = \frac{N_{\mathrm{He}}}{N_m} P_m = \frac{0.125\ \mathrm{kmol}}{0.1509\ \mathrm{kmol}}(100\ \mathrm{kPa}) = \mathbf{82.84\ kPa}$$

13-37 The mass fractions of components of a gas mixture are given. The mole fractions of each constituent, the mixture's apparent molecular weight, the partial pressure of each constituent, and the apparent specific heats of the mixture are to be determined.

Properties The molar masses of N_2, He, CH_4, and C_2H_6 are 28.0, 4.0, 16.0, and 30.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 1.039, 5.1926, 2.2537, and 1.7662 kJ/kg·K, respectively (Table A-2a).

Analysis We consider 100 kg of this mixture. The mole numbers of each component are

15% N_2
5% He
60% CH_4
20% C_2H_6
(by mass)

$$N_{\mathrm{N2}} = \frac{m_{\mathrm{N2}}}{M_{\mathrm{N2}}} = \frac{15\ \mathrm{kg}}{28\ \mathrm{kg/kmol}} = 0.5357\ \mathrm{kmol}$$

$$N_{\mathrm{He}} = \frac{m_{\mathrm{He}}}{M_{\mathrm{He}}} = \frac{5\ \mathrm{kg}}{4\ \mathrm{kg/kmol}} = 1.25\ \mathrm{kmol}$$

$$N_{\mathrm{CH4}} = \frac{m_{\mathrm{CH4}}}{M_{\mathrm{CH4}}} = \frac{60\ \mathrm{kg}}{16\ \mathrm{kg/kmol}} = 3.75\ \mathrm{kmol}$$

$$N_{\mathrm{C2H6}} = \frac{m_{\mathrm{C2H6}}}{M_{\mathrm{C2H6}}} = \frac{20\ \mathrm{kg}}{30\ \mathrm{kg/kmol}} = 0.6667\ \mathrm{kmol}$$

The mole number of the mixture is

$$N_m = N_{\mathrm{N2}} + N_{\mathrm{He}} + N_{\mathrm{CH4}} + N_{\mathrm{C2H6}} = 0.5357 + 1.25 + 3.75 + 0.6667 = 6.2024\ \mathrm{kmol}$$

and the mole fractions are

$$y_{\mathrm{N2}} = \frac{N_{\mathrm{N2}}}{N_m} = \frac{0.5357\ \mathrm{kmol}}{6.2024\ \mathrm{kmol}} = \mathbf{0.08637}$$

$$y_{\mathrm{He}} = \frac{N_{\mathrm{He}}}{N_m} = \frac{1.25\ \mathrm{kmol}}{6.2024\ \mathrm{kmol}} = \mathbf{0.2015}$$

$$y_{\mathrm{CH4}} = \frac{N_{\mathrm{CH4}}}{N_m} = \frac{3.75\ \mathrm{kmol}}{6.2024\ \mathrm{kmol}} = \mathbf{0.6046}$$

$$y_{\mathrm{C2H6}} = \frac{N_{\mathrm{C2H6}}}{N_m} = \frac{0.6667\ \mathrm{kmol}}{6.2024\ \mathrm{kmol}} = \mathbf{0.1075}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{100\ \mathrm{kg}}{6.2024\ \mathrm{kmol}} = \mathbf{16.12\ kg/kmol}$$

The partial pressure of each constituent for a mixture pressure of 1200 kPa are

$$P_{\mathrm{N2}} = y_{\mathrm{N2}} P_m = (0.08637)(1200\ \mathrm{kPa}) = \mathbf{103.6\ kPa}$$

$$P_{\mathrm{He}} = y_{\mathrm{He}} P_m = (0.2015)(1200\ \mathrm{kPa}) = \mathbf{241.8\ kPa}$$

$$P_{\mathrm{CH4}} = y_{\mathrm{CH4}} P_m = (0.6046)(1200\ \mathrm{kPa}) = \mathbf{725.5\ kPa}$$

$$P_{\mathrm{C2H6}} = y_{\mathrm{C2H6}} P_m = (0.1075)(1200\ \mathrm{kPa}) = \mathbf{129.0\ kPa}$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \mathrm{mf}_{\mathrm{N2}} c_{p,\mathrm{N2}} + \mathrm{mf}_{\mathrm{He}} c_{p,\mathrm{He}} + \mathrm{mf}_{\mathrm{CH4}} c_{p,\mathrm{CH4}} + \mathrm{mf}_{\mathrm{C2H6}} c_{p,\mathrm{C2H6}} \\ &= 0.15 \times 1.039 + 0.05 \times 5.1926 + 0.60 \times 2.2537 + 0.20 \times 1.7662 = \mathbf{2.121\ kJ/kg \cdot K} \end{aligned}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol \cdot K}}{16.12\ \mathrm{kg/kmol}} = 0.5158\ \mathrm{kJ/kg \cdot K}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 2.121 - 0.5158 = \mathbf{1.605\ kJ/kg \cdot K}$$

13-38 The volume fractions of components of a gas mixture are given. The mixture's apparent molecular weight and the apparent specific heats of the mixture are to be determined.

Properties The molar masses of O_2, N_2, CO_2, and CH_4 are 32.0, 28.0, 44.0, and 16.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 0.918, 1.039, 0.846, and 2.2537 kJ/kg·K, respectively (Table A-2).

Analysis We consider 100 kmol of this mixture. Noting that volume fractions are equal to the mole fractions, mass of each component are

$$\begin{aligned}
m_{\mathrm{O2}} &= N_{\mathrm{O2}}M_{\mathrm{O2}} = (30\ \mathrm{kmol})(32\ \mathrm{kg/kmol}) = 960\ \mathrm{kg}\\
m_{\mathrm{N2}} &= N_{\mathrm{N2}}M_{\mathrm{N2}} = (40\ \mathrm{kmol})(28\ \mathrm{kg/kmol}) = 1120\ \mathrm{kg}\\
m_{\mathrm{CO2}} &= N_{\mathrm{CO2}}M_{\mathrm{CO2}} = (10\ \mathrm{kmol})(44\ \mathrm{kg/kmol}) = 440\ \mathrm{kg}\\
m_{\mathrm{CH4}} &= N_{\mathrm{CH4}}M_{\mathrm{CH4}} = (20\ \mathrm{kmol})(16\ \mathrm{kg/kmol}) = 320\ \mathrm{kg}
\end{aligned}$$

30% O_2
40% N_2
10% CO_2
20% CH_4
(by volume)

The total mass is

$$\begin{aligned}
m_m &= m_{\mathrm{O2}} + m_{\mathrm{N2}} + m_{\mathrm{CO2}} + m_{\mathrm{CH4}}\\
&= 960 + 1120 + 440 + 320 = 2840\ \mathrm{kg}
\end{aligned}$$

Then the mass fractions are

$$\mathrm{mf}_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{m_m} = \frac{960\ \mathrm{kg}}{2840\ \mathrm{kg}} = 0.3380$$

$$\mathrm{mf}_{\mathrm{N2}} = \frac{m_{\mathrm{N2}}}{m_m} = \frac{1120\ \mathrm{kg}}{2840\ \mathrm{kg}} = 0.3944$$

$$\mathrm{mf}_{\mathrm{CO2}} = \frac{m_{\mathrm{CO2}}}{m_m} = \frac{440\ \mathrm{kg}}{2840\ \mathrm{kg}} = 0.1549$$

$$\mathrm{mf}_{\mathrm{CH4}} = \frac{m_{\mathrm{CH4}}}{m_m} = \frac{320\ \mathrm{kg}}{2840\ \mathrm{kg}} = 0.1127$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{2840\ \mathrm{kg}}{100\ \mathrm{kmol}} = \mathbf{28.40\ kg/kmol}$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned}
c_p &= \mathrm{mf}_{\mathrm{O2}}c_{p,\mathrm{O2}} + \mathrm{mf}_{\mathrm{N2}}c_{p,\mathrm{N2}} + \mathrm{mf}_{\mathrm{CO2}}c_{p,\mathrm{CO2}} + \mathrm{mf}_{\mathrm{CH4}}c_{p,\mathrm{CH4}}\\
&= 0.3380\times 0.918 + 0.3944\times 1.039 + 0.1549\times 0.846 + 0.1127\times 2.2537\\
&= \mathbf{1.1051\ kJ/kg\cdot K}
\end{aligned}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol\cdot K}}{28.40\ \mathrm{kg/kmol}} = 0.2927\ \mathrm{kJ/kg\cdot K}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 1.1051 - 0.2927 = \mathbf{0.8124\ kJ/kg\cdot K}$$

13-39 The mass fractions of components of a gas mixture are given. The volume occupied by 100 kg of this mixture is to be determined.

Properties The molar masses of CH_4, C_3H_8, and C_4H_{10} are 16.0, 44.0, and 58.0 kg/kmol, respectively (Table A-1).

Analysis The mole numbers of each component are

60% CH_4
25% C_3H_8
15% C_4H_{10}
(by mass)

$$N_{\mathrm{CH4}} = \frac{m_{\mathrm{CH4}}}{M_{\mathrm{CH4}}} = \frac{60\ \mathrm{kg}}{16\ \mathrm{kg/kmol}} = 3.75\ \mathrm{kmol}$$

$$N_{\mathrm{C3H8}} = \frac{m_{\mathrm{C3H8}}}{M_{\mathrm{C3H8}}} = \frac{25\ \mathrm{kg}}{44\ \mathrm{kg/kmol}} = 0.5682\ \mathrm{kmol}$$

$$N_{\mathrm{C4H10}} = \frac{m_{\mathrm{C4H10}}}{M_{\mathrm{C4H10}}} = \frac{15\ \mathrm{kg}}{58\ \mathrm{kg/kmol}} = 0.2586\ \mathrm{kmol}$$

The mole number of the mixture is

$$N_m = N_{\mathrm{CH4}} + N_{\mathrm{C3H8}} + N_{\mathrm{C4H10}} = 3.75 + 0.5682 + 0.2586 = 4.5768\ \mathrm{kmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{100\ \mathrm{kg}}{4.5768\ \mathrm{kmol}} = 21.85\ \mathrm{kg/kmol}$$

Then the volume of this ideal gas mixture is

$$V_m = \frac{N_m R_u T}{P} = \frac{(4.5768\ \mathrm{kmol})(8.314\ \mathrm{kPa\cdot m^3/kmol\cdot K})(310\ \mathrm{K})}{3000\ \mathrm{kPa}} = \mathbf{3.93\ m^3}$$

13-40E The mass fractions of components of a gas mixture are given. The mass of 5 ft^3 of this mixture and the partial volumes of the components are to be determined.

Properties The molar masses of N_2, O_2, and He are 28.0, 32.0, and 4.0 lbm/lbmol, respectively (Table A-1E).

Analysis We consider 100 lbm of this mixture for calculating the molar mass of the mixture. The mole numbers of each component are

$$N_{\mathrm{N2}} = \frac{m_{\mathrm{N2}}}{M_{\mathrm{N2}}} = \frac{60\,\mathrm{lbm}}{28\,\mathrm{lbm/lbmol}} = 2.1429\,\mathrm{lbmol}$$

$$N_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{M_{\mathrm{O2}}} = \frac{30\,\mathrm{lbm}}{32\,\mathrm{lbm/lbmol}} = 0.9375\,\mathrm{lbmol}$$

$$N_{\mathrm{He}} = \frac{m_{\mathrm{He}}}{M_{\mathrm{He}}} = \frac{10\,\mathrm{lbm}}{4\,\mathrm{lbm/lbmol}} = 2.5\,\mathrm{lbmol}$$

5 ft^3
60% N_2
30% O_2
10% He
(by mass)

The mole number of the mixture is

$$N_m = N_{\mathrm{N2}} + N_{\mathrm{O2}} + N_{\mathrm{He}} = 2.1429 + 0.9375 + 2.5 = 5.5804\,\mathrm{lbmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{100\,\mathrm{lbm}}{5.5804\,\mathrm{lbmol}} = 17.92\,\mathrm{lbm/lbmol}$$

Then the mass of this ideal gas mixture is

$$m = \frac{PVM_m}{R_uT} = \frac{(300\,\mathrm{psia})(5\,\mathrm{ft}^3)(17.92\,\mathrm{lbm/lbmol})}{(10.73\,\mathrm{psia\cdot ft^3/lbmol\cdot R})(530\,\mathrm{R})} = \mathbf{4.727\ lbm}$$

The mole fractions are

$$y_{\mathrm{N2}} = \frac{N_{\mathrm{N2}}}{N_m} = \frac{2.1429\,\mathrm{lbmol}}{5.5804\,\mathrm{lbmol}} = 0.3840$$

$$y_{\mathrm{O2}} = \frac{N_{\mathrm{O2}}}{N_m} = \frac{0.9375\,\mathrm{lbmol}}{5.5804\,\mathrm{lbmol}} = 0.1680$$

$$y_{\mathrm{He}} = \frac{N_{\mathrm{He}}}{N_m} = \frac{2.5\,\mathrm{lbmol}}{5.5804\,\mathrm{lbmol}} = 0.4480$$

Noting that volume fractions are equal to mole fractions, the partial volumes are determined from

$$V_{\mathrm{N2}} = y_{\mathrm{N2}}V_m = (0.3840)(5\,\mathrm{ft}^3) = \mathbf{1.92\ ft^3}$$

$$V_{\mathrm{O2}} = y_{\mathrm{O2}}V_m = (0.1680)(5\,\mathrm{ft}^3) = \mathbf{0.84\ ft^3}$$

$$V_{\mathrm{He}} = y_{\mathrm{He}}V_m = (0.4480)(5\,\mathrm{ft}^3) = \mathbf{2.24\ ft^3}$$

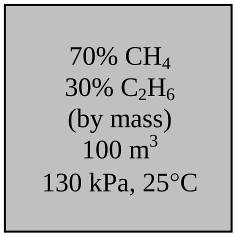
13-41 The mass fractions of components of a gas mixture are given. The partial pressure of ethane is to be determined.

Properties The molar masses of CH_4 and C_2H_6 are 16.0 and 30.0 kg/kmol, respectively (Table A-1).

Analysis We consider 100 kg of this mixture. The mole numbers of each component are

$$N_{\mathrm{CH4}} = \frac{m_{\mathrm{CH4}}}{M_{\mathrm{CH4}}} = \frac{70\ \mathrm{kg}}{16\ \mathrm{kg/kmol}} = 4.375\ \mathrm{kmol}$$

$$N_{\mathrm{C2H6}} = \frac{m_{\mathrm{C2H6}}}{M_{\mathrm{C2H6}}} = \frac{30\ \mathrm{kg}}{30\ \mathrm{kg/kmol}} = 1.0\ \mathrm{kmol}$$



The mole number of the mixture is

$$N_m = N_{\mathrm{CH4}} + N_{\mathrm{C2H6}} = 4.375 + 1.0 = 5.375\ \mathrm{kmol}$$

The mole fractions are

$$y_{\mathrm{CH4}} = \frac{N_{\mathrm{CH4}}}{N_m} = \frac{4.375\ \mathrm{kmol}}{5.375\ \mathrm{kmol}} = 0.8139$$

$$y_{\mathrm{C2H6}} = \frac{N_{\mathrm{C2H6}}}{N_m} = \frac{1.0\ \mathrm{kmol}}{5.375\ \mathrm{kmol}} = 0.1861$$

The final pressure of ethane in the final mixture is

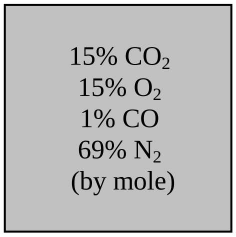
$$P_{\mathrm{C2H6}} = y_{\mathrm{C2H6}} P_m = (0.1861)(130\ \mathrm{kPa}) = \mathbf{24.19\ kPa}$$

13-42E The Orsat analysis (molar fractions) of components of a gas mixture are given. The mass flow rate of the mixture is to be determined.

Properties The molar masses of CO_2, O_2, N_2, and CO are 44.0, 32.0, 28.0, and 28.0 lbm/lbmol, respectively (Table A-1E).

Analysis The molar fraction of N_2 is

$$y_{\mathrm{N2}} = 1 - y_{\mathrm{CO2}} - y_{\mathrm{O2}} - y_{\mathrm{CO}} = 1 - 0.15 - 0.15 - 0.01 = 0.69$$

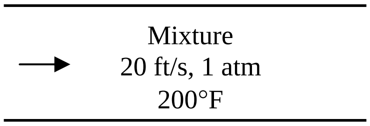


The molar mass of the mixture is determined from

$$\begin{aligned} M_m &= y_{\mathrm{CO2}} M_{\mathrm{CO2}} + y_{\mathrm{O2}} M_{\mathrm{O2}} + y_{\mathrm{CO}} M_{\mathrm{CO}} + y_{\mathrm{N2}} M_{\mathrm{N2}} \\ &= 0.15 \times 44 + 0.15 \times 32 + 0.01 \times 28 + 0.69 \times 28 \\ &= 31.00\ \mathrm{lbm/lbmol} \end{aligned}$$

The specific volume of the mixture is

$$\boldsymbol{v} = \frac{R_u T}{M_m P} = \frac{(10.73\ \mathrm{psia \cdot ft^3/lbmol \cdot R})(660\ \mathrm{R})}{(31.00\ \mathrm{lbm/lbmol})(14.7\ \mathrm{psia})} = 15.54\ \mathrm{ft^3/lbm}$$



The mass flow rate of these gases is then

$$\dot{m} = \frac{AV}{\boldsymbol{v}} = \frac{(10\ \mathrm{ft^2})(20\ \mathrm{ft/s})}{15.54\ \mathrm{ft^3/lbm}} = \mathbf{12.87\ lbm/s}$$

13-43 The volumetric fractions of components of a gas mixture before and after a separation unit are given. The changes in partial pressures of the components in the mixture before and after the separation unit are to be determined.

Analysis The partial pressures before the separation unit are

$$P_{\mathrm{CH4}} = y_{\mathrm{CH4}} P_m = (0.60)(100\ \mathrm{kPa}) = 60\ \mathrm{kPa}$$
$$P_{\mathrm{C2H6}} = y_{\mathrm{C2H6}} P_m = (0.20)(100\ \mathrm{kPa}) = 20\ \mathrm{kPa}$$
$$P_{\mathrm{C3H8}} = y_{\mathrm{C3H8}} P_m = (0.10)(100\ \mathrm{kPa}) = 10\ \mathrm{kPa}$$

The mole fraction of propane is 0.10 after the separation unit. The corresponding mole fractions of methane and ethane are determined as follows:

$$\frac{x}{0.6+0.2+x} = 0.01 \longrightarrow x = 0.00808$$
$$y_{\mathrm{CH4}} = \frac{0.60}{0.6+0.2+0.00808} = 0.7425$$
$$y_{\mathrm{C2H6}} = \frac{0.20}{0.6+0.2+0.00808} = 0.2475$$
$$y_{\mathrm{C3H8}} = \frac{0.00808}{0.6+0.2+0.00808} = 0.01$$

60% CH_4
20% C_2H_6
10% C_3H_8

(by volume)

The partial pressures after the separation unit are

$$P_{\mathrm{CH4}} = y_{\mathrm{CH4}} P_m = (0.7425)(100\ \mathrm{kPa}) = 74.25\ \mathrm{kPa}$$
$$P_{\mathrm{C2H6}} = y_{\mathrm{C2H6}} P_m = (0.2475)(100\ \mathrm{kPa}) = 24.75\ \mathrm{kPa}$$
$$P_{\mathrm{C3H8}} = y_{\mathrm{C3H8}} P_m = (0.01)(100\ \mathrm{kPa}) = 1\mathrm{kPa}$$

The changes in partial pressures are then

$$\Delta P_{\mathrm{CH4}} = 74.25 - 60 = \mathbf{14.25\ kPa}$$
$$\Delta P_{\mathrm{C2H6}} = 24.75 - 20 = \mathbf{4.75\ kPa}$$
$$\Delta P_{\mathrm{C3H8}} = 1 - 10 = \mathbf{-9\ kPa}$$

13-44 The partial pressure of R-134a in atmospheric air to form a 100-ppm contaminant is to be determined.

Analysis Noting that volume fractions and mole fractions are equal, the molar fraction of R-134a in air is

$$y_{\mathrm{R134a}} = \frac{100}{10^6} = 0.0001$$

The partial pressure of R-134a in air is then

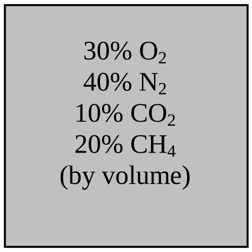
$$P_{\mathrm{R134a}} = y_{\mathrm{R134a}} P_m = (0.0001)(100\ \mathrm{kPa}) = \mathbf{0.01 kPa}$$

13-45E The volumetric analysis of a mixture of gases is given. The volumetric and mass flow rates are to be determined using three methods.

Properties The molar masses of O_2, N_2, CO_2, and CH_4 are 32.0, 28.0, 44.0, and 16.0 lbm/lbmol, respectively (Table A-1E).

Analysis (*a*) We consider 100 lbmol of this mixture. Noting that volume fractions are equal to the mole fractions, mass of each component are

$$\begin{aligned} m_{\text{O2}} &= N_{\text{O2}} M_{\text{O2}} = (30\text{ lbmol})(32\text{ lbm/lbmol}) = 960\text{ lbm} \\ m_{\text{N2}} &= N_{\text{N2}} M_{\text{N2}} = (40\text{ lbmol})(28\text{ lbm/lbmol}) = 1120\text{ lbm} \\ m_{\text{CO2}} &= N_{\text{CO2}} M_{\text{CO2}} = (10\text{ lbmol})(44\text{ lbm/lbmol}) = 440\text{ lbm} \\ m_{\text{CH4}} &= N_{\text{CH4}} M_{\text{CH4}} = (20\text{ lbmol})(16\text{ lbm/lbmol}) = 320\text{ lbm} \end{aligned}$$

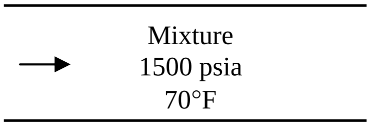


The total mass is

$$\begin{aligned} m_m &= m_{\text{O2}} + m_{\text{N2}} + m_{\text{CO2}} + m_{\text{CH4}} \\ &= 960 + 1120 + 440 + 320 = 2840\text{ lbm} \end{aligned}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{2840\text{ lbm}}{100\text{ lbmol}} = 28.40\text{ lbm/lbmol}$$



The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{10.73\text{ psia}\cdot\text{ft}^3\text{/lbmol}\cdot\text{R}}{28.40\text{ lbm/lbmol}} = 0.3778\text{ psia}\cdot\text{ft}^3\text{/lbm}\cdot\text{R}$$

The specific volume of the mixture is

$$\boldsymbol{v} = \frac{RT}{P} = \frac{(0.3778\text{ psia}\cdot\text{ft}^3\text{/lbm}\cdot\text{R})(530\text{ R})}{1500\text{ psia}} = 0.1335\text{ ft}^3\text{/lbm}$$

The volume flow rate is

$$\dot{\boldsymbol{V}} = AV = \frac{\pi D^2}{4}V = \frac{\pi(1/12\text{ ft})^2}{4}(10\text{ ft/s}) = \mathbf{0.05454\ ft^3/s}$$

and the mass flow rate is

$$\dot{m} = \frac{\dot{\boldsymbol{V}}}{\boldsymbol{v}} = \frac{0.05454\text{ ft}^3\text{/s}}{0.1335\text{ ft}^3\text{/lbm}} = \mathbf{0.4085\ lbm/s}$$

(*b*) To use the Amagat's law for this real gas mixture, we first need the mole fractions and the *Z* of each component at the mixture temperature and pressure. The compressibility factors are obtained using Fig. A-15 to be

$$\left.\begin{aligned} T_{R,\text{O2}} &= \frac{T_m}{T_{\text{cr,O2}}} = \frac{530\text{ R}}{278.6\text{ R}} = 1.902 \\ P_{R,\text{O2}} &= \frac{P_m}{P_{\text{cr,O2}}} = \frac{1500\text{ psia}}{736\text{ psia}} = 2.038 \end{aligned}\right\} Z_{\text{O2}} = 0.94 \qquad \left.\begin{aligned} T_{R,\text{N2}} &= \frac{530\text{ R}}{227.1\text{ R}} = 2.334 \\ P_{R,\text{CN}} &= \frac{1500\text{ psia}}{492\text{ psia}} = 3.049 \end{aligned}\right\} Z_{\text{N2}} = 0.99$$

$$\left.\begin{array}{l} T_{R,\mathrm{CO2}} = \dfrac{530\ \mathrm{R}}{547.5\ \mathrm{R}} = 0.968 \\ P_{R,\mathrm{CO2}} = \dfrac{1500\ \mathrm{psia}}{1071\ \mathrm{psia}} = 1.401 \end{array}\right\} Z_{\mathrm{CO2}} = 0.21 \qquad \left.\begin{array}{l} T_{R,\mathrm{CH4}} = \dfrac{530\ \mathrm{R}}{343.9\ \mathrm{R}} = 1.541 \\ P_{R,\mathrm{CH4}} = \dfrac{1500\ \mathrm{psia}}{673\ \mathrm{psia}} = 2.229 \end{array}\right\} Z_{\mathrm{CO2}} = 0.85$$

and

$$\begin{aligned} Z_m &= \sum y_i Z_i = y_{\mathrm{O2}} Z_{\mathrm{O2}} + y_{\mathrm{O2}} Z_{\mathrm{O2}} + y_{\mathrm{CO2}} Z_{\mathrm{CO2}} + y_{\mathrm{CH4}} Z_{\mathrm{CH4}} \\ &= (0.30)(0.94) + (0.40)(0.99) + (0.10)(0.21) + (0.20)(0.85) = 0.869 \end{aligned}$$

Then,

$$v = \frac{Z_m RT}{P} = \frac{(0.869)(0.3778\ \mathrm{psia \cdot ft^3/lbm \cdot R})(530\ \mathrm{R})}{1500\ \mathrm{psia}} = 0.1160\ \mathrm{ft^3/lbm}$$

$$\dot{V} = \mathbf{0.05454\ ft^3/s}$$

$$\dot{m} = \frac{\dot{V}}{v} = \frac{0.05454\ \mathrm{ft^3/s}}{0.1160\ \mathrm{ft^3/lbm}} = \mathbf{0.4702\ lbm/s}$$

(*c*) To use Kay's rule, we need to determine the pseudo-critical temperature and pseudo-critical pressure of the mixture using the critical point properties of mixture gases.

$$\begin{aligned} T'_{\mathrm{cr},m} &= \sum y_i T_{\mathrm{cr},i} = y_{\mathrm{O2}} T_{\mathrm{cr,O2}} + y_{\mathrm{N2}} T_{\mathrm{cr,N2}} + y_{\mathrm{CO2}} T_{\mathrm{cr,CO2}} + y_{\mathrm{CH4}} T_{\mathrm{cr,CH4}} \\ &= (0.30)(278.6\ \mathrm{R}) + (0.40)(227.1\ \mathrm{R}) + (0.10)(547.5\ \mathrm{R}) + (0.20)(343.9\ \mathrm{R}) = 298.0\ \mathrm{R} \\ P'_{\mathrm{cr},m} &= \sum y_i P_{\mathrm{cr},i} = y_{\mathrm{O2}} P_{\mathrm{cr,O2}} + + y_{\mathrm{N2}} P_{\mathrm{cr,N2}} + y_{\mathrm{CO2}} P_{\mathrm{cr,CO2}} + y_{\mathrm{CH4}} P_{\mathrm{cr,CH4}} \\ &= (0.30)(736\ \mathrm{psia}) + (0.40)(492\ \mathrm{psia}) + (0.10)(1071\ \mathrm{psia}) + (0.20)(673\ \mathrm{psia}) = 659.3\ \mathrm{psia} \end{aligned}$$

and

$$\left.\begin{array}{l} T_R = \dfrac{T_m}{T'_{\mathrm{cr},m}} = \dfrac{530\ \mathrm{R}}{298.0\ \mathrm{R}} = 1.779 \\ P_R = \dfrac{P_m}{P'_{\mathrm{cr},m}} = \dfrac{1500\ \mathrm{psia}}{659.3\ \mathrm{psia}} = 2.275 \end{array}\right\} Z_m = 0.915 \qquad \text{(Fig. A-15)}$$

Then,

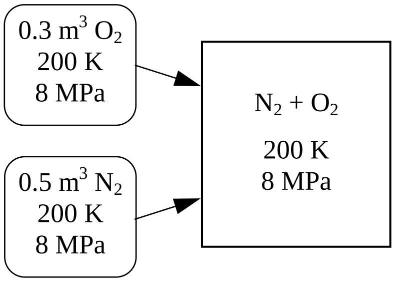
$$v = \frac{Z_m RT}{P} = \frac{(0.915)(0.3778\ \mathrm{psia \cdot ft^3/lbm \cdot R})(530\ \mathrm{R})}{1500\ \mathrm{psia}} = 0.1221\ \mathrm{ft^3/lbm}$$

$$\dot{V} = \mathbf{0.05454\ ft^3/s}$$

$$\dot{m} = \frac{\dot{V}}{v} = \frac{0.05454\ \mathrm{ft^3/s}}{0.1221\ \mathrm{ft^3/lbm}} = \mathbf{0.4467\ lbm/s}$$

13-46 The volumes, temperatures, and pressures of two gases forming a mixture are given. The volume of the mixture is to be determined using three methods.

Analysis (*a*) Under specified conditions both O_2 and N_2 will considerably deviate from the ideal gas behavior. Treating the mixture as an ideal gas,



$$N_{O_2} = \left(\frac{P\mathbf{V}}{R_u T}\right)_{O_2} = \frac{(8000\text{ kPa})(0.3\text{ m}^3)}{(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(200\text{ K})} = 1.443\text{ kmol}$$

$$N_{N_2} = \left(\frac{P\mathbf{V}}{R_u T}\right)_{N_2} = \frac{(8000\text{ kPa})(0.5\text{ m}^3)}{(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(200\text{ K})} = 2.406\text{ kmol}$$

$$N_m = N_{O_2} + N_{N_2} = 1.443\text{ kmol} + 2.406\text{ kmol}$$
$$= 3.849\text{ kmol}$$

$$\mathbf{V}_m = \frac{N_m R_u T_m}{P_m} = \frac{(3.849\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(200\text{ K})}{8000\text{ kPa}} = \mathbf{0.8\text{ m}^3}$$

(*b*) To use Kay's rule, we need to determine the pseudo-critical temperature and pseudo-critical pressure of the mixture using the critical point properties of O_2 and N_2 from Table A-1. But we first need to determine the Z and the mole numbers of each component at the mixture temperature and pressure (Fig. A-15),

$$O_2:\quad \left.\begin{aligned} T_{R,O_2} &= \frac{T_m}{T_{\text{cr},O_2}} = \frac{200\text{ K}}{154.8\text{ K}} = 1.292 \\ P_{R,O_2} &= \frac{P_m}{P_{\text{cr},O_2}} = \frac{8\text{ MPa}}{5.08\text{ MPa}} = 1.575 \end{aligned}\right\} Z_{O_2} = 0.77$$

$$N_2:\quad \left.\begin{aligned} T_{R,N_2} &= \frac{T_m}{T_{\text{cr},N_2}} = \frac{200\text{K}}{126.2\text{K}} = 1.585 \\ P_{R,N_2} &= \frac{P_m}{P_{\text{cr},N_2}} = \frac{8\text{ MPa}}{3.39\text{ MPa}} = 2.360 \end{aligned}\right\} Z_{N_2} = 0.863$$

$$N_{O_2} = \left(\frac{P\mathbf{V}}{ZR_u T}\right)_{O_2} = \frac{(8000\text{ kPa})(0.3\text{ m}^3)}{(0.77)(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(200\text{ K})} = 1.874\text{ kmol}$$

$$N_{N_2} = \left(\frac{P\mathbf{V}}{ZR_u T}\right)_{N_2} = \frac{(8000\text{ kPa})(0.5\text{ m}^3)}{(0.863)(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(200\text{ K})} = 2.787\text{ kmol}$$

$$N_m = N_{O_2} + N_{N_2} = 1.874\text{ kmol} + 2.787\text{ kmol} = 4.661\text{ kmol}$$

The mole fractions are

$$y_{O_2} = \frac{N_{O_2}}{N_m} = \frac{1.874\text{kmol}}{4.661\text{kmol}} = 0.402$$

$$y_{N_2} = \frac{N_{N_2}}{N_m} = \frac{2.787\text{kmol}}{4.661\text{kmol}} = 0.598$$

$$T'_{\text{cr},m} = \sum y_i T_{\text{cr},i} = y_{O_2} T_{\text{cr},O_2} + y_{N_2} T_{\text{cr},N_2}$$
$$= (0.402)(154.8\text{K}) + (0.598)(126.2\text{K}) = 137.7\text{K}$$

$$P'_{\text{cr},m} = \sum y_i P_{\text{cr},i} = y_{O_2} P_{\text{cr},O_2} + y_{N_2} P_{\text{cr},N_2}$$
$$= (0.402)(5.08\text{MPa}) + (0.598)(3.39\text{MPa}) = 4.07\text{MPa}$$

Then,

$$\left.\begin{aligned} T_R &= \frac{T_m}{T'_{\mathrm{cr,O_2}}} = \frac{200\ \mathrm{K}}{137.7\ \mathrm{K}} = 1.452 \\ P_R &= \frac{P_m}{P'_{\mathrm{cr,O_2}}} = \frac{8\ \mathrm{MPa}}{4.07\ \mathrm{MPa}} = 1.966 \end{aligned}\right\} Z_m = 0.82 \qquad \text{(Fig. A-15)}$$

Thus,

$$V_m = \frac{Z_m N_m R_u T_m}{P_m} = \frac{(0.82)(4.661\ \mathrm{kmol})(8.314\ \mathrm{kPa\cdot m^3/kmol\cdot K})(200\ \mathrm{K})}{8000\ \mathrm{kPa}} = \mathbf{0.79\ m^3}$$

(*c*) To use the Amagat's law for this real gas mixture, we first need the *Z* of each component at the mixture temperature and pressure, which are determined in part (*b*). Then,

$$Z_m = \sum y_i Z_i = y_{\mathrm{O_2}} Z_{\mathrm{O_2}} + y_{\mathrm{N_2}} Z_{\mathrm{N_2}} = (0.402)(0.77) + (0.598)(0.863) = 0.83$$

Thus,

$$V_m = \frac{Z_m N_m R_u T_m}{P_m} = \frac{(0.83)(4.661\ \mathrm{kmol})(8.314\ \mathrm{kPa\cdot m^3/kmol\cdot K})(200\ \mathrm{K})}{8000\ \mathrm{kPa}} = \mathbf{0.80\ m^3}$$

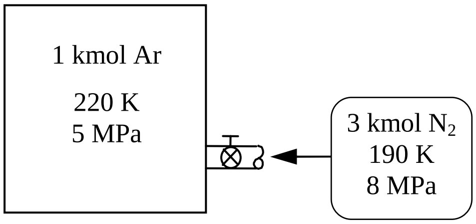
13-47 [*Also solved by EES on enclosed CD***]** The mole numbers, temperatures, and pressures of two gases forming a mixture are given. The final temperature is also given. The pressure of the mixture is to be determined using two methods.

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,

$$\left.\begin{array}{ll}\text{Initial state:} & P_1\mathbf{V}_1 = N_1R_uT_1 \\ \text{Final state:} & P_2\mathbf{V}_2 = N_2R_uT_2\end{array}\right\} P_2 = \frac{N_2T_2}{N_1T_1}P_1 = \frac{(4)(200\text{ K})}{(1)(220\text{ K})}(5\text{ MPa}) = \mathbf{18.2\ MPa}$$

(*b*) Initially,

$$\left.\begin{array}{l} T_R = \dfrac{T_1}{T_{\text{cr,Ar}}} = \dfrac{220\text{ K}}{151.0\text{ K}} = 1.457 \\[2ex] P_R = \dfrac{P_1}{P_{\text{cr,Ar}}} = \dfrac{5\text{ MPa}}{4.86\text{ MPa}} = 1.0278 \end{array}\right\} Z_{\text{Ar}} = 0.90 \quad \text{(Fig. A-15)}$$



Then the volume of the tank is

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

After mixing,

$$\text{Ar:}\quad \left.\begin{array}{l} T_{R,\text{Ar}} = \dfrac{T_m}{T_{\text{cr,Ar}}} = \dfrac{200\text{K}}{151.0\text{K}} = 1.325 \\[2ex] \mathbf{V}_{R,\text{Ar}} = \dfrac{v_{\text{Ar}}}{R_uT_{\text{cr,Ar}}/P_{\text{cr,Ar}}} = \dfrac{\mathbf{V}_m/N_{\text{Ar}}}{R_uT_{\text{cr,Ar}}/P_{\text{cr,Ar}}} \\[2ex] \quad = \dfrac{(0.33\text{ m}^3)/(1\text{ kmol})}{(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(151.0\text{ K})/(4860\text{ kPa})} = 1.278 \end{array}\right\} P_R = 0.90 \quad \text{(Fig. A-15)}$$

$$N_2\text{:}\quad \left.\begin{array}{l} T_{R,N_2} = \dfrac{T_m}{T_{\text{cr},N_2}} = \dfrac{200\text{K}}{126.2\text{K}} = 1.585 \\[2ex] \mathbf{V}_{R,N_2} = \dfrac{v_{N_2}}{R_uT_{\text{cr},N_2}/P_{\text{cr},N_2}} = \dfrac{\mathbf{V}_m/N_{N_2}}{R_uT_{\text{cr},N_2}/P_{\text{cr},N_2}} \\[2ex] \quad = \dfrac{(0.33\text{ m}^3)/(3\text{ kmol})}{(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(126.2\text{ K})/(3390\text{ kPa})} = 0.355 \end{array}\right\} P_R = 3.75 \quad \text{(Fig. A-15)}$$

Thus,

$$P_{\text{Ar}} = (P_RP_{\text{cr}})_{\text{Ar}} = (0.90)(4.86\text{ MPa}) = 4.37\text{ MPa}$$
$$P_{N_2} = (P_RP_{\text{cr}})_{N_2} = (3.75)(3.39\text{ MPa}) = 12.7\text{ MPa}$$

and

$$P_m = P_{\text{Ar}} + P_{N_2} = 4.37\text{ MPa} + 12.7\text{ MPa} = \mathbf{17.1\ MPa}$$

13-48 EES Problem 13-47 is reconsidered. The effect of the moles of nitrogen supplied to the tank on the final pressure of the mixture is to be studied using the ideal-gas equation of state and the compressibility chart with Dalton's law.

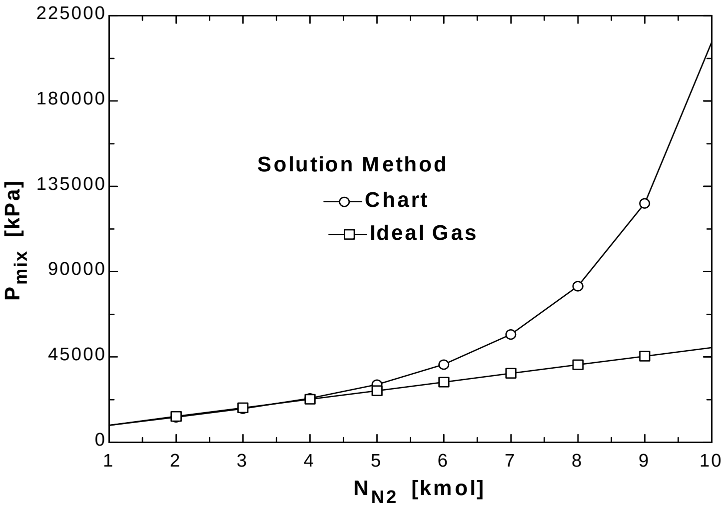
Analysis The problem is solved using EES, and the solution is given below.

```
"Input Data"
R_u = 8.314 [kJ/kmol-K] "universal Gas Constant"
T_Ar = 220 [K]
P_Ar = 5000 [kPa]  "Pressure for only Argon in the tank initially."
N_Ar = 1 [kmol]
{N_N2 = 3 [kmol]}
T_mix = 200 [K]
T_cr_Ar=151.0 [K]  "Critical Constants are found in Table A.1 of the text"
P_cr_Ar=4860 [kPa]
T_cr_N2=126.2 [K]
P_cr_N2=3390 [kPa]

"Ideal-gas Solution:"
P_Ar*V_Tank_IG = N_Ar*R_u*T_Ar  "Apply the ideal gas law the gas in the tank."
P_mix_IG*V_Tank_IG = N_mix*R_u*T_mix  "Ideal-gas mixture pressure"
N_mix=N_Ar + N_N2  "Moles of mixture"

"Real Gas Solution:"
P_Ar*V_Tank_RG = Z_Ar_1*N_Ar*R_u*T_Ar "Real gas volume of tank"
T_R=T_Ar/T_cr_Ar "Initial reduced Temp. of Ar"
P_R=P_Ar/P_cr_Ar "Initial reduced Press. of Ar"
Z_Ar_1=COMPRESS(T_R, P_R ) "Initial compressibility factor for Ar"
P_Ar_mix*V_Tank_RG = Z_Ar_mix*N_Ar*R_u*T_mix  "Real gas Ar Pressure in mixture"
T_R_Ar_mix=T_mix/T_cr_Ar             "Reduced Temp. of Ar in mixture"
P_R_Ar_mix=P_Ar_mix/P_cr_Ar       "Reduced Press. of Ar in mixture"
Z_Ar_mix=COMPRESS(T_R_Ar_mix, P_R_Ar_mix ) "Compressibility factor for Ar in mixture"
P_N2_mix*V_Tank_RG = Z_N2_mix*N_N2*R_u*T_mix "Real gas N2 Pressure in mixture"
T_R_N2_mix=T_mix/T_cr_N2 "Reduced Temp. of N2 in mixture"
P_R_N2_mix=P_N2_mix/P_cr_N2 "Reduced Press. of N2 in mixture"
Z_N2_mix=COMPRESS(T_R_N2_mix, P_R_N2_mix ) "Compressibility factor for N2 in mixture"
P_mix=P_R_Ar_mix*P_cr_Ar +P_R_N2_mix*P_cr_N2 "Mixture pressure by Dalton's law. 23800"
```

N_{N2} [kmol]	P_{mix} [kPa]	$P_{mix,IG}$ [kPa]
1	9009	9091
2	13276	13636
3	17793	18182
4	23254	22727
5	30565	27273
6	41067	31818
7	56970	36364
8	82372	40909
9	126040	45455
10	211047	50000



Properties of Gas Mixtures

13-49C Yes. Yes (extensive property).

13-50C No (intensive property).

13-51C The answers are the same for entropy.

13-52C Yes. Yes (conservation of energy).

13-53C We have to use the partial pressure.

13-54C 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.)

13-55 Volumetric fractions of the constituents of a mixture are given. The mixture undergoes an adiabatic compression process. The makeup of the mixture on a mass basis and the internal energy change per unit mass of mixture are to be determined.

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

Properties **1** The molar masses of CO_2, CO, O_2, and N_2 are 44.0, 28.0, 32.0, and 28.0 kg/kmol, respectively (Table A-1). **2** The process is reversible.

Analysis Noting that volume fractions are equal to mole fractions in ideal gas mixtures, the molar mass of the mixture is determined to be

$$\begin{aligned}M_m &= y_{\mathrm{CO_2}}M_{\mathrm{CO_2}} + y_{\mathrm{CO}}M_{\mathrm{CO}} + y_{\mathrm{O_2}}M_{\mathrm{O_2}} + y_{\mathrm{N_2}}M_{\mathrm{N_2}}\\ &= (0.15)(44)+(0.05)(28)+(0.10)(32)+(0.70)(28)\\ &= 30.80\ \mathrm{kg/kmol}\end{aligned}$$

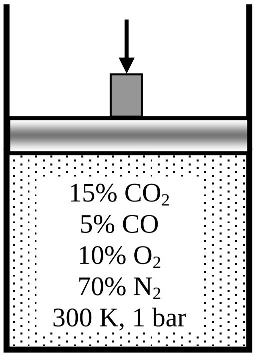
The mass fractions are

$$\mathrm{mf}_{\mathrm{CO_2}} = y_{\mathrm{CO_2}}\frac{M_{\mathrm{CO_2}}}{M_m} = (0.15)\frac{44\ \mathrm{kg/kmol}}{30.80\ \mathrm{kg/kmol}} = \mathbf{0.2143}$$

$$\mathrm{mf}_{\mathrm{CO}} = y_{\mathrm{CO}}\frac{M_{\mathrm{CO}}}{M_m} = (0.05)\frac{28\ \mathrm{kg/kmol}}{30.80\ \mathrm{kg/kmol}} = \mathbf{0.0454}$$

$$\mathrm{mf}_{\mathrm{O_2}} = y_{\mathrm{O_2}}\frac{M_{\mathrm{O_2}}}{M_m} = (0.10)\frac{32\ \mathrm{kg/kmol}}{30.80\ \mathrm{kg/kmol}} = \mathbf{0.1039}$$

$$\mathrm{mf}_{\mathrm{N_2}} = y_{\mathrm{N_2}}\frac{M_{\mathrm{N_2}}}{M_m} = (0.70)\frac{28\ \mathrm{kg/kmol}}{30.80\ \mathrm{kg/kmol}} = \mathbf{0.6364}$$



The final pressure of mixture is expressed from ideal gas relation to be

$$P_2 = P_1 r\frac{T_2}{T_1} = (100\ \mathrm{kPa})(8)\frac{T_2}{300\ \mathrm{K}} = 2.667T_2 \qquad \text{(Eq. 1)}$$

since the final temperature is not known. We assume that the process is reversible as well being adiabatic (i.e. isentropic). Using Dalton's law to find partial pressures, the entropies at the initial state are determined from EES to be:

$$T = 300\ \mathrm{K},\ P = (0.2143\times100) = 21.43\ \mathrm{kPa} \longrightarrow s_{\mathrm{CO_2},1} = 5.2190\ \mathrm{kJ/kg.K}$$

$$T = 300\ \mathrm{K},\ P = (0.04545\times100) = 4.55\ \mathrm{kPa} \longrightarrow s_{\mathrm{CO},1} = 79483\ \mathrm{kJ/kg.K}$$

$$T = 300\ \mathrm{K},\ P = (0.1039\times100) = 10.39\ \mathrm{kPa} \longrightarrow s_{\mathrm{N_2},1} = 6.9485\ \mathrm{kJ/kg.K}$$

$$T = 300\ \mathrm{K},\ P = (0.6364\times100) = 63.64\ \mathrm{kPa} \longrightarrow s_{\mathrm{O_2},1} = 7.0115\ \mathrm{kJ/kg.K}$$

The final state entropies cannot be determined at this point since the final pressure and temperature are not known. However, for an isentropic process, the entropy change is zero and the final temperature and the final pressure may be determined from

$$\Delta s_{\mathrm{total}} = \mathrm{mf}_{\mathrm{CO_2}}\Delta s_{\mathrm{CO_2}} + \mathrm{mf}_{\mathrm{CO}}\Delta s_{\mathrm{CO}} + \mathrm{mf}_{\mathrm{O_2}}\Delta s_{\mathrm{O_2}} + \mathrm{mf}_{\mathrm{N_2}}\Delta s_{\mathrm{N_2}} = 0$$

and using Eq. (1). The solution may be obtained using EES to be T_2 = 631.4 K, P_2 = 1684 kPa

The initial and final internal energies are (from EES)

$$T_1 = 300\text{ K} \longrightarrow \begin{aligned} u_{\text{CO}_2,1} &= -8997\text{ kJ/kg} \\ u_{\text{CC},1} &= -4033\text{ kJ/kg} \\ u_{\text{O}_2,1} &= -76.24\text{ kJ/kg} \\ u_{\text{N}_2,1} &= -87.11\text{ kJ/kg}, \end{aligned}$$

$$T_2 = 631.4\text{ K} \longrightarrow \begin{aligned} u_{\text{CO}_2,2} &= -8734\text{ kJ/kg} \\ u_{\text{CO},2} &= -3780\text{ kJ/kg} \\ u_{\text{O}_2,2} &= 156.8\text{ kJ/kg} \\ u_{\text{N}_2,2} &= 163.9\text{ kJ/kg} \end{aligned}$$

The internal energy change per unit mass of mixture is determined from

$$\begin{aligned} \Delta u_{\text{mixture}} &= \text{mf}_{\text{CO}_2}(u_{\text{CO}_2,2} - u_{\text{CO}_2,1}) + \text{mf}_{\text{CO}}(u_{\text{CO},2} - u_{\text{CO},1}) + \text{mf}_{\text{O}_2}(u_{\text{O}_2,2} - u_{\text{O}_2,1}) + \text{mf}_{\text{N}_2}(u_{\text{N}_2,2} - u_{\text{N}_2,1}) \\ &= 0.2143\big[(-8734) - (-8997)\big] + 0.0454\big[(-3780) - (-4033)\big] \\ &\quad + 0.1039\big[156.8 - (-76.24)\big]6 + 0.6364\big[163.9 - (-87.11)\big] \\ &= \mathbf{251.8\ kJ/kg} \end{aligned}$$

13-56 Propane and air mixture is compressed isentropically in an internal combustion engine. The work input is to be determined.

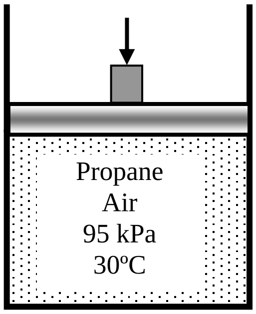
Assumptions Under specified conditions propane and air can be treated as ideal gases, and the mixture as an ideal gas mixture.

Properties The molar masses of C_3H_8 and air are 44.0 and 28.97 kg/kmol, respectively (TableA-1).

Analysis Given the air-fuel ratio, the mass fractions are determined to be

$$\text{mf}_\text{air} = \frac{\text{AF}}{\text{AF}+1} = \frac{16}{17} = 0.9412$$

$$\text{mf}_{C_3H_8} = \frac{1}{\text{AF}+1} = \frac{1}{17} = 0.05882$$



The molar mass of the mixture is determined to be

$$M_m = \frac{1}{\dfrac{\text{mf}_\text{air}}{M_\text{air}} + \dfrac{\text{mf}_{C_3H_8}}{M_{C_3H_8}}} = \frac{1}{\dfrac{0.9412}{28.97\text{ kg/kmol}} + \dfrac{0.05882}{44.0\text{ kg/kmol}}} = 29.56\text{ kg/kmol}$$

The mole fractions are

$$y_\text{air} = \text{mf}_\text{air}\frac{M_m}{M_\text{air}} = (0.9412)\frac{29.56\text{ kg/kmol}}{28.97\text{ kg/kmol}} = 0.9606$$

$$y_{C_3H_8} = \text{mf}_{C_3H_8}\frac{M_m}{M_{C_3H_8}} = (0.05882)\frac{29.56\text{ kg/kmol}}{44.0\text{ kg/kmol}} = 0.03944$$

The final pressure is expressed from ideal gas relation to be

$$P_2 = P_1 r\frac{T_2}{T_1} = (95\text{ kPa})(9.5)\frac{T_2}{(30+273.15)\text{ K}} = 2.977T_2 \qquad (1)$$

since the final temperature is not known. Using Dalton's law to find partial pressures, the entropies at the initial state are determined from EES to be:

$$T = 30°\text{C},\ P = (0.9606\times 95) = 91.26\text{ kPa} \longrightarrow s_\text{air,1} = 5.7417\text{ kJ/kg.K}$$

$$T = 30°\text{C},\ P = (0.03944\times 95) = 3.75\text{ kPa} \longrightarrow s_{C_3H_8,1} = 6.7697\text{ kJ/kg.K}$$

The final state entropies cannot be determined at this point since the final pressure and temperature are not known. However, for an isentropic process, the entropy change is zero and the final temperature and the final pressure may be determined from

$$\Delta s_\text{total} = mf_\text{air}\Delta s_\text{air} + mf_{C_3H_8}\Delta s_{C_3H_8} = 0$$

and using Eq. (1). The solution may be obtained using EES to be

T_2 = 654.9 K, P_2 = 1951 kPa

The initial and final internal energies are (from EES)

$$T_1 = 30°\text{C} \longrightarrow \begin{array}{l} u_\text{air,1} = 216.5\text{ kJ/kg} \\ u_{C_3H_8,1} = -2404\text{ kJ/kg} \end{array} \qquad T_2 = 654.9\text{ K} \longrightarrow \begin{array}{l} u_\text{air,2} = 477.1\text{ kJ/kg} \\ u_{C_3H_8,2} = -1607\text{ kJ/kg} \end{array}$$

Noting that the heat transfer is zero, an energy balance on the system gives

$$q_\text{in} + w_\text{in} = \Delta u_m \longrightarrow w_\text{in} = \Delta u_m$$

where $\Delta u_m = mf_\text{air}(u_\text{air,2} - u_\text{air,1}) + mf_{C_3H_8}(u_{C_3H_8,2} - u_{C_3H_8,1})$

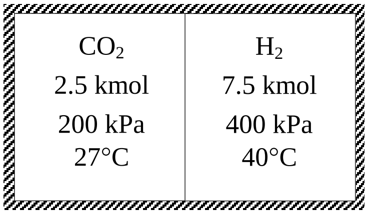
Substituting, $w_\text{in} = \Delta u_m = (0.9412)(477.1-216.5) + (0.05882)[(-1607)-(-2404)] = \mathbf{292.2\ kJ/kg}$

13-57 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



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

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

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

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

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

$$T_m = \mathbf{35.8°C} \quad \left(308.8 \text{ K}\right)$$

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

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

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

Thus,

$$\mathbf{V}_m = \mathbf{V}_{CO_2} + \mathbf{V}_{H_2} = 31.18 \text{ m}^3 + 48.79 \text{ m}^3 = 79.97 \text{ m}^3$$

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

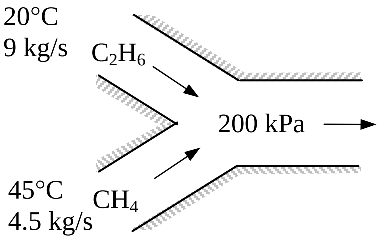
and

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

13-58 [*Also solved by EES on enclosed CD***]** The temperatures and pressures of two gases forming a mixture in a mixing chamber are given. The mixture temperature and the rate of entropy generation are to be determined.

Assumptions **1** Under specified conditions both C_2H_6 and CH_4 can be treated as ideal gases, and the mixture as an ideal gas mixture. **2** The mixing chamber is insulated and thus there is no heat transfer. **3** There are no other forms of work involved. **3** This is a steady-flow process. **4** The kinetic and potential energy changes are negligible.

Properties The specific heats of C_2H_6 and CH_4 are 1.7662 kJ/kg.°C and 2.2537 kJ/kg.°C, respectively. (Table A-2b).



Analysis (*a*) The enthalpy of ideal gases is independent of pressure, and thus the two gases can be treated independently even after mixing. Noting that $\dot{W} = \dot{Q} = 0$, the steady-flow energy balance equation reduces to

$$\begin{aligned}
\dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}} = 0\\
\dot{E}_{\text{in}} &= \dot{E}_{\text{out}}\\
\sum \dot{m}_i h_i &= \sum \dot{m}_e h_e\\
0 &= \sum \dot{m}_e h_e - \sum \dot{m}_i h_i = \dot{m}_{C_2H_6}\left(h_e - h_i\right)_{C_2H_6} + \dot{m}_{CH_4}\left(h_e - h_i\right)_{CH_4}\\
0 &= \left[\dot{m}c_p\left(T_e - T_i\right)\right]_{C_2H_6} + \left[\dot{m}c_p\left(T_e - T_i\right)\right]_{CH_4}
\end{aligned}$$

Using c_p values at room temperature and substituting, the exit temperature of the mixture becomes

$$\begin{aligned}
0 &= (9\text{ kg/s})(1.7662\text{ kJ/kg}\cdot°\text{C})(T_m - 20°\text{C}) + (4.5\text{ kg/s})(2.2537\text{ kJ/kg}\cdot°\text{C})(T_m - 45°\text{C})\\
T_m &= \mathbf{29.7°C}\quad (302.7\text{ K})
\end{aligned}$$

(*b*) The rate of entropy change associated with this process is determined from an entropy balance on the mixing chamber,

$$\begin{aligned}
\dot{S}_{\text{in}} - \dot{S}_{\text{out}} + \dot{S}_{\text{gen}} &= \Delta\dot{S}_{\text{system}}^{\nearrow 0} = 0\\
[\dot{m}(s_1 - s_2)]_{C_2H_6} + [\dot{m}(s_1 - s_2)]_{CH_4} + \dot{S}_{\text{gen}} &= 0\\
\dot{S}_{\text{gen}} &= [\dot{m}(s_2 - s_1)]_{C_2H_6} + [\dot{m}(s_2 - s_1)]_{CH_4}
\end{aligned}$$

The molar flow rate of the two gases in the mixture is

$$\begin{aligned}
\dot{N}_{C_2H_6} &= \left(\frac{\dot{m}}{M}\right)_{C_2H_6} = \frac{9\text{ kg/s}}{30\text{ kg/kmol}} = 0.3\text{ kmol/s}\\
\dot{N}_{CH_4} &= \left(\frac{\dot{m}}{M}\right)_{CH_4} = \frac{4.5\text{ kg/s}}{16\text{ kg/kmol}} = 0.2813\text{ kmol/s}
\end{aligned}$$

Then the mole fraction of each gas becomes

$$\begin{aligned}
y_{C_2H_6} &= \frac{0.3}{0.3 + 0.2813} = 0.516\\
y_{CH_4} &= \frac{0.2813}{0.3 + 0.2813} = 0.484
\end{aligned}$$

Thus,

$$(s_2 - s_1)_{C_2H_6} = \left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{yP_{m,2}}{P_1} \right)_{C_2H_6} = \left(c_p \ln\frac{T_2}{T_1} - R\ln y \right)_{C_2H_6}$$

$$= (1.7662 \text{ kJ/kg}\cdot\text{K})\ln\frac{302.7 \text{ K}}{293 \text{ K}} - (0.2765 \text{ kJ/kg}\cdot\text{K})\ln(0.516) = 0.240 \text{ kJ/kg}\cdot\text{K}$$

$$(s_2 - s_1)_{CH_4} = \left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{yP_{m,2}}{P_1} \right)_{CH_4} = \left(c_p \ln\frac{T_2}{T_1} - R\ln y \right)_{CH_4}$$

$$= (2.2537 \text{ kJ/kg}\cdot\text{K})\ln\frac{302.7 \text{ K}}{318 \text{ K}} - (0.5182 \text{ kJ/kg}\cdot\text{K})\ln(0.484) = 0.265 \text{ kJ/kg}\cdot\text{K}$$

Noting that $P_{m,2} = P_{i,1} = 200$ kPa and substituting,

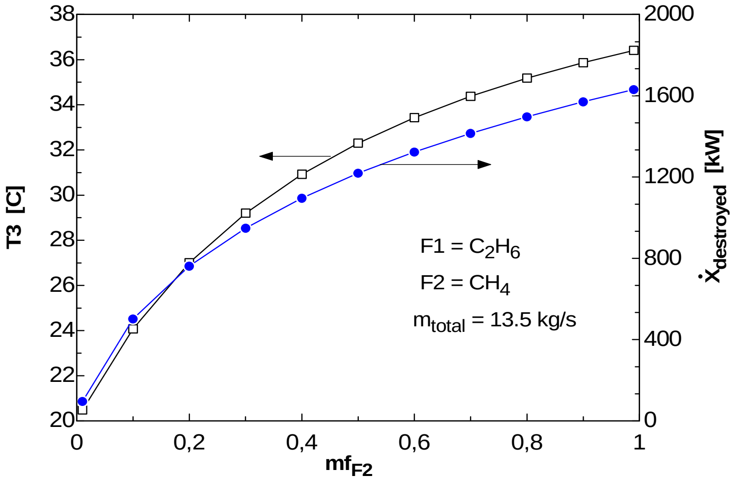
$$\dot{S}_{\text{gen}} = (9 \text{ kg/s})(0.240 \text{ kJ/kg}\cdot\text{K}) + (4.5 \text{ kg/s})(0.265 \text{ kJ/kg}\cdot\text{K}) = \mathbf{3.353\,kW/K}$$

13-59 EES Problem 13-58 is reconsidered. The effect of the mass fraction of methane in the mixture on the mixture temperature and the rate of exergy destruction is to be investigated.

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

```
"Input from the Diagram Window"
{Fluid1$='C2H6'
Fluid2$='CH4'
m_dot_F1=9 [kg/s]
m_dot_F2=m_dot_F1/2
T1=20 [C]
T2=45 [C]
P=200 [kPa]}
{mf_F2=0.1}
{m_dot_total =13.5 [kg/s]
m_dot_F2 =mf_F2*m_dot_total}
 m_dot_total = m_dot_F1 +  m_dot_F2
T_o = 25 [C]
"Conservation of energy for this steady-state, steady-flow control volume is"
E_dot_in=E_dot_out
E_dot_in=m_dot_F1*enthalpy(Fluid1$,T=T1) +m_dot_F2 *enthalpy(Fluid2$,T=T2)
E_dot_out=m_dot_F1*enthalpy(Fluid1$,T=T3) +m_dot_F2 *enthalpy(Fluid2$,T=T3)
"For entropy calculations the partial pressures are used."
Mwt_F1=MOLARMASS(Fluid1$)
N_dot_F1=m_dot_F1/Mwt_F1
Mwt_F2=MOLARMASS(Fluid2$)
N_dot_F2=m_dot_F2 /Mwt_F2
N_dot_tot=N_dot_F1+N_dot_F2
y_F1=IF(fluid1$,Fluid2$,N_dot_F1/N_dot_tot,1,N_dot_F1/N_dot_tot)
y_F2=IF(fluid1$,Fluid2$,N_dot_F2/N_dot_tot,1,N_dot_F2/N_dot_tot)
"If the two fluids are the same, the mole fractions are both  1 ."
"The entropy change of each fluid is:"
DELTAs_F1=entropy(Fluid1$, T=T3, P=y_F1*P)-entropy(Fluid1$, T=T1, P=P)
DELTAs_F2=entropy(Fluid2$, T=T3, P=y_F2*P)-entropy(Fluid2$, T=T2, P=P)
"And the entropy generation is:"
S_dot_gen=m_dot_F1*DELTAs_F1+m_dot_F2*DELTAs_F2
"Then the exergy destroyed is:"
X_dot_destroyed = (T_o+273)*S_dot_gen
```

mf_{F2}	T3 [C]	$X_{destroyed}$ [kW]
0.01	95.93	20.48
0.1	502.5	24.08
0.2	761.4	27
0.3	948.5	29.2
0.4	1096	30.92
0.5	1219	32.3
0.6	1324	33.43
0.7	1415	34.38
0.8	1497	35.18
0.9	1570	35.87
0.99	1631	36.41



13-60 A mixture of hydrogen and oxygen is considered. The entropy change of this mixture between the two specified states is to be determined.

Assumptions Hydrogen and oxygen are ideal gases.

Properties The gas constants of hydrogen and oxygen are 4.124 and 0.2598 kJ/kg·K, respectively (Table A-1).

Analysis The effective gas constant of this mixture is

$$R = \mathrm{mf}_{\mathrm{H2}} R_{\mathrm{H2}} + \mathrm{mf}_{\mathrm{O2}} R_{\mathrm{O2}} = (0.33)(4.1240) + (0.67)(0.2598) = 1.5350\ \mathrm{kJ/kg \cdot K}$$ Since the temperature of the two states is the same, the entropy change is determined from

$$s_2 - s_1 = -R \ln \frac{P_2}{P_1} = -(1.5350\ \mathrm{kJ/kg \cdot K}) \ln \frac{150\ \mathrm{kPa}}{750\ \mathrm{kPa}} = \mathbf{2.470\ kJ/kg \cdot K}$$

13-61 A mixture of nitrogen and carbon dioxide is heated at constant pressure in a closed system. The work produced is to be determined.

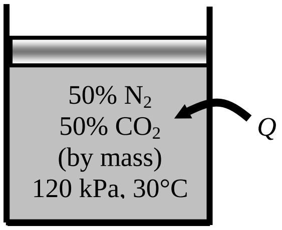
Assumptions **1** Nitrogen and carbon dioxide are ideal gases. **2** The process is reversible.

Properties The mole numbers of nitrogen and carbon dioxide are 28.0 and 44.0 kg/kmol, respectively (Table A-1).

Analysis One kg of this mixture consists of 0.5 kg of nitrogen and 0.5 kg of carbon dioxide or 0.5 kg×28.0 kg/kmol=14.0 kmol of nitrogen and 0.5 kg×44.0 kg/kmol=22.0 kmol of carbon dioxide. The constituent mole fraction are then

$$y_{\mathrm{N2}} = \frac{N_{\mathrm{N2}}}{N_{\mathrm{total}}} = \frac{14\ \mathrm{kmol}}{36\ \mathrm{kmol}} = 0.3889$$

$$y_{\mathrm{CO2}} = \frac{N_{\mathrm{CO2}}}{N_{\mathrm{total}}} = \frac{22\ \mathrm{kmol}}{36\ \mathrm{kmol}} = 0.6111$$



The effective molecular weight of this mixture is

$$\begin{aligned} M &= y_{\mathrm{N2}} M_{\mathrm{N2}} + y_{\mathrm{CO2}} M_{\mathrm{CO2}} \\ &= (0.3889)(28) + (0.6111)(44) = 37.78\ \mathrm{kg/kmol} \end{aligned}$$

The work done is determined from

$$\begin{aligned} w &= \int_1^2 P d\boldsymbol{V} = P_2 \boldsymbol{v}_2 - P_1 \boldsymbol{v}_1 = R(T_2 - T_1) \\ &= \frac{R_u}{M}(T_2 - T_1) = \frac{8.314\ \mathrm{kJ/kmol \cdot K}}{37.78\ \mathrm{kg/kmol}}(200 - 30)\mathrm{K} \\ &= \mathbf{37.4\ kJ/kg} \end{aligned}$$

13-62E The mass fractions of components of a gas mixture are given. This mixture is compressed in an isentropic process. The final mixture temperature and the work required per unit mass of the mixture are to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of N_2, He, CH_4, and C_2H_6 are 28.0, 4.0, 16.0, and 30.0 lbm/lbmol, respectively (Table A-1E). The constant-pressure specific heats of these gases at room temperature are 0.248, 1.25, 0.532, and 0.427 Btu/lbm·R, respectively (Table A-2Ea).

Analysis We consider 100 lbm of this mixture. The mole numbers of each component are

$$N_{\text{N2}} = \frac{m_{\text{N2}}}{M_{\text{N2}}} = \frac{15\text{ lbm}}{28\text{ lbm/lbmol}} = 0.5357\text{ lbmol}$$

$$N_{\text{He}} = \frac{m_{\text{He}}}{M_{\text{He}}} = \frac{5\text{ lbm}}{4\text{ lbm/lbmol}} = 1.25\text{ lbmol}$$

$$N_{\text{CH4}} = \frac{m_{\text{CH4}}}{M_{\text{CH4}}} = \frac{60\text{ lbm}}{16\text{ lbm/lbmol}} = 3.75\text{ lbmol}$$

$$N_{\text{C2H6}} = \frac{m_{\text{C2H6}}}{M_{\text{C2H6}}} = \frac{20\text{ lbm}}{30\text{ lbm/lbmol}} = 0.6667\text{ lbmol}$$

15% N_2
5% He
60% CH_4
20% C_2H_6
(by mass)

20 psia, 100°F

The mole number of the mixture is

$$N_m = N_{\text{N2}} + N_{\text{He}} + N_{\text{CH4}} + N_{\text{C2H6}} = 0.5357 + 1.25 + 3.75 + 0.6667 = 6.2024\text{ lbmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{100\text{ lbm}}{6.2024\text{ lbmol}} = 16.12\text{ lbm/lbmol}$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \text{mf}_{\text{N2}} c_{p,\text{N2}} + \text{mf}_{\text{He}} c_{p,\text{He}} + \text{mf}_{\text{CH4}} c_{p,\text{CH4}} + \text{mf}_{\text{C2H6}} c_{p,\text{C2H6}} \\ &= 0.15 \times 0.248 + 0.05 \times 1.25 + 0.60 \times 0.532 + 0.20 \times 0.427 \\ &= 0.5043\text{ Btu/lbm}\cdot\text{R} \end{aligned}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{1.9858\text{ Btu/lbmol}\cdot\text{R}}{16.12\text{ lbm/lbmol}} = 0.1232\ \text{ Btu/lbm}\cdot\text{R}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 0.5043 - 0.1232 = 0.3811\text{ Btu/lbm}\cdot\text{R}$$

The specific heat ratio is

$$k = \frac{c_p}{c_v} = \frac{0.5043}{0.3811} = 1.323$$

The temperature at the end of the compression is

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (560\text{ R})\left(\frac{200\text{ psia}}{20\text{ psia}}\right)^{0.323/1.323} = \mathbf{982\ R}$$

An energy balance on the adiabatic compression process gives

$$w_{\text{in}} = c_p(T_2 - T_1) = (0.5043\text{ Btu/lbm}\cdot\text{R})(982 - 560)\text{ R} = \mathbf{213\ Btu/lbm}$$

13-63 The mass fractions of components of a gas mixture are given. This mixture is compressed in a reversible, isothermal, steady-flow compressor. The work and heat transfer for this compression per unit mass of the mixture are to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

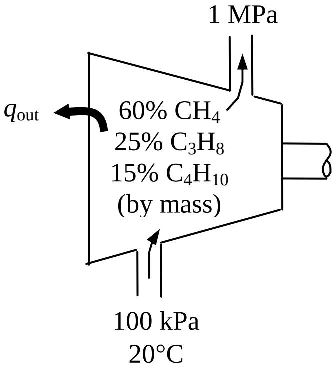
Properties The molar masses of CH_4, C_3H_8, and C_4H_{10} are 16.0, 44.0, and 58.0 lbm/lbmol, respectively (Table A-1E).

Analysis The mole numbers of each component are

$$N_{\text{CH4}} = \frac{m_{\text{CH4}}}{M_{\text{CH4}}} = \frac{60\text{ lbm}}{16\text{ lbm/lbmol}} = 3.75\text{ lbmol}$$

$$N_{\text{C3H8}} = \frac{m_{\text{C3H8}}}{M_{\text{C3H8}}} = \frac{25\text{ lbm}}{44\text{ lbm/lbmol}} = 0.5682\text{ lbmol}$$

$$N_{\text{C4H10}} = \frac{m_{\text{C4H10}}}{M_{\text{C4H10}}} = \frac{15\text{ lbm}}{58\text{ lbm/lbmol}} = 0.2586\text{ lbmol}$$



The mole number of the mixture is

$$\begin{aligned} N_m &= N_{\text{CH4}} + N_{\text{C3H8}} + N_{\text{C4H10}} \\ &= 3.75 + 0.5682 + 0.2586 = 4.5768\text{ lbmol} \end{aligned}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{100\text{ lbm}}{4.5768\text{ lbmol}} = 21.85\text{ lbm/lbmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\text{ kJ/kmol}\cdot\text{K}}{21.85\text{ kg/kmol}} = 0.3805\text{ kJ/kg}\cdot\text{K}$$

For a reversible, isothermal process, the work input is

$$w_{\text{in}} = RT\ln\left(\frac{P_2}{P_1}\right) = (0.3805\text{ kJ/kg}\cdot\text{K})(293\text{ K})\ln\left(\frac{1000\text{ kPa}}{100\text{ kPa}}\right) = \mathbf{257\ kJ/kg}$$

An energy balance on the control volume gives

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta\dot{E}_{\text{system}}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

$$\begin{aligned} \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{m}h_1 + \dot{W}_{\text{in}} &= \dot{m}h_2 + \dot{Q}_{\text{out}} \\ \dot{W}_{\text{in}} - \dot{Q}_{\text{out}} &= \dot{m}(h_2 - h_1) \\ w_{\text{in}} - q_{\text{out}} &= c_p(T_2 - T_1) = 0 \quad \text{since } T_2 = T_1 \\ w_{\text{in}} &= q_{\text{out}} \end{aligned}$$

That is,

$$q_{\text{out}} = w_{\text{in}} = \mathbf{257\ kJ/kg}$$

13-64 The masses of components of a gas mixture are given. This mixture is heated at constant pressure. The change in the volume of the mixture and the total heat transferred to the mixture are to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of O_2, CO_2, and He are 32.0, 44.0, and 4.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 0.918, 0.846, and 5.1926 kJ/kg·K, respectively (Table A-2a).

Analysis The total mass of the mixture is

$$m_m = m_{\mathrm{O2}} + m_{\mathrm{CO2}} + m_{\mathrm{He}} = 0.1 + 1 + 0.5 = 1.6\ \mathrm{kg}$$

The mole numbers of each component are

0.1 kg O_2
1 kg CO_2
0.5 kg He

350 kPa, 10°C

$$N_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{M_{\mathrm{O2}}} = \frac{0.1\ \mathrm{kg}}{32\ \mathrm{kg/kmol}} = 0.003125\ \mathrm{kmol}$$

$$N_{\mathrm{CO2}} = \frac{m_{\mathrm{CO2}}}{M_{\mathrm{CO2}}} = \frac{1\ \mathrm{kg}}{44\ \mathrm{kg/kmol}} = 0.02273\ \mathrm{kmol}$$

$$N_{\mathrm{He}} = \frac{m_{\mathrm{He}}}{M_{\mathrm{He}}} = \frac{0.5\ \mathrm{kg}}{4\ \mathrm{kg/kmol}} = 0.125\ \mathrm{kmol}$$

The mole number of the mixture is

$$N_m = N_{\mathrm{O2}} + N_{\mathrm{CO2}} + N_{\mathrm{He}} = 0.003125 + 0.02273 + 0.125 = 0.15086\ \mathrm{kmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{1.6\ \mathrm{kg}}{0.15086\ \mathrm{kmol}} = 10.61\ \mathrm{kg/kmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol\cdot K}}{10.61\ \mathrm{kg/kmol}} = 0.7836\ \mathrm{kJ/kg\cdot K}$$

The mass fractions are

$$\mathrm{mf}_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{m_m} = \frac{0.1\ \mathrm{kg}}{1.6\ \mathrm{kg}} = 0.0625$$

$$\mathrm{mf}_{\mathrm{CO2}} = \frac{m_{\mathrm{CO2}}}{m_m} = \frac{1\ \mathrm{kg}}{1.6\ \mathrm{kg}} = 0.625$$

$$\mathrm{mf}_{\mathrm{He}} = \frac{m_{\mathrm{He}}}{m_m} = \frac{0.5\ \mathrm{kg}}{1.6\ \mathrm{kg}} = 0.3125$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \mathrm{mf}_{\mathrm{O2}} c_{p,\mathrm{O2}} + \mathrm{mf}_{\mathrm{CO2}} c_{p,\mathrm{CO2}} + \mathrm{mf}_{\mathrm{He}} c_{p,\mathrm{He}} \\ &= 0.0625 \times 0.918 + 0.625 \times 0.846 + 0.3125 \times 5.1926 \\ &= 2.209\ \mathrm{kJ/kg\cdot K} \end{aligned}$$

The change in the volume of this ideal gas mixture is

$$\Delta \boldsymbol{V}_m = \frac{m_m R \Delta T}{P} = \frac{(1.6\ \mathrm{kg})(0.7836\ \mathrm{kPa\cdot m^3/kg\cdot K})(260-10)\ \mathrm{K}}{350\ \mathrm{kPa}} = \mathbf{0.8955\ m^3}$$

The heat transfer is determined to be

$$q_{\mathrm{in}} = c_p (T_2 - T_1) = (2.209\ \mathrm{kJ/kg\cdot K})(260-10)\ \mathrm{K} = \mathbf{552\ kJ/kg}$$

13-65E The volume fractions of components of a gas mixture during the expansion process of the ideal Otto cycle are given. The thermal efficiency of this cycle is to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of N_2, O_2, H_2O, and CO_2 are 28.0, 32.0, 18.0, and 44.0 lbm/lbmol, respectively (Table A-1E). The constant-pressure specific heats of these gases at room temperature are 0.248, 0.219, 0.445, and 0.203 Btu/lbm·R, respectively. The air properties at room temperature are c_p = 0.240 Btu/lbm·R, c_v = 0.171 Btu/lbm·R, k = 1.4 (Table A-2Ea).

Analysis We consider 100 lbmol of this mixture. Noting that volume fractions are equal to the mole fractions, mass of each component are

$$\begin{aligned}
m_{\text{N2}} &= N_{\text{N2}}M_{\text{N2}} = (25\,\text{lbmol})(28\,\text{lbm/lbmol}) = 700\,\text{lbm}\\
m_{\text{O2}} &= N_{\text{O2}}M_{\text{O2}} = (7\,\text{lbmol})(32\,\text{lbm/lbmol}) = 224\,\text{lbm}\\
m_{\text{H2O}} &= N_{\text{H2O}}M_{\text{H2O}} = (28\,\text{lbmol})(18\,\text{lbm/lbmol}) = 504\,\text{lbm}\\
m_{\text{CO2}} &= N_{\text{CO2}}M_{\text{CO2}} = (40\,\text{lbmol})(44\,\text{lbm/lbmol}) = 1760\,\text{lbm}
\end{aligned}$$

25% N_2
7% O_2
28% H_2O
40% CO_2
(by volume)

The total mass is

$$\begin{aligned}
m_m &= m_{\text{N2}} + m_{\text{O2}} + m_{\text{H2O}} + m_{\text{CO2}}\\
&= 700 + 224 + 504 + 1760\\
&= 3188\,\text{lbm}
\end{aligned}$$

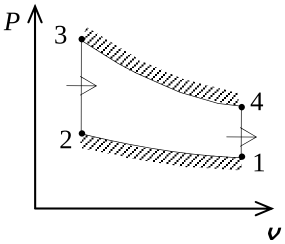
Then the mass fractions are

$$\text{mf}_{\text{N2}} = \frac{m_{\text{N2}}}{m_m} = \frac{700\,\text{lbm}}{3188\,\text{lbm}} = 0.2196$$

$$\text{mf}_{\text{O2}} = \frac{m_{\text{O2}}}{m_m} = \frac{224\,\text{lbm}}{3188\,\text{lbm}} = 0.07026$$

$$\text{mf}_{\text{H2O}} = \frac{m_{\text{H2O}}}{m_m} = \frac{504\,\text{lbm}}{3188\,\text{lbm}} = 0.1581$$

$$\text{mf}_{\text{CO2}} = \frac{m_{\text{CO2}}}{m_m} = \frac{1760\,\text{lbm}}{3188\,\text{lbm}} = 0.5521$$



The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned}
c_p &= \text{mf}_{\text{N2}}c_{p,\text{N2}} + \text{mf}_{\text{O2}}c_{p,\text{O2}} + \text{mf}_{\text{H2O}}c_{p,\text{H2O}} + \text{mf}_{\text{CO2}}c_{p,\text{CO2}}\\
&= 0.2196\times 0.248 + 0.07026\times 0.219 + 0.1581\times 0.445 + 0.5521\times 0.203\\
&= 0.2523\,\text{Btu/lbm}\cdot\text{R}
\end{aligned}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{3188\,\text{lbm}}{100\,\text{lbmol}} = 31.88\,\text{lbm/lbmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{1.9858\,\text{Btu/lbmol}\cdot\text{R}}{31.88\,\text{lbm/lbmol}} = 0.06229\,\text{Btu/lbm}\cdot\text{R}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 0.2523 - 0.06229 = 0.1900\,\text{Btu/lbm}\cdot\text{R}$$

The specific heat ratio is

$$k = \frac{c_p}{c_v} = \frac{0.2523}{0.1900} = 1.328$$

The average of the air properties at room temperature and combustion gas properties are

$$c_{p,\text{avg}} = 0.5(0.2523 + 0.240) = 0.2462\ \text{Btu/lbm}\cdot\text{R}$$
$$c_{v,\text{avg}} = 0.5(0.1900 + 0.171) = 0.1805\ \text{Btu/lbm}\cdot\text{R}$$
$$k_{\text{avg}} = 0.5(1.328 + 1.4) = 1.364$$

These average properties will be used for heat addition and rejection processes. For compression, the air properties at room temperature and during expansion, the mixture properties will be used. During the compression process,

$$T_2 = T_1 r^{k-1} = (515\ \text{R})(7)^{0.4} = 1122\ \text{R}$$

During the heat addition process,

$$q_{\text{in}} = c_{v,\text{avg}}(T_3 - T_2) = (0.1805\ \text{Btu/lbm}\cdot\text{R})(2060 - 1122)\ \text{R} = 169.3\ \text{Btu/lbm}$$

During the expansion process,

$$T_4 = T_3\left(\frac{1}{r}\right)^{k-1} = (2060\ \text{R})\left(\frac{1}{7}\right)^{0.364} = 1014\ \text{R}$$

During the heat rejection process,

$$q_{\text{out}} = c_{v,\text{avg}}(T_4 - T_1) = (0.1805\ \text{Btu/lbm}\cdot\text{R})(1014 - 515)\ \text{R} = 90.1\ \text{Btu/lbm}$$

The thermal efficiency of the cycle is then

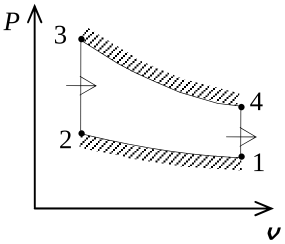
$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{90.1\ \text{Btu/lbm}}{169.3\ \text{Btu/lbm}} = \mathbf{0.468}$$

13-66E The thermal efficiency of the cycle in the previous problem is to be compared to that predicted by air standard analysis?

Assumptions Air-standard assumptions are applicable.

Properties The air properties at room temperature are c_p = 0.240 Btu/lbm·R, c_v = 0.171 Btu/lbm·R, k = 1.4 (Table A-2Ea).

Analysis In the previous problem, the thermal efficiency of the cycle was determined to be **0.468** (46.8%). The thermal efficiency with air-standard model is determined from



$$\eta_{\text{th}} = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{7^{0.4}} = \mathbf{0.541}$$

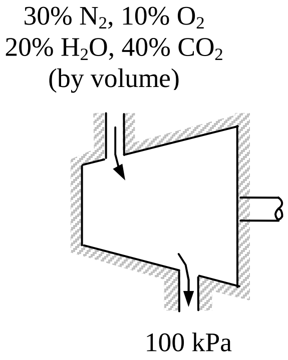
which is significantly greater than that calculated with gas mixture analysis in the previous problem.

13-67 The volume fractions of components of a gas mixture passing through the turbine of a simple ideal Brayton cycle are given. The thermal efficiency of this cycle is to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of N_2, O_2, H_2O, and CO_2 are 28.0, 32.0, 18.0, and 44.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 1.039, 0.918, 1.8723, and 0.846 kJ/kg·K, respectively. The air properties at room temperature are c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K, k = 1.4 (Table A-2a).

Analysis We consider 100 kmol of this mixture. Noting that volume fractions are equal to the mole fractions, mass of each component are

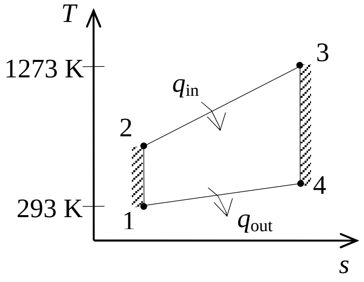


$$m_{\text{N2}} = N_{\text{N2}} M_{\text{N2}} = (30\text{ kmol})(28\text{ kg/kmol}) = 840\text{ kg}$$
$$m_{\text{O2}} = N_{\text{O2}} M_{\text{O2}} = (10\text{ kmol})(32\text{ kg/kmol}) = 320\text{ kg}$$
$$m_{\text{H2O}} = N_{\text{H2O}} M_{\text{H2O}} = (20\text{ kmol})(18\text{ kg/kmol}) = 360\text{ kg}$$
$$m_{\text{CO2}} = N_{\text{CO2}} M_{\text{CO2}} = (40\text{ kmol})(44\text{ kg/kmol}) = 1760\text{ kg}$$

The total mass is

$$\begin{aligned} m_m &= m_{\text{N2}} + m_{\text{O2}} + m_{\text{H2O}} + m_{\text{CO2}} \\ &= 840 + 320 + 360 + 1760 \\ &= 3280\text{ kg} \end{aligned}$$

Then the mass fractions are



$$\text{mf}_{\text{N2}} = \frac{m_{\text{N2}}}{m_m} = \frac{840\text{ kg}}{3280\text{ kg}} = 0.2561$$
$$\text{mf}_{\text{O2}} = \frac{m_{\text{O2}}}{m_m} = \frac{320\text{ kg}}{3280\text{ kg}} = 0.09756$$
$$\text{mf}_{\text{H2O}} = \frac{m_{\text{H2O}}}{m_m} = \frac{360\text{ kg}}{3280\text{ kg}} = 0.1098$$
$$\text{mf}_{\text{CO2}} = \frac{m_{\text{CO2}}}{m_m} = \frac{1760\text{ kg}}{3280\text{ kg}} = 0.5366$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \text{mf}_{\text{N2}} c_{p,\text{N2}} + \text{mf}_{\text{O2}} c_{p,\text{O2}} + \text{mf}_{\text{H2O}} c_{p,\text{H2O}} + \text{mf}_{\text{CO2}} c_{p,\text{CO2}} \\ &= 0.2561 \times 1.039 + 0.09756 \times 0.918 + 0.1098 \times 1.8723 + 0.5366 \times 0.846 \\ &= 1.015\text{ kJ/kg}\cdot\text{K} \end{aligned}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{3280\text{ kg}}{100\text{ kmol}} = 32.80\text{ kg/kmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\text{ kJ/kmol}\cdot\text{K}}{32.80\text{ kg/kmol}} = 0.2535\text{ kJ/kg}\cdot\text{K}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 1.015 - 0.2535 = 0.762\text{ kJ/kg}\cdot\text{K}$$

The specific heat ratio is

$$k = \frac{c_p}{c_v} = \frac{1.015}{0.762} = 1.332$$

The average of the air properties at room temperature and combustion gas properties are

$$\begin{aligned} c_{p,\text{avg}} &= 0.5(1.015 + 1.005) = 1.010\ \text{kJ/kg}\cdot\text{K} \\ c_{v,\text{avg}} &= 0.5(0.762 + 0.718) = 0.740\ \text{kJ/kg}\cdot\text{K} \\ k_{\text{avg}} &= 0.5(1.332 + 1.4) = 1.366 \end{aligned}$$

These average properties will be used for heat addition and rejection processes. For compression, the air properties at room temperature and during expansion, the mixture properties will be used. During the compression process,

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (293\ \text{K})(8)^{0.4/1.4} = 531\ \text{K}$$

During the heat addition process,

$$q_{\text{in}} = c_{p,\text{avg}}(T_3 - T_2) = (1.010\ \text{kJ/kg}\cdot\text{K})(1273 - 531)\ \text{K} = 749.4\ \text{kJ/kg}$$

During the expansion process,

$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (1273\ \text{K})\left(\frac{1}{8}\right)^{0.332/1.332} = 758\ \text{K}$$

During the heat rejection process,

$$q_{\text{out}} = c_{p,\text{avg}}(T_4 - T_1) = (1.010\ \text{kJ/kg}\cdot\text{K})(758 - 293)\ \text{K} = 469.7\ \text{kJ/kg}$$

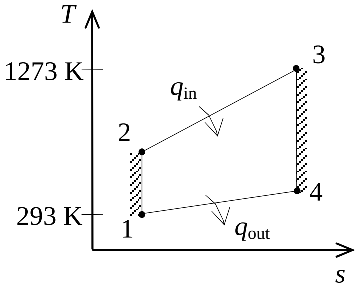
The thermal efficiency of the cycle is then

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{469.7\ \text{kJ/kg}}{749.4\ \text{kJ/kg}} = \mathbf{0.373}$$

13-68 The thermal efficiency of the cycle in the previous problem is to be compared to that predicted by air standard analysis?

Assumptions Air-standard assumptions are applicable.

Properties The air properties at room temperature are c_p = 1.005 kJ/kg·K, c_v = 1.4 kJ/kg·K, k = 1.4 (Table A-2a).



Analysis In the previous problem, the thermal efficiency of the cycle was determined to be **0.373** (37.3%). The thermal efficiency with air-standard model is determined from

$$\eta_{\text{th}} = 1 - \frac{1}{r_p^{(k-1)/k}} = 1 - \frac{1}{8^{0.4/1.4}} = \mathbf{0.448}$$

which is significantly greater than that calculated with gas mixture analysis in the previous problem.

13-69E The mass fractions of a natural gas mixture at a specified pressure and temperature trapped in a geological location are given. This natural gas is pumped to the surface. The work required is to be determined using Kay's rule and the enthalpy-departure method.

Properties The molar masses of CH_4 and C_2H_6 are 16.0 and 30.0 lbm/lbmol, respectively. The critical properties are 343.9 R, 673 psia for CH_4 and 549.8 R and 708 psia for C_2H_6 (Table A-1E). The constant-pressure specific heats of these gases at room temperature are 0.532 and 0.427 Btu/lbm·R, respectively (Table A-2Ea).

Analysis We consider 100 lbm of this mixture. Then the mole numbers of each component are

$$N_{\text{CH4}} = \frac{m_{\text{CH4}}}{M_{\text{CH4}}} = \frac{75\text{ lbm}}{16\text{ lbm/lbmol}} = 4.6875\text{ lbmol}$$

$$N_{\text{C2H6}} = \frac{m_{\text{C2H6}}}{M_{\text{C2H6}}} = \frac{25\text{ lbm}}{30\text{ lbm/lbmol}} = 0.8333\text{ lbmol}$$

75% CH_4
25% C_2H_6
(by mass)
2000 psia
300°F

The mole number of the mixture and the mole fractions are

$$N_m = 4.6875 + 0.8333 = 5.5208\text{ lbmol}$$

$$y_{\text{CH4}} = \frac{N_{\text{CH4}}}{N_m} = \frac{4.6875\text{ lbmol}}{5.5208\text{ lbmol}} = 0.8491$$

$$y_{\text{C2H6}} = \frac{N_{\text{C2H6}}}{N_m} = \frac{0.8333\text{ lbmol}}{5.5208\text{ lbmol}} = 0.1509$$

Then the apparent molecular weight of the mixture becomes

$$M_m = \frac{m_m}{N_m} = \frac{100\text{ lbm}}{5.5208\text{ lbmol}} = 18.11\text{ lbm/lbmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{1.9858\text{ Btu/lbmol}\cdot\text{R}}{18.11\text{ lbm/lbmol}} = 0.1097\text{ Btu/lbm}\cdot\text{R}$$

The constant-pressure specific heat of the mixture is determined from

$$c_p = \text{mf}_{\text{CH4}}c_{p,\text{CH4}} + \text{mf}_{\text{C2H6}}c_{p,\text{C2H6}} = 0.75\times 0.532 + 0.25\times 0.427 = 0.506\text{ Btu/lbm}\cdot\text{R}$$

To use Kay's rule, we need to determine the pseudo-critical temperature and pseudo-critical pressure of the mixture using the critical point properties of gases.

$$\begin{aligned} T'_{\text{cr},m} &= \sum y_i T_{\text{cr},i} = y_{\text{CH4}}T_{\text{cr,Ch4}} + y_{\text{C2H6}}T_{\text{cr,C2H6}} \\ &= (0.8491)(343.9\text{ R}) + (0.1509)(549.8\text{ R}) = 375.0\text{ R} \end{aligned}$$

$$\begin{aligned} P'_{\text{cr},m} &= \sum y_i P_{\text{cr},i} = y_{\text{Ch4}}P_{\text{cr,Ch4}} + y_{\text{C2H6}}P_{\text{cr,C2H6}} \\ &= (0.8491)(673\text{ psia}) + (0.1509)(708\text{ psia}) = 678.3\text{ psia} \end{aligned}$$

The compressibility factor of the gas mixture in the reservoir and the mass of this gas are

$$\left.\begin{aligned} T_R &= \frac{T_m}{T'_{\text{cr},m}} = \frac{760\text{ R}}{375.0\text{ R}} = 2.027 \\ P_R &= \frac{P_m}{P'_{\text{cr},m}} = \frac{2000\text{ psia}}{678.3\text{ psia}} = 2.949 \end{aligned}\right\} Z_m = 0.963 \qquad \text{(Fig. A-15)}$$

$$m = \frac{PV}{Z_m RT} = \frac{(2000\text{ psia})(1\times10^6\text{ ft}^3)}{(0.963)(0.5925\text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(760\text{ R})} = 4.612\times10^6\text{ lbm}$$

The enthalpy departure factors in the reservoir and the surface are (from EES or Fig. A-29)

$$\left.\begin{aligned} T_{R1} &= \frac{T_m}{T'_{\text{cr},m}} = \frac{760\text{ R}}{375.0\text{ R}} = 2.027 \\ P_{R1} &= \frac{P_m}{P'_{\text{cr},m}} = \frac{2000\text{ psia}}{678.3\text{ psia}} = 2.949 \end{aligned}\right\} Z_{h1} = 0.703$$

$$\left.\begin{aligned} T_{R2} &= \frac{T_m}{T'_{\text{cr},m}} = \frac{660\text{ R}}{375.0\text{ R}} = 1.76 \\ P_{R2} &= \frac{P_m}{P'_{\text{cr},m}} = \frac{20\text{ psia}}{678.3\text{ psia}} = 0.0295 \end{aligned}\right\} Z_{h2} = 0.0112$$

The enthalpy change for the ideal gas mixture is

$$(h_2 - h_1)_{\text{ideal}} = c_p(T_2 - T_1) = (0.506\text{ Btu/lbm}\cdot\text{R})(760-660)\text{R} = 50.6\text{ Btu/lbm}$$

The enthalpy change with departure factors is

$$\begin{aligned} h_2 - h_1 &= (h_2 - h_1)_{\text{ideal}} - RT'_{\text{cr},m}(Z_{h2} - Z_{h1}) \\ &= 50.6 - (0.1096)(375)(0.0112 - 0.703) \\ &= 79.0\text{ Btu/lbm} \end{aligned}$$

The work input is then

$$W_{\text{in}} = m(h_2 - h_1) = (4.612\times10^6\text{ lbm})(79.0\text{ Btu/lbm}) = \mathbf{3.64\times10^8\ Btu}$$

13-70 In a liquid-oxygen plant, it is proposed that the pressure and temperature of air be adiabatically reduced. It is to be determined whether this process is possible and the work produced is to be determined using Kay's rule and the departure charts.

Assumptions Air is a gas mixture with 21% O_2 and 79% N_2, by mole.

Properties The molar masses of O_2 and N_2 are 32.0 and 28.0 kg/kmol, respectively. The critical properties are 154.8 K, 5.08 MPa for O_2 and 126.2 K and 3.39 MPa for N_2 (Table A-1).

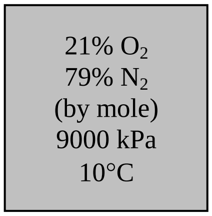
Analysis To use Kay's rule, we need to determine the pseudo-critical temperature and pseudo-critical pressure of the mixture using the critical point properties of gases.

$$\begin{aligned}T'_{\text{cr},m} &= \sum y_i T_{\text{cr},i} = y_{\text{O2}} T_{\text{cr,O2}} + y_{\text{N2}} T_{\text{cr,N2}} \\ &= (0.21)(154.8\text{ K}) + (0.79)(126.2\text{ K}) = 132.2\text{ K}\end{aligned}$$

$$\begin{aligned}P'_{\text{cr},m} &= \sum y_i P_{\text{cr},i} = y_{\text{O2}} P_{\text{cr,O2}} + y_{\text{N2}} P_{\text{cr,N2}} \\ &= (0.21)(5.08\text{ MPa}) + (0.79)(3.39\text{ MPa}) = 3.745\text{ MPa}\end{aligned}$$

The enthalpy and entropy departure factors at the initial and final states are (from EES)

$$\left.\begin{aligned}T_{R1} &= \frac{T_{m1}}{T'_{\text{cr},m}} = \frac{283\text{ K}}{132.2\text{ K}} = 2.141 \\ P_{R1} &= \frac{P_{m1}}{P'_{\text{cr},m}} = \frac{9\text{ MPa}}{3.745\text{ MPa}} = 2.403\end{aligned}\right\} \begin{aligned}Z_{h1} &= 0.513 \\ Z_{s1} &= 0.235\end{aligned}$$



$$\left.\begin{aligned}T_{R2} &= \frac{T_{m2}}{T'_{\text{cr},m}} = \frac{200\text{ K}}{132.2\text{ K}} = 1.513 \\ P_{R2} &= \frac{P_{m2}}{P'_{\text{cr},m}} = \frac{0.050\text{ MPa}}{3.745\text{ MPa}} = 0.0134\end{aligned}\right\} \begin{aligned}Z_{h2} &= 0.0069 \\ Z_{s2} &= 0.0035\end{aligned}$$

The enthalpy and entropy changes of the air under the ideal gas assumption is (Properties are from Table A-17)

$$(h_2 - h_1)_{\text{ideal}} = 199.97 - 283.14 = -83.2\text{ kJ/kg}$$

$$(s_2 - s_1)_{\text{ideal}} = s_2^{\text{o}} - s_1^{\text{o}} - R\ln\frac{P_2}{P_1} = 1.29559 - 1.64345 - (0.287)\ln\frac{50}{9000} = 1.1425\text{ kJ/kg}\cdot\text{K}$$

With departure factors, the enthalpy change (i.e., the work output) and the entropy change are

$$\begin{aligned}w_{\text{out}} &= h_1 - h_2 = (h_1 - h_2)_{\text{ideal}} - RT'_{\text{cr}}(Z_{h1} - Z_{h2}) \\ &= 83.2 - (0.287)(132.2)(0.513 - 0.0069) = \mathbf{64.0\text{ kJ/kg}}\end{aligned}$$

$$\begin{aligned}s_2 - s_1 &= (s_2 - s_1)_{\text{ideal}} - R(Z_{s2} - Z_{s1}) \\ &= 1.1425 - (0.287)(0.0035 - 0.235) = \mathbf{1.209\text{ kJ/kg}\cdot\text{K}}\end{aligned}$$

The entropy change in this case is equal to the entropy generation during the process since the process is adiabatic. The positive value of entropy generation shows that this process is possible.

13-71E [*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.

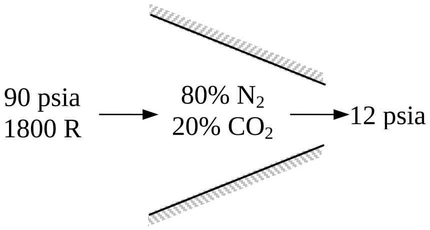
Properties The specific heats of N_2 and CO_2 are $c_{p,\mathrm{N2}}$ = 0.248 Btu/lbm.R, $c_{\upsilon,\mathrm{N2}}$ = 0.177 Btu/lbm.R, $c_{p,\mathrm{CO2}}$ = 0.203 Btu/lbm.R, and $c_{\upsilon,\mathrm{CO2}}$ = 0.158 Btu/lbm.R. (Table A-2E).

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_υ, and k values of this mixture are determined from

$$\begin{aligned} c_{p,m} &= \sum \mathrm{mf}_i c_{p,i} = \mathrm{mf}_{\mathrm{N_2}} c_{p,\mathrm{N_2}} + \mathrm{mf}_{\mathrm{CO_2}} c_{p,\mathrm{CO_2}} \\ &= (0.8)(0.248) + (0.2)(0.203) \\ &= 0.239\ \mathrm{Btu/lbm\cdot R} \end{aligned}$$

$$\begin{aligned} c_{\upsilon,m} &= \sum \mathrm{mf}_i c_{\upsilon,i} = \mathrm{mf}_{\mathrm{N_2}} c_{\upsilon,\mathrm{N_2}} + \mathrm{mf}_{\mathrm{CO_2}} c_{\upsilon,\mathrm{CO_2}} \\ &= (0.8)(0.177) + (0.2)(0.158) \\ &= 0.173\ \mathrm{Btu/lbm\cdot R} \end{aligned}$$

$$k_m = \frac{c_{p,m}}{c_{\upsilon,m}} = \frac{0.239\ \mathrm{Btu/lbm\cdot R}}{0.173\ \mathrm{Btu/lbm\cdot R}} = 1.382$$



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

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (1800\ \mathrm{R})\left(\frac{12\ \mathrm{psia}}{90\ \mathrm{psia}}\right)^{0.382/1.382} = 1031.3\ \mathrm{R}$$

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,

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

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

$$h_1 + V_1^2/2 = h_2 + V_2^2/2$$

$$0 = c_p(T_2 - T_1) + \frac{V_2^2 - V_1^{2\,\nearrow 0}}{2}$$

$$V_2 = \sqrt{2c_p(T_1 - T_2)} = \sqrt{2(0.239\ \mathrm{Btu/lbm\cdot R})(1800 - 1092.8)\ \mathrm{R}\left(\frac{25{,}037\ \mathrm{ft^2/s^2}}{1\ \mathrm{Btu/lbm}}\right)} = \mathbf{2{,}909\ \ ft/s}$$

13-72E EES Problem 13-71E is reconsidered. The problem is first to be solved and then, for all other conditions being the same, the problem is to be resolved 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.

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

```
"Input Data"
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"
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)
```

SOLUTION of the stated problem

```
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]
```

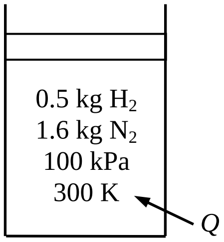
SOLUTION of the problem with exit velocity of 2600 ft/s

```
DELTAs_CO2=-0.005444 [Btu/lbm-R]     DELTAs_mix=0 [Btu/lbm-R]
DELTAs_N2=0.05015 [Btu/lbm-R]        Eta_N=0.92
h[1]=-3142 [Btu/lbm]                 h[2]=-3277 [Btu/lbm]
h_s2=-3288 [Btu/lbm]                 mf_CO2=0.9021 [lbm_CO2/lbm_mix]
mf_N2=0.09793 [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=76.89 [psia]
P_1_N2=13.11 [psia]                  P_2_CO2=10.25 [psia]
P_2_N2=1.748 [psia]                  T[1]=1800 [R]
T[2]=1323 [R]                        T_s2=1279 [R]
Vel[1]=0 [ft/s]                      Vel[2]=2600 [ft/s]
y_CO2=0.8543 [ft/s]                  y_N2=0.1457 [lbmol_N2/lbmol_mix]
```

13-73 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 1.049 kJ/kg.K, respectively. (Table A-2b).



Analysis (*a*) Noting that $P_2 = P_1$ and $\mathbf{V}_2 = 2\mathbf{V}_1$,

$$\frac{P_2\mathbf{V}_2}{T_2} = \frac{P_1\mathbf{V}_1}{T_1} \longrightarrow T_2 = \frac{2\mathbf{V}_1}{\mathbf{V}_1}T_1 = 2T_1 = (2)(300\text{ K}) = 600\text{ K}$$

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

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

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

since W_{b} and ΔU combine into ΔH for quasi-equilibrium constant pressure processes.

$$\begin{aligned}Q_{\text{in}} &= \Delta H = \Delta H_{\text{H}_2} + \Delta H_{\text{N}_2} = \left[mc_{p,\text{avg}}(T_2 - T_1)\right]_{\text{H}_2} + \left[mc_{p,\text{avg}}(T_2 - T_1)\right]_{\text{N}_2} \\ &= (0.5\text{ kg})(14.501\text{ kJ/kg}\cdot\text{K})(600-300)\text{K} + (1.6\text{ kg})(1.049\text{ kJ/kg}\cdot\text{K})(600-300)\text{K} \\ &= \mathbf{2679\ kJ}\end{aligned}$$

(*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

$$\begin{aligned}\Delta S_{\text{H}_2} &= \left[m(s_2 - s_1)\right]_{\text{H}_2} = m_{\text{H}_2}\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}^{\nearrow 0}\right)_{\text{H}_2} = m_{\text{H}_2}\left(c_p \ln\frac{T_2}{T_1}\right)_{\text{H}_2} \\ &= (0.5\text{ kg})(14.501\text{ kJ/kg}\cdot\text{K})\ln\frac{600\text{ K}}{300\text{ K}} \\ &= 5.026\text{ kJ/K}\end{aligned}$$

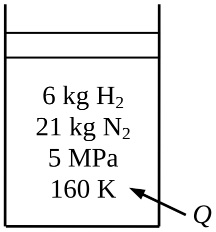
$$\begin{aligned}\Delta S_{\text{N}_2} &= \left[m(s_2 - s_1)\right]_{\text{N}_2} = m_{\text{N}_2}\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}^{\nearrow 0}\right)_{\text{N}_2} = m_{\text{N}_2}\left(c_p \ln\frac{T_2}{T_1}\right)_{\text{N}_2} \\ &= (1.6\text{ kg})(1.049\text{ kJ/kg}\cdot\text{K})\ln\frac{600\text{ K}}{300\text{ K}} \\ &= 1.163\text{ kJ/K}\end{aligned}$$

$$\Delta S_{\text{total}} = \Delta S_{\text{H}_2} + \Delta S_{\text{N}_2} = 5.026\text{ kJ/K} + 1.163\text{ kJ/K} = \mathbf{6.19\ kJ/K}$$

13-74 Heat is transferred to a gas mixture contained in a piston cylinder device. The initial state and the final temperature are given. The heat transfer is to be determined for the ideal gas and non-ideal gas cases.

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

Analysis From the energy balance relation,



$$E_{\text{in}} - E_{\text{out}} = \Delta E$$

$$Q_{\text{in}} - W_{b,\text{out}} = \Delta U$$

$$Q_{\text{in}} = \Delta H = \Delta H_{\text{H}_2} + \Delta H_{\text{N}_2} = N_{\text{H}_2}\left(\bar{h}_2 - \bar{h}_1\right)_{\text{H}_2} + N_{\text{N}_2}\left(\bar{h}_2 - \bar{h}_1\right)_{\text{N}_2}$$

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

$$N_{\text{H}_2} = \frac{m_{\text{H}_2}}{M_{\text{H}_2}} = \frac{6\ \text{kg}}{2\ \text{kg/kmol}} = 3\ \text{kmol}$$

$$N_{\text{N}_2} = \frac{m_{\text{N}_2}}{M_{\text{N}_2}} = \frac{21\ \text{kg}}{28\ \text{kg/kmol}} = 0.75\ \text{kmol}$$

(*a*) Assuming ideal gas behavior, the inlet and exit enthalpies of H_2 and N_2 are determined from the ideal gas tables to be

$$H_2:\quad \bar{h}_1 = \bar{h}_{@160\ \text{K}} = 4{,}535.4\ \text{kJ/kmol}, \qquad \bar{h}_2 = \bar{h}_{@\,200\ \text{K}} = 5{,}669.2\ \text{kJ/kmol}$$

$$N_2:\quad \bar{h}_1 = \bar{h}_{@160\ \text{K}} = 4{,}648\ \text{kJ/kmol}, \qquad \bar{h}_2 = \bar{h}_{@\,200\ \text{K}} = 5{,}810\ \text{kJ/kmol}$$

Thus, $Q_{\text{ideal}} = 3 \times \left(5{,}669.2 - 4{,}535.4\right) + 0.75 \times \left(5{,}810 - 4{,}648\right) = \mathbf{4273\ \ kJ}$

(*b*) Using Amagat's law and the generalized enthalpy departure chart, the enthalpy change of each gas is determined to be

$$\text{H}_2:\quad \left.\begin{array}{l} T_{R_1,\text{H}_2} = \dfrac{T_{m,1}}{T_{\text{cr,H}_2}} = \dfrac{160}{33.3} = 4.805 \\[2ex] P_{R_1,\text{H}_2} = P_{R_2,\text{H}_2} = \dfrac{P_m}{P_{\text{cr,H}_2}} = \dfrac{5}{1.30} = 3.846 \\[2ex] T_{R_2,\text{H}_2} = \dfrac{T_{m,2}}{T_{\text{cr,H}_2}} = \dfrac{200}{33.3} = 6.006 \end{array}\right\} \begin{array}{l} Z_{h_1} \cong 0 \\[2ex] Z_{h_2} \cong 0 \end{array} \qquad \text{(Fig. A-29)}$$

Thus H_2 can be treated as an ideal gas during this process.

$$\text{N}_2:\quad \left.\begin{array}{l} T_{R_1,\text{N}_2} = \dfrac{T_{m,1}}{T_{\text{cr,N}_2}} = \dfrac{160}{126.2} = 1.27 \\[2ex] P_{R_1,\text{N}_2} = P_{R_2,\text{N}_2} = \dfrac{P_m}{P_{\text{cr,N}_2}} = \dfrac{5}{3.39} = 1.47 \\[2ex] T_{R_2,\text{N}_2} = \dfrac{T_{m,2}}{T_{\text{cr,N}_2}} = \dfrac{200}{126.2} = 1.58 \end{array}\right\} \begin{array}{l} Z_{h_1} = 1.3 \\[2ex] Z_{h_2} = 0.7 \end{array} \qquad \text{(Fig. A-29)}$$

Therefore,

$$\left(\bar{h}_2 - \bar{h}_1\right)_{\text{H}_2} = \left(\bar{h}_2 - \bar{h}_1\right)_{\text{H}_2\text{,ideal}} = 5{,}669.2 - 4{,}535.4 = 1{,}133.8\text{kJ/kmol}$$

$$\left(\bar{h}_2 - \bar{h}_1\right)_{\text{N}_2} = R_u T_{cr}\left(Z_{h_1} - Z_{h_2}\right) + \left(\bar{h}_2 - \bar{h}_1\right)_{\text{ideal}}$$

$$= (8.314\text{kPa}\cdot\text{m}^3\text{/kmol}\cdot\text{K})(126.2\text{K})(1.3 - 0.7) + (5{,}810 - 4{,}648)\text{kJ/kmol} = 1{,}791.5\text{kJ/kmol}$$

Substituting, $Q_{\text{in}} = \left(3\ \text{kmol}\right)\left(1{,}133.8\ \text{kJ/kmol}\right) + \left(0.75\ \text{kmol}\right)\left(1{,}791.5\ \text{kJ/kmol}\right) = \mathbf{4745\ kJ}$

13-75 Heat is transferred to a gas mixture contained in a piston cylinder device discussed in previous problem. The total entropy change and the exergy destruction are to be determined for two cases.

Analysis The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the piston-cylinder device and its immediate surroundings so that the boundary temperature of the extended system is the environment temperature at all times. It gives

$$S_{\text{in}} - S_{\text{out}} + S_{\text{gen}} = \Delta S_{\text{system}}$$

$$\frac{Q_{\text{in}}}{T_{\text{boundary}}} + S_{\text{gen}} = \Delta S_{\text{water}} \quad \to \quad S_{\text{gen}} = m(s_2 - s_1) - \frac{Q_{\text{in}}}{T_{\text{surr}}}$$

Then the exergy destroyed during a process can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$.

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

$$\Delta S_i = m_i \left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}^{\nearrow 0} \right)_i = m_i c_{p,i} \ln\frac{T_2}{T_1}$$

Assuming ideal gas behavior and using c_p values at the average temperature, the ΔS of H_2 and N_2 are determined from

$$\Delta S_{H_2,\text{ideal}} = (6\text{ kg})(13.60\text{ kJ/kg}\cdot\text{K})\ln\frac{200\text{ K}}{160\text{ K}} = 18.21\text{ kJ/K}$$

$$\Delta S_{N_2,\text{ideal}} = (21\text{ kg})(1.039\text{ kJ/kg}\cdot\text{K})\ln\frac{200\text{ K}}{160\text{ K}} = 4.87\text{ kJ/K}$$

and

$$S_{\text{gen}} = 18.21\text{ kJ/K} + 4.87\text{ kJ/K} - \frac{4273\text{ kJ}}{303\text{ K}} = \mathbf{8.98\text{ kJ/K}}$$

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = (303\text{ K})(8.98\text{ kJ/K}) = \mathbf{2721\text{ kJ}}$$

(*b*) Using Amagat's law and the generalized entropy departure chart, the entropy change of each gas is determined to be

$$H_2: \quad \left.\begin{array}{l} T_{R_1,H_2} = \dfrac{T_{m,1}}{T_{\text{cr},H_2}} = \dfrac{160}{33.3} = 4.805 \\ P_{R_1,H_2} = P_{R_2,H_2} = \dfrac{P_m}{P_{\text{cr},H_2}} = \dfrac{5}{1.30} = 3.846 \\ T_{R_2,H_2} = \dfrac{T_{m,2}}{T_{\text{cr},H_2}} = \dfrac{200}{33.3} = 6.006 \end{array}\right\} \begin{array}{l} Z_{s_1} \cong 1 \\ \\ Z_{s_2} \cong 1 \end{array} \qquad \text{(Table A-30)}$$

Thus H_2 can be treated as an ideal gas during this process.

$$N_2: \quad \left.\begin{array}{l} T_{R_1,N_2} = \dfrac{T_{m,1}}{T_{\text{cr},N_2}} = \dfrac{160}{126.2} = 1.268 \\ P_{R_1,N_2} = P_{R_2,N_2} = \dfrac{P_m}{P_{\text{cr},N_2}} = \dfrac{5}{3.39} = 1.475 \\ T_{R_2,N_2} = \dfrac{T_{m,2}}{T_{\text{cr},N_2}} = \dfrac{200}{126.2} = 1.585 \end{array}\right\} \begin{array}{l} Z_{s_1} = 0.8 \\ \\ Z_{s_2} = 0.4 \end{array} \qquad \text{(Table A-30)}$$

Therefore,

$$\Delta S_{H_2} = \Delta S_{H_2,\text{ideal}} = 18.21 \text{ kJ/K}$$

$$\begin{aligned}\Delta S_{N_2} &= N_{N_2} R_u \left(Z_{s_1} - Z_{s_2}\right) + \Delta S_{N_2,\text{ideal}} \\ &= (0.75 \text{ kmol})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(0.8 - 0.4) + (4.87 \text{ kJ/K}) \\ &= 7.37 \text{ kJ/K}\end{aligned}$$

$$\Delta S_{\text{surr}} = \frac{Q_{\text{surr}}}{T_0} = \frac{-4745 \text{ kJ}}{303 \text{ K}} = -15.66 \text{ kJ/K}$$

and

$$S_{\text{gen}} = 18.21 \text{ kJ/K} + 7.37 \text{ kJ/K} - \frac{4745 \text{ kJ}}{303 \text{ K}} = \mathbf{9.92\ kJ/K}$$

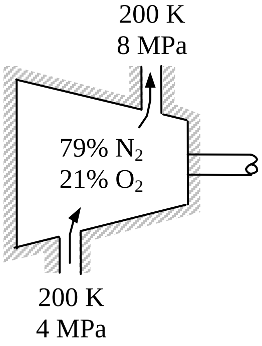
$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = (303 \text{ K})(9.92 \text{ kJ/K}) = \mathbf{3006\ kJ}$$

13-76 Air is compressed isothermally in a steady-flow device. The power input to the compressor and the rate of heat rejection are to be determined for ideal and non-ideal gas cases.

Assumptions **1** This is a steady-flow process. **2** The kinetic and potential energy changes are negligible.

Properties The molar mass of air is 29.0 kg/kmol. (Table A-1).

Analysis The mass flow rate of air can be expressed in terms of the mole numbers as



$$\dot{N} = \frac{\dot{m}}{M} = \frac{2.90\ \text{kg/s}}{29.0\ \text{kg/kmol}} = 0.10\ \text{kmol/s}$$

(*a*) Assuming ideal gas behavior, the Δh and Δs of air during this process is

$$\Delta\bar{h} = 0\ (\text{isothermal process})$$

$$\Delta\bar{s} = \bar{c}_p \ln\frac{T_2}{T_1}^{\nearrow 0} - R_u \ln\frac{P_2}{P_1} = -R_u \ln\frac{P_2}{P_1}$$

$$= -(8.314\ \text{kJ/kg}\cdot\text{K})\ln\frac{8\ \text{MPa}}{4\ \text{MPa}} = -5.763\ \text{kJ/kmol}\cdot\text{K}$$

Disregarding any changes in kinetic and potential energies, the steady-flow energy balance equation for the isothermal process of an ideal gas reduces to

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

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

$$\dot{W}_{\text{in}} + \dot{N}\bar{h}_1 = \dot{Q}_{\text{out}} + \dot{N}\bar{h}_2$$

$$\dot{W}_{\text{in}} - \dot{Q}_{\text{out}} = \dot{N}\Delta\bar{h}^{\nearrow 0} = 0 \longrightarrow \dot{W}_{\text{in}} = \dot{Q}_{\text{out}}$$

Also for an isothermal, internally reversible process the heat transfer is related to the entropy change by $Q = T\Delta S = NT\Delta\bar{s}$,

$$\dot{Q} = \dot{N}T\Delta\bar{s} = (0.10\ \text{kmol/s})(200\ \text{K})(-5.763\ \text{kJ/kmol}\cdot\text{K}) = -115.3\ \text{kW} \ \rightarrow\ \dot{Q}_{\text{out}} = 115.3\ \text{kW}$$

Therefore,

$$\dot{W}_{\text{in}} = \dot{Q}_{\text{out}} = \mathbf{115.3\ kW}$$

(*b*) Using Amagat's law and the generalized charts, the enthalpy and entropy changes of each gas are determined from

$$\bar{h}_2 - \bar{h}_1 = R_u T_{cr}(Z_{h_1} - Z_{h_2}) + (\bar{h}_2 - \bar{h}_1)_{\text{ideal}}^{\nearrow 0}$$

$$\bar{s}_2 - \bar{s}_1 = R_u(Z_{s_1} - Z_{s_2}) + (\bar{s}_2 - \bar{s}_1)_{\text{ideal}}$$

where

$$\text{N}_2:\quad \left.\begin{aligned} P_{R_1} &= \frac{P_{m,1}}{P_{\text{cr,N}_2}} = \frac{4}{3.39} = 1.18 \\ T_{R_1} = T_{R_2} &= \frac{T_m}{T_{\text{cr,N}_2}} = \frac{220}{126.2} = 1.74 \\ P_{R_2} &= \frac{P_{m,2}}{P_{\text{cr,N}_2}} = \frac{8}{3.39} = 2.36 \end{aligned}\right\} \begin{aligned} Z_{h_1} &= 0.4,\ Z_{s_1} = 0.2 \\ Z_{h_2} &= 0.8,\ Z_{s_2} = 0.35 \end{aligned} \qquad \text{(Tables A-29 and A-30)}$$

$$\text{O}_2\text{:}\quad \left.\begin{array}{l} P_{R_1} = \dfrac{P_{m,1}}{P_{\text{cr,O}_2}} = \dfrac{4}{5.08} = 0.787 \\ T_{R_1} = T_{R_2} = \dfrac{T_m}{T_{\text{cr,O}_2}} = \dfrac{220}{154.8} = 1.421 \\ P_{R_2} = \dfrac{P_{m,2}}{P_{\text{cr,O}_2}} = \dfrac{8}{5.08} = 1.575 \end{array}\right\} \begin{array}{l} Z_{h_1} = 0.4,\ Z_{s_1} = 0.25 \\ \\ Z_{h_2} = 1.0,\ Z_{s_2} = 0.5 \end{array} \qquad \text{(Tables A-29 and A-30)}$$

Then,

$$\begin{aligned} \bar{h}_2 - \bar{h}_1 &= y_i \Delta \bar{h}_i = y_{\text{N}_2}(\bar{h}_2 - \bar{h}_1)_{\text{N}_2} + y_{\text{O}_2}(\bar{h}_2 - \bar{h}_1)_{\text{O}_2} \\ &= (0.79)(8.314)(126.2)(0.4 - 0.8) + (0.21)(8.314)(154.8)(0.4 - 1.0) + 0 \\ &= -494 \text{kJ/kmol} \end{aligned}$$

$$\begin{aligned} \bar{s}_2 - \bar{s}_1 &= y_i \Delta \bar{s}_i = y_{\text{N}_2}(\bar{s}_2 - \bar{s}_1)_{\text{N}_2} + y_{\text{O}_2}(\bar{s}_2 - \bar{s}_1)_{\text{O}_2} \\ &= (0.79)(8.314)(0.2 - 0.35) + (0.21)(8.314)(0.25 - 0.5) + (-5.763) \\ &= -7.18 \text{kJ/kmol} \cdot \text{K} \end{aligned}$$

Thus,

$$\dot{Q}_{\text{out}} = -\dot{N} T \Delta \bar{s} = -(0.10 \text{ kmol/s})(200 \text{ K})(-7.18 \text{ kJ/kmol} \cdot \text{K}) = \mathbf{143.6\ \ kW}$$

$$\begin{aligned} \dot{E}_{\text{in}} - \dot{E}_{\text{out}} &= \Delta \dot{E}_{\text{system}}^{\nearrow 0\,(\text{steady})} = 0 \\ \dot{E}_{\text{in}} &= \dot{E}_{\text{out}} \\ \dot{W}_{\text{in}} + \dot{N}\bar{h}_1 &= \dot{Q}_{\text{out}} + \dot{N}\bar{h}_2 \\ \dot{W}_{\text{in}} &= \dot{Q}_{\text{out}} + \dot{N}(\bar{h}_2 - \bar{h}_1) \longrightarrow \dot{W}_{\text{in}} = 143.6 \text{ kW} + (0.10 \text{kmol/s})(-494 \text{kJ/kmol}) = \mathbf{94.2\ \ kW} \end{aligned}$$

13-77 EES Problem 13-76 is reconsidered. The results obtained by assuming ideal behavior, real gas behavior with Amagat's law, and real gas behavior with EES data are to be compared.

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

```
"Input Data:"
y_N2 = 0.79
y_O2 = 0.21
T[1]=200 [K] "Inlet temperature"
T[2]=200 [K] "Exit temmperature"
P[1]=4000 [kPa]
P[2]=8000 [kPa]
m_dot = 2.9 [kg/s]
R_u = 8.314 [kJ/kmol-K]
DELTAe_bar_sys = 0 "Steady-flow analysis for all cases"
m_dot = N_dot * (y_N2*molarmass(N2)+y_O2*molarmass(O2))

"Ideal gas:"
e_bar_in_IG - e_bar_out_IG = DELTAe_bar_sys
e_bar_in_IG =w_bar_in_IG + h_bar_IG[1]
e_bar_out_IG = q_bar_out_IG +h_bar_IG[2]
h_bar_IG[1] = y_N2*enthalpy(N2,T=T[1]) +  y_O2*enthalpy(O2,T=T[1])
h_bar_IG[2] = y_N2*enthalpy(N2,T=T[2]) +  y_O2*enthalpy(O2,T=T[2])
"The pocess is isothermal so h_bar_IG's are equal. q_bar_IG is found from the entropy change:"

q_bar_out_IG = -T[1]*DELTAs_IG
s_IG[2]= y_N2*entropy(N2,T=T[2],P=y_N2*P[2]) +  y_O2*entropy(O2,T=T[2],P=y_O2*P[2])
s_IG[1] =y_N2*entropy(N2,T=T[1],P=y_N2*P[1]) +  y_O2*entropy(O2,T=T[1],P=y_O2*P[1])
DELTAs_IG =s_IG[2]-s_IG[1]
Q_dot_out_IG=N_dot*q_bar_out_IG
W_dot_in_IG=N_dot*w_bar_in_IG

"EES:"
PN2[1]=y_N2*P[1]
PO2[1]=y_O2*P[1]
PN2[2]=y_N2*P[2]
PO2[2]=y_O2*P[2]
e_bar_in_EES - e_bar_out_EES = DELTAe_bar_sys
e_bar_in_EES =w_bar_in_EES + h_bar_EES[1]
e_bar_out_EES = q_bar_out_EES+h_bar_EES[2]
h_bar_EES[1] = y_N2*enthalpy(Nitrogen,T=T[1], P=PN2[1]) +
y_O2*enthalpy(Oxygen,T=T[1],P=PO2[1])
h_bar_EES[2] = y_N2*enthalpy(Nitrogen,T=T[2],P=PN2[2]) +
y_O2*enthalpy(Oxygen,T=T[2],P=PO2[2])
q_bar_out_EES = -T[1]*DELTAs_EES
DELTAs_EES =y_N2*entropy(Nitrogen,T=T[2],P=PN2[2]) +
y_O2*entropy(Oxygen,T=T[2],P=PO2[2]) - y_N2*entropy(Nitrogen,T=T[1],P=PN2[1]) -
y_O2*entropy(Oxygen,T=T[1],P=PO2[1])
Q_dot_out_EES=N_dot*q_bar_out_EES
W_dot_in_EES=N_dot*w_bar_in_EES

"Amagat's Rule:"
Tcr_N2=126.2 [K] "Table A.1"
Tcr_O2=154.8 [K]
Pcr_N2=3390 [kPa] "Table A.1"
Pcr_O2=5080 [kPa]
```

```
e_bar_in_Zchart - e_bar_out_Zchart = DELTAe_bar_sys
e_bar_in_Zchart=w_bar_in_Zchart + h_bar_Zchart[1]
e_bar_out_Zchart =q_bar_out_Zchart +  h_bar_Zchart[2]
q_bar_out_Zchart = -T[1]*DELTAs_Zchart
Q_dot_out_Zchart=N_dot*q_bar_out_Zchart
W_dot_in_Zchart=N_dot*w_bar_in_Zchart
"State 1by compressability chart"

Tr_N2[1]=T[1]/Tcr_N2
Pr_N2[1]=y_N2*P[1]/Pcr_N2
Tr_O2[1]=T[1]/Tcr_O2
Pr_O2[1]=y_O2*P[1]/Pcr_O2
DELTAh_bar_1_N2=ENTHDEP(Tr_N2[1], Pr_N2[1])*R_u*Tcr_N2  "Enthalpy departure, N2"
DELTAh_bar_1_O2=ENTHDEP(Tr_O2[1], Pr_O2[1])*R_u*Tcr_O2 "Enthalpy departure, O2"
h_bar_Zchart[1]=h_bar_IG[1]-(y_N2*DELTAh_bar_1_N2+y_O2*DELTAh_bar_1_O2) "Enthalpy of
real gas using charts"

DELTAs_N2[1]=ENTRDEP(Tr_N2[1], Pr_N2[1])*R_u "Entropy departure, N2"
DELTAs_O2[1]=ENTRDEP(Tr_O2[1], Pr_O2[1])*R_u "Entropy departure, O2"
s[1]=s_IG[1]-(y_N2*DELTAs_N2[1]+y_O2*DELTAs_O2[1]) "Entropy of real gas using charts"
"State 2 by compressability chart"

Tr_N2[2]=T[2]/Tcr_N2
Pr_N2[2]=y_N2*P[2]/Pcr_N2
Tr_O2[2]=T[2]/Tcr_O2
Pr_O2[2]=y_O2*P[2]/Pcr_O2
DELTAh_bar_2_N2=ENTHDEP(Tr_N2[2], Pr_N2[2])*R_u*Tcr_N2  "Enthalpy departure, N2"
DELTAh_bar_2_O2=ENTHDEP(Tr_O2[2], Pr_O2[2])*R_u*Tcr_O2 "Enthalpy departure, O2"
h_bar_Zchart[2]=h_bar_IG[2]-(y_N2*DELTAh_bar_2_N2+y_O2*DELTAh_bar_2_O2) "Enthalpy of

real gas using charts"
DELTAs_N2[2]=ENTRDEP(Tr_N2[2], Pr_N2[2])*R_u "Entropy departure, N2"
DELTAs_O2[2]=ENTRDEP(Tr_O2[2], Pr_O2[2])*R_u "Entropy departure, O2"
s[2]=s_IG[2]-(y_N2*DELTAs_N2[2]+y_O2*DELTAs_O2[2]) "Entropy of real gas using charts"
DELTAs_Zchart = s[2]-s[1] "[kJ/kmol-K]"
```

```
SOLUTION
DELTAe_bar_sys=0 [kJ/kmol]              DELTAh_bar_1_N2=461.2
DELTAh_bar_1_O2=147.6                   DELTAh_bar_2_N2=907.8
DELTAh_bar_2_O2=299.5                   DELTAs_EES=-7.23 [kJ/kmol-K]
DELTAs_IG=-5.763 [kJ/kmol-K]            DELTAs_N2[1]=1.831
DELTAs_N2[2]=3.644                      DELTAs_O2[1]=0.5361
DELTAs_O2[2]=1.094                      DELTAs_Zchart=-7.312 [kJ/kmol-K]
e_bar_in_EES=-2173 [kJ/kmol]            e_bar_in_IG=-1633 [kJ/kmol]
e_bar_in_Zchart=-2103                   e_bar_out_EES=-2173 [kJ/kmol]
e_bar_out_IG=-1633 [kJ/kmol]            e_bar_out_Zchart=-2103
h_bar_EES[1]=-3235                      h_bar_EES[2]=-3619
h_bar_IG[1]=-2785                       h_bar_IG[2]=-2785
h_bar_Zchart[1]=-3181                   h_bar_Zchart[2]=-3565
m_dot=2.9 [kg/s]                        N_dot=0.1005 [kmol/s]
Pcr_N2=3390 [kPa]                       Pcr_O2=5080 [kPa]
P[1]=4000 [kPa]                         P[2]=8000 [kPa]
PN2[1]=3160                             PN2[2]=6320
PO2[1]=840                              PO2[2]=1680
Pr_N2[1]=0.9322                         Pr_N2[2]=1.864
Pr_O2[1]=0.1654                         Pr_O2[2]=0.3307
q_bar_out_EES=1446 [kJ/kmol]            q_bar_out_IG=1153 [kJ/kmol]
```

```
q_bar_out_Zchart=1462                    Q_dot_out_EES=145.3 [kW]
Q_dot_out_IG=115.9 [kW]                  Q_dot_out_Zchart=147 [kW]
R_u=8.314 [kJ/kmol-K]                    s[1]=155.1
s[2]=147.8                               s_IG[1]=156.7
s_IG[2]=150.9                            Tcr_N2=126.2 [K]
Tcr_O2=154.8 [K]                         T[1]=200 [K]
T[2]=200 [K]                             Tr_N2[1]=1.585
Tr_N2[2]=1.585                           Tr_O2[1]=1.292
Tr_O2[2]=1.292                           w_bar_in_EES=1062 [kJ/kmol]
w_bar_in_IG=1153 [kJ/kmol]               w_bar_in_Zchart=1078 [kJ/kmmol]
W_dot_in_EES=106.8 [kW]                  W_dot_in_IG=115.9 [kW]
W_dot_in_Zchart=108.3 [kW]               y_N2=0.79
y_O2=0.21
```

13-78 The volumetric fractions of the constituents of a mixture of products of combustion are given. The average molar mass of the mixture, the average specific heat, and the partial pressure of the water vapor in the mixture are to be determined.

Assumptions Under specified conditions all N_2, O_2, H_2O, and CO_2 can be treated as ideal gases, and the mixture as an ideal gas mixture.

Properties The molar masses of CO_2, H_2O, O_2, and N_2 are 44.0, 18.0, 32.0, and 28.0 kg/kmol, respectively (Table A-1). The specific heats of CO_2, H_2O, O_2, and N_2 at 600 K are 1.075, 2.015, 1.003, and 1.075 kJ/kg.K, respectively (Table A-2b). The specific heat of water vapor at 600 K is obtained from EES.

Analysis For convenience, consider 100 kmol of mixture. Noting that volume fractions are equal to mole fractions in ideal gas mixtures, the average molar mass of the mixture is determined to be

$$
\begin{aligned}
M_m &= \frac{N_{\mathrm{CO_2}}M_{\mathrm{CO_2}} + N_{\mathrm{H_2O}}M_{\mathrm{H_2O}} + N_{\mathrm{O_2}}M_{\mathrm{O_2}} + N_{\mathrm{N_2}}M_{\mathrm{N_2}}}{N_{\mathrm{CO_2}} + N_{\mathrm{H_2O}} + N_{\mathrm{O_2}} + N_{\mathrm{N_2}}} \\
&= \frac{(4.89\ \mathrm{kmol})(44\ \mathrm{kg/kmol}) + (6.50)(18) + (12.20)(32) + (76.41)(28)}{(4.89 + 6.50 + 12.20 + 76.41)\ \mathrm{kmol}} \\
&= \mathbf{28.62\ kg/kmol}
\end{aligned}
$$

76.41% N_2
12.20% O_2
6.50% H_2O
4.89% CO_2

600 K
200 kPa

The average specific heat is determined from

$$
\begin{aligned}
c_{p,m} &= \frac{N_{\mathrm{CO_2}}c_{p,\mathrm{CO_2}}M_{\mathrm{CO_2}} + N_{\mathrm{H_2O}}c_{p,\mathrm{H_2O}}M_{\mathrm{H_2O}} + N_{\mathrm{O_2}}c_{p,\mathrm{O_2}}M_{\mathrm{O_2}} + N_{\mathrm{N_2}}c_{p,\mathrm{N_2}}M_{\mathrm{N_2}}}{N_{\mathrm{CO_2}} + N_{\mathrm{H_2O}} + N_{\mathrm{O_2}} + N_{\mathrm{N_2}}} \\
&= \frac{(4.89\ \mathrm{kmol})(1.075\ \mathrm{kJ/kg.K})(44\ \mathrm{kg/kmol}) + (6.50)(2.015)(18) + (12.20)(1.003)(32) + (76.41)(1.075)(28)}{(4.89 + 6.50 + 12.20 + 76.41)\ \mathrm{kmol}} \\
&= \mathbf{31.59\ kJ/kmol.K}
\end{aligned}
$$

The partial pressure of the water in the mixture is

$$
y_v = \frac{N_{\mathrm{H_2O}}}{N_{\mathrm{CO_2}} + N_{\mathrm{H_2O}} + N_{\mathrm{O_2}} + N_{\mathrm{N_2}}} = \frac{6.50\ \mathrm{kmol}}{(4.89 + 6.50 + 12.20 + 76.41)\ \mathrm{kmol}} = 0.0650
$$

$$
P_v = y_v P_m = (0.0650)(200\ \mathrm{kPa}) = \mathbf{13.0\ kPa}
$$

Special Topic: Chemical Potential and the Separation Work of Mixtures

13-79C No, a process that separates a mixture into its components without requiring any work (exergy) input is impossible since such a process would violate the 2nd law of thermodynamics.

13-80C Yes, the volume of the mixture can be more or less than the sum of the initial volumes of the mixing liquids because of the attractive or repulsive forces acting between dissimilar molecules.

13-81C The person who claims that the temperature of the mixture can be higher than the temperatures of the components is right since the total enthalpy of the mixture of two components at the same pressure and temperature, in general, is not equal to the sum of the total enthalpies of the individual components before mixing, the difference being the enthalpy (or heat) of mixing, which is the heat released or absorbed as two or more components are mixed isothermally.

13-82C Mixtures or solutions in which the effects of molecules of different components on each other are negligible are called ideal solutions (or ideal mixtures). The ideal-gas mixture is just one category of ideal solutions. For ideal solutions, the enthalpy change and the volume change due to mixing are zero, but the entropy change is not. The chemical potential of a component of an ideal mixture is independent of the identity of the other constituents of the mixture. The chemical potential of a component in an ideal mixture is equal to the Gibbs function of the pure component.

13-83 Brackish water is used to produce fresh water. The minimum power input and the minimum height the brackish water must be raised by a pump for reverse osmosis are to be determined.

Assumptions **1** The brackish water is an ideal solution since it is dilute. **2** The total dissolved solids in water can be treated as table salt (NaCl). **3** The environment temperature is also 12°C.

Properties The molar masses of water and salt are M_w = 18.0 kg/kmol and M_s = 58.44 kg/kmol. The gas constant of pure water is R_w = 0.4615 kJ/kg·K (Table A-1). The density of fresh water is 1000 kg/m^3.

Analysis First we determine the mole fraction of pure water in brackish water using Eqs. 13-4 and 13-5. Noting that mf$_s$ = 0.00078 and mf$_w$ = 1- mf$_s$ = 0.99922,

$$M_\text{m} = \frac{1}{\sum \frac{\text{mf}_i}{M_i}} = \frac{1}{\frac{\text{mf}_s}{M_s} + \frac{\text{mf}_w}{M_w}} = \frac{1}{\frac{0.00078}{58.44} + \frac{0.99922}{18.0}} = 18.01\,\text{kg/kmol}$$

$$y_i = \text{mf}_i \frac{M_m}{M_i} \quad \rightarrow \quad y_w = \text{mf}_w \frac{M_m}{M_w} = (0.99922)\frac{18.01\,\text{kg/kmol}}{18.0\,\text{kg/kmol}} = 0.99976$$

The minimum work input required to produce 1 kg of freshwater from brackish water is

$$w_{\text{min, in}} = R_w T_0 \ln(1/y_w) = (0.4615\,\text{kJ/kg}\cdot\text{K})(285.15\,\text{K})\ln(1/0.99976) = 0.03159\,\text{kJ/kg fresh water}$$

Therefore, 0.03159 kJ of work is needed to produce 1 kg of fresh water is mixed with seawater reversibly. Therefore, the required power input to produce fresh water at the specified rate is

$$\dot{W}_{\text{min, in}} = \rho\dot{V}w_{\text{min, in}} = (1000\,\text{kg/m}^3)(0.280\,\text{m}^3\text{/s})(0.03159\,\text{kJ/kg})\left(\frac{1\,\text{kW}}{1\,\text{kJ/s}}\right) = \mathbf{8.85\ kW}$$

The minimum height to which the brackish water must be pumped is

$$\Delta z_{\text{min}} = \frac{w_{\text{min,in}}}{g} = \left(\frac{0.03159\,\text{kJ/kg}}{9.81\,\text{m/s}^2}\right)\left(\frac{1\,\text{kg.m/s}^2}{1\,\text{N}}\right)\left(\frac{1000\,\text{N.m}}{1\,\text{kJ}}\right) = \mathbf{3.22\ m}$$

13-84 A river is discharging into the ocean at a specified rate. The amount of power that can be generated is to be determined.

Assumptions **1** The seawater is an ideal solution since it is dilute. **2** The total dissolved solids in water can be treated as table salt (NaCl). **3** The environment temperature is also 15°C.

Properties The molar masses of water and salt are M_w = 18.0 kg/kmol and M_s = 58.44 kg/kmol. The gas constant of pure water is R_w = 0.4615 kJ/kg·K (Table A-1). The density of river water is 1000 kg/m^3.

Analysis First we determine the mole fraction of pure water in ocean water using Eqs. 13-4 and 13-5. Noting that mf$_s$ = 0.035 and mf$_w$ = 1- mf$_s$ = 0.965,

$$M_\mathrm{m} = \frac{1}{\sum \frac{\mathrm{mf}_i}{M_i}} = \frac{1}{\frac{\mathrm{mf}_s}{M_s} + \frac{\mathrm{mf}_w}{M_w}} = \frac{1}{\frac{0.035}{58.44} + \frac{0.965}{18.0}} = 18.45\ \mathrm{kg/kmol}$$

$$y_i = \mathrm{mf}_i \frac{M_m}{M_i} \quad \rightarrow \quad y_w = \mathrm{mf}_w \frac{M_m}{M_w} = (0.965)\frac{18.45\ \mathrm{kg/kmol}}{18.0\ \mathrm{kg/kmol}} = 0.9891$$

The maximum work output associated with mixing 1 kg of seawater (or the minimum work input required to produce 1 kg of freshwater from seawater) is

$$w_{\mathrm{max,\,out}} = R_w T_0 \ln(1/y_w) = (0.4615\ \mathrm{kJ/kg\cdot K})(288.15\ \mathrm{K})\ln(1/0.9891) = 1.46\ \mathrm{kJ/kg\ fresh\ water}$$

Therefore, 1.46 kJ of work can be produced as 1 kg of fresh water is mixed with seawater reversibly. Therefore, the power that can be generated as a river with a flow rate of 400,000 m^3/s mixes reversibly with seawater is

$$\dot{W}_{\mathrm{max\ out}} = \rho \dot{V} w_{\mathrm{max\ out}} = (1000\ \mathrm{kg/m^3})(4\times 10^5\ \mathrm{m^3/s})(1.46\ \mathrm{kJ/kg})\left(\frac{1\ \mathrm{kW}}{1\ \mathrm{kJ/s}}\right) = \mathbf{582\times 10^6\ kW}$$

Discussion This is more power than produced by all nuclear power plants (112 of them) in the U.S., which shows the tremendous amount of power potential wasted as the rivers discharge into the seas.

13-85 EES Problem 13-84 is reconsidered. The effect of the salinity of the ocean on the maximum power generated is to be investigated.

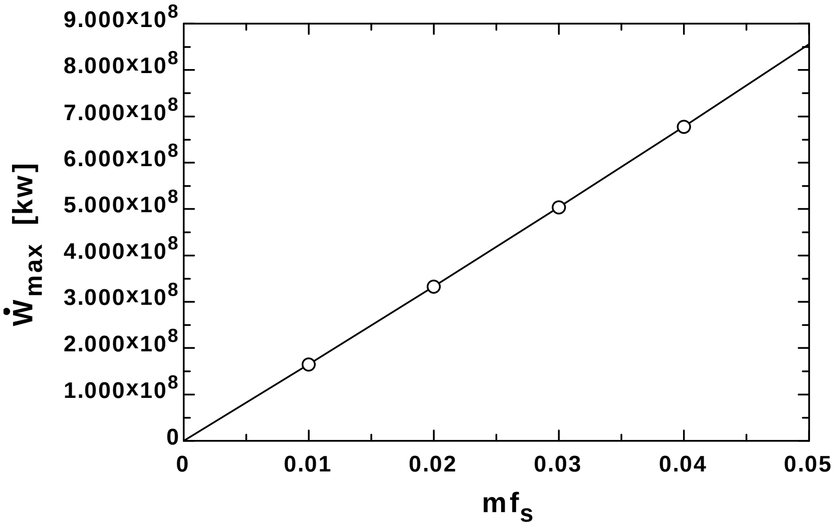
Analysis The problem is solved using EES, and the solution is given below.

```
"Properties:"
M_w = 18.0 [kg/kmol] "Molar masses of water"
M_s = 58.44 [kg/kmol] "Molar masses of salt"
R_w = 0.4615 [kJ/kg-K] "Gas constant of pure water"
roh_w = 1000 [kg/m^3]  "density of river water"
V_dot = 4E5 [m^3/s]
T_0 = 15 [C]

"Analysis:

First we determine the mole fraction of pure water in ocean
water using Eqs. 13-4 and 13-5. "
mf_s = 0.035 "mass fraction of the salt in seawater = salinity"
mf_w = 1- mf_s "mass fraction of the water in seawater"
"Molar mass of the seawater is:"
M_m=1/(mf_s/m_s+mf_w/M_w)
"Mole fraction of the water is:"
y_w=mf_w*M_m/M_w
"The maximum work output associated with mixing 1 kg of seawater
(or the minimum work input required to produce 1 kg of freshwater from
seawater) is:"
w_maxout =R_w*(T_0+273.15)*ln(1/y_w) "[kJ/kg fresh water]"
 "The power that can be generated as a river with a flow rate of 400,000 m^3/s mixes
reversibly with seawater is"
W_dot_max=roh_w*V_dot*w_maxout
"Discussion  This is more power than produced by all nuclear power plants (112 of them) in the
US., which shows the tremendous amount of power potential wasted as the rivers discharge into
the seas."
```

mf_s	W_{max} [kW]
0	0
0.01	1.652E+08
0.02	3.333E+08
0.03	5.043E+08
0.04	6.783E+08
0.05	8.554E+08



13-86E Brackish water is used to produce fresh water. The mole fractions, the minimum work inputs required to separate 1 lbm of brackish water and to obtain 1 lbm of fresh water are to be determined.

Assumptions **1** The brackish water is an ideal solution since it is dilute. **2** The total dissolved solids in water can be treated as table salt (NaCl). **3** The environment temperature is equal to the water temperature.

Properties The molar masses of water and salt are M_w = 18.0 lbm/lbmol and M_s = 58.44 lbm/lbmol. The gas constant of pure water is R_w = 0.1102 Btu/lbm·R (Table A-1E).

Analysis (*a*) First we determine the mole fraction of pure water in brackish water using Eqs. 13-4 and 13-5. Noting that $\mathrm{mf}_s = 0.0012$ and $\mathrm{mf}_w = 1 - \mathrm{mf}_s = 0.9988$,

$$M_\mathrm{m} = \frac{1}{\sum \frac{\mathrm{mf}_i}{M_i}} = \frac{1}{\frac{\mathrm{mf}_s}{M_s} + \frac{\mathrm{mf}_w}{M_w}} = \frac{1}{\frac{0.0012}{58.44} + \frac{0.9988}{18.0}} = 18.015\ \mathrm{lbm/lbmol}$$

$$y_i = \mathrm{mf}_i \frac{M_m}{M_i} \quad \rightarrow \quad y_w = \mathrm{mf}_w \frac{M_m}{M_w} = (0.9988)\frac{18.015\ \mathrm{lbm/lbmol}}{18.0\ \mathrm{lbm/lbmol}} = \mathbf{0.99963}$$

$$y_s = 1 - y_w = 1 - 0.99963 = \mathbf{0.00037}$$

(*b*) The minimum work input required to separate 1 lbmol of brackish water is

$$\begin{aligned} w_{\mathrm{min,in}} &= -R_w T_0 (y_w \ln y_w + y_s \ln y_s) \\ &= -(0.1102\ \mathrm{Btu/lbmol.R})(525\ \mathrm{R})[0.99963 \ln(0.99963) + 0.00037 \ln(0.00037)] \\ &= -\mathbf{0.191\ Btu/lbm}\ \text{brackish water} \end{aligned}$$

(*c*) The minimum work input required to produce 1 lbm of freshwater from brackish water is

$$w_{\mathrm{min,\,in}} = R_w T_0 \ln(1/y_w) = (0.1102\ \mathrm{Btu/lbm \cdot R})(525\ \mathrm{R})\ln(1/0.99963) = \mathbf{0.0214\ Btu/lbm\ fresh\ water}$$

Discussion Note that it takes about 9 times work to separate 1 lbm of brackish water into pure water and salt compared to producing 1 lbm of fresh water from a large body of brackish water.

13-87 A desalination plant produces fresh water from seawater. The second law efficiency of the plant is to be determined.

Assumptions **1** The seawater is an ideal solution since it is dilute. **2** The total dissolved solids in water can be treated as table salt (NaCl). **3** The environment temperature is equal to the seawater temperature.

Properties The molar masses of water and salt are M_w = 18.0 kg/kmol and M_s = 58.44 kg/kmol. The gas constant of pure water is R_w = 0.4615 kJ/kg·K (Table A-1). The density of river water is 1000 kg/m^3.

Analysis First we determine the mole fraction of pure water in seawater using Eqs. 13-4 and 13-5. Noting that $\text{mf}_s = 0.032$ and $\text{mf}_w = 1 - \text{mf}_s = 0.968$,

$$M_\text{m} = \frac{1}{\sum \dfrac{\text{mf}_i}{M_i}} = \frac{1}{\dfrac{\text{mf}_s}{M_s} + \dfrac{\text{mf}_w}{M_w}} = \frac{1}{\dfrac{0.032}{58.44} + \dfrac{0.968}{18.0}} = 18.41\,\text{kg/kmol}$$

$$y_i = \text{mf}_i \frac{M_m}{M_i} \quad \rightarrow \quad y_w = \text{mf}_w \frac{M_m}{M_w} = (0.968)\frac{18.41\,\text{kg/kmol}}{18.0\,\text{kg/kmol}} = 0.9900$$

The maximum work output associated with mixing 1 kg of seawater (or the minimum work input required to produce 1 kg of freshwater from seawater) is

$$w_\text{max, out} = R_w T_0 \ln(1/y_w) = (0.4615\,\text{kJ/kg}\cdot\text{K})(283.15\,\text{K})\ln(1/0.990) = 1.313\,\text{kJ/kg fresh water}$$

The power that can be generated as 1.4 m^3/s fresh water mixes reversibly with seawater is

$$\dot{W}_\text{max out} = \rho \dot{V} w_\text{max out} = (1000\,\text{kg/m}^3)(1.4\,\text{m}^3\text{/s})(1.313\,\text{kJ/kg})\left(\frac{1\,\text{kW}}{1\,\text{kJ/s}}\right) = 1.84\,\text{kW}$$

Then the second law efficiency of the plant becomes

$$\eta_\text{II} = \frac{\dot{W}_\text{min,in}}{\dot{W}_\text{in}} = \frac{1.83\ \text{MW}}{8.5\,\text{MW}} = 0.216 = \mathbf{21.6\%}$$

13-88 The power consumption and the second law efficiency of a desalination plant are given. The power that can be produced if the fresh water produced is mixed with the seawater reversibly is to be determined.

Assumptions **1** This is a steady-flow process. **2** The kinetic and potential energy changes are negligible.

Analysis From the definition of the second law efficiency

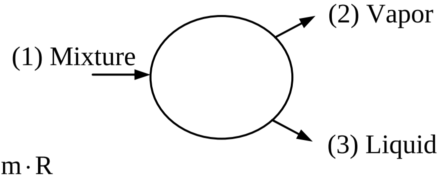
$$\eta_\text{II} = \frac{\dot{W}_\text{rev}}{\dot{W}_\text{actual}} \quad \rightarrow \quad 0.18 = \frac{\dot{W}_\text{rev}}{3.3\,\text{MW}} \quad \rightarrow \quad \dot{W}_\text{rev} = \mathbf{0.594\,MW}$$

which is the maximum power that can be generated.

13-89E It is to be determined if it is it possible for an adiabatic liquid-vapor separator to separate wet steam at 100 psia and 90 percent quality, so that the pressure of the outlet streams is greater than 100 psia.

Analysis Because the separator divides the inlet stream into the liquid and vapor portions,

$$\dot{m}_2 = x\dot{m}_1 = 0.9\dot{m}_1$$
$$\dot{m}_3 = (1-x)\dot{m}_1 = 0.1\dot{m}_1$$



According to the water property tables at 100 psia (Table A-5E),

$$s_1 = s_f + xs_{fg} = 0.47427 + 0.9\times 1.12888 = 1.4903\ \text{Btu/lbm}\cdot\text{R}$$

When the increase in entropy principle is adapted to this system, it becomes

$$\begin{aligned}\dot{m}_2 s_2 + \dot{m}_3 s_3 &\ge \dot{m}_1 s_1\\ x\dot{m}_1 s_2 + (1-x)\dot{m}_1 s_3 &\ge \dot{m}_1 s_1\\ 0.9s_2 + 0.1s_3 &\ge s_1\\ &\ge 1.4903\ \text{Btu/lbm}\cdot\text{R}\end{aligned}$$

To test this hypothesis, let’s assume the outlet pressures are 110 psia. Then,

$$s_2 = s_g = 1.5954\ \text{Btu/lbm}\cdot\text{R}$$
$$s_3 = s_f = 0.48341\ \text{Btu/lbm}\cdot\text{R}$$

The left-hand side of the above equation is

$$0.9s_2 + 0.1s_3 = 0.9\times 1.5954 + 0.1\times 0.48341 = 1.4842\ \text{Btu/lbm}\cdot\text{R}$$

which is less than the minimum possible specific entropy. Hence, the outlet pressure cannot be 110 psia. Inspection of the water table in light of above equation proves that the pressure at the separator outlet cannot be greater than that at the inlet.

Review Problems

13-90 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

$$N_{O_2} = 21\text{ kmol} \longrightarrow m_{O_2} = N_{O_2}M_{O_2} = (21\text{ kmol})(32\text{ kg/kmol}) = 672\text{ kg}$$

$$N_{N_2} = 78\text{ kmol} \longrightarrow m_{N_2} = N_{N_2}M_{N_2} = (78\text{ kmol})(28\text{ kg/kmol}) = 2184\text{ kg}$$

$$N_{Ar} = 1\text{ kmol} \longrightarrow m_{Ar} = N_{Ar}M_{Ar} = (1\text{ kmol})(40\text{ kg/kmol}) = 40\text{ kg}$$

$$m_m = m_{O_2} + m_{N_2} + m_{Ar} = 672\text{ kg} + 2184\text{ kg} + 40\text{ kg} = 2896\text{ kg}$$

AIR

21% O_2
78% N_2
1% Ar

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

$$\text{mf}_{O_2} = \frac{m_{O_2}}{m_m} = \frac{672\text{ kg}}{2896\text{ kg}} = 0.232 \text{ or } \mathbf{23.2\%}$$

$$\text{mf}_{N_2} = \frac{m_{N_2}}{m_m} = \frac{2184\text{ kg}}{2896\text{ kg}} = 0.754 \text{ or } \mathbf{75.4\%}$$

$$\text{mf}_{Ar} = \frac{m_{Ar}}{m_m} = \frac{40\text{ kg}}{2896\text{ kg}} = 0.014 \text{ or } \mathbf{1.4\%}$$

The molar mass of the mixture is determined from its definitions,

$$M_m = \frac{m_m}{N_m} = \frac{2{,}896\text{ kg}}{100\text{ kmol}} = \mathbf{28.96\ kg/kmol}$$

13-91 Using Dalton’s law, it is to be shown that $Z_m = \sum_{i=1}^{k} y_i Z_i$ for a real-gas mixture.

Analysis Using the compressibility factor, the pressure of a component of a real-gas mixture and of the pressure of the gas mixture can be expressed as

$$P_i = \frac{Z_i N_i R_u T_m}{V_m} \quad \text{and} \quad P_m = \frac{Z_m N_m R_u T_m}{V_m}$$

Dalton's law can be expressed as $P_m = \sum P_i(T_m, V_m)$. Substituting,

$$\frac{Z_m N_m R_u T_m}{V_m} = \sum \frac{Z_i N_i R_u T_m}{V_m}$$

Simplifying,

$$Z_m N_m = \sum Z_i N_i$$

Dividing by N_m,

$$Z_m = \sum y_i Z_i$$

where Z_i is determined at the mixture temperature and volume.

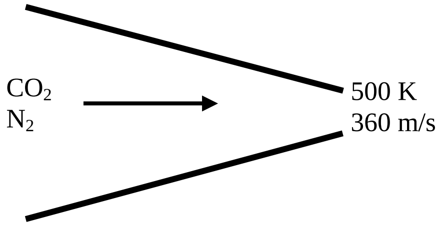
13-92 A mixture of carbon dioxide and nitrogen flows through a converging nozzle. The required make up of the mixture on a mass basis is to be determined.

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

Properties The molar masses of CO_2 and N_2 are 44.0 and 28.0 kg/kmol, respectively (Table A-1). The specific heat ratios of CO_2 and N_2 at 500 K are $k_{CO2} = 1.229$ and $k_{N2} = 1.391$ (Table A-2).

Analysis The molar mass of the mixture is determined from

$$M_m = y_{CO_2} M_{CO_2} + y_{N_2} M_{N_2}$$



The molar fractions are related to each other by

$$y_{CO_2} + y_{N_2} = 1$$

The gas constant of the mixture is given by

$$R_m = \frac{R_u}{M_m}$$

The specific heat ratio of the mixture is expressed as

$$k = \mathrm{mf}_{CO_2} k_{CO_2} + \mathrm{mf}_{N_2} k_{N_2}$$

The mass fractions are

$$\mathrm{mf}_{CO_2} = y_{CO_2} \frac{M_{CO_2}}{M_m}$$

$$\mathrm{mf}_{N_2} = y_{N_2} \frac{M_{N_2}}{M_m}$$

The exit velocity equals the speed of sound at 500 K

$$V_{\text{exit}} = \sqrt{kR_m T\left(\frac{1000\ \text{m}^2/\text{s}^2}{1\ \text{kJ/kg}}\right)}$$

Substituting the given values and known properties and solving the above equations simultaneously using EES, we find

$$\mathrm{mf}_{CO_2} = \mathbf{0.838}$$

$$\mathrm{mf}_{N_2} = \mathbf{0.162}$$

13-93 The mole numbers, pressure, and temperature of the constituents of a gas mixture are given. The volume of the tank containing this gas mixture is to be determined using three methods.

Analysis (*a*) Under specified conditions both N_2 and CH_4 will considerably deviate from the ideal gas behavior. Treating the mixture as an ideal gas gives

$$N_m = N_{N_2} + N_{CH_4} = 2 \text{ kmol} + 6 \text{ kmol} = 8 \text{ kmol}$$

and

$$\boldsymbol{V}_m = \frac{N_m R_u T_m}{P_m} = \frac{(8 \text{ kmol})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(200 \text{ K})}{12{,}000 \text{ kPa}} = \mathbf{1.11\ m^3}$$

2 kmol N_2
6 kmol CH_4

200 K
12 MPa

(*b*) To use Kay's rule, we first need to determine the pseudo-critical temperature and pseudo-critical pressure of the mixture using the critical point properties of N_2 and CH_4 from Table A-1,

$$y_{N_2} = \frac{N_{N_2}}{N_m} = \frac{2 \text{ kmol}}{8 \text{ kmol}} = 0.25 \quad \text{and} \quad y_{CH_4} = \frac{N_{CH_4}}{N_m} = \frac{6 \text{ kmol}}{8 \text{ kmol}} = 0.75$$

$$\begin{aligned} T'_{\text{cr},m} &= \sum y_i T_{\text{cr},i} = y_{N_2} T_{\text{cr},N_2} + y_{CH_4} T_{\text{cr},CH_4} \\ &= (0.25)(126.2 \text{ K}) + (0.75)(191.1\text{K}) = 174.9\text{K} \end{aligned}$$

$$\begin{aligned} P'_{\text{cr},m} &= \sum y_i P_{\text{cr},i} = y_{N_2} P_{\text{cr},N_2} + y_{CH_4} P_{\text{cr},CH_4} \\ &= (0.25)(3.39 \text{ MPa}) + (0.75)(4.64 \text{ MPa}) = 4.33 \text{ MPa} \end{aligned}$$

Then,

$$\left.\begin{aligned} T_R &= \frac{T_m}{T'_{\text{cr},m}} = \frac{200}{174.9} = 1.144 \\ P_R &= \frac{P_m}{P'_{\text{cr},m}} = \frac{12}{4.33} = 2.77 \end{aligned}\right\} Z_m = 0.47 \qquad \text{(Fig. A-15)}$$

Thus,

$$\boldsymbol{V}_m = \frac{Z_m N_m R_u T_m}{P_m} = Z_m \boldsymbol{V}_{\text{ideal}} = (0.47)(1.11 \text{ m}^3) = \mathbf{0.52\ m^3}$$

(*c*) To use the Amagat's law for this real gas mixture, we first need to determine the Z of each component at the mixture temperature and pressure,

$$N_2: \quad \left.\begin{aligned} T_{R,N_2} &= \frac{T_m}{T_{\text{cr},N_2}} = \frac{200}{126.2} = 1.585 \\ P_{R,N_2} &= \frac{P_m}{P_{\text{cr},N_2}} = \frac{12}{3.39} = 3.54 \end{aligned}\right\} Z_{N_2} = 0.85 \qquad \text{(Fig. A-15)}$$

$$CH_4: \quad \left.\begin{aligned} T_{R,CH_4} &= \frac{T_m}{T_{\text{cr},CH_4}} = \frac{200}{191.1} = 1.047 \\ P_{R,CH_4} &= \frac{P_m}{P_{\text{cr},CH_4}} = \frac{12}{4.64} = 2.586 \end{aligned}\right\} Z_{CH_4} = 0.37 \qquad \text{(Fig. A-15)}$$

Mixture:

$$Z_m = \sum y_i Z_i = y_{N_2} Z_{N_2} + y_{CH_4} Z_{CH_4} = (0.25)(0.85) + (0.75)(0.37) = 0.49$$

Thus,

$$\boldsymbol{V}_m = \frac{Z_m N_m R_u T_m}{P_m} = Z_m \boldsymbol{V}_{\text{ideal}} = (0.49)(1.11 \text{ m}^3) = \mathbf{0.544\ m^3}$$

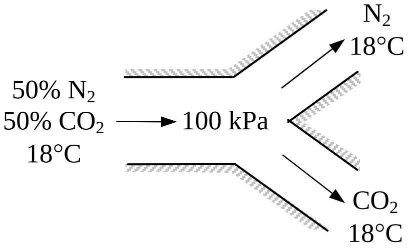
13-94 A stream of gas mixture at a given pressure and temperature is to be separated into its constituents steadily. The minimum work required is to be determined.

Assumptions **1** Both the N_2 and CO_2 gases and their mixture are ideal gases. **2** This is a steady-flow process. **3** The kinetic and potential energy changes are negligible.

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

Analysis The minimum work required to separate a gas mixture into its components is equal to the reversible work associated with the mixing process, which is equal to the exergy destruction (or irreversibility) associated with the mixing process since

$$X_{\text{destroyed}} = W_{\text{rev,out}} - W_{\text{act},u}^{\nearrow 0} = W_{\text{rev,out}} = T_0 S_{\text{gen}}$$



where S_{gen} is the entropy generation associated with the steady-flow mixing process. The entropy change associated with a constant pressure and temperature adiabatic mixing process is determined from

$$\begin{aligned}\bar{s}_{\text{gen}} &= \sum \Delta\bar{s}_i = -R_u \sum y_i \ln y_i = -(8.314 \text{ kJ/kmol}\cdot\text{K})[0.5\ln(0.5) + 0.5\ln(0.5)] \\ &= 5.763 \text{ kJ/kmol}\cdot\text{K}\end{aligned}$$

$$M_m = \sum y_i M_i = (0.5)(28 \text{ kg/kmol}) + (0.5)(44 \text{ kg/kmol}) = 36 \text{ kg/kmol}$$

$$s_{\text{gen}} = \frac{\bar{s}_{\text{gen}}}{M_m} = \frac{5.763 \text{ kJ/kmol}\cdot\text{K}}{36 \text{ kg/kmol}} = 0.160 \text{ kJ/kg}\cdot\text{K}$$

$$x_{\text{destroyed}} = T_0 s_{\text{gen}} = (291 \text{ K})(0.160 \text{ kJ/kg}\cdot\text{K}) = \mathbf{46.6\ kJ/kg}$$

13-95 A mixture of carbon dioxide, nitrogen, and oxygen is compressed isothermally. The required work is to be determined.

Assumptions **1** Nitrogen, oxygen, and carbon dioxide are ideal gases. **2** The process is reversible.

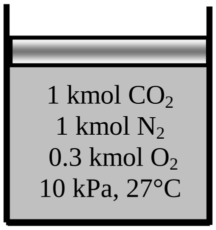
Properties The mole numbers of nitrogen, oxygen, and carbon dioxide are 28.0, 32.0, and 44.0 kg/kmol, respectively (Table A-1).

Analysis The mole fractions are

$$y_{\mathrm{CO2}} = \frac{N_{\mathrm{CO2}}}{N_{\mathrm{total}}} = \frac{1\,\mathrm{kmol}}{2.3\,\mathrm{kmol}} = 0.4348$$

$$y_{\mathrm{N2}} = \frac{N_{\mathrm{N2}}}{N_{\mathrm{total}}} = \frac{1\,\mathrm{kmol}}{2.3\,\mathrm{kmol}} = 0.4348$$

$$y_{\mathrm{O2}} = \frac{N_{\mathrm{O2}}}{N_{\mathrm{total}}} = \frac{0.3\,\mathrm{kmol}}{2.3\,\mathrm{kmol}} = 0.1304$$



The gas constant for this mixture is then

$$R = \frac{R_u}{y_{\mathrm{CO2}}M_{\mathrm{CO2}} + y_{\mathrm{N2}}M_{\mathrm{N2}} + y_{\mathrm{O2}}M_{\mathrm{O2}}}$$
$$= \frac{8.314\,\mathrm{kJ/kmol\cdot K}}{(0.4348\times 44 + 0.4348\times 28 + 0.1304\times 32)\mathrm{kg/kmol}} = 0.2343\,\mathrm{kJ/kg\cdot K}$$

The mass of this mixture of gases is

$$m = N_{\mathrm{CO2}}M_{\mathrm{CO2}} + N_{\mathrm{N2}}M_{\mathrm{N2}} + N_{\mathrm{O2}}M_{\mathrm{O2}} = 1\times 44 + 1\times 28 + 0.3\times 32 = 81.6\,\mathrm{kg}$$

Noting that $P\boldsymbol{v} = RT$ for an ideal gas, the work done for this process is then

$$W_{\mathrm{out}} = m\int_1^2 P\,d\boldsymbol{v} = mRT\int_1^2 \frac{d\boldsymbol{v}}{\boldsymbol{v}} = mRT\ln\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1} = mRT\ln\frac{P_1}{P_2}$$
$$= (81.6\,\mathrm{kg})(0.2343\,\mathrm{kJ/kg\cdot K})(300\,\mathrm{K})\ln\frac{10\,\mathrm{kPa}}{100\,\mathrm{kPa}}$$
$$= \mathbf{-13{,}200\,kJ}$$

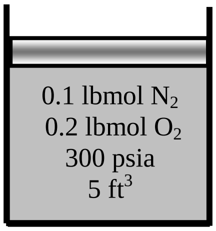
The negative sign shows that the work is done on the system.

13-96E A mixture of nitrogen and oxygen is expanded isothermally. The work produced is to be determined.

Assumptions **1** Nitrogen and oxygen are ideal gases. **2** The process is reversible.

Properties The mole numbers of nitrogen and oxygen are 28.0 and 32.0 lbm/lbmol, respectively (Table A-1E).

Analysis The mole fractions are



$$y_{N2} = \frac{N_{N2}}{N_{total}} = \frac{0.1\,\text{lbmol}}{0.3\,\text{lbmol}} = 0.3333$$

$$y_{O2} = \frac{N_{O2}}{N_{total}} = \frac{0.2\,\text{kmol}}{0.3\,\text{kmol}} = 0.6667$$

The gas constant for this mixture is then

$$\begin{aligned} R &= \frac{R_u}{y_{N2}M_{N2} + y_{O2}M_{O2}} \\ &= \frac{1.9858\,\text{Btu/lbmol}\cdot\text{R}}{(0.3333\times 28 + 0.6667\times 32)\text{lbm/lbmol}} \\ &= 0.06475\,\text{Btu/lbm}\cdot\text{R} \\ &= (0.06475\,\text{Btu/lbm}\cdot\text{R})\left(\frac{5.404\,\text{psia}\cdot\text{ft}^3}{1\,\text{Btu}}\right) \\ &= 0.3499\,\text{psia}\cdot\text{ft}^3\text{/lbm}\cdot\text{R} \end{aligned}$$

The mass of this mixture of gases is

$$m = N_{N2}M_{N2} + N_{O2}M_{O2} = 0.1\times 28 + 0.2\times 32 = 9.2\,\text{lbm}$$

The temperature of the mixture is

$$T_1 = \frac{P_1 \mathbf{V}_1}{mR} = \frac{(300\,\text{psia})(5\,\text{ft}^3)}{(9.2\,\text{lbm})(0.3499\,\text{psia}\cdot\text{ft}^3\text{/lbm}\cdot\text{R})} = 466.0\,\text{R}$$

Noting that $P\boldsymbol{v} = RT$ for an ideal gas, the work done for this process is then

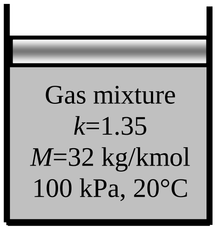
$$\begin{aligned} W_{out} &= m\int_1^2 P d\boldsymbol{v} = mRT\int_1^2 \frac{d\boldsymbol{v}}{\boldsymbol{v}} = mRT\ln\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1} \\ &= (9.2\,\text{lbm})(0.06475\,\text{Btu/lbm}\cdot\text{R})(466\,\text{R})\ln\frac{10\,\text{ft}^3}{5\,\text{ft}^3} \\ &= \mathbf{192.4\,Btu} \end{aligned}$$

13-97 The specific heat ratio and an apparent molecular weight of a mixture of ideal gases are given. The work required to compress this mixture isentropically in a closed system is to be determined.

Analysis For an isentropic process of an ideal gas with constant specific heats, the work is expresses as

$$w_{\text{out}} = \int_1^2 P d\boldsymbol{v} = P_1\boldsymbol{v}_1^k \int_1^2 \boldsymbol{v}^{-k} d\boldsymbol{v} = \frac{P_1\boldsymbol{v}_1^k}{1-k}(\boldsymbol{v}_{21}^{1-k} - \boldsymbol{v}_1^{1-k})$$

$$= \frac{P_1\boldsymbol{v}_1^k}{1-k}(\boldsymbol{v}_{21}^{1-k} - \boldsymbol{v}_1^{1-k}) = \frac{P_1\boldsymbol{v}_1^k}{1-k}\left[\left(\frac{\boldsymbol{v}_2}{\boldsymbol{v}_1}\right)^{1-k} - 1\right]$$



since $P_1\boldsymbol{v}_1^k = P_1\boldsymbol{v}^k$ for an isentropic process. Also,

$$P_1\boldsymbol{v}_1 = RT_1$$

$$(\boldsymbol{v}_2/\boldsymbol{v}_1)^k = P_1/P_2$$

Substituting, we obtain

$$w_{\text{out}} = \frac{R_u T_1}{M(1-k)}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right]$$

$$= \frac{(8.314)(293)}{(32)(1-1.35)}\left[\left(\frac{1000}{100}\right)^{(1.35-1)/1.35} - 1\right]$$

$$= \mathbf{-177.6\ kJ/kg}$$

The negative sign shows that the work is done on the system.

13-98 A mixture of gases is assembled by filling an evacuated tank with neon, oxygen, and nitrogen added one after another. The mass of each constituent in the resulting mixture, the apparent molecular weight of the mixture, and the fraction of the tank volume occupied by nitrogen are to be determined.

Properties The molar masses of Ne, O_2, and N_2 are 20.18, 32.0, 28.0 kg/kmol, respectively and the gas constants are 0.4119, 0.2598, and 0.2968 kJ/kg·K, respectively (Table A-1).

Analysis The mass of each constituent is calculated by

35 kPa Ne
70 kPa O_2
35 kPa N_2
0.15 m^3
60°C

$$m_{\text{Ne}} = \frac{P_{\text{Ne}}\mathcal{V}_m}{R_{\text{Ne}}T} = \frac{(35\,\text{kPa})(0.15\,\text{m}^3)}{(0.4119\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(333\,\text{K})} = \mathbf{0.03828\ kg}$$

$$m_{\text{O2}} = \frac{P_{\text{O2}}\mathcal{V}_m}{R_{\text{O2}}T} = \frac{(70\,\text{kPa})(0.15\,\text{m}^3)}{(0.2598\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(333\,\text{K})} = \mathbf{0.1214\ kg}$$

$$m_{\text{N2}} = \frac{P_{\text{N2}}\mathcal{V}_m}{R_{\text{N2}}T} = \frac{(35\,\text{kPa})(0.15\,\text{m}^3)}{(0.2968\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(333\,\text{K})} = \mathbf{0.05312\ kg}$$

The mole number of each constituent is

$$N_{\text{Ne}} = \frac{m_{\text{Ne}}}{M_{\text{Ne}}} = \frac{0.03828\,\text{kg}}{20.18\,\text{kg/kmol}} = 0.001896\,\text{kmol}$$

$$N_{\text{O2}} = \frac{m_{\text{O2}}}{M_{\text{O2}}} = \frac{0.1214\,\text{kg}}{32.0\,\text{kg/kmol}} = 0.003794\,\text{kmol}$$

$$N_{\text{N2}} = \frac{m_{\text{N2}}}{M_{\text{N2}}} = \frac{0.05312\,\text{kg}}{28.0\,\text{kg/kmol}} = 0.001897\,\text{kmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{(0.03828 + 0.1214 + 0.05312)\,\text{kg}}{(0.001896 + 0.003794 + 0.001897)\,\text{kmol}} = \frac{0.2128\,\text{kg}}{0.007586\,\text{kmol}} = \mathbf{28.05\ kg/kmol}$$

The mole fraction of nitrogen is

$$y_{\text{N2}} = \frac{P_{\text{N2}}}{P_m} = \frac{35\,\text{kPa}}{140\,\text{kPa}} = 0.25$$

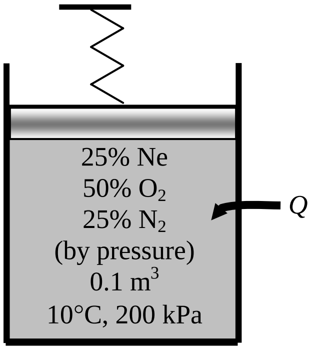
The partial volume occupied by nitrogen is then

$$\mathcal{V}_{\text{N2}} = y_{\text{N2}}\mathcal{V}_m = (0.25)(0.15\,\text{m}^3) = \mathbf{0.0375\ m^3}$$

13-99 A portion of the gas in the previous problem is placed in a spring-loaded piston-cylinder device. The device is now heated until the pressure rises to a specified value. The total work and heat transfer for this process are to be determined.

Properties The molar masses of Ne, O_2, and N_2 are 20.18, 32.0, 28.0 kg/kmol, respectively and the gas constants are 0.4119, 0.2598, and 0.2968 kJ/kg·K, respectively (Table A-1). The constant-volume specific volumes are 0.6179, 0.658, and 0.743 kJ/kg·K, respectively (Table A-2a).

Analysis Using the data from the previous problem, the mass fractions are



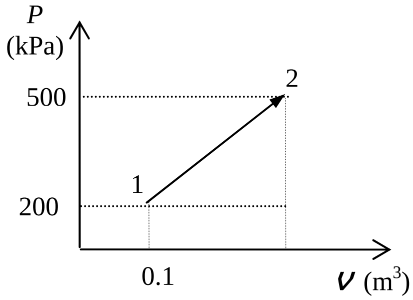
$$\mathrm{mf}_{\mathrm{Ne}} = \frac{m_{\mathrm{Ne}}}{m_m} = \frac{0.03828\ \mathrm{kg}}{0.2128\ \mathrm{kg}} = 0.1799$$

$$\mathrm{mf}_{\mathrm{O2}} = \frac{m_{\mathrm{O2}}}{m_m} = \frac{0.1214\ \mathrm{kg}}{0.2128\ \mathrm{kg}} = 0.5705$$

$$\mathrm{mf}_{\mathrm{N2}} = \frac{m_{\mathrm{N2}}}{m_m} = \frac{0.05312\ \mathrm{kg}}{0.2128\ \mathrm{kg}} = 0.2496$$

The constant-volume specific heat of the mixture is determined from

$$\begin{aligned} c_v &= \mathrm{mf}_{\mathrm{Ne}} c_{v,\mathrm{Ne}} + \mathrm{mf}_{\mathrm{O2}} c_{v,\mathrm{O2}} + \mathrm{mf}_{\mathrm{N2}} c_{v,\mathrm{N2}} \\ &= 0.1799 \times 0.6179 + 0.5705 \times 0.658 + 0.2496 \times 0.743 \\ &= 0.672\ \mathrm{kJ/kg \cdot K} \end{aligned}$$



The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol \cdot K}}{28.05\ \mathrm{kg/kmol}} = 0.2964\ \mathrm{kJ/kg \cdot K}$$

The mass contained in the system is

$$m = \frac{P_1 \mathbf{V}_1}{RT_1} = \frac{(200\ \mathrm{kPa})(0.1\ \mathrm{m^3})}{(0.2964\ \mathrm{kPa \cdot m^3/kg \cdot K})(283\ \mathrm{K})} = 0.2384\ \mathrm{kg}$$

Noting that the pressure changes linearly with volume, the final volume is determined by linear interpolation to be

$$\frac{500-200}{1000-200} = \frac{\mathbf{V}_2 - 0.1}{1.0-0.1} \longrightarrow \mathbf{V}_2 = 0.4375\ \mathrm{m^3}$$

The final temperature is

$$T_2 = \frac{P_2 \mathbf{V}_2}{mR} = \frac{(500\ \mathrm{kPa})(0.4375\ \mathrm{m^3})}{(0.2384\ \mathrm{kg})(0.2964\ \mathrm{kPa \cdot m^3/kg \cdot K})} = 3096\ \mathrm{K}$$

The work done during this process is

$$W_{\mathrm{out}} = \frac{P_1 + P_2}{2}(\mathbf{V}_2 - \mathbf{V}_1) = \frac{(500+200)\ \mathrm{kPa}}{2}(0.4375 - 0.1)\ \mathrm{m^3} = \mathbf{118\ kJ}$$

An energy balance on the system gives

$$Q_{\mathrm{in}} = W_{\mathrm{out}} + mc_v(T_2 - T_1) = 118 + (0.2384\ \mathrm{kg})(0.672\ \mathrm{kJ/kg \cdot K})(3096 - 283)\ \mathrm{K} = \mathbf{569\ kJ}$$

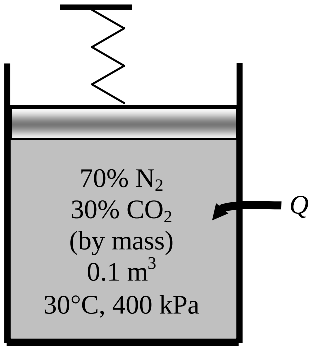
13-100 A spring-loaded piston-cylinder device is filled with a mixture of nitrogen and carbon dioxide whose mass fractions are given. The gas is heated until the volume has doubled. The total work and heat transfer for this process are to be determined.

Properties The molar masses of N_2 and CO_2 are 28.0 and 44.0 kg/kmol, respectively (Table A-1). The constant-volume specific heats of these gases at room temperature are 0.743 and 0.657 kJ/kg·K, respectively (Table A-2a).

Analysis We consider 100 kg of this mixture. The mole numbers of each component are

$$N_{N2} = \frac{m_{N2}}{M_{N2}} = \frac{70\text{ kg}}{28\text{ kg/kmol}} = 2.5\text{ kmol}$$

$$N_{CO2} = \frac{m_{CO2}}{M_{CO2}} = \frac{30\text{ kg}}{44\text{ kg/kmol}} = 0.6818\text{ kmol}$$



The mole number of the mixture is

$$N_m = N_{N2} + N_{CO2} = 2.5 + 0.6818 = 3.1818\text{ kmol}$$

The apparent molecular weight of the mixture is

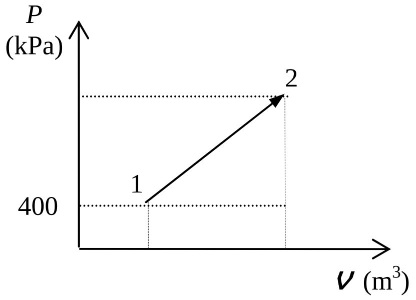
$$M_m = \frac{m_m}{N_m} = \frac{100\text{ kg}}{3.1818\text{ kmol}} = 31.43\text{ kg/kmol}$$

The constant-volume specific heat of the mixture is determined from

$$c_v = \text{mf}_{N2}c_{v,N2} + \text{mf}_{CO2}c_{v,CO2} = 0.70\times0.743 + 0.30\times0.657 = 0.717\text{ kJ/kg}\cdot\text{K}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.134\text{ kJ/kmol}\cdot\text{K}}{31.43\text{ kg/kmol}} = 0.2645\text{ kJ/kg}\cdot\text{K}$$



Noting that the pressure changes linearly with volume, the initial volume is determined by linear interpolation using the data of the previous problem to be

$$\frac{400-200}{1000-200} = \frac{V_1 - 0.1}{1.0-0.1} \longrightarrow V_1 = 0.325\text{ m}^3$$

The final volume is

$$V_2 = 2V_1 = 2(0.325\text{ m}^3) = 0.650\text{ m}^3$$

The final pressure is similarly determined by linear interpolation using the data of the previous problem to be

$$\frac{P_2-200}{1000-200} = \frac{0.650-0.1}{1.0-0.1} \longrightarrow P_2 = 689\text{ kPa}$$

The mass contained in the system is

$$m = \frac{P_1V_1}{RT_1} = \frac{(400\text{ kPa})(0.325\text{ m}^3)}{(0.2645\text{ kPa}\cdot\text{m}^3\text{/kg}\cdot\text{K})(303\text{ K})} = 1.622\text{ kg}$$

The final temperature is

$$T_2 = \frac{P_2V_2}{mR} = \frac{(689\text{ kPa})(0.650\text{ m}^3)}{(1.622\text{ kg})(0.2645\text{ kPa}\cdot\text{m}^3\text{/kg}\cdot\text{K})} = 1044\text{ K}$$

The work done during this process is

$$W_{out} = \frac{P_1+P_2}{2}(V_2 - V_1) = \frac{(400+689)\text{ kPa}}{2}(0.650-0.325)\text{ m}^3 = \mathbf{177\text{ kJ}}$$

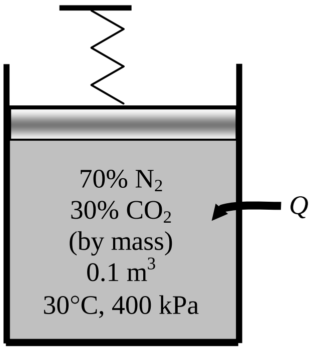
An energy balance on the system gives

$$Q_{in} = W_{out} + mc_v(T_2 - T_1) = 177 + (1.622\text{ kg})(0.717\text{ kJ/kg}\cdot\text{K})(1044-303)\text{ K} = \mathbf{1039\text{ kJ}}$$

13-101 A spring-loaded piston-cylinder device is filled with a mixture of nitrogen and carbon dioxide whose mass fractions are given. The gas is heated until the pressure has tripled. The total work and heat transfer for this process 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). The constant-volume specific heats of these gases at room temperature are 0.743 and 0.657 kJ/kg·K, respectively (Table A-2a).

Analysis We consider 100 kg of this mixture. The mole numbers of each component are



$$N_{\text{N2}} = \frac{m_{\text{N2}}}{M_{\text{N2}}} = \frac{70\ \text{kg}}{28\ \text{kg/kmol}} = 2.5\ \text{kmol}$$

$$N_{\text{CO2}} = \frac{m_{\text{CO2}}}{M_{\text{CO2}}} = \frac{30\ \text{kg}}{44\ \text{kg/kmol}} = 0.6818\ \text{kmol}$$

The mole number of the mixture is

$$N_m = N_{\text{N2}} + N_{\text{CO2}} = 2.5 + 0.6818 = 3.1818\ \text{kmol}$$

The apparent molecular weight of the mixture is

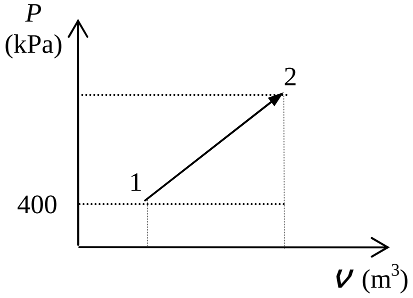
$$M_m = \frac{m_m}{N_m} = \frac{100\ \text{kg}}{3.1818\ \text{kmol}} = 31.43\ \text{kg/kmol}$$

The constant-volume specific heat of the mixture is determined from

$$c_v = \text{mf}_{\text{N2}} c_{v,\text{N2}} + \text{mf}_{\text{CO2}} c_{v,\text{CO2}} = 0.70 \times 0.743 + 0.30 \times 0.657 = 0.717\ \text{kJ/kg} \cdot \text{K}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.134\ \text{kJ/kmol} \cdot \text{K}}{31.43\ \text{kg/kmol}} = 0.2645\ \text{kJ/kg} \cdot \text{K}$$



Noting that the pressure changes linearly with volume, the initial volume is determined by linear interpolation using the data of the earlier problem to be

$$\frac{400 - 200}{1000 - 200} = \frac{V_1 - 0.1}{1.0 - 0.1} \longrightarrow V_1 = 0.325\ \text{m}^3$$

The final pressure is

$$P_2 = 3P_1 = 3(400\ \text{kPa}) = 1200\ \text{kPa}$$

The final volume is similarly determined by linear interpolation using the data of the earlier problem to be

$$\frac{1200 - 200}{1000 - 200} = \frac{V_2 - 0.1}{1.0 - 0.1} \longrightarrow V_2 = 1.225\ \text{m}^3$$

The mass contained in the system is

$$m = \frac{P_1 V_1}{RT_1} = \frac{(400\ \text{kPa})(0.325\ \text{m}^3)}{(0.2645\ \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(303\ \text{K})} = 1.622\ \text{kg}$$

The final temperature is

$$T_2 = \frac{P_2 V_2}{mR} = \frac{(1200\ \text{kPa})(1.225\ \text{m}^3)}{(1.622\ \text{kg})(0.2645\ \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})} = 3426\ \text{K}$$

The work done during this process is

$$W_{\text{out}} = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{(400 + 1200)\ \text{kPa}}{2}(1.225 - 0.325)\ \text{m}^3 = \mathbf{720\ kJ}$$

An energy balance on the system gives

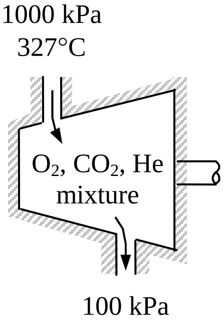
$$Q_{\text{in}} = W_{\text{out}} + mc_v(T_2 - T_1) = 720 + (1.622\ \text{kg})(0.717\ \text{kJ/kg} \cdot \text{K})(3426 - 303)\ \text{K} = \mathbf{4352\ kJ}$$

13-102 The masses of components of a gas mixture are given. This mixture is expanded in an adiabatic, steady-flow turbine of specified isentropic efficiency. The second law efficiency and the exergy destruction during this expansion process are to be determined.

Assumptions All gases will be modeled as ideal gases with constant specific heats.

Properties The molar masses of O_2, CO_2, and He are 32.0, 44.0, and 4.0 kg/kmol, respectively (Table A-1). The constant-pressure specific heats of these gases at room temperature are 0.918, 0.846, and 5.1926 kJ/kg·K, respectively (Table A-2a).

Analysis The total mass of the mixture is



$$m_m = m_{\text{O2}} + m_{\text{CO2}} + m_{\text{He}} = 0.1 + 1 + 0.5 = 1.6\ \text{kg}$$

The mole numbers of each component are

$$N_{\text{O2}} = \frac{m_{\text{O2}}}{M_{\text{O2}}} = \frac{0.1\ \text{kg}}{32\ \text{kg/kmol}} = 0.003125\ \text{kmol}$$

$$N_{\text{CO2}} = \frac{m_{\text{CO2}}}{M_{\text{CO2}}} = \frac{1\ \text{kg}}{44\ \text{kg/kmol}} = 0.02273\ \text{kmol}$$

$$N_{\text{He}} = \frac{m_{\text{He}}}{M_{\text{He}}} = \frac{0.5\ \text{kg}}{4\ \text{kg/kmol}} = 0.125\ \text{kmol}$$

The mole number of the mixture is

$$N_m = N_{\text{O2}} + N_{\text{CO2}} + N_{\text{He}} = 0.003125 + 0.02273 + 0.125 = 0.15086\ \text{kmol}$$

The apparent molecular weight of the mixture is

$$M_m = \frac{m_m}{N_m} = \frac{1.6\ \text{kg}}{0.15086\ \text{kmol}} = 10.61\ \text{kg/kmol}$$

The apparent gas constant of the mixture is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \text{kJ/kmol}\cdot\text{K}}{10.61\ \text{kg/kmol}} = 0.7836\ \text{kJ/kg}\cdot\text{K}$$

The mass fractions are

$$\text{mf}_{\text{O2}} = \frac{m_{\text{O2}}}{m_m} = \frac{0.1\ \text{kg}}{1.6\ \text{kg}} = 0.0625$$

$$\text{mf}_{\text{CO2}} = \frac{m_{\text{CO2}}}{m_m} = \frac{1\ \text{kg}}{1.6\ \text{kg}} = 0.625$$

$$\text{mf}_{\text{He}} = \frac{m_{\text{He}}}{m_m} = \frac{0.5\ \text{kg}}{1.6\ \text{kg}} = 0.3125$$

The constant-pressure specific heat of the mixture is determined from

$$\begin{aligned} c_p &= \text{mf}_{\text{O2}} c_{p,\text{O2}} + \text{mf}_{\text{CO2}} c_{p,\text{CO2}} + \text{mf}_{\text{He}} c_{p,\text{He}} \\ &= 0.0625 \times 0.918 + 0.625 \times 0.846 + 0.3125 \times 5.1926 \\ &= 2.209\ \text{kJ/kg}\cdot\text{K} \end{aligned}$$

Then the constant-volume specific heat is

$$c_v = c_p - R = 2.209 - 0.7836 = 1.425\ \text{kJ/kg}\cdot\text{K}$$

The specific heat ratio is

$$k=\frac{c_p}{c_v}=\frac{2.209}{1.425}=1.550$$

The temperature at the end of the expansion for the isentropic process is

$$T_{2s}=T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k}=(600\text{ K})\left(\frac{100\text{ kPa}}{1000\text{ kPa}}\right)^{0.55/1.55}=265\text{ K}$$

Using the definition of turbine isentropic efficiency, the actual outlet temperature is

$$T_2=T_1-\eta_{\text{turb}}(T_1-T_{2s})=(600\text{ K})-(0.90)(600-265)=299\text{ K}$$

The entropy change of the gas mixture is

$$s_2-s_1=c_p\ln\frac{T_2}{T_1}-R\ln\frac{P_2}{P_1}=(2.209)\ln\frac{299}{600}-(0.7836)\ln\frac{100}{1000}=0.2658\text{ kJ/kg}\cdot\text{K}$$

The actual work produced is

$$w_{\text{out}}=h_1-h_2=c_p(T_1-T_2)=(2.209\text{ kJ/kg}\cdot\text{K})(600-299)\text{ K}=665\text{ kJ/kg}$$

The reversible work output is

$$w_{\text{rev,out}}=h_1-h_2-T_0(s_1-s_2)=665\text{ kJ/kg}-(298\text{ K})(-0.2658\text{ kJ/kg}\cdot\text{K})=744\text{ kJ/kg}$$

The second-law efficiency and the exergy destruction are then

$$\eta_{\text{II}}=\frac{w_{\text{out}}}{w_{\text{rev,out}}}=\frac{665}{744}=\mathbf{0.894}$$

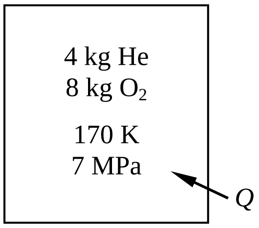
$$x_{\text{dest}}=w_{\text{rev,out}}-w_{\text{out}}=744-665=\mathbf{79\text{ kJ/kg}}$$

13-103 The masses, pressures, and temperatures of the constituents of a gas mixture in a tank are given. Heat is transferred to the tank. The final pressure of the mixture and the heat transfer are to be determined.

Assumptions He is an ideal gas and O_2 is a nonideal gas.

Properties The molar masses of He and O_2 are 4.0 and 32.0 kg/kmol. (Table A-1)

Analysis (*a*) The number of moles of each gas is



$$N_{He} = \frac{m_{He}}{M_{He}} = \frac{4\text{ kg}}{4.0\text{ kg/kmol}} = 1\text{ kmol}$$

$$N_{O_2} = \frac{m_{O_2}}{M_{O_2}} = \frac{8\text{ kg}}{32\text{ kg/kmol}} = 0.25\text{ kmol}$$

$$N_m = N_{He} + N_{O_2} = 1\text{ kmol} + 0.25\text{ kmol} = 1.25\text{ kmol}$$

Then the partial volume of each gas and the volume of the tank are

He: $$\boldsymbol{V}_{He} = \frac{N_{He}R_uT_1}{P_{m,1}} = \frac{(1\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3\text{/kmol}\cdot\text{K})(170\text{ K})}{7000\text{ kPa}} = 0.202\text{ m}^3$$

O$_2$: $$\left.\begin{aligned} P_{R_1} &= \frac{P_{m,1}}{P_{cr,O_2}} = \frac{7}{5.08} = 1.38 \\ T_{R_1} &= \frac{T_1}{T_{cr,O_2}} = \frac{170}{154.8} = 1.10 \end{aligned}\right\} Z_1 = 0.53 \qquad \text{(Fig. A-15)}$$

$$\boldsymbol{V}_{O_2} = \frac{ZN_{O_2}R_uT_1}{P_{m,1}} = \frac{(0.53)(0.25\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3\text{/kg}\cdot\text{K})(170\text{ K})}{7000\text{ kPa}} = 0.027\text{ m}^3$$

$$\boldsymbol{V}_{tank} = \boldsymbol{V}_{He} + \boldsymbol{V}_{O_2} = 0.202\text{ m}^3 + 0.027\text{ m}^3 = 0.229\text{ m}^3$$

The partial pressure of each gas and the total final pressure is

He: $$P_{He,2} = \frac{N_{He}R_uT_2}{\boldsymbol{V}_{tank}} = \frac{(1\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3\text{/kmol}\cdot\text{K})(220\text{ K})}{0.229\text{ m}^3} = 7987\text{ kPa}$$

O$_2$: $$\left.\begin{aligned} T_{R_2} &= \frac{T_2}{T_{cr,O_2}} = \frac{220}{154.8} = 1.42 \\ \boldsymbol{v}_{R,O_2} &= \frac{\bar{\boldsymbol{v}}_{O_2}}{R_uT_{cr,O_2}/P_{cr,O_2}} = \frac{\boldsymbol{V}_m/N_{O_2}}{R_uT_{cr,O_2}/P_{cr,O_2}} \\ &= \frac{(0.229\text{ m}^3)/(0.25\text{ kmol})}{(8.314\text{ kPa}\cdot\text{m}^3\text{/kmol}\cdot\text{K})(154.8\text{ K})/(5080\text{ kPa})} = 3.616 \end{aligned}\right\} P_R = 0.39 \qquad \text{(Fig. A-15)}$$

$$P_{O_2} = (P_RP_{cr})_{O_2} = (0.39)(5080\text{ kPa}) = 1981\text{ kPa} = 1.981\text{ MPa}$$

$$P_{m,2} = P_{He} + P_{O_2} = 7.987\text{ MPa} + 1.981\text{ MPa} = \mathbf{9.97\ MPa}$$

(*b*) We take both gases as the system. No work or mass crosses the system boundary, therefore this is a closed system with no work interactions. Then the energy balance for this closed system reduces to

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

$$Q_{in} = \Delta U = \Delta U_{He} + \Delta U_{O_2}$$

He: $$\Delta U_{He} = mc_v(T_m - T_1) = (4\text{ kg})(3.1156\text{ kJ/kg}\cdot\text{K})(220-170)\text{K} = 623.1\text{ kJ}$$

O_2:

$$\left.\begin{aligned} T_{R_1} &= 1.10 \\ P_{R_1} &= 1.38 \end{aligned}\right\} Z_{h_1} = 2.2$$

$$\left.\begin{aligned} T_{R_2} &= 1.42 \\ P_{R_2} &= \frac{9.97}{5.08} = 1.963 \end{aligned}\right\} Z_{h_2} = 1.2 \qquad \text{(Fig. A-29)}$$

$$\begin{aligned} \bar{h}_2 - \bar{h}_1 &= R_u T_{\text{cr}} (Z_{h_1} - Z_{h_2}) + (\bar{h}_2 - \bar{h}_1)_{\text{ideal}} \\ &= (8.314 \text{ kJ/kmol}\cdot\text{K})(154.8 \text{ K})(2.2 - 1.2) + (6404 - 4949)\text{kJ/kmol} = 2742 \text{ kJ/kmol} \end{aligned}$$

Also,

$$P_{\text{He},1} = \frac{N_{\text{He}} R_u T_1}{V_{\text{tank}}} = \frac{(1 \text{ kmol})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(170 \text{ K})}{0.229 \text{ m}^3} = 6{,}172 \text{ kPa}$$

$$P_{O_2,1} = P_{m,1} - P_{\text{He},1} = 7000 \text{ kPa} - 6172 \text{ kPa} = 828 \text{ kPa}$$

Thus,

$$\begin{aligned} \Delta U_{O_2} &= N_{O_2} (\bar{h}_2 - \bar{h}_1) - (P_2 V_2 - P_1 V_1) = N_{O_2} (\bar{h}_2 - \bar{h}_1) - (P_{O_2,2} - P_{O_2,1}) V_{\text{tank}} \\ &= (0.25 \text{ kmol})(2742 \text{ kJ/kmol}) - (1981 - 828)(0.229)\text{kPa}\cdot\text{m}^3 = 421.5 \text{ kJ} \end{aligned}$$

Substituting,

$$Q_{\text{in}} = 623.1 \text{ kJ} + 421.5 \text{ kJ} = \mathbf{1045\ kJ}$$

13-104 A mixture of carbon dioxide and methane expands through a turbine. The power produced by the mixture is to be determined using ideal gas approximation and Kay's rule.

Assumptions The expansion process is reversible and adiabatic (isentropic).

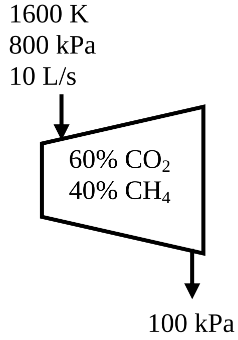
Properties The molar masses of CO_2 and CH_4 are 44.0 and 16.0 kg/kmol and respectively. The critical properties are 304.2 K, 7390 kPa for CO_2 and 191.1 K and 4640 kPa for CH_4 (Table A-1).

Analysis The molar mass of the mixture is determined to be

$$M_m = y_{\mathrm{CO_2}} M_{\mathrm{CO_2}} + y_{\mathrm{CH_4}} M_{\mathrm{CH_4}} = (0.60)(44) + (0.40)(16) = 32.80\ \mathrm{kg/kmol}$$

The gas constant is

$$R = \frac{R_u}{M_m} = \frac{8.314\ \mathrm{kJ/kmol.K}}{32.8\ \mathrm{kg/kmol}} = 0.2533\ \mathrm{kJ/kg.K}$$



The mass fractions are

$$\mathrm{mf}_{\mathrm{CO_2}} = y_{\mathrm{CO_2}} \frac{M_{\mathrm{CO_2}}}{M_m} = (0.60)\frac{44\ \mathrm{kg/kmol}}{32.8\ \mathrm{kg/kmol}} = 0.8049$$

$$\mathrm{mf}_{\mathrm{CH_4}} = y_{\mathrm{CH_4}} \frac{M_{\mathrm{CH_4}}}{M_m} = (0.40)\frac{16\ \mathrm{kg/kmol}}{32.8\ \mathrm{kg/kmol}} = 0.1951$$

Ideal gas solution:

Using Dalton's law to find partial pressures, the entropies at the initial state are determined from EES to be:

$$T = 1600\ \mathrm{K},\ P = (0.60 \times 800) = 480\ \mathrm{kPa} \longrightarrow s_{\mathrm{CO_2},1} = 6.424\ \mathrm{kJ/kg.K}$$

$$T = 1600\ \mathrm{K},\ P = (0.40 \times 800) = 320\ \mathrm{kPa} \longrightarrow s_{\mathrm{CH_4},1} = 17.188\ \mathrm{kJ/kg.K}$$

The final state entropies cannot be determined at this point since the final temperature is not known. However, for an isentropic process, the entropy change is zero and the final temperature may be determined from

$$\Delta s_{\mathrm{total}} = mf_{\mathrm{CO_2}} \Delta s_{\mathrm{CO_2}} + mf_{\mathrm{CH_4}} \Delta s_{\mathrm{CH_4}}$$

$$0 = mf_{\mathrm{CO_2}} (s_{\mathrm{CO_2},2} - s_{\mathrm{CO_2},1}) + mf_{\mathrm{CH_4}} (s_{\mathrm{CH_4},2} - s_{\mathrm{CH_4},1})$$

The solution is obtained using EES to be

T_2 = 1243 K

The initial and final enthalpies and the changes in enthalpy are (from EES)

$$T_1 = 1600\ \mathrm{K} \longrightarrow \begin{array}{l} h_{\mathrm{CO_2},1} = -7408\ \mathrm{kJ/kg} \\ u_{\mathrm{CH_4},1} = 747.4\ \mathrm{kJ/kg} \end{array} \qquad T_2 = 1243\ \mathrm{K} \longrightarrow \begin{array}{l} h_{\mathrm{CO_2},2} = -7877\ \mathrm{kJ/kg} \\ u_{\mathrm{CH_4},2} = -1136\ \mathrm{kJ/kg} \end{array}$$

Noting that the heat transfer is zero, an energy balance on the system gives

$$\dot{Q}_{\mathrm{in}} - \dot{W}_{\mathrm{out}} = \dot{m}\Delta h_m \longrightarrow \dot{W}_{\mathrm{out}} = -\dot{m}\Delta h_m$$

where

$$\Delta h_m = \mathrm{mf}_{\mathrm{CO_2}} (h_{\mathrm{CO_2},2} - h_{\mathrm{CO_2},1}) + \mathrm{mf}_{\mathrm{CH_4}} (h_{\mathrm{CH_4},2} - h_{\mathrm{CH_4},1})$$

$$= (0.8049)\big[(-7877) - (-7408)\big] + (0.1951)\big[(-1136) - (747.4)\big] = -745.9\ \mathrm{kJ/kg}$$

The mass flow rate is

$$\dot{m} = \frac{P_1 \dot{V}_1}{RT_1} = \frac{(800\ \mathrm{kPa})(0.010\ \mathrm{m^3/s})}{(0.2533\ \mathrm{kJ/kg.K})(1600\ \mathrm{K})} = 0.01974\ \mathrm{kg/s}$$

Substituting, $\dot{W}_{\mathrm{out}} = \dot{m}\Delta h_m = -(0.01974)(-745.9\ \mathrm{kJ/kg}) = \mathbf{14.72\ kW}$

Kay’s rule solution:

The critical temperature and pressure of the mixture is

$$T_{\rm cr} = y_{\rm CO_2} T_{\rm cr,CO_2} + y_{\rm CH_4} T_{\rm cr,CH_4} = (0.60)(304.2\ {\rm K}) + (0.40)(191.1\ {\rm K}) = 259.0\ {\rm K}$$

$$P_{\rm cr} = y_{\rm CO_2} P_{\rm cr,CO_2} + y_{\rm CH_4} P_{\rm cr,CH_4} = (0.60)(7390\ {\rm kPa}) + (0.40)(4640\ {\rm kPa}) = 6290\ {\rm kPa}$$

State 1 properties:

$$\left.\begin{aligned} T_{R1} &= \frac{T_1}{T_{\rm cr}} = \frac{1600\ {\rm K}}{259.0\ {\rm K}} = 6.178 \\ P_{R1} &= \frac{P_1}{P_{\rm cr}} = \frac{800\ {\rm kPa}}{6290\ {\rm kPa}} = 0.127 \end{aligned}\right\} \begin{aligned} Z_1 &= 1.002 \\ Z_{h1} &= -0.01025 \quad \text{(from EES)} \\ Z_{s1} &= 0.0001277 \end{aligned}$$

$$\Delta h_1 = Z_{h1} R T_{\rm cr} = (-0.01025)(0.2533\ {\rm kJ/kg.K})(259.0\ {\rm K}) = -0.6714\ {\rm kJ/kg}$$

$$\begin{aligned} h_1 &= mf_{\rm CO_2} h_{\rm CO_2,1} + mf_{\rm CH_4} h_{\rm CH_4,1} - \Delta h_1 \\ &= (0.8049)(-7408) + (0.1951)(747.1) - (-0.6714) = -5813\ {\rm kJ/kg} \end{aligned}$$

$$\Delta s_1 = Z_{s1} R = (0.0001277)(0.2533\ {\rm kJ/kg.K}) = 0.00003234\ {\rm kJ/kg.K}$$

$$\begin{aligned} s_1 &= {\rm mf}_{\rm CO_2} s_{\rm CO_2,1} + {\rm mf}_{\rm CH_4} s_{\rm CH_4,1} - \Delta s_1 \\ &= (0.8049)(6.424) + (0.1951)(17.188) - (0.00003234) = 8.529\ {\rm kJ/kg.K} \end{aligned}$$

The final state entropies cannot be determined at this point since the final temperature is not known. However, for an isentropic process, the entropy change is zero and the final temperature may be determined from

$$\begin{aligned} \Delta s_{\rm total} &= {\rm mf}_{\rm CO_2} \Delta s_{\rm CO_2} + {\rm mf}_{\rm CH_4} \Delta s_{\rm CH_4} \\ 0 &= {\rm mf}_{\rm CO_2} (s_{\rm CO_2,2} - s_{\rm CO_2,1}) + {\rm mf}_{\rm CH_4} (s_{\rm CH_4,2} - s_{\rm CH_4,1}) \end{aligned}$$

The solution is obtained using EES to be

$$T_2 = 1243\ {\rm K}$$

The initial and final enthalpies and the changes in enthalpy are

$$\left.\begin{aligned} T_{R2} &= \frac{T_2}{T_{\rm cr}} = \frac{1243\ {\rm K}}{259.0\ {\rm K}} = 4.80 \\ P_{R2} &= \frac{P_2}{P_{\rm cr}} = \frac{100\ {\rm kPa}}{6290\ {\rm kPa}} = 0.016 \end{aligned}\right\} \begin{aligned} Z_{h2} &= -0.00007368 \\ Z_{s2} &= 0.0001171 \end{aligned} \quad \text{(from EES)}$$

$$\Delta h_2 = Z_{h2} R T_{cr} = (-0.000007368)(0.2533\ {\rm kJ/kg.K})(259.0\ {\rm K}) = -0.04828\ {\rm kJ/kg}$$

$$\begin{aligned} h_2 &= {\rm mf}_{\rm CO_2} h_{\rm CO_2,2} + {\rm mf}_{\rm CH_4} h_{\rm CH_4,2} - \Delta h_2 \\ &= (0.8049)(-7877) + (0.1951)(-1136) - (-0.4828) = -6559\ {\rm kJ/kg} \end{aligned}$$

Noting that the heat transfer is zero, an energy balance on the system gives

$$\dot{Q}_{\rm in} - \dot{W}_{\rm out} = \dot{m}\Delta h_m \longrightarrow \dot{W}_{\rm out} = -\dot{m}(h_2 - h_1)$$

where the mass flow rate is

$$\dot{m} = \frac{P_1 \dot{V}_1}{Z_1 R T_1} = \frac{(800\ {\rm kPa})(0.010\ {\rm m^3/s})}{(1.002)(0.2533\ {\rm kJ/kg.K})(1600\ {\rm K})} = 0.01970\ {\rm kg/s}$$

Substituting,

$$\dot{W}_{\rm out} = -(0.01970\ \ {\rm kg/s})\big[(-6559) - (-5813)\ {\rm kJ/kg}\big] = \mathbf{14.71\ kW}$$

13-105 EES A program is to be written to determine the mole fractions of the components of a mixture of three 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. Also, the program is to be run for a sample case.

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

```
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
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
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
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
```

13-106 EES A program is to be written to determine the entropy change of a mixture of 3 ideal gases when the mole fractions and other properties of the constituent gases are given. Also, the program is to be run for a sample case.

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

```
T1=300 [K]
T2=600 [K]
P1=100 [kPa]
P2=500 [kPa]
A$ = 'N2'
B$ = 'O2'
C$ = 'Argon'
y_A = 0.71
y_B = 0.28
y_C = 0.01
MM_A = molarmass(A$)
MM_B = molarmass(B$)
MM_C = molarmass(C$)
MM_mix = y_A*MM_A+ y_B*MM_B+ y_C*MM_C
mf_A = y_A*MM_A/MM_mix
mf_B = y_B*MM_B/MM_mix
mf_C = y_C*MM_C/MM_mix
DELTAs_mix=mf_A*(entropy(A$,T=T2,P=y_B*P2)-
entropy(A$,T=T1,P=y_A*P1))+mf_B*(entropy(B$,T=T2,P=y_B*P2)-
entropy(B$,T=T1,P=y_B*P1))+mf_C*(entropy(C$,T=T2,P=y_C*P2)-
entropy(C$,T=T1,P=y_C*P1))
```

```
SOLUTION
A$='N2'
B$='O2'
C$='Argon'
DELTAs_mix=12.41 [kJ/kg-K]
mf_A=0.68
mf_B=0.3063
mf_C=0.01366
MM_A=28.01 [kg/kmol]
MM_B=32 [kg/kmol]
MM_C=39.95 [kg/kmol]
MM_mix=29.25 [kJ/kmol]
P1=100 [kPa]
P2=500 [kPa]
T1=300 [K]
T2=600 [K]
y_A=0.71
y_B=0.28
y_C=0.01
```

Fundamentals of Engineering (FE) Exam Problems

13-107 An ideal gas mixture whose apparent molar mass is 36 kg/kmol consists of nitrogen N_2 and three other gases. If the mole fraction of nitrogen is 0.30, its mass fraction is

(a) 0.15	(b) 0.23	(c) 0.30	(d) 0.39	(e) 0.70

Answer (b) 0.23

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
M_mix=36 "kg/kmol"
M_N2=28 "kg/kmol"
y_N2=0.3
mf_N2=(M_N2/M_mix)*y_N2

"Some Wrong Solutions with Common Mistakes:"
W1_mf = y_N2 "Taking mass fraction to be equal to mole fraction"
W2_mf= y_N2*(M_mix/M_N2) "Using the molar mass ratio backwords"
W3_mf= 1-mf_N2 "Taking the complement of the mass fraction"
```

13-108 An ideal gas mixture consists of 2 kmol of N_2 and 6 kmol of CO_2. The mass fraction of CO_2 in the mixture is

(a) 0.175	(b) 0.250	(c) 0.500	(d) 0.750	(e) 0.825

Answer (e) 0.825

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
N1=2 "kmol"
N2=6 "kmol"
N_mix=N1+N2
MM1=28 "kg/kmol"
MM2=44 "kg/kmol"
m_mix=N1*MM1+N2*MM2
mf2=N2*MM2/m_mix

"Some Wrong Solutions with Common Mistakes:"
W1_mf = N2/N_mix "Using mole fraction"
W2_mf = 1-mf2 "The wrong mass fraction"
```

13-109 An ideal gas mixture consists of 2 kmol of N_2 and 4 kmol of CO_2. The apparent gas constant of the mixture is

(a) 0.215 kJ/kg·K (b) 0.225 kJ/kg·K (c) 0.243 kJ/kg·K (d) 0.875 kJ/kg·K
(e) 1.24 kJ/kg·K

Answer (a) 0.215 kJ/kg·K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Ru=8.314 "kJ/kmol.K"
N1=2 "kmol"
N2=4 "kmol"
MM1=28 "kg/kmol"
MM2=44 "kg/kmol"
R1=Ru/MM1
R2=Ru/MM2
N_mix=N1+N2
y1=N1/N_mix
y2=N2/N_mix
MM_mix=y1*MM1+y2*MM2
R_mix=Ru/MM_mix

"Some Wrong Solutions with Common Mistakes:"
W1_Rmix =(R1+R2)/2 "Taking the arithmetic average of gas constants"
W2_Rmix= y1*R1+y2*R2 "Using wrong relation for Rmixture"
```

13-110 A rigid tank is divided into two compartments by a partition. One compartment contains 3 kmol of N_2 at 600 kPa pressure and the other compartment contains 7 kmol of CO_2 at 200 kPa. Now the partition is removed, and the two gases form a homogeneous mixture at 300 kPa. The partial pressure of N_2 in the mixture is

(a) 75 kPa (b) 90 kPa (c) 150 kPa (d) 175 kPa (e) 225 kPa

Answer (b) 90 kPa

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1 = 600 "kPa"
P2 = 200 "kPa"
P_mix=300 "kPa"
N1=3 "kmol"
N2=7 "kmol"
MM1=28 "kg/kmol"
MM2=44 "kg/kmol"
N_mix=N1+N2
y1=N1/N_mix
y2=N2/N_mix
P_N2=y1*P_mix

"Some Wrong Solutions with Common Mistakes:"
W1_P1= P_mix/2 "Assuming equal partial pressures"
W2_P1= mf1*P_mix; mf1=N1*MM1/(N1*MM1+N2*MM2) "Using mass fractions"
W3_P1 = P_mix*N1*P1/(N1*P1+N2*P2) "Using some kind of weighed averaging"
```

13-111 An 80-L rigid tank contains an ideal gas mixture of 5 g of N_2 and 5 g of CO_2 at a specified pressure and temperature. If N_2 were separated from the mixture and stored at mixture temperature and pressure, its volume would be

(a) 32 L (b) 36 L (c) 40 L (d) 49 L (e) 80 L

Answer (d) 49 L

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
V_mix=80 "L"
m1=5 "g"
m2=5 "g"
MM1=28 "kg/kmol"
MM2=44 "kg/kmol"
N1=m1/MM1
N2=m2/MM2
N_mix=N1+N2
y1=N1/N_mix
V1=y1*V_mix  "L"

"Some Wrong Solutions with Common Mistakes:"
W1_V1=V_mix*m1/(m1+m2)  "Using mass fractions"
W2_V1= V_mix "Assuming the volume to be the mixture volume"
```

13-112 An ideal gas mixture consists of 3 kg of Ar and 6 kg of CO_2 gases. The mixture is now heated at constant volume from 250 K to 350 K. The amount of heat transfer is

(a) 374 kJ (b) 436 kJ (c) 488 kJ (d) 525 kJ (e) 664 kJ

Answer (c) 488 kJ

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
T1=250 "K"
T2=350 "K"
Cv1=0.3122; Cp1=0.5203 "kJ/kg.K"
Cv2=0.657; Cp2=0.846 "kJ/kg.K"
m1=3 "kg"
m2=6 "kg"
MM1=39.95 "kg/kmol"
MM2=44 "kg/kmol"
"Applying Energy balance gives Q=DeltaU=DeltaU_Ar+DeltaU_CO2"
Q=(m1*Cv1+m2*Cv2)*(T2-T1)

"Some Wrong Solutions with Common Mistakes:"
W1_Q = (m1+m2)*(Cv1+Cv2)/2*(T2-T1)  "Using arithmetic average of properties"
W2_Q = (m1*Cp1+m2*Cp2)*(T2-T1)"Using Cp instead of Cv"
W3_Q = (m1*Cv1+m2*Cv2)*T2 "Using T2 instead of T2-T1"
```

13-113 An ideal gas mixture consists of 30% helium and 70% argon gases by mass. The mixture is now expanded isentropically in a turbine from 400°C and 1.2 MPa to a pressure of 200 kPa. The mixture temperature at turbine exit is

(a) 195°C (b) 56°C (c) 112°C (d) 130°C (e) 400°C

Answer (b) 56°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
T1=400+273"K"
P1=1200 "kPa"
P2=200 "kPa"
mf_He=0.3
mf_Ar=0.7
k1=1.667
k2=1.667
"The specific heat ratio k of the mixture is also 1.667 since k=1.667 for all componet gases"
k_mix=1.667
T2=T1*(P2/P1)^((k_mix-1)/k_mix)-273

"Some Wrong Solutions with Common Mistakes:"
W1_T2 = (T1-273)*(P2/P1)^((k_mix-1)/k_mix) "Using C for T1 instead of K"
W2_T2 = T1*(P2/P1)^((k_air-1)/k_air)-273; k_air=1.4 "Using k value for air"
W3_T2 = T1*P2/P1 "Assuming T to be proportional to P"
```

13-114 One compartment of an insulated rigid tank contains 2 kmol of CO_2 at 20°C and 150 kPa while the other compartment contains 5 kmol of H_2 gas at 35°C and 300 kPa. Now the partition between the two gases is removed, and the two gases form a homogeneous ideal gas mixture. The temperature of the mixture is

(a) 25°C (b) 29°C (c) 22°C (d) 32°C (e) 34°C

Answer (b) 29°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
N_H2=5 "kmol"
T1_H2=35 "C"
P1_H2=300 "kPa"
N_CO2=2 "kmol"
T1_CO2=20 "C"
P1_CO2=150 "kPa"
Cv_H2=10.183; Cp_H2=14.307 "kJ/kg.K"
Cv_CO2=0.657; Cp_CO2=0.846 "kJ/kg.K"
MM_H2=2 "kg/kmol"
MM_CO2=44 "kg/kmol"
m_H2=N_H2*MM_H2
m_CO2=N_CO2*MM_CO2
"Applying Energy balance gives 0=DeltaU=DeltaU_H2+DeltaU_CO2"
0=m_H2*Cv_H2*(T2-T1_H2)+m_CO2*Cv_CO2*(T2-T1_CO2)

"Some Wrong Solutions with Common Mistakes:"
0=m_H2*Cp_H2*(W1_T2-T1_H2)+m_CO2*Cp_CO2*(W1_T2-T1_CO2) "Using Cp instead of Cv"
0=N_H2*Cv_H2*(W2_T2-T1_H2)+N_CO2*Cv_CO2*(W2_T2-T1_CO2) "Using N instead of mass"
W3_T2 = (T1_H2+T1_CO2)/2 "Assuming averate temperature"
```

13-115 A piston-cylinder device contains an ideal gas mixture of 3 kmol of He gas and 7 kmol of Ar gas at 50°C and 400 kPa. Now the gas expands at constant pressure until its volume doubles. The amount of heat transfer to the gas mixture is

(a) 6.2 MJ (b) 42 MJ (c) 27 MJ (d) 10 MJ (e) 67 MJ

Answer (e) 67 MJ

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
N_He=3 "kmol"
N_Ar=7 "kmol"
T1=50+273 "C"
P1=400 "kPa"
P2=P1
"T2=2T1 since PV/T=const for ideal gases and it is given that P=constant"
T2=2*T1 "K"
MM_He=4 "kg/kmol"
MM_Ar=39.95 "kg/kmol"
m_He=N_He*MM_He
m_Ar=N_Ar*MM_Ar
Cp_Ar=0.5203; Cv_Ar = 3122 "kJ/kg.C"
Cp_He=5.1926; Cv_He = 3.1156 "kJ/kg.K"
"For a P=const process, Q=DeltaH since DeltaU+Wb is DeltaH"
Q=m_Ar*Cp_Ar*(T2-T1)+m_He*Cp_He*(T2-T1)

"Some Wrong Solutions with Common Mistakes:"
W1_Q =m_Ar*Cv_Ar*(T2-T1)+m_He*Cv_He*(T2-T1) "Using Cv instead of Cp"
W2_Q=N_Ar*Cp_Ar*(T2-T1)+N_He*Cp_He*(T2-T1) "Using N instead of mass"
W3_Q=m_Ar*Cp_Ar*(T22-T1)+m_He*Cp_He*(T22-T1); T22=2*(T1-273)+273 "Using C for T1"
W4_Q=(m_Ar+m_He)*0.5*(Cp_Ar+Cp_He)*(T2-T1) "Using arithmetic averate of Cp"
```

13-116 An ideal gas mixture of helium and argon gases with identical mass fractions enters a turbine at 1200 K and 1 MPa at a rate of 0.3 kg/s, and expands isentropically to 100 kPa. The power output of the turbine is

(a) 478 kW (b) 619 kW (c) 926 kW (d) 729 kW (e) 564 kW

Answer (b) 619 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
m=0.3 "kg/s"
T1=1200 "K"
P1=1000 "kPa"
P2=100 "kPa"
mf_He=0.5
mf_Ar=0.5
k_He=1.667
k_Ar=1.667
Cp_Ar=0.5203
Cp_He=5.1926
Cp_mix=mf_He*Cp_He+mf_Ar*Cp_Ar
"The specific heat ratio k of the mixture is also 1.667 since k=1.667 for all componet gases"
k_mix=1.667
T2=T1*(P2/P1)^((k_mix-1)/k_mix)
-W_out=m*Cp_mix*(T2-T1)

"Some Wrong Solutions with Common Mistakes:"
W1_Wout= - m*Cp_mix*(T22-T1); T22 = (T1-273)*(P2/P1)^((k_mix-1)/k_mix)+273 "Using C for T1 instead of K"
W2_Wout= - m*Cp_mix*(T222-T1); T222 = T1*(P2/P1)^((k_air-1)/k_air)-273; k_air=1.4 "Using k value for air"
W3_Wout= - m*Cp_mix*(T2222-T1); T2222 = T1*P2/P1 "Assuming T to be proportional to P"
W4_Wout= - m*0.5*(Cp_Ar+Cp_He)*(T2-T1) "Using arithmetic average for Cp"
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13-117 … 13-119 Design and Essay Problem

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