PROBLEM 11.82

**Known:** An expression is provided for the enthalpy departure for use when an equation of state explicit in pressure is in hand.

**Find:** (a) Derive the expression. (b) Using (a), obtain an expression for the enthalpy departure for a gas obeying the Redlich-Kwong equation. (c) Using (b), evaluate \( h_2 - h_1 \) for CO\(_2\) in a process at 300 K from 50 to 20 bar.

**Analysis:** (a) Beginning with \( h = h(T, V) \), write \( dh = \frac{\partial h}{\partial V} dV + \frac{\partial h}{\partial T} dT \). Then, at fixed \( T \)

\[
\frac{dV}{V} = \frac{1}{2} \frac{d^2 h}{dV^2} \frac{dV}{V} \Rightarrow h(T, V) - h(T, V') = \int \left( \frac{dh}{dV} \right)_T dV
\]

with \( h = u + pv \), \( (\partial h/\partial V)_T = (\partial u/\partial V)_T + (\partial (pv)/\partial V)_T \). Introducing Eq. 11.47 this becomes

\[
\frac{\partial h}{\partial V} = \left[ T \frac{\partial p}{\partial V} - p \right] + \frac{2}{3} (pv) Q_T
\]

In writing Eq. 2.63 with \( v = \epsilon (\rho v) \)

\[
h(T, V) - h(T, V') = \int \left[ T \frac{\partial p}{\partial V} - p \right] dV + [pv]_T (V, V') - [pv]_T (V, V')
\]

In the limit as \( p \to 0 \), \( V' \to \infty \) and \( [pv]_T (V, V') \to RT \), \( h(T, V) \to h^*(T) \), so

\[
h(T, V) - h^*(T) = \int \left[ T \frac{\partial p}{\partial V} - p \right] dV + pv - RT
\]

or

\[
h^*(T) - h(T, V) = RT \left[ 1 - \frac{pv}{RT} \right] - \frac{1}{2} \int_0^\infty \left[ T \frac{\partial p}{\partial V} - p \right] dV
\]

With \( T = T_k, T_c \), and expressing this on a molar basis,

\[
\frac{h^*(T) - h(T, V)}{RT} = T \left[ 1 - \epsilon - \frac{1}{2} \frac{1}{RT} \int_0^\infty \left[ T \frac{\partial p}{\partial V} - p \right] dV \right]
\]

(b) Using the Redlich-Kwong equation of state,

\[
t = \frac{RT}{V - \alpha} + \frac{1}{2} \frac{a}{V(\gamma + 1)V} = \frac{RT}{V - \epsilon} + \frac{1}{2} \frac{\epsilon}{V(\gamma + 1)V}
\]

\[
\frac{1}{T} - \frac{1}{h^*(T)} = \frac{RT}{V - \alpha} \left[ 1 - \frac{3a}{RT^2} \frac{dV}{V(\gamma + 1)V} \right]
\]

\[
\frac{1}{T} = \frac{1}{h^*(T)} - \frac{3a}{2bRT^2} \ln \left( \frac{1 + \frac{a}{V}}{1 + \frac{a}{\alpha}} \right)
\]

So

\[
\frac{h^*(T) - h(T, V)}{RT} = T \left[ 1 - \frac{3a}{2bRT} \ln \left( \frac{1 + \frac{a}{V}}{1 + \frac{a}{\alpha}} \right) \right]
\]

(c) At 300 K, \( P = 50 \) bar, \( P_2 = 20 \) bar. Obtaining \( a, b \) from Table A-2, the Redlich-Kwong equation can be solved to give \( V_1 = 0.3475 \text{ mol} / \text{K} \), \( V_2 = 1.119 \text{ mol} / \text{K} \).

The corresponding values of \( Z \) are \( Z_1 = 0.697 \), \( Z_2 = 0.897 \) with Eq. (b)

\[
\frac{h_2 - h_1}{RT} = \left( Z_2 - Z_1 + \frac{3a}{2bRT^2} \ln \left[ \frac{1 + \frac{a}{V}}{1 + \frac{a}{\alpha}} \right] \right)
\]

Inserting values:

\[
\frac{h_2 - h_1}{RT} = (0.897 - 0.697 + \frac{3(1.042 \text{ bar} \cdot \text{mol}^{-1} \cdot \text{K})^{0.5}}{2 \times 1.09 \text{ mol} / \text{K} \cdot \text{atm}^{-0.5}}) \ln \left[ \frac{1 + \frac{0.02963}{1.119}}{1 + \frac{0.02963}{0.3475}} \right]
\]

\[
= 1.948 \frac{\text{K}^2}{\text{mol}}
\]
PROBLEM 11.89

KNOWN: \( \text{O}_2 \) undergoes a throttling process from 100 bar, 300 K to 20 bar.

FIND: Determine the temperature after throttling, and compare with the value obtained using the ideal gas model.

SCHEMATIC & GIVEN DATA:

\[
\text{Valve} \quad \begin{array}{c}
1 \\
P_1 = 100 \text{ bar} \\
T_1 = 300 \text{ K} \\
T_2 = ?
\end{array}
\]

ENGINEERING MODEL:

The expansion across the valve adheres to the throttling process model of Section 4.10, for which \( h_2 = h_1 \).

ANALYSIS: Using Eq. 11.85 with \( h_2 = h_1 \), we get

\[
\frac{T_2}{T_1} - \frac{T_1}{T_2} = \frac{T_2}{T_1} - \frac{T_1}{T_2} = \frac{h^*_{T_2} - h^*_{T_1}}{R T_2} = \frac{h^*_{T_1} - h^*_{T_2}}{R T_1}
\]

(1)

with data from Table A-1: \( T_c = 154 \text{ K} \), \( P_c = 50.5 \text{ bar} \),

\( P_{1R} = \frac{100}{50.5} = 1.98 \) \( P_{2R} = \frac{20}{50.5} = 0.4 \), \( T_{1R} = \frac{300}{154} = 1.95 \)

Fig. A-4 gives \( \left[ \frac{h^*_{T_2} - h^*_{T_1}}{R T_2} \right] = 0.5 \). Table A-23 gives \( h^*_{T_1} = 8736 \text{ kJ/kg mole} \).

Thus, Eq. (1) becomes

\[
\frac{T_2}{T_1} - \frac{T_1}{T_2} = 8736 \text{ kJ/kg mole} - \frac{(8.314 \text{ kJ/mol} \cdot \text{K})(154 \text{ K})(0.5)}{640.2}
\]

\[
= 8096 \text{ kJ/kg mole}
\]

Equation (2) can then be used in a trial procedure with data from Table A-23: \( \frac{h^*_{T_2}}{R T_2} \), and from Fig. A-4: \( \left[ \frac{h^*_{T_1} - h^*_{T_2}}{R T_2} \right] = 0.1 \). Iterating, \( T_2 = 280 \text{ K} \).

1. At \( T_2 = 280 \text{ K} \), Table A-23 gives \( h^*_2 = 8150 \text{ kJ/kg mole} \). Using

\( T_{2R} = \frac{280}{154} = 1.82 \) \( P_{2R} = 0.4 \), Fig. A-4 gives \( \left[ \frac{h^*_{T_2} - h^*_{T_1}}{R T_2} \right] = 0.1 \).

With these values, the left side of Eq. 2 is

\[
\frac{T_2}{T_1} - \frac{T_1}{T_2} = 8150 - \frac{(8.314 \text{ kJ/mol} \cdot \text{K})(280 \text{ K})(0.1)}{640.2}
\]

which is within 1% of the value 8096 kJ/kg mole on the right side of Eq. (2). The approximate nature of obtaining data from the generalized chart does not justify additional iteration.
PROBLEM 13.16

**KNOWN:** Coal with the mass analysis below burns completely with the theoretical amount of air.

\[
\{71.1\%C, 5.1\%H_2, 9.0\%O_2, 1.4\%N_2, 5.8\%S, 7.6\%Ash\}
\]

**FIND:** Determine (a) the amount of \(SO_2\) produced, in kg per kg of coal, and (b) the air-fuel ratio on a mass basis.

**ENGINEERING MODEL:** (i) \(3.76\text{ kmol of } N_2\) accompany each \(\text{kmol of } O_2\) in the air, and the \(N_2\) is inert. (ii) The ash is non-combustible.

**ANALYSIS:** On the basis of 100 kg of coal, the amounts of the substances present are, respectively

\[
\begin{array}{cccc}
\text{Substance} & m_i (\text{kg}) & \dot{m}_i & \frac{m_i}{m_{100}} (\text{kmol}) \\
C: & 71.1 & 12 & 5.925 \\
H_2: & 5.1 & 2.016 & 2.530 \\
O_2: & 9.0 & 32 & 0.281 \\
N_2: & 1.4 & 28.01 & 0.050 \\
S: & 5.8 & 32.06 & 0.181 \\
Ash: & 7.6 & -- & -- \\
\end{array}
\]

For complete combustion with the theoretical amount of air

\[
(5.925C + 2.530H_2 + 0.281O_2 + 0.050SO_2 + 0.181S + \text{Ash}) + \gamma \left(2O_2 + 3.76N_2\right)
\]

\[
\rightarrow \beta \text{CO}_2 + \gamma \text{H}_2\text{O} + \delta \text{SO}_2 + \varepsilon \text{N}_2
\]

\[
\begin{align*}
C: & \quad 5.925 = \beta \\
H_2: & \quad \gamma = 2.530 \\
S: & \quad 0.181 = \delta \\
O: & \quad (0.281)z + \dot{m}_w(z) = (5.925)z + 2.530 + (0.181)2 \Rightarrow \dot{m}_w = 7.09 \\
N: & \quad (0.05)z + (7.09)(3.76)z = 0.2 \Rightarrow z = 26.71
\end{align*}
\]

(a) The amount of \(SO_2\) produced is \(0.181\text{ kmol per 100 kg of coal. Thus}

\[
\frac{m_{SO_2}}{m_{100}} = \frac{0.181(64.06)}{100} = 0.116 \frac{\text{kg of } SO_2}{\text{kg of coal}}
\]

(b) The amount of air required is \((7.09)(4.76)\text{ kmol per 100 kg of coal. Thus}

\[
AF = \frac{(7.09)(4.76)(28.97)}{100} = 9.777 \frac{\text{kg of air}}{\text{kg of coal}}
\]
PROBLEM 13.26

KNOWN: A liquid fuel mixture with a known mass analysis is burned completely with excess air at a specified temperature and relative humidity.

FIND: (a) Determine the equivalent hydrocarbon composition, C₆H₆, with the same carbon-hydrogen ratio on a mass basis as the mixture.
(b) If the products are cooled below their dew point, determine the amount of water vapor condensed.

SCHEMATIC & GIVEN DATA:

\[ \{ 40\% \text{ C}_8\text{H}_{18}, 60\% \text{ C}_{10}\text{H}_{22} \} \]

Hot products

10% excess air

Cooling at 25°C, 1 atm, \( \phi = 0.8 \)

Gaseous products remaining after condensation

Initial state of water vapor

Final state of water vapor

\( P_f (25°C) \)

ENGINEERING MODEL: (1) 3.76 kmol of \( \text{N}_2 \) accompany each kmol of \( \text{O}_2 \) in the air. (2) The \( \text{N}_2 \) and \( \text{H}_2\text{O} \) in the supply air are inert. (3) The air and products are both modeled as ideal gas mixtures.

ANALYSIS: (a) Assuming 100 kg of liquid fuel

\[
\begin{align*}
\text{C}_8\text{H}_{18} & \quad 40 & 114 & 0.3509 \\
\text{C}_{10}\text{H}_{22} & \quad 60 & 192 & 0.4225
\end{align*}
\]

Thus, in 100 kg of fuel, there are the following amounts of C and H, respectively

\[
\begin{align*}
\text{C} & \quad [0.3509 \text{ kmol (C)}] [8 \text{ kmol (C)}] + [0.4225] [10] = 7.0322 \text{ kmol (C)} \\
\text{H} & \quad [0.3509] [18] + [0.4225] [22] = 15.61 \text{ kmol (H)}
\end{align*}
\]

The "equivalent" hydrocarbon composition is

\[
\text{C}_7\text{H}_{15.61}
\] (a)

(b) Complete combustion with the theoretical amount of air is described by

\[
(0.3509 \text{ C}_8\text{H}_{18} + 0.4225 \text{ C}_{10}\text{H}_{22}) + \alpha_{\text{Ar}} (\text{O}_2 + 3.76 \text{ N}_2) \to 7.0322 \text{ C}_8\text{H}_{18} + 7.805 \text{ H}_2\text{O} + \alpha_{\text{Ar}} 3.76 \text{ N}_2
\]

\[
\alpha_{\text{Ar}} = \frac{7.0322 + \frac{7.805}{2}}{10.935} = 10.935
\]

Complete combustion with 10% excess air is then

\[
(0.3509 \text{ C}_8\text{H}_{18} + 0.4225 \text{ C}_{10}\text{H}_{22}) + 12.0285 (\text{O}_2 + 3.76 \text{ N}_2)
\to 7.0322 \text{ C}_8\text{H}_{18} + 7.805 \text{ H}_2\text{O} + 1.0935 \text{ O}_2 + 45.227 \text{ N}_2
\]

Consider next a moist air mixture at 25°C, 1 atm, \( \phi = 80\% \) in which there is

\[
12.0285 (4.76) = 57.256 \text{ kmol of dry air and } n_V \text{ kmol of water vapor. The partial pressure of water vapor is}
\]

\[
P_v = \left( \frac{n_V}{n_{\text{Ar}} + n_v} \right) P = \left( \frac{n_V}{57.256 + n_v} \right) (1.01325 \text{ bar})
\]

Also, \( P_v (25°C) = 0.8 (0.03149) = 0.02535 \text{ bar}. Collecting results

\[
0.02535 = \frac{n_V}{57.256 + n_v} (1.01325) \Rightarrow n_V = 1.4693 \text{ kmol}
\]

29
When water vapor is present in the combustion air, Eq. (1) reads

\[
(0.2509 \text{C}_8\text{H}_8 + 0.4225 \text{C}_6\text{H}_{12}) + 12.0285 (\text{O}_2 + 3.76 \text{N}_2) + 1.4693 \text{H}_2\text{O} \\
\rightarrow 7.0322 \text{CO}_2 + 9.2743 \text{H}_2\text{O} + 1.0935 \text{O}_2 + 45.227 \text{N}_2
\]

According to the model introduced in chap. 12, the gaseous products remaining after the products have been cooled to 25°C would contain saturated water vapor at 25°C. That is, the partial pressure of the water vapor in this mixture would be \( p_V(25°C) = 0.03169 \) bar. The partial pressure is expressed as

\[
P_V = \left( \frac{n'_V}{n_{\text{dry}} + n'_V} \right) P
\]

where \( n_{\text{dry}} = 7.0322 + 1.0935 + 45.227 = 53.353 \). Accordingly, from Eq. (2)

\[
0.03169 = \left( \frac{n'_V}{53.353 + n'_V} \right) (1.01325) \Rightarrow n'_V = 1.7225 \text{ kmol}
\]

Since there is 9.2743 kmol of H₂O per 100 kg of fuel in the products, the amount of water that condenses is 9.2743 - 1.7225 = 7.5518 kmol(H₂O) per 100 kg of fuel. Thus

\[
M_{\text{cond}} = \left[ \frac{7.5518 \text{ kmol (H}_2\text{O)}}{100 \text{ kg (fuel)}} \right] \left[ \frac{18.02 \text{ kg (H}_2\text{O})}{1 \text{ kmol (H}_2\text{O})} \right] = 1.361 \text{ kg (H}_2\text{O)} \text{ per kg (fuel)}
\]
PROBLEM 13.46

KNOWN: Propane enters a combustion chamber with known temperature and pressure and a given molar flow rate, where it burns completely with 200% theoretical air. The temperature of the exiting combustion products is specified.

FIND: Determine the heat transfer rate for each of two exit temperatures.

SCHEMATIC & GIVEN DATA:

\[
\dot{Q}_{cv} = 0.7 \text{ kmol/s}
\]

ENGINEERING MODEL:
1. 3.76 moles of N₂ accompany each mole of O₂ in the air. (3) The N₂ is inert. (4) The products are modeled as an ideal gas mixture. (6) The control volume is at steady state with no \( W. \)

ANALYSIS: Theoretical combustion: \[ C_3 H_8 + 5( O_2 + 3.76 N_2) \rightarrow 3 CO_2 + 4H_2O + 18.8 N_2 \]

Actual combustion: \[ C_3 H_8 + [10( O_2 + 3.76 N_2) - 3] CO_2 + 4H_2O + 5O_2 + 37.6 N_2 \]

\[ T_p = 560K \]

The energy rate balance can be written as:

\[
\dot{Q}_{cv} = \dot{\dot{\dot{Q}}}_{fuel} \left( \left( h_f^{\text{fuel}} + \Delta H_f^{\text{fuel}} \right)_{\text{fuel}} + 10 \left( h_f^{\text{air}} + \Delta H_f^{\text{air}} \right)_{\text{air}} + 37.6 \left( h_f^{\text{air}} + \Delta H_f^{\text{air}} \right)_{\text{N}_2} \right)
- 3 \left( h_f^{\text{air}} + \Delta H_f^{\text{air}} \right)_{\text{CO}_2, \text{out}} - 4 \left( h_f^{\text{air}} + \Delta H_f^{\text{air}} \right)_{\text{H}_2O, \text{out}} - 5 \left( h_f^{\text{air}} + \Delta H_f^{\text{air}} \right)_{O_2, \text{out}} - 37.6 \left( h_f^{\text{air}} + \Delta H_f^{\text{air}} \right)_{N_2, \text{out}}
\]

\[
\frac{\dot{Q}_{cv}}{\dot{\dot{\dot{Q}}}_{fuel}} = 3 \left( \frac{h_f^{\text{CO}_2} + h_f^{\text{CO}_2}}{\text{CO}_2, \text{in}} - \frac{h_f^{\text{CO}_2}}{\text{CO}_2, \text{out}} \right) + 4 \left( \frac{h_f^{\text{H}_2O}}{\text{H}_2O, \text{in}} - \frac{h_f^{\text{H}_2O}}{\text{H}_2O, \text{out}} \right) + 5 \left( \frac{h_f^{\text{N}_2}}{\text{N}_2, \text{in}} - \frac{h_f^{\text{N}_2}}{\text{N}_2, \text{out}} \right) - \left( \frac{h_f^{\text{C}_3\text{H}_8}}{\text{C}_3\text{H}_8} \right)
\]

With data from Table A-23:

\[
\frac{\dot{Q}_{cv}}{\dot{\dot{\dot{Q}}}_{fuel}} = 3 \left[ -393.520 + (20,407 - 9,364) \right] + 4 \left[ (-241,820 + (18,959 - 9,904)) \right]
+ 5 \left[ 141,54 - 8682 \right] + 37.6 \left[ 141,54 - 8682 \right] = -103,850
\]

\[
= -1,645,299 \text{ J/Kmol}
\]

\[
\frac{\dot{Q}_{cv}}{\dot{\dot{\dot{Q}}}_{fuel}} = (0.7 \text{ kmol}) (-1.645 \times 10^9 \text{ J/Kmol}) \left| \frac{1 \text{ kW}}{1 \text{ kw/}\text{J}} \right| = 1.152 \times 10^6 \text{ kW}
\]

\[ T_p = 298K \]

In this case, condensation might occur in the product gas mixture. To check this, determine the dew point temperature of the products, as follows: \( N_v = 4, \) \( N_{tot} = 49.6 \rightarrow Y_v = 4/49.6 = 0.08065 \)

\[ P_v = (0.08065)(1.01325 \text{ bar}) = 0.08172 \text{ bar} \]

From Table A-2, \( T_{dew} \approx 242°C \)

Since 298 K = 25°C is less than the dew point, there is condensation. The following model will be used:

\[
\text{fuel} \rightarrow \text{product gases saturated \( (P_v = P_g \approx 0.25°C, 0.081 \text{ bar}) \)}
\]

\[ 3 CO_2 + N_v N_2 + 5O_2 + 37.6 N_2 \]

\[ N_g = 4 - N_v, N_{tot} = 45.6 + N_v \]

\[ \text{Saturated liquid at 25°C} \]
To find $y_v$ and $y_f$

$$
y_v = \frac{P_v}{P} = \frac{0.03169}{1.01325} = 0.03128
$$

and

$$
y_v = \frac{n_v}{95.6 + n_v} \Rightarrow n_v = 1.4724
$$

Finally, collecting results

$$
C_3H_8 + 10O_2 + 3.76N_2 \rightarrow (3O_2 + 1.4724H_2O(g) + 5O_2 + 37.6N_2) + 2.5276H_2O(g)
$$

The energy balance becomes

$$
\frac{\dot{Q}_{cv}}{N_{fuel}} = 3 \left[ h_{f,C_3H_8}^o \right] + 1.4724 \left[ h_{f,H_2O(g)}^o \right] + 2.5276 \left[ h_{f,H_2O(l)}^o \right] - \left[ h_{f,C_3H_8}^o \right] \tag{Table A-25}
$$

$$
= 3(-393.520) + 1.4724(-241.820) + 2.5276(-285.830) - (-103.850)
$$

$$
= -2.155 \times 10^6 \text{ kJ/kmol fuel}
$$

$$
\dot{Q}_{cv} = (0.7)(-2.155 \times 10^6) = -1.5085 \times 10^6 \text{ kW} \tag{T_p = 298K}
$$

Note: Cooling the gases to 298K and condensing some of the water vapor increases the heat transfer rate substantially.
13.49 Liquid ethanol (C₂H₅OH), at 77°F, 1 atm enters a combustion chamber operating at steady state and burns completely with dry air entering at 340°F, 1 atm. The fuel flow rate is 50 lb/s and the equivalence ratio is 0.8. Products of combustion exit at 2000°F, 1 atm. Ignoring kinetic and potential energy effects, determine
(a) the air-fuel ratio on a mass basis.
(b) the rate of heat transfer, in Btu/s.

**KNOWN:** Streams of liquid ethanol and air with specified equivalence ratio, temperature, and pressure enter and react in a combustion chamber at steady state. The mass flow rate of fuel is given. The products exit the chamber at 2000°F, 1 atm.

**FIND:** (a) the air-fuel ratio on a mass basis and (b) the rate of heat transfer

**SCHEMATIC AND GIVEN DATA:**

\[
\begin{align*}
C_2H_5OH(g) & \quad 77°F = 537°F, \, 1 \text{ atm} \\
\dot{m}_{\text{fuel}} &= 50 \text{ lb/s} \\
\text{Air} & \quad 340°F = 800°F, \, 1 \text{ atm} \\
& \quad \text{Combustion products} \\
& \quad (CO_2, H_2O(g), O_2, N_2) \\
& \quad 2000°F = 2460°F
\end{align*}
\]

**ENGINEERING MODEL:**
1. The control volume identified by a dashed line on the accompanying figure operates at steady state with \(\dot{W}_{cv} = 0\).
2. Kinetic and potential energy effects can be ignored.
3. Each mole of oxygen in the combustion air is accompanied by 3.76 moles of nitrogen, which is inert.
4. The combustion air and the products of combustion each form ideal gas mixtures.

**ANALYSIS:** (a) The balanced chemical equation for complete combustion of liquid ethanol with theoretical air is

\[
C_2H_5OH(l) + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 11.28N_2
\]

The molar air-fuel ratio with theoretical air is

\[
\bar{AF}_{\text{theoretical}} = \frac{3(4.76 \text{ lbmol air})}{1 \text{ lbmol} C_2H_5OH} = 14.28 \text{ lbmol(air)/lbmol(C}_2\text{H}_5\text{OH)}}
\]

Equivalence ratio can be expressed in terms of molar air-fuel ratio by

1
Problem 13.49 (Continued) – Page 2

\[
\text{Equivalence Ratio} = \frac{\overline{F_A}}{\overline{F_{A_{\text{theoretical}}}}} = \frac{1}{\overline{A_F}} = \frac{\overline{A_F}_{\text{theoretical}}}{\overline{A_F}}
\]

The actual molar air-fuel ratio is

\[
\overline{A_F} = \frac{\overline{A_F}_{\text{theoretical}}}{\text{Equivalence Ratio}} = \frac{14.28 \frac{\text{lb mol air}}{\text{lb mol C}_2\text{H}_5\text{OH}}}{0.8} = 17.85 \frac{\text{lb mol (air)}}{\text{lb mol (C}_2\text{H}_5\text{OH)}}
\]

Thus, the air fuel ratio on a mass basis is

\[
\overline{A_F} = \overline{A_F}_{\text{theoretical}} \left( \frac{M_{\text{air}}}{M_{\text{fuel}}} \right) = \left( 17.85 \frac{\text{lb mol air}}{\text{lb mol C}_2\text{H}_5\text{OH}} \right) \left( \frac{28.97 \frac{\text{lb air}}{\text{lb mol air}}}{46.07 \frac{\text{lb C}_2\text{H}_5\text{OH}}{\text{lb mol C}_2\text{H}_5\text{OH}}} \right)
\]

\[
\overline{A_F} = 11.22 \frac{\text{lb air}}{\text{lb C}_2\text{H}_5\text{OH}}
\]

(b) Using the molar air-fuel ratio from Part (a), the balanced chemical equation is

\[
\text{C}_2\text{H}_5\text{OH(l)} + \left( 17.85/4.76 \right)(\text{O}_2 + 3.76\text{N}_2) \rightarrow a\text{CO}_2 + b\text{H}_2\text{O} + c\text{O}_2 + d\text{N}_2
\]

or

\[
\text{C}_2\text{H}_5\text{OH(l)} + 3.75(\text{O}_2 + 3.76\text{N}_2) \rightarrow a\text{CO}_2 + b\text{H}_2\text{O} + c\text{O}_2 + d\text{N}_2
\]

Applying conservation of mass to carbon, hydrogen, oxygen, and nitrogen, respectively

C: 2 = a

H: 6 = 2b \rightarrow b = 3

O: 1 + 2(3.75) = 2a + b + 2c = 2(2) + 3 + 2c \rightarrow c = 0.75

N: 2(3.76)(3.75) = 2d \rightarrow d = 14.1

The balanced chemical equation for actual combustion is

\[
\text{C}_2\text{H}_5\text{OH(l)} + 3.75(\text{O}_2 + 3.76\text{N}_2) \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O} + 0.75\text{O}_2 + 14.1\text{N}_2
\]

The energy rate balance at steady state reduces to

\[
\frac{\dot{Q}}{n_F} = \overline{h_p} - \overline{h_R}
\]

where
Problem 13.49 (Continued) – Page 3

\[ \bar{h}_r = \left( \bar{h}_r^0 + \Delta \bar{h} \right)_{C_2H_5OH} + 3.75 \left( \bar{h}_r^0 + \Delta \bar{h} \right)_{H_2O} + 14.1 \left( \bar{h}_r^0 + \Delta \bar{h} \right)_{N_2} \]

and

\[ \bar{h}_p = 2 \left( \bar{h}_p^0 + \Delta \bar{h} \right)_{CO_2} + 3 \left( \bar{h}_p^0 + \Delta \bar{h} \right)_{H_2O} + 0.75 \left( \bar{h}_p^0 + \Delta \bar{h} \right)_{O_2} + 14.1 \left( \bar{h}_p^0 + \Delta \bar{h} \right)_{N_2} \]

With the enthalpy of formation for C\textsubscript{2}H\textsubscript{5}OH(l) from Table A-25E and enthalpy values for O\textsubscript{2} and N\textsubscript{2} from Table A-23E

\[
\bar{h}_r = \left[ \left( \bar{h}_r^0 \right)_{C_2H_5OH} + 3.75 \left( \Delta \bar{h} \right)_{H_2O} + 14.1 \left( \Delta \bar{h} \right)_{N_2} \right]
\]

\[ = [-119,470] + 3.75[5,602.0 - 3,725.1] + 14.1[5,564.4 - 3729.5] \]

\[ = -86,560 \text{ Btu/lbmol}(C_2H_5OH) \]

With enthalpy of formation values for CO\textsubscript{2} and H\textsubscript{2}O(g) from Table A-25E, and enthalpy values for CO\textsubscript{2}, H\textsubscript{2}O, O\textsubscript{2}, and N\textsubscript{2} from Table A-23E

\[
\bar{h}_p = \left[ 2 \left( \bar{h}_p^0 + \Delta \bar{h} \right)_{CO_2} + 3 \left( \bar{h}_p^0 + \Delta \bar{h} \right)_{H_2O} + 0.75 \left( \Delta \bar{h} \right)_{O_2} + 14.1 \left( \Delta \bar{h} \right)_{N_2} \right]
\]

\[ = 2[-169,300 + 27,249 - 4027.5] + 3[-104,040 + 22,298 - 4,258.0] + 0.75[19,097 - 3,725.1] + 14.1[18,260 - 3,729.5] \]

\[ = -333,748 \text{ Btu/lbmol}(C_2H_5OH) \]

Thus, the heat transfer rate per lbmol of fuel entering is

\[
\frac{\dot{Q}_{cv}}{\bar{n}_F} = -333,748 - (-86,560) = -247,188 \text{ Btu/lbmol}(C_2H_5OH)
\]

The fuel molar flow rate is

\[
\bar{n}_F = \frac{\dot{m}_F}{M_F} = \frac{50 \text{ lb C}_2\text{H}_5\text{OH}}{46.07 \text{ lb mol C}_2\text{H}_5\text{OH}} = 1.09 \text{ lb mol C}_2\text{H}_5\text{OH/s}}
\]

Finally, the rate of heat transfer is

\[
\dot{Q}_{cv} = \left( \frac{\dot{Q}_{cv}}{\bar{n}_F} \right) \bar{n}_F = \left( -247,188 \frac{\text{Btu}}{\text{lb mol C}_2\text{H}_5\text{OH}} \right) \left( 1.09 \frac{\text{lb mol C}_2\text{H}_5\text{OH}}{\text{s}} \right) = -269,435 \text{ Btu/s}
\]

The negative sign indicates heat transfer is from the control volume to the surroundings, as expected.