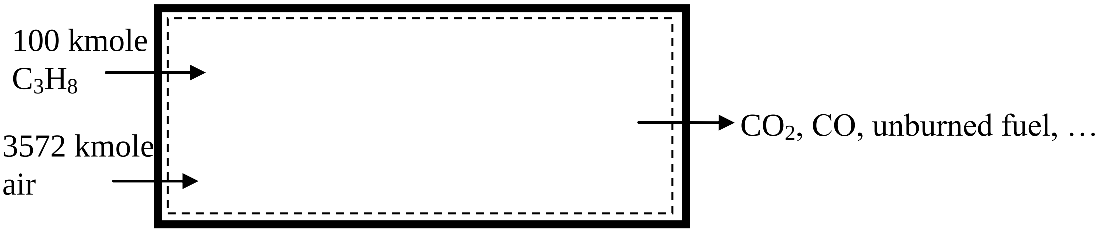
CANKAYA UNIVERSITY
FACULTY OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT
ME 212 THERMODYNAMICS II

CHAPTER 13

EXAMPLES SOLUTIONS

1) One hundred kmol of propane (C_3H_8) together with 3572 kmol of air enter a furnace per unit of time. Carbon dioxide, carbon monoxide, and unburned fuel appear in the products of combustion exiting the furnace. Determine the percent excess or deficiency of air, whichever is appropriate.



<u>Assumptions:</u>

1) 3.76 kmol of N_2 accompanying each kmol of O_2 in air.
2) N_2 is inert gas.

The data are provided for actual operation. Thus:

$$\overline{AF} = \frac{3572}{100} = 35.72 \frac{\text{kmol air}}{\text{kmol fuel}}$$

The balance equation for complete combustion with the theoretical amount of air is:

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$$

The theoretical air/fuel ratio is:

$$\left(\overline{AF}\right)_{theo} = \frac{5(4.76)}{1} = 23.8 \frac{\text{kmol air}}{\text{kmol fuel}}$$

Accordingly,

$$\%\,\text{excess} = \left(\frac{35.72 - 23.8}{23.8}\right)(100) = 50\%$$

2) Propane (C_3H_8) is burned with air. For each case, obtain the balanced reaction equation for complete combustion.

a) with the theoretical amount of air.

b) with 20% excess air.

c) with 20% excess air, but only 90% of the propane being consumed in the reaction.

Assumptions:

1) 3.76 kmol of N_2 accompanying each kmol of O_2 in air.
2) N_2 is inert gas.

a) Complete combustion with the theoretical amount of air.

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$$

b) Complete combustion with 20% excess air:

$$C_3H_8 + 5(1.2)(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + \alpha O_2 + (5)(1.2)(3.76N_2)$$

$$O: (6)(2) = 6 + 4 + 2\alpha \Rightarrow \alpha = 1$$

$$\therefore\ C_3H_8 + 6(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 1O_2 + 22.56N_2$$

c) Combustion with 20% excess air. 90% of the fuel is burned.

$$C_3H_8 + 6(O_2 + 3.76N_2) \rightarrow 0.1\ C_3H_8 + \alpha CO_2 + \beta H_2O + \gamma O_2 + 22.56N_2$$

$$C : 3 = 0.3 + \alpha \ \Rightarrow \alpha = 2.7$$
$$H : 8 = 0.8 + 2\beta \ \Rightarrow \beta = 3.6$$
$$O : 12 = 2(2.7) + 3.6 + 2\gamma \ \Rightarrow \gamma = 1.5$$

$$\therefore\ C_3H_8 + 6(O_2 + 3.76N_2) \rightarrow 0.1\ C_3H_8 + 2.7CO_2 + 3.6H_2O + 1.5O_2 + 22.56N_2$$

3) A fuel mixture with the molar analysis 70% CH_4, 20% CO, 5% O_2, and 5% N_2 burns completely with 20% excess air. Determine:
a) the balanced reaction equation.
b) the air-fuel ratio, both on a molar and mass basis.

<u>Assumptions:</u>

1) 3.76 kmol of N_2 accompanying each kmol of O_2 in air.
2) N_2 is inert gas.

On the basis of 1 mol of fuel mixture, the reaction equation for complete combustion with the theoretical amount of air is:

$$(0.7CH_4+0.20CO+0.05O_2+0.05N_2) + \alpha(O_2+3.76N_2) \rightarrow \beta CO_2 + \gamma H_2O + (3.76\alpha + 0.05) N_2$$

$C : 0.7 + 0.2 = \beta \Rightarrow \beta = 0.9$
$H : 2.8 = 2\gamma \Rightarrow \gamma = 1.4$
$O : 0.2 + 0.1 + 2\alpha = 2(0.9) + 1.4 \Rightarrow \alpha = 1.45$

Thus,

$$(0.7CH_4+0.20CO+0.05O_2+0.05N_2) + 1.45(O_2+3.76N_2) \rightarrow 0.9CO_2 + 1.4H_2O + 5.952N_2$$

Thus the reaction for complete combustion with 20% excess air is:

$$(0.7CH_4+0.20CO+0.05O_2+0.05N_2) + (1.2)(1.45)(O_2+3.76N_2) \rightarrow 0.9CO_2 + 1.4H_2O + \alpha O_2 + [(1.7)(3.76)+0.05]N_2$$

$O : 0.2 + 0.1 + 2(1.74) = 1.8 + 1.4 + 2\alpha \Rightarrow \alpha = 0.29$

Accordingly;

$$(0.7CH_4+0.20CO+0.05O_2+0.05N_2) + 1.74(O_2+3.76N_2) \rightarrow 0.9CO_2 + 1.4H_2O + 0.29O_2 + 6.59N_2$$

b) The air fuel ratio is:

$$\overline{AF} = \frac{(1.74)(4.76)}{1} = 8.25\frac{\text{kmol air}}{\text{kmol fuel}}$$

The fuel molecular mass is:

$M_f = (0.7)(16.04) + (0.2)(28.01) + (0.05)(32) + 0.05(28.01) = 19.831$

so;

$$AF = \left(\overline{AF}\right)\left(\frac{M_{air}}{M_{fuel}}\right) = (8.25)\left(\frac{28.97}{19.831}\right) = 12.05\frac{\text{kg air}}{\text{kg fuel}}$$

4) A fuel mixture with the molar analysis 94.4% CH_4, 3.4% C_2H_6, 0.6% C_3H_8, 0.5% C_4H_{10}, 1.1% N_2 burns completely with 20% excess air in a reactor operating at steady state. If the molar flow rate of the fuel is 0.1 kmol/h, determine the molar flow rate of the air, in kmol/h.

<u>Assumptions:</u>

1) 3.76 kmol of N_2 accompanying each kmol of O_2 in air.
2) N_2 is inert gas.

On the basis of 1 mol of fuel mixture, complete combustion with the theoretical amount of air is:

$$(0.944CH_4+0.034C_2H_6+0.006C_3H_8+0.005C_4H_{10}+0.011N_2) + \alpha(O_2+3.76N_2) \rightarrow \beta\, CO_2 + \gamma\, H_2O + (3.76\alpha + 0.011)\, N_2$$

$$C : 0.944 + 2(0.034) + 3(0.0006) + 4(0.005) = \beta \Rightarrow \beta = 1.05$$
$$H : 4(0.944) + 6(0.034) + 8(0.0006) + 10(0.005) = 2\gamma \Rightarrow \gamma = 2.039$$
$$O : 2\alpha = 2(1.05) + 2.039 \Rightarrow \alpha = 2.0695$$

Combustion with 20% excess air means that the molar flow rate is:

$$\overline{AF} = \frac{1.2(2.0695)(4.76)}{1} = 11.82 \frac{\text{kmol air}}{\text{kmol fuel}}$$

Thus, with $\dot{n}_{fuel} = 0.1\,\text{kmol/h}$

$$\dot{n}_{air} = 1.182\,\text{kmol air/h}$$

5) Dodecane ($C_{12}H_{26}$) burns completely with 150% of theoretical air. Determine:
a) the air-fuel ratio on a molar and mass basis.
b) the dew point temperature of the combustion products, in ^oC, when cooled at 1 atm.

<u>Assumptions:</u>

1) 3.76 kmol of N_2 accompanying each kmol of O_2 in air.
2) N_2 is inert gas.

a) For complete combustion with the theoretical amount of air:

$$C_{12}H_{26} + \alpha(O_2+3.76N_2) \rightarrow \beta CO_2 + \gamma H_2O + 3.76\alpha N_2$$

C : 12 = β
O : $2\alpha = 2(12) + 13 \Rightarrow \alpha = 18.5$
H : $26 = 2\gamma \Rightarrow \gamma = 13$

Then, complete combustion with 150% of the theoretical amount of air:

$$C_{12}H_{26} + (1.5)(18.5)(O_2 + 3.76N_2) \rightarrow 12CO_2 + 13H_2O + \gamma O_2 + (1.5)(18.5)3.76N_2$$

O : $2(1.5)(18.5) = 24 + 13 + 2\gamma \Rightarrow \gamma = 9.25$

Accordingly:

$$\overline{AF} = \frac{(1.5)(18.5)(4.76)}{1} = 132.09\frac{\text{kmol air}}{\text{kmol fuel}}$$

$$AF = \left(\overline{AF}\right)\left(\frac{M_{air}}{M_{fuel}}\right) = (132.09)\left(\frac{28.97}{(12)(12.01)+(26)(1.009)}\right) = 22.46\frac{\text{kg air}}{\text{kg fuel}}$$

b) The partial pressure of the water in the combustion products is

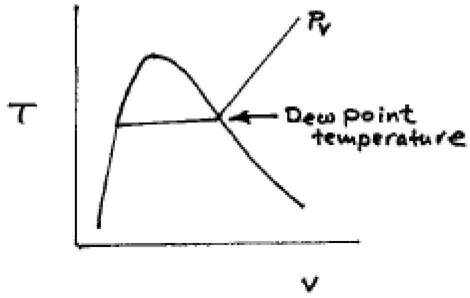
$p_v = Y_v p_1$ where;

$$Y_v = \frac{13}{(12+13+9.25+104.34)} = 0.0938$$

so

$$p_v = (0.0938)(1.01325\,\text{bar}) = 0.09504\,\text{bar}$$

Then, from tables: $T_{dew} = 44.8^oC$



P_v
T
Dew point temperature
v

6) Carbon burns with 80% theoretical air yielding CO_2, CO, and N_2 only. Determine:
a) the balanced reaction equation.
b) the air-fuel ratio on a mass basis.
c) the analysis of the products on a molar basis.

Assumptions:

1) 3.76 moles of N_2 accompanying each mole of O_2 in air.
2) N_2 is inert gas.

a) Complete combustion of C with the theoretical amount of air is described by:

$$C + (O_2 + 3.76N_2) \Rightarrow CO_2 + 3.76N_2$$

Thus, combustion with 80% theoretical air produces CO_2, CO, and N_2 is:

$$C + (0.80)(O_2 + 3.76N_2) \Rightarrow aCO_2 + bCO + (0.80)(3.76)N_2$$

C : 1 = a + b $\Rightarrow$ b = 1-a
O : (0.80)(2) = 2a + b $\Rightarrow$ 1.6 = 2a + (1-a) $\Rightarrow$ a = 0.6 $\Rightarrow$ b = 0.4

Accordingly, the balanced reaction equation is:

$$C + (0.80)(O_2 + 3.76N_2) \Rightarrow 0.6CO_2 + 0.4CO + 3.008N_2$$

b) The air fuel ratio is:

$$\overline{AF} = \frac{(0.80)(4.76)}{1} = 3.808 \frac{\text{kmol air}}{\text{kmol fuel}}$$

$$AF = \left(\overline{AF}\right)\left(\frac{M_{air}}{M_{fuel}}\right) = (3.808)\left(\frac{28.97}{12.01}\right) = 9.19 \frac{\text{kg air}}{\text{kg fuel}}$$

c) The molar analysis of the products is:

$$\%CO_2 = \left(\frac{0.6}{4.008}\right)(100) = 15\%$$

$$\%CO = \left(\frac{0.4}{4.008}\right)(100) = 10\%$$

$$\%N_2 = \left(\frac{3.008}{4.008}\right)(100) = 75\%$$

7) Liquid methanol (CH_3OH) burns with air. The product gas is analyzed and the laboratory report gives only the following percentages on a dry molar basis: 7.1% CO_2, 2.4% CO, and 0.84% CH_3OH. Assuming the balance consists of O_2 and N_2, determine:

a) the percentage of O_2 and N_2 in the dry molar analysis.

b) the percent excess air.

Assumptions:

1) 3.76 moles of N_2 accompanying each mole of O_2 in the combustion air.
2) N_2 is inert gas.
3) The dry products include only CO_2, CO, CH_3OH, O_2 and N_2.

a) On the basis of 100 moles of dry products:

$$yCH_3OH + \alpha(O_2+3.76N_2) \rightarrow 7.1CO_2 + 2.4CO + 0.84CH_3OH + xN_2 + (89.66-x)O_2 + wH_2O$$

Note : For the dry products, $7.1 + 2.4 + 0.84 + x + z = 100 \Rightarrow x + z = 89.66$, or $z = 89.66 - x$

C : $y = 7.1 + 2.4 + 0.84 \Rightarrow y = 10.34$

H : $4(10.34) = (0.84)(4) + 2w \Rightarrow w = 19$

O : $(10.34) + 2\alpha = (7.1)(2) + 2.4 + 0.84 + 2(89.66 - x) + 19 \Rightarrow \alpha = 102.71 - x$

$$N: \left.\begin{matrix}(\alpha)(2)(3.76) = 2x \\ \Rightarrow 3.76\alpha = x\end{matrix}\right\} \alpha = 102.71 - 3.76\alpha \Rightarrow \alpha = 21.578 \Rightarrow x = 81.13 \text{ and } 89.66 - x = 8.53$$

Accordingly;

$\%N_2 = 81.13$ and $\%O_2 = 8.53$

b) For complete combustion with the theoretical amount of air

$$CH_3OH + \alpha(O_2+3.76N_2) \rightarrow \beta CO_2 + \gamma H_2O + 3.76\alpha N_2$$

C : $1 = \beta$

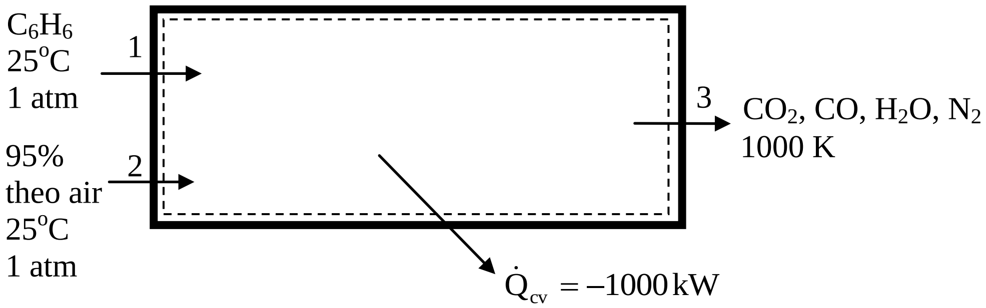
H : $4 = 2\gamma \Rightarrow \gamma = 2$

O : $1 + 2\alpha = 2(1) + 2 \Rightarrow \alpha = 3/2$

$$\begin{pmatrix}\%\,\text{theoretical} \\ \text{air}\end{pmatrix} = \left(\frac{(21.578)(4.76)/10.34}{(1.5)(4.76)/1}\right)(100) = 139$$

$$\Rightarrow \%\ \text{excess air} = 39$$

8) Benzene gas (C_6H_6) at 25°C, 1 atm enters a combustion chamber operating at steady state and burns with 95% theoretical air entering at 25°C, 1 atm. The combustion products exit at 1000 K and include only CO_2, CO, H_2O, and N_2. Determine the mass flow rate of the fuel, in kg/s, to provide heat transfer at a rate of 1000 kW.



Assumptions:

1) The control volume shown is at steady state with $\dot{W}_{cv} = 0$ and negligible kinetic/potential energy effects.
2) 3.76 moles of N_2 accompany each mole of O_2 in the combustion air and N_2 is inert.
3) The ideal gas model is applicable to the combustion air and the products of combustion.

The balanced reaction equation for combustion with the theoretical amount of air is:

$C_6H_6 + (7.5)(O_2 + 3.76N_2) \rightarrow 6CO_2 + 3H_2O + 28.2N_2$

The balanced reaction equation for combustion with 95% theoretical air is:

$C_6H_6 + (7.125)(O_2 + 3.76N_2) \rightarrow 5.25CO_2 + 0.75CO + 3H_2O + 26.79N_2$

An energy rate balance reduces to:

$$0 = \frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} - \underbrace{\frac{\dot{W}_{cv}}{\dot{n}_{fuel}}}_{=0} + \left(\bar{h}_{fuel}\right)_1 + \left[7.125\bar{h}_{O_2} + 26.79\bar{h}_{N_2}\right]_2 - \left[5.25\bar{h}_{CO_2} + 0.75\bar{h}_{CO} + 3\bar{h}_{H_2O} + 26.79\bar{h}_{N_2}\right]_3$$

with $\bar{h} = \bar{h}_f^o + \Delta\bar{h}$

$$\frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} = 5.25\left[\bar{h}_f^o + \Delta\bar{h}\right]_{CO_2} + 0.75\left[\bar{h}_f^o + \Delta\bar{h}\right]_{CO} + 3\left[\bar{h}_f^o + \Delta\bar{h}\right]_{H_2O} + 26.79\left[\bar{h}_f^o + \Delta\bar{h}\right]_{N_2} - \left(\bar{h}_f^o\right)_{fuel}$$

with data from the ideal gas tables:

$$\frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} = 5.25[-393520 + 42769 - 9364] + 0.75[-110530 + 30355 - 8669]$$
$$+ 3[-241820 + 35882 - 9904] + 26.79[30129 - 8669] - 82930$$

$$\Rightarrow \frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} = -2112780 \, \text{kJ / kmol fuel}$$

Then, for $\dot{Q}_{cv} = -1000 \, \text{kW} = -1000 \, \text{kJ / s}$

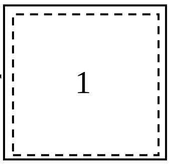
$$\Rightarrow \dot{n}_{fuel} = \frac{-10^3 \, \text{kJ / s}}{-2112780 \, \text{kJ / kmol fuel}} = 4.73 \times 10^{-4} \, \frac{\text{kmol fuel}}{\text{s}}$$

with $M = 78.11 \frac{\text{kg fuel}}{\text{kmol fuel}}$ from tables;

$$\dot{n}_{fuel} = \left(4.73 \times 10^{-4} \, \frac{\text{kmol fuel}}{\text{s}}\right)\left(78.11 \frac{\text{kg fuel}}{\text{kmol fuel}}\right) = 0.037 \, \frac{\text{kg fuel}}{\text{s}}$$

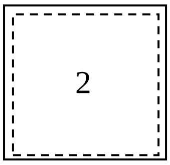
9) A closed, rigid vessel initially contains a gaseous mixture of 1 kmol of Octane (C_8H_{18}) and 300% of theoretical air at 25°C, 1 atm. If the mixture burns completely, determine the heat transfer from the vessel, in kJ, and the final pressure, in atm, for a final temperature of 1000 K.

1 kmol C_8H_{18}
300% theo air
25°C, 1 atm



initial

Products
T_2 = 100 K
p_2 = ?



final

<u>Assumptions:</u>

1) $W = 0$
2) 3.76 moles of N_2 accompany each mole of O_2 in the air and N_2 is inert.
3) The ideal gas model is applicable to initial and final mixtures.

Combustion equation for 300% theoretical air is:

$$C_8H_{18} + 3(12.5)(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 25O_2 + 141N_2$$

The energy balance reduces to $Q - W = U_P - U_R = (U_{final} - U_{initial})$

$$\therefore Q = (8\bar{u}_{CO_2} + 9\bar{u}_{H_2O} + 25\bar{u}_{O_2} + 141\bar{u}_{N_2})_f - (1\bar{u}_{C_8H_{18}} + 37.5\bar{u}_{O_2} + 141\bar{u}_{N_2})_i$$

For the ideal gas, $\bar{u} = \bar{h} - \bar{R}T$

Substituting for $\bar{u}$ and collecting $R\bar{T}$ terms,

$$\therefore Q = (8\bar{h}_{CO_2} + 9\bar{h}_{H_2O} + 25\bar{h}_{O_2} + 141\bar{h}_{N_2})_2 - (\bar{h}_{C_8H_{18}} + 37.5\bar{h}_{O_2} + 141\bar{h}_{N_2})_1 - \bar{R}(183T_2 - 179.5T_1)$$

Define $\bar{h} = \bar{h}_f^o + \Delta\bar{h}$ and $\bar{h}_f^o = 0$ for O_2 and N_2. Using data from tables:

$$\therefore Q = 8[-395520 + 42769 - 9364]_{CO_2} + 9[-241820 + 35882 - 9904]_{H_2O} + 25[31389 - 3682]_{O_2} + 141[30129 - 8669]_{N_2} - (-208450)_{C_8H_{18(g)}} - 8.314[(183)(1000) - (179.5)(298)]$$

$$\Rightarrow Q = -2098251 \text{kJ}$$

Using the ideal gas equation for a constant volume process,

$$p_1V = n_1\bar{R}T_1 \quad \text{and} \quad p_2V = n_2\bar{R}T_2$$

$$\frac{p_2}{p_1} = \left(\frac{n_2}{n_1}\right)\left(\frac{T_2}{T_1}\right) = \left(\frac{183}{179.5}\right)\left(\frac{1000}{298}\right) = 3.421$$

$$p_2 = (3.421)p_1 = 3.421(1) = 3.421 \text{atm}$$

10) Determine the enthalpy of combustion for gaseous butane (C_4H_{10}), in kJ per kmol of fuel and kJ per kg of fuel, at 25°C, 1 atm, determine:

a) water vapor in the products.

b) liquid vapor in the products.

Assumptions:

1) Combustion is with the theoretical amount of air.
2) 3.76 moles of N_2 accompany each mole of O_2 in the air and N_2 is inert.
3) The combustion air and the combustion products can be modeled as ideal gases.

Complete combustion of C_4H_{10} with the theoretical amount of air is described by:

$$C_4H_{10} + (6.5)(O_2 + 3.76N_2) \rightarrow 4CO_2 + 5H_2O + 24.4N_2$$

The enthalpy of combustion is:

$$\bar{h}_{RP} = 4(\bar{h}_f^o)_{CO_2} + 5(\bar{h}_f^o)_{H_2O} - (\bar{h}_f^o)_{C_4H_{10}}$$

a) H_2O is a vapor:

$$\bar{h}_{RP} = 4(-393520) + 5(-241820) - (-126150) = -2.657 \times 10^6 \text{ kJ/kmol}(C_4H_{10})$$

For C_4H_{10}, M = 58.12 $\frac{\text{kg fuel}}{\text{kmol fuel}}$, so;

and

$$\bar{h}_{RP} = \frac{-2.657 \times 10^6}{58.12} = -45716 \text{ kJ/kg}$$

a) H_2O is a liquid:

$$\bar{h}_{RP} = 4(-393520) + 5(-285830) - (-126150) = -2.877 \times 10^6 \text{ kJ/kmol}(C_4H_{10})$$

For C_4H_{10}, M = 58.12 $\frac{\text{kg fuel}}{\text{kmol fuel}}$, so;

and

$$\bar{h}_{RP} = \frac{-2.877 \times 10^6}{58.12} = -49501 \text{ kJ/kg}$$

11) Determine the higher heating value, in kJ per kmol of fuel and in kJ per kg of fuel, at 25^oC, 1 atm for

a) liquid octane (C_8H_{18}).
b) gaseous hydrogen (H_2).
c) liquid methanol (CH_3OH).
d) gaseous butane (C_4H_{10}).

Assumptions:

1) Combustion is with the theoretical amount of air.
2) 3.76 moles of N_2 accompany each mole of O_2 in the air and N_2 is inert.
3) The combustion air and the gaseous products can be modeled as ideal gases. The water formed on combustion is a liquid.

a) Liquid octane (C_8H_{18}):

The reaction equation for complete combustion with the theoretical amount of air is:

$$C_8H_{18} + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2$$

The enthalpy of combustion at 25^oC, 1atm is:

$$\bar{h}_{RP} = 8(\bar{h}_f^o)_{CO_2} + 9(\bar{h}_f^o)_{H_2O(l)} - (\bar{h}_f^o)_{C_8H_{18}}$$

$$\bar{h}_{RP} = 8(-393520) + 9(-285830) - (-249910) = -5470720\,kJ/kmol\,(C_8H_{18}).$$

Accordingly;

$$\overline{HHV} = 5470720\,kJ/kmol\,(C_8H_{18})$$

$$HHV = \frac{5470720\,kJ/kmol\,(C_8H_{18})}{114.22\,kg/kmol\,(C_8H_{18})} = 47896\,kJ/kg\,(C_8H_{18})$$

b) gaseous hydrogen (H_2):

The reaction equation for complete combustion with the theoretical amount of air is:

$$H_2 + 1/2(O_2 + 3.76N_2) \rightarrow H_2O + 1.88N_2$$

The enthalpy of combustion at 25^oC, 1atm is:

$$\bar{h}_{RP} = (\bar{h}_f^o)_{H_2O(l)} = -285300\,kJ/kmol\,(H_2)$$

Accordingly;

$$\overline{HHV} = 285300\,kJ/kmol\,(H_2)$$

$$HHV = \frac{285300\,kJ/kmol\,(H_2)}{2.018\,kg/kmol\,(H_2)} = 141378\,kJ/kg\,(H_2)$$

c) Liquid methanol (CH_3OH):

The reaction equation for complete combustion with the theoretical amount of air is:

$CH_3OH + 1.5(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 5.64N_2$

The enthalpy of combustion at 25°C, 1atm is:

$$\bar{h}_{RP} = (\bar{h}_f^o)_{CO_2} + 2(\bar{h}_f^o)_{H_2O(l)} - (\bar{h}_f^o)_{CH_3OH}$$

$$\bar{h}_{RP} = 2(-285830) + (-393520) - (-238810) = -726370\,kJ/kmol\,(CH_3OH)$$

Accordingly;

$$\overline{HHV} = 726370\,kJ/kmol\,(CH_3OH)$$

$$HHV = \frac{726370\,kJ/kmol\,(CH_3OH)}{32.05\,kg/kmol\,(CH_3OH)} = 22664\,kJ/kg\,(CH_3OH)$$

d) Gaseous butane (C_4H_{10}):

The reaction equation is:

$C_4H_{10} + 6.5(O_2 + 3.76N_2) \rightarrow 4CO_2 + 5H_2O + 24.44N_2$

The enthalpy of combustion at 25°C, 1atm is:

$$\bar{h}_{RP} = 4(\bar{h}_f^o)_{CO_2} + 5(\bar{h}_f^o)_{H_2O(l)} - (\bar{h}_f^o)_{C_4H_{10}(g)}$$

$$\bar{h}_{RP} = 4(-393520) + 5(-285830) - (-126150) = -2877080\,kJ/kmol\,(C_4H_{10})$$

Accordingly;

$$\overline{HHV} = 2877080\,kJ/kmol\,(C_4H_{10})$$

$$HHV = \frac{2877080\,kJ/kmol\,(C_4H_{10})}{58.12\,kg/kmol\,(C_4H_{10})} = 49502\,kJ/kg\,(C_4H_{10})$$

12) For each of the following fuels, determine the adiabatic flame temperature, in K, for complete combustion with 200% of theoretical air in a combustor operating at steady state. The reactants enter at 25°C, 1 atm.

a) carbon

b) hydrogen (H_2).

c) liquid octane (C_8H_{18}).

Assumptions:

1) For the control volume shown in the accompanying figure $\dot{Q}_{cv} = \dot{W}_{cv} = 0$ and the effects of kinetic and potential energy are negligible.

2) 3.76 moles of N_2 accompany each mole of O_2 in the air and N_2 is inert.

3) The ideal gas model is applicable to the combustion air and products.

a) Fuel is carbon (C):

Complete combustion of C with the 200% of theoretical amount of air is described by:

$C + 2(O_2 + 3.76N_2) \rightarrow CO_2 + O_2 + 7.52N_2$

An energy rate balance at steady state reduces to:

$$0 = \frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} - \frac{\dot{W}_{cv}}{\dot{n}_{fuel}} + (\bar{h}_C)_1 + (2\bar{h}_{O_2} + 7.52\bar{h}_{N_2})_2 - (\bar{h}_{CO_2} + \bar{h}_{O_2} + 7.52\bar{h}_{N_2})_3$$

with $\bar{h} = \bar{h}_f^o + \Delta\bar{h}$ and noting that $\bar{h}_f^o = 0$ for C, O_2 and N_2.

$$\Rightarrow 0 = -\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{CO_2} - \left[\bar{h}(T_3) - \bar{h}(298)\right]_{O_2} - 7.52\left[\bar{h}(T_3) - \bar{h}(298)\right]_{N_2}$$

Accordingly, with data from the ideal gas tables:

$$\bar{h}_{CO_2}(T_3) + \bar{h}_{O_2}(T_3) + 7.52\bar{h}_{N_2}(T_3) = -(-393520 - 9364) + 8682 + 7.52(8669) = 476757$$

Solving, $T_3 \cong$ 1506 K

b) Fuel is hydrogen (H_2):

Complete combustion of H_2 with the 200% of theoretical amount of air is described by:

$H_2 + O_2 + 3.76N_2 \rightarrow H_2O + 1/2O_2 + 3.76N_2$

An energy rate balance at steady state reduces to:

$$0 = \frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} - \frac{\dot{W}_{cv}}{\dot{n}_{fuel}} + (\bar{h}_{H_2})_1 + (\bar{h}_{O_2} + 3.76\bar{h}_{N_2})_2 - (\bar{h}_{H_2O} + 1/2\bar{h}_{O_2} + 3.76\bar{h}_{N_2})_3$$

with $\bar{h} = \bar{h}_f^o + \Delta\bar{h}$ and noting that $\bar{h}_f^o = 0$ for H_2, O_2 and N_2.

$$\Rightarrow 0 = -\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{H_2O} - \frac{1}{2}\left[\bar{h}(T_3) - \bar{h}(298)\right]_{O_2} - 3.76\left[\bar{h}(T_3) - \bar{h}(298)\right]_{N_2}$$

Accordingly, with data from the ideal gas tables:

$$\bar{h}_{H_2O}(T_3) + \frac{1}{2}\bar{h}_{O_2}(T_3) + 3.76\bar{h}_{N_2}(T_3) = -(-241820 - 9904) + \frac{1}{2}(8682) + 3.76(8669) = 288660$$

Solving, $T_3 \cong 1647$ K

c) Fuel is liquid octane (C_8H_{18}):

Complete combustion of C_8H_{18} with the 200% of theoretical amount of air is described by:

$C_8H_{18} + 25(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 12.5O_2 + 94N_2$

An energy rate balance at steady state reduces to:

$$0 = \frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} - \frac{\dot{W}_{cv}}{\dot{n}_{fuel}} + (\bar{h}_{C_8H_{18}})_1 + (25\bar{h}_{O_2} + 94\bar{h}_{N_2})_2 - (8\bar{h}_{CO_2} + 9\bar{h}_{H_2O} + 12.5\bar{h}_{O_2} + 94\bar{h}_{N_2})_3$$

with $\bar{h} = \bar{h}_f^o + \Delta\bar{h}$ and noting that $\bar{h}_f^o = 0$ for O_2 and N_2.

$$\Rightarrow 0 = \left[\bar{h}_f^o\right]_{C_8H_{18}} - 8\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{CO_2} - 9\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{H_2O} - 12.5\left[\bar{h}(T_3) - \bar{h}(298)\right]_{O_2}$$
$$- 94\left[\bar{h}(T_3) - \bar{h}(298)\right]_{N_2}$$

Accordingly, with data from the ideal gas tables:

$$\begin{aligned} 8\bar{h}_{CO_2}(T_3) + 9\bar{h}_{H_2O}(T_3) + 12.5\bar{h}_{O_2}(T_3) + 94\bar{h}_{N_2}(T_3) &= -249910 - 8(-393520 - 9364) \\ &\quad - 9(-241820 - 9904) + 12.5(8682) + 94(8669) \\ &= 6162089 \end{aligned}$$

Solving, $T_3 \cong 1507$ K

13) Methane (CH_4) at 25^{o}C 1 atm enters an insulated reactor operating at steady state and burns with the theoretical amount of air entering at 25^{o}C, 1 atm. Determine the temperature of the exiting combustion products if:

a) combustion is complete.

b) 90% of the carbon in the fuel burns to CO_2 and the rest burns to CO.

Neglect kinetic and potential energy effects.

Assumptions:

1) For the control volume shown in the accompanying figure operates at steady state with $\dot{Q}_{cv} = \dot{W}_{cv} = 0$ and the effects of kinetic and potential energy is negligible.

2) 3.76 moles of N_2 accompany each mole of O_2 in the air and N_2 is inert.

3) The ideal gas model is applicable to the combustion air and products.

4) Combustion is with the theoretical amount of air.

a) Complete combustion of CH_4 with the theoretical amount of air is described by:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

An energy balance gives: $T_2 \cong 2328$ K

b) Combustion of CH_4 with 90% of the carbon in the fuel going to CO_2 is described by:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow 0.9CO_2 + 0.1CO + 2H_2O + 0.05O_2 + 7.52N_2$$

An energy rate balance at steady state reduces to give:

$$0 = \frac{\dot{Q}_{cv}}{\dot{n}_{fuel}} - \frac{\dot{W}_{cv}}{\dot{n}_{fuel}} + (\bar{h}_{CH_4})_1 + (2\bar{h}_{O_2} + 7.52\bar{h}_{N_2})_2 - (0.9\bar{h}_{CO_2} + 0.1\bar{h}_{CO} + 2\bar{h}_{H_2O} + 0.05\bar{h}_{O_2} + 7.52\bar{h}_{N_2})_3$$

with $\bar{h} = \bar{h}_f^o + \Delta\bar{h}$ and noting that $\bar{h}_f^o = 0$ for O_2 and N_2. This becomes:

$$\Rightarrow 0 = \left[\bar{h}_f^o\right]_{CH_4} - 0.9\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{CO_2} - 0.1\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{CO}$$
$$- 2\left[\bar{h}_f^o + \bar{h}(T_3) - \bar{h}(298)\right]_{H_2O} - 0.05\left[\bar{h}(T_3) - \bar{h}(298)\right]_{O_2} - 7.52\left[\bar{h}(T_3) - \bar{h}(298)\right]_{N_2}$$

Solving,

$$0.9\bar{h}_{CO_2}(T_3) + 0.1\bar{h}_{CO}(T_3) + 2\bar{h}_{H_2O}(T_3) + 0.05\bar{h}_{O_2}(T_3) + 7.52\bar{h}_{N_2}(T_3) = \left[\bar{h}_f^o\right]_{CH_4} - 0.9\left[\bar{h}_f^o - \bar{h}(298)\right]_{CO_2}$$
$$- 0.1\left[\bar{h}_f^o - \bar{h}(298)\right]_{CO} - 2\left[\bar{h}_f^o - \bar{h}(298)\right]_{H_2O} - 0.05\bar{h}_{O_2}(298) - 7.52\bar{h}_{N_2}(298)$$

With data from the ideal gas tables:

$$0.9\bar{h}_{CO_2}(T_3) + 0.1\bar{h}_{CO}(T_3) + 2\bar{h}_{H_2O}(T_3) + 0.05\bar{h}_{O_2}(T_3) + 7.52\bar{h}_{N_2}(T_3) = -74850 - 0.9(-393520 - 9364)$$
$$- 0.1(-110530 - 8669) - 2(-241820 - 9904) + 0.05(8682) + 7.52(8669)$$
$$= 868739$$

Solving, $T_3 \cong 2265$ K