

# ME 18b Homework Solutions

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## Homework 6

Due Tuesday May 20, 2008 (accepted until 5 pm).

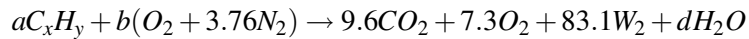
Reading: Chapter 14 and 15 in Sonntag, Borgnakke & Van Wylen.

### 6.1 Burning of a fuel (S, B & V 14.31)

A fuel,  $C_xH_y$ , is burned with dry air, and the product composition is measured on a dry mole basis to be: 9.6% $CO_2$ , 7.3% $O_2$ , 83.1% $N_2$ . Find the fuel composition (x/y) and the percent theoretical air used.

#### Solution (10 points)

Assume the reaction equation is:



Atom Balance:

$$C: \quad ax = 9.6$$

$$H: \quad ay = 2d$$

$$O: \quad 2b = 2 \times 9.6 + 2 \times 7.3 + d$$

$$N: \quad 3.76b = 2 \times 83.1$$

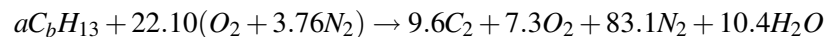
Then, solve that:

$$b = 22.10, \quad d = 10.4$$

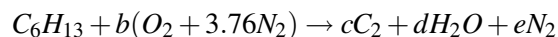
And

$$\frac{x}{y} = \frac{9.6}{2 \times 10.4} = \underline{\underline{0.461}}$$

For example:



where,  $a = 1.6$ . When using 100% theoretical air:



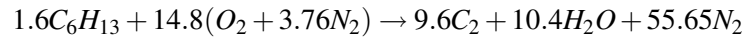
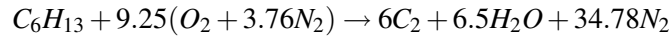
Atom Balance:

$$C: \quad c = 6$$

$$H: \quad 13 = 2d, \quad d = 6.5$$

$$O: \quad 2b = 2c + d = 13 + 6.5 = 18.5, \quad b = 9.25$$

$$N: \quad 9.25 \times 3.766 = e = 34.78$$

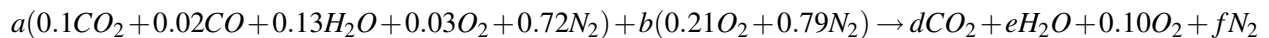


Then,  $\frac{22.10}{14.8} = 1.5$ , so 150% theoretical air is used.

## 6.2 Exhaust gases from an IC engine (S,B & V 14.36; answer in book)

The hot exhaust gas from an internal combustion engine is analyzed and found to have the following percent composition on a volumetric basis at the engine exhaust manifold: 10% CO<sub>2</sub>, 2% CO, 13% H<sub>2</sub>O, 3% O<sub>2</sub>, 72% N<sub>2</sub>. This gas is fed to an exhaust gas reactor and mixed with a certain amount of air to eliminate the carbon monoxide, as shown in the figure. It has been determined that a mole fraction of 10% oxygen in the mixture at state 3 will ensure that no CO remains. What must be the ratio of volumetric flow rates entering the reactor?

### Solution (30 points)



Atom balance:

$$C: \quad 0.1a + 0.02a = d = 0.12a$$

$$H: \quad 2a \times 0.13 = 2e, \quad e = 0.13a$$

$$N: \quad 2a \times 0.72 + 2b \times 0.79 = 2f, \quad f = 0.72a + 0.79b$$

$$O: \quad 2a \times 0.1 + 0.02a + 0.13a + 2a \times 0.03 + 0.21 \times b \times 2 = 2d + e + 0.2 = 0.41a + 0.42b$$

$$0.2 = 0.04a + 0.42b$$

$$10\%O_2 \text{ in stream 3} \rightarrow d + e + 0.1 + f = 1.0.$$

Solve above equations and get  $a = 0.585, b = 0.421$ .

So,  $\frac{b}{a} = 0.719$

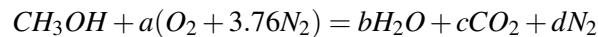
### 6.3 Methanol combustion

An alternative to using petroleum or natural gas as fuels is methanol (CH<sub>3</sub>OH), which can be produced from coal. Consider a combustion process in which liquid methanol is burned with 120% theoretical air in a steady flow process. The reactants enter the combustion chamber at 25°C, and the products exit at 60°C. The pressure is constant at 100 kPa

- Calculate the fuel air ratio.
- Calculate the heat transfer per kilomole of methanol, using the enthalpy of formation of methanol (Table A.15) and the gas tables (Tables A.12). (The book does not tell you, but use  $\bar{h}_{fg} = 8846 \text{ kJ/kM}$  for methanol.)
- Does the water in the products condense?
- If the products were at 50°C, does the water condense? What is the heat transfer per kilomole of methanol for this exit temperature? For the change in enthalpy of the liquid water use  $\Delta\bar{h} = M_{H_2O}[h_f(50^\circ\text{C}) - h_f(25^\circ\text{C})]$ .

#### Solution (30 points)

- Theoretical air amount of air can be calculated from the following balance:



The second term in the above equation is the contribution from air. It is assumed that this is the only reaction involved (no CO or NO<sub>x</sub>). Balancing the individual elements:

$$C: \quad 1 = c$$

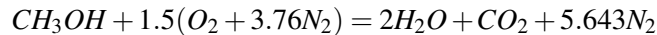
$$H: \quad 4 = 2b$$

$$N: \quad 3.76a = d$$

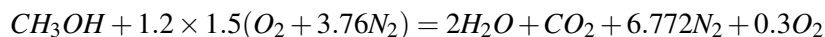
$$O: \quad 1 + 2a = b + 2c$$

Solving for the above:

$$a = 3/2, \quad b = 2, \quad c = 1, \quad d = 5.643$$



Since 120% theoretical air is used, the following equation describes the combustion process:



The fuel-air ratio can be calculated as follows:

$$F - A_{ratio} = \frac{M_{\text{CH}_3\text{OH}} \cdot n_{\text{CH}_3\text{OH}}}{M_{\text{O}_2} \cdot n_{\text{O}_2} + M_{\text{N}_2} \cdot n_{\text{N}_2}} = \frac{32.042 \cdot 1}{31.999 \cdot 1.8 + 28.013 \cdot 6.772} = \underline{\underline{0.1296}}$$

- b) Assuming that methanol is completely burned and no dissociation occurs, the energy equation can be written as:

$$Q_{exo} = (n_{CH_3OH}h_{CH_3OH} + n_{O_2}h_{O_2} + n_{N_2}h_{N_2})_{reactants} - (n_{H_2O}h_{H_2O} + n_{CO_2}h_{CO_2} + n_{N_2}h_{N_2} + n_{O_2}h_{O_2})_{products}$$

$$h_{CH_3OH}(25^\circ C) = \bar{h}^o_{f,liquid} = \bar{h}^o_{f,gas} - h_{fg} = -239222 \text{ kJ/kmol}$$

Similarly, read enthalpy from tables and calculate that:

$$\underline{Q_{exo} = 627058 \text{ kJ/kmol}}$$

- c) To find the state of the water we must first calculate the partial pressure of the water:

$$y_{H_2O} = \frac{2}{2 + 1 + 0.3 + 6.772} = 0.1985$$

$$y_{H_2O} = \frac{P_{H_2O}}{P_{total}} \rightarrow P_{H_2O} = 19.85 \text{ kPa}$$

Since the partial pressure of  $H_2O$  is less than the saturation pressure for the same temperature  $P_{sat}(60^\circ C) = 19.94 \text{ kPa}$ , then the steam does not condense.

- d) Changing the final temperature to  $50^\circ C$ , part of the water will be in liquid form (since  $P_{sat}(50^\circ C) = 12.349 \text{ kPa}$  and the mole fraction  $y_{H_2O}$  is the same).

$$\frac{P_{sat}}{P_{total}} = \frac{(n_{H_2O})_{vapor}}{(n_{total})_{gaseous}} = \frac{(n_{H_2O})_{vapor}}{(n_{H_2O})_{vapor} + 1 + 0.3 + 6.772} = \frac{12.349 \text{ kPa}}{100 \text{ kPa}}$$

$$(n_{H_2O})_{vapor} = 1.1373$$

$$(n_{H_2O})_{liquid} + (n_{H_2O})_{vapor} = 2$$

So,  $(n_{H_2O})_{liquid} = 0.8627$ . Then, the energy difference becomes:

$$Q_{exo} = (n_i h_i)_{reactants} - ((n_{H_2O})_{liquid} (h_{H_2O})_{liquid} + (n_{H_2O})_{vapor} (h_{H_2O})_{vapor} + n_{CO_2} h_{CO_2} + n_{N_2} h_{N_2} + n_{O_2} h_{O_2})_{products}$$

$$\underline{Q_{exo} = 667266 \text{ kJ/kmol}}$$

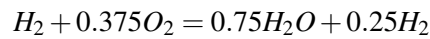
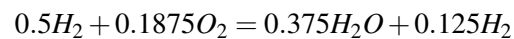
## 6.4 Space Shuttle Engines

Each of the main engines on the Space Shuttle burns liquid hydrogen  $H_2$  and liquid oxygen  $O_2$  at a mass ratio of 1 kg  $H_2$  to 6 kg  $O_2$ .

- Write a balanced chemical equation for the reaction. If there is excess  $O_2$ , the products are  $H_2O$  and  $O_2$ . If there is deficient  $O_2$  the products are  $H_2O$  and  $H_2$ . Assume that there is no dissociation of the products.
- The fuel and oxidizer pumps increase the pressure of the  $H_2$  and the  $O_2$  to 20 MPa. The oxygen and hydrogen enter a pre-burner that increases their temperatures to 900 K; these gaseous reactants at 900 K then enter the combustion chamber. If the temperature in the combustion chamber is 3400 K, what is the heat transfer to or from the combustion chamber in kJ per 1 kilogram of  $H_2$  fuel? Assume that the combustion process happens at a constant pressure.
- Assume that there is no heat transfer in the combustion chamber. Find the adiabatic flame temperature.

**Solution (30 points)**

a) One kilogram of  $H_2$  is 0.5kmol while 6kg of  $O_2$  is  $6/32 = 0.1875$  so we can write:



b) The energy equation is:

$$h_{H_2}(900K) = 17657kJ/kmol$$

$$h_{H_2}(3400K) = 103736kJ/kmol$$

$$h_{O_2}(900K) = 19241kJ/kmol$$

$$h_{H_2}(3400K) = -92753kJ/kmol$$

$$H_{in} = 17656 + 0.375 \times 19241 = 24872.4kJ/kmol$$

$$H_{out} = 0.75 \times (-92753) + 0.25 \times 103736 = -43630.8kJ/kmol$$

$$Q_{exo} = H_{in} - H_{out} = 68503.2kJ/kmol = 34251.6kJ/kg(H_2)$$

c) If there is no heat transfer in the combustion chamber, then

$$Q_{exo} = H_{in} - H_{out} = 0$$

$$H_{in} = H_{out}$$

Try different final temperature to get above relation. The temperature should be close to 4705k.