Homework 2

2.60/2.62/10.390 Fundamentals of Advanced Energy Conversion
Spring 2020

Total points: 100 (Undergraduate) | 150 (Graduate)

(Only use EES for Problem 2)

Problem 1. Carbon Dioxide Emissions [40% for Undergrads and 35% for Grads]

Consider a power plant with a power rating of 100 MWe which can use lignite, methane or octane as fuel. The environment is at standard conditions. Suppose first that the plant has a first law efficiency of 35%, defined based on the lower heating value of the fuels.

a. For each fuel, calculate the required fuel flow rate and CO_2 emission rate. Explain their relative values, and comment on which is the best fuel and why.

b. Is it reasonable to assume the same efficiency for all fuels? Why?

c. Now keep the efficiency the same for lignite but take 52% for octane and 58% for methane. Calculate CO_2 emissions as $kgCO_2/MJe$ for each fuel.

d. The plant runs at 75% capacity factor, calculate the total CO_2 emitted yearly from each plant, in $kgCO_2$.

Now, and for methane only:

e. Calculate the adiabatic flame temperature assuming air excess of 35% and that the reaction is complete.

f. Based on the adiabatic flame temperature and that of the environment, calculate a maximum first law efficiency using the standard "Carnot efficiency".

g. Correct the efficiency to account for the fact that the heat source has finite flowrate, and to allow for a 10K temperature difference between the source, the heat engine and the environment.

h. What is the second law efficiency of this plant?

Problem 2. Propane Combustion [40% for Undergrads and 35% for Grads]

Stoichiometric gaseous propane (C_3H_8) air mixture undergoes isentropic compression from STP to 2 MPa, then combustion at constant pressure. During compression the mixture composition is frozen at its initial state. The products of combustion contain only CO_2, CO, O_2, H_2O, H_2 and N_2. The isentropic index is 1.4.

Use EES to:

a. Calculate the products temperature without and with dissociation.

b. Calculate the products composition with dissociation.

Use the following as the dissociation reactions in the equilibrium calculations, find the equilibrium constant data in the notes or other sources:

$$CO_2 \leftrightarrow CO + \frac{1}{2}O_2$$
$$H_2O + CO \leftrightarrow H_2 + CO_2$$
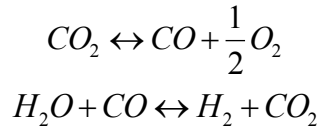
c. **(for Grads only)** Repeat (a) and (b) for the case when the original fuel-air mixture undergoes volume reduction to 1/10th of its original volume (with frozen composition) then constant volume combustion.

Problem 3. Biomass Utilization [20% for Undergrads and 30% for Grads]

Biomass from agriculture and forests is a large source of renewable energy and fuel. It can be burned for heating, electricity generation or to produce biofuels. If used in its raw form, it is carbon dioxide neutral since it is part of the carbon cycle. In this problem we use woody biomass whose chemical formula can be assumed to be $C_6H_{12}O_6$. The original biomass is 85% wood and 15% moisture.

Technology I: Combustion

One way to utilize biomass is to burn it in air in an adiabatic combustion chamber and use the products in a steam cycle to produce work. Biomass and air enter the combustion chamber at atmospheric conditions.

a. If the combustion is stoichiometric, calculate the temperature of products assuming complete combustion.

b. The combustion products are cooled down to 50°C and 1 atm. The maximum temperature of the power cycle is 550°C. Calculate the maximum possible efficiency for the system, and maximum efficiency of the power cycle (both based on the logarithmic mean temperature).

c. If the second law efficiency of the power cycle is 60%, calculate the work produced by the plant per mole of biomass.

d. What is the overall fuel utilization efficiency of this configuration?

[For Grads Only] Technology II: Gasification

In this process, one mole of biomass and 6.5 moles of H_2O enter a steam reformer at atmospheric conditions to produce a mixture of CO, CO_2, H_2 and H_2O at 500°C. Next, the mixture goes through a water-gas shift reactor (WGS) to convert CO to CO_2. In the WGS, one mole of H_2O (at 25°C) is added for every mole of CO originally in the mixture. The mixture leaves WGS reactor at 100°C. The resulting mixture is used in the fuel cell to generate work. A schematic is shown in the following figure:
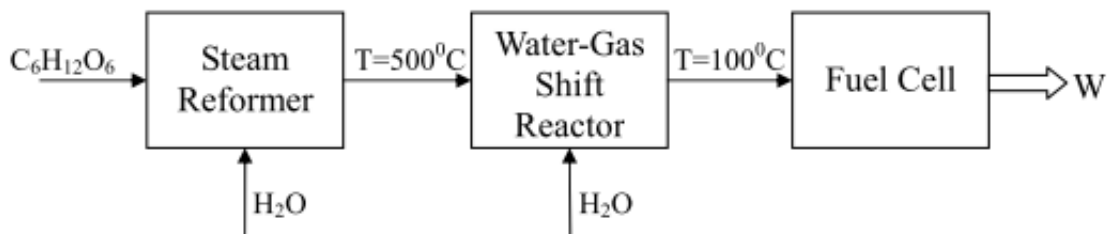
e. What is the composition of the gas leaving the steam reformer if the temperature of the mixture is 500°C. Assume that this mixture of CO, CO_2, H_2 and H_2O is at equilibrium.

f. What is the heat transfer required in the steam reformer?

g. If CO concentration leaving the WGS is negligible, what is the hydrogen concentration in the gas leaving the WGS reactor?

h. Evaluate the overall process efficiency, including the reforming and WGS process, if no waste heat is recuperated.

The following information might be useful in your calculations:

1. LHV of woody biomass is 21 MJ/kg.
2. Thermodynamic properties:

Enthalpy of formations	Specific heat
$\hat{h}^o_{f,H_2O(g)} = -242 \ kJ \,/\, mol$	$\hat{c}_{p,O_2} = 33.4 \ J \,/\, mol.K$
	$\hat{c}_{p,N_2} = 31.1 \ J \,/\, mol.K$
$\hat{h}^o_{f,H_2O(l)} = -286 \ kJ \,/\, mol$	$\hat{c}_{p,CO_2} = 50.6 \ J \,/\, mol.K$
$\hat{h}^o_{f,CO} = -110.6 \ kJ \,/\, mol$	$\hat{c}_{p,H_2} = 30.0 \ J \,/\, mol.K$
$\hat{h}^o_{f,CO_2} = -393.8 \ kJ \,/\, mol$	$\hat{c}_{p,CO} = 29.3 \ J \,/\, mol.K$
$\hat{h}^o_{f,C_6H_{12}O_6} = -1267.1 \ kJ \,/\, mol$	$\hat{c}_{p,H_2O} = 38.2 \ J \,/\, mol.K$
	$\hat{c}_{p,C_6H_{12}O_6} = 75.6 \ J \,/\, mol.K$

3. Thermodynamic equilibrium constant for WGS reaction:

Table 1: Equilibrium constant values for water-gas shift reaction $CO_2+H_2 \Leftrightarrow CO+H_2O$	
$Log_{10} \ K_p(T)$	$T \ (K)$
-19.6	100
-5.018	298
-2.139	500
-0.159	1000
0.135	1200
0.333	1400
0.474	1600
0.577	1800

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