Exam Energy from Biomass

4S610

Tuesday, March 14, 2006

This exam consists of **4** questions. Questions 1, 3 and 4 are rewarded with 30 points, question 2 with 10 points. Read the questions carefully. Be brief and concise. Try to use variables as long as possible in your answer and fill in the numbers at the end. Don't forget the correct units!

Please, separate the answers to questions 1, 2, 3 and 4 on different pieces of paper.

Success!

1 Wood combustion

a. Mention 3 advantages of using renewable fuels, such as wood, as an energy source, in comparison to fossil fuels.

b. What are the 3 main components of wood? Can you indicate the distribution of these 3 components, i.e. in which proportions are these components present in wood?

c. The major component is a carbohydrate described by the formula $C_6(H_2O)_5$. Calculate its gross heat of combustion (HHV) and net heat of combustion (LHV).
Required information:
Molecular Weights: C = 12 g/mol, H = 1 g/mol, O = 16 g/mol.
Empirical correlation for HHV [kJ/g]:
$HHV = 34.91Y_C + 117.83Y_H + 10.05Y_S - 1.51Y_N - 10.34Y_O - 2.11Y_{ASH}$
Enthalpy of evaporation of water:
$\Delta H_{vap,H_2O} = 2.442kJ/g$

d. Write down the equation for complete combustion of mentioned component, using air as oxidant. Air is approximately 80 vol% nitrogen and 20 vol% oxygen.

e. What temperature will be reached for complete combustion by air, if there are no heat losses? In other words, set up an energy balance to calculate the adiabatic temperature increase. Assume that incoming fuel and oxygen are at room temperature (25^0C).

The heat capacity Cp for gases formed is temperature-dependent (see the graph below), but may be approximated by the following average values: Cp,CO2 = 55.0 J/mol K, Cp,H2O = 44.1 J/mol K, Cp,N2 = 34.2 J/mol K

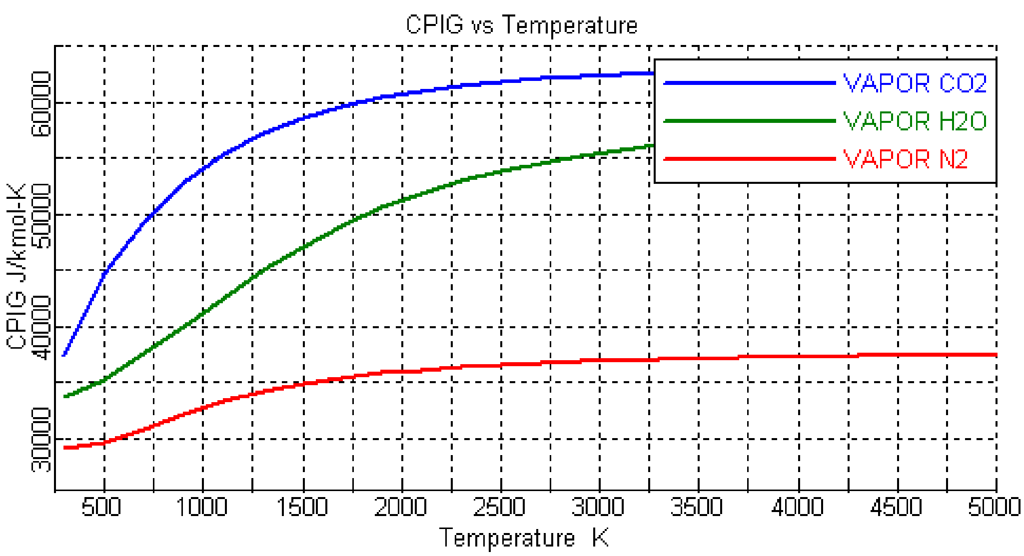

Figure 1: Ideal gas heat capacity versus temperature

2 Wood gasification

a. Instead of combustion of wood, it can also be gasified. What would be the advantages of gasification? (hint: think about 'efficiency' and 'emissions to environment')

b. What is the difference between an updraft fixed bed gasifier and a CFB (Circulating Fluidized Bed) gasifier? Please draw schematic pictures and compare these 2 types of gasifiers qualitatively in terms of:
o hydrodynamics (gas velocity, solid residence time, mixing/homogeneity, particle size of the feed)
o operating conditions, e.g. gas outlet temperature
o tar production
o suitability for small-scale or large-scale

3 Air Staging

Air staging is a widely applied method in biomass combustion systems. It is used to reach acceptable emission levels of, for instance, carbon monoxide CO.

a. What is the main cause of CO emissions?

b. Explain briefly the principle of air staging to minimize CO emissions (how and why it works).

We will now study the CO burn out in the last sections of a biomass combustion system. The fuel gases arising from the previous sections contains 50 wt% carbon monoxide, $Y_{\mathrm{CO}}^{\mathrm{fu}} = 0.5$, and no oxygen, $Y_{\mathrm{O}_2}^{\mathrm{fu}} = 0.0$. This fuel gas flows with a rate of $m^{\mathrm{fu}} = 1$ kg/s into a reactor with volume $V = 1$ m^3. Secondary air with 23 wt% oxygen is added to this same reactor at a rate of m^{air}. The oxygen in the air stream reacts with the carbon monoxide in the fuel stream to form carbon dioxide:

$$\mathrm{CO} + \frac{1}{2}\mathrm{O}_2 \longrightarrow \mathrm{CO}_2$$

The reaction rate ω [kmol/m^{3}s] is given by

$$\omega = A Y_{\mathrm{CO}} Y_{\mathrm{O}_2} \exp(-T_a/T),$$

with $A = 10^6$ kmol/m^{3}s and $T_a = 10^4$ K. The reactor can be considered to be a perfectly stirred reactor in steady state. The temperature T of the mixture in the reactor is $T = 1000$ K

c. The reactor is operated at stoichiometric conditions. Compute the air rate m^{air}.

d. Give the conservation equations for total mass, O_2 and CO mass fraction. (Advise: check the dimensions of the different terms.)

e. Show that

$$\frac{Y_{\mathrm{CO}}}{M_{\mathrm{CO}}} = 2\frac{Y_{\mathrm{O}_2}}{M_{\mathrm{O}_2}}$$

f. Compute Y_{CO} and Y_{O_2} in the reactor.

The mixture leaves the reactor through a pipe with radius $R = 0.1$ m. The temperature in the pipe is $T = 1300$ K and the flow through the pipe can be assumed to be a plug flow.

g. Give the conservation equations for total mass, O_2 and CO mass fraction.

h. Show that again

$$\frac{Y_{\mathrm{CO}}}{M_{\mathrm{CO}}} = 2\frac{Y_{\mathrm{O}_2}}{M_{\mathrm{O}_2}}.$$

i. Compute Y_{CO} and Y_{O_2} as function of the axial distance x from the inlet of the pipe. Use the fact that the solution of $df/dx = Bf^2$ is given by

$$f = \frac{-1}{B(x - C)}$$

with C an integration constant.

4 Changing from coal combustion to biomass

An energy company in the Netherlands wants to change their pulverized coal combustion plant to biomass as a fuel. For this purpose they purchase wood pellets. The wood is milled with the same equipment as the coal, but because of the different mechanical properties this results in particles of different size. In case of the coal we will only look at the char burnout. The char particles are of size $r_p^c = 50\mu m$, whereas the biomass particles have a radius of $r_p^b = 2mm$. Furthermore the porosity, the reaction rate and the density of the biomass relative to the char particles are respectively $\varepsilon^b/\varepsilon^c = 0.5$, $k^b/k^c = 4$ and $\rho^b/\rho^c = 2/3$. The mass fraction of oxygen far from the individual particles equals 0.23. The effective diffusion in the particles is given by $D_e = \varepsilon^2 D$ and the molar masses of C, H and O are 12, 1 and 16, in g/mol.

a. What does the Thiele modulus express (in words)?

b. What does the mass Biot number express (in words)?

c. What is the relative Thiele modulus Th^b/Th^c?

d. What is the relative mass Biot number Bi^b/Bi^c?

e. The following statement holds: if the char combustion is dominated by surface reactions, then it is also the case for biomass. Please explain this statement, based on the relative Thiele modulus and Biot number!

Now consider combustion with surface reactions for which the reactions can be written:

Char:

$$1kgC + \nu^c kgO_2 \rightarrow AkgCO_2 \tag{1}$$

Biomass:

$$1kgCH_{1.4}O_{0.6} + \nu^b kgO_2 \rightarrow BkgCO_2 + CkgH_2O \tag{2}$$

f. Write these equations in mole fractions?

g. Determine ν^c, ν^b, A, B and C!

The Spalding number of the mass transfer in such a process is
$(Y_{O_{2\infty}} - Y_{O_{2r_p}})/(\nu + Y_{O_{2r_p}})$.

h. Draw a profile of the oxygen along $r = 0...\infty$ if the surface reactions are oxygen limited.

i. Determine the transfer number B for both types of particles with the use of the answers of g) and h).

j. Give a general expression for the particle burnout time in terms of the initial diameter D_0 and the rate constant K.

The rate constant is given as

$$K = \frac{8\rho D}{\rho_p} \ln(1+B) \tag{3}$$

k. What is the burnout time for the biomass particle if the burnout time for the char is equal to 1 second?