Exam Energy from Biomass

4S610

Thursday, March 17, 2005

This exam consists of **4** questions. All questions are rewarded with the same number of 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 and 2 from the answers to questions 3 and 4 on different pieces of paper.

Success!

1 The greenhouse effect

Complete combustion of organic fuels ($C_xH_yO_z$) results in heat, water vapor and carbon dioxide CO_2. The emission of CO_2 is believed to be the main cause of the greenhouse effect.

a. Write down the global reactions for the complete oxidation of methane, coal and biomass using the values given in table 1.

b. Determine the mass of CO_2 produced per unit of energy for methane, coal and biomass.

Fuel	Composition	Heating value (MJ/kg)
Methane	CH_4	30.0
Coal	$C_{20}H_{20}O$	32.0
Biomass	$C_5H_7O_3$	19.0

Element	Mass (kg/kmol)
C	12
H	1
O	16

Table 1: Heating values for different fuels (left) and molar mass of different elements (right).

2 Carbon monoxide burnout

Hot flue gases coming from a biomass grate furnace flow through a pipe with radius $R = 0.1$ m and length $L = 5$ m. The velocity u of the gas is constant along the radius of the pipe. At the inlet, the gas mixture contains 2.0 wt% carbon monoxide, $Y_{\mathrm{CO}}^{in} = 0.02$. In the pipe, the CO reacts with oxygen radicals to form carbon dioxide:

$$\mathrm{CO} + \mathrm{O} \longrightarrow \mathrm{CO_2}$$

Assuming that there are enough oxygen radicals present, the reaction rate ω [kg/m^{3}s] is given by

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

with $A = 10^2$ kg/m^{3}s and $T_a = 2000$ K. The temperature T and the density ρ of the mixture in the pipe are constant: $T = 1000$ K and $\rho = 0.5$ kg/m^3. In order to comply with safety regulations, the maximum allowed CO concentration at the end of the pipe is $Y_{\mathrm{CO}}^{out} = 10^{-6}$. What is the maximum gas velocity $u_{\max}$ that satisfies this condition?
First assume that the pipe can be considered as a **perfectly stirred reactor** in steady state.

a. Write down the conservation equations for total mass and CO mass fraction. (Advise: check the dimensions of the different terms.)

b. Express Y_{CO}^{out} as a function of the other variables.

c. Compute the maximum gas velocity $u_{\max}$.

Now assume that the pipe can be considered as a **plug flow reactor** in steady state.

d. Write down the conservation equations for total mass and CO mass fraction.

e. Solve the equation for $Y_{\mathrm{CO}}(x)$.

f. Compute the maximum gas velocity $u_{\max}$.

g. Explain the difference in $u_{\max}$ for the two different cases by looking at the distribution of the reaction rate in the pipe.

3 Thermo-gravimetric analysis (TGA)

TGA experiments can be used to perform a proximate analysis of solid fuels. In TGA, a small piece of biomass is suspended on a balance pan in a furnace filled with nitrogen. After 45 minutes, the temperature of the furnace is slowly increased from room temperature to 110°C and kept constant for a few minutes. Subsequently, the temperature is increased from 110 to 600°C. Finally, air is added to the system. The weight of the sample is measured as function of time (and therefore temperature). In figure 1 the mass of the sample is shown against time.

a. Explain the measured curve in figure 1 by describing the thermo-chemical processes taking place during the experiment.

b. Determine the composition of the biomass sample in weight percentage on a **wet** basis.

c. Determine the composition of the biomass sample in weight percentage on a **dry** basis.

d. Determine the composition of the biomass sample in weight percentage on a **dry and ash-free** basis.

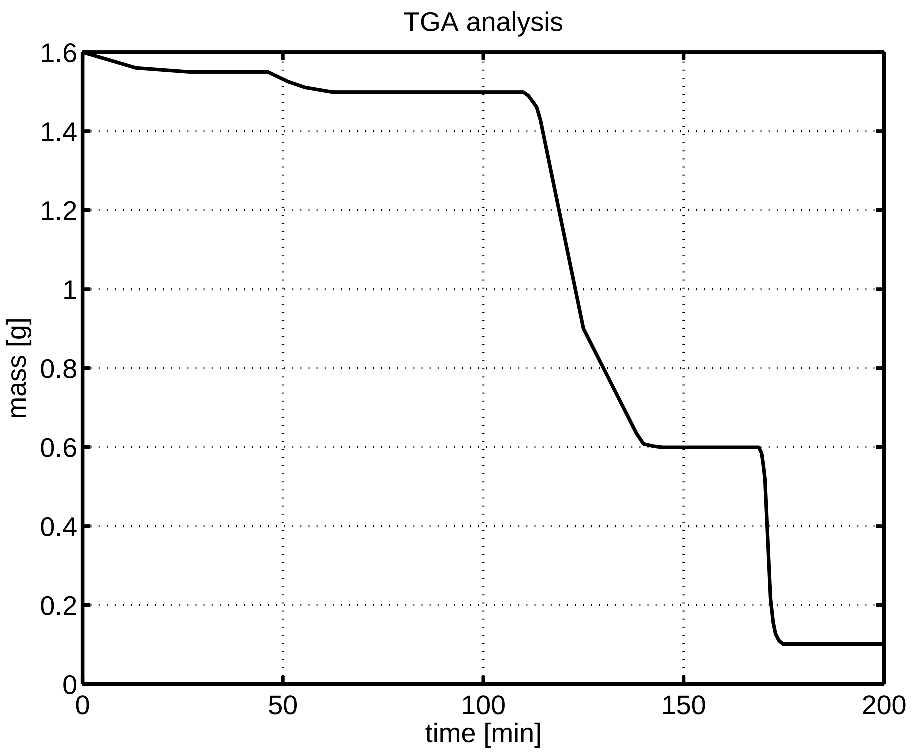
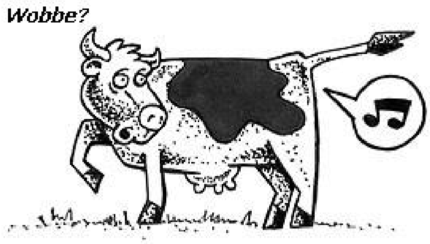


Figure 1: Weight of biomass sample against time during a TGA experiment.



4 Biogas and safety

A gasification unit is designed to deliver only CO and H_2. Some ingenious concept is used in which the ratio of the produced CO and H_2 can be adjusted to any value. Now the owner of the plant wants to produce a gas that is within the regular Wobbe range. Specifically he wants the Wobbe index to be equal to the one of Groningen natural gas, $W = 43.7$ MJ/m^3. The density of CO is $\rho_{\mathrm{CO}} = 1.250$ kg/m^3, the molar mass is 28 g/mol and the gross calorific value is 283 MJ/kmol. These values for hydrogen are $\rho_{\mathrm{H_2}} = 0.09$ kg/m^3, $M_{\mathrm{H_2}} = 2$ g/mol and the gross calorific value is 286 MJ/kmol. The density of dry air is $\rho_{air} = 1.293$ kg/m^3.

a. Determine the heating value of hydrogen and carbon monoxide in MJ/m^3

b. Determine the Wobbe index for pure hydrogen and pure carbon monoxide

c. The density of a binary gas mixture is given by

$$\rho = \left(\frac{\rho_1}{M_1} + \frac{\rho_2}{M_2}\right)(X_1 M_1 + X_2 M_2) = n\,(X_1 M_1 + X_2 M_2) \qquad (1)$$

Write the expression for the Wobbe index of a mixture of hydrogen and carbon monoxide. Use the mole fraction of carbon monoxide X, the molar mass of carbon monoxide, M_{CO}, the molar mass ratio $\alpha = M_{\mathrm{H_2}}/M_{\mathrm{CO}}$, the heating values, ρ_{air} and n as variables.

d. Assume that the gross calorific values of hydrogen and carbon monoxide are equal and take for both the value $HHV = (HHV_{\mathrm{CO}} + HHV_{\mathrm{H_2}})/2$. It has been said to the owner of the plant that the Wobbe of Groningen natural gas can not be achieved with a mixture of CO and H_2. Now calculate X if 70 % of this Wobbe number should be retained.

e. What can you say about the thermal energy output of this mixture compared to natural gas?

f. What can you say about the laminar burning velocity of this mixture compared to natural gas?