TENTAMEN OPGAVE 'Energy from biomass'

1. Torrefaction of wood

Points: a=5, b=5, c=5, d=5, e=5, f=10, g=5 (total = 40)

a. Thermal processing of solid biofuels (e.g. wood) may be distinguished into 3 categories: pyrolysis, gasification and combustion. Explain briefly the fundamental differences, with focus on the air equivalence ratio.

b. Torrefaction and fast pyrolysis both belong to the first category.
Torrefaction is a process in which wood is roasted at temperatures in the range of 250-300°C, in which mainly hemicellulose (the least thermally stable component) reacts.
Please give a description of a fast pyrolysis process; in which aspects does it differ from torrefaction?

c. Suppose that woody biomass consists of 50 wt% cellulose, 25 wt% hemicellulose and 25 wt% lignin. Calculate the average composition of wood.
Required information:
Molecular Weights: C = 12 g/mol, H = 1 g/mol, O = 16 g/mol.
cellulose = $(C_6(H_2O)_5)_n$, hemicellulose = $(C_5(H_2O)_4)_n$, lignin = $(C_{40}H_{44}O_6)_n$

d. Calculate gross heat of combustion (HHV) and net heat of combustion (LHV) of wood.
Empirical correlation for HHV [kJ/g]:
$HHV = 34.91\ Y_C + 117.83\ Y_H + 10.05\ Y_S - 1.51\ Y_N - 10.34\ Y_O - 2.11\ Y_{ASH}$
Enthalpy of evaporation of water:
$\Delta H_{vap,H2O} = 2.442$ kJ/g

e. Wood is reacted in a torrefaction process, and after completion of the process 86.4% of the wood is recovered with an (increased) HHV of 24.6 kJ/g. Assuming that the weight loss is only H_2O (g) (this assumption is not completely realistic), calculate the reaction enthalpy. Is the reaction endo- or exothermic?

f. Set up an overall enthalpy balance for the torrefaction process, using the following process conditions:
Incoming wood @ 25°C, Products (torrefied wood and steam) @ 300°C
The heat capacity Cp is temperature-dependent, but may be approximated by the following average values:
$Cp,_{TORREFIED\_WOOD} = 1.03$ kJ/kg K, $Cp,_{H2O} = 2$ kJ/kg K.
Is the overall process endo- or exothermic? What would be the effect of ash or moisture present in the wood feedstock?

g. As the fibrous structure of wood is destroyed in the torrefaction process, torrefied wood is much more brittle and can be easily pulverized. For which type of gasifier would that be beneficial: fixed bed, fluidized bed or entrained flow, and why? What are the advantages of this type of gasifier?

(hint: think about 'operating conditions' and its effect on tar production, unreacted carbon and reactor capacity)

UITWERKING TENTAMEN OPGAVE 'Energy from biomass'

a. Pyrolysis = thermal decomposition of solid fuels in the absence of oxygen, air equivalence ratio ER = 0; Gasification = partial oxidation of solid fuel producing a combustible gas, ER=0.25-0.50, Combustion = complete oxidation of solid fuel, ER >= 1.

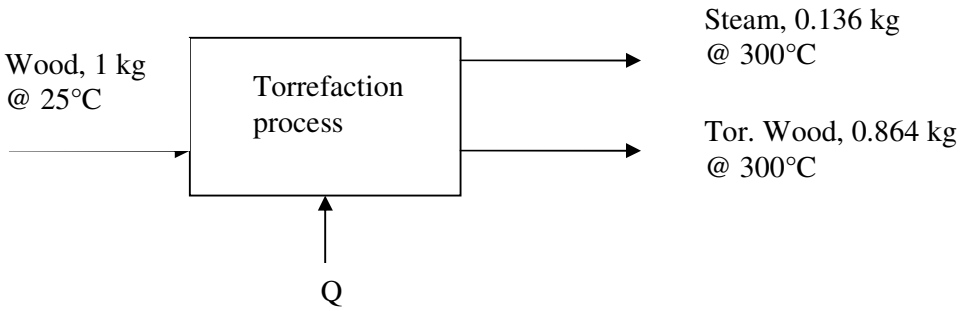
b. Fast pyrolysis: wood is heated very quickly to temperatures around 500°C. Wood (i.e. mainly the hemicellulose and cellulose fraction) decomposes into volatiles, which are quenched to liquid bio-oil. The yield of bio-oil can be up to 70 wt%, with 15% of gases and 15% of char.

c. cellulose = $(C_6(H_2O)_5)_n$, MW = 162, C: 44.4 wt%, H: 6.2 wt%, O: 49.4%
hemi-cellulose = $(C_5(H_2O)_4)_n$, MW = 132, C: 45.5 wt%, H: 6.1 wt%, O: 48.5%
lignin = $C_{40}H_{44}O_6$, MW = 620, C: 77.4 wt%, H: 7.1 wt%, O: 15.5%
<u>average:</u> C: 50% x 44.4 % + 25% x 45.5% + 25% x 77.4% = 52.9%, likewise H: 6.4%, O: 40.7%

d. HHV = 34.91 Yc + 117.83 Yh – 10.34 Yo = 21.8 kJ/g
LHV = HHV – Yh/2·18·2.442 = 20.4 kJ/g

e. Wood torrefaction: 1 g wood → 0.864 g Torrefied Wood + 0.136 g H_2O (g)
Reaction enthalpy = HHVout – HHVin = 0.864·24.6 + 0.136·2.442 – 1·21.8 = 21.6-21.8 = -0.2 kJ/g; mildly exothermic!

f.



$$\Phi_{m,wood} \cdot HHV_{wood} + Q =$$
$$\Phi_{m,tor.wood} \cdot HHV_{tor.wood} + \Phi_{m,tor.wood} \int_{25}^{300} Cp,tw\, dT + \Phi_{m,H2O} \cdot HHV_{H2O} + \Phi_{m,H2O} \int_{25}^{300} Cp,h2o\ dT$$

21.8 + Q = 0.864*24.6 + Cp,tw*(300-25) + 0.136*2.442 + Cp, h2o*(300-25) = 22.4 → Q= 0.6 kJ/g; endothermic because the wood enters 'cold'!
If ash and moisture are present, these have to be heated c.q. evaporated inside the torrefaction process, and hence the process becomes more endothermic.

g. Pulverized fuel is required by an entrained flow gasifier, as the particles need be very small in order to be entrained by the flow. Advantages: high operating temperatures can be realized (because there is no sand in the gasifier), high capacity, no carbon in bottom slag and negligible tar formation.