Solution Exercise 11: Biomass, Options for technical use

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Question 1: General Questions

a) Oil is formed out of plankton over a time period of roughly 200 million years

b) Biological base materials:

- Oil crops (rape, sunflowers, animal fats)
- Lignocellulosic biomass (Wood, straw, energy crop)
- Sewage sludge, manure, wet wastes
- Photosynthetic micro-organisms (Microalgae, bacteria)

c) The air-fuel equivalence ratio λ describes the ratio between the actual available amount of air to the stoichiometrically necessary amount of air for a complete combustion

Pyrolysis: $\lambda = 0$;
Gasification: $0 < \lambda < 1$
Combustion: $\lambda > 1$

d) Main difference gasification operation modes:

- Autothermal gasification: Partial combustion of the raw material to provide thermal energy
- Allothermal gasification: Thermal energy is provided by external heat source and transferred into the gasifier via heat exchanger tubes

e) Optimization of anaerobic digestion process:

The temperature inside the digestor should be kept around 30°C with a residence time of the biomass between 20 and 30 days. A shorter residence time leads to a lower production of biogas. The production of biogas does not further increase for a residence time larger than 30 days.

Question 2: Production of steam with waste wood chips from a sawmill

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Your engineering company receives an order to develop a combustion process of waste wood chips from a sawmill to produce steam for electricity generation in a steam turbine. To run the process in an optimal way, surplus heat is used in a pre-drying process step to reduce the water content of the wood chips before entering the combustion chamber. Dry wood chips can be regarded as $C_6H_{10.4}O_5$. The process diagram is shown in figure 1. As a good approximation, formula (1) can be used to calculate the combustion process.

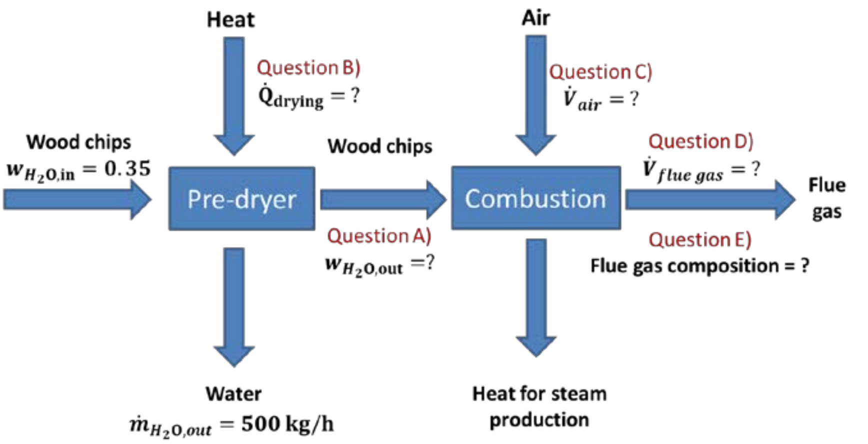

Figure 1: Process scheme of biomass power plant

$$C_nH_aO_b + (n + a/4 - b/2)\ O_2 \rightarrow n\ CO_2 + a/2\ H_2O \qquad (1)$$

A. The pre-dryer is fed with 2000 kg/h of wood chips with a water content w_{H_2O} of 0.35. Calculate the water content after the pre-dryer if 500 kg/h of water are evaporated.

$$\dot{m}_{H_2O,in} = \dot{m}_{wood\ chips,wet} \cdot w_{wood\ chips,wet} = 2000\frac{kg}{h} \cdot 0.35 = 700\ kg/h$$

$$\dot{m}_{biomass,dry} = \dot{m}_{wood\ chips,wet} - \dot{m}_{H_2O,in} = 2000\frac{kg}{h} - 700\frac{kg}{h} = 1300\ kg/h$$

$$\dot{m}_{H_2O,dry\ wood\ chips} = \dot{m}_{H_2O,in} - \dot{m}_{H_2O,evap} = 700\frac{kg}{h} - 500\frac{kg}{h} = 200\ kg/h$$

$$w_{wood\ chips,dry} = \frac{\dot{m}_{H_2O,dry\ wood\ chips}}{\dot{m}_{H_2O,dry\ wood\ chips} + \dot{m}_{biomass,dry}} = \frac{200}{200 + 1300} = 0.1333$$

B. Which amount of heat is required to evaporate the water? Please calculate with an evaporation enthalpy for H_2O of 40.8 MJ/kmol.

$$\dot{n}_{H_2O,evap} = \frac{\dot{m}_{H_2O,evap}}{\tilde{M}_{H_2O}} = \frac{500\,\frac{kg}{h}}{18\frac{kg}{kmol}} = 27.778\,\frac{kmol}{h}$$

$$\dot{Q}_{evap} = \dot{n}_{H_2O,evap} \cdot \Delta H_{vap,H_2O} = 27.778\,\frac{kmol}{h} \cdot 40.8\,\frac{MJ}{kmol} = 1133.33\,\frac{MJ}{h} = 314.81\,kW$$

C. Calculate the required volume flow of air for a stoichiometric combustion of the wood chips. The composition of the combustion air is y_{N_2} = 0.79 and y_{O_2} = 0.21. The molar volume of air at standard conditions is 22.4 m^3/kmol

$$\dot{n}_{C_6H_{10.4}O_5} = \frac{\dot{m}_{C_6H_{10.4}O_5}}{\tilde{M}_{C_6H_{10.4}O_5}} = \frac{1300\,\frac{kg}{h}}{162.4\,\frac{kg}{kmol}} = 8.00\,\frac{kmol}{h}$$

$$\frac{\dot{n}_{C_6H_{10.4}O_5}}{\dot{n}_{O_2}} = \frac{1}{n+\frac{a}{4}+\frac{b}{2}} = \frac{1}{6+2.6-2.5} = \frac{1}{6.1} = 0.16$$

$$\dot{n}_{O_2} = \frac{\dot{n}_{C_6H_{10.4}O_5}}{0.16} = \frac{8.00\,\frac{kmol}{h}}{0.16} = 48.8\,\frac{kmol}{h}$$

$$\dot{n}_{air} = \frac{\dot{n}_{O_2}}{\tilde{y}_{O_2,air}} = \frac{48.8\,\frac{kmol}{h}}{0.21} = 232.52\,\frac{kmol}{h}$$

$$\dot{V}_{air} = \dot{n}_{air} \cdot \tilde{V}_m = 232.52\,\frac{kmol}{h} \cdot 22.4\,\frac{m^3}{kmol} = 5208.54\,\frac{m^3}{h}$$

D. Calculate the flue gas composition after the combustion chamber.

Also consider the N_2 content of the combustion air which is constant before and after the combustion

$$\dot{n}_{N_2,in} = \dot{n}_{N_2,out} = \tilde{y}_{N_2,air} \cdot \dot{n}_{air} = 0.79 \cdot 232.52\,\frac{kmol}{h} = 183.70\,\frac{kmol}{h}$$

$$\dot{n}_{CO_2,flue\ gas} = 6 \cdot \dot{n}_{C_6H_{10.4}O_5} = 6 \cdot 8.00\,\frac{kmol}{h} = 48.00\,\frac{kmol}{h}$$

$$\dot{n}_{H_2O,flue\ gas} = 5.2 \cdot \dot{n}_{C_6H_{10.4}O_5} + \frac{\dot{m}_{H_2O,dry\ wood\ chips}}{\tilde{M}_{H_2O}} = \left(5.2 \cdot 8.00 + \frac{200}{18}\right)\frac{kmol}{h} = 52.73\,\frac{kmol}{h}$$

$$\tilde{y}_{H_2O,flue\ gas} = \frac{\dot{n}_{H_2O,flue\ gas}}{\dot{n}_{H_2O,flue\ gas} + \dot{n}_{CO_2,flue\ gas} + \dot{n}_{N_2,in}} = \frac{48.03}{48.03 + 52.73 + 183.7} = 0.185$$

$$\tilde{y}_{CO_2,flue\ gas} = \frac{\dot{n}_{CO_2,flue\ gas}}{\dot{n}_{H_2O,flue\ gas} + \dot{n}_{CO_2,flue\ gas} + \dot{n}_{N_2,in}} = \frac{52.73}{48.03 + 52.73 + 183.7} = 0.169$$

$$\tilde{y}_{N_2,flue\ gas} = \frac{\dot{n}_{N_2,flue\ gas}}{\dot{n}_{H_2O,flue\ gas} + \dot{n}_{CO_2,flue\ gas} + \dot{n}_{N_2,in}} = \frac{183.7}{48.03 + 52.73 + 183.7} = 0.646$$

Question 3: Cold gas efficiency of a gasification process

Dry biomass is gasified in a fluidized bed gasifier. The efficiency of the gasification process has to be judged for a given product gas composition by means of the cold gas efficiency. 2000 Nm^3/h of air and 200 kg/h of steam are used as gasification agents. The product gas composition is given in *Table 2*. Air is as a mixture of 79 Vol.-% N_2 and 21 Vol.-% O_2. All gases can be regarded as ideal. Calculate at norm temperature T_N and norm pressure p_N.

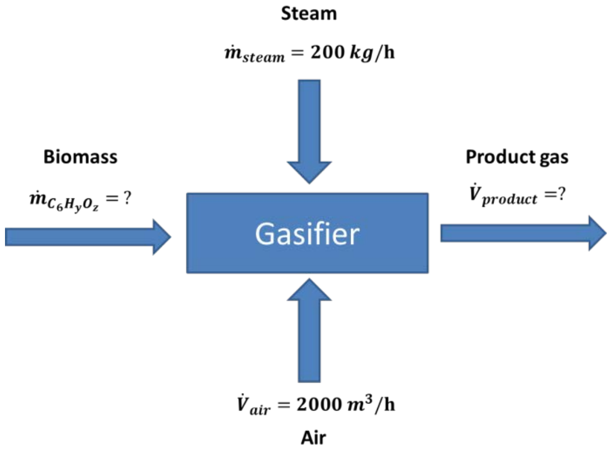

Table 2: Product gas composition after the gasifier

	H_2	CO_2	CO	CH_4	N_2
Vol.-%	27	22	11	7	33

a) The volume flow of nitrogen remains constant during the process

$$\dot{V}_{N_2} = \dot{V}_{air} \cdot \tilde{y}_{N_2,air} = 1580\ {Nm^3}/{h}$$

$$\dot{V}_{product} = \frac{\dot{V}_{N_2}}{\tilde{y}_{N_2,prod}} = 4787.88\ {Nm^3}/{h}$$

b) First, the molar flows of every element in the product gas has to be determined

$$\dot{n}_{C,tot} = \frac{p_N \cdot \dot{V}_{product} \cdot (\tilde{y}_{CO_2} + \tilde{y}_{CO} + \tilde{y}_{CH_4})}{R \cdot T_N} = 8.54 \cdot 10^4\ {mol}/{h}$$

$$\dot{n}_{H,tot} = \frac{p_N \cdot \dot{V}_{product} \cdot (2 \cdot \tilde{y}_{H_2} + 4 \cdot \tilde{y}_{CH_4})}{R \cdot T_N} = 1.75 \cdot 10^5\ {mol}/{h}$$

$$\dot{n}_{O,tot} = \frac{p_N \cdot \dot{V}_{product} \cdot (\tilde{y}_{CO} + 2 \cdot \tilde{y}_{CO_2})}{R \cdot T_N} = 1.17 \cdot 10^5\ {mol}/{h}$$

Then, the molar flow of H and O of the steam has to be determined

$$\dot{n}_{H,steam} = 2 \cdot \frac{\dot{m}_{steam}}{\widetilde{M}_{H_2O}} = 2.22 \cdot 10^4\ {mol}/{h}$$

$$\dot{n}_{O,steam} = \frac{\dot{m}_{steam}}{\widetilde{M}_{H_2O}} = 1.11 \cdot 10^4\ {mol}/{h}$$

Also the molar flow of O that comes into the reactor with air has to be determined

$$\dot{n}_{O,air} = 2 \cdot \tilde{y}_{O_{2,air}} \frac{p_N \cdot \dot{V}_{air}}{R \cdot T_N} = 3.75 \cdot 10^4\ {mol}/{h}$$

$$\dot{n}_{H,Biomass} = \dot{n}_{H,tot} - \dot{n}_{H,steam} = 1.53 \cdot 10^5\ {mol}/{h}$$

$$\dot{n}_{O,Biomass} = \dot{n}_{O,tot} - \dot{n}_{O,steam} - \dot{n}_{O,air} = 6.89 \cdot 10^4\ {mol}/{h}$$

Since carbon only enters the gasifier with biomass, the total molar carbon flow can be used as reference:

$$x = 6\ (Number\ of\ carbon\ atoms\ in\ exemplary\ biomass\ molecule)$$

$$y = x \cdot \frac{\dot{n}_{H,Biomass}}{\dot{n}_{C,tot}} = 10.73$$

$$z = x \cdot \frac{\dot{n}_{O,Biomass}}{\dot{n}_{C,tot}} = 4.83$$

Now, the molar mass of the biomass can be determined:

$$\widetilde{M}_{Biomass} = \frac{12 \cdot x + 1 \cdot y + 16 \cdot z}{1000} = 0.160\ \frac{kg}{mol}$$

$$\dot{n}_{Biomass} = \frac{\dot{n}_{C,tot}}{x} = 1.42 \cdot 10^4 \frac{mol}{h}$$

$$\dot{m}_{Biomass} = \dot{n}_{biomass} \cdot \widetilde{M}_{biomass} = 2280 \ \frac{kg}{h}$$

c) The molar mass of the exemplary biomass molecule and the mass flow of biomass entering the gasifier are needed to calculate the cold gas efficiency

$$LHV_{product} = \tilde{y}_{CH_4} \cdot LHV_{CH_4} + \tilde{y}_{CO} \cdot LHV_{CO} + \tilde{y}_{H_2} \cdot LHV_{H_2} = 6.81 \ {}^{MJ}/_{m^3}$$

$$\eta_{CG} = \frac{\dot{V}_{product} \cdot LHV_{product}}{\dot{m}_{Biomass} \cdot LHV_{biomass}} = 0.75$$

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Reasons for conversion of biomass into gas

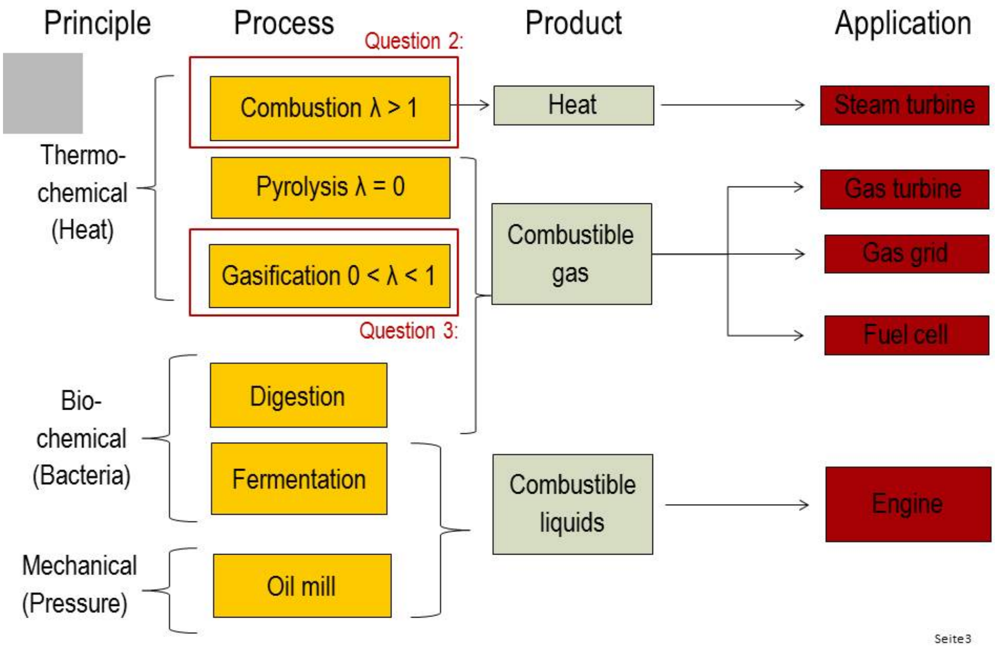
- Better handling
- Better transportability
- Better combustion properties
- Possibility to do synthetic chemistry

Compared with solid biomass

(tree trunks, wood chips, wood pellets)

Source: www.heizungsfinder.de

Conversion routes of biomass



Comparison moisture vs. water content

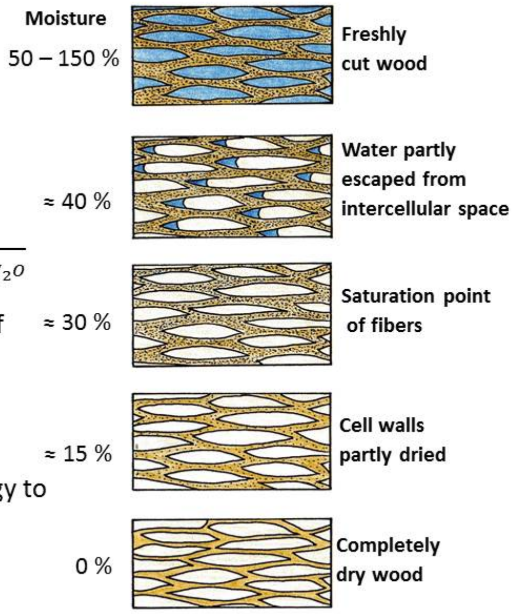
– **Moisture z_{H_2O}:**

– $z_{H_2O} = \frac{m_{H_2O}}{m_{Biomass,dry}}$

– **Water content w_{H_2O}:**

– $w_{H_2O} = \frac{m_{H_2O}}{m_{Biomass,wet}} = \frac{m_{H_2O}}{m_{Biomass,dry} + m_{H_2O}}$

- How much water is contained in 300 kg of wood with a water content of 25 % ?
- How high is the moisture content z_{H_2O} ?
- How high is the required amount of energy to reduce the water content by 50 % ?
- $\Delta H_{vap,water} = 2.44 \frac{MJ}{kg}$



www.diekreativewerkstatt.de

Question 2 – Combustion of wooden biomass

- Basic formula for a combustion:

$$-C_nH_aO_b + (n + a/4 - b/2)\ O_2 \rightarrow n\ CO_2 + a/2\ H_2O$$

- Calculate the stoichiometric necessary volume flow of O_2 for the combustion of 1000 kg/h dry biomass with the ratio formula $C_6H_{8.58}O_{3.96}$
- $\widetilde{M}_{C_6H_{8.58}O_{3.96}} = 144\ ^{g}/_{mol}$
- $\widetilde{V}_m = 22.4\ ^{L}/_{mol}$

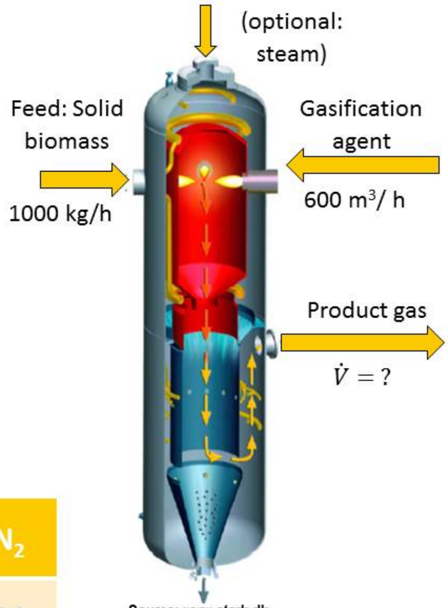
- Calculate the actual air-fuel equivalence ratio λ if 5500 m³/h are used as combustion air
- $\tilde{y}_{O_2,air} = 0.21$; $\tilde{y}_{N_2,air} = 0.79$
- $\lambda_{AF} = \frac{Actual\ amount\ of\ air\ for\ combustion}{Stoichiometric\ amount\ of\ air\ for\ complete}$

www.grundofen.de

Question 3 – Hints for gasification process

- Hint: **Total flow of N_2** remains **constant** during process
- 1000 kg/h of biomass are gasified with 600 m³/ h of air that serves as gasification agent
- Calculate the total volume flow of product gas by means of the data given in the following table:
- Calculate at normal conditions and with ideal gases
- $\widetilde{V}_m = 22.4\ ^{m^3}/_{kmol}$; $\tilde{y}_{N_2,air} = 0.79$

	H_2	CO_2	CO	CH_4	N_2
Vol.-%	24	27	13	12	24



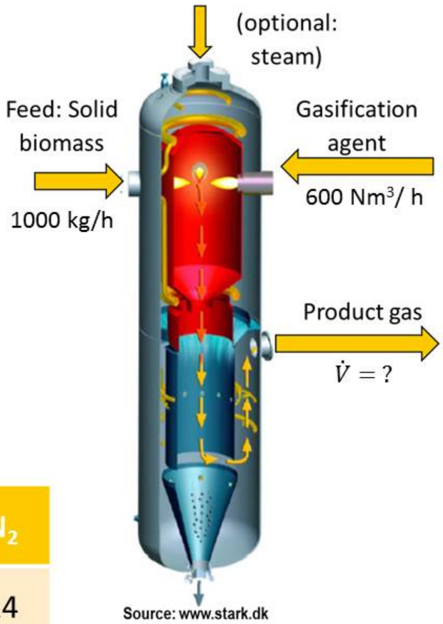
Source: www.stark.dk

Question 3 – Hints for gasification process

- Calculate the lower heating value of the product gas:
- $LHV_{CO} = 12.63 \, {}^{MJ}/_{Nm^3}$
- $LHV_{H_2} = 10.78 \, {}^{MJ}/_{Nm^3}$
- $LHV_{CH_4} = 35.88 \, {}^{MJ}/_{Nm^3}$
- $LHV_{Fuel} = 20 \, {}^{MJ}/_{kg}$

- Calculate the cold gas efficiency η_{CG} of the gasification process
- $\eta_{CG} = \frac{LHV_{product} \cdot \dot{V}_{product}}{LHV_{fuel} \cdot \dot{m}_{fuel}}$

	H_2	CO_2	CO	CH_4	N_2
Vol.-%	24	27	13	12	24



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