Effect of Fast Pyrolysis Conditions on the Biomass Solid Residues at High Temperatures (1000-1400°C)

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Effect of Fast Pyrolysis Conditions on the Biomass Solid Residues at High Temperatures (1000-1400°C)

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Objectives

- Woody (pine, beech) and herbaceous biomass (alfalfa straw, wheat straw, rice husk)
- Pyrolysis of smaller and larger particle size (> 0.5 mm)
- Experimental investigations and modeling of char yield at fast heating rates \((10^{2}-10^{4}^\circ\text{C/s})\) and at high temperatures (up to 1500\(^\circ\text{C}\))
- Potassium and silicon bearing compounds influence on the char yield, reactivity and morphology
## Experimental setup

<table>
<thead>
<tr>
<th>Operational parameter</th>
<th>Wire mesh reactor</th>
<th>Single particle reactor</th>
<th>Drop tube reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Temperature [°C]</td>
<td>1650</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Heating rate [°C/s]</td>
<td>≤ 5000</td>
<td>≤ 200</td>
<td>≤ ≈ 10^4</td>
</tr>
<tr>
<td>Particle size range [mm]</td>
<td>≤0.65</td>
<td>≥ 3</td>
<td>≤ 1</td>
</tr>
</tbody>
</table>
Luleå University Drop-Tube Furnace

- Atmosphere: N$_2$, O$_2$, H$_2$, CO$_2$, H$_2$O, Ar, CO
- $T_{\text{maximal}}$: 1500°C
- Heating rates: up to $10^4$°C/s

Diagram elements:
- Biomass feeder (syringe pump)
- Syringe pump (water)
- Cooling water
- Ceramic packed bed
- Tube furnaces
- Mass flow controllers
- Gas cylinders
- Optical accesses
- Gas/tar analysis
- Cyclone
- Filter for soot collection
- Char bin
Char yield comparison

WMR (1000°C, 1 s holding time, 0.2mm)  DTF (≈10⁴°C/s) and WMR (10³°C/s, 1 s, 0.2mm)

- (Graph 1) Char yields of wood and herbaceous biomass in the WMR decreased with the increasing temperature
- (Graph 1) At heating rates (> 600°C/s), the char yield is nearly constant, except wheat straw
- (Graph 2) DTF heating rates led to the char yield decrease
- (Graph 2) At final temperatures (> 1000°C) in the DTF, only wheat straw char showed 3.5% points decrease
Graphs 1 and 2 show char yield (daf) of pinewood (1), leached wheat straw (2), beechwood (3), wheat straw (4) and alfalfa straw (5) over the potassium content in original biomass.

Potassium compared to all other ash elements in the fuels had the highest influence on the char yield (daf).

At intermediate heating rates (WMR), potassium influenced the char yield significantly more than at high heating rates in the DTF.
Graph 1 shows that silica has no influence on the char yield compared to potassium. Graph 2 shows that the reactivities of pinewood and rice husk chars were similar in oxidation, indicating less influence of silica on the char reactivity. Graph 2 shows that the alkali rich wheat straw chars were 6, 18 and 50 times more reactive than wood and rice husk chars.
The larger pinewood particles (> 0.85 mm) required more than 1 s holding time for the complete conversion at intermediate and fast heating rates.

The influence of heating rate on the char yields was less pronounced for particle sizes from 0.85 to 4 mm obtained at temperatures > 1000°C/s.

**WMR:**
- Heating rate: 1000°C/s
- Holding time: 1 s
- Particle size: 0.25-0.355 mm, 0.85-1 mm

**DTF:**
- Heating rate: 10^4°C/s
- Residence time: 1 s
- Particle size: 0.2-0.4 mm, 0.85-1 mm

**SPR:**
- Heating rate: 200°C/s
- Particle size: 3-5 mm pine cubes
Char and soot yields in the drop tube reactor

- Both graphs compared char and soot yields of woody (Graph 1) and herbaceous biomass (Graph 2)
- Lignin content of leached wheat straw decreased from 25.6 to 15.6 wt.%
- Lignin has a stronger influence on the soot formation than potassium
Soot morphology with TEM microscopy

Pinewood soot, 1250°C

- Mean $d_p = 77.7$ nm
- $\sigma_g = 2.2$
- Min. $d_p = 27$ nm
- Max. $d_p = 263$ nm

Wheat straw soot, 1250°C

- Mean $d_p = 42.6$ nm
- $\sigma_g = 1.9$
- Min. $d_p = 11.5$ nm
- Max. $d_p = 165.4$ nm

Pinewood soot, 1400°C

- Mean $d_p = 47.8$ nm
- $\sigma_g = 1.9$
- Min. $d_p = 8.9$ nm
- Max. $d_p = 174$ nm

Wheat straw soot, 1400°C

- Mean $d_p = 30.8$ nm
- $\sigma_g = 1.8$
- Min. $d_p = 10.3$ nm
- Max. $d_p = 102.1$ nm
Soot morphology with TEM microscopy

- Pinewood formed particles with the pre-dominating multi cores and located on a larger distance
- Beechwood formed a mixture of multi cores and single cores at 1250 and 1400°C
- Wheat straw soot particles were mostly with single cores
- TEM microscopy showed a more graphitic structure of beechwood and wheat straw soot particles
1D modeling of fast pyrolysis

Broido-Shafizadeh schema*

Original biomass \rightarrow Metaplast \rightarrow Volatiles \rightarrow Char

Reaction equations*:

\[ r_i = k_i \cdot m_i \]
\[ k_i = -k_0,i \cdot \exp \left( -\frac{E_{a,i}}{R \cdot T} \right) \]
\[ E_{a,3} = E_{a,3}(\omega) = E_a \cdot (1 - (1 - C_1)) \cdot \left( 1 - \exp \left( \frac{\omega}{C_2} \right) \right) \]

Initial boundary conditions*:

\[ m_{BM}(0) = 1 \]
\[ m_{MP}(0) = m_{VM}(0) = m_{Char}(0) = 0 \]
\[ T_{particle}(0,r) = T_{amb} \]

\( C_1, C_2 = \text{constants} \)
\( \omega = \text{potassium content} \)

*Broido et al., 1971, Bradbury et al. 1979 et al.
**1D modeling of fast pyrolysis**

**Pinewood 0.2mm particles**

**Advantages:**
- Internal thermal gradient
- Potassium effect on the char yield
- A simple 1D model
- Unique kinetic parameters

**Improvement:**
- No differences in the char yield of smaller and larger particles => secondary reactions
- Oversimplifications
Summary

- The heat treatment temperature and potassium content affected the char yield stronger than the heating rates and differences in the plant cell wall compounds between 600 and 3000°C/s.

- Potassium compared to all other ash elements in the fuels had the highest influence on the char yield.

- At intermediate heating rates (WMR), the catalytic effect of potassium was more pronounced than at high DTF heating rates.

- Low lignin content leads to the lower soot yields.

- The proposed kinetic model for the fast biomass pyrolysis is relatively simple and predicts reasonably the char yield of wood and herbaceous biomass particles < 10 mm.
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