Studying the combustion of biomass particles using a Lagrangian Method

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Overview

1. Motivation

2. Modeling approaches

3. Lagrangian modeling of biomass combustion

4. Results
   a) Comparison coal/biomass particle motion
   b) Temperature distribution in biomass particles
   c) Impact of a non-uniform temperature distribution on the combustion process
   d) Slagging

5. Conclusions
Co-combustion

- Combustion of two different fuels in the same combustion system (e.g. coal (~90% wt) and biomass (~10% wt)).

  ➡️ Reduction of CO₂ emissions

- **Negative aspects:**
  - High slagging and fouling tendency
  - High carbon content in fly and bottom ash

  ➡️ CFD modelling of co-combustion in order to optimize the combustion process
Modeling approaches

Eulerian modeling of pulverized coal combustion

- Particles are assumed to be sufficiently small to adapt instantly to the local conditions of the carrier field.

  ➡️ Transport equations are written for the gas/particle mixture assuming a negligible slip-velocity between the gas phase and the fuel particles

Lagrangian modeling of biomass combustion – a post-processing approach

- Due to the increased inertial forces biomass particles do **NOT** instantly adapt to the local conditions of the carrier field

  ➡️ Lagrangian modeling of the particle movement.

- Mass fractions of biomass are assumed to be small

  ➡️ Post-processing approach
Langrangian modeling of biomass combustion

• Particle motion
  
  a) Momentum equation for dense particles
  \[
  \frac{d\vec{u}_p}{dt} = \frac{\vec{u}_s - \vec{u}_p}{\tau_p} + \vec{g} \quad \text{where} \quad \tau_p = \frac{\rho_p}{\rho_f} \frac{4d_p}{3C_d |\vec{u}_s - \vec{u}_p|}
  \]

  b) Closure is obtained through the use of a stochastic term
  \[
  d\vec{u}_s = -\frac{1}{\rho_f} \nabla \langle P \rangle dt - \frac{\vec{u}_s - \langle \vec{u}_f \rangle}{T^*_L} dt + \sqrt{C_0 \varepsilon} \ d\vec{W}
  \]
  
  where \( d\vec{W} \) is an increment of the Wiener process and \( T^*_L = \frac{T_L}{1 + \beta |\vec{u}_s - \vec{u}_p|} \sqrt{\frac{2\kappa}{3}} \)

• Physicochemical phenomena
  
  a) Particle drying – pressure equilibrium assumption
  
  □ Mass transfer \( \dot{m}_{vap} = 2\pi r_p \frac{\lambda}{c_p} \text{Sh} \ln \left( \frac{1 - c_{vap}^\infty}{1 - c_{vap}^{sat}} \right) \) where \( c_{vap}^{sat} = f(T_p) \)
  
  □ Heat transfer \( \dot{q}_{evap} = L_v^0 \dot{m}_{vap} \)
Langrangian modeling of biomass combustion

b) Devolatilisation – Kobayashi model

- Kinetic is given by two competitive reactions

\[ \frac{dm_{ch}}{dt} = -(k_1 + k_2)m_{ch} \text{ where } k_{1,2} = f(T_p) \]

- Heat release of the slightly endothermic reactions is neglected

c) Char combustion - \( C + \frac{1}{2}O_2 \rightarrow CO \)

- Mass transfer

\[ \frac{dm_{ck}}{dt} = -S_e P_{O_2}^\infty K_{glob} \text{ where } K_{glob} = f(T_p) \]

- Heat release

\[ \Delta_f h_{comb} = \Delta_f h_{CO}(T_p) - \left( \Delta_f h_{ck}(T_p) + \frac{1}{2} \Delta_f h_{O_2}(T_f) \right) \]

All physicochemical phenomena depend on the particle temperature!
Impact of the particle temperature profile

Small particles e.g. coal (no temperature gradient)

Raw fuel particle ➔ Dried fuel particle ➔ Char particle ➔ Ash particle

Large particles e.g. biomass (temperature gradient)

Raw fuel particle ➔ Dried fuel particle ➔ Char particle ➔ Ash particle
Combustion System

- Thermal power: 3MWth
- 10 m long; 1,5m diameter

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Mass flow rate Air (kg/s)</th>
<th>Mass flow rate Coal (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary air (red)</td>
<td>0,19</td>
<td>0,125</td>
</tr>
<tr>
<td>Secondary swirled air (green)</td>
<td>0,64</td>
<td>-</td>
</tr>
<tr>
<td>Tertiary air (blue)</td>
<td>0,58</td>
<td>-</td>
</tr>
</tbody>
</table>
Results: Flow field characteristics

- Simulated velocity field of the gas phase obtained using an Eulerian approach.

Three distinct recirculation zones can be observed:

- Internal recirculation
- External recirculation

Velocity[Z]
- 4.870e+01
- 3.467e+01
- 2.065e+01
- 6.623e+00
- -7.401e+00
Results: Coal particle movement

- Simulated particle motion of coal particles (25µm) using a Lagrangian approach.

! Coal particles are sufficiently small to adapt instantly to local flow field changes!
Results: Comparison coal/biomass

- Simulated particle motion of coal (25µm) and biomass (800µm) particles using a Lagrangian approach.

! Biomass particles do NOT instantly adapt to local flow field changes!

Impact on the physicochemical phenomena
Results: Biomass particle temperature

- Temperatures in the particle core (layer1) and the most outer layer (layer5);
  Biomass particles 800µm.

![Diagram showing particle temperature](image)
Results: Impact on devolatilisation

- Coal mass fraction in the particle core (layer1) and the most outer layer (layer5);
  Biomass particles 800µm.
Results: Comparison of mono-/multilayer

- Coal mass fractions obtained considering (multi-layer) and neglecting (mono-layer) temperature gradients inside the particles; Biomass particles 800µm.

! Devolatilisation lasts longer!

Mono-layer

Multi-layer
Results: Comparison of mono-/multilayer

- Char mass fractions obtained considering (multi-layer) and neglecting (mono-layer) temperature gradients inside the particles; Biomass particles 800µm.
Slagging models

Coal particles

- The slagging probability is given by:
  \[ \kappa = \begin{cases} \frac{\mu_c}{\mu_p} & \text{si } \mu_p > \mu_c \\ 1 & \text{si } \mu_p \leq \mu_c \end{cases} \]

- Additionally, a critical temperature condition is considered. If the particle temperature is lower than the critical temperature \( T_c \) it will not stick to the wall.

Biomass particles

- The slagging probability is a function of the melted ash mass fraction:
  \[ \kappa = Y_{f,\text{sel}}(T_p) \frac{m_{\text{sel}}}{m_{\text{silice}}} + Y_{f,\text{silice}}(T_p) \frac{m_{\text{silice}}}{m_{\text{sel}} + m_{\text{silice}}} \]

- Additionally, a critical temperature condition is considered. If the particle temperature is lower than the critical temperature it will not stick to the wall
Results: Slagging of coal particles

- Mass flux of deposited particles for several critical temperatures $T_c$ and viscosities $\mu_c$

<table>
<thead>
<tr>
<th>Case</th>
<th>$\mu_c$ (Pa s)</th>
<th>$T_c$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$10^6$</td>
<td>1 173</td>
</tr>
<tr>
<td>Case 2</td>
<td>$10^4$</td>
<td>1 273</td>
</tr>
<tr>
<td>Case 3</td>
<td>768</td>
<td>1 400</td>
</tr>
</tbody>
</table>

High deposition rate

Low deposition rate
Results: Slagging of biomass particles

- Mass flux of deposited particles for several critical temperatures $T_c$

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>900</td>
</tr>
<tr>
<td>Case 2</td>
<td>1000</td>
</tr>
<tr>
<td>Case 3</td>
<td>1402</td>
</tr>
</tbody>
</table>

High deposition rate

Low deposition rate
Conclusion

- **Slipping velocities between the gas phase and the fuel particles are considered applying the Lagrangian approach**
  - Coal particles adapt instantly to local flow field changes.
  - Biomass particles **don’t** adapt instantly to local flow field changes.

- **Determination of particle temperature profiles by means of a multilayer model**
  - The temperature profile has a significant impact on the devolatilisation process.
  - Better prediction of the particle composition (coal, char, ash and moisture content) at the outlet.
  - Differences concerning unburned carbon can be neglected.

- **Implementation of a slagging model which allows to predict the areas where slagging is more likely to occur**
Thank you for your attention