CFD Simulation of Biofuel and Coal Co-Combustion in a Pulverized Coal Fired Furnace

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CFD simulation of biofuel and coal co-combustion: Scope

- CFD applied to simulate co-combustion in a (normally) pulverized coal fired unit
  - Main fuel: Russian hard coal
  - Supplementary fuel 1: Torrefied biomass (TF)
    - TF shares of to 30 wt-% and 50 wt-% considered
    - 24 % and 43 % on energy basis
  - Supplementary fuel 2: Pyrolysis oil (bio-oil, BO)
    - BO share of 25 % by energy

- Focus: combustion / furnace process
  - Ignored: biofuel availability, storage etc.
- Fast pyrolysis for bio-oil production
  - Biomass pyrolysis eg. in CFB reactor + rapid cooling & quenching ⇒ pyrolysis oil + char + NCG
    - organic oil yield 40-70 wt-%, dry (wood)
## CFD modelling approach: Summary

### CFD code used for simulations: Fluent 12.1

List of relevant CFD sub-models applied:

<table>
<thead>
<tr>
<th>Turbulence (code)</th>
<th>standard k-ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation (code)</td>
<td>Discrete Ordinates.WSGGM for gas radiative properties</td>
</tr>
<tr>
<td>Turb.-ch. interaction (VTT)</td>
<td>Eddy Dissipation Concept (EDC)</td>
</tr>
<tr>
<td>Main chemistry (VTT)</td>
<td>Global 3-step scheme with CO and H₂ as intermediates</td>
</tr>
<tr>
<td>Soot (Fortum/VTT)</td>
<td>BYU model (Fortum/VTT specific, user defined)</td>
</tr>
<tr>
<td>Fuel particles/droplets (Fortum/VTT)</td>
<td>Lagrangian tracking, user-defined sub-models for pulverized coal, torrefied biomass and pyrolysis oil</td>
</tr>
<tr>
<td>NOx (Fortum/VTT)</td>
<td>NOx sub-model for pulverized fuel combustion (global chemistry + EDC type of mixing model)</td>
</tr>
</tbody>
</table>
CFD case example: a PC furnace

- Full load: $275 \text{ MW}_{\text{fuel}}$
  - corner firing design
  - 12 low NOx coal burners
  - 8 gas/oil burners
  - over fire air system (OFA)

- Computational domain
  - mesh size: 1.6 million cells
  - 100 % hexahedral cell topology
Fuels in co-combustion

- Russian hard coal

- Torrefied biomass

- Pyrolysis oil (bio-oil)

- Basic assumption: coal and TF are milled together in existing coal mills

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture [w-%]</td>
<td>9.6</td>
<td>6.7</td>
</tr>
<tr>
<td>Ultimate analysis [w-%,dry]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>71.8</td>
<td>53.2</td>
</tr>
<tr>
<td>H</td>
<td>4.8</td>
<td>5.8</td>
</tr>
<tr>
<td>O</td>
<td>9.1</td>
<td>40.5</td>
</tr>
<tr>
<td>N</td>
<td>2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>S</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td>ash + others</td>
<td>11.7</td>
<td>0.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bio-Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture [w-%]</td>
</tr>
<tr>
<td>Ultimate analysis [w-%,dry]</td>
</tr>
<tr>
<td>C</td>
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<tr>
<td>H</td>
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<tr>
<td>O</td>
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<tr>
<td>N</td>
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<tr>
<td>S</td>
</tr>
<tr>
<td>ash + others</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>LHV [MJ/kg], wet</th>
<th>LHV [MJ/kg], dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>volatiles</td>
<td>35.7</td>
<td>82.5</td>
</tr>
<tr>
<td>char</td>
<td>52.6</td>
<td>17.1</td>
</tr>
<tr>
<td>FR (fuel ratio)</td>
<td>1.47</td>
<td>0.21</td>
</tr>
<tr>
<td>LHV [MJ/kg]</td>
<td>24.5</td>
<td>18.4</td>
</tr>
</tbody>
</table>
Estimated fuel particle size distributions after milling

- Coal fineness is assumed to degrade as TF fraction increases
  - experimental milling results
- TF particle size distribution is assumed to remain unchanged between the cases
- Bio-oil presumed to be atomized (Y-type of oil gun) with $d_{32} = 80 \ \mu m$
## CFD case comparison

<table>
<thead>
<tr>
<th></th>
<th>Coal 100%</th>
<th>TF 30 wt-%</th>
<th>TF 50 wt-%</th>
<th>BO 25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel input [MW]</td>
<td>275</td>
<td>275</td>
<td>275</td>
<td>275</td>
</tr>
<tr>
<td>coal [%]</td>
<td>100</td>
<td>76</td>
<td>57</td>
<td>75</td>
</tr>
<tr>
<td>TF [%]</td>
<td>0</td>
<td>24</td>
<td>43</td>
<td>25</td>
</tr>
<tr>
<td>Total fuel flow rate [kg/s]</td>
<td>11.2</td>
<td>12.1</td>
<td>12.8</td>
<td>12.7</td>
</tr>
<tr>
<td>Total Stoichiometric Ratio</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>SR coal burner</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>SR oil burner</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1.0</td>
</tr>
<tr>
<td>SR burner zone</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.85</td>
</tr>
<tr>
<td>Flue gas $O_2$ (vol-%, wet)</td>
<td>4.4</td>
<td>4.4</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Air flow rate [kg/s]</td>
<td>123.5</td>
<td>121.2</td>
<td>119.3</td>
<td>122.1</td>
</tr>
<tr>
<td>Flue gas flow rate [kg/s]</td>
<td>133.3</td>
<td>132.2</td>
<td>131.3</td>
<td>133.6</td>
</tr>
</tbody>
</table>

+ sensitivity study: TF 50 wt-% with the original coal fineness
CFD simulation results: Gas temperature

Coal 100 %

TF 50 wt-%

BO 25 %

T [°C]

1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850

↑

↓
CFD simulation results: FEGT & Heat transfer

- Evap. heat transfer below nose [MW]
- FEGT (nose) [°C]

Graph showing comparison of evaporation heat transfer and FEGT for different fuel types:
- Coal
- TF 30 wt-%
- TF 50 wt-%
- TF 50 wt-%, fine coal
- BO 25 %
CFD simulation results: Burnout

Char combustion & gasification
TF 50 wt-%
**CFD simulation results: Fly ash UBC**

- UBC mainly originated from coal, while TF only has a minor contribution

- Degrading milling for coal

- Increased UBC in TF co-firing

- Sensitivity study indicates…
  - no change in UBC, if coal fineness is maintained (eg. separate crushing of TF)
CFD simulation results: CO concentration

Coal 100 %
SR bzone = 1.0

TF 50 wt-%
SR bzone = 1.0

BO 25 %
SR bzone = 0.85
CFD simulation results: CO at nose and domain exit

- CO_out [ppm]
- CO_nose [ppm]

<table>
<thead>
<tr>
<th>Material</th>
<th>CO_out</th>
<th>CO_nose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>~270</td>
<td>~300</td>
</tr>
<tr>
<td>TF 30 wt-%</td>
<td>~500</td>
<td>~400</td>
</tr>
<tr>
<td>TF 50 wt-%</td>
<td>~400</td>
<td>~350</td>
</tr>
<tr>
<td>TF 50 wt-%, fine coal</td>
<td>~200</td>
<td>~250</td>
</tr>
<tr>
<td>BO 25 %</td>
<td>~500</td>
<td>~550</td>
</tr>
</tbody>
</table>
CFD simulation results: NO concentration

Coal 100 %

TF 50 wt-%

BO 25 %
CFD simulation results: NOx emission

NOx [mg/m^3, dry 6 % O2]

- Coal
- TF 30 wt-%
- TF 50 wt-%
- TF 50 wt-%, fine coal
- BO 25 %
CFD simulation results: Fouling & corrosion tendencies

- Low risk of slagging and corrosion of evaporator walls in the furnace and cases investigated
  - Mainly oxidizing conditions next to walls: particles and unburned gases flow to the centre of the furnace
- Superheater zone might be more vulnerable to corrosion in co-firing cases
  - Biomass originated ash involved
  - Reduced total ash flow
  - Predicted increase in FEGT

\( \text{O}_2 \text{ concentration} \quad \text{TF 50 wt-\%} \)
\( \text{Particle concentration at BNR levels / TF 50 wt-\%} \)
CFD simulation results: Summary

- Torrefied biomass and bio-oil co-combustion with coal investigated in a PC furnace up to TF share of 50 wt-% and BO share of 25 % by energy
- No drastic change in combustion and furnace heat transfer predicted in general
  - Co-firing seems feasible from the combustion point of view
  - Flame stability possibly an issue with high bio shares or at partial burner load in TF co-firing
- Small reduction in evaporator heat transfer and slight increase in FEGT predicted
- Fly ash UBC estimated to increase in TF cases
  - Direct consequence of degrading coal particle fineness
  - Reduced total ash flow
  - Solid combustion efficiency not much affected
- Actual CO trend unclear due to model uncertainty but no remarkable change expected
- NOx emission reduction up to 20% (or more) possible
- Improved burner operation in TF co-firing, if coal fineness can be maintained (eg. separate crushing of TF)
  - Heat transfer, comb. efficiency, UBC, CO, NOx
- Superheater region might become more vulnerable to corrosion considering the increase in FEGT among other things
Acknowledgements

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