Modeling of fuel flow in commercial scale CFB furnace

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INTRODUCTION

- ERA-NET Bioenergy project: Advanced Biomass Combustion Modelling for Clean Energy Production
- Goal was to develop and improve the modelling methods for biomass combustion in circulating fluidized bed (CFB) boilers
  - fluidization behavior
  - combustion properties
  - emissions formation
  - heat transfer
- Improved models for biomass combustion
- Models enable more accurate development, design and analysis of CFB boilers utilizing biomass.

Project partners

Lappeenranta University of Technology
INTRODUCTION

- CO₂ in energy production deemed an emission
  - EU: share of renewables to 20% by 2020 with reduction of 20% of CO₂-emissions compared to 1990 levels
  - Biomass defined as CO₂-neutral
    - Combustion and co-combustion of biomass to replace fossil fuels

- Much research aimed in utilization of biomass in energy production
  - Direct combustion, co-combustion, fuel pretreatment technologies and thermal conversion processes
  - Typically biomass, compared to fossil fuels such as coal
    - Higher diversity in chemical composition and physical properties
    - Higher moisture and volatile material content
    - Lower density and heating value (lower energy density)
    - Can contain harmful compounds (alkalis, chlorine..)
  - Biomass sets challenges to some conventional technologies, while fluidized beds can handle them quite easily
CFB AND BIOMASS

Fluidized beds are insensitive to changes in fuel chemical and physical properties, high moisture content and enable high with efficiency with low rank fuels.

As fuel particle enters the furnace it is immediately surrounded by hot gas and solids, which causes rapid temperature rise:
- Drying
- Devolatilization
- Fragmentation
- Combustion

These have additional effects on the hydrodynamics as particle density and size/shape can change.
CFB MODEL FRAME

- Flow of solids
  - Semi-empirical submodels and potential flow
- Flow of gas
  - Simplified momentum equation (solids drag and pressure)
- Flow of fuel
  - Convection, diffusion and forces
- Combustion and gasification of fuel
  - Drying, devolatilization, char combustion, water-gas and Boudouard reactions
- Comminution of solids
- Combustion and gasification reactions
- Heat transfer within bed and to surfaces
- Sorbent reactions and sulfur capture
- Post-solver for NO\textsubscript{x} emissions
CFB MODEL FRAME

- Solid material types
  - fuel, sand, sorbent
  - combustible fuel
  - inert ash
  - sorbent (CaCO$_3$, CaO, CaSO$_4$, CaS, inert)
- Gas components
  - O$_2$, CO$_2$, H$_2$O, SO$_2$, CO, H$_2$, CH$_4$, C$_2$H$_4$, C$_g$, H$_2$S, NO, N$_2$O, HCN, NH$_3$, Ar, N$_2$
FUEL FLOW MODEL

Continuity equation of fuel char

\[
\int_A \varepsilon_{c,i} \rho_c v_{c,i} \cdot dA - \int_A D_{c,i} f_{0,i} \left( \frac{\varepsilon_{c,i} \rho_c}{f_{0,i}} \right) \cdot dA = \int_V \phi_{c,i} dV - \int_V R_{c,i} dV - \int_V \sum_{j,j \neq i} k_{c,ij} \varepsilon_{c,i} \rho_c dV + \int_V \sum_{j,j \neq i} k_{c,ji} \varepsilon_{c,j} \rho_c dV
\]

The continuity equation has already included the convection term, but in the old code, the velocity has been set to zero and the char has spread by dispersion towards the given target profile \( f_{0,i} \).

Char momentum equation

\[
\frac{d}{dt} \int_V \rho u dV + \int_A \varepsilon_{c,i} \rho_c \bar{u}_{c,i} \bar{u}_{c,i} \cdot dA = \int_V \varepsilon_{c,i} \rho_c g dV + \int_V K_{g-c} (\bar{u}_g - \bar{u}_c) dV + \int_V K_{s-c} (\bar{u}_s - \bar{u}_c) dV
\]

Pressure and viscous terms are neglected.
FUEL FLOW MODEL

- For momentum exchange Gidaspow and Syamlal models were used
  - Syamlal (1987) model for solids – fuel momentum exchange
  - Radial distribution coefficient by Lebowitz (1964)

\[
K_{sf} = \frac{3(1+e)(\pi / 2 + \mu \pi^2 / 8)\varepsilon_s \varepsilon_s \rho_f \rho_f (d_s + d_f)^2 g_0 |\bar{u}_s - \bar{u}_f|}{2\pi (\rho_s d_s^3 + \rho_f d_f^3)}
\]

\[
g_0 = \frac{1}{\varepsilon_g} + \frac{3d_s d_f}{\varepsilon_g^2 (d_s + d_f)} \sum_{i=1}^{M} \varepsilon_i
\]

- Gidaspow (1992) model for gas – fuel momentum exchange
- Schiller-Nauman drag coefficient (1933)

\[
K_{g-c} = \begin{cases} 
\frac{3}{4} C_D \frac{\varepsilon_c \varepsilon_g \rho_g |\bar{u}_g - \bar{u}_c|}{d_c} e^{-2.65} & \varepsilon_g > 0.8 \\
150 \frac{\varepsilon_c (1-\varepsilon_g) \mu_g}{\varepsilon_g d_c^2} + 1.75 \frac{\rho_g \varepsilon_g |\bar{u}_g - \bar{u}_c|}{d_c} & \varepsilon_g \leq 0.8 
\end{cases}
\]

\[
C_D = \begin{cases} 
\frac{24}{\varepsilon_g \text{Re}_c} (1 + 0.15(\varepsilon_g \text{Re}_c)^{0.687}) & \text{Re}_c < 1000 \\
0.44 & \text{Re}_c \geq 1000
\end{cases}
\]
FUEL FLOW MODEL

Transient term then modified and used as a relaxation term in the iteration

$$\frac{d}{dt} \int_V \rho u dV = \rho V \frac{(u^*_i - u_i)}{c_\tau}$$

Where $u$ is previous iteration round value and $u^*$ is the new velocity to be solved and $c_\tau$ is momentum response time.

Further more, the momentum equation is discretized in three dimensions for staggered grid approach. After discretization, solution of forces and convective flows for each cell, momentum equation and rest of the model parameters are solved iteratively until pseudo-steady-state is reached.
SMALL SCALE TESTS

Fuel feed 1 kg/s (h=1.0m).

Grid air 10 kg/s

Open top

Domain size 4 m x 2 m x 8 m.
Live calculation cells 10 x 5 x 20.

Circulating solids returned to bottom.
Fuel flow not returned
(separation efficiency of fuel = 0).
No sand or sorbent in the system.
Bed of fuel ash formed in the bottom,
bed mass 1000 kg
SMALL SCALE TESTS

- Only regular dispersion (no target dispersion or convection)
SMALL SCALE TESTS

- Original model, with small dispersion to target profile (no convection)
SMALL SCALE TESTS

- Convection solved (2,0,2 m/s) with small dispersion
SMALL SCALE TESTS

- Convection solved (2,0,2 m/s) with small dispersion and using large particle size
SMALL SCALE TESTS

- Convection solved (2,0,2 m/s) with small dispersion and using small particle size
COMMERCIAL SCALE VALIDATION

Several balances simulated and validated against measurement data.

Effect of boundary conditions and different variables was tested and compared.
COMMERCIAL SCALE VALIDATION

- Three iso-surfaces for finest and largest fuel fraction
- Fines elutriated by drag from gas and solids
- Large particles are gravity dominated and stay in bed
COMMERCIAL SCALE VALIDATION

Cross-section from 13 m height: modeled and measured temperatures.

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CONCLUSIONS

- New submodel for fuel convection was introduced to an existing three dimensional model frame of circulating fluidized beds
- Submodel considers four forces: inertia, gravity and drag from gas and solids.
- Submodel was tested in small test environment to study affect of different parameters and qualitative behaviour
- Later the submodel was used in simulation of commercial scale CFB unit combusting 100% biomass and validated against probe measurements with good agreement
Thank you for your attention!

Questions?