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Modeling of fuel flow in commercial scale CFB furnace

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ABSTRACT

Design of CFB boilers is strongly connected to type of fuel utilized, the flow and reactions of fuel are the most important aspects of furnace performance and characteristics, such as temperature and atmosphere regions, heat transfer and emissions. As utilization of biomass in energy production has gained popularity, several boiler manufacturers have built plants firing only biomass. CFB furnaces have previously been mostly utilized in combustion of coal and models were developed for this in mind. As coal and biomasses are hugely different fuels, coal being ground to certain particle size distribution and being relatively dry, and biomasses having large variations in size and shape distribution, high moisture content and chemical composition. (Jäntti et al 2012) These significant changes in the fuel properties may lead to situations where models developed for coal are not usable for other type of fuels.

Comprehensive modeling of circulating fluidized bed (CFB) boilers is challenging. The commercial scale furnace geometries are large and calculations with computational fluid dynamics (CFD) would take much computational power and time. Several simplifications are required in order for the computational models to be computationally realizable. This means that the equations used in CFD need to be modified to take into consideration the larger computational cells while giving reasonably accurate description of phenomena occurring in the furnace.

This paper describes how an existing three dimensional steady-state model frame for CFB furnaces (Hyppänen et al 1991, Myöhänen et al 2003, Myöhänen et al 2011) was modified to improve prediction capabilities for fuel flow. The developed model is simplified from CFD momentum equation of fuel phase and includes four force terms: gravity, inertia and drag from both gas and solid phase. The developed model was validated using measurement data from commercial CFB unit firing 100% biomass. The developed model was found suitable based on the predicted and measured temperature distribution inside the furnace.

Keywords: Fluidized beds, modeling, fuel flow,



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1 Introduction

An interest towards reducing carbon dioxide emissions has set major challenges for energy production. How to supply the increasing demand and still meet the global targets set for reduction of greenhouse gases? The European Union has set the target share of renewables to 20% in energy production by 2020 with reduction of 20% of CO₂-emissions compared to 1990 levels. An increase in renewables and lowering of CO₂-emissions is believed to be possible with combustion or co-combustion of biomass since it has been classified carbon neutral. Other methods of biomass utilization, so called second generation or advanced biofuels, may require extensive processing to change the physical or chemical properties of raw biomass, such as pelletization or torrefaction, or even convert the solid biomass into another phase, such as biodiesel or biogas. By laws of thermodynamics, every conversion process leads to losses and reduction in the total net energy of fuel and when considered that fuel processing is energy intensive, it can be argued that the total net energy value is lower for more processed fuels.

The need for raw biomass processing derives from physical and chemical properties of biomass. Coal and oil have been used in energy production long for their high energy content and energy density. They are also both relatively dry fuels, as moisture reduces the lower heating value dramatically. Biomasses have often higher moisture content and quite low material and energy densities. Biomasses are diverse, from excrement to wood to agricultural residue. This diversity is not only limited to differences between different kinds of biomasses but variation can be found in smaller scales. For example woody biomass properties depend on type of tree, age, location and many other variables. Even different parts of the same tree can have very different properties, for example considering leaves or needles and the branches. (Alakangas 2005) Suffice to say that as fuel biomasses can have very much varying chemical and physical properties. Compared to coal, the higher moisture content and variation of properties and low energy density are main reasons for biomass processing. Some processes require homogeneous or high rank fuel and combustion of wet fuel is not an option. The low energy density can be improved for example by densification, drying or torrefaction.

For fluidized beds the varying properties, high moisture content or low energy content of biomass doesn't cause difficulties. Often local biomass resources are used in direct combustion, which reduces the transportation costs and emissions. There are several fluidized bed boilers operating around the world utilizing only biomass and retrofitting to co-combustion has also gained popularity. In fluidized bed combustion the furnace contains bed of ash or sand which dominates the characteristics of the process. The untreated, heterogeneous and wet fuel is fed into the bed and is rapidly dried and combusted with high efficiency without any penalties to furnace process performance. In order to understand the furnace process better, modeling tools have been developed to analyze the interconnected phenomena of multiphase hydrodynamics, thermal conversion processes and heat transfer inside the CFB furnace. The flow and reactions of fuel inside the furnace is fundamental part of combustor which ultimately defines the temperature and emission levels inside the furnace.



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2 Three dimensional model frame

2.1 Model description

An existing model frame is used for simulation of combustion, gasification and carbon capture in commercial scale circulating fluidized bed (CFB) applications.

The model frame for circulating fluidized beds is three dimensional to allow better analysis of feed points and effect of mixing. A block mesh is used to discretize the furnace/reactor domain. For large commercial units, normal mesh size is approximately 150.000-300.000 cells with cell volume around 5 liters. In addition to normal mesh, there is a wall layer near the walls with respect to core-annulus model. The solids separators, return leg and possible external heat exchangers are modeled with their own zero dimensional models. The number of these can be freely selected.

While the real CFB process is transient, with rapid fluctuations of bed and formation and break-up clusters, on average the process is quite steady and the model is simulating a steady-state solution.

The complex and heavily interconnected physics of reaction kinetics, hydrodynamics of particles and fluidization agent and heat transfer between phases and boundaries of the reactor/furnace are handled with semi-empirical approach. This means that conservation equations of mass, momentum and energy are solved normally, but mostly the reactions and hydrodynamic interaction is handled through empirical correlations rather than detailed solution of complex sets of equations. This approach is selected due to computational reasons as well as due to lack of applicable and comprehensible theory in many areas of CFB process.

The model frame solves and handles 16 gas species, 4 sorbent compounds and fuel is divided into 4 components: char, volatiles, ash and moisture. 4 NO_x-species are considered and solved as a post-processor based on the converged furnace process solution.

Model frame contains several reactions such as heating of fuel, evaporation, pyrolysis, devolatilization and gasification, char combustion, 8 sorbent reactions and comminution of solids (between 6 defined fractions for each solid component).

The fluid dynamics is handled with potential flow solution of gas phase momentum equation and semi-empirical vertical profile of bed material and solids according to the function form presented by Johnsson & Lecker. The horizontally distribution of solids is achieved by spreading the amount of material obtained from vertical profile to the whole furnace cross-section, taking into consideration the core-annulus model.

The heat transfer mechanisms of convection and radiation are considered between the suspension and wall or internal surfaces placed in to the furnace. [Hyppänen et al 1991, Myöhänen et al 2003, Myöhänen et al 2011]



2.2 Fuel convection model

The earlier mass balance for solids is described in Equation 1 written for finite volume method. The first part represents the convection term, second dispersion (with fractional target profile of $f_{0,i}$, obtained from empirical correlation by Johnsson & Lecker), third char source term and fourth reaction sink term, fifth and sixth are comminution terms to and from other size fractions.

$$\oint_A \varepsilon_{c,i} \rho_c \vec{u}_{c,i} \cdot dA - \oint_A D_{c,i} f_{0,i} \left(\frac{\varepsilon_{c,i} \rho_c}{f_{0,i}} \right) \cdot dA = \int_V \phi_{c,i}''' dV - \int_V R_{c,i}''' dV - \int_V \sum_{j,j \neq i} k_{C,c,ij} \varepsilon_{c,i} \rho_c dV + \int_V \sum_{j,j \neq i} k_{C,c,ji} \varepsilon_{c,j} \rho_c dV \quad (1)$$

The developed model for fuel convection is built upon solution of fuel momentum equation, presented in Equation 2. The momentum equation is reduced from general momentum equation: the pressure term is neglected as small compared to other terms, the stress term is left out as the diffusion/dispersion term in the fuel continuity equation is assumed to handle the turbulent mixing of fuel. The transient term is modified to serve only in the numerical solution of steady state by defining it as expressed in Equation 3.

$$\frac{d}{dt} \int_V \rho u dV + \oint_A \varepsilon_{c,i} \rho_c \vec{u}_{c,i} \vec{u}_{c,i} \cdot dA = \int_V \varepsilon_{c,i} \rho_c \mathbf{g} dV + \int_V K_{g-c} (\vec{u}_g - \vec{u}_c) dV + \int_V K_{s-c} (\vec{u}_s - \vec{u}_c) dV \quad (2)$$

$$\frac{d}{dt} \int_V \rho u dV = \rho V \frac{(u_i^* - u_i)}{c_t} \quad (3)$$

Where u is previous iteration round value and u^* is the new velocity to be solved and c_t is momentum response time, which was taken for many simulation cases as 0.0001 s. Introducing Equation 4 to Equation 5 for momentum exchange coefficients $K_{\text{gas-char}}$ and $K_{\text{solid-char}}$, which are based upon literature and models suggested by Gidaspow (Equation 4), Syamlal (Equation 5) with Schiller-Naumann drag model C_D , presented in Equation 6 and radial dispersion coefficient g_0 in Equation 7.

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

$$K_{s-c} = \frac{3(1+e)(\pi/2 + \mu\pi^2/8) \varepsilon_s \varepsilon_c \rho_s \rho_c (d_s + d_c)^2 g_0 |\vec{u}_s - \vec{u}_c|}{2\pi(\rho_s d_c^3 + \rho_s d_c^3)} \quad (5)$$



$$C_D = \begin{cases} \frac{24}{\varepsilon_g \text{Re}_c} (1 + 0.15(\varepsilon_g \text{Re}_c)^{0.687}) & \text{Re}_c < 1000 \\ 0.44 & \text{Re}_c \geq 1000 \end{cases} \quad (6)$$

$$g_0 = \frac{1}{\varepsilon_g} + \frac{3d_s d}{\varepsilon_g^2 (d_c + d_s)} \sum_{i=1}^n \frac{\varepsilon_i}{d_i} \quad (7)$$

Three dimensional model frame uses staggered grid approach in solution of momentum equation, which needs to be considered in calculation of force terms in momentum equation. As density cell centers are cell surface values for momentum and vice versa, central difference method was adapted for solving the forces acting on the momentum cell surfaces. Equation 8 presents methodology for taking the staggered grid discretization into consideration for forces (source terms and convective term in momentum equation). For example gravitational force $F_{g,i}$ (eq. 8) considers half of mass for cell i and other half from neighboring cell $i+1$.

$$F_{g,i} = \left(\rho_i \frac{V_i}{2} + \rho_{i+1} \frac{V_{i+1}}{2} \right) \mathbf{g} \quad (8)$$

3 Results / Modeling

3.1 Small scale model tests

Small scale test domain was generated to qualitatively test the functionality of the fuel convection model. The domain has open top which leads to separator which is only returning the bed but not the fuel to the lower part of the domain. Thus the domain should have constant bed inventory of 1000 kg with fresh fuel feed of 1 kg/s from the side to illustrate where the fuel is flowing. The bottom of the domain is inlet for 10 kg/s of grid air. Table 1 presents the test geometry details.

Figure 1 presents flue char flow in two extreme cases, with small particles ($d_s=32 \mu\text{m}$) and large particles ($d_s=4 \text{ mm}$). Fresh fuel is fed from side of the domain and whereas the smaller fuel particles are swept immediately upwards by the gas and bed particles, the larger particles drop to the bottom of the bed. The simulations were performed with very small dispersion to test the qualitative behavior of the fuel convection model. Testing and parameter studies were also performed on several other parameters such as fuel density, mesh size effect, effect of dispersion for example.

Table 1. Test geometry

	x	y	z	total
Domain dimensions	4 m	2 m	8 m	64 m ³
Number of cells	10	5	20	1000
Cell dimensions	0.4 m	0.4 m	0.4 m	0.064 m ³

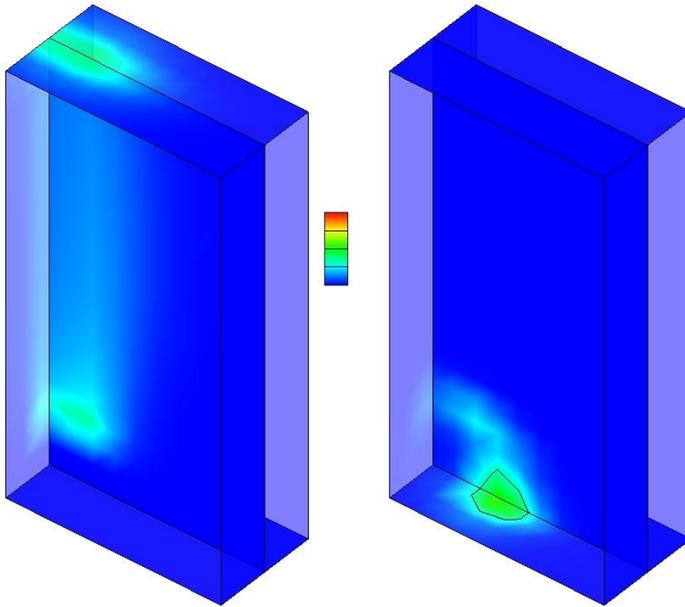


Figure 1. Test cases with small (on left) and large (on right) particle size. The contours of char (left) or devolatilization (right) illustrates clearly the path of freshly fed fuel.

3.2 Validations in commercial scale

After successful testing of the fuel convection model, the model was used in simulation commercial scale CFB unit firing solely biomass. The model was also used in validation process, where probe measurements inside the furnace in various locations and plant measurements were used to improve model results by trying to duplicate them and then compared against the measurements. Overall results were in good agreement with both plant and probe measurements. In best cases the level and profile shape matched almost perfectly, while in other cases differences of less than 10% could be found for temperatures. Differences were larger for plant and probe emission measurements in certain cases. Since no furnace measurements of gaseous species were performed with balances selected for simulations, the emission probe measurements can only be used as qualitative comparison. It is difficult to estimate possible changes in the gas composition after the furnace, therefore the plant measurements contain large uncertainties. The plant oxygen measurements (place uncertain) give good correspondence to oxygen level modeled to leave each CFB unit separator.

Figure 2 illustrates the three iso-surfaces for the finest fraction and the largest fractions of char. It can be seen that the forces dominating the fuel flow are similar than in the small test case, the finer char particles are driven upwards by gas and bed material while the largest particles stay in the bed region.

Figure 3 presents comparison between the measured and modeled results of temperature (simulated balance) and oxygen concentration (of balance very close to simulated case) in validated commercial scale furnace.

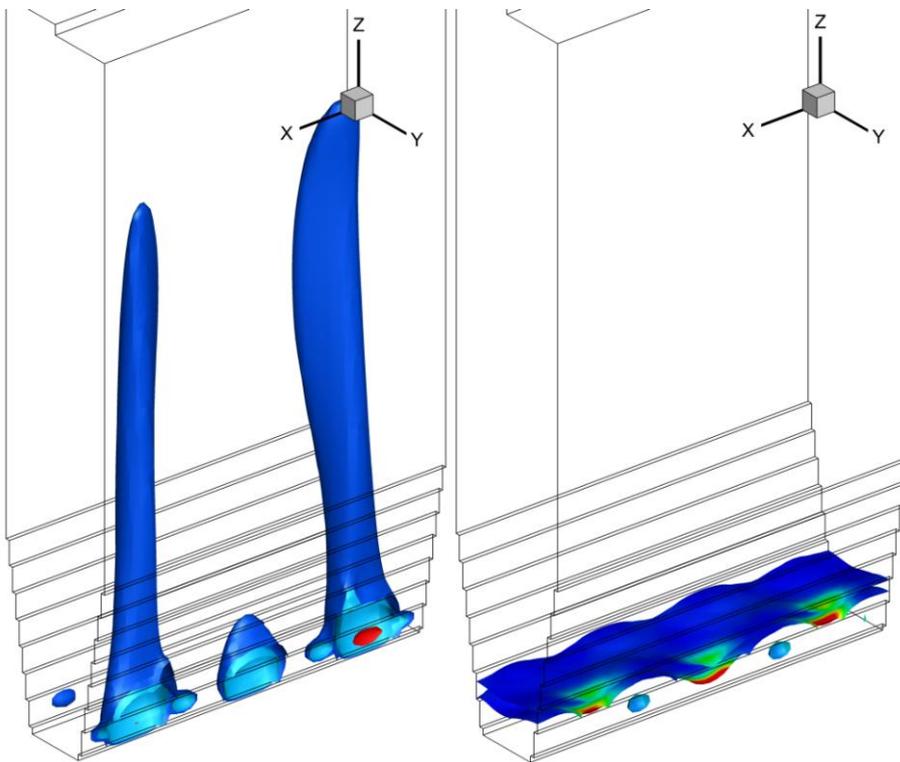


Figure 2. Char fractional iso-surfaces with smallest fraction (on left) and largest fraction (on right).

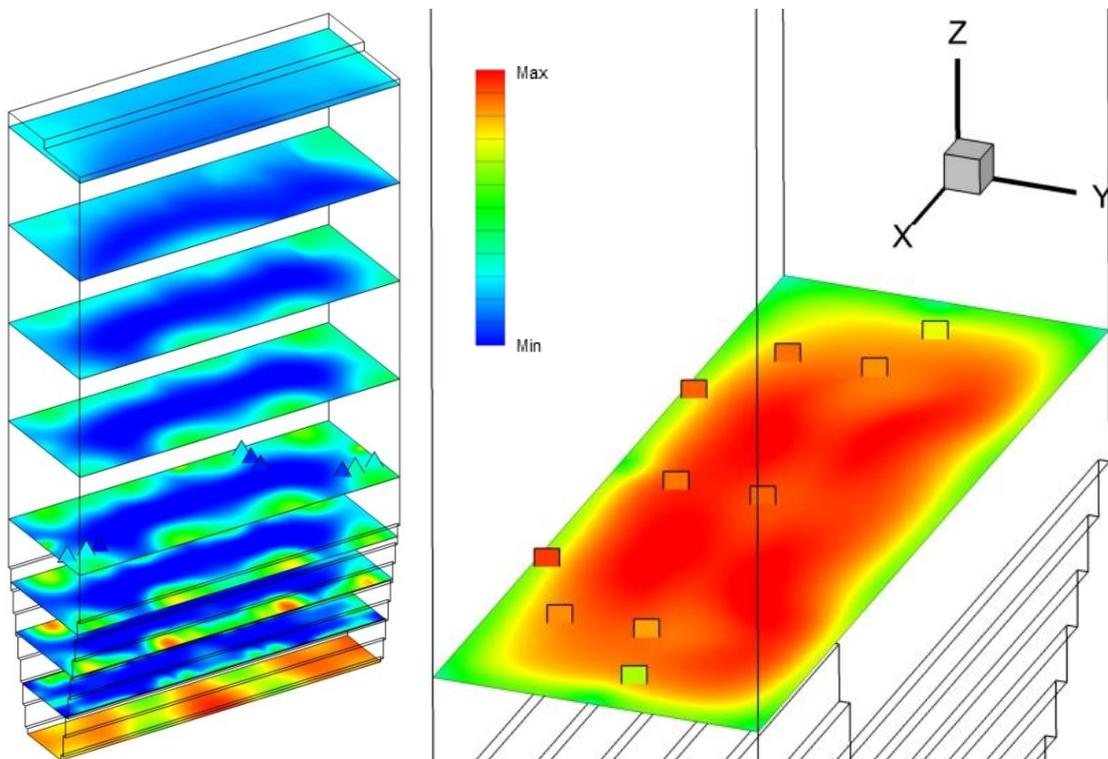


Figure 3. Measurements and model results of oxygen concentration (on left) and temperature (on right).



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4 Conclusions

A new submodel was successfully developed into existing three dimensional CFB furnace code to govern fuel convection. The submodel considers inertia from fuel feeding, gravity, gas and bed material drag as forces affecting to the fuel flow. The submodel was successfully used in simulation of three different balances of commercial scale CFB unit combusting 100% biofuel. The temperature comparison of modeled results to probe and plant measurements are in good agreement.

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Nomenclature

A	surface area	[m ²]
C_D	drag coefficient	[-]
D	diffusion coefficient	[m ² /s]
F	force	[N]
K	momentum exchange coefficient	[-]
R	reaction rate	[kg/s]
V	volume	[m ³]
c_τ	momentum response time	[s]
d	diameter	[m]
f	profile	[-]
g	acceleration due to gravity	9.81 m/s ²
g_0	radial dispersion coefficient	[-]
k	coefficient	[-]
t	time	[s]
u	velocity	[m/s]
ε	volume fraction	[-]
ρ	density	[kg/m ³]
μ	dynamic viscosity	[kg/m s]
ϕ	generation, source term	[kg/s]
Re	Reynolds number	[-]

Subscripts & Superscripts

C	comminution
c	char
g	gas
solid	solid
i, j	indexes
0	target



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* new
''' volumetric

REFERENCES

Alakangas, E. 2005. Properties of wood fuels used in Finland – BIOSOUTH-project. Project report. VTT Processes.

Hyppänen, T., Lee, Y.Y. and Rainio, A. 1991. A three-dimensional model for circulating fluidized bed boilers. Proceedings of the 11th International conference on Fluidized Bed Combustion.

Jäntti, T. and Nuortimo, K. 2012. Foster Wheeler Advanced Bio CFB Technology for Large Scale Biomass & Peat Firing Power Plants. Russia Power 2012.

Myöhänen, K., Hyppänen, T., Miettinen, J. and Parkkonen, R. 2003. Three-dimensional modeling and model validation of circulating fluidized bed combustion. Proceedings of the 17th International conference on Fluidized Bed Combustion.

Myöhänen, K. and Hyppänen, T. 2011. A Three-dimensional model frame for modelling combustion and gasification in circulating fluidized bed furnaces. International Journal of Chemical Reactor Engineering, 9 A25.