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Modelling of 1 MW Solid Biomass Combustor: Simplified Balance-Based Bed Model Coupled with Freeboard CFD Simulation

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This paper evaluates the combustion process of solid biomass fuel in a 1 MW grate furnace by using data obtained from a real unit and mathematical modelling tools. Investigated grate furnace consists of combustion chamber with continuous feeding and heat exchanger. The combustion chamber is equipped with multiple primary, secondary and tertiary air inlets. Combustion air is distributed into four areas, two under and two above the grate bed. Temperature is monitored inside the combustion chamber by three thermocouples and gaseous combustion products are analysed in the stack.

The present mathematical model is based on an assessment of existing simplified approaches to the fixed bed modelling, see e.g. (Johansson et al. 2007; Frey et al. 2003). This approach means that the process may be simulated without specialised bed simulation software using the tools available in commercial CFD software. The discussed approaches differ mainly by the complexity of treatment of the solid fuel layer, but also by the degree of interaction between the fixed bed and the freeboard region.

1. Introduction

There are a number of published approaches to the modelling of fixed bed combustion on grates. In this work we focus our attention on grates with counter-current combustion and continuous horizontal feeding. The most comprehensive modelling approach to such a process includes individual particles in the bed, the motion and conversion of which is simulated as in (Simsek et al., 2009) for spherical particles. Such approach is required in cases where particles are large (thermally thick) and they mix inside the bed due to grate movement. The resulting model of the combined motion of particles with fluid flow and reactions is however computationally very demanding and at the present is not a part of any commercial software. The difficulty is not only in description of the motion of individual particles as in (Peters and Dziugys, 2011), but also their individual thermal conversion, change of dimensions and disintegration, coupled with the flow through the bed of these particles. For a comprehensive review of grate firing focused especially on biomass see (Yin et al., 2008).

Models describing the thermal conversion of individual large particles have been proposed by several researchers. For example (Peters et al., 2002) and (Peters and Dziugys, 2011) used a particle-resolved model for a packed bed of spherical particles, whereas (Galgano and Di Blasi, 2006) reported a coupled model of a single cylindrical wood log with CFD simulation of reacting flow. Naturally, it would be extremely difficult to model a complete packed bed of non-spherical particles as the packing is irregular and changes during the thermal conversion process. Some attempts have been made to

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characterize such packing conditions as in (Hamel and Krumm, 2008), but to the authors' knowledge so far no simulation based on a model of grate combustion involving a coupled particle/flow simulation approach for a bed of non-spherical particles has been reported in the literature.

A number of models have been implemented in the past ten years that do not involve the simulation of individual large particles of fuel, but rather assume homogeneous isotropic packed bed. A notable example from this group is the model developed by Yang and co-workers (Goh et al. 2001) that has been applied in a number of studies, e.g. (Yang et al., 2003) or (Yao Bin Yang et al., 2005). This model and others of this category including also e.g. (Kær 2004), (van der Lans et al., 2000) or (Epelbaum and Zhang, 2007) invoke a number of assumptions about the packing conditions that result in models (approximations) of process rates (drying, devolatilization, char oxidation), heat transfer rates (convective, radiative), and pressure drop, which are necessary for the treatment of the bed as continuous two-phase region. These models are most suitable for homogeneous fuels consisting of small particles like wood chips or cut straw, but have been applied also to complex fuels like municipal solid waste. It is however difficult to include in this type of model realistic representation of phenomena like fuel mixing and channelling in the bed (Yang et al., 2004). Perhaps even more importantly, none of these models has been developed to such a degree to become widely applicable in practical computations performed by others than the model developers. Thus applying such a model in an industrial computational analysis is not at all straightforward and entails a number of difficulties due to which it is in most cases impractical.

The complexity of development, validation, implementation and usage of the above discussed models is the reason for continued usage of much simpler approximations in the modelling of grate combustion furnaces or boilers. In the absence of a detailed bed model there are however only very limited options how to construct a model of the grate combustor.

First, one can completely obliterate the bed model if measured data are available that characterize the composition, temperature, local flow rate of gas leaving the bed and bed surface temperature. These data may be used directly as boundary conditions for a CFD model of the freeboard region. In reality, it is however very difficult to obtain such data and more importantly, such a model can only describe the conditions in an existing combustor. Such model lacks the predictive capability expected and required from mathematical models in general. Nevertheless, measured data of this kind originating from a large-scale laboratory incineration unit have been published and used as input for a combustion simulation e.g. in (Kim et al., 1996; Frey et al. 2003).

Second option is to calculate boundary inlet conditions for freeboard simulation using a guessed or experience-based profile of fuel conversion along the grate length as e.g. in (Dong and Blasiak, 2001), (Klason et al., 2008) and (Yin et al. 2008). Such an approach is satisfactory mainly in cases, where the subject of investigation lies sufficiently downstream from the grate and the fixed bed. On the other hand, it will not provide reliable information on flow and temperature distribution in the vicinity of the fuel bed, which is typically in the primary combustion zone (below secondary air inlets). This approach is however quite practical as it does not require the development of a complex bed combustion model and a balance calculation is able to provide all necessary information.

This work reports the simulation of a 1 MW grate biomass combustor based on the latter type of bed description combined with a reactive flow simulation in the freeboard region. Additionally, the model enables prediction of air preheating in wall ducts that bring the air to primary and secondary inlets (below the grate and above the fuel bed).

2. Model description

The selected approach uses an external balance calculation to calculate values of boundary conditions and source terms for a CFD simulation (e.g. mass flow rates, product gas composition, etc.). Effects of drying, pyrolysis and char burnout processes, which are schematically indicated in Figure 2, are included. In the freeboard region, simulation includes the combustion of devolatilised fuel, radiative heat transfer and turbulent flow. CFD simulation is based on a two-equation turbulence model with simplified description of chemical reactions for good model practicability. The modelling approach assumes quasi-steady state of the combustion process with an unchanging spatial position of the combustion front. The drying, devolatilization and char oxidation fronts are substituted by zones, where drying, devolatilization and char combustion is assumed to occur. The balance model enables to pre-define conversion degree for each of the three basic processes (drying, devolatilization and char oxidation) in each of the zones.

2.1 Model geometry

The modelled biomass boiler is displayed in Figure 1 including accessories like heat exchanger for combustion air preheating, cyclone for the collection of particulate emissions, air fans etc. Great part of the geometry has been included into the CFD model, consisting of the combustion chamber, air supply tubes, solid walls of the combustion chamber and part of the boiler's heat exchanger, as shown in Figure 2. The air is distributed by external tubes and internal channels constructed within the walls of the combustion chamber into three zones. Primary combustion air is supplied in two zones under the grate, secondary air is brought above the fuel bed and tertiary air is distributed above the crown of the combustion chamber, as shown in Figure 3. The system includes also flue gas recycling, which improves combustion efficiency by enhancing mixing in the combustion chamber. In Figure 4 are displayed the assumed zones of the fuel bed.

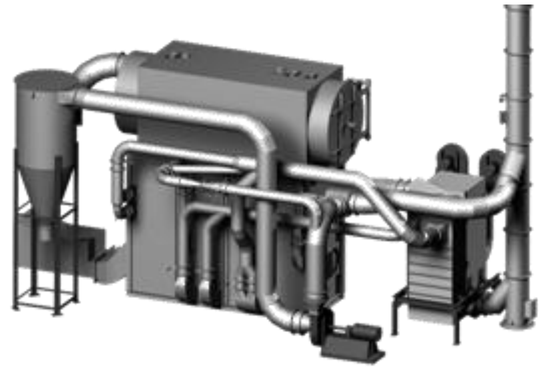

Figure 1 Complete biomass boiler

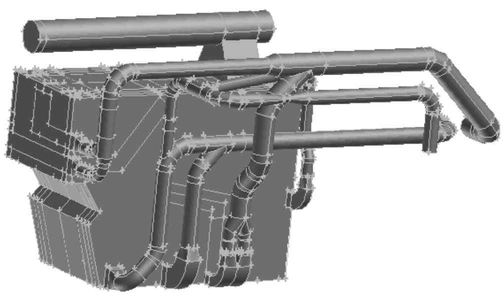

Figure 2 Modelled geometry

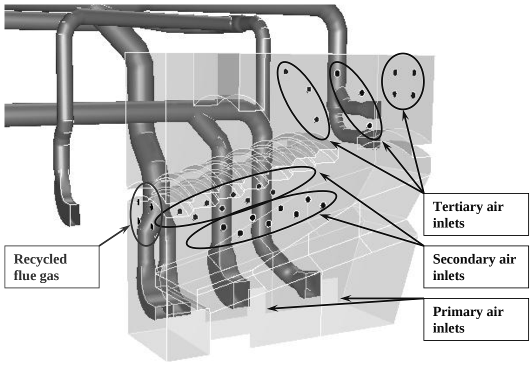

Figure 3 Air supply system in the grate furnace

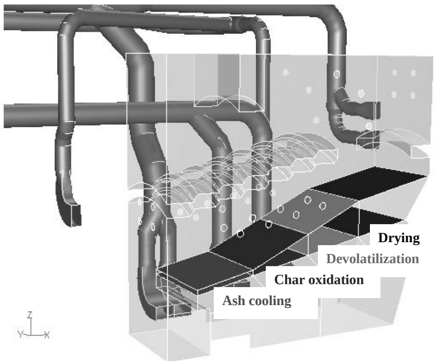

Figure 4 Assumed sections in the fixed bed

The model includes air distribution system within one domain together with the fuel bed and freeboard region. This enables to analyze the quality of combustion air distribution as well as to include air preheating in the distribution channels in the walls of the combustion chamber. The walls of the combustion chamber are composed of three layers of material, namely chamotte, refractory concrete and outer mineral wool insulation layer, covered by a thin steel plate. The air passages are constructed within the concrete layer. Whole simulation model was developed in the ANSYS FLUENT software without external coding, except for a few user defined functions.

2.2 Fuel bed and freeboard model

The modelled operating regime is defined by real conditions recorded in autumn operation of the facility (low heat demand). The modelled regime is a low-duty condition (27 % of nominal duty), which is interesting mainly for the decreased mixing in the combustion chamber. Therefore it was important to perform an assessment of how adequate is the air supply system in such difficult conditions. Combustion efficiency is supported by recycling 23 % of the flue gas, which supports mixing of devolatilised fuel with combustion air and flue gas in the combustion chamber. Air supply is kept high for the same reasons, with excess air ratio 2.37. This lowers temperature of the flue gas, but keeps velocity (and mixing) of flue gas on a satisfactory level, which is important to provide complete burnout of the devolatilised gases within the combustion chamber.

Fuel bed was modelled by volumetric mass and energy sources, calculated from the balance model. Pressure drop of the fuel bed was included in the simulation by predefined shape of the fuel layer and assuming constant and isotropic properties of the porous layer. Information about the pressure drop of fuel beds is scarce in the literature, thus a typical pressure drop of 100 Pa per 10 cm of bed thickness was assumed. For each zone, volumetric mass and energy sources were calculated from the balance. Mass supplied by a mass source to the code however does not have its own temperature, it obtains temperature from the cell where it is generated. In the presence of nonuniform temperature in the porous fuel layer this however means that energy conservation is not ensured and the resulting error must be corrected. As we know location where the error occurs, it was sufficient to make an energy balance in the simulation and to make a corresponding correction directly in the fuel zones.

The flow in the whole unit is fully turbulent, so an adequate yet computationally manageable model was employed, namely two-equation model, so-called realizable k-ε model as published in (Shih et al. 1995). The model is known to provide good accuracy in predicting the rate of dissipation of round jets, which are an important flow feature in the investigated unit.

The gaseous components included in the simulation were O_2, N_2, CO, H_2, CO_2, and an artificial hydrocarbon molecule substituting the real mix of various compounds, the formula of which was determined in the balance calculation as $C_{1,54}H_{4,28}$. Besides these, carbon in the char has been modelled as imaginary small particles consisting of C atoms and carried by the gaseous phase. Reaction parameters of the carbon (activation energy, pre-exponential factor) were set equal as for anthracite (Fluent 2006). Therefore the reaction mechanism included four global reactions for the four fuel compounds.

Chemistry was modelled by a combined eddy-dissipation/finite-rate model based on the turbulence-controlled model (Magnussen and Hjertager 1977), combined with a finite-rate Arrhenius reaction rate, which serves as a kinetic switch that prevents reactions before the flame holder.

Radiation was modelled by the discrete ordinates method, which is suitable for applications with optically thin media with localized heat sources, which corresponds to the present case. Absorption coefficient was modelled by the popular weighted-sum-of-grey-gases model. It was however necessary to increase optical thickness in the modelled fuel layer as most radiation is absorbed by the surface layer of the bed. The porous medium used as a substitute for the bed does not work as an opaque wall for radiation and neither it is possible to construct a perfectly permeable opaque wall in ANSYS FLUENT. Therefore a workaround used in this simulation was based on artificial increase of the value of the absorption coefficient by 10 orders of magnitude to make the porous zones optically thick and in effect virtually opaque.

3. Results

Simulation has shown a satisfactory combustion air distribution with differences between symmetrical openings on opposite sides of the chamber below 15 %. These differences are caused by non-symmetry of air distribution ducts that is clearly displayed in Figures 1 through 4. The good air distribution makes also the flow pattern inside the freeboard region quite symmetrical, as documented by Figure 5. Individual air ports entering the combustion chamber receive air flow rates within a relatively small range with minimum value equal to 60 % of the maximum flow rate.

The predicted temperature in combustion chamber is relatively low, as corresponds to the low firing rate with large dilution by excess air and recycled flue gas. Peak temperature is around 1,000 °C, with regions of the highest temperature located above the fuel layer in the vicinity of walls, below secondary air inlets, as documented by Figure 6.

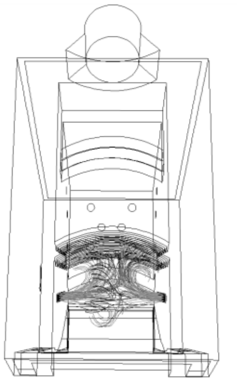

Figure 5 Streamlines of secondary air

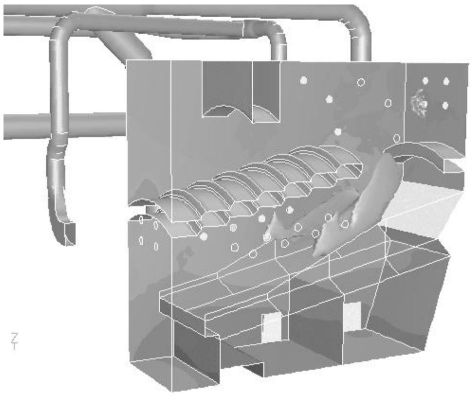

Figure 6 Isothermal surfaces of 800°C

The simulation with finite rate "switch" has led to a rather surprising result, as great part of the combustible compounds was observed to leave the combustion chamber unburned. Probably the low predicted temperatures and low level of turbulence in part of the combustion chamber have caused this behaviour. In reality however, perfect combustion was observed as proven by stack measurements. Therefore the finite rate switch has been removed and simulation has been repeated with the eddy-dissipation model. Resulting peak flame temperature has in this case increased by about 200 °C and the burnout of combustible matter was perfect, corresponding to reality.

4. Conclusion

This article reports a simulation of a grate biomass combustor performed within a commercial software system ANSYS FLUENT. Fuel bed is modeled by assuming reaction zones (semi-empirically) and providing boundary conditions from a balance calculation. Model setup is described and results of the simulation are reported. Results show a good air distribution and detailed information about temperature distribution as well as preheating of secondary air in wall channels. The model proved to be practicable and readily applicable for industrial analyses that are not directly focused on processes within the fuel bed, but on other features and processes in studied grate combustion units.

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