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Three-dimensional modeling of fuel flow with a holistic circulating fluidized bed furnace model

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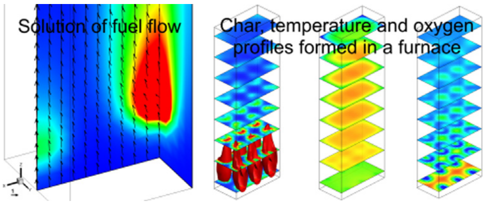
HIGHLIGHTS

- New fuel flow model was introduced to an existing CFB model frame.
- Fuel flow profiles determined by the physical properties of the fuel.
- Presented model improves comparison of different fuels.

GRAPHICAL ABSTRACT



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ABSTRACT

To study the mixing and flow of fuel inside commercial scale circulating fluidized bed (CFB) furnaces, a new model was introduced to solve the flow of fuel in an existing semi-empirical, steady state, three-dimensional Eulerian model frame. The fuel flow model is a simplified momentum equation which is based on the momentum balance considering the fuel inertia, gravity, and drag force from gaseous and solid phase. The model improves the prediction capabilities of fuel flow patterns in the existing model frame for conventional and especially renewable fuels, such as biomass. The fuel flow model improves the analysis of CFBs and can be utilized in the design and development of commercial CFB units.

1. Introduction

1.1. Overview

As the computational capabilities have developed, the usage of computational fluid dynamics (CFD) has increased significantly in the modeling of industrial applications. CFD is increasingly used as a supportive tool for research and development as well as in the design and dimensioning of existing and new products. CFD is especially useful in applications in which comprehensive measurements are not possible or are impractical, as in large industrial furnaces, for example.

When considering industrial furnace applications, the combustion air and flue gas form one phase, with species of gas components. The fuel, liquid or solid, is considered as its own phase. In fluidized bed furnaces, the vast amount of bed material particles (mostly fuel ash, sorbent, and make-up sand) forms the third phase. In a multiphase system, the fundamental conservation equations of mass, species, momentum, and energy have to be described for each phase.

The fluidized bed combustion is a complex and interconnected process of fluidization hydrodynamics and mixing of gas, bed material, and fuel (all forming the suspension), reactions, and heat transfer in and between the suspension and surfaces. In fluidization, the fluid (gas) flows through a bed of solid particles setting the bed to a fluid-like state. Depending on the fluid flow rate

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Abbreviations: CFB, circulating fluidized bed; CFD, computational fluid dynamics; DEM, discrete element method; DNS, direct numerical simulation; EMMS, energy minimization multi-scale; LBM, Lattice–Boltzmann method; LES, large eddy simulation; MP-PIC, multiphase particle-in-cell; PSD, particle size distribution; RANS, Reynolds averaged Navier–Stokes

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and bed particle properties, the fluidized bed can demonstrate different behavior, from static packed to bubbling or circulating fluidized bed (CFB), all the way to pneumatic transport. The state of fluidization affects the mixing between the materials and reactants in the furnace.

There are several approaches to the modeling of phenomena related to fluidized bed processes as summarized by Singh et al. (2013). For the computations of flows, reactions, and heat transfer, several different methods and models are available which add to the computational costs of the holistic modeling of fluidized bed processes. Here, discussion is limited to the approaches relating to the solution of the momentum equation and to the modeling of the fuel flow.

Since commercial CFB furnaces are significantly larger than laboratory equipment, the computational costs of having an academic level, three-dimensional detailed resolution in the commercial scale simulations is not yet practical for engineering purposes. Simplified models, often with empirical background, are used to achieve good results in acceptable computational times for large units.

Often in works published on holistic three-dimensional CFB model frames, the multiphase and fuel flow are handled with semi-empirical and dispersion driven approach (Knoebig et al., 1999; Koski et al., 2011; Luecke et al., 2004; Myöhänen and Hyppänen, 2011; Myöhänen, 2011; Pallarès and Johnsson, 2008; Pallarès et al., 2008; Petersen and Werther, 2005; Wischnewski et al., 2010), which can produce good results with previously known, tested and more homogeneous material pairs, such as bed material and coal. For heterogeneous material pairs, such as a mixture of denser bed material and low density biomass, the previously used approach may not be suitable. Additionally, for new types of fuels, empirical parameters are required in the models, which might be difficult to obtain without actually measuring those parameters from an existing CFB unit firing the new fuels.

In this paper, an existing holistic, steady-state, three-dimensional CFB furnace model frame has been modified to include a more detailed solution of the momentum equation of fuel. The introduced model utilizes the physical properties of the fuel in the solution of the fuel flow field rather than empirically determined information. The aim of this work was to obtain and introduce a more accurate and more physical estimation of fuel flow and mixing inside the furnace. The new model is presented and compared with the previous modeling approach to highlight the differences with unconventional fuels especially for biomass, which has been shown to differ significantly from conventional fuels.

1.2. Modeling of flows in circulating fluidized beds

1D and 1.5D models of CFB are suitable for simplified mass and energy balance solutions for the process simulation or design, and 2D simulations have their place in the modeling of mainly vertical flow and mixing. Lateral mixing of fuel is especially important in large scale furnaces and requires the use of 3D modeling. (Basu, 1999; Nikolopoulos et al., 2013) The CFB furnace hydrodynamics make the process inherently fluctuating, and on this basis, transient modeling would be logical. However, transient simulation in 3D leads to long computational times (Adamczyk et al., 2013; Pallarès and Johnsson, 2006), and for this reason, the most comprehensive 3D CFB furnace models are steady-state models (Hyppänen et al., 1991; Knoebig et al., 1999; Pallarès and Johnsson, 2008).

Fluidized beds are multiphase flow systems in which at least two phases have to be considered: the fluid phase, consisting of air and flue gas in a typical combustion process, and the particulate phase, consisting typically of fuel ash or make up material. Also additional fluid or solid phases can be included, such as gaseous, liquid or solid fuel, or sorbent for sulfur capture. The modeling approaches for these phases are discussed later in greater detail.

Another important approach to consider is the coupling, i.e. how to consider the interaction of the phases. This interaction has to be taken into account in all of the conservation equations: mass (such as evaporation and condensation), momentum (drag), or energy (heat transfer). In one-way coupling, one phase affects another without being affected back, while in two-way coupling, true interaction is considered (Crowe and Michaelides, 2006). According to Alletto and Breuer (2012), the two-way coupling should be taken into account after the particle phase volume fraction exceeds 10^{-6}, which means that the flow is still quite dilute and the particle–particle interaction can be neglected. As the particle volume fraction exceeds 10^{-3}, the flow can be considered to be in transition towards dense, and the particle collisions should be included with four-way coupling (Alletto and Breuer, 2012). The fuel and sorbent phases are minor phases in CFB furnaces, which gives justification for one-way momentum coupling, i.e. gas and bed material affect the flow of fuel and sorbent without changing the flows of gas and bed material substantially. One-way coupling reduces the computational costs significantly.

The following chapters discuss the available methods for the modeling of gas and particulate phases. Different methods can provide varying levels of details having varying computational costs. The study of the fine details of the flow phenomena leads to small spatial and temporal scales, while the simulation of the whole furnace process requires the balancing of the available computational resources and calculation time.

1.3. Gas modeling approaches

In fluidized beds, the gaseous phase is always modeled as a continuous, i.e. the Eulerian phase. The more cells in the discretization of the computational domain, the higher the resolution and level of detail. Drawbacks include higher memory requirements and longer computational times. Further consideration of the gas phase modeling leads to the choice of how to close the momentum equation regarding turbulence. Many of the models for the gas phase are computationally too expensive for commercial scale furnaces.

Various models have been used in fluidized bed simulations with Eulerian–Eulerian and Eulerian–Lagrangian approach from direct numerical simulation (DNS) (Duret et al., 2012; Duret et al., 2013; Gui et al., 2010; Puragliesi et al., 2011; Ström and Sasic, 2013; Xiong et al., 2012) and Lattice–Boltzmann method (LBM) (van der Hoef et al., 2006). Their high resolution and computational costs limit their use to microscale. Large eddy simulation (LES) has been successfully utilized in the modeling of the hydrodynamics of small fluidized beds in 2D and 3D, but currently commercial scale is not yet feasible (Alletto and Breuer, 2012; Gui et al., 2008; Luo et al., 2013; Zhou et al., 2007).

Reynolds averaged Navier–Stokes (RANS) is currently the most widely used approach in CFD to tackle simulating of gas flow in industrial scale problems. The level of detail obtained is limited, with averaging procedure and modeling of small scale flow phenomena. Several authors (Al-Rashed et al., 2013; Li et al., 2011; Liu et al., 2011; Shah et al., 2012; Taivassalo et al., 2012) have used RANS in their fluidized bed related research.

1.4. Particle modeling approaches

Similarly to the fluid flow, there are several approaches to the modeling of the particle phase with a varying level of accuracy and need for computational resources. The particulate phase can be considered as a continuous, Eulerian phase or as a Lagrangian phase consisting of single or groups of particles. The Lagrangian phase does not require the discretization of the computational