Chemical Engineering Science 66 (2011) 5628–5637

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

A novel multigrid technique for Lagrangian modeling of fuel mixing in fluidized beds

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ARTICLE INFO

Article history:
Received 10 February 2011
Received in revised form
30 June 2011
Accepted 28 July 2011
Available online 6 August 2011

Keywords:
Multigrid
Lagrangian simulations
Mixing
Dispersion
Fuel
Fluidization

ABSTRACT

This paper presents a novel Lagrangian approach to model fuel mixing in gas–solid fluidized beds. In the mixing process, fuel particles are considerably larger than the inert bed material and therefore, the present work proposes three grids to account for the difference in size between the fuel particles and inert solids. The information between the grids is exchanged using an algorithm presented in the paper. A statistical method has been developed to analyze the distribution of the fuel particles in the bed. The results for the preferential positions, velocity vectors and horizontal dispersion coefficients are compared with experimental data in a bed applying simplified scaling relationships for different operating conditions. The effects of initial bed height and inlet gas velocity on the fuel mixing are investigated.

It is found that the proposed Lagrangian modeling can capture the complex pattern of the movement of the fuel particles, in spite of the large difference in diameter between inert and fuel particles.

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1. Introduction

Fluidized bed technology is used in numerous industrial applications, including combustion of solid fuels such as biomass and coal. Although the fluidized bed technology has been commercially applied over several decades, there is still a lack of knowledge that can provide a detailed understanding of the combustion process in the furnace. Especially, the understanding of mixing of fuel particles is crucial in order to be able to minimize the number of fuel feeding ports as well as lowering the excess air (which represents an energy loss). Thus, it is important to develop tools for reliable design and scale up of fluidized-bed boilers, including modeling from first principles by Computational Fluid Dynamics (CFD).

Despite the importance of fuel mixing, literature gives limited work on this phenomenon, mostly focused on experiments to estimate a dispersion coefficient (Highley and Merrick, 1971; Xiang et al., 1987; Niklasson et al., 2002; Pallarès and Johnsson, 2006). According to the authors' knowledge, only Liu and Chen (2010) provide a numerical study of fuel dispersion. They obtained the lateral dispersion coefficient in wide fluidized beds ranging from 0.4 to 12.8 m by tracking fictitious tracer particles without mass. They concluded that the Fickian diffusion equation could well describe the lateral solid dispersion in the beds tested. Liu and Chen then used the Fickian diffusion equation to study the distribution of the fuel particles over the cross section of fluidized beds, assuming the dispersion rate of the fuel particles to be the same as that of the inert bed material. This assumption is questionable because in the fuel mixing process fuel and inert particles are substantially different in size and density.

In recent decades, numerical tools, together with experiments, have increasingly been used to investigate gas–solid flows related to fluidization. A two-fluid (Eulerian–Eulerian) model, which describes both the gas and solid phases as interpenetrating continua, has been the common approach to simulate fluidization systems, typically applying the kinetic theory of granular flow (KTGF), which is an extension of the classical kinetic theory of gases to dense particle flow (Gidaspow, 1994; Elwald and Almstedt, 1998; Benyahia et al., 2000; Taghipour et al., 2005). Most Eulerian models have been limited to solids, where particles have the same diameter. However, in most industrial applications there is a solids size distribution. In the case of combustion in fluidized beds, there is typically a low mass fraction of fuel particles (less than 3%) of average size of the order of some 10 mm, with a density of 600–1000 kg/m^3, in an inert bed of finer solids (less than 1 mm) of higher particle density (2500 kg/m^3), typically consisting of bed ash or silica sand.

It is far from straightforward on how to propose a framework for continuum modeling of mixtures with more than one type of solid particles. Jenkins and Mancini (1989) were probably the first to propose a model for a binary mixture of particles. Their central assumption is that two types of particles in the mixture have the

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0009-2509/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2011.07.060

same granular temperature. This assumption was disputed in recent years by several research groups (e.g. Huilin et al., 2001; Iddir et al., 2005) due to the highly dissipative nature of particle–particle interaction encountered in flows of granular media. A concept of unequal granular temperatures of the solid phases was therefore introduced in the kinetic theory framework and, as a consequence, new balance laws and constitutive relations (in the form of transport coefficients) were derived (Huilin et al., 2001; Iddir et al., 2005). It, however, remains to be seen whether such modifications lead to a correct prediction of the particulate stresses associated with both solid phases.

On the other hand, in recent years, as a result of rapid development of computing power, Lagrangian or discrete particle methods (DPM) have been employed to model many multiphase flow applications. In DPM solid particles are tracked individually through the flow domain by solving Newton's second law of motion (Tsuji et al., 1993). Zhu et al. (2008) and Zhou et al. (2010) provide a comprehensive review of work using DPM. Although DPM is simple to apply and gives detailed information on the dynamics of particles, it is computationally demanding and in spite of the strong development of computer capacity it is still not applicable to large fluidized bed units.

Tsuji et al. (1993) were one of the first groups using the Lagrangian technique to study fluidization. They simulated a two-dimensional fluidized bed consisting of solid particles of a single size. Gas–solid systems involving more than one size of solid particles have also been investigated within the Lagrangian framework. So far, such studies mostly involved particles of similar properties. Hoomans et al. (2000) numerically analyzed a binary mixture of particles of equal density, but somewhat different in size (2.5 mm and 4.0 mm). Feng et al. (2004) studied segregation and mixing in a bidisperse gas–solid fluidized bed with solid particles of the same density and also with a relatively small difference in size (1.0 mm and 2.0 mm). Similar studies have also been performed by Beetstra et al. (2007a) and Tagamia et al. (2009).

In all the simulation work reported above, single grids were used to resolve the fluid flow and the motion of solid particles. In such a method, attention must be paid to the choice of the cell size. The requirements on the cell size are somewhat conflicting: on the one hand, the grid must be fine enough to accurately solve the governing equations and predict distinct features of the flow, on the other hand, it has to be sufficiently large to give a suitable representation of the local volume fraction of the particulate phase, which is an important parameter for calculating the drag force. Thus, a single-grid approach yields relatively accurate results when the particles are of similar size and not too large. However, when simulating the behavior of fuel particles in a bulk of inert solids employing a single grid in the simulations might lead to severely conflicting requirements related to the size of the computational cells. Namely, if the size of the cell is chosen based on the size of the fuel particles, such a cell will include far too many inert particles and thereby the flow of the carrier phase and the motion of the inert particles will not be solved accurately. On the other hand, if the grid is designed based on the size of the inert material, the cell size might be smaller than the size of the fuel particles. This conflicts with the requirement of the Lagrangian model in which the particles are approximated as point sources and therefore, the size of the discrete phase should be smaller than the size of the cells used to resolve the continuous phase. Thus, there exists a need to develop an approach that can deal with mixtures of particles in CFD simulations corresponding to fuel mixing. In the present paper we propose a multigrid Lagrangian approach to handle the substantial difference in size between the solid particles in such mixtures. The approach we suggest here in fact uses three grids for the simulations: one coarse, one fine and the one that is moving. The fine grid is used to resolve the gas flow field and track the small particles, whereas the drag force on the large particles is calculated using the coarse grid. The moving grid is applied to calculate the pressure gradient force on the fuel particles.

To validate the approach, numerical results of fuel mixing in the form of preferential positions and horizontal dispersion of the fuel particles are obtained using the multigrid simulations and compared with available experimental data given by Pallarès and Johnsson (2006). The simulations are performed under ambient conditions (the same as in the experiments) and the goal is to study the movement of the fuel particles in fluidized beds from a fluid dynamics point of view. Effects of operating parameters, i.e. the fluidization velocity and the amount of the bed material, are also investigated.

2. Multigrid technique

A multigrid Lagrangian technique has been developed and implemented in the present work to deal with mixtures of solids with considerable difference in size. As shown in Fig. 1, a computational cell of the coarse grid contains a number of cells belonging to the fine grid. The fine grid is used to resolve the gas flow field and to obtain the interaction force between the gas phase and the inert particles. To calculate the drag force on the fuel particles, the volume fraction of the fuel particles is calculated in the coarse grid. The fact that the drag force on the fuel particles is obtained in the coarse grid guarantees that the relating volume fraction never approaches the value corresponding to the maximum packing of particles. In such a way, we avoid ambiguities related to implementations of any of the drag laws for volume fractions close to the maximum packing of particles. Another value required for the drag force calculation is the gas velocity in the coarse cells. This is taken as the averaged velocity of the gas in the small cells included in each large cell. For instance, for the large cell shown in Fig. 1, the velocity of the gas in the center of the large cell is taken as the average value of the velocity of the gas in the 36 small cells. In this approach, the drag force source term due to the presence of the fuel particles in a coarse cell is then equally distributed into the small cells incorporated in the large cell.

Since the fuel particles are substantially larger than the inert particles, a fuel particle will occupy the volume of a number of small cells (Fig. 2). To calculate the solid volume fraction in the fine grid, the small cells partially or entirely occupied by the fuel

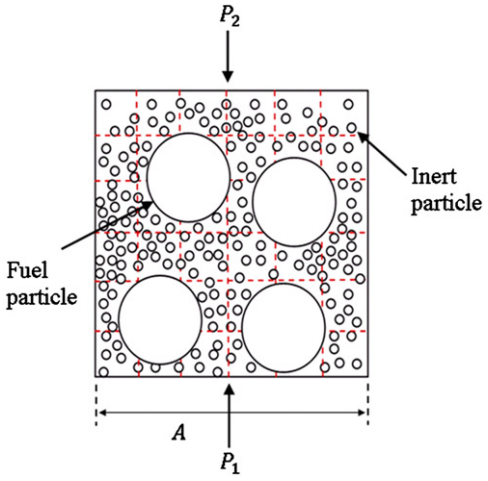

Fig. 1. Fuel and inert particles in a coarse cell including a number of fine cells.

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