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A new model for two-dimensional numerical simulation of pseudo-2D gas–solids fluidized beds

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HIGHLIGHTS

- Simple but effective model for 2D simulation of pseudo-2D fluidized bed.
- The model accounts for the important wall friction in pseudo-2D system.
- Significant improvements over the traditional 2D simulations.

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ABSTRACT

Pseudo-two dimensional (pseudo-2D) fluidized beds, for which the thickness of the system is much smaller than the other two dimensions, are widely used to perform fundamental studies on bubble behavior, solids mixing, or clustering phenomenon in different gas–solids fluidization systems. The abundant data from such experimental systems are very useful for numerical model development and validation. However, it has been reported that two-dimensional (2D) computational fluid dynamic (CFD) simulations of pseudo-2D gas–solids fluidized beds usually predict poor quantitative agreement with the experimental data, especially for the solids velocity field. In this paper, a new model is proposed to improve the 2D numerical simulations of pseudo-2D gas–solids fluidized beds by properly accounting for the frictional effect of the front and back walls. Two previously reported pseudo-2D experimental systems were simulated with this model. Compared to the traditional 2D simulations, significant improvements in the numerical predictions have been observed and the predicted results are in better agreement with the available experimental data.

1. Introduction

In experimental studies of fluidized beds, pseudo-2D fluidized beds (also referred to as 2D fluidized beds) are frequently encountered in literature. These beds usually have a rectangular cross section with one dimension significantly less than the other, typically by an order of magnitude. There is no strict guideline on how a pseudo-2D column should be designed. A general rule for constructing a pseudo-2D fluidized bed is that the bed thickness should be less than the characteristic length of the flow, i.e., bubble size, to facilitate better observation or imaging measurement (Jin et al., 2001). A unique feature of a pseudo-2D system is its ability to facilitate the employment of non-intrusive visual or imaging techniques to directly observe and measure the complex inside flow movements. With this distinctive advantage, pseudo-2D systems have been widely used in fundamental fluidization studies, such as the studies of bubble properties, jet penetration, solids clustering, solids flow patterns, and solids mixing and segregation, (e.g. Rowe et al., 1965; Lim et al., 1990; Caicedo et al., 2003; Goldschmidt et al., 2003; Zhong and Zhang, 2005; Pallares and Johnsson, 2006; Busciglio et al., 2008; Laverman et al., 2008; Zhang et al., 2008; Xu and Zhu, 2011). The qualitative and quantitative information gathered from these pseudo-2D systems has been used to develop models for describing the gas–solids flow. The established models are then utilized to improve understanding of flow behaviors in three-dimensional (3D) fluidized beds including those used in various industrial processes.

With fast acceleration in computational power and continuous development in numerical algorithms, computational fluid dynamics (CFD) has become an effective complementary tool to the experiment for understanding the complex hydrodynamics in

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gas–solids flows (Grace and Li, 2010). Prior to application of CFD models to complex industrial processes, extensive validation of the numerical models is needed (Grace and Taghipour, 2004). In this regard, large amounts of accurate experimental data are needed for model validation. Through employment of advanced imaging techniques, such as Particle Image Velocimetry (PIV) and Digital Image Analysis (DIA), a great amount of quantitative information is available for pseudo-2D fluidized beds. Such experimental data are highly useful for CFD model validation owing to the high data quality and simple geometrical configuration.

Abundant numerical studies of different gas–solids fluidization systems can be found in open literature. In most CFD studies, 2D simulations were used to simulate the flow hydrodynamics in both pseudo-2D and 3D cylindrical fluidization systems. The differences between 2D and 3D simulations of gas–solids fluidized beds and the applicability of simulating a 3D cylindrical column by a 2D model have been discussed in several papers (Peirano et al., 2001; Cammarata et al., 2003; Xie et al., 2008a, 2008b; Li et al., 2010b, accepted for publication; Cloete et al., 2013a). Unlike the 3D cylindrical gas–solids fluidized beds, it is natural that 2D simulations are used to simulate pseudo-2D experimental systems for predicting the flow hydrodynamics as has been done in previous studies (Busciglio et al., 2009; Li et al., 2010a; Hernandez-Jimenez et al., 2011). Good qualitative agreement on general flow behaviors including patterns of solids mixing and bubble movement, and satisfactory quantitative agreement on bed expansion, bubble size distribution, shape factors between 2D numerical simulations and experimental measurements have been reported. However, there exist significant differences between the predictions of 2D numerical simulations and the experimental data from pseudo-2D columns with respect to bubble rising velocity and solids velocity, especially the latter. It has been reported by several researchers that 2D numerical simulations significantly over-predicted the solids velocity in pseudo-2D bubbling fluidized beds (Li et al., 2010a; Hernandez-Jimenez et al., 2011; Cloete et al., 2013b).

In a thin pseudo-2D fluidized bed, the front and back walls restrict the solids movement in two directions and the friction exerted by the front and back walls further influences the solids movement. This leads to different flow behaviors from a 3D cylindrical system as has been discussed in previous studies (Rowe and Everett, 1972; Geldart, 1970; Cranfield and Geldart, 1974; Glicksman and McAndrews, 1985). For example, the bubble coalescence, bubble properties, and even the bed expansion in a pseudo-2D bed differ from those in a 3D bed. Strictly speaking, the gas–solids flow in a pseudo-2D fluidized bed does not follow an absolute 2D pattern. In some pseudo-2D fluidized beds with considerable thickness, there might exist strong 3D flow behaviors which not only cause issues in detecting small bubbles for most non-invasive visual or imaging techniques, but also prevent the modeler from simplifying the flow into 2D. Even in pseudo-2D beds with small bed thickness where a good 2D flow is expected, the 2D numerical simulations cannot yield reasonable agreement with the experimental solids velocity field. It has been demonstrated that the frictional effect from the front and back walls, which is not accounted for in the 2D simulations, leads to the deviation for solids velocity and bubble rising velocity (Li et al., 2010a; Cloete et al., 2013b). The wall effect in numerical simulations of pseudo-2D gas–solids systems has been investigated in several numerical studies (Kawaguchi et al., 1998; Feng and Yu, 2010; Li et al., 2010a, 2012; Cloete et al., 2013b). These studies all recommended a 3D simulation to get more accurate prediction of pseudo-2D gas–solids fluidized beds, i.e. the wall effect must be included. However, for a 3D simulation of thin pseudo-2D column, sufficient grid resolution in the thickness direction is needed to account for the frictional effect from the front and back walls and to resolve the possible 3D flow behavior. The large computational cell aspect ratio tends to cause difficulty in computation convergence when normal grid sizes are used for the other two dimensions. Furthermore, the flow behavior of the third dimension in a thin pseudo-2D column is of less interest for model validation purpose. Considering the expensive computational cost associated with the 3D simulations and the target flow field information for validation, it is therefore preferential to conduct 2D simulations for pseudo-2D fluidized beds.

The objective of this study is to propose a model for 2D simulations to account for the front and back wall effect in a pseudo-2D gas–solids fluidized bed for better numerical prediction. This paper is organized as follows. First, a brief summary of the two-fluid model is presented. The new model is then proposed to account for the frictional effect of the front and back walls in a 2D simulation after introducing certain assumptions for the pseudo-2D fluidization system modeling. The newly proposed method is utilized to simulate two experimentally studied pseudo-2D bubbling fluidized beds. Finally, the numerical results are analyzed and compared to the experimental data for validation.

2. Two-fluid model

In this study, a two-fluid model (TFM), which treats both gas and solids phases as interpenetrating continuums, is used to simulate the gas–solids flow in fluidized beds. The governing equations derived from an appropriate averaging procedure are solved using the finite volume method. In order to close the governing equations, constitutive correlations derived from the granular kinetic theory are used for describing the solids phase stress. The governing equations, along with constitutive correlations, are solved in an open-source CFD code, MFIX, which is developed at the U.S. Department of Energy's National Energy Technology Laboratory. A brief summary of equations solved in MFIX is provided in Table 1. More details on the theory and numerical techniques used by MFIX can be found at https://mfix.netl.doe.gov (Syamlal et al., 1993; Syamlal, 1998).

3. Friction model for front and back walls

For the gas phase, a non-slip boundary condition is usually applied in gas–solids flow simulations, which is believed to be reasonable for most cases. For a pseudo-2D fluidized system with mono-dispersed solid particles, it has been demonstrated that the solids phase behavior dominates the flow and the effect of the gas flow boundary condition is negligible (Li et al., 2012). Different wall boundary conditions for the solids phase can be found in literature covering free-slip, partial-slip, and non-slip boundary conditions. It is generally believed that the partial-slip boundary condition is more physical, which accounts for both shear force and flux of fluctuation energy imposed by the wall on the solids flow (Johnson and Jackson, 1987; Jenkins, 1992; Schneiderbauer et al., 2012).

The effect of front and back walls cannot be modeled through the wall boundary conditions as these walls are not included in the computational domain of 2D simulation. To account for the wall effect on the solids flow, the shear stress and flux of fluctuation energy applied by the front and back walls must be taken into account. To simplify this analysis, the collisions between particles and the front and back walls are assumed to be sliding (Jenkins, 1992; Li and Benyahia, 2012). Hence, the shear force applied to the granular flow by these walls can be calculated based on the boundary condition proposed by Jenkins and Louge (1997) at the small friction/all sliding limit. This simplification is justified