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Wall effects on space averaged two-fluid model equations for simulations of gas–solid flows in risers

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HIGHLIGHTS

- Two-fluid model was used for numerical simulation of gas–solid flow in a riser with Geldart group B particles.
- Space averaging applied over the gas–solid drag and the convective term to analyze the subgrid-scale modeling.
- Wall effects were studied for subgrid-scale models.
- Subgrid-scale models showed dependence on distance from the wall, averaging size and solid volume fraction.
- Results obtained for Geldart group B particles clearly differ from those presented in the literature for Geldart group A particles.

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ABSTRACT

For the study of gas–solid flows in a circulating fluidized bed (CFB) riser, the model based on the Eulerian description of phases is widely used. Such a description requires the usage of a fine mesh and a short time step in the numerical simulations. Due to the constraint of long calculation times with fine meshes, it becomes practical to simulate the gas–solid flow in a CFB riser with coarse meshes. This work is the continuation of formulating the subgrid-scale models for the space averaged two-fluid model equations which can be used in coarse mesh simulations of gas–solid flows in risers. In this study, the vertical component of the drag force and the convective term are analyzed and their dependence on the averaging size and solid volume fraction with the distance from the wall is presented.

1. Introduction

Multiphase flows in industrial units such as circulating fluidized beds are heterogeneous and exhibit large fluctuations over spatiotemporal scales. The modeling of gas–solid two-phase flows in a CFB riser is mainly done with the use of a two-fluid model (Anderson and Jackson, 1967; Gidaspow, 1994; Lun et al., 1984). In the two-fluid model formulation, both phases are treated as interpenetrating continua. The continuity and momentum equations are solved for both phases. The closure models for the solid phase momentum equation based on the kinetic theory of granular flow can well predict the core-annulus flow regime (Benyahia et al., 2007).

Computational fluid dynamics (CFD) simulation of gas–solid flows using a two-fluid model usually requires a very fine mesh to capture the mesoscale structures. This restricts the simulation of large scale fluidized bed units because of infeasible calculation time. For practical calculation purposes, the gas–solid flows in risers are usually simulated with coarse meshes, and as a result, the information about the mesoscale structures in the flow field is lost. This lost information about the mesoscale structures must be retrieved in the form of appropriate closure models when performing coarse mesh size simulations. Many attempts have been made by various research groups for the formulation of closures which can be used in coarse mesh simulations of gas–solid flows in risers (Agrawal et al., 2001; De Wilde, 2005; Igci et al., 2008; Wang and Li, 2007; Yang et al., 2004; Zhang and VanderHeyden, 2002).

When Reynolds averaging is applied to the Navier–Stokes equations as in the single phase flow, there is a need to model the Reynolds stresses which arise from the velocity fluctuations.

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Similarly, for two-phase gas–solid flows, the macroscopic averaging approach, also known as filtering approach, is applied over the equations. Different macroscopic averaging approaches such as ensemble phase averaging (Zhang and VanderHeyden, 2002), time averaging (Benyahia, 2008; Hrenya and Sinclair, 1997; Kallio et al., 2008) and space averaging (Igci et al., 2008; Shah et al., 2012) have been performed over the two-fluid model equations.

All these averaging approaches result for the need to develop the closure models. Kallio et al. (2008) analyzed different terms in the momentum equation to study the magnitude of the closure models by performing time averaging over the equations. In their analysis, the main terms which showed highest magnitude were the gas–solid drag force and the Reynolds stresses arising from the velocity fluctuations. Igci et al. (2008) showed in their analysis that the contribution from the Reynolds stresses is much larger than the particle phase stress and also the contribution from the drag force is much larger than the term arising from the correlation between the fluctuations in the solid volume fraction and in the pressure gradient.

During the last decade, the gas–solid drag force is the term which has received highest attention when seeking the closures for the coarse mesh simulations. For example, the approach used in the energy-minimization multi-scale (EMMS) model has concentrated only on the drag force term when performing coarse mesh simulations (Wang and Li, 2007; Yang et al., 2004). For the filtered model equations, subgrid-scale modeling of the drag force is very important. In the filtered two-fluid model equations, details about the filtered drag coefficient is presented (Igci et al., 2008). Also, in the time averaging studies by Kallio et al. (2008), the importance of correction to the drag force was presented. Coarse mesh simulation results into the loss of information about the mesoscale structures of the flow field, which leads to uniform solids concentration profiles and eventually higher solids mass flux. Thus, there is a need to correct the overestimated drag force which consequently reduces the higher solids mass flux.

Another important issue which has raised attention for the closures in the filtered two-fluid model equations is the effects caused due to the bounding walls. Igci and Sundaresan (2011) recognized the need of wall correction to the filtered drag coefficient, the filtered particle phase normal stress and the filtered particle phase shear viscosity, and formulated closure models based on the distance from the wall. Recently, Igci et al. (2012) used the idea of including the wall corrections in their simulations for different mesh sizes and obtained a reasonable agreement with experimental results. They showed that the results predicted by the filtered two-fluid model equations are nearly filter length independent. The study by Igci et al. (2012) shows the feasibility of space averaging approach in which the closure models obtained from the fine mesh simulation are applied to the coarse mesh simulation. The study of Igci and Sundaresan (2011) dealt with FCC particles belonging to Geldart group A. In the present study, a case of larger Geldart group B particles in a wider solids volume fraction range is analyzed.

In this work, the same methodology of space averaging over the two-fluid model equations as used by Igci et al. (2008) has been followed. A two-dimensional fine mesh simulation of the gas–solid flow in a CFB riser using the two-fluid model was performed in the CFD package Fluent 6.3.26. The simulation results are then space averaged over different averaging sizes to analyze the behavior of subgrid-scale models which can be used for coarse mesh simulations.

Space averaging on the two main terms, vertical component of the drag force term and the convective term, in the two-fluid model, has been performed and then the behavior of the subgrid-scale models for different averaging sizes and solid volume fraction values is analyzed. The same notations are used in this work which were defined in our prior study (Shah et al., 2012). The obtained results showed strong dependence of the subgrid-scale models on the averaging size and solid volume fraction values as a function of distance from the wall. To explain the observed behavior of the correction factor in the different averaging regions, the standard deviations of different variables were calculated to evaluate the fluctuation characteristics of the flow properties as function of the lateral coordinate.

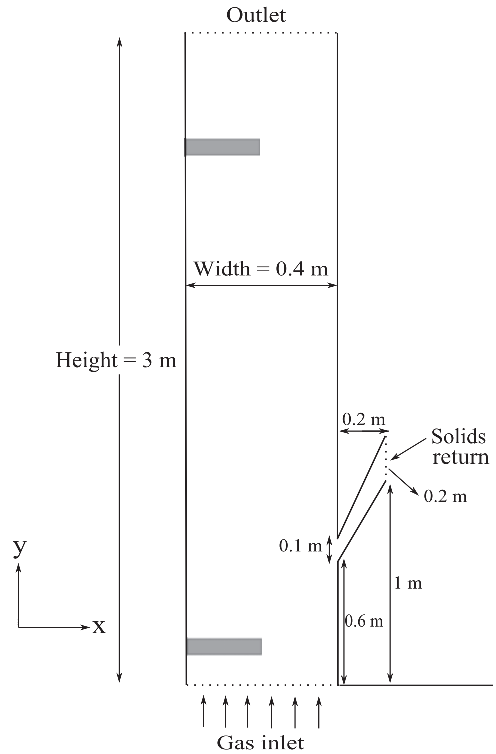

Fig. 1. Schematic drawing of the circulating fluidized bed riser and the small channel of the return leg. The selected areas seen in the lower and upper parts of the riser will be referred to later. The solid lines along the riser height and in the return leg channel represent the walls.

2. Methodology

2.1. Domain for CFD simulation

Kallio et al. (2009) give a systematic description of the experimental unit and validate the CFD modeling method by comparing measurements with results obtained from a CFD simulation, where the same models and mesh as in the present paper were used. The main components of the CFB unit include a riser, a solid separation unit, and a return leg with a loop seal. The dimensions of the CFB riser are as follows; 3 m height, 0.4 m width, and 0.015 m depth. As mentioned in Agrawal et al. (2001), ideally, 3D simulations are better than 2D simulations. In gas–solid flow systems, the qualitative analysis of heterogeneous structures can be studied by 2D simulations. In the experimental unit of our case study, we had very small depth of 0.015 m which is too small to study the fluctuations in the third direction. For this reason, our simulation was only conducted in 2D. At the bottom of the riser, an uniform gas inlet was assumed due to the difficulties in defining the computational mesh near the nozzles as located in the experiments. During the measurement, the fluidization gas velocity was 3.5 m/s and the average solids inventory in the CFB riser was about 2.5 kg. A schematic of the geometry is shown in Fig. 1.