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Parametric study of the time-averaged gas–solid drag force in circulating fluidized bed conditions

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ABSTRACT

Steady state modeling based on time-averaged transport equations is a computationally efficient method for CFD simulation of large industrial-scale circulating fluidized beds. The feasible alternative for steady state modeling is to carry out transient simulations in a coarse mesh, which would require mesh resolution dependent closure laws and lead to long simulations in order to characterize the average process behavior. These closures could be avoided by simulations with adequate spatial and temporal resolutions, but the required computational effort renders such simulations unfeasible in industrial scale applications in near future. Equation closures for steady state modeling can be developed by time-averaging results from transient simulations. One of the largest terms to be modeled is the time-averaged drag force. In the present work, parameters that need to be accounted for in a model for the time-averaged drag force were studied by analyzing time-averaged results from a number of transient 2D simulations carried out with fairly fine spatial resolution. The analysis was limited to Geldart B particles. In the literature, the solid volume fraction, distance to the wall and the gas–solid slip velocity have been included as parameters in drag correction functions developed for transient coarse-mesh simulations. In the present work, the same parameters are found to have significant effects on the time-averaged gas–solid drag force. Additionally, solid density, particle size and gas phase laminar viscosity are shown to have significant effects on the average drag force. Thus process conditions, which significantly vary inside a CFB, need to be accounted for in the model.

1. Introduction

The flow patterns in a circulating fluidized bed (CFB) are characterized by large spatial and temporal fluctuations in solid concentration as well as in gas and solid velocities. Length scales of these variations can be very small, down to a few particle diameters, which constitutes a difficult challenge for computational fluid dynamic (CFD) simulation of industrial scale CFBs utilized in energy production and conversion processes. Similar computational mesh related spatial resolution challenges are encountered both with Eulerian–Eulerian two-fluid models and with the multi-phase particle-in-cell methods [1]. Resolving the smallest flow structures would require a very fine mesh that would be computationally unfeasible for simulation of typical industrial scale processes. As a result, coarser meshes that filter out the fine sub-grid scale flow structures are commonly used. To account for the filtered information, corrections or sub-grid scale models for the terms in the transport equations should be applied. Such closure models have been proposed in the literature for different terms in the gas and solid phase momentum equations on the basis of theoretical considerations and analysis of results from transient simulations of fairly small geometries with high spatial resolution. As the filtering scale depends on the resolution of the simulation, these closure models should have the resolution as a parameter which complicates derivation of the closure laws. No general closures that would cover all typical conditions in circulating fluidized beds and all terms in the equations have yet been proposed.

To avoid mesh dependence in the closures and to speed up the simulations, steady state modeling has been suggested as an alternative for the transient simulations [2,3]. Transient coarse mesh simulations filter out spatial fluctuations smaller than the mesh spacing and temporal fluctuations shorter than the time step. Steady-state simulation models are derived by time-averaging the transient equations, which filters out all temporal variations in the flow properties. Closures need to be developed to account for the effects of the filtered variations. These closures are of a similar character as the sub-grid closures required for transient coarse mesh simulations. In both cases, the closures describe clustering of particles and fluctuations in flow properties. A closure for a very coarse mesh should approach the closure for a time-averaged equation, since a volume average over a distance longer than the longest length-scales of the fluctuations should produce the same result as a time

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average in a single point, when the statistical characteristics over the averaging space and time frame are the same. That would be the case if there would be no spatial gradients in the time-averaged flow field. Although this condition is never exactly met, the gradients in the time-averaged volume fraction and velocities are often small compared to the fluctuations, for example in the center of a large CFB riser.

To evaluate the need for equation closures, a study of the terms in the time-averaged momentum equations in CFB conditions was carried out by Kallio et al. [4]. One of the largest terms in the momentum equations was the gas–solid drag force, for which several closures have been proposed to describe the effects of clustering of particles. Closures can be derived on experimental basis like what was done by Kallio et al. [5] who applied a drag law that was based on the empirical equations suggested by Matsen [6] for bed expansion in CFB and BFB conditions and on the Ergun [7] equation at the packing limit. In recent years, instead of using empirical correlations as basis, it has been more common to develop models based on transient simulations in fine meshes.

Agrawal et al. [8], Andrews et al. [9], and Igci et al. [10,11] developed closures for the average drag and stress terms through 2D simulations in small domains with periodic boundary conditions and, by volume-averaging the results, they derived closures for the sub-grid scales. In Igci and Sundaresan [12] and Igci et al. [13], wall effects were included in the analysis of a case of Geldart A particles and in the closures that were derived by volume-averaging 2D transient simulation results for the drag force and the normal and shear stresses of the solid phase. Milioli et al. [14] further developed the closures by including the slip velocity between the phases in the equations. Shah et al. [15] studied wall effects on the gas–solid drag force in a case of Geldart B particles through volume-averaging 2D transient simulation results for a small CFB. Zhang and VanderHeyden [16] discussed the effects of mesh spacing on Reynolds stresses and the drag force. In Zhang and VanderHeyden [17], an added-mass force closure was suggested for the correlation between fluctuations of the pressure gradient of the continuous phase and fluctuations of solid volume fraction. De Wilde [18] analyzed the same term from simulations and accounted also for the average drag force in the derivation of new closure models that were applied in De Wilde et al. [19] for steady state simulation of a riser. In addition to models based on measurement data and transient simulation results, closures for the gas–solid drag force have been suggested on the basis of theoretical analysis of clustering flow in dense gas–solid suspensions [20,21]. Common to all the suggested sub-grid and steady-state drag models is that the predicted drag force is reduced from what the homogeneous flow drag correlations would predict in the same flow conditions.

The models presented in the literature often take into account only a small number of factors that can affect the magnitude of fluctuations in flow properties. To improve our understanding of the requirements for a comprehensive filtered drag law, the present study analyzes the effects of material properties on the average drag force applicable to steady state modeling. In addition, the effects of process conditions on the required drag closures are evaluated. The analysis is based on time-averaging the results from transient Eulerian–Eulerian simulations of circulating fluidized beds of Geldart B particles. Since 3D simulations are very time consuming, development of sub-grid closure laws has commonly been carried out by averaging results from 2D simulations. For the same reason, this parametric study is carried out in 2D. Although the observed quantitative effects of the studied parameters cannot be applied to 3D simulations with high accuracy, some implications for further 3D studies and closure development can be derived, since the parameters required for drag correction in 2D should be significant also in 3D geometries. Still, as long as a similar dataset from 3D simulations is not available, the data collected in the present study can be used to derive models for the time-averaged drag force. Furthermore, the results of the present study provide an indication which parameters should be included in the drag correction functions applicable to coarse mesh simulations.

2. Methodology

2.1. Transient simulations

A large number of 2D simulations were carried out for analysis of the required closures for the time-averaged momentum equations. A selection of the simulations with varying gas viscosities, gas densities, solid densities, particle sizes, riser size and mesh spacings was chosen for the present analysis. The geometry is a simple riser with straight walls. A uniform gas inflow is introduced at the bottom and gas and solids exit the riser through the top edge of the simulated domain. Solids that leave the riser are fed back through a return channel located at 0.6–0.7 m height.

The simulations analyzed are listed in Table 1. Although gas density and viscosity in most industrial applications are strongly coupled, here their values were changed independently to separate their individual effects. Thus some of the simulations don't necessarily represent typical CFB conditions as used today.

The numerical simulations were carried out with the commercial code ANSYS Fluent v.14 [22]. The simulations were based on the Eulerian–Eulerian multiphase approach with the kinetic theory of granular flow (KTGF) models. In this study, models available in Fluent v.14 were used and they are listed in Table 2 with references to the corresponding authors.

For the drag term the standard Gidaspow [23] model based on the Ergun [7] and Wen–Yu [24] drag laws was used. For the momentum second order discretization was applied and for the volume fraction equation the QUICK scheme was applied. The time step was 0.001 s for the 12.5 mm and 25 mm meshes and 0.0005 s for the 6.25 mm mesh. For each case, approximately 5 s was simulated before starting to calculate the average values and at least a further 120 s of flow time was simulated to compute the averages. This presented a reasonable compromise between simulation time and accuracy of the average values. Comparisons with measurements have been made earlier for some simulations with the same models in a 0.4 m wide geometry [25]. The measurement and simulation results were in good qualitative agreement and even quantitatively the results were reasonably good considering that the simulations were carried out in 2D. Thus the chosen approach should be sufficiently accurate for the present study.

To allow simulation of a large number of cases in a reasonably short time, most simulations in this work were carried out in a coarse mesh with 12–25 mm spacing. To study effects of the mesh spacing, one simulation was done in a finer 6.3 mm mesh. At the same time, also the time step was halved, i.e., reduced from 0.001 s to 0.0005 s. Fig. 1 shows a comparison of the obtained time-averaged solid volume fraction fields in Cases 1, 3 and 2, where the mesh spacing was 6.3 mm, 12.5 mm and 25 mm, respectively. No significant qualitative change in the solid distribution can be observed. The majority of the simulations analyzed in the present work were carried out in a 2D mesh with 12.5 mm mesh spacing. Although the quantitative results slightly change when the mesh is coarsened, the qualitative results don't show any significant sensitivity to mesh spacing and time step and thus the chosen meshes were considered sufficient for this qualitative parametric study. Some simulations were also carried out in a 50 mm mesh, which produced significantly altered flow patterns. Consequently, simulations with such coarse meshes were omitted from the analysis.

2.2. Time-averaging of the transient simulation results

Time-averaged equations can be developed by averaging the transient equations over time. The instantaneous values are written as a sum of the time-average and a fluctuation: $\phi = \overline{\phi} + \phi^{'}$. Favre averaging is applied on velocities: $U_{q,i} = \overline{\alpha_q u_{q,i}}/\overline{\alpha_q}$, $u_{q,i} = U_{q,i} + u^{''}_{q,i}$. The time-