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Sub-grid drag models for horizontal cylinder arrays immersed in gas-particle multiphase flows

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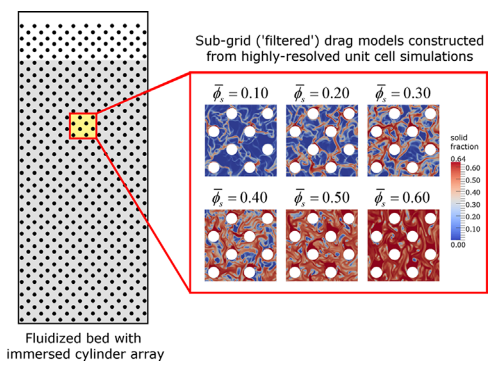
HIGHLIGHTS

- Filtered drag models developed for gas-particle flow around arrays of cylinders.
- Model for effective cylinder-suspension drag constructed.
- Cylinder arrays also affect clustering behavior and modify gas–solid drag.
- Set of filtered constitutive equations to model cylinder arrays presented.

GRAPHICAL ABSTRACT

Representative snapshots of periodic unit cell simulations used to construct sub-grid 'filtered' drag models for fluidized beds with cylinder arrays.



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ABSTRACT

Immersed cylindrical tube arrays often are used as heat exchangers in gas-particle fluidized beds. In multiphase computational fluid dynamics (CFD) simulations of large fluidized beds, explicit resolution of small cylinders is computationally infeasible. Instead, the cylinder array may be viewed as an effective porous medium in coarse-grid simulations. The cylinders' influence on the suspension as a whole, manifested as an effective drag force, and on the relative motion between gas and particles, manifested as a correction to the gas-particle drag, must be modeled via suitable sub-grid constitutive relationships. In this work, highly-resolved unit-cell simulations of flow around an array of horizontal cylinders, arranged in a staggered configuration, are filtered to construct sub-grid, or 'filtered', drag models, which can be implemented in coarse-grid simulations. The force on the suspension exerted by the cylinders is composed of, as expected, a buoyancy contribution, and a kinetic component analogous to fluid drag on a single cylinder. Furthermore, the introduction of tubes also is found to enhance segregation at the scale of the cylinder size, which, in turn, leads to a reduction in the filtered gas-particle drag.

1. Introduction

Cylindrical tube arrays often are used in industrial fluidized bed systems as internal heat exchangers. The presence of these tube bundles strongly affects the dynamics of particle clusters and gas

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bubbles, which, in turn, affects the macroscopic flow (Yurong et al., 2004; Asegehegn et al., 2011; Schreiber et al., 2011, to name a few studies). To obtain good quantitative predictions, the grid used in computational fluid dynamics (CFD) simulations needs to be fine enough to resolve flow phenomenon at the smallest length-scales (Agrawal et al., 2001). To resolve the flow around cylinders a few centimeters in diameter in devices that may be tens of meters tall, the required number of cells would be $O(10^6)$ in two-dimensional (2D) models and up to $O(10^9)$ in three-dimensional (3D) CFD models. The prohibitive computational cost of such fine-grid simulations necessitates the development of multiscale methods where the cylinders do not have to be explicitly resolved.

One approach is to use coarse-grid simulations, where the cylinders are replaced by an effective uniform, stationary porous medium, and the effects of the unresolved cylinders on the gas-particle flow are captured using sub-grid models. The objective of this work is to construct these sub-grid models by filtering the results from periodic cell CFD simulations with immersed horizontal cylinder arrays. The influence of the immersed cylinders on the gas–solid suspension is mainly felt via two ways. First, the cylinders can exert a drag force directly on the suspension. Second, the cylinders may change the clustering behavior of particles, which indirectly affects the filtered gas-particle drag. Both mechanisms are investigated, and the corresponding filtered models for cylinder-suspension drag and gas–solid drag are presented.

2. Background

A characteristic feature of gas-particle flows in fluidized beds is the rapid formation and dissociation of inhomogeneous particle clusters. Macroscopic flow properties, such as solid fraction profile and particle mass inventory, are strongly influenced by the gas flow around these microscopic particle clusters (Igci et al., 2008; Parmentier et al., 2012). Particle clusters are known to have a characteristic length scale of $O(10d_p)$, where d_p is the particle diameter (Agrawal et al., 2001). Hence, for applications where particle diameters typically range from 50 μm to 500 μm, cell sizes on the order of a few millimeters are required—small enough to resolve fine particle clusters. For large-scale industrial applications, where the devices can be up to 10 m in size, $O(10^3)$ cells are needed along each direction, i.e., millions of cells for 2D and billions of cells for 3D simulations. Simulations with $O(10^6)–O(10^9)$ cells are numerically very expensive and generally require access to powerful computing resources.

Often, arrays of heat transfer tubes are immersed in fluidized beds. To accurately resolve the flow around individual tubes, the cell size must also be sufficiently smaller than the cylinder diameter and spacing, in addition to being small enough to resolve fine particle clusters. These high-resolution simulations provide detailed information on the microscopic flow of clusters and bubbles. However, for commercial-scale devices, the macroscopic quantities, such as bed height, solids holdup, and axial pressure variation, usually are of greater interest.

A number of authors have proposed using sub-grid, or 'filtered', constitutive models in coarse-grid CFD simulations, similar to the large-eddy simulation technique used in single-phase turbulence. These coarse-grid simulations cannot explicitly resolve small-scale features such as clusters, but their influences are incorporated as sub-grid constitutive relationships (Agrawal et al., 2001). In a series of papers from Princeton University (Andrews et al., 2005; Igci et al., 2008; Igci and Sundaresan, 2011a,b; Igci et al., 2011; Milioli et al., 2013), sub-grid models for filtered gas–solid drag, particle- and gas-phase viscosities, and particle-phase pressure are developed by filtering the results from highly-resolved simulations of gas-particle flows in smaller periodic domains. Parmentier et al. (2012) further show, through a budget analysis, that the filtered sub-grid drag is the most important correction. Implementations of their sub-grid drag model in coarse-grid simulations, without any corrections for filtered stresses, produce reasonably good results for macroscopic flow predictions. Other authors have proposed alternate sub-grid gas-particle drag corrections, a discussion of the various formulations is presented by Schneiderbauer et al. (in press).

Although most research has focused on gas–solid flows away from boundaries, corrections for vertical walls are introduced in Igci and Sundaresan (2011b). The filtered gas–solid drag coefficient is found to be significantly smaller close to the walls, which strongly suggests that immersed boundaries—such as an array of cooling tubes—can significantly affect the filtered relationships.

No attempts have been made to develop sub-grid models for immersed cylinder arrays. There may be hundreds of cooling tubes in commercial devices, which makes it computationally infeasible to resolve the cylinders explicitly in CFD simulations. However, it may be possible to replace the exact representation of the cylinder array by an effective uniform, stationary porous medium. The objective of this work is to develop filtered relationships that model the effects of the cylinder array on the gas–solid suspension. The approach followed in this study is based on the work of the Princeton University group, particularly the methods used by Igci et al. (2008) and Igci and Sundaresan (2011a). Highly-resolved simulations of a periodic cell with immersed cylinders are analyzed to construct filtered constitutive relationships for cylinder-suspension drag and gas–solid drag. Sub-grid models for stresses presently are ignored as Parmentier et al. (2012) have shown the drag corrections to be adequate.

3. Filtered two-fluid model equations for cylinder drag

Kinetic-theory-based microscopic two-fluid model (Ding and Gidaspow, 1990; Gidaspow, 1994) have been used to simulate multiphase flow in a number of fluidized bed systems, and have been the starting point of several recent studies that have developed filtered models (Andrews et al., 2005; Igci et al., 2008; Igci and Sundaresan, 2011a,b; Parmentier et al., 2012; Holloway and Sundaresan, 2012; Milioli et al., 2013; Agrawal et al., 2013). In this work, the microscopic two-fluid model also is used to construct filtered drag models with an immersed cylinder array. The flow is assumed to be isothermal and non-reactive. A summary of the microscopic two-fluid model conservation equations is presented in Table 1, which are solved using the open-source code MFIX (Syamlal et al., 1993; Syamlal, 1998).

Instead of the more detailed partial differential equation formulation, a simpler algebraic approximation of the granular energy equation is used (Eq. (5) in Table 1, where θ_s is the solids granular temperature). This is a necessary choice so that the cut-cell capability in MFIX (Dietiker, 2012) can be used to model curved cylinder boundaries. Li et al. (2011) also have used the cut-cell feature and algebraic approximation for granular energy to model a tube bundle in a bubbling bed. Their simulation results show reasonably good agreement with experimental measurements of bubble dynamics, suggesting that the algebraic approximation is an acceptable simplification.

The objective of this work is to develop filtered drag relationships that model the presence of a cylinder array. In this study, a staggered arrangement of horizontally oriented cylinders is used (Fig. 1) because it is a common configuration for cooling tube bundles (Kim et al., 2003; Li et al., 2011). Sometimes, arrays of vertical cooling tubes are also employed, but to develop filtered models for vertical cylinder arrays, computationally expensive 3D simulations must be necessarily performed. Deriving filtered corrections for horizontal cylinder arrays is more tractable as it