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Analysis of the flow in inhomogeneous particle beds using the spatially averaged two-fluid equations

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Abstract

The drag force term appearing in two-fluid models for fluid–particle flows is commonly closed by expressing it as a function of the local quantities, such as the local particle volume fraction, the local slip velocity between the particle and fluid phases, and the local mean-squared fluctuating velocity of the particles. The adequacy of such closures for inhomogeneous suspensions has been debated in the literature and some researchers have suggested the need for additional terms involving spatial gradients in these quantities. To test this proposition, simulations of flow in inhomogeneous steady beds of particles have been performed using the lattice-Boltzmann method. The particle beds consisted of disordered assemblies with a density profile on a scale much larger than the particle radius. Inhomogeneous beds with a controlled density profile were generated in three different ways, (i) by inhomogeneous stretching of the particle bed in one direction, (ii) by applying an inhomogeneous force to the particle phase during random motion of the particles, and (iii) by taking snapshots of a direct simulation of a traveling wave in a fluidization simulation. The global structure of the three beds was comparable, while assessment of the radial distribution functions showed that the three beds exhibited clearly different microscopic structures.

The force profiles along the inhomogeneous direction of the particle bed were obtained from the flow simulations. These were analyzed by applying spatial averaging in a manner identical to the averaging procedure that is used to derive the two-fluid model equations. The force profiles were compared to predictions based on flow simulations of homogeneous disordered particle beds over a range of volume fractions. To assess the role of the microstructure of the particle bed also simulations were executed where the homogeneous disordered bed was modified by either applying homogeneous stretching or by applying a lubrication force during generation of the particle bed.

This study demonstrated that the microscopic structure of the particle bed has a severe impact on the closure of the drag force. Our computations did not reveal any evidence supporting the need for terms involving gradients in particle volume fraction in the drag force closure.

Keywords: Lattice-Boltzmann; Drag force; Suspension; Closure

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1. Introduction

Fluid–particle systems such as fluidized beds manifest structures over a wide range of spatial and time scales. Experiments have revealed traveling voidage waves in liquid fluidized beds (Anderson and Jackson, 1968; Duru et al., 2002), bubble-like voids in beds fluidized by liquids (Duru et al., 2002) and gases (Rowe, 1964), and particle clusters in dilute fluidized beds. The origin of these structures has been the subject of many theoretical studies and numerical simulations, which have been reviewed by Jackson (2000). It is now known that averaged equations of motion (commonly referred to as the two-fluid model equations), obtained by ensemble or volume averaging the Navier–Stokes equations for the fluid and the Newton's equations for the motion of individual particles, coupled with very simple phenomenological closures for the effective stresses and the interphase interaction force appearing in them, can yield such structures in a qualitatively correct manner (Glasser et al., 1996, 1997; Jackson, 2000; Sundaresan, 2003). An important challenge ahead of us is the construction of more accurate and validated closures for the two-fluid model that can lead to quantitative predictions.

In most fluidized suspension flow problems and flows through fixed beds encountered in practice, the dominant terms appearing on the right hand side of the momentum balance equations are the body force term, the term accounting for the effect of the locally averaged pressure gradient in the continuous fluid phase, and the interphase interaction force term; there is little difficulty in describing the first of these terms, and the pressure gradient is computed as a part of the solution, when the two phases are incompressible. The interphase interaction term requires closure modeling, and the quantitative predictions of the two-fluid model depend strongly on the accuracy of the closure modeling of this term. The interphase interaction force is usually written as a sum of different contributions: the quasi-steady drag force, the added mass force, Basset history force, the inertial lift force, the Saffman lift force, etc. In most practical situations, the largest contribution to the interphase interaction force comes from the drag force, and hence the focus tends to be on improved closures for the drag force term.

It is commonly assumed that the local-average drag force in fluid–particle systems can be quantified purely in terms of local quantities, i.e., the local particle volume fraction (or equivalently voidage), the local average velocities of the fluid and particle phases, local mean-squared fluctuation velocity of the particles, and the fluid properties (e.g. Wylie et al., 2003). Spatial gradients in these quantities are generally not accounted for in the closure for the drag force. It was suggested by Foscolo and Gibilaro (1984) that the drag force should include a term proportional to the gradient in particle volume fraction and that this term plays an important role in the stabilization of some homogeneously fluidized states; this has been received with some skepticism in the literature (Batchelor, 1988).

More recently, Marchioro et al. (2000, 2001) have analyzed slow viscous flow of a fluid in domains with a small spatial gradient in particle volume fraction and explored the effects of these gradients on terms arising in two-fluid model equations. Wang and Prosperetti (2001) applied this approach to study slow viscous flows in fixed beds of stationary or spinning particles, allowing for a small-amplitude, sinusoidal variation of the particle volume fraction and found that the commonly used closure relations for the interphase interaction force, which are based on particle volume fraction, velocities and the pressure, are, in general, insufficient.

In the present study, we focus on fluid flow through assemblies of uniformly sized spherical particles and address the following two questions:

- Is it adequate to model the drag force on the basis of local quantities alone, without bringing in explicitly a dependence on gradients in particle volume fraction?
- Drag force models for fluid flow through random assemblies of particles typically consider the particle size and particle volume fraction as parameters characterizing the bed. However, macroscopically similar (and disordered) particle assemblies can have different microstructural details (such as the radial distribution function). How important are these details for the drag force between the fluid and particle phases?

To address these questions, we have performed detailed simulations of fluid flow in fixed beds of uniformly sized spherical particles in a variety of configurations. Simulations have been performed in homogeneous fixed