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A semi-empirical model for the drag force and fluid–particle interaction in polydisperse suspensions

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ABSTRACT

Fluid flow through stationary or moving particle beds is a common process in industrial units. The two-phase hydrodynamics strongly influences the performances and characteristics of reactors and contactors in general, but the possibility to model comprehensively the details of the two-phase field of motion still lacks. Computational methods and multi-scale modeling are capable of providing essential information at the microscopic scale. In the present paper, recently published data on the fluid–particle interaction obtained at the sub-particle scale are used to propose a semi-empirical model for the calculation of the fluid–particle interaction, named the basis of computer simulations of fluid–solid flows. The proposed approach starts from flow through monodisperse particle beds and leads to a general expression valid over a very wide range of Reynolds' number and porosity and, most notably, accounts for polydispersion in a consistent and general way. Available actual drag force data from lattice-Boltzmann simulations for mono- and bi-disperse systems are fitted by a physically consistent and computationally efficient model, obtaining a very good agreement over a broad range of conditions. The resulting model is validated both against lattice-Boltzmann simulations involving ten different species and against experimental measurements in real two-component beds fluidized by a liquid exhibiting the layer inversion phenomenon. The model is shown to predict well the correct values under a significant variability of operating conditions. Finally a discussion of the application of the model in the context of numerical simulations is presented.

1. Introduction

Relative motion between a fluid and dense particle systems is encountered in many industrial process units. Proper quantification of fluid–particle interactions, in particular the drag force, is crucial for obtaining good performances. From a modeling point of view, the effects of the velocity and voidage on the inter-phase momentum transfer have been subjected to extensive studies in the literature, which led to a number of relatively accurate expressions valid for monodisperse suspensions that cover many orders of magnitude of the Reynolds number and from dense packings to highly dilute systems (Di Felice, 1994; Gidaspow, 1994; Gibilaro, 2001; Hill et al., 2001a; Mazzei and Lettieri, 2007; Cheng, 2009).

However, recently the need to capture more details and features of flow through real particle beds has revealed that a considerable importance rely also on the consideration of the ever-present diameter distribution of the particulate phase, i.e. its polydispersion. The study of system inhomogeneities has become feasible especially in the context of numerical simulations, which allow property variations along the system to be fully accounted for and an improvement in capturing more and more complex behaviors. Typical approaches used in dense fluidised beds, named two-fluid model (TFM) (see e.g. Anderson and Jackson, 1967; Ding and Gidaspow, 1990) or discrete element method (DEM) (see e.g. Hoomans et al., 1996; Xu and Yu, 1997; Di Renzo and Di Maio, 2007) simulations of fluid–solid multiphase systems, allow highly complex features to be captured effectively, such as local variation of the flow field, porosity, component distribution (Owoyemi et al., 2007; Beetstra et al., 2007; Di Renzo et al., 2008) as well as combined hydrodynamics and heat transfer (see e.g. Kuipers et al., 1992; Di Maio et al., 2009; Zhou et al., 2009). However, they still require at some degree the definition of a drag force model that allows the microscopic flow features at the sub-particle scale to be taken into account at the computational cell scale.

Unfortunately data on the effect of the diameter distribution on the local flow field are extremely hard, if not impossible, to get from experimental tests. However, recent computational studies of the fully resolved flow, based on the lattice-Boltzmann

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methodology (LBM) (Hill et al., 2001b; van der Hoef et al., 2005; Sarkar et al., 2009; Yin and Sundaresan, 2009), have provided a significant dataset of the distribution of actual fluid drag on each particle under various conditions, including the effect of different size or different local velocity, that proves extremely useful to elaborate a larger scale model.

Detailed LBM simulations of the flow through uniform and random particle beds were carried out at low-Reynolds number and a wide range of voidage values by Hill et al. (2001b) and at low and moderate-Reynolds number and various voidage values by van der Hoef et al. (2005). In both studies a model was also derived. However, as it will be demonstrated in Section 2, these models still suffer some discrepancy with respect to commonly established and well verified correlations at high voidage values and moderate-to-high Reynolds number. Moreover, in one case (Hill et al., 2001b) the model is based on different correlation parameters for different combinations of the input data, resulting in a non-continuous description of the phenomenon (Benyahia et al., 2006).

The aim of this study is to propose a reformulated drag force model for monodisperse beds and a modification of the correction for polydisperse systems that improve the consistency, accuracy and computational efficiency with respect to those appeared until now. In the first part of the analysis a new model for the calculation of the drag on systems with mono-disperse particle diameters will be presented. In the second part its extension to polydisperse systems will be discussed.

2. Mono-disperse suspension

2.1. Fluid–particle interaction

In case the detailed flow through the interstices among the particles is accessible to the simulations, nearly exact data on inter-phase momentum exchange can be extracted directly. However, such simulations of real suspensions at even lab-scale are typically unfeasible due to computational limitations, so that some sort of averaging is necessary. It is in this particular step that the inter-phase closure appears explicitly. In the context of locally-averaged equations of motion, the momentum balance equation of the fluid phase can be expressed as

$$\frac{\partial(\varepsilon\rho_f\mathbf{U})}{\partial t}+\nabla\cdot(\varepsilon\rho_f\mathbf{UU})=-\nabla P+\nabla\cdot\boldsymbol{\tau}+\mathbf{S}+\rho_f\varepsilon\mathbf{g} \tag{1}$$

where ρ_f , $\mathbf{U}$ and P are the fluid density, local fluid velocity and absolute pressure, respectively, ε is the volumetric fraction of the fluid (or voidage), $\boldsymbol{\tau}$ is the deviatoric stress tensor, $\mathbf{S}$ is the fluid–particle inter-phase momentum exchange per unit volume and $\mathbf{g}$ the acceleration of gravity. Fig. 1 shows a schematic representation of a dense area of the system in which it is possible to identify the local velocity $\mathbf{U}$ and the voidage ε near the ith particle. In Eq. (1) the fluid–particle interaction at the particle level is included in the source term $\mathbf{S}$. In Eulerian–Langrangian simulations, the computation of this term is carried out starting from the point of view of the particles, i.e. the action of drag, generalized buoyancy and other contributions (e.g. lift, added mass, Basset's history integral, where applicable) are calculated for each particle and the cumulative volumetric opposite action is applied to the fluid as $\mathbf{S}$ in Eq. (1).

Since there has been some ambiguity in the literature on the definitions of the fluid–particle interaction force, drag and buoyancy, an attempt will be made to define clearly all forces that enter the following derivation. A vertical unit vector along the direction z pointing upwards is assumed positive and all relations will be in terms of force moduli along this direction.

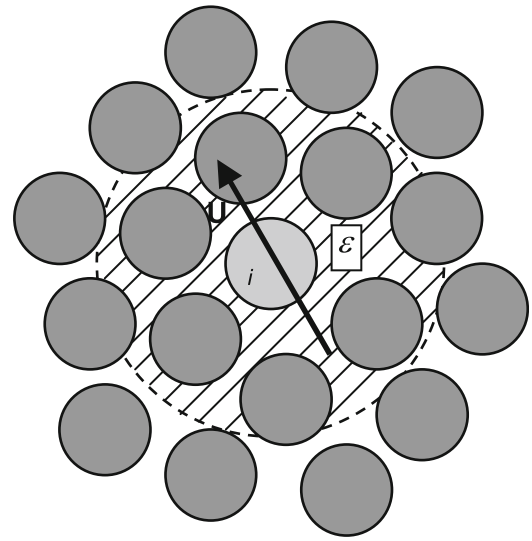

Fig. 1. Local velocity U and voidage ε in a region of system in which a collection of solid particles surrounds the ith one.

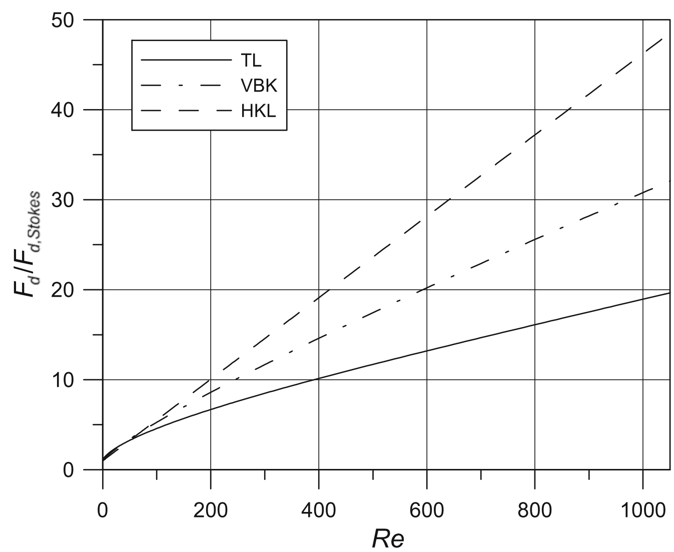

Fig. 2. Comparison between dimensionless drag force predicted by the model of Hill et al. (2001b) (HKL) and van der Hoef et al. (2005) (VBK) with the one of Turton and Levenspiel (1986) (TL) for motion around a single sphere.

With focus on conditions where the fluid–particle interaction consists only of the drag force F_d and generalized buoyancy, this *whole* interaction force on a particle is defined as

$$W=F_d+V_p\left(-\frac{\partial P}{\partial z}\right) \tag{2}$$

where V_p is the particle volume. Considering flow through a monodisperse bed with Mp particles in the control volume Ψ, uniform and constant voidage and velocity, the fluid–particle source term in Eq. (1) corresponds to

$$S=-\frac{\sum_{i=1}^{Mp}W_i}{\Psi}=-\frac{Mp\,W}{\Psi} \tag{3}$$

If one further assumes that $\nabla\cdot\boldsymbol{\tau}$ is negligible in Eq. (1) and considers the net pressure gradient:

$$\left(-\frac{\partial p}{\partial z}\right)=\left(-\frac{\partial P}{\partial z}\right)-\rho_f g \tag{4}$$