Particuology 23 (2015) 40–48

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Validation of fluid–particle interaction force relationships in binary-solid suspensions

Marco Rotondi, Renzo Di Felice*, Paolo Pagliai

Department of Civil, Chemical and Environmental Engineering, University of Genova, Via Opera Pia 15, 16145 Genova, Italy

ARTICLE INFO

Article history:
Received 26 September 2014
Received in revised form
24 November 2014
Accepted 18 December 2014
Available online 28 April 2015

Keywords:
Solid–fluid suspensions
Solid–fluid interaction forces
Drag force
Buoyancy force

ABSTRACT

In this work several relationships governing solid–fluid dynamic interaction forces were validated against experimental data for a single particle settling in a suspension of other smaller particles. It was observed that force relationships based on Lattice-Boltzmann simulations did not perform as well as other interaction types tested. Nonetheless, it is apparent that, in the case of a suspension of different particle types, it is important that the correct choice is made as to how the contribution to the overall fluid–particle interaction force is split between buoyancy and drag. Experimental evidence clearly suggests that the "generalized" Archimedes' principle (where the foreign particle is considered to displace the whole suspension and not just the fluid) provides the best result.

Introduction

The use of computational approaches to predict the fluid dynamic behavior of physical systems has become much more common during the last decade, as a consequence of the exponential increase in computer performance. Physical problems that were once considered intractable, because of their complexity, have now been solved, providing detailed predictions of both transient and steady-state systems. The numerical output of a computational simulation must compare well with empirical measurements to represent a significant contribution. Currently, satisfactory results can generally be achieved for single-phase systems, but not for multi-phase systems. This is because of the greater complexity of fluid dynamic interactions between the phases, making their mathematical definition more difficult to quantify.

A suspension of rigid solid particles in a Newtonian fluid is a highly complex system that can be described by computational fluid dynamics. A large number of numerical simulations of solid–fluid suspensions have been published during the last few years, predominantly using the Navier–Stokes equations. The solid–fluid interaction force represents the most significant term in these equations. It contains at least two contributions of different physical origins, namely the buoyancy force and the drag force. The buoyancy force arises because the solid phase is submerged in the fluid phase, whilst the drag force is due to the relative velocity between the two phases. There have been numerous attempts to identify the correct closure relationships for the quantification of the solid–fluid interaction forces. The whole spectrum of particle–fluid suspensions has been covered, from gas–solid fluidization (Gan, Zhao, Berrouk, Yang, & Shan, 2012; Loboreiro et al., 2008; Vejahati, Mahinpay, Ellis, & Nikko, 2009) to liquid–solid systems (Huang, 2011; Hadinoto & Chew, 2010) and from spouted beds (Du, Bao, Xu, & Wei, 2006) to applied processes such as biomass pyrolysis (Papadikis, Gu, Fivga, & Bridgwater, 2010).

Unfortunately, in all of these works, comparisons between numerical predictions and experimental observations are made for quantities that are not easily measured nor directly correlated to the selected relationships, such as the bubble rising velocity or the bubble volume fraction in the suspension. Therefore, the usefulness of the numerical comparison is rather limited, since there is no clear indication as to which set of equations is the most suitable. Moreover, nearly all of these previous studies require knowledge of other physical parameters, such as the solid–solid or the solid-wall restitution coefficient, thus adding a further element of uncertainty to the simulated system.

This work aims to overcome these afore mentioned weaknesses. The specific system under consideration is a single particle falling in a suspension of other particles, in steady-state conditions, such that only the buoyant and the interphase drag are significant

* Corresponding author. Tel.: +39 0103532924.
E-mail address: renzo.difelice@unige.it (R. Di Felice).

http://dx.doi.org/10.1016/j.partic.2014.12.010

Notation

C_D	drag coefficient
d	particle diameter (m)
F_B	buoyancy force (N)
F_D	drag force (N)
F_T	overall fluid–particle interaction force (N)
g	acceleration due to gravity (m/s^2)
n	numerical parameter
Re	Reynolds number
u	velocity (m/s)
V_p	particle volume (m^3)

Greek letters

β	numerical parameter
ϕ	volume concentration
μ	viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

b	bulk
f	fluid
i	ith particle type
j	jth particle type
L	large particle
p	particle
pf	pseudo-fluid
S	small particle

(and in need of quantification). Predicted values are compared with measured values, taking into account the relative velocity between the falling particle and the fluid phase. This is an easily measured quantity and is directly influenced by the forces under investigation.

Fluid dynamic interaction for solid–fluid systems

Monocomponent-solid systems

Before considering fluid–particle interaction forces in a binary-solid suspension, it is useful to briefly point out some important aspects relating to single-solid type suspensions.

The quantification of the overall fluid–particle interaction force has been the main research goal of a large number of scientific studies. Consequently, a large number of relationships have been proposed and are currently used in numerical simulations. It is possible to classify three different types of relationships, based on the approach used. In the first case, fluid–particle interactions have been studied by purely theoretical analyses, for instance, in the work of Batchelor (1972) on the sedimentation of random suspensions of equal spheres, and in the cell model of Happel and Epstein (1954). Although this type of approach is preferable, it suffers from severe limitations regarding the flow regimes and the particle volume concentrations investigated. Consequently, their results have limited practical application. However, these problems are not encountered by methodologies based purely on experimental observation. Available data, on either the pressure drop in fixed and extended beds of solid particles or the velocity–voidage relationship for suspended spheres, cover the whole ranges of flow regimes and particle volume concentrations. As a result, the derivation of universally valid relationships has been possible (e.g. Di Felice, 1994; Foscolo & Gibilaro, 1987; Gidaspow, 1994; Mazzei & Lettieri, 2007; Wen & Yu, 1966).

More recently, new sources of information have been made available by the simulation of solid–fluid suspensions based on the Lattice-Boltzmann numerical approach. The advantage of this method lies in the tight control of the system conditions, thus avoiding uncertainties and limitations inherent to experimental measurements (Rong, Dong, & Yu, 2013; van der Hoef, Beetstra, & Kuipers, 2005; Yin & Sundaresan, 2008).

Regardless of whether a theoretical or experimental procedure is used, the overall fluid interaction force can only be estimated. As mentioned, this force is composed of two contributions, the buoyancy force and the drag force. Two main methods of calculating the buoyancy force have been suggested thus far (Di Felice, 1995). The first involves setting the buoyancy by following the “classical” Archimedes’ principle, where the solid phase is simply displacing the fluid. In the second approach, the suspended solid displaces not only the fluid, but also the suspension as a whole, representing a “generalized” application of Archimedes’ law. Drag force is estimated, in both cases, as the difference between the overall force on a particle, F_T, and the buoyancy force. In other words, if V_p is the particle volume, then

$$F_D = F_T - F_B = F_T - V_p \rho g, \tag{1}$$

in the first case, and

$$F_D = F_T - F_B = F_T - V_p \rho_b g, \tag{2}$$

in the second, ρ_b is the suspension bulk density, according to

$$\rho_b = \phi_p \rho_b + (1 - \phi_p)\rho. \tag{3}$$

Arguments supporting which view is preferable have already been reviewed in some detail and therefore will not be reported here (Di Felice, 1995, for example). It is easily shown that the application of each approach, for fixed beds and fluidized suspensions in steady-state conditions, results in a difference in drag force estimation by a factor of $(1 - \phi_p)$, with the “classical” application of the Archimedes’ principle producing the larger value.

Although interesting, from a numerical point of view, the buoyancy choice is irrelevant in the steady-state condition. Different results are obtained when an unsteady-state system is considered, as shown first by Fan, Han, and Brodkey (1987) then later by Mazzei, Lettieri, Elson, and Colman (2006), where the system stability is investigated under small perturbations to explain the transition from homogeneous to bubbling regimes. Mazzei and Lettieri (2008) successfully simulated expanding and contracting homogeneous fluidized beds and their transition to bubbling. More recently Zhou, Kuang, Chu, and Yu (2010) investigated fluidization, pneumatic conveying, and hydrocyclones via computational simulations. These studies, however, predicted little practical difference in the system behavior. Making such a comparison with experimental observations therefore has little use in a model discrimination exercise.

When numerically quantifying the drag force, it is customary to express it relative to the single particle system by introducing a “voidage function”, $g(\phi)$. The “voidage function” deals with the fluid–particle fluid dynamic interactions in a suspension, thus

$$F_D = C_D \frac{\rho u^2}{2} \frac{\pi d^2}{4} g(\phi), \tag{4}$$

where u is the equivalent superficial velocity

$$u = |u_p - u_f|(1 - \phi_p), \tag{5}$$

and C_D is the single particle drag coefficient, a function only of the system Reynolds number

$$Re = \frac{d \rho u}{\mu}. \tag{6}$$