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Numerical analysis of frictional behavior of dense gas–solid systems

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ABSTRACT

Dense gas–solid flows show significantly higher stresses compared with dilute flows, mainly attributable to particle–particle friction in dense particle flows. Several models developed have considered particle–particle friction; however, they generally underestimate its effect in dense regions of the gas–solid system, leading to unrealistic predictions in their flow patterns. Recently, several attempts have been made to formulate such flows and the impact of particle–particle friction on predicting flow patterns based on modified frictional viscosity models by including effects of bulk density changes on frictional pressure of the solid phase. The solid–wall boundary is also expected to have considerable effect on friction because particulate phases generally slip over the solid surface that directly affects particle–particle frictional forces. Polydispersity of the solid phase also leads to higher friction between particles as more particles have sustained contact in polydispersed systems. Their effects were investigated by performing CFD simulations of particle settlement to calculate the slope angle of resting material of non-cohesive particles as they settle on a solid surface. This slope angle is directly affected by frictional forces and may be a reasonably good measure of frictional forces between particles. The calculated slope angle, as a measure of frictional forces inside the system are compared with experimental values of this slope angle as well as simulation results from the literature.

Introduction

Fluidization is a phenomenon by which solid particles are transformed into a fluid-like state by contact with fluidization media (e.g., gas). Various process applications have been designed based on fluid–solid contact such as drying, absorption, combustion, carbonation, coal gasification, methanol to olefin production, and catalytic cracking. Complex flow phenomena observed in particulate flows are attributed to particle–particle and particle–fluid interfacial force exchange. Accurate direct numerical simulations (DNS) of these flow phenomena are possible for small-scale systems containing few particles; however, due to current limitations in computational resources, they cannot be applied to large-scale cases.

An efficient approach to overcome this issue is to use averaged fluid flow equations solved on a coarse computational domain and to track the motion of each individual particle following Newton's law of motion with necessary closures for particle–fluid interaction forces. This approach is called the discrete element model (DEM), which uses the Lagrangian frame for tracking particles. However, such simulations become almost impossible to conduct for industrial-scale systems where the flow rate of particles is measured in tons per second. Therefore, to date, the most realistic approach to describe large-scale processes involving fluid–particle flow is based on the averaged continuum equations of motion for both fluid and particle phases, often called the two-fluid model (TFM). The continuum approach (sometimes called the Eulerian approach) generally relies on closures for the solid phase stresses that are usually derived from the kinetic theory of granular flow (KTGF) in the collisional regime and from soil mechanics principles in the dense-frictional regime. The basic equations of TFM (the continuity and momentum equations for each phase) are derived from the general Reynolds transport theorem. However, the equations should be closed using averaging techniques and introducing constitutive equations based on the flow behavior (Arastoopour, 2001; Gidaspow, 1994; Igci, Andrews, Sundaresan, Pannala, & O'Brien, 2008; Milioli, Milioli, Holloway, Agrawal, & Sundaresan, 2013; Nikolopoulos et al., 2013).

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Nomenclature

C_d	Drag coefficient
d_p	Particle diameter, m
e_{pp}	Particle–particle coefficient of restitution
$g_{0,pp}$	Radial distribution function
$\vec{g}$	Gravitational acceleration vector, m/s^2
I_{2D}	Second invariant of solid deviatoric stress tensor, s^{-1}
$\bar{\bar{I}}$	Identity matrix
k_{θ_p}	Granular conductivity, kg/(m s)
n	Compactness factor
P	Pressure, kPa
T	Time, s
$\vec{v}$	Mean velocity vector, m/s

Greek letters

$\alpha_{p,max}$	Maximum packing limit
$\alpha_{p,min}$	Minimum frictional limit for solid volume fraction
A	Volume fraction
$\bar{\beta}$	Drag coefficient, kg/(m^3 s)
γ_p	Granular temperature dissipation rate, m^2/s^3
$\bar{\bar{\delta}}$	Dirac delta function
H	0.5(1 + e$_{pp}$)
θ_p	Granular temperature, m^2/s^2
Λ	Bulk viscosity, kg/(m s)
M	Viscosity, kg/(m s)
P	Density, kg/m^3
$\bar{\bar{\sigma}}$	Normal stress tensor, kPa
$\bar{\bar{\tau}}$	Shear stress tensor, kPa
φ	Critical state angle of internal friction, °
ω_m	Slope angle of resting material, °

Subscripts

g	Gas
p	Particle
fric	Frictional
col	Collisional
kin	Kinetic

kinetic-collisional regime (Lun, Savage, Jeffrey, & Chepurniy, 1984) and from soil mechanics theories in the dense-frictional regime (Johnson & Jackson, 1987; Savage, 1998). The solid viscosity and solid pressure that appear in the momentum equations have contributions from three mechanisms: the kinetic component, the collisional component, and the frictional component. There is a general acceptance of kinetic-theory-based relations in the modeling of granular flows that provides closure for the kinetic and collisional components of the solid stress tensor, but the kinetic theory cannot provide closure for the frictional part of the solid stress tensor (Gidaspow, 1994; Lun et al., 1984).

The work on the frictional stress tensor in multiphase granular flow started with the pioneering work of Johnson and Jackson (1987) and was continued by Schaeffer (1987), who proposed a strain-rate-independent contribution for solid stress tensor applicable in plastic regimes where flow is dense and slow and there is sustainable contact between particles (inter-particular friction). This work has been modified and improved in several studies (Nikolopoulos et al., 2012; Savage, 1998; Srivastava & Sundaresan, 2003). Nikolopoulos et al. (2012) have shown how the frictional viscosity model of Schaeffer (1987) fails to predict cessation of granular particles under sustained stress caused by friction. Shaeffer's model predicts continuous flow of granules under stress, while adding a term to solid viscosity as a contribution of solid frictions. Therefore, it predicts a slope angle of resting material equal to zero for a mass of particles poured on a surface (Laux, 1998; Nikolopoulos et al., 2012). It also has been shown that the prediction of the slope angle of resting material is a strong function of the solid frictional viscosity model, which is used to describe the frictional stress tensor of the solid phase (Dartevelle, 2003; Laux, 1998; Nikolopoulos et al., 2012). Slope angle of resting material is a measure of friction in gas–solid flows and is usually measured experimentally as the angle between particulate solids and solid surface where the solid particulates become stationary. Friction plays an important role in modeling bubbling fluidized beds (BFBs) and circulating fluidized beds (CFBs), and especially in dense flow regimes such as diplegs, L-valves, and downcomers. In other gas–solid systems where the flow of particles is fast and dilute (e.g., risers), the kinetic and collisional stress tensors are generally capable of capturing the physics involved in the process.

In this study, the effects of different model parameters on CFD simulation of the predicted slope angle of resting material of non-cohesive particles are investigated. Results are compared with experimental data (from Nikolopoulos et al., 2012) for the same particle size and density used in this study (462 μm and 2600 kg/m^3). In this study, improved and more reliable parameters for modeling the frictional force are obtained. Note that the slope angle of resting material used in this work should not be confused with angle of repose; angle of repose should be measured in an ASTM standard procedure and thus could be different than angle made by the slope angle of resting material with a solid surface.

Governing and constitutive equations

Conservation of mass and continuity equations for gas and solid phases are, respectively (without mass transfer),

$$\frac{\partial\left(\alpha_g\rho_g\right)}{\partial t} + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\right) = 0, \quad (1)$$

$$\frac{\partial\left(\alpha_p\rho_p\right)}{\partial t} + \nabla\cdot\left(\alpha_p\rho_p\vec{v}_g\right) = 0, \quad (2)$$

$$\alpha_g + \alpha_p = 1. \quad (3)$$

The momentum equations for the gas and particulate phases are based on the Navier–Stokes equation modified to include drag between phases. The corresponding equations of momentum conservation are

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{v}_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right) = -\alpha_g\nabla P + \nabla\cdot\bar{\bar{\tau}}_g + \alpha_g\rho_g\vec{g} - \bar{\beta}\left(\vec{v}_g - \vec{v}_p\right), \quad (4)$$

$$\frac{\partial}{\partial t}\left(\alpha_p\rho_p\vec{v}_p\right) + \nabla\cdot\left(\alpha_p\rho_p\vec{v}_p\vec{v}_p\right) = -\alpha_p\nabla P - \nabla P_p + \nabla\cdot\bar{\bar{\tau}}_p + \alpha_p\rho_p\vec{g} + \bar{\beta}\left(\vec{v}_g - \vec{v}_p\right). \quad (5)$$

The KTGF is used to close some undefined terms in these equations, namely, solid stress tensor and solid pressure. The stresses experienced by particles due to translation and instantaneous collisions are referred to as solid-phase kinetic and collisional stresses. Kinetic and collisional stresses depend on the magnitude of the particle velocity fluctuations, also called granular temperature, θ. The transport equation is derived based on the KTGF (Gidaspow, 1994),