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Original Research Paper

CFD simulation of particle segregation in a rotating drum. Part I: Eulerian solid phase kinetic viscosity

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ABSTRACT

Although the Eulerian approach coupling the kinetic theory of granular flow is usually used to study granular flows with relative lower solid fractions, it can be used to study relative denser granular flows if appropriate solid phase kinetic viscosity values were adopted. A granular bed surface fitting (BSF) method is proposed to determine the appropriate solid phase kinetic viscosities of the granular flows in a rotating drum. The specularity coefficient is also used to address the interaction between particles and the drum wall. The BSF solid phase kinetic viscosity increases with decreasing of particle sizes and drum rotational speeds. The BSF solid phase kinetic viscosity and the specularity coefficient follow a power-law relationship with 0.6–1.1 as the exponent of the specularity coefficient. The BSF solid phase kinetic viscosities for the particles of two different sizes are used to study particle segregation in a rotating drum. The core thickening segregation mechanism and the segregation band formations are well predicted.

1. Introduction

Mixing of particles of different physical/chemical properties is a common process in industry. When particles of different properties are mixed, they may perform segregation and affect the product quality [1]. Several experimental methodologies have been adopted to investigate particle segregation, including the freeze-slicing method [2], the bed surface monitoring method [3–5], and the particle motion tracking method by using radioactive tracers [6–8] or other signals [9,10]. Our recent review article has summarized some of them [11]. Except for using the experimental techniques for particle segregation investigation, the rapid advances in the computational efficiency and the developments of the granular flow theories allow the computer numerical modeling becoming a powerful tool to study particle segregation at different scales.

Two types of the computer numerical modeling methods are commonly used to study particle segregation, namely the Lagrangian approach and the Eulerian approach. The Lagrangian approach considers all the individual particles in the area of interest as a distinct entity and the motion of individual particles is numerically simulated [12–14]. On the other hand, the particles of interests are regarded as a single continuum phase in the Eulerian approach and the continuum solid phase follows the conservation laws typically used for the constitutive fluids [15–17]. Although the Lagrangian approach can provide useful information at the particle scale, its computation is very expensive mainly due to the massive numbers of the particles of interest. The computationally cheaper Eulerian approach is thus preferred in the large scale modeling [18] and is used to study particle segregation in a rotating drum in this work. The granular flows studies using the Eulerian approach are typically rapid and have lower solid volume fractions (say less than 0.3). The interactions between constitutive particles are mainly based on the kinetic theory of granular flow (KTGF) and its derivatives [19–21]. Nevertheless, many granular flows encountered in industry have higher solid volume fractions (say 0.3–0.6). Some phenomenological relations have been superimposed to the context of KTGF-Eulerian approach to study the granular flows with higher solid volume fractions [22,23] and the relation developed by the French group GDR MiDi is one of the most promising relations [24]. Their relation described the local empirical rheology by a dynamic frictional coefficient and the analytical solution of the GDR MiDi constitutive relation was given by Jop et al. [25]. The GDR MiDi relation has been used to study the granular flows with higher solid volume fractions on an inclined plane [26,27]. However, particle segregation in a rotating drum is reported to

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Nomenclature

Symbols

C_D	drag coefficient [–]
$C_{fr,sisj}$	friction coefficient between *i*th and *j*th solids-phase particles [–]
d_s	particle diameter [m]
e_{ss}	restitution coefficient [–]
$g_{0,ss}$	radial distribution function [–]
I_{2D}	second invariant of the deviatoric stress tensor [–]
K	inter-phase exchange coefficient [–]
$k_{\theta s}$	diffusion coefficient [–]
P	pressure [Pa]
p_s	pressure of solids pressure [Pa]
Re_s	relative Reynolds number [–]
α	volume fraction [–]
β	angle of internal friction [degree]
$\gamma_{\theta s}$	rate of collisional energy dissipation [kgs^{-3}m^{-1}]
θ_s	granular temperature [m^{2}s^{-2}]
λ	bulk viscosity [kgm^{-1}s^{-1}]
μ_g	viscosity of gas phase [kgm^{-1}s^{-1}]
μ_s	granular viscosity [kgm^{-1}s^{-1}]
ρ	density [kgm^{-3}]
φ	inter-phase energy exchange [kgs^{-3}m^{-1}]
$\bar{\bar{I}}$	unit vector [–]
$\vec{g}$	gravitational acceleration [ms^{-2}]
$\vec{v}$	velocity [ms^{-1}]
$\bar{\bar{\tau}}$	stress–strain tensor [Pa]

Indices

g	gas phase [–]
s_i	*i*th component of solids phase [–]
s_j	*j*th component of solids phase [–]

be affected by the ratio of the drum size to the particle size, and this size ratio is not included in the relation of GDR MiDi [28]. Other modifications of the KTGF-Eulerian approach should be considered for the particle segregation in a rotating drum in this work.

The KTGF-Eulerian approach modifications can be done by developing new relations of the collisional-kinetic stress tensor and the frictional stress tensor in the constitutive Navier-Stokes equation [15]. Most of the tensor-modified KTGF-Eulerian approaches were applied to study the rapid granular flows with lower solid volume fractions [29,30]. Only few attempts applied the modified KTGF-Eulerian approaches to study the granular flows with higher solid volumes [31–33]. Here, a new KTGF-Eulerian approach modification is proposed and the modified approach is used to study particle segregation in a rotating drum. The results are presented into two parts. In Part I of this work, the modification of the KTGF-Eulerian approach is described and the granular flows in the rotating drum are investigated at different particle-wall contact conditions. In Part II of this work, particle segregation in a rotating drum by a binary mixture is simulated at different particle-wall contact conditions using the modified KTGF-Eulerian approach and the predicted results are compared with experimentation.

2. Simulations and experiments

The granular flows in a rotating drum using air as the interstitial fluid are simulated using the KTGF coupled Eulerian approach. The gas and solid phases are assumed as interpenetrating phases. The hydrodynamics of these phases are obtained by solving the conservation equations of mass and momentum with the KTGF closure relations [17]. The governing conservation equations are summarized in Table 1. In this study, the closure relation is based on the stress–strain tensor of the solid phase, which includes the collisional stress, the kinetic stress and the frictional stress. In the stress tensor, the solid phase viscosity, μ_s, is the sum of the kinetic viscosity, $\mu_{s,kin}$, the collisional viscosity, $\mu_{s,col}$, and the frictional viscosity, $\mu_{s,fr}$ as

$$\mu_s = \mu_{s,kin} + \mu_{s,col} + \mu_{s,fr} \tag{1}$$

The subscript *s* denotes the solid phase. The Syamlal-O'Brien model was used to determine the collisional viscosity in Eq. (1) as,

$$\mu_{s,col} = \frac{4}{5}\alpha_s \rho_s d_s g_0 (1 + e_s)\left(\frac{\theta_s}{\pi}\right)^{\frac{1}{2}} \tag{2}$$

where α, ρ, d, g_0, e_s and θ_s represent the solid volume fraction, the particle density, the particle size, the solid radial distribution function, the particle restitution coefficient and the granular temperature, respectively. The frictional viscosity in Eq. (1) is estimated by

$$\mu_{s_i,fr} = \frac{p_{s_i} \sin\beta}{2\sqrt{I_{2D}}} \tag{3}$$

where p_{si}, β and I_{2D} are the solid phase pressure, the angle of internal friction, and the second invariant of deviatoric stress tensor, respectively. Other closure relations are listed in Table 2.

In our previous work, the kinetic viscosity in Eq. (1) was empirically determined by the angle of repose of the granular bed in the rotating drum at a non-slip particle-wall contact condition [17]. However, the particle bed in the rotating drum does not always show a flat surface and the bed angle of repose is also affected by the particle-wall contact condition [34]. Using a simple bed angle of repose value for the solid phase kinetic viscosity determination is thus ambiguous. In this study, the value of the kinetic viscosity is determined by an improved granular bed surface fitting (BSF) method at *different* particle-wall contact conditions. The BSF method uses a trial-and-error method to determine the solid phase kinetic viscosity by the following steps.

(1) An arbitrary kinetic viscosity value is chosen and is used to simulate the granular flow (single component) in the rotating drum.
(2) The end-view bed surface is then compared with the end-view bed surface obtained by experimentation. A typical example of the comparison between the end-view granular bed from the simulation and that from the experimental observation is shown in Fig. 1.
(3) If the bed surface profile predicted by the guessed kinetic viscosity is in a good agreement with the experimental observation (i.e., the green region in Fig. 1(c) is small enough), the guessed kinetic viscosity value is then the BSF kinetic viscosity at the given operating condition. If the guessed kinetic viscosity does not provide a good CFD bed profile prediction, a new granular viscosity value is adopted for a new CFD simulation.

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