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Discrete element method study of shear-driven granular segregation in a slowly rotating horizontal drum

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ABSTRACT

Segregation and mixing of granular materials are complex processes and are not fully understood. Motivated by industrial need, we performed a simulation using the discrete element method to study size segregation of a binary mixture of granular particles in a horizontal rotating drum. Particles of two different sizes were poured into the drum until it was 50% full. Shear-driven segregation was induced by rotating the side-plates of the drum in the opposite direction to that of the cylindrical wall. We found that radial segregation diminished in these systems but did not completely vanish. In an ordinary rotating drum, a radial core of smaller particles is formed in the center of the drum, surrounded by larger revolving particles. In our system, however, the smaller particles were found to migrate toward the side-plates. The shear from anti-spinning side-plates reduces the voidage and increases the bulk density. As such, smaller particles in the mixer tend to move to denser regions. We varied the shear by changing the coefficient of friction on the side-plates to study the influence of shear rate on this migration. We also compared the extent of radial segregation with stationary side-plates and with side-plates moving in different angular directions.

Introduction

Granular materials are very common and they are useful for many applications. These materials exhibit varieties of complex behavior, some of which are not fully understood. For example, when these systems are perturbed or subjected to vibration, the particles will self-organize into isolated regions consisting of similar shapes, densities, or sizes that accumulate together (Porion, Sommier, Faugère, & Evesque, 2004). This isolation or segregation of particulate systems into groups has perplexed researchers for many decades. Moreover, it remains a challenge for industries that involve processes in which different types of particles are mixed (Remy, Khinast, & Glasser, 2011). Particle segregation is also undesirable while transporting particulate materials from one place to another. Apart from human-made examples, one finds similar processes in nature, such as in landslides and avalanches, where larger rocks accumulate at the top of smaller rocks (Kudrolli, 2004). Understanding segregation in geophysical processes is also important for modeling sediment transport in rivers (Dietrich, Kirchner, Ikeda, & Iseya, 1989; Paola & Seal, 1995). In industries dealing with granular particles, a solution to the segregation issue is mandatory for better materials processing and handling (Kudrolli, 2004; Shinbrot, 2000). An increasing number of numerical and experimental works are being reported in efforts to understand the underlying physics of mixing and segregation in granular flows (Baumann, Jánosi, & Wolf, 1995; Cantelaube & Bideau, 1995; Chand, Khaskheli, Qadir, Ge, & Shi, 2012; Clément, Rajchenbach, & Duran, 1995; Hill, Caprihan, & Kakalios, 1997; Khakhar, McCarthy, & Ottino, 1997; Khakhar, Orpe, & Hajra, 2003); however, to date, no successful theoretical framework is available to entirely explain this curious phenomenon (Hajra, Bhattacharya, & McCarthy, 2010), and particularly for the case of size separation in rotating drums (Kudrolli, 2004).

A rotating drum partially filled with granular mixes is an interesting model system because of its direct analog to industrial application (Grajales, Xavier, Henrique, & Thomeo, 2012; Reyes et al., 2015; Watkinson & Brimacombe, 1982). This system is simple enough to enable one to study segregation and mixing, both

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experimentally and numerically. When a horizontal drum consisting of bi-disperse particles is rotated around its axis, segregation is observed in which the smaller and larger particles split into groups (Khakhar et al., 2003). If the length of the drum is longer than its diameter, axial segregation occurs, with alternating smaller-size-rich bands and larger-size-rich bands formed across the axial direction (Kuo, Shih, & Hsu, 2006). In drums of smaller diameter, radial segregation is observed, where the smaller particles gather to a radial core surrounded by larger ones (Chakraborty, Nott, & Prakash, 2000; Chand et al., 2012; Henein, Brimacombe, & Watkinson, 1985; Khakhar et al., 1997). This radial segregation remains a controversial issue in the literature. It was found that the radial core of smaller particles can be well explained by a mechanism involving percolation and balancing between the gravitational and centrifugal forces during rotation (Turner & Nakagawa, 2000). Reverse segregation, with larger particles in the center, has also been reported (Thomas, 2000). In another finding, Jain, Ottino, and Lueptow (2005) reported that segregation diminished when the larger particles also had higher density. Radial segregation can also be reduced by making drum thinner (Chand et al., 2012). In a thinner drum, the role of the side-walls seems to be one of the causes of diminishing radial segregation (Chand et al., 2012; Huang, Liu, & Kuo, 2013). With regard to axial segregation, there are some reports suggesting that the formation of segregation bands occurs in the vicinity of the side-plates of the drums (Kudrolli, 2004; Kuo, Hsu, & Hsiao, 2005). Owing to this characteristic, side-plates have received much recent attention with respect to the segregation mechanism (Huang et al., 2013). In thinner drums, both side-plates are very near to each other, thus producing higher shear and diffusing the particles. The segregation consequently drops and mixing is observed (Chand et al., 2012; Fan & Hill, 2011; Kuo et al., 2006). Earlier work mainly focused on the influence of side-plate friction on mixing and radial segregation. In our previous work, we used stationary side-plates to increase the shear effect (Chand et al., 2012). It was concluded that roughened side-plates dramatically affected the segregation in thinner drums. Such systems could be good mixers.

Huang et al. (2013) recently determined experimentally that spinning the side-plates in the direction opposite to that of the cylindrical wall created axial bands in longer drums. Their work focused on the role of side-plates of longer drums on axial band formation. Angular velocity of the anti-spinning plates was varied to apply shear on the particles. Anti-spinning side-plates produced more shear on flowing particles. Reducing the length of the drum and changing the friction on the side-plates could increase the shear stress further. Such types of shear-driven segregation have been reported in other systems (Fan & Hill, 2011); however, the influence of higher shear from side-plates in thinner drums has received relatively little attention, especially in discrete element method (DEM)-based simulation work.

In this paper, we present a DEM simulation to investigate the influence of friction on anti-spinning side-plates during mixing and segregation processes in a half-filled horizontal rotating drum. Our drum was of a fixed size and we only varied the coefficient of friction on the side-plates. We addressed the gradual diminishing of radial segregation from spinning to stationary and then to anti-spinning motion of the side-plates.

Discrete element method simulations

Description of the model

DEM was used in this study to simulate granular dynamics. In this method, we employed a soft sphere model for contacts between elastic spherical particles. We used a commercially available DEM model of the computational fluid dynamics package STAR-CCM+ Version 9.04, released by CD-Adapco (http://www.cd-adapco.com/products/star-ccm-plus). DEM in STAR-CCM+ is implemented within the Lagrangian multiphase model; the method involves direct integration of motion equations for each particle (Baran, Kodl, & Aglave, 2013; Di Renzo & Di Maio, 2004; Johnson, 1985; Mindlin & Deresiewicz, 1953).

The law of conservation of momentum for two spherical particles i and j is given as:

$$m_i \frac{dv_i}{dt} = \sum_j F_{ij} + F_g, \tag{1}$$

where m_i and v_i are the mass and velocity of particle i, respectively. Particle i is in contact with other particles or the container j. This contact produces contact force F_{ij}. The last term in Eq. (1) is the gravity force $F_g = m_i g$.

The particle is three-dimensional so it has rotational degrees of freedom, the equations for which can be solved using the law of conversation of angular momentum:

$$\frac{d}{dt} I_i \omega_i = \sum_j \tau_{ij}, \tag{2}$$

where I_i and ω_i are the momentum of inertia and the rotational velocity of the particle i, respectively. The term τ_{ij} is the torque produced at the point of contact between particle i and particle or container j, which can be defined as:

$$\tau_{ij} = r_{ij} F_{ij}. \tag{3}$$

The contact force F_{ij} in Eq. (1) is the function of overlap between two particles or a particle and its container:

$$F_{ij} = F^{\mathrm{n}} + F^{\mathrm{t}}, \tag{4}$$

where F^{n} is the normal component and F^{t} is the tangential component of the contact force. STAR-CCM+ uses the non-linear Hertz–Mindlin contact model (Di Renzo & Di Maio, 2004; Kruggel-Emden, Simsek, Rickelt, Wirtz, & Scherer, 2007) to calculate normal and tangential components of the contact force, as given in Eq. (4):

$$F^{\mathrm{n}} = -K^{\mathrm{n}} \left(\delta^{\mathrm{n}}\right)^{3/2} - N^{\mathrm{n}} v_{ij}^{\mathrm{n}}, \tag{5}$$

$$F^{\mathrm{t}} = -K^{\mathrm{t}} \delta^{\mathrm{t}} - N^{\mathrm{t}} v_{ij}^{\mathrm{t}}, \tag{6}$$

where δ^{n} and δ^{t} are the overlaps in the normal and tangential directions, respectively, at the contact point; v_{ij}^{n} and v_{ij}^{t} are the respective normal and tangential velocity components of the relative velocity at the contact point. K^{n} is normal spring stiffness, which can be expressed as:

$$K^{\mathrm{n}} = \frac{4}{3} E_{\mathrm{eq}} \sqrt{R_{\mathrm{eq}} \delta^{\mathrm{n}}}, \tag{7}$$

and K^{t} is tangential spring stiffness, which can be expressed as:

$$K^{\mathrm{t}} = 8 G_{\mathrm{eq}} \sqrt{R_{\mathrm{eq}} \delta^{\mathrm{t}}}. \tag{8}$$

N^{n} and N^{t} are the normal and tangential damping components:

$$N^{\mathrm{n}} = \sqrt{\left(5K^{\mathrm{n}} M_{\mathrm{eq}}\right)} \frac{-In\left(\varepsilon^{\mathrm{n}}\right)}{\sqrt{\pi^2 + \left(In\left(\varepsilon^{\mathrm{n}}\right)\right)^2}}, \tag{9}$$

$$N^{\mathrm{t}} = \sqrt{\left(5K^{\mathrm{t}} M_{\mathrm{eq}}\right)} \frac{-In\left(\varepsilon^{\mathrm{t}}\right)}{\sqrt{\pi^2 + \left(In\left(\varepsilon^{\mathrm{t}}\right)\right)^2}}, \tag{10}$$

where ε^{n} and ε^{t} are the normal and tangential coefficients of restitution, respectively, and are model parameters that are set by the user.