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Density-induced granular segregation in a slurry rotating drum

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We experimentally investigated the effects of interstitial fluid density and viscosity on density-induced granular segregation in a rotating drum. Image processing and a particle-tracking method were used for determining the segregation index and dynamic properties of granular materials. The results indicate that the interstitial fluid density has a crucial role in density-induced granular segregation. A dimensionless factor was defined for quantifying the effect of interstitial fluid density on density-induced granular segregation. The segregation intensity increased as the interstitial fluid viscosity increased. In addition, the Stokes number associated with density-induced granular segregation was discussed in this study.

Introduction

Granular materials (e.g., sand, metal powder, glass beads, rock, coffee beans, pills, salt, wheat, and rice), commonly found in the nature, can behave as solids, liquids, or gases (Ristow, 1994; Jaeger et al., 1996; Mellmann, 2001; Liu et al., 2005; Yang et al., 2008; Jain et al., 2005a). These materials are widely used in industries, such as the pharmaceutical, gasification, pyrolysis, food, metal powder injection molding, additive manufacturing, and metallurgical industries. Rotating drums have been widely used for studying the flow mechanics and segregation mechanism of granular materials because the flow field in a drum is relatively simple (Dury and Ristow, 1997; Khakhar et al., 1997; Ding et al., 2002; Hill et al., 2004; Jain et al., 2005b; Chaudhuri et al., 2006; Chou et al., 2010; Liao et al., 2010a,b; Pereira et al., 2011; Tripathi and Khakhar, 2011; Aissa et al., 2012; Arntz et al., 2014; Liao et al., 2014b). In a rotating drum, two distinct flow regions exist: the flowing layer and the fixed layer. Physical processes primarily occur in the flowing layer when the granular materials flow downward. Four flow motions, namely slumping, rolling, cataracting, and centrifuging, become evident as the rotational speed increases (Mellmann, 2001). Granular materials may segregate because of differences in particle density, size, surface roughness, restitution coefficient, and shape, causing severe problems in many industrial processes. Understanding the segregation mechanism of granular materials is essential for improving industrial processes and ensuring high product quality (Rosato et al., 1987; Hsiau and Yu, 1997; Hsiau and Chen, 2002; Hsiau et al., 2002; Breu et al., 2003; Kuo et al., 2005; Ciamarra et al., 2006; Rapaport, 2007; Brito et al., 2008; Liao et al., 2010a,b; Tripathi and Khakhar, 2013; Liao et al., 2014a,b). In a binary granular mixture system, where components have different densities, segregation occurs because of the buoyancy effect. Dense particles sink to the lower level of the flowing layer and form a core at the center of the drum (Ristow, 1994; Jain et al., 2005a; Liao et al., 2014b).

Arntz et al. (2014) conducted a discrete element method simulation of a binary mixture in a drum and reported that three parameters, namely differences in the radius, density, and mass, predominantly determined the segregation behavior. The authors indicated that these three parameters were associated with percolation, buoyancy, and inertia mechanisms, respectively. Liao et al. (2014b) demonstrated that the dimensionless difference in the dynamic angle of repose and the density ratio had strong effects on streak segregation patterns caused by density. In addition, the authors provided a phase diagram for identifying three pattern regimes: core segregation, streak segregation, and mixing. Jain et al. (2005a) studied the mixing and segregation behavior of particles by combining the size and density effect of particles in a rotating drum. Dry and slurry granular materials are both essential in powder technological and industrial processes. Granular materials consist of a collection of discrete solid particles dispersed in interstitial fluid. The interstitial fluid has a crucial role in transport properties and mixing and segregation mechanisms (Samadani and Kudrolli, 2000; Fiedor and Ottino, 2003; Jain et al., 2004; Finger and Stannarius, 2007; Liao and Hsiau, 2009; Liao et al., 2010a,b; Chou et al., 2011). Fiedor and Ottino (2003) studied the dynamics

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of the axial segregation and coarsening of dry granular materials and slurries in tubes. The authors indicated that the fraction of the surface area of small-rich particles increases because the viscosity of the interstitial fluid increases. Finger and Stannarius (2007) investigated the influence of the viscosity of the interstitial fluid on the coarsening of axial segregation patterns in a horizontally rotating mixer. The authors demonstrated that the viscosity of the interstitial fluid has a crucial role in the pattern dynamics and the structure of segregation patterns. Furthermore, they demonstrated that the density effect of the interstitial fluid does not influence the formation and evolution of segregation patterns of granular materials. However, Jain et al. (2004) indicated that the flow behavior of granular materials in a quasi-two-dimensional (2D) rotating drum remains similar even if the interstitial fluid used is different. Furthermore, they indicated that the physical mechanism of the granular flow is not strongly influenced by the interstitial fluid. Liao and Hsiau (2009) demonstrated that self-diffusion coefficients and granular temperatures decreased because the interstitial fluid was extra viscous, resulting in a large viscous force. Liao et al. (2010a,b) reported that the granular mixing rate increases as the interstitial fluid viscosity increases. They proposed a simple model and indicated that the thickness of the mixing region is the dominant parameter influencing the mixing rate in a slurry rotating drum. Chou et al. (2011) demonstrated that the size-induced granular segregation index decreases as the interstitial fluid viscosity increases in a slurry rotating drum.

Some theoretical models were developed to study the density-induced segregation in the past (Khakhar et al., 1997; Yoon and Jenkins, 2006; Sarkar and Khakhar, 2008; Tripathi and Khakhar, 2011; Tripathi and Khakhar, 2013; Fan and Hill, 2015). Khakhar et al. (1997) developed a model to study the density-induced segregation and proposed a buoyancy mechanism in a rotating drum. They indicated that the particles lighter than the surrounding mixture of particles experience a buoyancy force greater than their weight and rise to the free surface, and the particles heavier than the surrounding mixture sink. Tripathi and Khakhar (2011) studied the sedimentation of a heavier particle in a steady, gravity-driven granular flow of otherwise identical spheres, on a rough inclined plane by taking a hydrodynamic approach. They found the drag force to be given by a modified Stokes drag law and buoyancy force by the Archimedes principle. Khakhar and his colleagues also illuminated the form of the inverse drag function by considering movement of particles differing in density through an effective medium and showed the drag increased with an effective temperature in his recently reported studies (Sarkar and Khakhar, 2008; Tripathi and Khakhar, 2013). Yoon and Jenkins (2006) employed a kinetic theory for binary mixtures of slightly inelastic, frictionless particles to study segregation in a uniformly agitated system under gravity. They found that, although the granular temperature differences can be significant with increasing differences in the density or size of the particles, the segregation is not greatly affected. Fan and Hill (2015) used kinetic theory and mixture theory to study the density-induced segregation in a vertical chute. They found that in sparse flows, the heavier particles segregate to the lower shear rates. There is no segregation reversal at high solid fraction in density-induced segregation system. They also reported that kinetic theory predicted well the segregation at low solid fraction but breaks down at the higher solid fraction.

Understanding density-induced segregation mechanisms in slurry granular systems, where many unknown physical mechanisms exist, is interesting. In this study, an extensive series of experiments was performed for investigating the influence of the interstitial fluid density and viscosity on the granular segregation mechanism and dynamic properties in a slurry rotating drum. The time evolutions of the segregation index, final steady-state segregation index, dynamic angle of repose, dynamic properties, and Stokes number (St) were also examined.

Experimental procedure

A quasi-2D rotating drum is shown schematically in Fig. 1a. The diameter and the axial length d of the drum were 50 cm and 0.9 cm, respectively; h represents the thickness of the flowing layer and h_{m} represents the maximum thickness of the flowing layer at the center of the flowing surface. Furthermore, θ_r is the dynamic angle of repose of particles (Fig. 1a). Two types of beads with the same size (diameter: 3 ± 0.1 mm) but with different densities (stainless steel: 7.93 g/cm^3 and black polyformaldehyde (POM): 1.41 g/cm^3) were used as granular materials. The density ratio of the binary mixture was 5.62. Wall friction has a significant effect on particle motions when the axial length is extremely short. Axial motion may become more influential as the axial thickness increases. After referring to previous studies, we built a drum with a dimensionless axial thickness (ratio of the drum axial length to the particle diameter) of 3 for balancing the effects of wall friction and axial motion (Jain et al., 2005a, 2005b; Chou et al., 2010; Liao et al., 2010a,b) and used stainless steel beads as tracer particles. The front and back faceplates of the rotating drum were composed of transparent glass for permitting optical access and avoiding an electrostatic effect. A water–glycerin mixture was used as the interstitial fluid in slurry systems, and the weight percent concentration of glycerin ranged from 0% to 80%. Within this range, the corresponding interstitial fluid viscosity μ varied from 1 to 60.1 cP at room temperature (20°C). The interstitial fluid density increased from 1.00 g/cm^3 (pure water) to 1.20 g/cm^3 (80% glycerin). A small hole was left in the top of the rotating drum for injecting liquid into the drum. After the drum was completely filled with the interstitial fluid, the hole was sealed. A dry system using air as the interstitial fluid served as a reference.

A servo motor was used to drive the drum, of which the rotating speed was fixed at 2 rpm, corresponding to a Froude number, $F_r = R\omega^2/g$, of 1.12×10^{-3}, where ω is the rotating speed, R is the radius, and g is the acceleration of gravity. In each test, the volume fraction of heavy and light beads was 50%. The initial loading of binary mixture is schematically illustrated in Fig. 1b. Stainless beads were on top of the POM particles. A DV (SONY HDR-SR8) motion corder analyzer, with a frame speed of 30 frames per second (FPS) was used for recording the flow motion inside the drum, and a spatial resolution of 800×600 pixels was used for recording particle motion during radial segregation.

It is not easy to measure the volume concentrations of particles when the granular packing bed is quasi 2D or 3D. In previous studies (Khakhar et al., 1997; Li and McCarthy, 2006; Shi et al., 2007; Liao et al., 2010a,b; Chou et al., 2010; Chou et al., 2011), the area concentrations and the intensity of segregation were measured by calculating the areas of particles from the digital images. In this study, the segregation index was measured by the similar technique. By using image processing, the frames were digitized to grayscale levels in the range of 0–255 in consideration of the different colors of the tracer and background particles (Chou et al., 2010; Liao et al., 2010a,b; Chou et al., 2011). Then those images are segmented so that the segregation condition could be determined. The segregation index was widely used to quantify the granular segregation in the past (Danckwerts, 1952; Khakhar et al., 1997; Khakhar et al., 2003; Li and McCarthy, 2006; Shi et al., 2007; Liao et al., 2010a,b; Chou et al., 2010; Chou et al., 2011). The segregation index I_s is as follows:

$$I_s = \sqrt{\frac{\sum_{i=1}^{N} (C - C_{avg})^2}{M - 1}} \tag{1}$$