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Effects of density ratio, rotation speed, and fill level on density-induced granular streak segregation in a rotating drum

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ABSTRACT

Granular materials segregate because of differences in density, size, surface roughness, or shape, thus causing critical problems in many industries. In this study, we systematically and experimentally investigated the behavior of density-induced granular segregation in a circular thin rotating drum. We studied the effects of the density ratio, rotation speed, and fill level on the behavior of granular streak segregation. We used particle tracking velocimetry and image processing technology to determine the number of petals and the shape index of streak patterns. The results show that the density ratio, rotation speed, and fill level significantly influence the behavior of density-induced granular segregation, and the shape index decreases with an increase in the rotation speed. The passage time elongates when the density ratio is increased. Moreover, the final stable shape index does not increase monotonically with the fill level. The maximum shape index occurs at a fill level of 0.51.

1. Introduction

Granular materials and powders are accumulations of discrete solid particles dispersed in an interstitial fluid. Granular materials (e.g., salt, sugar, glass beads, steel balls, metal powders, coffee beans, pills, and rice) are commonly found in daily life and industrial processes and can behave as a solid, liquid, or gas. Granular mixtures may segregate under external driving forces because of differences in density, size, surface roughness, or shape. Such segregation can cause unpredictable problems in industrial processes such as metal powder injection molding and the manufacturing of pharmaceutical and food products, and fluidized bed reactors. In addition, granular streak segregation patterns are crucial in geophysics and are relevant to rock formation. Thus, understanding the evolution and mechanism of granular segregation is essential [1–28].

Rotating drums are widely used to investigate the flow mechanics and segregation mechanism of granular flows because the flow field in such drums is relatively simple [1,3,6–10,12–20]. Granular flow in a rotating drum has different regimes depending on the Froude number. When the rotation speed is increased (with the increasing Froude number), four flow regimes become evident: slumping, rolling, cataracting, and centrifuging. Two regions are observed in the granular motions in a rotating drum with partially filled containers: a fixed bed region and a flowing layer region at a free surface where the mixing and segregation of granular matter occur. Core segregation typically occurs in a binary mixture with different sizes or densities in a rotating drum because of percolation and buoyancy effects [1,3,9–12,27,28]. Jain et al. [1,27] studied the behavior of granular mixing and segregation by combining the size and density effects of a binary mixture in a thin rotating drum. Arntz et al. [9] reported that three parameters predominantly determined the segregation behavior; namely, differences in the radius, density, and mass, which they found to be related to percolation, buoyancy, and inertia mechanisms, respectively.

Granular materials may also segregate spontaneously in a regular streak segregation pattern. Previous studies have investigated the formation behavior of size-induced streak segregation patterns [5,11–13]. Pattern formation is affected by many parameters such as the size ratio, rotation speed, fill level, and container geometry [11–15,17–19]. Gray and Hutter [5] experimentally studied the pattern formation in granular avalanches in a binary mixture with various grain sizes. They indicated that during motion, the kinetic sieving of a bidispersed granular mixture creates a two-layer shear band in which large particles lie on top of small particles. Makse et al. [11] indicated that granular streak segregation occurs when large grains have a wider repose angle than that of small grains. Moreover, they noted that stratification is related to the occurrence of avalanches. Hill et al. [12] studied radial segregation patterns in a size system in a thin rotating drum and found that the fill level plays a crucial role in the radial segregation pattern formation (systems involving size-induced streak segregation are called *S*-systems). Zuriguel et al. [13] found that the rotation speed, size of drum, and volume fraction of small particles are crucial parameters for

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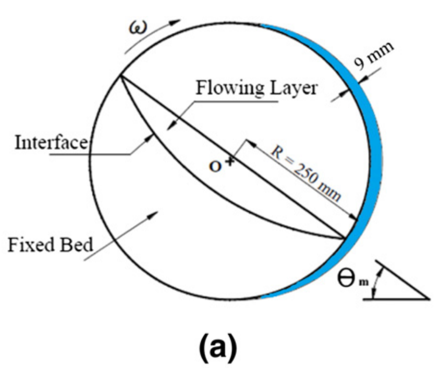
determining the granular segregation patterns in a size effect system. Hill et al. [19] indicated that the flowing layer is thinner and moves faster when it consists primarily of small particles. Conversely, a thicker and slower flowing layer is formed from large particles. Liao et al. [20] found that the dimensionless differences in the dynamic repose angle and density ratio strongly affected streak segregation patterns caused by the density. They provided a phase diagram in which three pattern regimes were identified: the core segregation regime, streak segregation regime, and mixing regime. Additionally, they demonstrated that streak segregation patterns can occur only for large dimensionless differences in the dynamic repose angle and density ratio.

Core segregation in a rotation drum has been extensively investigated in the past few decades; however, the formation mechanism of spontaneous streak segregation patterns is not clearly understood. In particular, few studies have reported density-induced streak segregation patterns (systems involving density-induced streak segregation are called *D*-systems). In this study, we focused on the evolution and behavior of density-induced spontaneous streak segregation patterns in a thin rotating drum. The effects of the density ratio (ρ_r), rotation speed (ω), and fill level (f) on the evolution and behavior of streak segregation patterns were systematically investigated.

2. Experimental procedure

In this study, a quasi two-dimensional rotating drum with a diameter of 50 cm and a bed thickness of 0.9 cm was used to investigate density-induced spontaneous granular streak segregation (Fig. 1). The front and back faceplates of the rotating drum were composed of clear glass to permit optical access. Four types of beads, all with the same size (3 ± 0.1 mm in diameter) but different densities (stainless steel = 7.93 g/cm^3, glass = 2.48 g/cm^3, polyformaldehyde (POM) = 1.41 g/cm^3, and polypropylene (PP) = 0.90 g/cm^3), were used as granular materials. The particle properties of the materials used in this study are listed in Table 1. The internal friction coefficients of the four materials were measured using a commercial Jenike shear tester. The values were 0.57 (stainless steel), 0.60 (glass), 0.58 (POM), and 0.62 (PP).



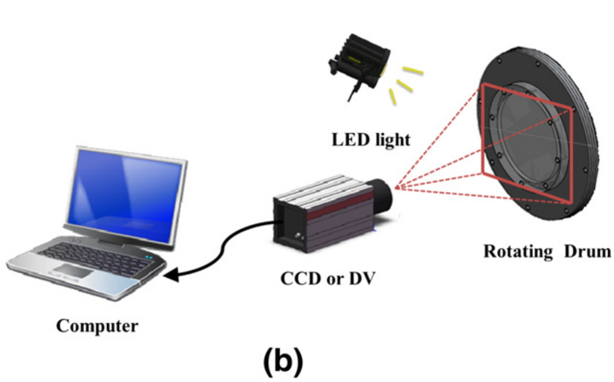


Fig. 1. (a) Skeleton diagram of the rotating drum and (b) experimental setup.

Table 1
Properties of the materials used in the experiments.

Granular material	Density (g/cm^3)	Diameter (mm)
Stainless steel	7.93	3 ± 0.1
Glass	2.48	
Polyformaldehyde (POM)	1.41	
Polypropylene (PP)	0.9	

Additionally, restitution coefficients of the four materials were measured using the drop test. The values were 0.85 (stainless steel), 0.91 (glass), 0.90 (POM), and 0.92 (PP). Moreover, the effects of surface friction on granular segregation in a rotating drum remain a problem. In this study, the restitution coefficients and friction coefficients of the four materials are close. So the effects of restitution coefficient and friction coefficient on segregation behavior are minimized. The dimensionless axial thickness of the drum, defined as the ratio of the drum axial length to the particle diameter, was set at 3. Notably, the wall friction effect becomes significant when the axial length is too short. Axial motion may become significant as the axial thickness is increased. Hence, a dimensionless axial thickness of 3 was applied to balance the wall friction and axial motion according to previous studies [20]. Six density ratios were used to study the density-induced evolution and dynamic behavior of granular streak segregation. The density ratios, ρ_h/ρ_l, were 8.81 (steel and PP), 5.62 (steel and POM), 3.20 (steel and glass), 2.76 (glass and PP), 1.76 (glass and POM), and 1.57 (POM and PP), where ρ_h is the density of heavy particles and ρ_l is the density of light particles in a binary mixture. In every experiment, the volume fractions of heavy and light beads were both 50%. Before each experiment, the binary mixture was thoroughly mixed with the large rotational speed of 20 rpm. Five rotation speeds and six filling levels of granular materials were applied to investigate density-induced granular streak segregation patterns. We focused on the rolling regime in which the flow is continuous. The experimental parameters used in the current study are listed in Table 2. Because of observational difficulties, only the flows adjacent to the front faceplate could be recorded and analyzed. The inner surface was carefully cleaned and polished with wax to reduce the wall friction effect before each experiment. A digital camera (SONY HDR-SR8) with a resolution of 640 × 480 pixels was used to record the flow motions inside the drum at a speed of 30 frames/s. To investigate the evolution and behavior of the density-induced granular streak segregation patterns, particle tracking velocimetry and image processing technology were used to determine the number of petals and the shape index of streak patterns [29–31]. A shape index was used as follows to quantify the density-induced granular streak segregation [12]:

$$\text{Shape index} \equiv \frac{p^2}{A}, \tag{1}$$

where p is the perimeter of the streak segregation pattern and A is the total area. In this study, the frames were digitized to gray levels ranging from 0 to 255 due to the different colors of the tracer particles and background particles by employing image processing technology as shown in Fig. 2. The image contrast was then enhanced so that the pixels inside

Table 2
Experimental parameters.

Experimental particle configuration	Density ratio (ρ_h/ρ_l)	Rotation speed (rpm)	Fill level
Steel & PP	8.81	0.6	0.45
Steel & POM	5.62	0.8	0.48
Steel & glass	3.20	1.0	0.51
Glass & PP	2.76	1.2	0.55
Glass & POM	1.76	1.4	0.58
POM & PP	1.57		0.61