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Density-induced granular migration dynamics in sheared slurry granular materials

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ABSTRACT

In this study, we report on experimental measurements of density-driven particle ring migration on sheared granular materials with different interstitial fluid viscosities. The dimensionless sinking depth and sinking rate describe the change in the granular ring position and quantify the particle sinking speed, respectively, are successfully measured by the PTV method. The results indicate that the interstitial fluid viscosity has a significant influence on determining the density-driven particle migration of the slurry granular flows. The dimensionless sinking depth and sinking rate are the largest in a dry system (interstitial fluid of air). The particle migration becomes weaker and causes a smaller dimensionless sinking depth and sinking rate as the interstitial fluid is more viscous. Both the dimensionless sinking depth and sinking rate are enhanced with an increase in wall velocity (shear rate). The sinking rate increases linearly with the final steady-state sinking depth, regardless of the interstitial fluid viscosity and wall velocity (shear rate).

1. Introduction

Granular materials are discrete solid particles that are easily found in nature. Granular materials are also widely used in industries such as pharmaceuticals, food, cement, polymers, powder metallurgy, and additive manufacturing. It is crucial to understand the flow behavior and the segregation mechanism; however, our understanding of granular flow is still poor. Random particle motion resulting from interactive collisions between particles is the dominant mechanism influencing the flow behavior of granular materials [1]. Granular materials do not flow homogeneously like a fluid when the shear force is small. There may coexist solid-like regions and shear band regions in the shear granular flows. The physical mechanisms occur mostly in the shear band region, and the thickness of the shear band is about five to ten particle diameters [2–7].

The shear cell was widely used to investigate the rheology of granular materials in recent years because the flowing field is relatively simple and suitable for fundamental research [8–15]. Liao and Hsiau [3] studied the transport properties in slurry sheared granular materials. They indicated that the interstitial fluid viscosity plays an important role in determining the transport properties of the granular flow. Both the self-diffusion coefficients and the granular temperature are reduced with an increasing interstitial fluid viscosity. Liao et al. [12] investigated the sinking dynamics of a heavy granular ring caused by the density-induced segregation effect tin sheared dry granular materials. They found that the sinking rate increases linearly with the final steady-state sinking depth for the same heavy granular ring structure, regardless of the wall velocity, solid fraction, and density ratio. Golick and Daniels [14] studied the mixing and subsequent re-segregation of different-sized particles in an annular shear cell. They reported that the mixing rate behaved as expected at a low confining pressure.

Granular segregation has been an important issue in many industrial processes (e.g., pharmaceutical products, foodstuffs, detergents, chemicals, and plastics) and in nature research (e.g., debris flow, sedimentation, avalanches, and landslides) over the past several decades. Thus far, it remains a complex and poorly understood process, particularly in density-driven segregation. A granular segregation mechanism can be influenced by external driving conditions, container geometry, interstitial fluid, and particle properties such as size, density, friction coefficient, shape, and restitution coefficient [16–23]. In the current study, we focus on the effects of interstitial fluid viscosity on density-driven particle migration in sheared granular flows. A granular system becomes a two-phase system if only solid and liquid or solid and air exist. Finger and Stannarius [16] investigated the influence of the viscosity of the interstitial liquid in a horizontally rotating mixer. They found that the viscosity of the interstitial liquid played a crucial role in the pattern dynamics and the structure of the segregation patterns. They also indicated that the density effect of interstitial fluid does not influence the formation and evolution of segregation patterns of the granular materials. Liao et al. [17] experimentally investigated the granular dynamics immersed in a water-glycerin mixture in a rotating drum. They found that the flowing layer became thicker, and the mean flow velocity was slower, in a more viscous fluid. However, the mixing rate increased

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with an increase in interstitial fluid viscosity. Liao et al. [18] experimentally studied density-driven granular segregation in a slurry rotating drum. They indicated that the final steady-state segregation index slightly increased with a decreasing Stokes number in a high-Stokes-number range, whereas the final steady-state segregation index increased sharply with a decreasing Stokes number in a low-Stokes-number range.

Handling the dry and slurry granular materials is important in technological and industrial processes. However, few studies have focused on density-driven granular segregation in sheared slurry granular flows. It is interesting to understand the density-driven particle migration and flowing behavior in slurry sheared granular flows. In this study, we conduct a series of experiments to investigate the influences of the interstitial fluid viscosity on density-driven particle migrations in slurry sheared granular flows. Four types of interstitial fluids served as interstitial fluids in this study: air, 50% glycerin-water mixture, 60% glycerin-water mixture, and 70% glycerin-water mixture (Table 1). The effect of the driving wall velocity (shear rate) on density-driven particle migrations is also investigated in this study.

2. Experimental setup

Fig. 1a shows a schematic representation of the shear cell apparatus. The shear device consisted of a rotating bottom disk and a stationary upper disk. The rotating bottom disk had an outside diameter of 0.45 m, and was driven by a 3-hp AC motor. The rotation speed was controlled by a variable-speed inverter and was measured by a tachometer. The bottom disk was made of transparent plexiglass to facilitate observing and recording the particle motion. An annular trough (inside diameter: 0.32 m; outside diameter: 0.42 m; depth: 0.045 m) was cut into the bottom disk. The stationary upper disk could be inserted into the trough, where the granular materials were placed in the test section. The height H of the test section could be adjusted and was measured by a dial indicator.

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 glass bead = 2.48 g/cm^3) were used as granular materials, and the density ratio of the binary mixture was fixed at 3.20 in this study. To study the particle migration, we carefully poured a flat layer of lighter particles (84% of total test particle volume) in random packings on the bottom of the annular channel, followed by a flat layer of heavier particles (16% of total test particle volume). These heavier particles formed a granular ring and served as tracer particles in each experiment. The average solid fraction was calculated from the total particle mass in the test section divided by the particle density and the test section volume:

$$\nu = \frac{m_t/\rho_t + m_b/\rho_b}{H\pi\left(r_0^2 - r_i^2\right)} \tag{1}$$

where m_t and m_b represent the mass of the entire granular ring (heavy particles) and the mass of the background (light) particles, respectively; r_i is the inside radius; and r_0 is the outside radius of the annular trough. In this study, we chose a relatively high solid fraction ($\nu = 0.5953$), and both walls (bottom and upper walls) had frequent contact with granular materials. Thus, the granular material occupied most of the space in the test section. A 3.0-mm layer of glass beads was adhered to both the bottom and the upper wall surfaces in a random packing organization to generate enough shear force in the flow to avoid crystallization. The small insert plot in Fig. 1a shows a 2D granular flow in the test section with a streamwise direction (u direction) as the x-axis, and transverse direction (v direction) as the y-axis ($y = 0$ at the moving boundary wall). Only the flows adjacent to the outer surface of the annular trough in the bottom disk were recorded and analyzed owing to the limitations of observation. Before each experimental run, the inner surface was cleaned and polished with wax to reduce the wall friction effect. The velocity of the bottom wall u_0 was calculated from the product of the rotational speed of the bottom disk and the outside radius of the trough. In the current study, we consider three wall velocities u_0 of 0.46 m/s, 0.54 m/s, and 0.61 m/s, corresponding to the shear rates $\gamma = d\langle u\rangle/dy$ of 13.793 1/s, 16.192 1/s, and 18.291 1/s, respectively. Table 2 lists the experimental parameters used in this study.

Table 1
Interstitial fluid properties at room temperature 20 °C.

Interstitial fluid	Density (kg/m^3)	Viscosity (Pa s)
Air	1.184	1.813×10^{-5}
50% glycerin-water mixture	1132	6.1×10^{-3}
60% glycerin-water mixture	1159	10.8×10^{-3}
70% glycerin-water mixture	1185	22.5×10^{-3}

To investigate the sinking dynamics of a granular ring, the flow motion was recorded using a high-speed camera at a resolution of 628 × 540 pixels (IDT MotionPro X3 PLUS). Fig. 1b shows a schematic drawing of the experimental setup. Images were captured at a speed of 30 FPS. Image-processing technology and a particle-tracking method were used to digitize each frame with gray levels ranging from 0 to 255 to show the colors of the tracer particles and background particles. This approach revealed the positions of the heavy particles and the average height of the heavy granular ring in every frame [3, 5]. Thus, the sinking process of the heavy granular ring can also be determined. To quantify the dynamics of sinking migration of the heavy particle ring, the dimensionless sinking depth S_d was defined as follows [12]:

$$S_d = \frac{h_0 - h(t)}{H} \tag{2}$$

where h_0 is the initial average height of the heavy particle ring, and $h(t)$ is the average sinking depth of the heavy particle ring in each frame. The channel height H was fixed at 33.35 mm, as Fig. 2 shows.

3. Results and discussion

To quantify the particle migration dynamics of the heavy particle ring, the dimensionless sinking depth S_d was plotted as a function of time with four different interstitial fluid viscosities at a specific wall velocity $u_0 = 0.54$ m/s. The solid fraction and the density ratio are 0.5953 and 3.20, respectively (Fig. 3). This shows that the dimensionless sinking depth gradually increases until reaching the final steady state in each case. Density-driven granular segregation occurs in binary mixtures of granular materials with different particle densities because of the buoyancy effect [23, 24]. Hence, the dimensionless sinking depth to which the stainless steel beads (heavy particles) is enhanced with time, as shown in Fig. 3. It can be found that the dimensionless sinking depth of the heavy particle ring has a limited final steady-state value because of the existence of the solid-like region in the bottom layers [3, 5, 6]. The particle relative motions and interactive collisions are stronger in the shear band region, creating a more diluted particle-packing structure. Hence, the heavy particles sink easily because of the smaller drag force in the shear band region. The figure also shows that the final steady-state sinking depth is smaller in a system with a greater viscosity of interstitial fluid, resulting in a greater viscous force. Additionally, the time evolution of the dimensionless sinking depth shown in Fig. 3 indicates that the dimensionless sinking depth increases exponentially with time until it approaches the final steady-state values in each case. This indicates that the experimental data show a good fit with the exponential relationship of

$$S_d = S_{d,final}\left(1 - \exp(-Kt)\right) \tag{3}$$

where $S_{d,final}$ is the dimensionless final steady-state sinking depth, K is the sinking rate, and t is time.