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The effects of particle density and interstitial fluid viscosity on the dynamic properties of granular slurries in a rotating drum

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ABSTRACT

Experiments were performed to measure the dynamic properties of granular matter in a slurry rotating drum. Five different fluid viscosities, including air and four different liquid viscosities with mixtures of water and glycerin, as well as three different particle densities were used in the experiments. In this study, the purpose was to quantify the effects of the particle density and fluid drag force in a granular system.

Particle tracking velocimetry was employed to measure the dynamic properties. Both the velocity of particle and granular temperature were obtained by averaging the experimental data. The angle of repose and diffusion coefficient were also calculated. The results show that the granular dynamic properties are strongly affected by the operational parameters. The mean velocity, obtained by averaging the velocities of all particles will decrease with an increase of the fluid viscosity. The average granular temperature will also decrease with increasing fluid viscosity. Moreover, the dimensionless number related to the dynamic properties is also discussed in the present study.

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1. Introduction

A granular material is an assembly of discrete solid particles (e.g. sand, glass, coffee beans, pills, salt, etc.) dispersed in an interstitial fluid. Such systems are widely found in nature and used in a wide variety of industrial processes. Some examples of the many large scale geophysical granular flows which occur in nature are hazardous natural events that include lahars [1], debris flows [2], snow avalanches [3] and dense pyroclastic flows [4]; these are often the most dramatic natural catastrophes causing large pecuniary losses. The processing of granular materials is important in many industries, including in the preparation of pharmaceuticals [5], foodstuffs, ceramics [6], detergents, chemicals, plastics [7], etc. The ubiquity of granular materials in the processes involved makes their efficient and economic handling very important [8]. Furthermore, their special properties (they can behave like solids, liquids or gases without being any of them) have attracted the attention of the scientific community over the last two decades [9,10].

There are many engineering applications, such as in the mineral, food processing and bulk material handing industries, in which granular materials are used in the process of drying, heating [11,12], chemical reactions [13–15], mixing and segregation [16–18]. In such systems, the particle flow/avalanche occurring at the free surface will behave like a fluid while in large region away from the free surface the material acts like a solid. This is a typical flow field in a rotating drum.

Rotating drums have become commonly used experimental devices for investigating the physics of granular flows, partly because of their simple closed geometry. Rotating drums are usually simply comprised of a cylinder rotating about its central axis so as to drive the particle motions. The particles in the system behave like a solid rotated within the drum as it moves about its axis until they reach their dynamic angle of repose after which point they roll down the pitched surface. The angle of repose is an important parameter affecting the behavior of the granular flow in a rotating drum. Several studies have been carried out where the segregation phenomenon is characterized by the angle of repose of the particles [19,20], and some studies also use this parameter (angle of repose) to indicate the transition of the flow regime [21,22]. Although the rotating drum is simple and can be operated relatively easily, the granular dynamic behavior is more complicated. Granular flow behavior in rotating drums can be separated into several flow regimes based on the particle motion. The particle flow behavior and mixing/segregation mechanisms may be different in each flow regime. Six identifiable flow regimes may be used to describe the particle motion in a dry granular system in a rotating drum depending on different operational conditions, including the rotational speed, wall friction coefficient, filling degree, and so on. The flow regimes include slipping, slumping, rolling, cascading, cataracting and centrifuging [21,23].

If the system is a slurry system, where only solids and liquids or solids and air exist at the same time, the behavior is different. Past studies have mostly been performed on dry granular systems, where the interstitial fluid is air. It has been found that the investigation of particle transport properties is about the influence of different particle materials, the size of the particles or the tank, even the rotation speed of

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the rotating drum, while the fluid (air) effects are small enough to be neglected [24–26]. However, some researchers have begun to focus on investigating the effects of the fluid viscosity on the particle flowing behavior and segregation phenomena in a slurry granular system. When the interstitial fluid is liquid, the fluid (liquid) effect cannot be neglected [27–29]. Medved et al. [30] investigated the convection motion of a slurry granular system in a vibrated bed. They found that the rise times of particles are slower in the liquid than in the dry system. Fiedor and Ottion [31] investigated the dynamics of axial segregation and the coarsening of dry and slurry granular systems. They indicated that the fraction of the surface area of small-rich particles increases due to the increasing viscosity of the interstitial fluid. Chou and Hsiau [32] used particle tracking velocimetry to investigate the dynamic properties and flowing behavior of immersed granular matter in a rotating drum. They provided the users with the possibility of deciding on the flow behavior of immersed granular bed material based on the phase diagram.

From the above discussion, we realize that the fluid kinematic viscosity exerts a significant effect on the granular flow behavior, but there many existing physical mechanisms that are yet unknown or poorly understood. Therefore, in this study, we report on experiments performed to investigate the dynamic properties of immersed granular matter in a rotating drum with fluids of different viscosities and different densities of particles.

2. Experimental procedure

A schematic representation of the quasi-two-dimensional circular drum used in the experiments is shown in Fig. 1. The diameter of the drum is 0.2 m and the axial length W is 0.02 m. The rotating drum was rotated with a stepper motor at a speed (ω) of 0.247 rad/s. The dimensionless axial thickness of the drum, defined as the ratio of the drum's axial length and the particle diameter, was set to 5 in this study. The rear surface is an aluminum plate. It could be used to reduce the electrostatic effects. A black paper was adhered to the rear surface of the rotating drum to minimize the optical noise effect in the digital images. The clear acrylic front plate is placed for flow visualization. A small hole in the side of the tank allowed liquid to be injected from a hopper. Because of the wall friction effect, the concentration profiles near the walls may be different than in the bulk material. Thus, we cleaned the end walls before each test to make sure that the walls were smooth and the wall friction effect between the wall and the granular flows is reduced.

In this study, three different kinds of mono-sized particles were used as the granular material. Their densities are 1410 kg/m^3 for polyformaldehyde beads, 2500 kg/m^3 for glass bead and 7900 kg/m^3 for steel beads. The filling degree is defined as the ratio of volume occupied by the granular material to the total drum volume. Since the experiment is defined as a quasi-two-dimensional experiment, the filling degree is defined as the ratio of the area occupied by the granular material to the total drum area. In all experiments, the filling degree of the granular material was 0.5. Details of the experimental conditions are provided in Table 1. There were five different kinds of interstitial fluid, including air, and four different liquid viscosities with mixtures of water and glycerin are used in this study. The water–glycerin mixtures with different glycerin weight fractions ϕ, varying μ from 1.00×10^{-3} Pa s (water, $\phi = 0$) to 15.2×10^{-3} Pa s (65% glycerin, $\phi = 0.65$), as listed in Table 2. In all of the slurry flow experiments, the drum was completely filled (no air content) with a water–glycerin mixture before being sealed.

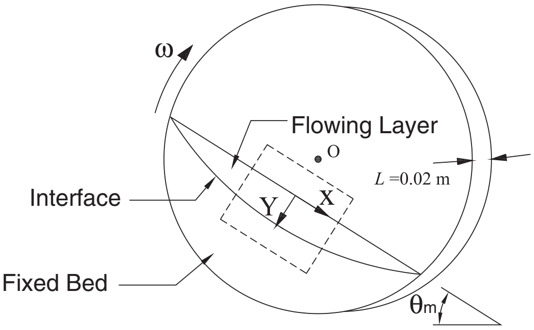

Fig. 1. Diagram of the tank rotated by the rotating drum. Two distinct flow regions inside the drum can be identified: the flowing layer region and the fixed bed region.

Consecutive images were recorded by a high-speed CMOS camera (IDT X-3 plus, 2000 frames per second (fps) at 1280 × 1024 pixels). The flow was illuminated by two halogen lamps. The digital images were transported to a personal computer for further analysis. The cross-correlation technique was used to calculate the shift of each tracer particle in every pair of consecutive images [33]. In this paper, we divided the specific region (dotted rectangle in Fig. 1) into several subregions for calculation. The ensemble average velocities in each bin are averaged from about 1100 tracer particles (6000 frames):

$$<u_i> = \frac{\sum_{k=1}^{N_i} u_{ki}}{N_i}, \tag{1}$$

$$<v_i> = \frac{\sum_{k=1}^{N_i} v_{ki}}{N_i}, \tag{2}$$

Where $<u_i>$ and $<v_i>$ denote the ensemble averaged velocities in the x and y directions, respectively, in the ith bin averaged from velocities from N_i tracer particles. The subscript k represents the kth tracer particle in the ith bin. The fluctuation velocities in the ith bin are defined as the root mean squares of the deviations between the local velocities and the ensemble averaged velocities:

$$<u'^2_i>^{1/2} = \sqrt{\frac{\sum_{k=1}^{N_i} (u_{ki} - <u_i>)^2}{N_i}}, \tag{3}$$

$$<v'^2_i>^{1/2} = \sqrt{\frac{\sum_{k=1}^{N_i} (v_{ki} - <v_i>)^2}{N_i}}. \tag{4}$$

The granular temperature T is defined as the specific fluctuation kinetic energy of the granular flow because of the random motions of the particles, and can be used to quantify the kinetic fluctuation energy of the granular flow. This is a key property for studying the dynamic behavior of granular flows [34–36]. A granular system behaves more like a liquid or a gas when it has a relatively higher granular temperature. The granular temperature in the ith bin in a quasi-two-dimensional system can be calculated by

$$T_i = \frac{<u'^2_i + v'^2_i>}{2}. \tag{5}$$

The velocity fluctuations induce the phenomenon of self-diffusion in granular shear flows. Einstein [37] first employed the concept for

Table 1
Experimental parameters: the rotation speed ω of the rotating drum is 0.247 rad/s, and the filling degree is 0.5.

Particle type	Polyformaldehyde ($\rho_s = 1410$ kg/m^3), glass ($\rho_s = 2500$ kg/m^3), steel ($\rho_s = 7900$ kg/m^3).
Fluid viscosity (μ)	0.01842, 1.005, 6.00, 10.8, 15.2 (mPa s)

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