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Original Research Paper

# Effect of adding a small amount of liquid on density-induced wet granular segregation in a rotating drum

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ABSTRACT

This study investigated the density-induced granular segregation phenomenon of wet granular materials in a quasi-2D rotating drum. The motions of the granular materials were recorded using a high-speed camera. Image-processing technology and the particle-tracking method were employed to measure the intensity of segregation, repose angle, and the velocities of heavy particles. We analysed the effects of the liquid content and rotation speed on the segregation index, angle of repose, and velocity of particles in the rotating drum. The experimental results reveal that the liquid content and rotation speed have significant influences on density-induced granular segregation behavior. The intensity of segregation is mitigated with a rise in liquid content because of the stronger cohesive force between particles. We also discuss the relationship between the intensity of segregation and the repose angle.


## 1. Introduction

Granular materials (e.g. sand, glass, coffee beans, pills, and salt) are widespread in nature. Granular materials are also widely used in industrial processes such as pharmaceutical, pyrolysis, gasification, additive manufacturing, polymer, and metallurgical processes. Rotating drums have been employed for investigating the mechanics of granular flows and segregation mechanisms in the past few years because the flowing field is relatively simple [1–5]. Two important flow regions exist in a rotating drum: the flowing layer region and the fixed-bed region. The physical mechanisms occur chiefly in the flowing layer. When the rotation speed is raised, four flow regimes emerge: slumping; rolling; cataracting; and centrifuging [2]. The repose angle of the granular materials is a critical parameter for examining the granular flow behavior in a rotating drum. The size of the drum, fill level, rotating speed, and the roughness of particles affect the repose angle.

Because of differences in size, shape, and density, granular materials may become segregated, resulting in severe challenges for most industries. In the past, many studies have investigated the segregation behavior of granular materials [5–24]. In rotating drums, segregation can occur in binary mixtures with granular materials of different sizes [4,6]. In a binary-mixture system with different densities, segregation also occurs through the buoyancy effect, and denser particles sink to the lower level of the flowing layer to form a core at the centre of the drum [6–8]. Jain et al. [6,8] examined mixing and segregation by combining the size and density effects of particles in a rotating drum. Arntz et al. [9] conducted a distinct element method simulation of a binary mixture in a drum and reported that three parameters predominantly determined the segregation behavior (i.e. differences in size, density, and mass). They indicated that these three parameters were related to the percolation, buoyancy and inertia mechanisms, respectively. Liao et al. [11] found that the dimensionless difference in the dynamic repose angle and density ratio had a strong effect on the streak segregation patterns caused by the density effect. In addition, they provided a phase diagram that identified three pattern regimes: core segregation; streak segregation; and mixing.

Understanding the granular segregation mechanism is crucial for improving industrial processes and ensuring high product quality. Granular segregation is also a common phenomenon in nature. Although the mechanism of size-induced segregation in dry granular materials has been widely investigated and discussed. Density-induced segregation in wet granular materials has received relatively less attention, particularly in experimental study in the past few years. The flowing mechanism becomes complex when a small amount of liquid is added to the granular materials, where the cohesive force increases because of the effects of a liquid bridge [25–35]. The wet system is a three-phase system

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involving solid, liquid, and gas phases. The liquid bridge force plays an important role in the wet granular system. Hence, segregation of granular materials is further complicated when liquids are present and liquid bridges are formed between particles. Samadani and Kudrolli [19,20] found that segregation was mitigated by adding a small amount of liquid in the silo and indicated that the number of liquid bridges influenced the flow behavior in wet granular systems. Chou et al. [15] indicated that the segregation condition could be predicted on the basis of the repose angle of the binary mixture in wet granular materials in a rotating drum, regardless of the liquid content or viscosity. Liu et al. [29] reported that small cohesion has no influence or even a positive influence on granular segregation, and that granular segregation is significantly mitigated by high cohesion. Liao and Hsiau [33] found that the effect of the liquid bridge force on the dynamic properties of wet granular matter is dependent on the kinetic energy of the granular system and liquid viscosity. Seah and Lim [34] studied the density segregation of dry and wet granular mixtures in gas fluidized beds by simulation. They found that density segregation was mitigated with increasing the amount of liquid present.

Understanding density-induced segregation mechanisms in wet granular materials, where many unknown physical mechanisms exist, is interesting and important. There were relatively few works concerning the issue of density-induced segregation in wet granular materials. In this paper, we focus on the effect of adding a small amount of liquid on density-induced segregation of wet granular materials in the rolling regimes with continuous granular flows in a rotating drum. Regarding binary mixture systems, we discuss differences in the intensity of segregation, repose angle, and velocities of heavy particles caused by adding varying liquid contents to the granular materials. We also discuss the effect of the rotation speed on density-induced wet granular segregation behavior.

## 2. Experimental procedure

The quasi-2D rotating drum is shown schematically in Fig. 1(a). The diameter of the drum is 300 mm, and the axial length $d$ of the drum is 15 mm. Two types of beads of the same size (3 ± 0.1 mm in diameter), but with different densities (white glass particle = 2.48 g/cm$^3$, and red polypropylene particle (PP) = 0.90 g/cm$^3$) were used as the granular materials. The density ratio of the particles was 2.76. The dimensionless axial thickness of the drum, defined as the ratio of the drum axial length and the particle diameter, was 5. When the axial length was too short, wall friction had a significant influence on the particle motion and flow behavior. The axial particle motion may become more influential with an increase in axial thickness. Therefore, a dimensionless axial thickness of 5 was used to achieve a balance between the wall friction and axial motion, in accordance with previous studies [6,8,9,14]. Heavy white glass beads served as tracer particles in this study. The front and back faceplates of the rotating drum were composed of clear glass to permit optical access and to avoid the electrostatic effect. Before each experiment, the glass faceplates were coated with inorganic film (i.e. silicone water repellent) to prevent the effect of the liquid bridge from occurring between the particles and walls. We set the filling fraction of the granular materials at 0.5 in all the experiments, and the volume fraction of the heavy and light particles was 50–50%. The initial loading of the particle is illustrated in Fig. 1(b), with the white glass beads on the surface and the PPs on the bottom. Four rotation speeds (1, 2, 3, and 4 rpm) were set to investigate the density-induced wet granular segregation behavior in this study. A DV camcorder (Sony DCR-TRV900 NTSC) was used to record the flow motion inside the drum, with a capture speed of 30 frames per second (FPS).

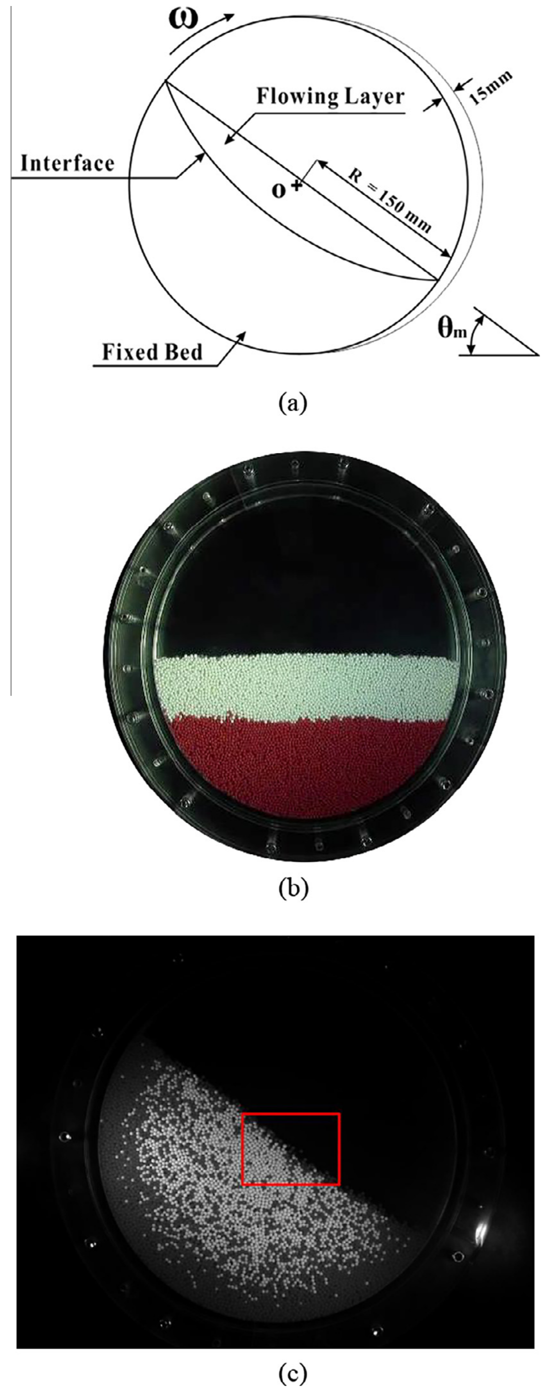


**Fig. 1.** (a) Skeleton diagram of the rotating drum, (b) initial loading of the binary mixture, and (c) measurement of the velocity field.

A small amount of water was added to the granular materials to examine density-induced wet granular segregation in a rotating drum. A certain amount of water and particles was inserted into a sealed jar, which was shaken until the water was mixed sufficiently with the particles before each experiment. Afterward, the wet particles were carefully poured into the drum. We measured the weight of the sealed jar with the residual water to account for any errors. The dimensionless liquid volume $V^*$ is defined as $V^* = V_l/(V_l + V_s)$, where $V_l$ is the volume of the liquid, and $V_s$ represents the total volume of the particles. Five liquid contents (0; $2.99 \times 10^{-3}$; $4.91 \times 10^{-3}$; $6.86 \times 10^{-3}$; and $9.78 \times 10^{-3}$) were used to investigate the density-induced wet segregation behavior. The