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Density segregation in a vertically vibrated granular bed

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ABSTRACT

The dominant mechanism affecting the flow behavior of granular materials is the random motions of particles that results from the interactive collisions between particles. The velocity fluctuations induce the segregation in granular flows. The different densities of granular materials with different filling layers and packing ratios were used to investigate the segregation mechanisms in a vibrated granular bed in this study. The image processing techniques were employed to track the motion of granular materials. The fluctuating velocities of granular materials were measured under segregation in a vibrated granular bed. The segregation phenomena depend on the packing ratio and the filling layer of the stainless steel–glass mixtures. At the fewer filling layers, the heavier stainless steel beads migrate to the bottom regions with the lower granular temperature, so the granular temperature plays a significant role on density segregation. For the higher filling layers, the bulk convection motion is the main mechanism affecting segregation, so the heavier beads clump to the convection center and the clump size enlarges with the increasing packing ratio of heavier beads due to the bulk convection motion.

1. Introduction

Granular material is an assembly of discrete solid particles dispersed in an interstitial fluid. Granular material flows have wide applications in industries, such as the transport of coal, ore, plastics, grains, mineral concentrate, sand, powders, food products, and pharmaceuticals. Shakers are important devices to mix and to dry granular materials in industries [1–3]. Jaeger and Nagel [4] presented a good review of the related studies which investigated the phenomena of granular systems under vibration. Shakers are also used to sort granular materials according to particle size in pharmaceutical, powder metallurgy, and food industries. Many studies show that a granular bed can be fluidized and several different kinds of complicated phenomena under external vibration can be generated [5,6]. The size segregation of granular materials is the most interesting phenomenon [7–10].

Many effects cause the segregation of granular materials, for example, the differences in the particle sizes, the particle density, the angle-of-repose of the materials, the shear of granular flow, and the granular temperature gradient [11,12]. There have been two major mechanisms proposed for the segregation phenomenon in a shaker: reorganization [7–9] and convection [13,14]. Knight et al. [10] investigated the flow paths of a larger particle in a vibrated granular bed with many smaller particles. The smaller particles move upward in the container center and move downward in a boundary layer along the side walls. The larger particles move upward with the convective smaller particles flowing towards the free surface close to the walls. They claimed that the convection was the mechanism causing the segregation of granules. The two convection-cell phenomenon in a shaker has been widely studied [15–22]. Hsiau and Chen [17] found that the strength of the convection increased with the increasing vibrational strength. Hsiau et al. [18] investigated the effects of container geometry, wall friction, and vibrational condition on convection cells in a two-dimensional vibrated granular bed. Taguchi [21] studied the convection cells numerically and proposed that they were induced by elastic interaction between the particles. Gallas et al. [22] used a molecular dynamics method to study convection cells in a two-dimensional system. They found that different types of convection cells occurred because of the existence of walls and the vibrational amplitude.

The other possible mechanism causing segregation, particle reorganization, is a result of different sizes of granular materials. The smaller particles easily fall through the voids to the bottom of the bed. The granular materials undergo a transition from a dense (solid-like) state to a dilute (liquid-like) state [23]. During the bed expansion process, the larger voids among particles are formed causing the reorganization of particles and the smaller particles are easier falling down through the voids to the bottom [7,24]. The reorganization mechanism disappears at very low vibrational acceleration since there are not enough relative movements among particles to cause larger voids. When the vibrational acceleration is too high, the voids are so large that the larger particles can also fall down through the voids, therefore there is no segregation phenomenon in the granular bed either. Barker and Metha [24] analyzed the importance of the particle rearrangement mechanism and the

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convective mechanisms. They pointed out that the amplitude, frequency, and acceleration of vibration are important factors to determine the dominant mechanism (reorganization and convection) in the segregation process. However, there are still relatively few literatures investigating the density segregation in a vibrated granular bed.

In this paper, the mixtures of stainless steel and glass spherical beads with different filling layers and packing ratios in a two-dimensional vibrated granular bed were used to investigate the density segregation mechanisms. The image processing techniques were employed to track the motion of granular material. The fluctuating velocity and convection motion of granular materials were measured under density segregation in the vibrated granular bed. The mechanisms of granular temperature and convection motion of density segregation in the vibrated granular bed were discussed. The effects of the totally filling layers and the packing ratios of stainless steel beads in the stainless steel–glass mixtures on density segregation were also discussed in the paper.

2. Experimental setup

The experimental apparatus is illustrated in Fig. 1(a). A Techron VTS-100 electromagnetic vibrational system served as the vertical shaker. The shaker was vertically driven by sinusoidal signals produced by a function generator (Meter Inc. DDS FG-503) through a power amplifier (Techron Mode 5530). The vibrational frequency f and acceleration a were measured by a Dytran 3136A accelerometer fixed at the shaker and connected to an oscilloscope (Tektronix TDS 210). The vibrational radian frequency ω and amplitude r could be calculated from the relations $\omega = 2\pi f$ and $r = a/\omega^2$, respectively. The

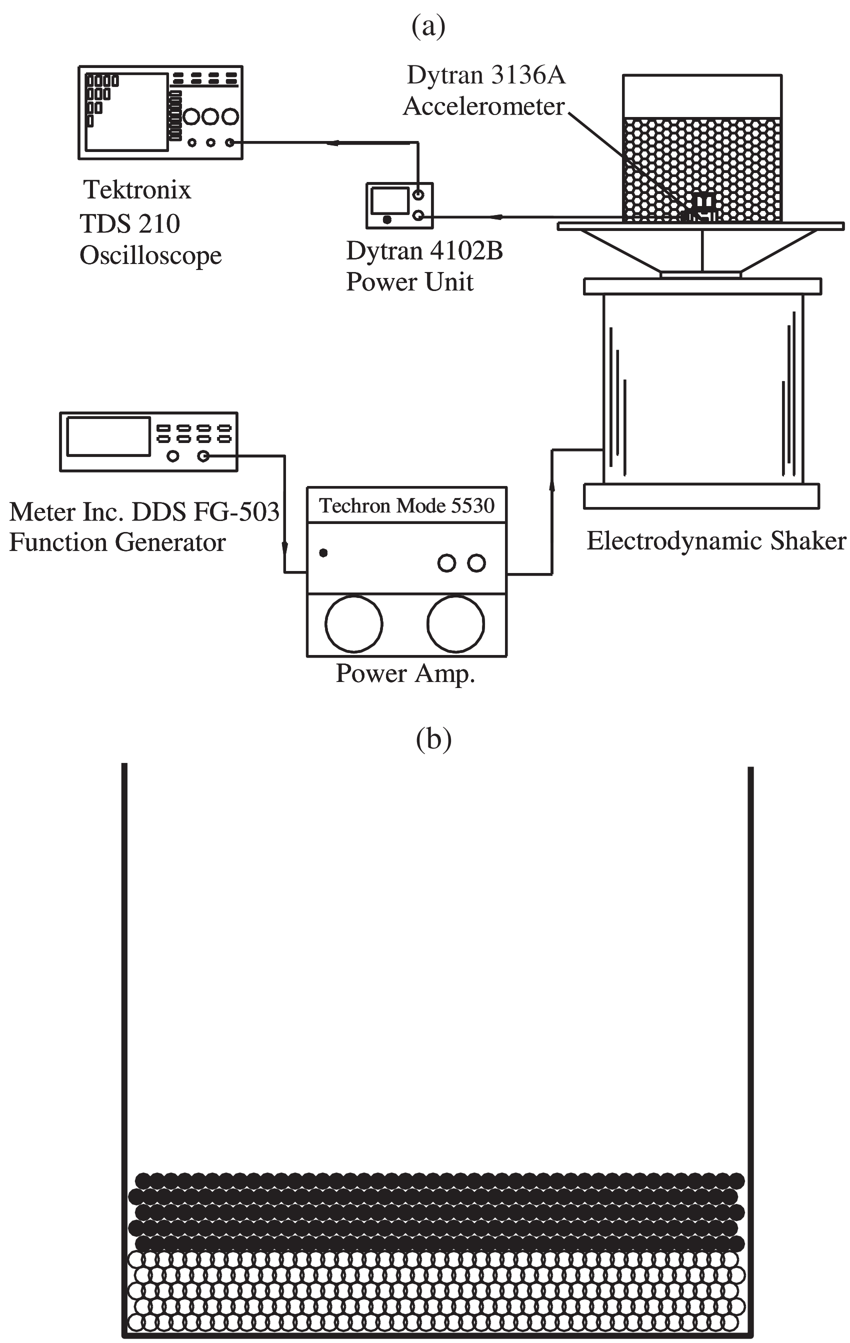

Fig. 1. (a)The schematic drawing of the experimental apparatus and (b) the initial packing state of the stainless steel–glass mixtures, $L = 10$ and $L_S/L = 0.5$: upper region is the stainless steel beads and the lower region is the glass beads.