Powder Technology 286 (2015) 629–635

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Confinement-induced horizontal segregation in a vertically shaken granular bed

Xuejiao Yang [a], Ning Zheng [a,b,*], Pingping Wen [a], Liangsheng Li [c,*], Qingfan Shi [a,*]

[a] School of Physics, Beijing Institute of Technology, Beijing 100081, China
[b] Key Laboratory of Cluster Science of Ministry of Education, Beijing 100081, China
[c] Science and Technology on Electromagnetic Scattering Laboratory, Beijing 100854, China

ARTICLE INFO

Article history:
Received 15 April 2015
Received in revised form 28 August 2015
Accepted 31 August 2015
Available online 2 September 2015

Keywords:
Granular materials
Segregation
Pattern formation
Spatial confinement

ABSTRACT

With appropriate spatial confinement to the upper surface of a vertically shaken granular mixture, an uncommon segregation behavior, horizontal segregation (HS) where two types of particles separate along the horizontal orientation, is found. By quantitatively tuning confined space above the granular bed, we plot different phase diagrams and find a qualitative dissimilarity. In particular, the HS disappears when the effect of confinement becomes weak. Additionally, we gradually evacuate air out of the container, and measure the segregation extent of HS as a function of air pressure. It is found that all the segregation behaviors change to mixed state at a low pressure. We also examine the existence of the HS with different granular mixtures and confinement boundaries. The experimental observation confirms that the formation of the HS depends on the interstitial air and confinement.

1. Introduction

Excited by a vertical vibration, a fluidized granular bed consisting of small and large particles tends to create various segregation patterns, for example, the well-known Brazil nut effect (BNE) [1], the reverse Brazil nut effect (RBNE) [2] and the sandwich pattern (SP) [3]. The fundamental curiosity of these striking behaviors associated with industrial importance has motivated intensive research into granular segregation [4–6]. For these seemingly-simple yet complex phenomena, many mechanisms including convection [7], interstitial medium [8], geometrical mechanism [9], kinetic energy [10], surface friction [11], competition between percolation and condensation [12], etc., have been presented to account for the formation of the segregation patterns. Specifically, the possible mechanisms responsible for the BNE or RBNE include air-drag effects [20], the competition between the percolation and condensation [12], the competition between the buoyancy and geometric forces [21]. To some extent, the latter two competition mechanisms could interrelate with each other. The scaling of the geometric forces suggests that they can be compared to the effective percolation effect. The condensation is driven by the two species having different temperatures. If one equates their driving force due to the condensation tendency with an effective buoyancy force, then the two mechanisms could be equivalent. In the perspective of Trujillo et al., the increased pseudo-thermal buoyancy force can also be related to the presence of the bulk-convective motion [20,21]. Although considerable progress has been made, a unified framework to understand these observations is still lacking. The consensus is to date that a few of these mechanisms are simultaneously responsible for the segregation, each being dominant in different parameter regimes [13,14]. However, these experimental and theoretical studies mainly concentrate on granular materials with a free upper surface.

For a vibrating granular bed with confinement that restricts free space above the bed, most research focuses on the compaction properties or the dynamics of a single species of particle. Mueggenburg experimentally discovered that when a confining force was used to limit the dilation of the granular packings during the vibration, the compaction was greatly reduced. The confinement is thus important for the structural rearrangements and the resulting compaction of the granular system [15]. In addition, confined granular fluids, placed in a vertically shaken shallow box, were used to achieve a homogeneous stationary state in which the hydrodynamic modes were studied [16]. Azéma et al. analyzed the vibrational dynamics of a constrained granular system in response to harmonic forcing, exploring the evolution of the constrained packing in the course of the harmonic loading and its scaling with the loading parameters [17]. By contrast, the studies on the segregation behaviors of a vibrated granular mixture with upper-boundary confinement are still lacking.

In this paper, we first observe an unusual segregation behavior referred to as a horizontal segregation (HS) in a confined, binary granular mixture subjected to a vertical vibration. We introduce a ratio $\chi = d/h_0$ to characterize the extent of the confinement above the granular bed.

* Corresponding authors.
E-mail addresses: ningzheng@bit.edu.cn (N. Zheng), liliangshengbititp@163.com (L. Li), qfshi123@bit.edu.cn (Q. Shi).

http://dx.doi.org/10.1016/j.powtec.2015.08.051
0032-5910/

The gap d is the distance from the bottom of the container to the lower surface of the piston, and h_0 indicates the initial bed height. Only tuning the ratio χ, we can obtain various segregation patterns with other conditions fixed. We also plot and compare phase diagrams of the frequency f vs. the dimensionless acceleration Γ with different confinement, finding a qualitative dissimilarity when the confinement varies. In addition, we examine the existence of the HS with different mixtures and confinement boundaries. Finally, we evacuate the interstitial air in the granular bed, and reconfirm the crucial air effect on the segregation. On the basis of these experimental evidences, we propose a qualitative analysis for the confinement role on the segregation behavior.

2. Experimental setup

The granular mixture that is filled in a rectangular, glass container with a dimension of 40 mm long, 10 mm wide and 50 mm high consists of copper particles of the density 8.38 g/cm^3 and of the diameter 320 $\pm$ 30 μm, and alumina particles of the density 1.65 g/cm^3 and of the diameter 170 $\pm$ 20 μm. The container is attached to an electromechanical shaker which can provide vertical sinusoidal motion, with the ratio of the horizontal vibration amplitude to the vertical vibration amplitude less than 3%, see Fig. 1(a).

The top opening of the container is sealed by a rectangular, aluminum piston, which can be moved freely along the vertical direction through manipulating the piston rod and rotating steel nuts on the rod. The piston is not air-tight, but it contacts the inner wall of the container so close that no particles can leak out during the vibration. The free space above the granular bed can be controlled by the piston, where a gap d, the distance from the container base to the lower surface of the piston is defined (see Fig. 1(b)). The initial height of the granular bed used in our experiment is 0.98 cm. With a fixed height, the smaller the ratio χ is, the stronger the confinement effect is.

Before each experimental realization, the particles filled into the container by a funnel are mixed intimately. Each volume of the granular components, in the proportion 50%:50%, used in the binary mixture is 2 ml for all trials. To eliminate the undesirable influences which disturb the resulting segregation as much as possible, the temperature and humidity are maintained at 25 $\pm$ 1 °C and 50 $\pm$ 5%, respectively. An antielectrostatic surfactant is sprayed on the inner wall of the container uniformly to minimize the side-effect from the accumulation of electrostatic charges. Additionally, every 20 min a fresh mixture replaces the used sample to avoid possible charges buildup and particles fragmentation.

After all experimental conditions have been well prepared, we control the shaker to vibrate at the various frequencies f, from 20 to 200 Hz, and acceleration strength Γ, from 2 to 20. The frequency f and the dimensionless acceleration $\Gamma = A\omega^2/g$ generally act as control parameters, where ω is the angular frequency of the vibration, A is the vibration amplitude, and g is the gravity acceleration. During the vibration, the piston is fixed. We record each stable spatial configuration of the granular bed by a high-resolution digital camera. It is considered stable only if the patterns maintain 5 min or longer at given conditions.

To obtain the phase diagram which describes the different configurations of the vibrating granular bed, we manually scan the vibrating frequency and dimensionless acceleration. Namely, we start from a fixed frequency and dimensionless acceleration. After the spatial configuration of the granular bed reaches stability, we determine the configuration by a visual inspection. Then, we reset the status to mixed state, and vibrate the granular bed with the same frequency and increasing dimensionless acceleration. The stable configuration of the granular bed is recorded once again. If the configuration is similar with the last one, we continue to increase the acceleration, until a new segregation status is found. Then we decrease the acceleration to an appropriate value, where the configuration is very difficult to be distinguished from two types of configurations. We choose this vibration condition as the dot on the boundary. After examining all dimensionless accelerations at the fixed frequency, we adopt another neighboring frequency and repeat the procedure. In this way, we can find a rough boundary of different regions. After finishing the manual scan, sometimes we examine more vibration status near the rough boundary to find more dots to make the boundary smooth.

3. Results and discussions

To investigate the effect of the confinement on granular segregation patterns, $f-\Gamma$ phase diagrams are obtained with different ratios χ, as shown in Fig. 2. At first when $\chi = \infty$, namely the piston is removed, the phase diagram is shown in Fig. 2(a). At the low frequency region,

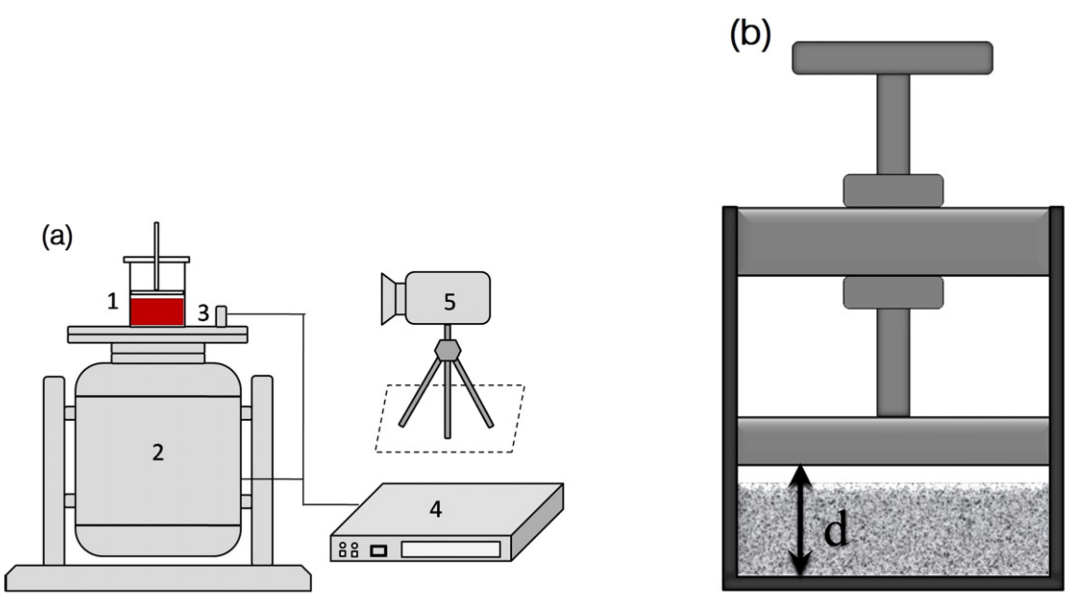

Fig. 1. (Color online) (a) Schematic of the experimental setup, not to scale. (1) Rectangular glass container sealed by a rigid piston, (2) shaker, (3) feedback sensor, (4) vibration controller, (5) digital camcorder. (b) The design details of the sealed container are shown. A rigid, rectangular piston is used to confine the free space above the granular bed. Here a ratio $\chi = d/h_0$ to characterize the extent of the confinement above the granular bed is defined, d, namely the distance from the bottom of the container to the lower surface of the piston, h_0, the initial bed height. The position of the piston can be adjusted freely through the rod and steel nuts on the rod. When an appropriate distance is acquired, the two nuts are tightened to fasten the piston. Thus the piston is motionless relative to the container during the vibration.