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Segregation patterns in binary granular mixtures with same layer-thickness under vertical vibration

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ABSTRACT

Inspired by the theoretical prediction [Phys. Rev. Lett. 86, 3423 (2001)] and the disputed experimental results [Phys. Rev. Lett. 89, 189601(2002), Phys. Rev. Lett. 90, 014302 (2003)] about the problem of granular segregation, we systematically investigate the pattern of binary granular mixtures consisting of same layer-thickness under vertical vibration. Various kinds of mixtures with different diameters and densities particles are poured into the glass cylinder that is sealed and evacuated to an air pressure less than 50 Pa to observe separation patterns. It is found that these granular mixtures behave like five kinds of segregation patterns for different driving control parameters, i.e., Brazil nut (BN), reversed Brazil nut (RBN), Mixed states, light-BN (LBN), and light-RBN (LRBN). The latter two regimes are neither purely segregated nor completely mixed states. Moreover, BN phenomenon takes place in the area of low density ratio and found to be independent of layer-thickness, while RBN is sensitive to both the layer-thickness and frequency and occurs at the large density ratio area. Our result may be helpful for the establishment of theory about the segregation and mixing of granular mixtures.

1. Introduction

It is well known that, segregation of granular mixtures of different sizes is a common occurrence. When a particle mixture is shaken vertically or jostled, larger particles generally rise to form a layer on the top while the smaller particles filter down to form a layer on the bottom, known as the Brazil nut segregation (BN). Since this phenomenon has a bearing on many industrial processes such as mineral processing, powder metallurgy, transportation, pharmaceutical production, food manufacturing, and concrete mixing, etc. [1–3], it has been an attractive area of research in the past eighty decades. In addition to engineering applications, the mechanism of separation is also an important concern to researchers. The most commonly quoted two models are: (1) the larger particles are pushed to top by the smaller particles which fall into the underneath voids during each shaking cycle [4–7], and (2) global convection drives the larger ones to the top of mixture whereas small ones tend to sink to the bottom [8,9]. The other researches stated that, arching [10], inertia [11,12], buoyancy [13], friction [14], pressure [15], density drive [16–19] are also crucial elements in explaining BN. For further reveal the puzzle of mixture segregation, Hong et al. proposed a competition mechanism between the percolation and the condensation of particles under two important conditions: *same layer-thickness* and *intermediate granular temperature*. Here, the same layer-thickness represents the same number of layers for two species in binary mixture, and the intermediate temperature means that the system temperature is in a state between two critical temperatures of two species. According to Hong's definition, a granular temperature signifies to the exciting degree of a system in analogy to a gas, and the critical temperature is a distinguish point below which a monodisperse system of hard spheres is in a condensation state while above it the system is in a fluidization state [20]. Consequently, they predicted the crossover transition from BN to RBN where the large particles sink to the bottom and the smaller ones appear to the top in a binary system as the following [21]

$$\frac{\rho_L}{\rho_S} \approx \frac{d_S}{d_L}, \tag{1}$$

where d_L, d_S, ρ_L, ρ_S are the diameter and the density of large and small particles, respectively. If the density ratio is smaller than the inverse of the diameter ratio the system should behave RBN and vice versa. From then on, the occurrence condition of RBN began to face the challenges. Breu et al. [21] claimed that 82% of experimental data confirm this prediction by deliberately adjusting the amplitude and frequency

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of vertical vibration. However, two crucial conditions of *same layer-thickness* and *intermediate temperature* were not measured directly and therefore no definite conclusion can be drawn from their published data [22,27]. On the other hand, the other studies could not verify this prediction experimentally [23,24] and numerically [14]. For example, Canul-Chay et al. did not find evidence of RBN although they carried out many experiments according to Hong's two main conditions. In fact, when the granular bed is motivated, a temperature gradient exists along the vertical direction due to gravity [23], i.e., the particles at bottom get highest temperature while the top ones get lowest. Therefore, an intermediate granular temperature for the binary mixture is difficult to attain experimentally. These previous results inspire us, if we run a new experiment for the binary mixture consisting of same layer-thickness by deliberately adjusting the parameters of vertical vibration such as amplitude and frequency, what segregation patterns can be observed?

In this paper, we focus on the investigation of behaviors of same layer-thickness system by deliberately controlling the dimensionless acceleration and frequency, and using wide range of densities of particles. We expect that the present results could be helpful for establishing new segregation model of binary mixtures. In addition, better understanding of segregation conditions helps make it possible to tune, avoid or invert the segregation patterns of granules.

2. Experimental setup

A vertical vibration system is used to investigate the segregation of the binary mixtures. The container is a glass cylindrical cell of inner diameter 45 mm and height 150 mm, which is vertically placed and fixed on a machined flat copper substrate. This flat substrate is supported on the horizontal surface of an electromechanical shaker (JZK-60 T) which moves vertically with the ratio of the horizontal to the vertical vibration amplitude less than 5%. The vertical displacement function is $A\sin(2\pi ft)$, where A and f are the amplitude and frequency of the vibration, respectively. In general, vibration frequency f and dimensionless acceleration amplitude $\Gamma = 4\pi^2 Af^2/g$ are used as control parameters, where g is the acceleration of gravity. Our experimental apparatus can work in the range of acceleration Γ from 1.0 to 8.0 and range of frequency f from 10 to 100 Hz. Some previous works have shown that the air in the container may play complicated roles in the segregation process [15,25]. To eliminate the influence of air effectively, the container is sealed and evacuated by a mechanical pump to an air pressure below 50 Pa [26]. The particles used are the beads with different densities and sizes of granules (see Table 1). Their densities are ranging from 1.30 to 18.0 g/cm^3, and the diameters range from 0.25–3.00 mm that means there are several diameters of particles in this range. For example, there are 0.25, 0.38, 0.43, 0.48, 0.55, 1.05, 1.35, 1.57, 1.84, 2.20, 2.65 and 3.00 mm diameters of aluminum oxide particles. In addition, in order to reduce the accumulation of static charge, beads are well stirred before they were poured into the glass cylinder. In the experiments, we initially arrange the two granular species to an appropriate

Table 1
Granular particles used in experiments.

Material	Density (g/cm^3) ρ	Diameter (mm) d
Aluminum oxide	1.3	0.25–3.00
Magnesium	1.7	0.32–0.70
Glass	2.5	0.25–3.00
Zirconium oxide	2.9	0.25–1.13
Zirconium silicate	3.8	0.25–1.13
Titanium alloy	4.5	0.32–0.70
Ferrous alloy	7.4	0.25–0.70
Cobalt-chromium-molybdenum alloy	8.4	0.25–1.13
Copper	8.7	0.25–0.43
Tungsten alloy 1	13.8	0.55
Tungsten alloy 2	18.0	0.32–0.70

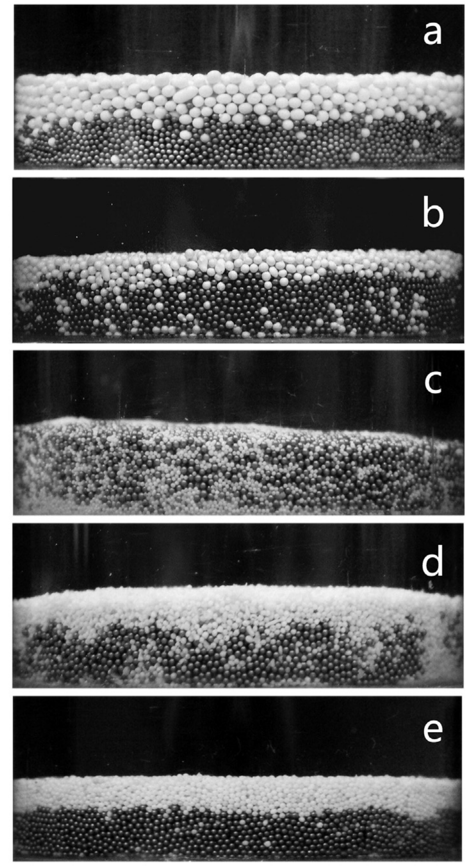

Fig. 1. Five kinds of segregated patterns: (a) BN, 1.12 mm Zirconium silicate and 0.55 mm Cobalt-chromium-molybdenum alloy; (b) LBN, 0.76 mm Zirconium silicate and 0.55 mm Cobalt-chromium-molybdenum alloy; (c) Mixed, 0.55 mm Cobalt-chromium-molybdenum alloy and 0.32 mm Aluminum oxide; (d) LRBN, 0.55 mm Cobalt-chromium-molybdenum alloy and 0.425 mm Aluminum oxide; (e) RBN, 0.55 mm Cobalt-chromium-molybdenum alloy and 0.475 mm Aluminum oxide.

layer-thickness, so as to avoid the BN or RBN phenomenon being completely destroyed. The experiment starts by the first stirring of the particles in the binary mixtures randomly. The container of the mixture is then vertically vibrated at fixed values of Γ and f. The value Γ of each experiments change by steps of $\Delta\Gamma = 0.1$. In each run, we monitor

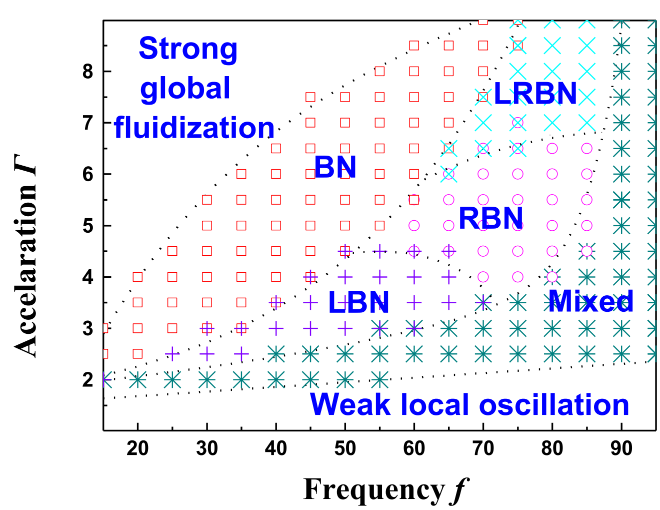

Fig. 2. Segregation patterns of the particles for different controlling parameters of the shaker. The binary mixture used consists of 0.24 mm Copper and 0.16 mm glass beads with the same layer-thickness. Lines are drawn to help guiding the eye.