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Experimental study of segregation patterns in binary granular mixtures under vertical vibration

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Abstract We report the experimental observations of the segregation patterns in initially well mixed copper and glass spheres subjected to a vertical sinusoidal vibration at different values of acceleration Γ and frequency f. A segregation phase diagram is obtained, which includes Brazil nut (BN), Reversed-BN (RBN) and sandwich segregation patterns at different Γ and f. The stable RBN segregation is experimentally found for the first time, in which large heavy particles move down to the bottom and form the lower-layer while small particles rise to the top and form an upper-layer. The boundary values (Γ, f), which separate regions of different patterns, depend on system's initial condition, i.e. hysteresis exists.

Keywords: granular matter, reversed Brazil nut (RBN), vibration, sandwich.

Segregation and mixing of granular materials of different sizes are of much concern in many industrial pro- cesses such as powder metallurgy, fertilizer and drug manufacturing, transportation, glass and concrete production, etc.[1—3]. When granular mixtures are vibrated 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 effect [4—11], a phenomenon resulting from percolation, geometrical reorganization, and global convection. Recently, the existence of other possible configurations has attracted much attention[12—15]1). Better understanding of particle segregation helps make it possible to tune, avoid or invert the segregation patterns of granules under different conditions. Recently, Hong et al. predicted conditions of the existence of the reversed Brazil nut (RBN) segregation by considering competition between the percolation effect and the condensation of particles[12]. With proper size and mass ratios of the two different particles, for example, $(d_A/d_B)^2 \leqslant m_A/m_B$ for a 3-dimensional system (d_A(d_B) is the diameter of particle A (B), and m_A(m_B) is the mass of particle A (B)), RBNS can possibly be formed. However, so far, to our knowledge, no experimental observation has yet been reported.

In this study we report our experimental observations on segregation patterns in initially uniformly mixed copper and glass spheres subjected to a vertical sinusoidal vibration at different values of acceleration Γ and driving frequency f ($\Gamma = 4\pi^2 f^2 A/g$, where Γ is a dimensionless acceleration amplitude, A the amplitude of the sinusoidal vibration, and g the gravitational acceleration). A segregation phase diagram (in the range of $1.0 \leqslant \Gamma \leqslant 7.0$ and 18 Hz $\leqslant f \leqslant$ 80 Hz) is obtained, which includes BN, RBN, and sandwich patterns (in Fig. 1 as regions of A/B, D and C, respectively). For the first time, stable RBN, in which large heavy particles move down to the bottom and form the lower-layer while small particles rise to the top and form an upper-layer, is observed. It is interesting to find a pattern of stripes on the top copper surface of the two-layer BN structure in region B as shown in the figure. The pattern is similar to that observed on a monodisperse granule system in vertical vibration[13], but the stripe pattern in the two-layer system is subject to higher Γ values. Another important feature observed is the hysteresis effect: the critical values of Γ that separate regions of different patterns are lower when the system is initially transformed from sandwich to BN pattern than for the transition from BN to sandwich pattern. This lower boundary line is shown in dotted line as Γ_1. The hysteresis also exists at the boundary which separates the RBN and sandwich patterns. The line shifts lower when the mixture transforms from RBN to sandwich (Γ_2) than from sandwich to BN pattern.

The binary mixture consists of larger copper spheres of diameter $d_A = 0.25 \pm 0.03$ mm with volume V = 4 mL and layer depth μ_A (in unit of d_A) ≈ 16, which is mixed uniformly with glass spheres of diameter $d_B = 0.12 \pm 0.02$ mm with the same volume V = 4 mL and layer depth μ_B (in unit of d_B) ≈ 32. The diameter ratio d_A/d_B is about 2 and the mass ratio m_A/m_B about 23. The container is a cylindrical glass cell of inner diameter 36 mm and height 150 mm, which is vertically placed and fixed on a machined flat copper substrate. This flat substrate is installed on an electromagnetic vibration exciter (JZK-60T), which is driven by a frequency synthesizer (10—100 Hz) and a power amplifier (1—800 W). The amplitude of sinusoidal acceleration is measured by an accelerometer. The entire apparatus is mounted on a horizontally leveled heavy base. The horizontal acceleration component compared to that of the vertical is less than 5%. The experimental Γ and f are in the range of 1.0—7.0 for Γ and 18—80 Hz for f.

1) Jiang, Z. et al., Sandwich segregation pattern in vibrational granular mixture, Acta Phys. Sin. (in Chinese), 2003.

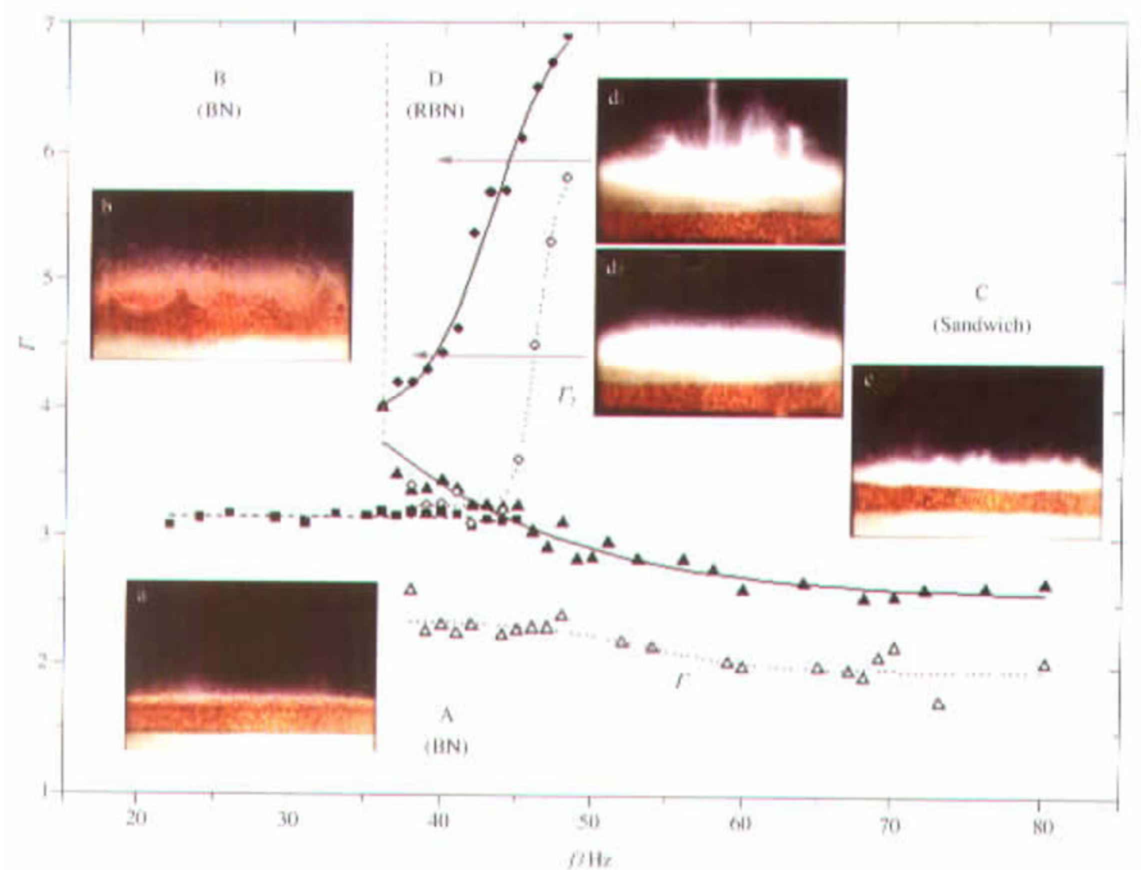

Fig. 1. Phase diagram shows various phenomena observed at different control conditions of Γ and f, and photographs taken after 1 h of vibration corresponding to the regions of this phase diagram. The lines on the data points are drawn to guide the eye. A, Region of Brazil nut (BN) segregation. Photo a is taken at Γ = 2.50 and f = 52 Hz; B, region of BN segregation. Photo b is taken at Γ = 4.10 and f = 28 Hz; C, sandwich segregation pattern. Photo c is taken at Γ = 5.20 and f = 46 Hz; D, RBN segregation region. Photo d_1 is taken at Γ = 4.30 and f = 42 Hz, where dancing localized excitation appears; Photo d_2 is taken at Γ = 5.10 and f = 42 Hz.

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 experimental run changes by steps of $\Delta\Gamma = 0.1$. In each run we monitor the pattern for at least half an hour and record the Γ and f of each steady pattern. In order to avoid the electrostatic effect, the environmental humidity is kept at (52±3)%.

Different segregation patterns are observed at various Γ and f. The phase diagram and photos of patterns in each regime are shown in the Fig. 1 as 4 regions A, B, C and D. In region A ($\Gamma \leqslant 3.2$), heaping and tilting appear soon after vibration is initiated, and separation of the binary mixture gradually occurs. When separation is attained, the upper copper-layer and the lower glass-layer are always well separated with a clear parting line; i.e. we do not find copper spheres in the glass layer and there are no glass spheres in the copper layer either. This parting line tilts at low Γ. There is a tendency that the higher the oscillation frequency, the longer the segregation process takes. As the value of Γ increases at a fixed frequency in region A, the tilting angle of the upper surface decreases. Photo a shows the image of Brazil nut segregation of the binary mixtures in region A of figure, where the larger particles rise and form an upper layer while smaller glass spheres filter down to form a lower layer at the bottom.

When $\Gamma \geqslant 3.0$, depending on the oscillation frequency, the segregation exhibits different phases which are indicated as regions B, C and D in the figure. In region B ($f < 36$ Hz and $\Gamma \geqslant 3.0$), the upper copper-layer particles fluidize and move up and down violently with pattern of stripes on the surface of the top layer. Meanwhile, there appears unstable and the wave moves at the interface between the upper copper-layer and lower glass-layer. Photo b is a side-view image of the pattern in region B. When Γ increases, the motion of the top surface of the copper-layer becomes so violent that the pattern of stripes gradually disappears into the strong turbulent movement.

When frequency is in the range of 36 Hz $<$ f $<$ 50 Hz, the RBN segregation takes place and is shown in the figure as region D. In this region, when $\Gamma < 4.5$, the mixture of particles initially forms an incomplete RBN pattern with a few small particles remaining at the bottom. These particles at the bottom gain kinetic energy from the oscillation and explode to the top, forming dancing oscillating localized excitation [14]. This dancing localized excitation lasts until all the small particles move to the upper-layer, and steady RBNs are achieved (see photo d_2). When $\Gamma \geqslant 4.5$, the dancing localized excitation stays at the top layer and never disappears as shown in photo d_1.

As frequency is higher than 36 Hz, another kind of segregation pattern, the copper grains sandwiched between top and bottom glass-layers, appears in region C of the figure, and the pattern is shown in photo c. In this region two different kinds of sandwich -forming processes are observed[1)]: (ⅰ) As the oscillation is initiated, BNS is first formed in one or two seconds with the lower glass-layer tilted. After some time, part of the glass particles in the tilted lower glass-layer rolls over from one side of the cell, and forms a top layer with part of the glass particles remaining at the bottom layer. (ⅱ) Another observed process is that sandwich of a copper-layer between two glass layers is formed through motion of clusters of small glass particles from top to bottom by the percolation effect and excitation of particles from bottom to top due to fluidization.

Once the sandwich is formed, it maintains a dynamic balance. At a higher Γ value, the dancing localized excitation can also be seen on the top surface of the upper glass-layer, similar to what observed in region D. However, the excitation amplitude is much smaller.

It must be noted that the boundaries that separate the four regions of the segregation patterns in phase diagram can not be well determined due to the experimental conditions and the complexity of granular properties. The boundary line between regions B and D can be determined within ± 1 Hz of the dotted line. It shall be noticed that once an RBN or sandwich pattern is obtained, it will remain even when Γ is changed to a value below the boundary lines. The new boundary lines are drawn in the figure as Γ_1 and Γ_2. This hysteresis effect strongly suggests that the observed RBN and sandwich patterns are stable. Segregation phenomena are related to many factors; for example, the interstitial air pressure and the size, mass, volume and surface properties of granules. All these factors will shift Γ and f boundary lines of the phase regions.

In summary, a phase diagram of segregation patterns in a mixture of glass and copper particles under vertical vibration of different Γ and f is obtained, in which the pattern of reversed Brazil nut segregation is experimentally observed for the first time. Depending upon system s initial condition, the boundary values of Γ shift. The hysteresis effect is shown to exist. A full understanding of the segregation mechanisms is still awaiting due to the complexity of granular properties. Our results show that the segregation conditions of the observed phenomena do not fully agree with Hong et al. s prediction. Further experimental and theoretical studies are needed for the explanation of the formation mechanisms of the above observed segregation patterns.

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References

1. Jaeger, H. M., Nagel, S. R., Behringer, R. P., Granular solids, Liquids, and gases, Rev. Mod. Phys., 1996, 68(4): 1259—1273.
2. De Gennes, P. G., Granular Matter: A tentative view, Rev. Mod. Phys., 1999, 71(2): S374—S381.
3. Kadanoff, L. P., Built upon sand: Theoretical ideas inspired by granular flows, Rev. Mod. Phys., 1999, 71(1): 435—443.
4. Williams, J. C., The segregation of particulate materials, Powder Technol., 1976, 15: 245—251.
5. Rosato, A., Prinz, F., Strandburg, K. J. et al., Why the Brazil nuts are on top: Size segregation of particulate matter by shaking, Phys. Rev. Lett., 1987, 58(10): 1038—1040.
6. Julliem, R., Meakin, P., Three-dimensional model for particle-size segregation by shaking, Phys. Rev. Lett., 1992, 69(4): 640—643.
7. Duran, J., Rajchenbach, J., Clenment, E., Arching effect model for particle size segregation, Phys. Rev. Lett., 1993, 70(16): 2431—2434.
8. Knight, J. B., Jaeger, H. M., Nagel, S., Vibration-induced size segregation in granular media: The convection connection, Phys. Rev. E, 1993, 70(24): 3728—3731.
9. Cooke, W., Warr, S., Huntley, J. M. et al., Particle size segregation in a two-dimensinal bed undergoing vertical vibration, Phys. Rev. E, 1996, 53(3): 2812—2822.
10. Julliem, R., Meakin, P., Pavlovitch, A., Three-dimensional model for particle-size segregation by shaking, Phys. Rev. Lett., 1992, 69(4): 640—642.
11. Herrmann, H. J., Hovi, J. P., Luding, S., Physics of Dry Granular Media, Dordrecht/Boston/Londen: Kluwer Academic Publishers, 1998, 553—703.
12. Hong, D. C., Quinn, P. V., Luding, S., Reverse Brazil nut problem: Competition between percolation and condensation, Phys Rev Lett., 2001, 86(15): 3423—3426.
13. Bizon, C., Shattuck, M. D., Swift, J. B. et al., Patterns in 3D vertically oscillated granular layers: Simulation and experiment, Phys. Rev. Lett., 1998, 80(1): 57—60.
14. Masaharu, I., Bifurcations of a driven granular system under gravity, Phys. Rev. E, 2001, 64(3): 031304-1—031304-14.
15. Burtally, N., King, P. J., Swift, M. R, Spontaneous air-driven separation in vertically vibrated fine granular mixtures, Science, 2002, 295(3): 1877—1879.

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1) See footnote 1) on page of 627.