Effects of Air on the Segregation of Particles in a Shaken Granular Bed

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Effects of interstitial air on the motions of a large intruder in a shaken granular bed are studied experimentally as a function of ambient air pressure, particle size of the bed, and the density of the intruder. It is found that the intruder always rises from the granular bed in the absence of air. However, the intruder can acquire both positive and negative buoyancy in the presence of air. Negative buoyancy can be observed only when both the density of the intruder and the particle size of the bed are small enough. This negative buoyancy can be explained by the unusual air pressure distribution found in the bed.

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Granular materials are ubiquitous and their dynamics are of central importance to many industrial processes. A remarkable and important property of these materials is that particles of different kinds often have a tendency to segregate. A well-known example of this segregation is the so-called ”Brazil nut effect” (BNE) [1–3] in which large particles are seen to rise to the top when a mixture of particles is shaken in a container. The BNE has been documented since at least 1939 [4] and has recently become the subject of intense studies [5–8]. At present, the most commonly quoted model is that the ascent of the larger particle is explained as the falling of smaller particles into the voids produced underneath the larger particle after each shaking cycle [2,9]. While the fundamental mechanism of the BNE is still controversial, a new phenomenon known as the reversed BNE (RBNE) [10] is recently reported in which the direction of the motion of the large particles is reversed.

One of the main difficulties in the understanding of the segregation process of granular materials is that nonlocal structure can be induced by the nonlinear interactions of the particles with the interstitial air under vibrations. It has been known that vibrations can induce convection flow in granular material [11–14] in the presence of air, and the existence of this flow has complicated the explanations of complex segregation phenomena observed. Up to date, there is still no general consensus [15,16] on the basic mechanism responsible for these air-driven effects.

The effects of air in a vibrating granular bed can be intriguing [17]. In an experiment [15] to measure the rise time T_r of a large sphere (intruder) in a vibrating granular bed, a peak in T_r is found when the density ratio of the intruder and the beads are systematically varied. There is a critical density ratio at which the upward motion of the intruder is slowest. This phenomenon is not sensitive to the variations in shaking parameters, background media, and system size. The peak, however, is sensitive to the background air pressure, P, in the cylinder. These observations indicate an intricate interplay among vibration-induced convections, dragged by interstitial air and intruder motions.

Currently there are still no satisfactory unified explanations for RBNE (reverse buoyancy) and the peak in T_r discussed above. The only consensus is that interstitial air is important. In this Letter, we report the results of our experimental investigation on the effects of interstitial air to the motion of the intruder ball in a vibrating granular bed. The air pressure distribution in the bed is measured. It is found that the intruder can acquire both positive or negative buoyancy in the presence of interstitial air. Negative buoyancy can be observed only when both the density of the intruder and the bead size of the bed are small enough. This negative buoyancy can be explained by the unusual air pressure distribution found in the bed.

The granular beds used in the experiments reported below consist of a hollow glass cylinder with an inner diameter (D) of 55 mm, which is filled with glass or steel beads of diameter d to a height H. The bottom of the glass cylinder is made of copper to facilitate the conduction of static electricity. This copper base is supported on the horizontal surface of an electromagnetic vibration exciter which can be driven to move vertically with a displacement $A\sin(2\pi f t)$, where A and f are the amplitude and frequency of the vibration, respectively. Our control parameters are f and the dimensionless acceleration amplitude $\Gamma = 4\pi^2 A f^2 g^{-1}$, where g is the acceleration due to gravity. The amplitude Γ is measured by an accelerometer. The entire apparatus is mounted on a horizontally leveled heavy base. In all experiments reported below, f is fixed at 30 Hz [18]. Diameters of the glass beads used in the experiments are 0.12 ± 0.02, 0.17 ± 0.01, 0.20 ± 0.02, 0.25 ± 0.03, and 0.70 ± 0.10 mm. Those of the steel beads are 0.19 ± 0.03 and 0.29 ± 0.07 mm.

Intruders of size D with various densities are fabricated from hollow bronze spheres of different shell thickness and hollow bronze spheres filled with different materials such as lead, copper powder, wax, plastic, glass powder, cotton, and tin. In our experiments, the density ratio $\chi \equiv \frac{\rho}{\rho_m}$ varies from 0.17 to 4.20, where ρ is the density of the intruder and ρ_m is the density of glass beads.

In order to reduce the accumulation of static charge, beads are kept in a metallic container and well stirred before they are poured into the glass cylinder. We initiate the experiment by first shaking the bed for 10 s to ensure thorough compaction of the bed. An intruder is then carefully introduced into the bed at a height h measured from the bottom of the bed. The intruder can be driven to rise or sink by the vibrations of the bed. Rise time and sink time of the intruder are then defined as the time taken for the intruder to reach the top and the bottom of the bed, respectively, after the vibration of the bed is switched on. Motions of the intruder can be tracked easily if the intruder is placed next to the transparent wall of the bed. However, difficulties arise when the intruder is placed along the axis of the cylinder because of the opacity of the bed. In such a case, rise time can still be easily measured as the intruder will be visible when it reaches the top.

To measure the sink time for intruders placed along the axis of the cylinder, a cotton thread (mass < 0.05 g and diameter < 20 μm) is stuck to the intruder to monitor the motion of the intruder in the opaque bed. Effects of the thread on the motion of the intruder have been checked by measuring the sink time and rise time of the intruders placed at various distances from the wall of the bed with and without the thread. It is found that the presence of the thread does not change the direction of the motion, but its presence usually slows down the intruder. Furthermore, both the sinking and rising motions of the intruder are not induced by convections of the bed because the direction of the motion of the intruder never reverses when the intruder is placed at a different distance from the axis of the cylinder. Thus, we conclude that motions of the intruder in the bed can be characterized by its motion next to the wall. Results reported below are the sink and rise times measured with the intruder placed next to the wall unless otherwise noted. All the data points reported are averages over ten measurements.

As mentioned above, the intruder can be driven to rise or sink in the granular bed. It is found that the its rise or sink time is a function of the density ratio χ. Figure 1 shows this dependence for an experiment performed at $\Gamma = 3.0$, $\rho_m = 2.5$ g/cm^3, $H = 60$ mm, $h = 30$ mm, $D = 9.0$ mm, and $d = (0.12 \pm 0.02)$ mm. One remarkable feature of the figure is that there seems to be a critical ratio χ_c at which the motion of the intruder stops. For $\chi > \chi_c$ the intruder rises to the top as usually reported [1–3]. However, when χ is less than χ_c, the intruder sinks to the bottom and stays there permanently. This latter phenomenon is known as the RBNE or reverse buoyancy [10]. One can see that both the rise time T_r and sink time T_s diverge at χ_c as if neutral buoyancy is achieved for the intruder. Experiments similar to those shown in Fig. 1 have also been repeated with different bead sizes of the bed to see if the critical density ratio χ_c found in Fig. 1 is a universal characteristic of the granular bed.

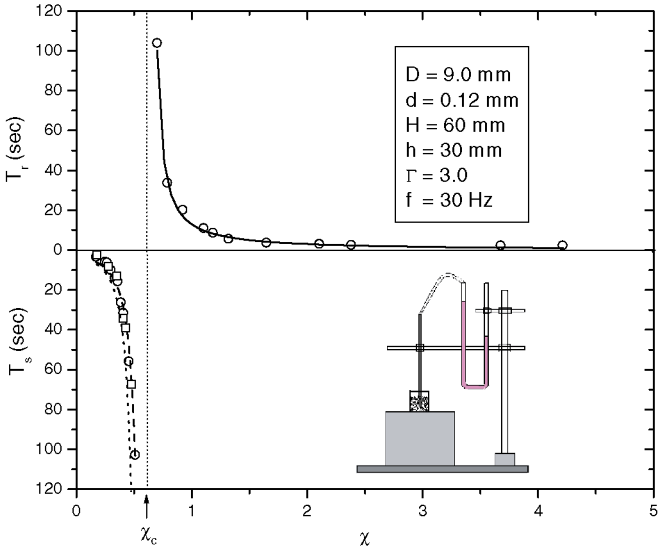

FIG. 1 (color online). The rise (sink) time of an intruder of density ρ diameter $D = 9.0$ mm in a glass bed ($\rho_m = 2.5$ g ml^{-1} and $d = 0.12 \pm 0.02$ mm) as a function of $\chi (\equiv \frac{\rho}{\rho_m})$ under a vibration of $\Gamma = 3.0$ and $f = 30$ Hz. The intruder is first placed at a height of 30 mm from the bottom of the bed. Also shown are the fits of the rise time to $T_r \propto (\chi - \chi_c)^{-1.0 \pm 0.1}$ (solid line), and sink time of the intruder measured near the wall to $T_s \propto (\chi - \chi_c)^{-2.3 \pm 0.9}$ (broken line) and that measured along the axis to $T_s \propto (\chi - \chi_c)^{-2.7 \pm 1.0}$ (dotted line). The critical density $\chi = \chi_c$ is marked by the vertical dotted line. Note that an unusual arrangement of the vertical axis is used to display T_r and T_s. The inset is a schematic of the setup used to measure the interstitial air pressure.

Figure 2(a) [Fig. 2(b)] shows the measured results of rise (sink) time of intruders in beds of glass beads of $d = 0.12$, 0.17, 0.20, and 0.25 mm at the same $\Gamma = 5.8$ when $h = 0$ mm ($h = 40$ mm) with $\chi > \chi_c$ ($\chi < \chi_c$). From Fig. 2(b), it can be seen that all the data from beads with size smaller than 0.25 mm lie more or less on a line similar to that shown in Fig. 1. The obvious deviation of data from 0.25 mm beads is probably due to the fact that when the size (inertia) of the beads increases, the effects of interstitial air will become less important. For example, RBNE cannot be observed in the previous experiment [15] where the bead size of 0.5 mm is used.

It is clear that the rise time for these beds all diverge at χ_c and that the RBNE shown in Fig. 1 is not sensitive to Γ and d as long as $\Gamma > 2.5$ and $d < 0.30$ mm. This suggests that the bed needs to be strongly fluidized for RBNE.

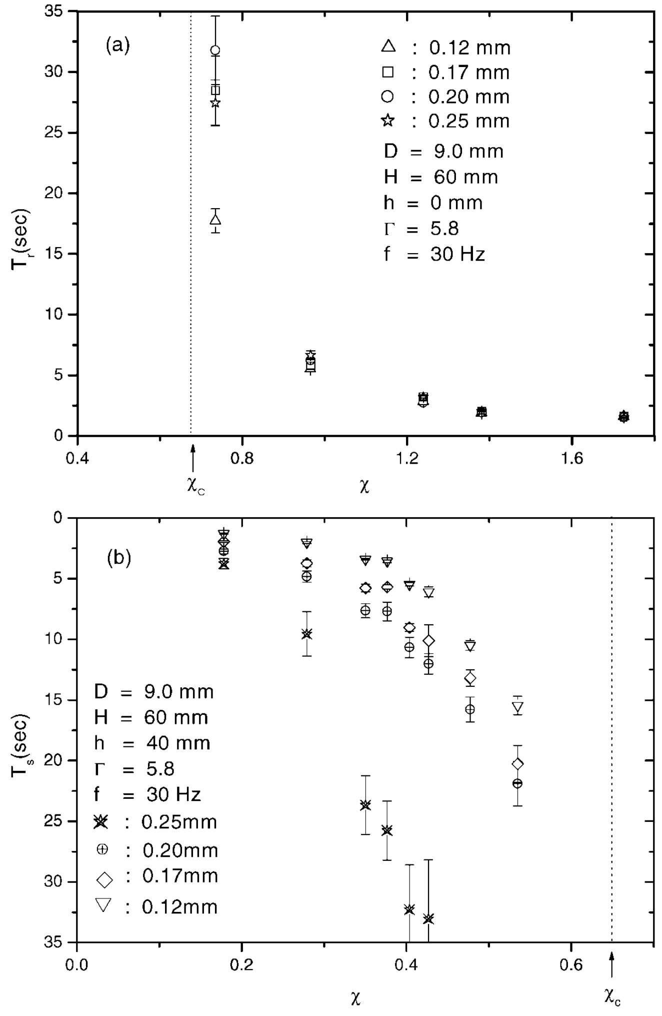

FIG. 2. (a) Density dependence of rise time for various bead sizes at $\Gamma = 5.8$. Initial positions of the intruder are at the bottom near the axis of the bed. The vertical dotted line shows the density χ_c at which all the measured rise times diverge. (b) The sink time of intruders with density $\chi < \chi_c$ in the bed conditions same as (a).

Obviously, χ_c is an important characteristic of the fluidized bed. Since the underlying fluid plays an important role in the characteristics of a fluidized bed, the presence of interstitial air in RBNE should also be important. To check this point, we have also performed experiments in an environment with reduced air pressure (0.1 atm) and find that RBNE disappears. We thus confirm that the interstitial air pressure plays an essential role in our system.

The phenomenon shown in Fig. 1 is very similar to the motion of a sphere of density ρ and radius a being placed in a viscous fluid medium with density ρ_c. When the motion of the sphere is dominated by the viscous force, the rise time or sink time is given by $T \propto a^{-2}(\rho - \rho_c)^{-1}$. However, the direction of the motion of the sphere is the opposite of that shown in Fig. 1. For the case of a fluid, the pressure induced by gravity will decrease linearly with the distance from the bottom of the container. If the same analogy can be applied to our observations in Fig. 1, the pressure induced in the beds by the vibrations will increase with the distance from the bottom of the fluidized bed in our experiment. Since interstitial air is needed to produce RBNE, it is very likely that the pressure gradient in the beds comes from the interstitial air. To check the existence of such a pressure gradient, a pressure probe consisting of a glass tube (diameter $= 3.0$ mm) is inserted into the beds to measure the air pressure at a different height from the bottom of the bed (the setup is shown in the inset of Fig. 1). The end of the probe in the bed is covered by a piece of cloth (mesh size ~ 0.10 mm) to prevent the beads from entering the tube. A U-shaped tube filled with water is connected to the pressure probe to measure the difference between the pressure inside the bed and that of the atmosphere. Pressure distribution along the axis is measured and shown in Fig. 3. It is found that air pressure inside the bed is lower due to the vibration and the pressure is at its lowest at the bottom of the bed. The drop in pressure inside the bed increases with Γ.

The results above show clearly that air plays an important role in inducing reverse buoyancy of the large intruder sphere in a vertically vibrating granular bed. But the beads of the granular bed must also be small enough (< 0.5 mm) to produce this effect. Presumably RBNE can be induced only when the granular bed is fully fluidized. If the beads are too large or heavy, their motions will not be fast enough for the energy transfer. For example, when the beads of the bed are changed to steel beads of average $d = 0.19$ and 0.29 mm, no RBNE and negative pressure can be observed.

The picture emerging from the above discussion is that the vibration of the beads seems to produce a fluidized bed

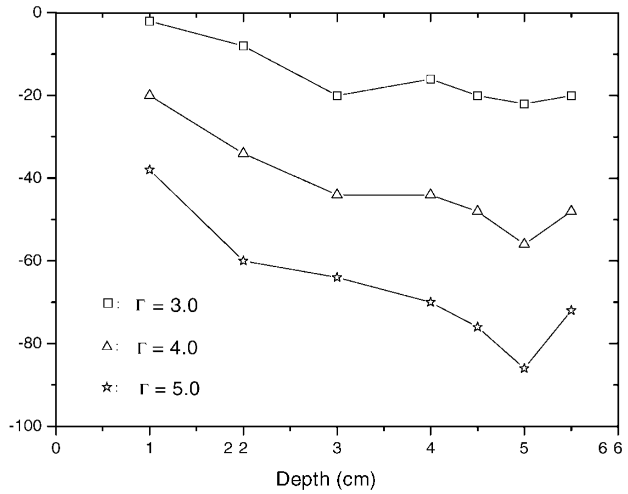

FIG. 3. Measured air pressure distribution along the axis of the bed in units of difference in height of water column in a U tube in a bed with $d = 0.12 \pm 0.02$ mm at different Γ. The depth is defined as the distance from the top of the bed. Points measured with the same Γ are connected to guide the eyes.

with a density of $\rho_c(\Gamma)$, which is about $0.65\rho_m$ obtained from the experimental data as shown in Figs. 1 and 2. RBNE is observed when the intruder of density ρ is smaller than ρ_c. Also shown in Fig. 1 are the fits of the data points to the functional form of $T \propto (\chi - \chi_c)^{-\alpha}$. It is found that the exponent α_r for the rise time is 1.0. The exponents α_s for the sink time are 2.3 when measured near the wall and 2.7 when measured along the axis with a thread attached to the intruder.

To understand the differences in α_r and α_s, we assume that the net force acting on the intruder in the granular bed can be modeled as the sum of (a) f_g due to gravity, (b) f_i, an upward inertia due to the motion of the beads, (c) f_p due to the pressure difference [$\propto (\chi_c - \chi)$], and (d) f_d, the drag of the beads on the intruder. Obviously, when $\rho > \rho_c$, the upward driving force is $f_i - (f_g + f_p + f_d)$ and when $\rho < \rho_c$, the downward driving force is $f_p - (f_i - f_g + f_d)$. These two forces vanish at $\rho = \rho_c$. Note that the upward force f_i is absent in the case of a fluid. In a fluid, the same exponent of $\alpha = 1$ is expected for both the rise and sink time because both the upward and downward driving forces have the same origin, namely, the difference between gravity and buoyancy, $(\rho - \rho_c)$. However, in our case, there is an additional upward driving force f_i which is not sensitive to $(\rho - \rho_c)$. Therefore, it is not surprising to find that the two exponents are different.

From the discussion above, the effect of air is important in the behavior of a granular bed with strong oscillations or small bead size. The reversed buoyancy reported by Shinbrot and Muzzio [10] is probably caused by the unusual air pressure gradient in the bed considering the small bead size (0.20 mm) used in their experiments. However, the existence of a peak in the rise time of the intruder reported by Mőbius *et al.* [15] cannot be explained by this air gradient. From our results, the air pressure gradient inside the bed can still play a role in their experiments. The existence of this peak can probably be understood once the mechanism responsible for the unusual air pressure gradient in the bed is known.

Finally, it must be mentioned that a model based on the competition between the effects of percolation and condensation has been proposed to explain RBNE successfully by Hong *et al.* [19] and recently claimed to be confirmed by an experiment [20]. However, this model cannot be directly related to our experiments as the effect of air is not considered in Ref. [19]. Furthermore, the global temperature needed in Ref. [19] is obviously missing in ours and similar experiments [21]. It is still not clear why RBNE were not observed in experiment [21] similar to Ref. [20]. Since the effects of percolation and condensation are collective behaviors of a large number of particles, our experiments with only a single intruder are probably not directly relevant to the understanding of the controversies related to this model [19–24].

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