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Air-driven Brazil nut effect

M. A. Naylor, Michael R. Swift, and P. J. King
School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, England

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A large heavy object may rise to the top of a bed of smaller particles under the influence of vertical vibration, the "Brazil nut effect." Recently it has been noted that interstitial air can influence the Brazil nut rise time. Here we report that the air movement induced by vertical vibration produces a very strong Brazil nut effect for fine granular beds. We use a porous-bottomed box to investigate the mechanism responsible for this effect and to demonstrate that it is related to the piling of fine beds, first reported by Chladni and studied by Faraday. Both effects are due to the strong interaction of the fine particles with the air, as it is forced through the bed by the vibration.

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A large heavy object, often referred to as an "intruder," rises to the top of a bed of smaller particles under the influence of vertical vibration, the "Brazil nut effect" (BNE) [1,2]. It has also been reported that there are situations for which the intruder moves to the bottom of the bed under vibration, the "reverse Brazil nut effect" (RBNE) [3]. The conditions for observing the BNE and the RBNE are currently the subject of vigorous debate [4–6] as is the behavior under vibration of multiple intruders [7–14]. For multiple intruders the dynamics may be strongly influenced by the interactions between the intruders mediated by the smaller grains [15].

Two principal mechanisms have been proposed for the single intruder BNE [1,2]. In the first, some of the smaller grains move underneath the intruder each time it is thrown upwards during vibration. Later in the cycle the intruder falls upon these smaller grains that resist its downward motion. In this way the intruder is ratcheted upwards during successive vibratory cycles [1]. In the second mechanism the intruder circulates on the granular convection currents usually found in vertically vibrated beds until it reaches the upper surface. It may then find it difficult to reenter the convective flow [2]. Neither mechanism invokes an interaction between the grains and the surrounding air.

Recently Möbius *et al.* have noted that the rise time of an intruder in a bed of 0.5 mm glass spheres depends in a nontrivial way on the ambient air pressure [16]. Here we report that the air flow induced by vertical vibration, and not just the presence of air, produces a very strong BNE for fine granular beds. We use a porous-bottomed box to investigate the mechanism responsible for this air-driven BNE. The top of the box can be either open or closed in order to change the flow of the air with respect to the granular bed, influencing the behavior of both the bed and the intruder. We show that the air-driven BNE is intimately related to the piling of fine beds first studied by Faraday [17] and more recently by others [18,19]. Both the air-driven BNE and Faraday piling are due to the interaction of the fine particles with the air, as it is forced through the bed by the vibration.

The experiments are based on a 5-mm diameter steel ball "Brazil nut" and a 20-mm deep bed of 125–150 μm diameter glass spheres, held in a glass sided box 40 mm high and 10 mm by 40 mm in horizontal section. This system is shown in Fig. 1. The base of the box is made of a 63-μm woven steel mesh supported by a 3-mm thick layer of metal foam, which itself is supported in places by metal pillars. Such a structure is rigid to particle collisions but extremely porous to air. The top of the box may be either open or closed by three small bungs. The box is mounted on a frame held between a pair of electromechanical transducers in such a way that the motion is accurately one-dimensional and in the vertical plane. The box undergoes sinusoidal vertical vibration with the maximum acceleration relative to the gravitational acceleration, $\Gamma = a\omega^2/g$, in the range 1–5. Here a is the amplitude of vibration, ω is the angular frequency, and g is the acceleration due to gravity. Our investigations have been carried out in the frequency range 20–60 Hz. The motion of the box is monitored using a capacitance cantilever accelerometer. Previous investigations have used either vertical "taps" separated by intervals of time or sinusoidal vibration. Continuous sinusoidal excitation avoids the complex displacement and acceleration transients that may result from tapping. It has been shown that a system may be sensitive to the excitation method used [6]; however, the effects that we will describe for sinusoidal excitation may also be demonstrated under tapping.

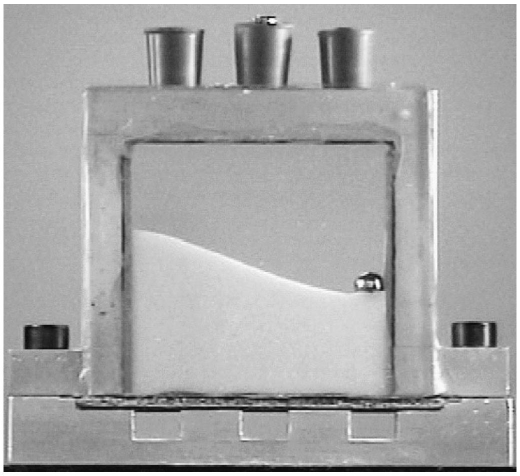

FIG. 1. Picture of the porous-bottomed box used in the experiments showing the method of construction. The ball may be positioned in the bed using an external magnet.

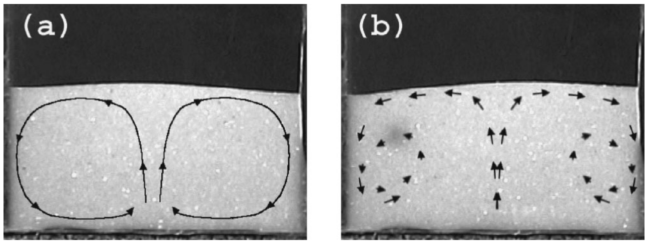

FIG. 2. Snapshots of the system vibrated at 50 Hz and $\Gamma = 2.8$ with the box top open. (a) Dominant granular convection currents. (b) The trajectories followed by the ball, showing that the motion is convection dominated. One cycle of the inner loop takes approximately 140 s. The ball can be seen as a dark region within the bed.

With the top of the box open, air is free to move with the granular bed. Under sufficient vertical vibration, the upper granular surface becomes slightly raised in the center, consistent with the two symmetrical convection cells in the bed [Fig. 2(a)]. The ball is found to exhibit two types of behavior. At low values of $\Gamma > 1$, it travels in the direction of the weak local convection. The speed of motion depends on the vibratory conditions and is generally slower than the current. During this motion the ball may reach the upper surface. It then remains there, partly submerged, being unable to reenter the convective flow. At higher values of Γ it also continues to follow the convection currents, again moving somewhat more slowly than the current. At these values of Γ, however, the ball generally remains in the interior of the bed, eventually moving to the center of a vigorous convective roll [Fig. 2(b)]. These behaviors are consistent with the experiments where the ball and grains are of sufficient size so that air plays a negligible role [2], or where air is removed.

With the top closed, air is forced through the granular bed, as it is thrown with respect to the base. Over a few vibratory cycles, the bed breaks symmetry and acquires a tilt, the Faraday effect [17]. The convection is now asymmetric and dominated by a single cell [Fig. 3(a)]. A ball positioned close to the bottom of the box immediately rises rapidly to the upper surface whatever its horizontal starting position, being little influenced by the convection currents [Fig. 3(b)]. It ‘‘floats’’ high on reaching the upper surface, with up to 80% of the ball volume above the level of the bed, and stays there as long as the top of the box remains closed. It is noteworthy that on one side of the bed the rapid upward movement of the ball is strongly against the direction of the downward convection current. Qualitatively, these same behaviors are observed in a similar system using a box with a nonporous base whether the top of the box is open or closed.

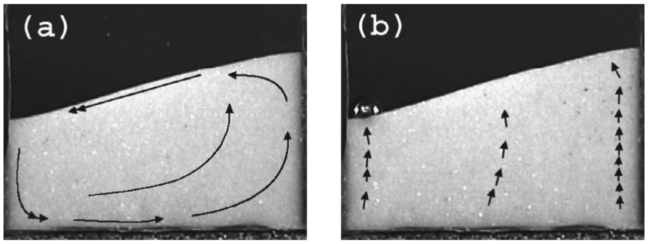

FIG. 3. Snapshots of the system vibrated at 50 Hz and $\Gamma = 2.8$ with the box top closed. (a) Dominant granular convection pattern in a closed box, the grains exhibiting Faraday tilting. The relative speed of convection is indicated by the number of arrowheads. (b) The trajectories of the intruder released from three different positions. The base of the arrows mark the position of the intruder at 4 s intervals. In each case the intruder rises rapidly to the surface even if the local direction of convection is downward.

If, following experiments with the top of the porous bottomed box closed, Fig. 3(b), the bungs are removed, then Faraday tilting ceases and the ball sinks into the granular bed and follows the local convection currents as in Fig. 2(b). It is possible to switch between these two types of behavior merely by opening or closing a single hole in the top of the box.

These experiments show that it is a forced air flow and not just the presence of air, which is responsible for the powerful air-driven BNE.

If the top of the porous-bottomed box is open, the air above and below the bed is free to move. At no part of the vibratory cycle does a pressure gradient develop across the bed, which is sufficiently strong to influence the dynamics of the grains. However, under the conditions of frequency and Γ that we have used, air is pumped in a net upward direction due to the variation in the bed dilation over each cycle. When the bed is thrown upwards from the surface, it is relatively compact and draws air through the porous base. During flight, the bed dilates due to grain-grain collisions. This allows the air to pass more easily upwards through the bed as it falls, the bed pushing only a little air back through the base of the box. We have carried out smoke tests, which confirm that, under vibration, there is indeed a net air flow through the box that is clearly upwards.

This air flow is blocked if the top of the porous-bottomed box is closed, or if a solid-bottomed box is used. A pressure gradient then develops across the bed, as it is thrown upwards with respect to the box; the pressure above the bed is higher than that below it [19]. The resulting downward air flow through the bed opposes the upward motion of the finer grains but has far less influence on the more massive intruder, causing the intruder to rise relative to the bed. At some stage of the cycle the pressure gradient must reverse so that air may return upward through the bed. Thomas and Squires [19] have shown that this occurs just before and following the initiation of bed impact with the base of the box, when grain mobility is expected to be low. The overall effect is a strongly air-enhanced ratcheting of the intruder upwards, acting to varying degrees throughout the bed. This net downward suction of the grains with respect to the intruder is also sufficient for the heavy ball to ride very high on the upper surface once it arrives there, as we observe.

Stroboscopic experiments provide additional support for this net downward force on the bed. With the top of the porous-bottomed box open, a gap can clearly be seen to form between the granular bed and the base of the box during each vibratory cycle. With the top closed the gap is no longer visible, consistent with a downward force influencing the granular motion. The impact of the bed with the base of the box can be observed as a small spike on the accelerometer output. This allows the accelerometer signals to be used to determine the phase at which the bed lands, 90° corresponding to the maximum upwards displacement of the box. At a frequency of 50 Hz and $\Gamma=2.8$ (as in Figs. 2 and 3), the bed lands at a phase angle of $346°\pm5°$ when the top of the box is open. This is consistent with the bed acting as a single object in free flight launched when the downwards acceleration of the box exceeds g. According to this description the expected maximum gap between the bed and the base would be approximately 600 μm. This corresponds to a gap of a few grain diameters in height as we have observed visually. With the top closed the bed lands at a phase angle of $245°\pm5°$. Applying the model of Kroll [20], which treats the bed as a porous medium with a fixed porosity moving through an incompressible fluid, leads to an expected maximum gap of approximately 20 μm, a factor of 30 less than the open top case. This is consistent with a gap that is not observable to the naked eye, as in our experiments. These results show that the air exerts a net downward force on the bed, which reduces the size of the maximum gap.

Finally, colored grains were used to investigate the role played by convection in the air-driven BNE. A small sample of bed grains was dyed using permanent ink. A horizontal layer of these colored grains 5 mm deep (corresponding to the diameter of the ball) was placed on the bottom of the empty box. Undyed grains were then placed on top to form a 20-mm deep bed with a horizontal upper surface. This system was then vibrated at a frequency of 30 Hz with $\Gamma=2.0$. With the top of the box open, the colored grains were seen to emerge at the upper surface of the bed after 34 s of vibration. Under the same vibratory conditions, a ball, initially positioned at the bottom of the bed halfway across the base, rose to the surface after 35 s. When the experiments were repeated with the top of the box closed the bed formed into a pile and colored grains were seen to emerge after approximately 100 s. The ball rose to the surface in 15 s, a factor of approximately seven times faster than convection and 2.4 times faster than in the case of the open-topped box, where air-enhanced ratcheting is not present. If, with the box top closed, the intruder is placed at the bottom of the bed with a layer of dyed grains above it then similar behavior to that seen by Liffman *et al.* [4] is observed. The ball rises through the layer dragging a few colored grains in its wake. Clearly, bed convection is not the dominant mechanism for the air-driven BNE.

Under the experimental conditions that we have investigated, we have observed that the strong, air-driven BNE occurs whenever there is Faraday tilting. Air must be present and either the top or the bottom of the box, or both, must be closed. We believe that the net downward pressure on the bed during much of the flight is responsible for both the air-driven BNE and the Faraday effect. If a nonzero surface slope develops, for any reason, then the downward force will have a resolved component that moves grains to enhance tilting. This is in agreement with the work of Thomas and Squires [19] who have concluded that it is the downward and horizontal components of the pressure force during bed flight, which produce tilting. They note that the reverse upward pressure occurs immediately before and during impact. Since the bed is compacting following collision, there is expected to be less air-driven movement of the grains at this time than during the period of downward force earlier in the cycle. This results in a weaker upward influence on the grains than the earlier downward influence.

Gutman has reported measurements on the throwing of a fine granular bed, which show that the downward pressure, caused by the upward movement of the bed, relaxes early in the bed flight and that the direction of the force is then upwards over an appreciable duration of the cycle before impact [21]. Referring to these results, Pak *et al.* have proposed that it is this upward force that is responsible for Faraday tilting [22]. The behaviors reported by Thomas and Squires are not consistent with Gutman's timings of the upward force [19,23]. Our observation of a strong, air-driven BNE also provides supporting evidence that, at least under our own experimental conditions, the influence of the downward force dominates. The net upward movement of the intruder requires that the air provides a net downward force on the grains over that part of the flight in which the bed is dilate.

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