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Qualitative Observations of Dense Particle Motion in a Vibration-Excited Granular Bed

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Abstract
The Brazil nut effect is a classic phenomenon in which larger objects typically migrate to the top of a bed of smaller granular media when exposed to vibration. An example of this phenomenon is finding Brazil nuts on the top of a can of mixed nuts. In this study, the Brazil nut problem is simulated by submerging a large particle in a bed of granular media and then subjecting the system to vibration. Stereoscopic X-ray imaging is used to visualize the large particle motion. These images are then compiled into movies where the particle motion may be tracked. Observations of the large particle motion are made under varying conditions of large particle material, vibration frequency, and bed height. Particle percolation, where smaller particles fill small voids beneath the large particles, is the dominate mechanism at higher vibration frequencies. However, as the frequency decreases, or as the disparity between the densities of the large and small particles decrease, the effects of convection become more pronounced.

Keywords
granular beds, flow visualization

Disciplines
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QUALITATIVE OBSERVATIONS OF DENSE PARTICLE MOTION IN A VIBRATION-EXCITED GRANULAR BED

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ABSTRACT

The Brazil nut effect is a classic phenomenon in which larger objects typically migrate to the top of a bed of smaller granular media when exposed to vibration. An example of this phenomenon is finding Brazil nuts on the top of a can of mixed nuts. In this study, the Brazil nut problem is simulated by submerging a large particle in a bed of granular media and then subjecting the system to vibration. Stereoscopic X-ray imaging is used to visualize the large particle motion. These images are then compiled into movies where the particle motion may be tracked. Observations of the large particle motion are made under varying conditions of large particle material, vibration frequency, and bed height. Particle percolation, where smaller particles fill small voids beneath the large particles, is the dominate mechanism at higher vibration frequencies. However, as the frequency decreases, or as the disparity between the densities of the large and small particles decrease, the effects of convection become more pronounced.

Keywords: Granular beds, Flow visualization

INTRODUCTION

The segregation of larger particles to the top of a granular mixture has been observed many times. One place it is often seen is in cans of mixed nuts where the larger Brazil nuts rise to the top, lending the name "Brazil nut effect" to the phenomenon. The understanding of this effect is important in many industries, including the pharmaceutical industry where uniform mixing of granular substances is imperative.

Numerous studies have taken place [1-6] to understand the mechanism by which the Brazil nut effect occurs. Multiple theories have been published, including convection where the particle follows a current similar to the current in a boiling pot of water, percolation where the particle rises due to the filling of the void created beneath it due to vibration by smaller particles, and air effects where the presence of air in the system can cause the large particle to become buoyant [6]. Despite these studies, it is yet unclear exactly how the Brazil nut effect occurs. Complicating this is that most studies focus on pseudo-two-dimensional representations of the effect, rather than three-dimensional systems where the effect is naturally seen. One such study by Ellenberger et al. [3] used disks in a flat container to simulate the Brazil nut effect in two-dimensions. The two-dimensional nature of the study allowed the use of optical cameras to monitor the movement of the particles. They concluded that percolation was the predominate mechanism in the upward movement of the large particle. They also found that both amplitude and frequency determined if the particle rose or sank in the bed material. Schnautz et al. [2] used a two-dimensional to study the Brazil nut effect in a system with a horizontal circular motion. This simulated conditions similar to miners panning for gold. From this study they found that the elasticity of the large particle, air between the particles, and gravity were all irrelevant to the occurrence of the Brazil nut effect.

Many conditions affect these proposed mechanisms. Among the conditions are the difference between the densities of the particles, the size of the particles, the height of the bed material in the container, and the frequency of the vibration. This study uses X-ray imaging to observe this phenomenon, allowing imaging inside a three-dimensional representation of the Brazil nut effect.

EXPERIMENTAL METHODS

Vibration Apparatus

As shown in Fig. 1, the vibration apparatus consist of a 10.2 cm internal diameter acrylic cylinder of height 20.3 cm and a sealed bottom. The cylinder is attached to a 44.5 N vibration exciter (essentially a large speaker) using a custom attachment that consists of four nylon bolts attached to a plywood base. The base is then bolted to the vibration exciter. The acrylic column is placed in the center of the four bolts and clamped down using a multi-purpose plastic tie.

The vibration is controlled by a function generator generating a sinusoidal signal, which is then amplified through a standard audio amplifier to approximately 3.5 volts (RMS) as measured on an oscilloscope in parallel with the vibration exciter. The vibration exciter replicates this signal, oscillating vertically in a sinusoidal manner. The frequencies studied in this experiment were 15 Hz, 25 Hz, and 35 Hz with amplitudes of approximately 7.0 mm, 2.5 mm, and 1.3 mm, respectively. The frequencies were chosen by experimentation to clearly show the Brazil nut effect in a reasonable time period (on the order of one minute). The amplitudes were varied to maintain a consistent maximum force on the column.

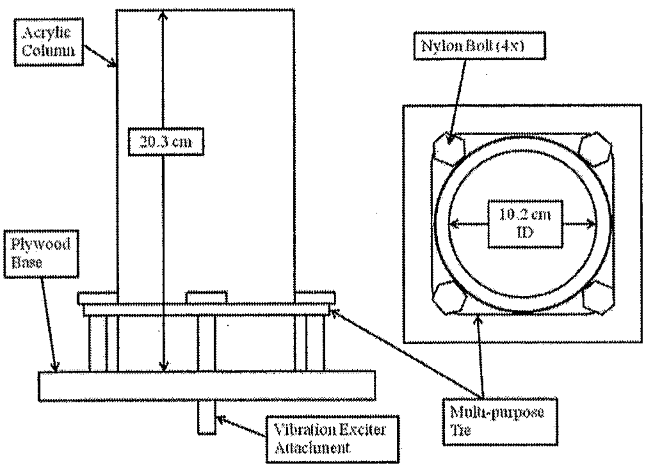


Fig. 1: Granular bed container and support schematic (not to scale).

X-ray Imaging System

As seen in Fig. 2, the X-ray system consists of two LORAD LPX200 X-ray sources mounted at 90 degrees to each other. Across from each source is a Precise Optics PS164X image intensifier and a DVC-1412 Monochrome Digital Camera with a resolution of 1388(H) × 1024(V). However, for this study the cameras are set for 2 × 2 binning to obtain a frame rate of 20 frames per second (fps), lowering the resolution to 640(H) × 512(V). The cameras are connected to a Pentium 4 computer with 4 GB of RAM running custom software for obtaining the X-ray images. More details on the X-ray equipment, data acquisition, and image reconstruction can be found in [7-9].

The X-ray images were obtained as sequential digital images. Due to the nature of the X-ray system, the original images were warped. A MATLAB script was used to unwarp the images, place the images from each camera next to each other, and then compile the images into an audio video interleave (.avi) digital movie format. The X-rays also produce a beam hardening effect where the intensity varies radially from the center of the granular bed even though the bed is homogeneous. Beam hardening corrections have not been applied in this study, but will be implemented in future work. Single frames are shown below; the actual movies can be viewed at http://www3.me.iastate.edu/heindel/researchXFV.html.

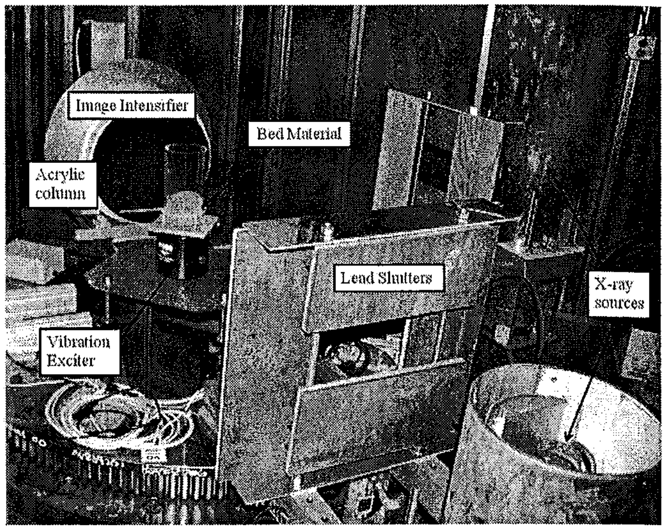


Fig. 2: X-ray system.

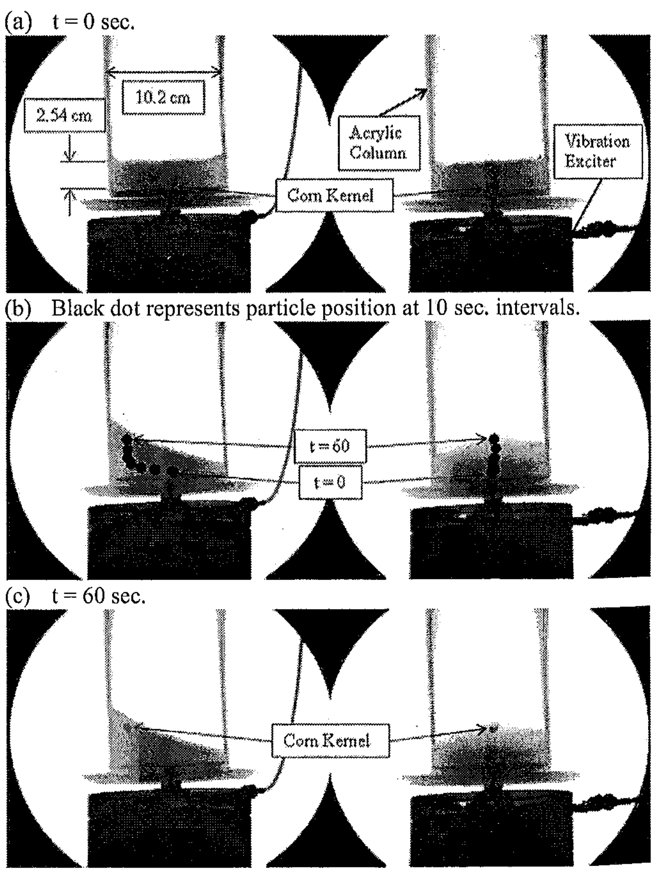


Fig. 3: Movement of a corn kernel tracer particle in a crushed walnut shell bed at 15 Hz vibration with 2.54 cm of bed material: (a) t = 0 sec., (b) particle position at 10 second intervals, and (c) t = 60 sec.

RESULTS

Similar Densities

Using a corn kernel (approximately 12 mm × 7 mm × 6 mm) soaked in potassium iodide as a tracer particle (density = 1.37 g/ml) and a bed material of crushed walnut shell (bulk density = 1.2 – 1.4 g/ml, particle size 0.42 to 1.00 mm) we can visualize what happens when the large particle is of similar density to the bed material. The initial bed height is 2.54 cm and it vibrates at 15 Hz with an amplitude of 7.0 mm. As shown in Fig. 3, two images were taken perpendicular to each other at each instant in time. The left image shows the x and z coordinates and the right shows the y and z coordinates. The corn kernel tracer has significant lateral movement from its initial position at the bottom center of the column (Fig. 3a) to when it breaks through the surface at t = 60 (Fig. 3c). This is especially clear in Fig. 3b where the position of the corn kernel tracer at an interval of 10 seconds has been marked. The extent of the lateral movement indicates that convection is a predominant mechanism in the Brazil nut effect under these conditions [5]. The bed surface becomes inclined during this 60 sec. period and the particle motion was visually observed to move down the incline, go beneath the surface at the bottom of the incline, then travel across the bottom of the column and re-emerge again at the top of the incline.

When the frequency of the system is increased to 35 Hz, the lateral movement is still present as shown in Fig. 4; however, it is no longer as pronounced. This indicates that percolation is causing a greater effect on the particle than convection, although convection is still present [5]. The bed material movement is very similar to that observed under 15 Hz vibration; however, the bed surface does not incline as much. The reason for this is still under investigation.

Disparate Bed and Particle Densities

At conditions where the bed and particle densities are significantly different, much less lateral particle movement is observed. As seen in Fig. 5, a 14.1 mm diameter glass marble tracer particle (density 5.11 g/ml) in a crushed walnut shell bed has some lateral movement, indicating the existence of the convection mechanism at this condition, but the majority of the movement is vertical. The effects of percolation once again become more pronounced at a higher frequency. Fig. 6 shows the same particle and bed materials at a frequency of 35 Hz. The final position of the particle is after it has surfaced and began to roll slightly. It is clear that the only significant movement is vertical, indicating the dominance of the particle percolation at this condition.

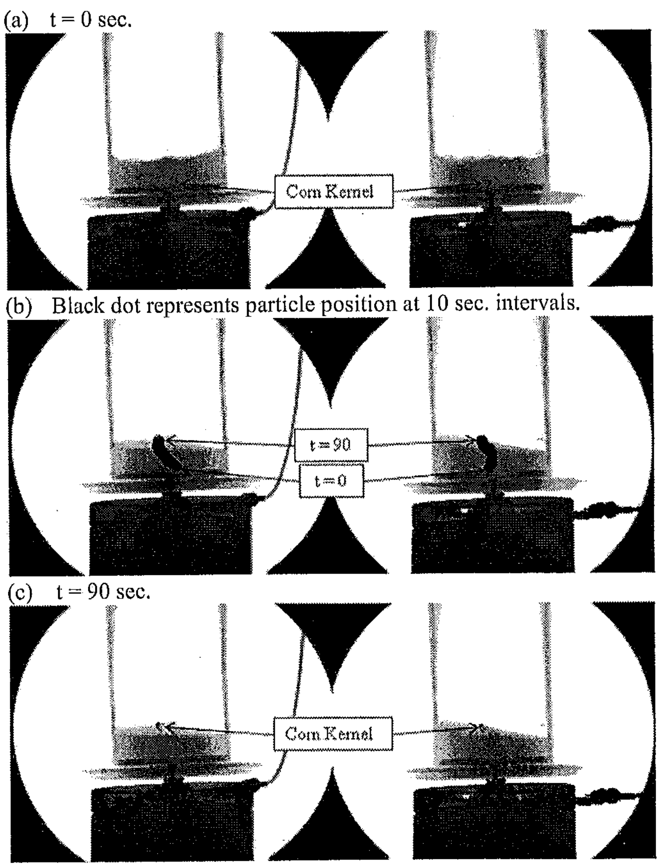


Fig. 4: Movement of a corn kernel tracer particle in a crushed walnut shell bed at 35 Hz vibration with 2.54 cm of bed material: (a) t = 0 sec., (b) particle position at 10 sec. intervals, and (c) t = 90 sec.

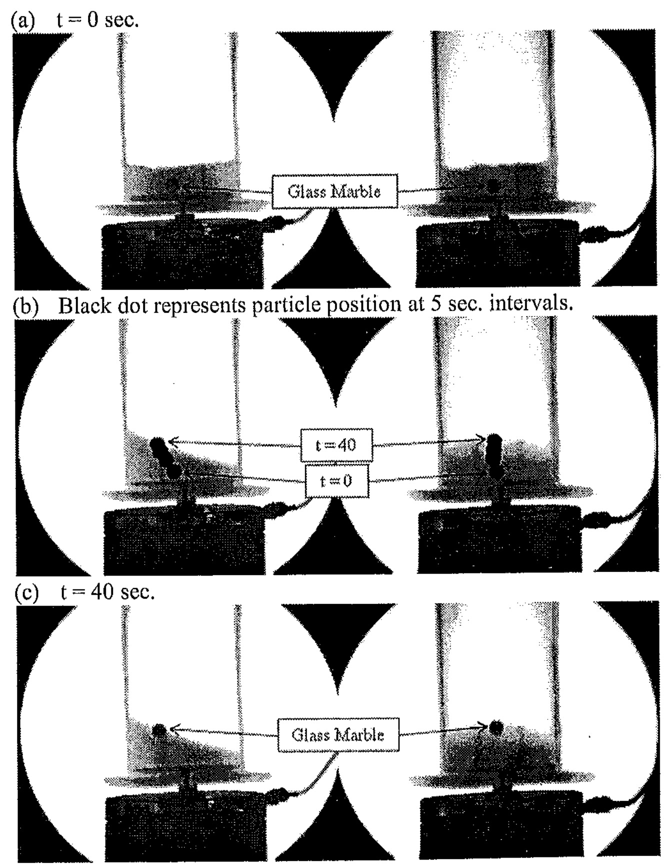
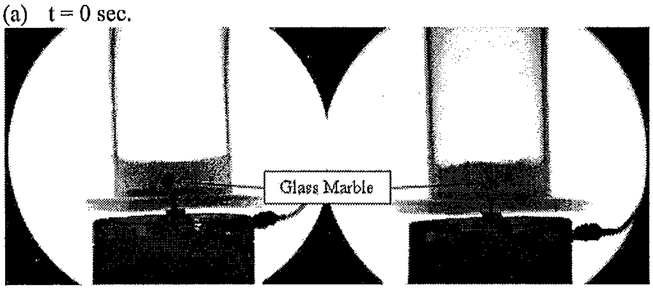
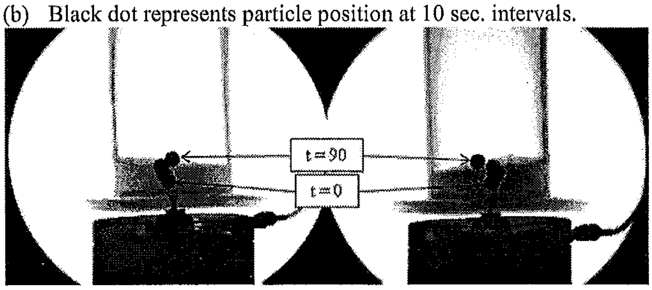


Fig. 5: Movement of a glass marble tracer particle in a crushed walnut shell bed at 15 Hz vibration with 2.54 cm of bed material: (a) t = 0 sec., (b) particle position at 5 sec. intervals, and (c) t = 40 sec.

(a) t = 0 sec.



(b) Black dot represents particle position at 10 sec. intervals.



(c) t = 90 sec.

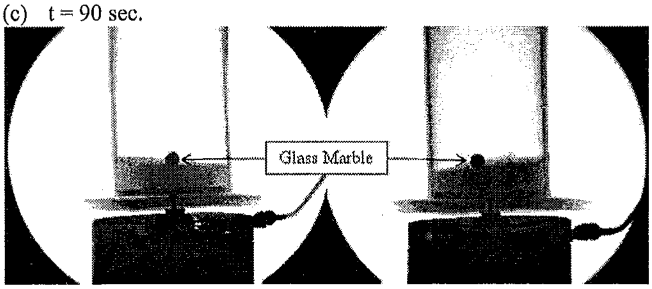


Fig. 6: Movement of a glass marble tracer particle in a crushed walnut shell bed at 35 Hz vibration with 2.54 cm of bed material: (a) t = 0 sec., (b) particle position at 10 sec. intervals, and (c) t = 90 sec.

Varied Bed Height

When the height of the granular bed is increased, the dominance of percolation or convection seems to be unaffected. In Fig. 7, the bed height has been increased to 6.08 cm of crushed walnut shell with a glass marble tracer particle, the movement over the first half of the ascension appears the same as it does in Fig. 5, which is the same condition only at a bed height of 2.54 cm. This limited data indicates that bed height appears to have no affect on the mechanism by which the Brazil nut effect occurs, although it may have some affect on the forces involved as the mass is doubled while the external force on the system remains constant. Further research is required to confirm this.

CONCLUSIONS

The use of X-ray stereography was used to visualize the Brazil nut effect on the three-dimensional movement of a large particle through a vibrating granular bed. The particle movement can be used to extrapolate the mechanisms affecting the system. Under relatively low vibration frequency with similar densities between the bed and the large particle material, the effects of convection were clearly observed. However, when either the vibration frequency or the difference in densities between the two materials was increased, the effects of convection were lessened and the effects of percolation were increased. Bed height did not appear to influence these conclusions.

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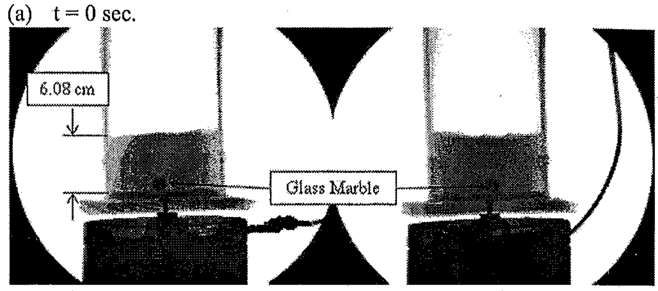
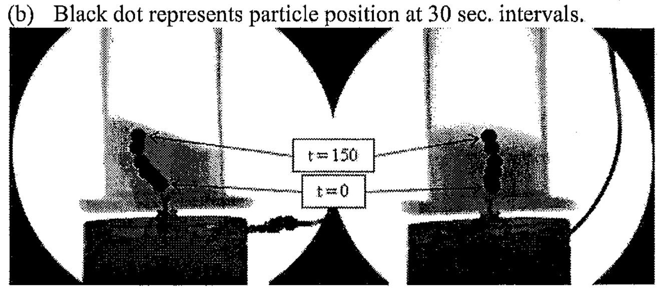
(a) t = 0 sec.



(b) Black dot represents particle position at 30 sec. intervals.



(c) t = 150 sec.

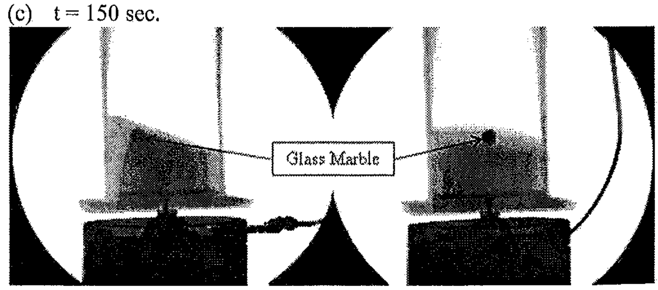


Fig. 7. Movement of a glass marble tracer particle in a crushed walnut shell bed at 15 Hz vibration with 6.08 cm of bed material: (a) t = 0 sec., (b) particle position at 30 sec. intervals, and (c) t = 150 sec.

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