Experimental study of granular convection in (real) two-dimension Brazil-nut effect

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Abstract. Brazil-nut Effect (BNE) experiment in (real) two-dimension is conducted. Container, bed particles, and intruder are made from the same material, i.e. 2 mm thickness acrylic plate. Dimensionless acceleration Γ and vibration frequency f are in the range of 2–4 and 13–17 Hz, respectively. It is observed that rise time $T_{\text{rise}}$ decreases with the increase of Γ similar to reported by others, but there is a range of $f$ and Γ, where $T_{\text{rise}}$ increases with the increase of Γ due to occurrence of Leidenfrost effect, which reduces convection flow of granular particles.

1. Introduction
When binary mixtures of granular materials are subjected to vibration, the larger particles rise to the top neglecting whether the larger ones are lighter or heavier than the smaller ones. This phenomenon is known as the Brazil-nut effect (BNE) [1]. One of the interesting properties of a BNE is the rise time $T_{\text{rise}}$, the time required by the intruder (larger particle) to move from its initial position to the surface of granular bed. For single intruder system $T_{\text{rise}}$ depends not linearly on density and diameter ratio of intruder and bed particles [2], it decreases as the dimensionless acceleration Γ increased and surface roughness of the intruder will also increase the $T_{\text{rise}}$ [3,4]. Experiment in observing BNE can be conducted in two- [5] and three-dimension system [6]. Observation of intruder in three-dimension system requires special techniques [7,8], while it is more simple in the pseudo two- [9] or two-dimension system [10].

2. Experiment
A two-dimension granular system is made of acrylic material with 2 mm thickness. It is including intruder, bed particles, and also the container box. The use of the same materials for all components will prevent the occurrence of unpredictable and annoying electrostatic charging [11]. Diameter of bed particle is 0.55 cm. Intruder in the form of a ring has 1 cm inner diameter and 1.4 cm outer diameter. The particles (bed particles and intruder) are put in 19 cm × 10 cm container box with thickness slightly larger than 2 mm. The additional space, only some paper slices thickness, is required in order to reduce friction between granular particles and the container wall.

The system is vibrated using sinusoidal signal with certain ranges of frequency $f$ (13–17 Hz) and normalized acceleration Γ (2–4).
while the amplitude is calculated from directly measured $\Gamma$. Details of experiment setup is similar to the pseudo two-dimension system in previous work [9]. Vibration is not introduced continuously to the system but with some stops for recording sharpened images. Some preliminary experiments have been conducted to observe whether the stops could influence the total time of $T_{\text{rise}}$ compared to the continuous experiment and the influence can be neglected. Tapping can also be used as time unit in measuring $T_{\text{rise}}$ as reported in [2]. In this work vibration is introduced every 1 s, then it stops for image recording process, and later it begins again with the same time duration of vibration. As the results $T_{\text{rise}}$ is always represented in multiple of 1 s.

After obtaining the images, from initial configuration until the intruder reached the surface of granular bed, the tracking process begins. Intruder and five marked bed particles are subject for tracking. A simple self-tailored web browser-based digitizing application [10] is used to determine position of the five particles in the recorded images. Position of intruder and selected particles will be plotted and analyzed.

3. Results and discussion

3.1. Motion of intruder and selected particles

The results of tracking selected particles and intruder for several combination of $(f, \Gamma)$ are given in figures 1 – 3. As initial configuration intruder is placed at the bottom and center of the container and the bed particles are poured randomly above it. About 285 bed particles are used. Five marked particles are placed at top-left corner (particle 2), top-right corner (particle 1), bottom-left corner (particle 4), bottom-right corner (particle 3), and about above of intruder (particle 5).

![Figure 1](image.png)

**Figure 1.** Position of intruder and other five particles for $f = 13$ Hz and $\Gamma = 2$, where initial particles position are indicated by black arrows and convection by purple arrows.

Figures 1–3 shows that convection flow in two-dimension BNE does exist. In order to allow the intruder to reach surface of the particles bed all bed particles must step aside or circulate in clockwise (CW) direction for bed particles in the right side of intruder (particle 1) and in counter clockwise
(CCW) direction for bed particles in the left side of the intruder (particle 2). And if it is possible particle 4 will follow particle 2 and particle 3 will follow particle 1. Particle 5 will be pushed slightly by the intruder along center of particles bed to the top direction, since it is located about above intruder in the initial configuration.

**Figure 2.** Position of intruder and other five particles for \( f = 13 \) Hz and \( \Gamma = 2.5 \), where initial particles position are indicated by black arrows and convection by purple arrows.

**Figure 3.** Position of intruder and other five particles for \( f = 13 \) Hz and \( \Gamma = 3 \), where initial particles position are indicated by black arrows and convection by purple arrows.

Because the system always depends on the initial configuration or randomly initial condition, it is rarely to find same trajectory for the six particles of interests even for the same values of \( f \) and \( \Gamma \). As
the intruder of particle 5 reach the surface of particles bed it can move to the right or to the left with no desirable preference. From this section it can be considered that convection flow plays important role in inducing the occurring of BNE.

3.2. Intruder rise time

The dimensionless acceleration $\Gamma$ plays important role in changing rise time $T_{\text{rise}}$ as reported as convection velocity $v_{\text{conv}}$ [3] and also $T_{\text{rise}}$ [4], which give similar results that $T_{\text{rise}}$ decreases as $\Gamma$ increased. In previous work $\Gamma$ can be represented indirectly with input voltage $V_{\text{in}}$ at the constant frequency $f$ and it is observed that $T_{\text{rise}}$ also decreases as $V_{\text{in}}$ increased [12]. Granular materials are more fluidized when energized with higher $\Gamma$ and the intruder can easier rise on the surface of granular bed.

Figure 4. The convection velocity $v_{\text{conv}}$ (convection strength) increases [3] (left) and rise time decreases [4] (right) with the increase of the dimensionless vibration acceleration $\Gamma$.

Figure 5. Intruder rise time $T_{\text{rise}}$ for each frequency $f$ against normalized acceleration $\Gamma$.

This work also gives similar results that $T_{\text{rise}}$ decreases as $\Gamma$ increased but only for certain ranges of $f$, e.g. for $f = 13$ Hz and $\Gamma = 1.75$ to 3.5, but later $T_{\text{rise}}$ starts to increase after that. For higher $f$ the
turning point, a point that differs the range of decreasing $T_{\text{rise}}$ to increasing one with the increase of $\Gamma$, is also shifted to the lower $\Gamma$ value. Detail discussion of this will be presented in the following section.

3.3. Leidenfrost–Brazil-nut effect
Leidenfrost effect in granular materials occurs when a crystalline cluster (solid-liquid phase) is elevated and supported by a dilute gaseous layer of fast beads (gas phase) underneath [13]. In this experiment Leidenfrost effect is also observed during the process of two-dimension BNE (figure 6).

![Floating cluster and Vapor like layer](image)

**Figure 6.** Snapshots of Leidenfrost effect for monodispersed granular system [13] (left) and Leidenfrost–Brazil-nut effect in two-dimension granular system observed in this work.

The existence of Leidenfrost effect in the BNE makes intruder rise time increases with the increase of $\Gamma$. This is consistent with report from other work, that compaction or 2-d hexagonal close packed (2-d HCP) can inhibit BNE and even prevent the intruder to reach the surface of granular bed [14]. The Leidenfrost effect causes the whole granular particles, the intruder and bed particles, moving as a unit. It also reduces convection flow which is required for promoting intruder in the BNE. It seems that the system act like a solid phase.

![Empirical model of $\Gamma_{\text{LBNE}}$](image)

**Figure 7.** Empirical model of $\Gamma_{\text{LBNE}}$ which can discriminate regions of BNE and LBNE.

An empirical model to discriminate the regions of BNE and Leidenfrost-BNE (LBNE) in $\Gamma-f$ plane, which is modified from [15], is proposed as
$$\Gamma_{\text{LBNE}} = \left( \frac{4\pi^2 f^2 D}{g} \right) \left( \frac{f_0}{f} \right)^\beta,$$

with $\Gamma_{\text{LBNE}}$ is a minimum $\Gamma$ to produce Leidenfrost-BNE, $D$ is bed particle diameter, $f$ is vibration frequency, $g$ is gravitation acceleration, and $f_0$ and $\beta$ are parameters to be adjusted. In this work following values of $D = 0.55 \text{ cm}$ and $g = 9.81 \text{ m/s}^2$ are used, which gives $f_0 = 12.8 \text{ Hz}$ and $\beta = 3.25$. Plot of (2) with the parameters is given in figure 7, which is able to separate BNE and LBNE regions.

4. Conclusion
An Experiment of a (real) two-dimension Brazil-nut effect has been performed for range of frequency 13-17 Hz and $\Gamma = 2$-4. Convection flow of granular was observed and recorded. Intruder rise time decreases with the increase of $\Gamma$ (for $\Gamma \leq 2.5$) as reported by others, but it increases with the increase of $\Gamma$ (for $\Gamma \geq 2.5$) due to the occurrence of Leidenfrost effect, which reduces convection flow that is required for BNE.

Acknowledgments
This work is supported by research scheme Penelitian Unggulan Perguruan Tinggi (Desentralisasi DIKTI) in year 2015 with contract number 310i/I1.C01/PL/2015.

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