Physics Letters A 378 (2014) 1303–1308

Contents lists available at ScienceDirect

Physics Letters A

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Patterns of convective flow in a vertically vibrated granular bed

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ARTICLE INFO

Article history:
Received 31 July 2013
Received in revised form 13 January 2014
Accepted 3 March 2014
Available online 12 March 2014
Communicated by R. Wu

Keywords:
Granular convection
Pattern
Vibration

ABSTRACT

When submitted to vertical vibrations for frequencies from 15 to 150 Hz, granular materials show several convective patterns, as symmetric, asymmetric, one single, one pair and multi-pairs of convection rolls. The vibration frequency (f) plays a significant role in the number of rolls and their flow directions, while the vibration acceleration (Γ) mainly affects the size of roll and strength of flow. The Γ–f phase diagram is presented and divided into the global, local, unstable and non-convection regions. Slope of the granular surface decreases with increase of Γ, and the grains at different positions collide with the bottom un-synchronously.

1. Introduction

Granular materials are well known as a strongly nonlinear dissipative system. Because of the frictional interactions and the inelastic collisions among granular particles and between particles and the side walls, the granular materials cannot be well described by the conventional theories of gas, liquid or solid. By supplying energy into the granular system through vibration, gas flow, rotation and other forms, the dynamic behavior of grains has received most attentions in the past years. Under vertical vibration, many phenomena have been found in granular system, such as convection [1], stratification [2], surface waves [3], arching [4], and size segregation [5,6]. One of the most prominent phenomena which is associated with other, and only partially understood yet is the vibration-induced convection. The convective flow in vibrated granular media was first observed by Faraday at 1831 [7], and it has attracted wide interest in both academic and industrial communities. Especially in the recent decades, granular convection has been investigated through some advanced measurement techniques, such as high-speed camera [8], positron emission particle tracking (PEPT) [9,10], magnetic resonance imaging (MRI) [11,12], and Particle Image Velocimetry (PIV) [13].

Previous works have studied the effects of vibration parameters on granular convection commonly by varying the acceleration Γ at a fixed frequency f. According to the level of vibrational acceleration, Hsiau and Pan [14] found that the granular layer in a vertical shaker had several types of motion, including the convective motion. Eshuis et al. [15] investigated the motion state transitions in a shallow bed. By discrete element simulations, at the fixed frequency $f = 7$ Hz, Lan et al. [16] found two symmetric vortex-like structures for rough wall in which the convective flow was upward in the center and downward near the sidewalls. Reversal of the flow direction could be achieved by reducing sidewall friction to zero. In the experiments of Wong et al. [17], for the frequency range from 14 to 18 Hz, an asymmetric convection roll with the formation of heap against one of the sidewall was observed. With the fixed frequency $f = 50$ Hz, Akiyama et al. [18] witnessed one symmetric pair of convection rolls covering the entire range of the granular bed. The same behavior was observed by Aoki et al. [19,20]. Furthermore, they found that when Γ was greater than a critical value, a further increase of Γ beyond this value would result in the transition from the downward to the upward mode of convection. For frequencies f around 110 Hz, Garcimartín et al. [21] reported that the bead layer developed a convective motion in the form of one or more rolls, and the speed of the beads near the walls decreased as the depth increased. In the simulation of Taguchi [22], he found that when Γ was not too big, the convective motion only concentrated near the surface region.

It can be concluded that the range of vibration frequency is relatively narrow in most of the previous studies. Although it's not new that different patterns of convective flow can be developed in different frequency band, each convective form still keeps independent. How they relate to each other and how they transition from one to another, have not been revealed yet. In other words, few attempts have been made on the dynamic transition between

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http://dx.doi.org/10.1016/j.physleta.2014.03.001

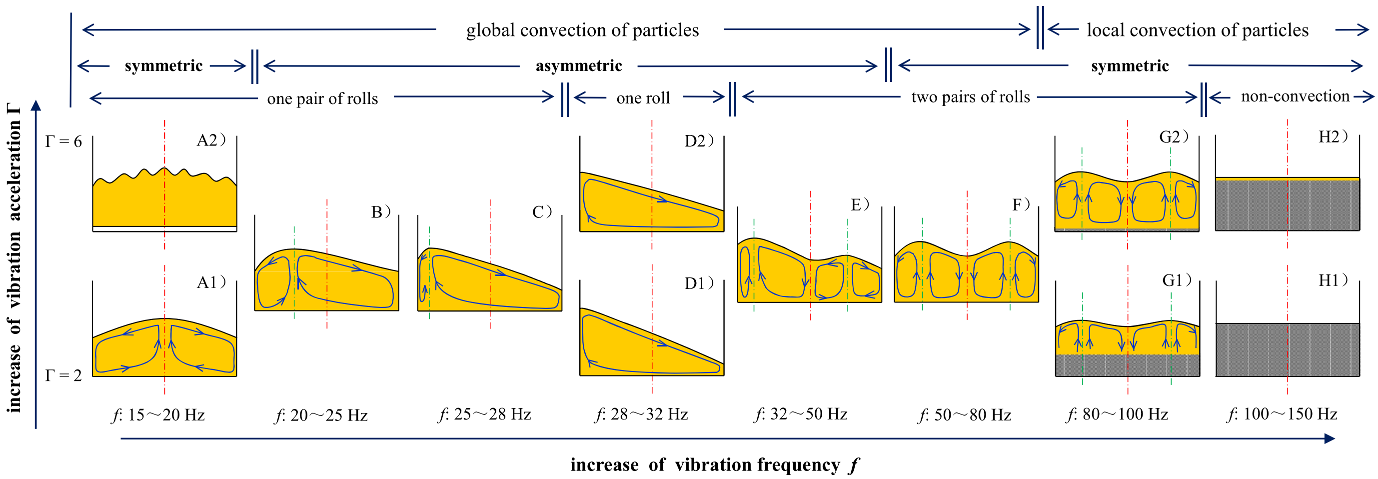

Fig. 1. Schematic diagram of the convection flows observed in the vibrated granular bed with different vibration parameters (f from 15 to 150 Hz, Γ from 1 to 6). The arrows show the directions of granular flow.

different convection states for a large frequency range. With the aim of extending this subject, here we carry on a detailed investigation of the convection patterns in a two-dimensional granular bed undergoing vertical oscillations, for a wider range of frequencies f from 15 Hz to 150 Hz. Effects of vibration parameters on the number and size of convection rolls, the direction and strength of convective flow are analyzed experimentally. Most of all, we focus on the existence conditions for different convection patterns and their dynamic transitions.

2. Experimental setup

For the granular materials, we use the molecular sieve beads of different diameters ($d = 1, 2, 4.5$ mm) with the standard deviation of 10%. The sphericity of beads s is 0.95, the real density ρ_s is 1500 $\mathrm{kg\,m^{-3}}$, and the packing density ρ_ε is 745 $\mathrm{kg\,m^{-3}}$. The container used in our experiments is made of Plexiglas with inner dimensions $L \times B \times H = 300 \times 20 \times 200$ mm (with L the container length, B the width, and H the height). The container is filled with beads to a height (H_0) of 90 mm, and then mounted onto an electro-magnetic shaker (LDS). The shaker is able to deliver a sinusoidal vibration vertically to the container with a distortion smaller than 1%. The main control parameters are the vibration frequency f and the dimensionless acceleration Γ, where, $\Gamma = A\omega^2/g$, $\omega = 2\pi f$. A is the amplitude, ω is the angular frequency, and g is the acceleration of gravity. Observation of the convective patterns in the granular layer is achieved visually by using of a high-definition digital camera. In order to make the granular system reach a steady state, we keep vibration for a long enough time at each initial setting condition.

3. Convection patterns of granular layer

Different ways of generating convection in a granular system have been identified: it can be friction (usually driven by the side-wall) for amplitudes that are not too much smaller than the grain diameter; it can be the influence of ambient air for grains smaller than 1 mm, and amplitudes considerably larger than the grain diameter, see, e.g., Ref. [23], and it can be buoyancy driven (for very large Γ). In this work, we mainly deal with the frictional convection rolls, since grains have a diameter larger or equal to 1 mm (for most tests with the 2 mm grains). The test is within the range of vibration parameters that f is from 15 to 150 Hz and Γ is from 1 to 6.

The results show that the vibration frequency f has a significant effect on the formation of convection in the vibrated granular bed. The number of convection rolls and the direction of convective flow will change by varying frequency f. However, variation of the size of roll and strength of convective motion can be induced by varying the dimensionless acceleration Γ at a fixed frequency. Fig. 1 shows a schematic diagram of the convection patterns with different vibration parameters. In our observations, there is almost without any hysteresis phenomenon in the transitions between different patterns, which means that once the rolls have formed, if Γ is decreased they revert to the previous pattern at a lower value of Γ.

At lower frequencies (f from 15 to 20 Hz) and with small Γ, in the region shown as Fig. 1(A1), the granular layer exhibits a stable symmetric convection. There is only one rising point at the center of the bed, just like the observation of Lan [16]. The initially flat surface of the grain system starts to deformation. The grains flow upward from the central bottom to the apex vertically and form a heap. After rolling down to the right or left sidewall along the surfaces, grains descend down along the sidewall and go towards the center at the base, closing the convective circle. The granular surface is relatively smooth, and there are no obvious jets (fluctuations) of grains at the free surface. However, for much larger acceleration Γ, within the region of Fig. 1(A2), the surface starts to fluctuate violently. An obvious gap between the bed base and the grain layer is observed, which is called as the unstable convection.

Within the range of frequencies f from 20 to 25 Hz, as shown in region of Fig. 1(B), the original symmetrical form of the convection is broken, resulting in one pair of asymmetric convection rolls with the rising point deviating from the center of the bed. One roll extends over a larger volume of the bed than the other. It also shows that the convection strength of the larger rolls is higher than that of the smaller one. With the increase of frequency f, the rising point moves further toward the side wall (the left wall in Fig. 1(C)). At the same time, the region that grain flow downward along the left side wall narrows gradually. In particular, with the frequency $f = 27$ Hz, only very thin, several layers of grains drop along the left sidewall. When the frequency is from 28 to 32 Hz, the convection within the granular bed evolves into one single roll with an inclined surface, shown in Fig. 1(D). Grains move upward along the left side wall to the rising vertex, then at the angled surface grains cascade down along the surface to the right sidewall. After traveling down to the vessel bottom in a thin stream near the right wall, the convection circle is closed by horizontal layer of grains moving into the left along the bottom of the vessel. It should be note that, when the frequency f is 28 Hz, there is an