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Original Research Paper

Climbing motion of grains in vibrating tubes with different geometries

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ABSTRACT

By inserting a vibrating tube into a static grain layer, the grains can climb along the tube, which presents a new way to convey grains continuously. In this study, both tubes with different sizes and cross-section shapes are used to probe the effect of geometry on climbing motion of grains. Under same vibration strength, grains in small diameter tube can climb directly into an equilibrium height. The grains in large diameter tube can't climb directly. However, if enough grains are initially filled in the tube to a certain height, the grains can climb much higher. The grain climbing is more sensitive to the tube size rather than shape of tube cross-section. With same tube diameter, the climbing motion becomes difficult with increase of grain diameter. Consistent with the experimental results, a model based on force analysis is presented.

1. Introduction

Granular materials are widely used in chemical, pharmaceutical, food, agricultural, manufacturing and powder industries [1–3]. Due to the special properties of non-equilibrium and highly dissipation, granular materials exhibit some behaviors quite different from conventional solids, liquids, and gases. When submitted to vertical vibrations, granular materials can behave in a variety of ways, such as granular convection [4,5], segregation [6], surface waves [7], and arching [8].

When a hollow tube is immersed in a granular bed that experiences vertical vibration, the surface level of the granular bed within the tube rises or falls, and finally stabilizes at a height difference from that outside the tube [9–13]. Akiyama et al. [11] proposed that this granular transport was induced by the difference in magnitude between the inter-grains and grain-wall friction. Maeno [12] reproduced this effect numerically. For the top-closed and bottom-open tube, Liu et al. [14] found that grains would rise against gravity and fill the tube placed upside down on the surface of a vibrating granular bed. This phenomenon was relative to the pressure fluctuation at the tube top and induced by the reciprocating air flow between the bed and the tube.

In our previous study [15], by inserting a tube into a grain bed, we found that the grains can climb along the tube when the tube vibrates vertically with a strong enough strength. Based on this founding, a new way to convey grains continuously by a vibrating tube is presented. In this way, the force chains between grains in the tube are necessary for grain climbing. During the vibrations of tube, grains in the tube are compacted and loosened alternately. The force between the tube and the grains varies periodically, thus leading to the climbing motion of grains. However, granular matter is a strongly nonlinear dissipative system which is influenced by many factors. Because of the frictional interactions and the inelastic collisions among grains and between grains and the tube wall, rule of grains climbing is complex. Until now, there are very few reports about this phenomenon. The reasons why grains climb and the factors impacting the climbing are thoroughly unclear. Preliminary research suggests that, grains in the tube can't climb if the tube diameter is too large or extremely small. The geometries of tubes may play some role in the force chain formation in the granular bed during vibrations. So in this study, we aim to know how the tube geometry influences the climbing motion of grains by experiments. Effects of tubes with different sizes and cross-section shapes on the phase diagram of grains climbing are investigated.

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2. Experimental set-up

The container used in our experiments is a cylinder with a 200 mm inner diameter and a 200 mm initial height layer (H). The container is filled with glass grains of 0.4 mm average diameter (d_m), with the standard deviation of 10%. The sphericity of grain (s) is 0.85, the material density (ρ_g) is 2500 kg/m^3, and the bulk density (ρ_ε) is 1526 kg/m^3. A transparent Plexiglas tube with 8 mm inner-diameter and 1.5 mm thickness is used. As shown in Fig. 1, the tube is inserted into the layer of glass grains with the depth of h_{in}, and then fixed to an electromagnetic vibrator (LDS V555), which is able to deliver a sinusoidal vibration vertically with a distortion smaller than 1%. The main control parameter is the dimensionless vibration strength Γ ($\Gamma = A(2\pi f)^2/g$, where A is the amplitude, f is the frequency, and g is the acceleration of gravity). Since the tube diameter (8 mm) is much smaller than the container diameter (200 mm), the height of grains in the container almost shows no difference as the height of grains in tube changes.

The tube is inserted into the grain layer with a depth (h_{in}) of 35 mm, and initially filled with certain height of glass grains (h_0). The tube vibrates at a frequency (f) of 12 Hz with different dimensionless vibration strength (Γ). A high-definition digital camera (Sony HDR-XR500, 30 fps, 1440 × 1080 pixel) allows us to record the images of height of the grains in the tube (h) as a function of time. Each test is performed three times, and the mean position accuracy is better than 1 mm. After vibration for a long enough time, the grains in tube reach a steady state, at which the height of grains in tube remains unchanging with further increase of vibration time for at least two minutes (1440 vibration cycles). The stabilized height of the grain layer in tube is achieved as the equilibrium height (h_{eq}).

3. Experimental results

3.1. Grain climbing in vibrating tube

Fig. 2 shows the height of the surface level of grains in the vibrating tube. When the dimensionless vibration strength (Γ) is strong enough, the grains climb along the tube directly and their surface finally stabilizes at an equilibrium height (h_{eq}) even without filling grains in the tube before vibrating ($h_0 = 0$). The grains climb faster and the equilibrium height (h_{eq}) becomes higher with increase of Γ, seeing the data $\Gamma = 5$ and $\Gamma = 3.5$ in Fig. 2a.

When the dimensionless vibration strength is smaller, such as $\Gamma = 2.4$, the grains in tube can't climb directly from the bed layer. In that case, we fill some grains into the tube before vibration, and the filled height is h_0. After vibration, if the grains initially

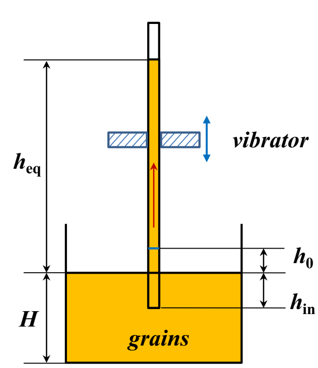

Fig. 1. Schematic figure of grains climbing in a vibrating tube, where h_{in} is the inserting depth of the tube and h_{eq} is the climbing height.

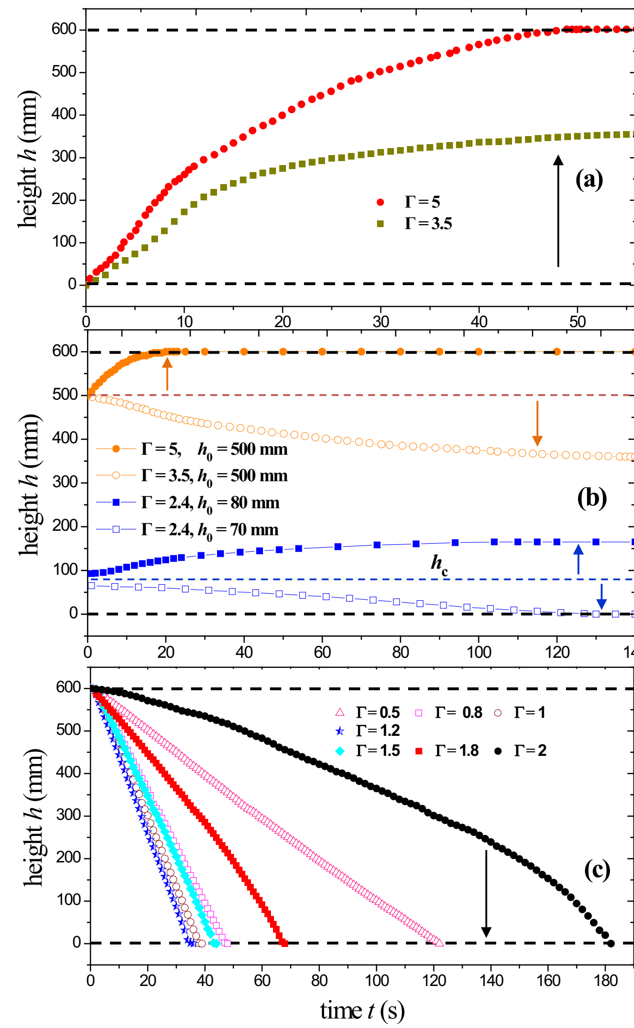

Fig. 2. Height (h) of the surface level of grains in the vibrating tube as a function of time (t) where the vibration frequency f = 12 Hz and the mean grain diameter d_m = 0.4 mm.

filled in tube fall, we stop the vibration, and continue to fill grains into the tube, with the height of grain layer increasing 1 mm for each time. We consider the filled height as the critical height (h_c), at which the granular layer in tube almost keep steady (not rising or falling) when submitted to vibration for a long enough time (about two minutes). In consequence, when the filled height (h_0) is slightly higher than the critical value (h_c, about 75 mm), the grains in tube climb and finally stay at the corresponding equilibrium height, seeing the solid square in Fig. 2b. If h_0 is lower than h_c, the initial filled grains fall into the bed layer, seeing the hollow square in Fig. 2b. In the same way, for $\Gamma = 5$, if the initial height h_0 (about 500 mm) is lower than h_{eq} (about 600 mm), the grains will climb into h_{eq}, seeing the solid circle in Fig. 2b. However, for $\Gamma = 3.5$, if h_0 (about 500 mm) is higher than h_{eq} (about 360 mm), the grains finally fall into h_{eq}, seeing the hollow circle in Fig. 2b.

When the dimensionless vibration strength is much weaker than a critical value (Γ_c), such as $\Gamma = 2$, the grains can't climb whether the tube is initially filled or not. If the tube is initially filled, the filled grains fall into the granular layer under the gravitational action. With the initial filling height $h_0 = 600$ mm, the height of grains in the tube (h) decreases with increasing vibration time (t) under different dimensionless vibration strength Γ, as shown in Fig. 2c. It also should be noted that, when the dimensionless