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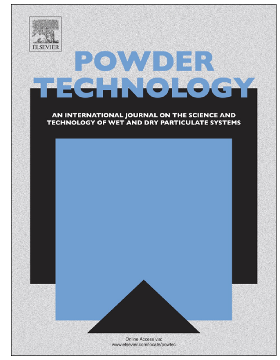

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Sealing Pipe Top Enhancing Transportation of Particulate Solids inside a Vertically Vibrating Pipe

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Abstract: Particles can move against gravity inside a vibrating tube inserted in a static granular bed. This offers a new approach for transporting bulk material. In this work, we demonstrate a method to enhance conveying of powder by sealing the tube top. With the same vibration conditions, a comparison of particle motion in an opened tube and closed top (sealed) pipe is made. Compared to an un-sealed pipe, particle upward motion within a sealed pipe is improved. With low vibration strength, only particles in the sealed tube can ascend. With increasing vibration strength, particles can climb in both tubes while particles in sealed pipe move faster and higher. The enhancement effect works well for particles of smaller size (d < 1mm), and the positive effect becomes weaker with an increase in particle diameter. In a sealed tube, the final height of the granular column increases as the tube length increases while the growth velocity is reduced. Particle conveying in sealed tube shows less dependence on tube diameter compared to an un-sealed tube. Sealing the tube top introduces air pressure difference during each vibration cycle, which induces an additional upward drag force on the particles in the tube. The drag force becomes significant compared to other relevant forces for small diameter particles at high levels of vibration.

Keywords: granular matter; conveying; vibration; pressure difference; drag force.

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1. Introduction

Bulk materials handling is by far the largest industrial activity, with over 16 billion tons of common products being handled annually, usually many times from source to use.[1] Granular materials require efficient and reliable material handling systems. To date, pneumatic conveying is a common mode of transporting bulk materials. However, a high likelihood of particle breakage[2] and pipeline blockage[3] for pneumatic systems troubles industrial companies. Some industrial analysts think that it could increase the throughput of powder-processing plants by as much as 40% by solving problems related to the handling and transport of granular materials.[4] Hence, even a small advancement in transportation technologies of bulk media could have profound impacts for industry. Accordingly, developing a new technology for transporting granular particles is of interest.

Granular media exhibits complex behaviors when submitted to vertical vibration, such as convection[5], segregation and mixing[6, 7], fluidization[8], and spouting[9]. Recently, it was found that particles could rise against gravity in a pipe placed upside down on the surface of a vibrating granular layer[10], or in the pipe undergoing vertical vibration by inserting a straight pipe into a steady granular bed. [11, 12] For the latter way, the rising velocity and height achieved can be adjusted by changing vibration strength and the inserted distance of the pipe in the bed. This novel effect demonstrated a unique approach for transporting granular materials continuously and vertically. Much efforts has been made to investigate this novel phenomenon more recently. Liu et al [13] established a semi-theoretical mathematical relation between the climbing height and time. Focussing on effects of pipe geometry and pipe size on particle climbing, Zhang et al [14] illustrated that particle climbing was more sensitive to the pipe size rather than the shape of the pipe cross-section. Liu et al [15] found that, the climbing in the tapered-tip pipe is enhanced because of the strengthened force chain in the particle assembly compared with the straight pipe. Based on discrete element method (DEM), Xu et al [16] quantified the change in solids volume fraction of particles in vibrating pipe for each vibration cycle. It illustrates that the formation of a dense region in the middle, and a low solids volume fraction region inside the lower end of the vibrating pipe is necessary for particle climbing. However, Fan et al [17] reported that particle climbing is caused by convection of the bulk material in the container. Due to frictional interactions and inelastic collisions between powder particles and between particles and the pipe wall, the nature of particle motion inside a vibrating tube is complex. The reasons why particles move upwards and accordingly the steps needed to improve conveying efficiency have not yet been fully understood.

In this paper, we demonstrate a way to enhance powder conveying under vertical vibration by sealing the top of the vibrating tube. The same experiments are performed both in an open top and closed pipe that are partially inserted in the granular silo with certain depth. The differences between particle motion in closed top tube and open top tube are analyzed by testing the effects of vibration strength, particle size and tube size (inner length and diameter) on particles climbing. A model based on pressure difference induced by vibration is proposed. The potential applications of this research are extending and improving the new approach for transporting bulk material vertically with more energy efficiency.

2. Experimental set-up

A schematic drawing of the experimental set-up for investigating the particles motion in vibrating tube is shown in figure 1. A 300 mm glass vessel is filled to a 200 mm initial height (H) with glass particles of 0.3 mm average diameter (d); 0.26 mm to 0.34 mm size distribution. The sphericity of particles (s) is 0.85 and the material density (ρ_g) is 2500 kg/m^3.

Five transparent plexi-glass tubes are used in the experiments. Three tubes have an 8 mm inner diameter (D) with lengths (L) of 480 mm, 600 mm and 800 mm respectively and two tubes with 12 mm and 20 mm inner diameter have same length of 480 mm. Rubber plugs are employed to seal the top-end of the tubes. The tube is inserted into the granular bed with a certain depth (H_{in} = 40 mm), then fixed on an electromagnetic vibrator (LDS V555) which that can generate a sinusoidal vibration vertically with a distortion smaller than 1%. The main control parameter is the dimensionless vibration strength Γ i.e. amplitude of vibration acceleration divided by gravitational acceleration. $\Gamma = A(2\pi f)^2/g$, where A is the vibration amplitude, f is the vibration frequency, and g is the acceleration of gravity. Since the pipe diameter is much smaller than the container diameter, the height of granular bed in the container shows almost no difference as the height of particles in pipe changes. The pipe is vibrated sinusoidally at the given vibration parameters (frequency f and dimensionless acceleration Γ). The dynamic motions (height h) of particles in the vibrating tube is recorded by a high-definition digital camera (Sony HDR-XR500, 30 fps, 1440×1080 pixel). After vibrating for a sufficiently long time, the granular column in the tube remain at an equilibrium height (h_{eq}). Three other sizes of glass particles (mean diameter d = 0.6, 1, and 2 mm) are used to explore the effect on of particle size on particles motion.

3. Results and Analysis

3.1. Effect of dimensionless vibration acceleration

The height of particles both in open top and closed top tubes with same length (L = 480 mm) as a function of vibration time was shown in figure 2. At a fixed frequency (f =12 Hz), there are few different behaviors of particles in the tubes with increase of dimensionless vibration acceleration (Γ) from 3 to 5.

(1) With the same vibration strength (Γ =3), only the particles in closed top tube can rise against gravity whereas particle cannot climb in the open top tube. The particles in closed top tube finally stabilizes at an equilibrium height (h_{eq} = 440 mm). However, the height of particles layer in open top tube stays at the initial level (h_{eq} = 0 mm) after vibration.

(2) With developing vibration strength (Γ = 3.4), particles both in both tubes can move upward. Even though, particles in closed top pipe finally are full of the tube, the equilibrium climbing height (h_{eq} = 480 mm), which is high than that in open top pipe (h_{eq} = 370 mm). It also can be seen that, particles in closed top tube climb faster than particles in open top tube. It takes only 25 seconds to fully fill the closed top pipe ($h_{eq} = L$), but particles in open top pipe needs 40 seconds only rise to 370 mm ($h_{eq} < L$).

(3) With further increase of vibration strength (Γ = 4), both the height of granular column in closed top and open top pipe grows after vibration, and the growth velocity increases compared to the situation of smaller vibration strength (Γ = 3). In opened tube, particles finally spout out after vibrating for 20s. Particles in closed pipe fill whole pipe with vibrating time of 23 s. In general, particles in closed pipe still climb faster than that in opened pipe for the initial vibration time (t < 15s).

(4) Particles both in closed top and open top tube ascend faster with further increase of dimensionless vibration strength (Γ) from 4 to 5. Compared to particles in closed pipe, particles in opened pipe climb slower in the initial few seconds, however, after vibration for

5s, the growth (climbing) velocity in opened pipe surpass in reverse.

Figure 3 shows the phase diagram of particles motion both in opened and sealed tubes. At the fixed vibration frequency (f = 12Hz), there is a critical values of dimensionless vibration strength ($\Gamma_C = 2.2$) below which the particles both in opened and closed pipe cannot ascend with vibration. With high level of vibration strength ($\Gamma_S \geq 4$) beyond which particles both in opened and closed pipe can climb, and finally full of the closed top pipe while spout out from the open top pipe. In the area where vibration strength (Γ) is between Γ_C and Γ_S, particles in sealed pipe climbs higher than in un-sealed pipe. To be specific, only particles in closed pipe can climb under the vibration strength range ($\Gamma_C \leq \Gamma \leq \Gamma_D$, yellow zone in fig. 3), and the final climbing height (h_{eq}) shows a monotonic increase with developing vibration strength. The particles in opened pipe can ascend with in green zone (in fig. 3) where vibration strength in the range of ($3.2 < \Gamma \leq 4$), however, the climbing speed and the final climbing height in opened pipe still lower than that in closed pipe with the same strength.

Particles both in opened and closed pipes cannot ascend in the area where the vibration strength (Γ) is smaller than (Γ_C). In consideration of that, before vibration we fully fill the pipe with particles (h = 480 mm), then vibrate the pipes with three different vibration strengths. Figure 4 shows evolution of particles height (h) in both pipes with time of vibration (t). Particles filled in both pipes fall undergoing vibration, and descend of particles become faster with increase of vibration strength (Γ) from 1.5 to 2.2. The descent velocity of particles in closed top pipe is much smaller than that in open top pipe with the same vibration strength. In the open top pipe, it takes 26s for particles totally falling into the granular bed underneath, while for closed top pipe it needs 59s. It also should be noted that, at Γ = 2.2, all the particles in open top pipe falls into the granular bed (h = 0 mm), whereas the initial filled particles in closed top pipe only falls into the middle of the pipe, finally stabilizes at a certain height (h = 260 mm). Sealing the top of pipe puts some resistance to prevent particles from dropping under gravity.

Summarizing the above, it can be seen that particles in both tubes cannot move upwards unless sufficient vibration strength acts on the tube ($\Gamma < \Gamma_C$). With increasing vibration strength but remaining at the lower level ($\Gamma_C \leq \Gamma < \Gamma_D$), only particles in the sealed tube can ascend. As the vibration intensity further increases, particles can move upward in both tubes while particles in the sealed pipe move faster and higher ($\Gamma_D \leq \Gamma < \Gamma_S$). In other word, sealing the tube top can improve the upward motion of particles undergoing vertical vibration. However the enhancement in the transport of particles will be suppressed for further increase of vibration strength ($\Gamma \geq \Gamma_S$).

3.2. Effect of vibration frequency

Figure 5 shows the effect of vibration frequency on particle motion inside the vibrating tube at a fixed vibration strength ($\Gamma = 5$). Using four different vibration frequencies (f = 12, 15, 20 and 40 Hz), the data continues to show the same pattern in that rising motion of the particles is enhanced by using a sealed tube instead of an open top tube. Moreover, upwards motion of the particles in both tubes decreases with an increase in vibration frequency as shown in fig. 5 where climbing velocity and final height of particles falls with higher frequencies. In particular, there is no motion of the particles in either the sealed or open top tubes at the highest vibration frequency (f = 40 Hz).

3.3. Effect of particle size

Figure 6 shows the evolution of the height of particles layer (h_{eq}) with respect to time both in open and closed top pipes using different particles size. With an increase of mean diameter (d) from 0.3 to 2 mm, the motion of particles in both pipes becomes weaker with increasing particle size. The final climbing height decreases, and particles with 2 mm diameter cannot ascend in either pipe. In addition, the difference between particle motion in closed top and in open top pipe is reduced with larger particle size. The positive effect of closing the pipe top on the enhancement of particle climbing is attenuated with bigger size particles. This approach to improve vertical conveying is only effective for particles smaller than 1 mm.

3.4. Effect of tube length

At the given vibration condition (frequency f =12 Hz and dimensionless vibration acceleration Γ = 4), the effect of length of pipe (L) on particle upward motion both in closed top and open top tube is presented in figure 7. In closed top pipe, particles climb highest in the pipe with longest inner length (L = 800mm), but the pipe is not completely filled by particles ($h_{eq} < L$). However, in pipes with shorter length (L = 600 mm and 480 mm), particles can rise and full of the pipe ($h_{eq} = L$). As the inner length decreases, the average speed of the upward movement is increased. With the same inner length (L = 800mm), climbing height of particles in open top pipe is smaller than that in closed top pipe. It also can be noted that particles in opened pipe (L = 800mm) ascends higher than that in closed pipe (L = 480mm), producing the phenomenon that particles spout out from the top of pipe with shorter inner length in figure 2.

3.5. Effect of tube diameter

Tube diameter (D) only has very small influence on particles motion in sealed tubes, as shown in figure 8. Particles in all three sealed tubes can ascend. The pattern is almost the same regarding growth velocity and final climbing height (tube fully filled) for particles in tubes with diameter of 8 and 12mm. Although particles in sealed tube with 20 mm diameter climb more slowly than particles in smaller size tubes, the particles still reach almost the same final climbing height. However, compared to sealed tubes, particles conveying in open top tubes shows much stronger dependence on tube diameter. With the top opened, particles climbing fails in tube with 20 mm diameter; particles in smaller size (8 and 12mm) tubes can moves upward, but the tube is not fully filled. Compared to 12 mm tube, there is a substantial increase both in rising height and growth velocity of granular column inside 8 mm tube.

4. Force Analysis

4.1 Overview

Analysis of the experimental results indicates that particles motion inside a vibrating tube is strengthened when the top of the tube is sealed, but this positive effect becomes suppressed with increasing particles size. To understand the mechanism of the difference between particles motion in open top and closed top tubes, we analyze the force on particles in the tube and discuss their dynamic motion in each cycle. Owing to the complexity of the actual motion, only an outline treatment is presented here. The tube experiences sinusoidal vibration as $s_{\text{tube}} = A\sin\omega t$, $v_{\text{tube}} = -\omega A\cos\omega t$, $a_{\text{tube}} = \omega^2 A\sin\omega t$, where t is the vibration time, s_{tube}, v_{tube}, a_{tube} are the tube's displacement, speed and acceleration, respectively. The underlying nature the physical behavior is that because of the frictional force developed between the tube wall and the particles within, when the tube moves up, an upward force is imposed on the particles (F_{wall}). If this friction force is larger than the weight of the particles (mg), the particles are lifted up a distance and a void almost instantaneously forms at the base of the tube in the main bed of powder. The void is subsequently filled by particles from adjacent regions of the bed. When the tube moves down, these particles in the filled zone impose an upward force (F_{bed}) on the particles in tube. Hence at the end of downward movement, there is a net income of particles inside the tube, resulting in "particles climbing". We will examine one-dimensional force equilibrium of the body of particles within the tube both in an open top and sealed tube during each vibration cycle.

4.2 Open Top Tube

For an open tube, there are three forces acting on the particles inside the tube (mg, F_{bed} and F_{wall}), as seen in figure 9(a). mg is the weight of the particles in the tube. It always acts in the downwards direction. F_{bed} is the force that the particles in the main bed, external to the tube, imposes on the particles within the tube. It always acts in the upwards direction but only when the particles in the tube are in contact with the bed which only occurs during the downwards part of motion of the tube. It displays an exponential relation with the inserting depth of the tube (h_{in}) [18-20], which is expressed as

$$F_{\mathrm{bed}} = C_{\mathrm{bed}} S \left(h_{\mathrm{in}} / D \right)^{b} \tag{1}$$

Where, b is the exponential coefficient, D is the tube diameter, $S = \pi D^2/4$ is the section area of the tube, and C_{bed} is the proportional coefficient. F_{wall} is the frictional shear force exerted between the tube wall and the particles entrained within. It acts to oppose relative motion between the particles and the tube. Several assumptions are made to analyze this friction force. One was to treat the granular system as a continuous medium. Vertical stresses in the granular system are transformed via contacts between the particles into horizontal stresses whilst moving the vertical boundary (tube wall). F_{wall} is influenced by the relative motion between tube wall and grains. When the wall slips uniformly with the particles, the friction between wall and particles can be computed according to the expression based on Bertho's experiments [21, 22].

$$F_{\mathrm{wall,uniform}} = mg - C_{\mathrm{dym}} G_{\mathrm{Jassen}} \tag{2}$$

Where $m = \rho_{\mathrm{layer}} S h$, C_{dym} is the dynamical coefficient, and G_{Jassen} is the force on bottom based on Janssen effect[23].

$$G_{\mathrm{Jassen}} = \rho_{\mathrm{layer}} g S \lambda \cdot \left[1 - \exp\left(-h/\lambda \right) \right] \tag{3}$$

Where, $\lambda = D/4\mu_{\mathrm{w}} k$, λ is an important parameter in the Janssen model known as the effective screening length, μ_{w} is the static friction coefficient between wall and particles, and k is the ratio between horizontal and vertical stresses, which gives an indication on how stresses are transmitted inside the grains. Under vibration, the wall undergoes accelerated motion, so the grains will be compacted and the force between the tube wall and the particles increases.

$$F_{\text{wall}} = C_{\text{g}} F_{\text{wall,uniform}} \tag{4}$$

Where, C_g is the coefficient induced by the tube's accelerated motion. Here, it is assumed that $C_{\text{g}} = \left[g + \left(a_{\text{tube}} - a_{\text{particle}} \right) \right] / g = 1 + \eta \Gamma$ when the tube is at accelerated rising/falling with reference to the particles in tube. η is a coefficient relevant to the relative motion between tube and particles, and $C_{\text{g}} = 1$ when the tube is at uniform or decelerated rising/falling. Therefore, we get the expression for the shear force (F_{wall}) from the moving wall

$$F_{\text{wall}} = (1 + \eta \Gamma) mg \left\{ 1 - C_{\text{dym}} \cdot \left(\lambda / h \right) \cdot \left[1 - \exp\left(-h / \lambda \right) \right] \right\} \tag{5}$$

Considering an open top tube, only two forces are active during the upwards phase of the motion. Particles can rise only when the upward force F_{wall} is large enough to overcome the weight of grains ($F_{\text{wall}} > mg$). Therefore, a minimum vibration strength (acceleration) acting on the tube (Γ_c) is necessary for upward motion of particles to occur.

4.3 Sealed Tube

In a sealed tube, there is an additional force active because the air pressure inside the tube (i.e. above the powder column within it) is lower than the atmospheric pressure ($P < P_0$) when the tube moves upward, as shown in figure 9(b).

By connecting a digital pressure meter to the hole drilled in the plug at the top of the sealed tube, we measured the pressure inside the tube (P_{tube}). Meanwhile, a high-speed camera was employed to record the motion of the tube and the particles inside the tube. Figure 10 shows the relationship between the pressure (difference) within the tube (P_{tube} - P_0) and the displacements of the tube and the particle at the surface level of the powder column over two vibration cycles for the beginning of vibration. The pressure difference (P_{tube} - P_0) is dependent on the relative movement between the tube and particles. When the tube moves upward, particle move upward as well. However, the tube moves faster than particles inside the tube. Therefore, the tube moves up relative to the particles, this creates more space above the powder surface in the tube which induces a pressure reduction compared to atmosphere (P_{tube} - $P_0 < 0$). The magnitude of the decrease in pressure is around 100 Pa. On the contrary, the pressure within the tube top is higher than the environmental pressure (P_{tube} - $P_0 > 0$) if the tube moves downward. In this case, the space above the powder surface in the tube decreases as the particle will keep rising for a short period when the tube moves downward, and then falling back more slowly than the tube.

Driven by the pressure difference due to tube moving upward, the interstitial air amongst the particles flows (upward) with a speed (u). Compared to the opened tube, this will induce an additional upward drag force (F_{d}) on the particles in the sealed tube in addition to F_{wall}, as shown in fig. 9(a). According to Darcy's law [24, 25], the vertical pressure gradient across the granular bed inside the tube is given by

$$\frac{\Delta P}{h} = \frac{\mu}{K} u \quad (6)$$

Where, K is termed the permeability coefficient for the bed, μ is the air viscosity and u is the average velocity of the fluid flow through the bed. The drag force on the bed medium (F_{d}) is related to the pressure drop by an equation:

$$F_d = S\Delta P \quad (7)$$

Substituting the cross sectional area of the tube $S = m/(\rho_{\text{layer}} h)$ into eq. (7), we can obtain the drag force as,

$$F_d = \frac{\Delta P/h}{\phi \rho_m} m \quad (8)$$

Where, ϕ is the packing fraction, and ρ_m is solid or true density of particle material ($\rho_{layer} = \phi\rho_m$), and m is the mass of granular bed. The permeability of the granular medium is well represent by Ergun relation [26],

$$K = (1-\phi)^3 d^2 / (180\phi^2) \tag{9}$$

The major unknown in the expression for the drag force is the velocity of the air as it moves through the particles in the tube. In consideration of the proportional relationship between the average velocity of air flow through the particle system (u) and the maximum speed of tube ($v_{tube} = A(2\pi f)$), (and knowing that u is smaller than v_{tube} due to the resistance from the bed), we make a simplifying assumption that $u \approx 0.2A(2\pi f) \approx 0.2\Gamma g/(2\pi f)$ as discussed in Ref [27].

Therefore, the ratio of upward air drag and gravity of the medium is

$$\frac{F_d}{mg} = \frac{\mu u}{k\phi\rho_m g} \tag{10}$$

4.4 Force Data and Results

To obtain indicative magnitudes of the different forces in the system at different levels of vibration intensity, typical values for the input parameters were selected. Three particle diameters (d) of 0.3 mm, 1 mm and 2 mm were investigated together with three levels of vibration intensity, Γ = 2, 3 and 5 (setting f = 12 Hz). The geometric parameters of tube diameter D and insertion depth h_{in} were set at 8 mm and 40 mm respectively. Regarding powder properties, powder solid density ρ_m = 2500 kg/m^3, packing fraction ϕ = 0.56 to 0.6, powder/wall friction coefficient μ_w = 0.05 and the stress ratio k = 0.38 to 0.40. Air viscosity is taken as μ =1.8×10^{-5} Pa·s. The following parameter values are also used C_{bed} = 3[18], C_{dym} = 1.01 and η =1. Inserting these values into the corresponding equations, we can obtain the magnitudes of the forces acting for the initial vibration cycle (the initial height of particles inside tube is equal to the insertion depth of tube in the bed $h = h_{in}$, 40 mm). The results are shown in figure 11.

The comparison of the magnitudes of forces that act on particles inside the tube can provide some clues to understand the observations present in this work. It is clear that for all particle diameters and vibration levels, the bed force (F_{bed}) which prevents the particles falling back down in the tube is always the dominant force in the system and explains the fundamental nature of the motion. Weight and wall friction force are approximately equal in magnitude; however the wall force increases strongly with increasing vibration intensity while obviously the weight force is insensitive to this. This explains the benefits of higher vibration levels in terms of achieving upwards particle motion. These three forces have a modest sensitivity to particle diameter (decreasing with as size increases) but this is not significant in terms of system behavior.

When the dimensionless vibration strength $\Gamma = 3$ ($\Gamma_C \leq \Gamma < \Gamma_D$) and with the same particle diameter (d = 0.3 mm), for the opened tube, the friction between the tube wall and the particles is not strong enough to overcome the gravity of particles ($F_{wall} < mg$, therefore the total force F_t ($F_t = F_{wall} - mg$) < 0 seen in fig. 11). Hence, particles lifted by the upward moving tube will suddenly fall into the void which prevent particles from the bed filling the void. As a result, no upward flow of particles in the open top tube is generated. However, when the tube is sealed at the top, due to the presence of an additional upward drag (F_d), the total upward forces are large enough to overcome the gravity ($F_{wall}+F_d > mg$, seen in fig. 11). It also means that the total force F_t ($F_t = F_{wall}+F_d - mg$) > 0. The upward drag forces impedes falling of the particles lifted by the tube. As a result, relatively more particles from the bed can enter the void in each vibration cycle compared to opened tube, seen in figure 9(b). Thus, the particles in sealed tube can rise, while failure in the opened tube with the same vibration strength, as shown in figure 3. If the tube vibrates at a low vibration strength ($\Gamma = 2$) which is smaller than the critical value ($\Gamma_c = 2.2$), particles in both tubes cannot move upward as the total upward forces ($F_{wall}+F_d$) are much smaller than or slight equal to mg. On the contrary, since the wall force is already high enough to support the gravity, $F_{wall} > mg$, particles in both tubes with high vibration strength (Γ = 5) can ascend. In addition, the drag force that is presented only for the sealed tube, increases strongly with vibration level but decreases strongly with increasing particle size. It is significant compared to the weight force for small particles but becomes almost negligible for the larger particles. Hence its positive effect on promoting upwards motion of the particles is only of value for fine grains.

5. Conclusion

Particles can be transferred vertically inside a vibrating tube inserted in a static container filled with granular material. The upwards motion is enhanced when the top of the tube is sealed. The additional benefits to motion that sealing the tube provides depend on the applied vibration intensity as outlined in the paper. Furthermore the final height of the granular column increases as the tube length (L) increases while the growth velocity is reduced compared to an open tube. Also particle conveying in sealed tube shows less dependence on tube diameter (D) compared to the opened tube. However the enhancement effect is suppressed with an increase in particle diameter. The improved performance of a sealed tube compared to an open tube can be shown to result from the generation of a drag force arising from the formation of a partial vacuum within the tube. Experimentally recorded effects can be explained by comparing the relative magnitudes of the forces that are present in the system. It is demonstrated that the drag force becomes significant compared to other relevant forces for small diameter particles at high levels of applied vibration.

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Figures.

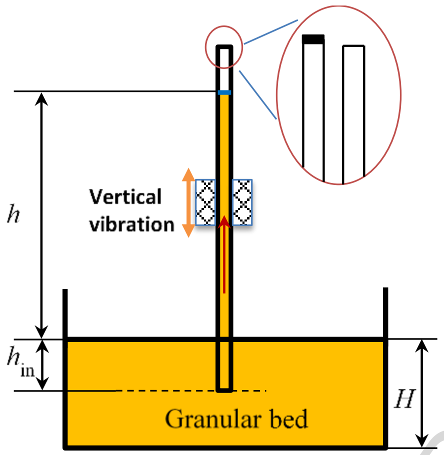

Figure. 1. Schematic figure of vibration lifting system.

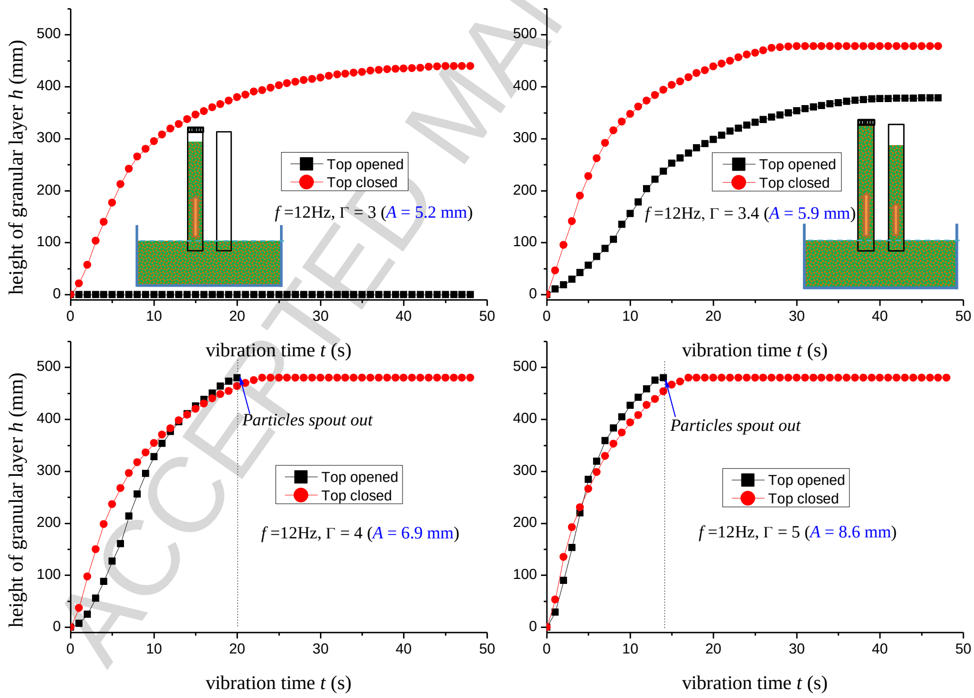

Fig. 2 Particle upward motions in vibrating pipe, the difference between open top (solid square) and closed top (solid circle) pipe under four kinds of dimensionless vibration strength at fixed vibration frequency *f* =12 Hz.

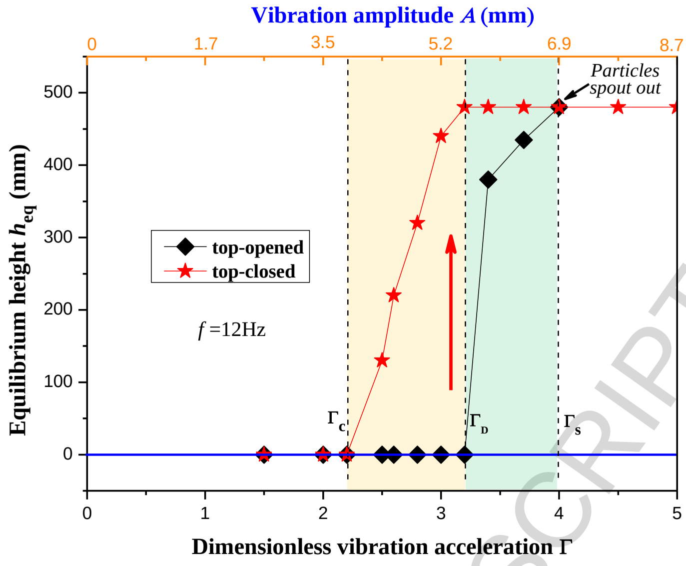

Fig. 3. Phase diagram of particle climbing, the difference between open top (solid diamond) and closed top (solid star) pipe where $f = 12$ Hz.

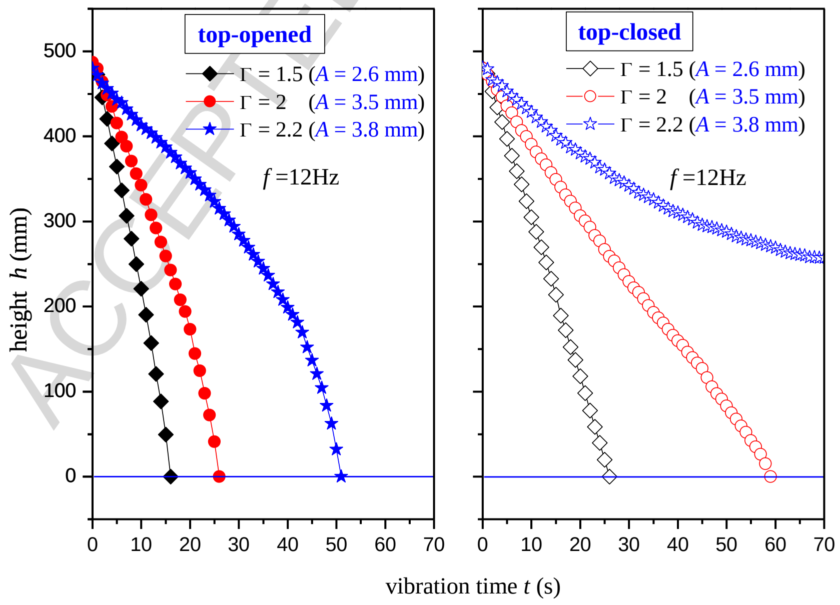

Fig. 4. Comparison particles falling with open top (solid) and closed top (hollow) pipes under 3 dimensionless vibration strengths at fixed vibration frequency $f = 12$ Hz.

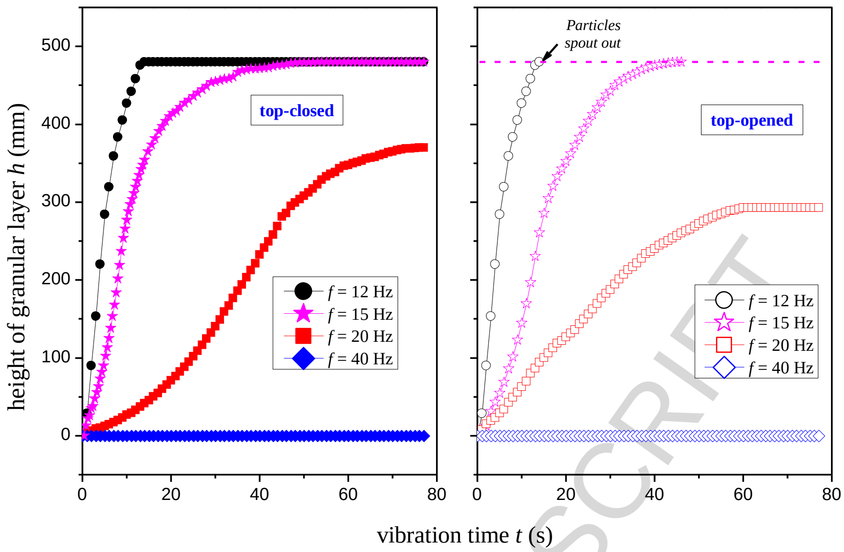

Fig. 5. Effect of vibration frequency on particles climbing both in closed top and open top tubes at a fixed dimensionless vibration strength (Γ = 5).

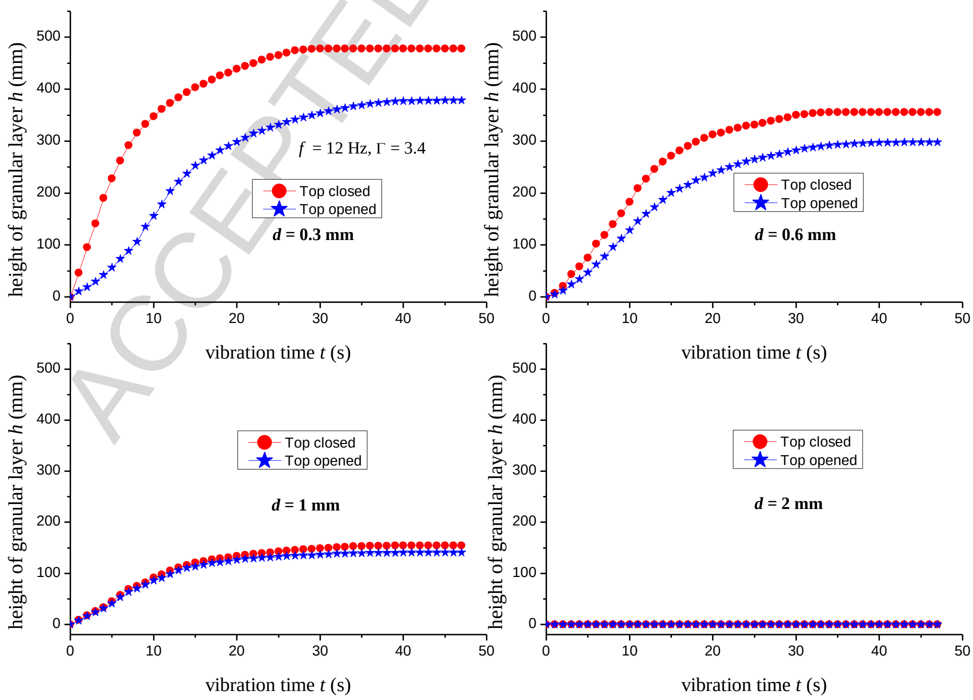

Fig. 6. Effect of particle size (*d*) on particles climbing both in closed top and open top

tubes where vibration frequency *f* = 12 Hz and the dimensionless vibration strength Γ = 3.4 (*A* = 5.9 mm).

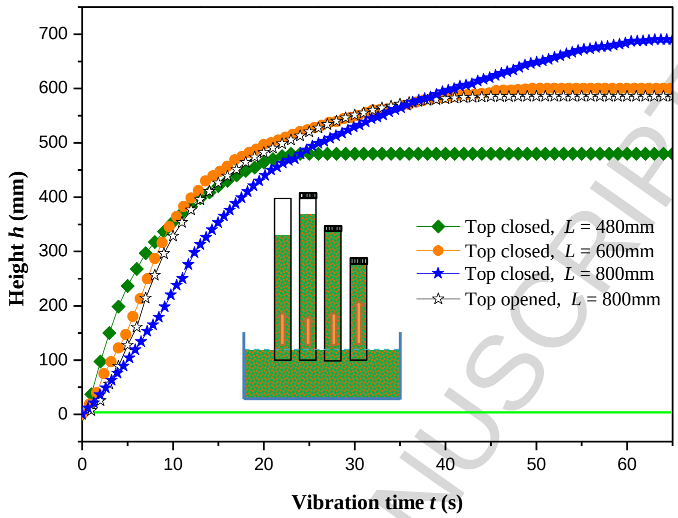

Fig. 7. Effect of pipe length (*L*) on particles climbing under the vibration conditions that vibration frequency *f* = 12 Hz and the dimensionless vibration strength Γ = 4 (*A* = 6.9mm).

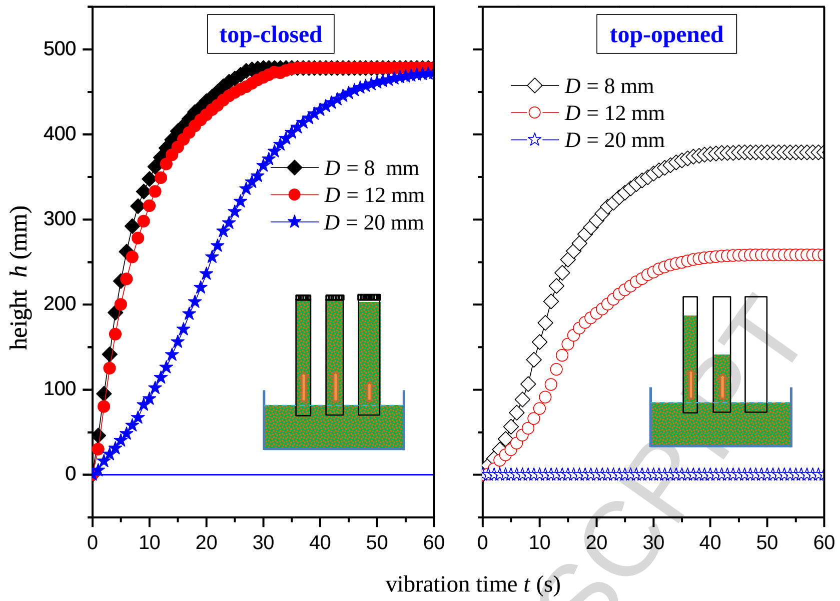

Fig. 8. Effect of tube diameter (*D*) on particles climbing under the vibration conditions that vibration frequency *f* = 12 Hz and the dimensionless vibration strength Γ = 3.4 (*A* = 5.9 mm).

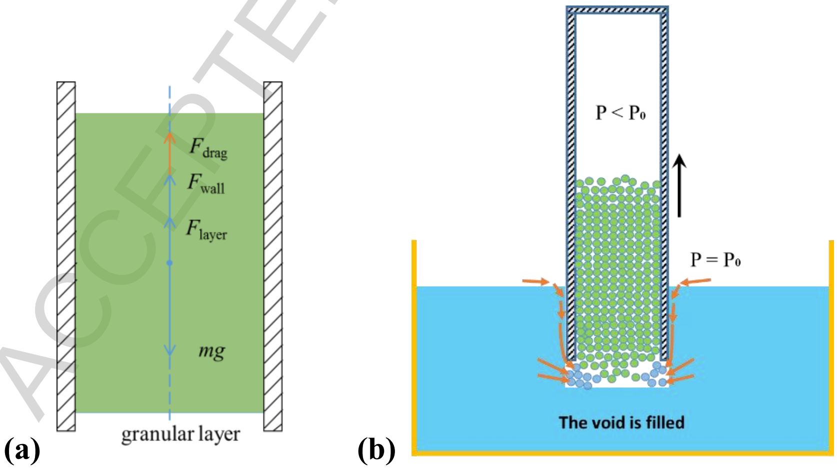

Fig. 9. (a) Forces acting on particles within vibrating tube. (b) The void underneath the tube filled by particles from the bed.

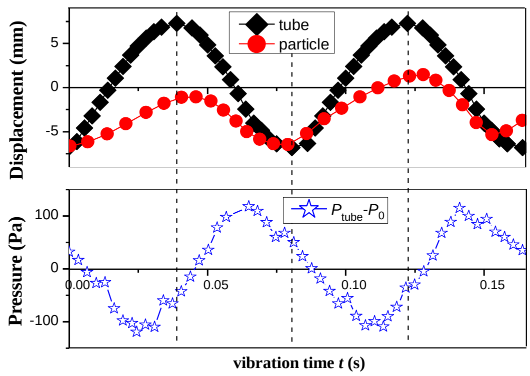

Fig. 10. Pressure within the sealed tube and the motion of the tube, and particle on the surface of granular column inside the tube over two vibration cycles where vibration frequency f = 12 Hz and the dimensionless vibration strength Γ = 4.

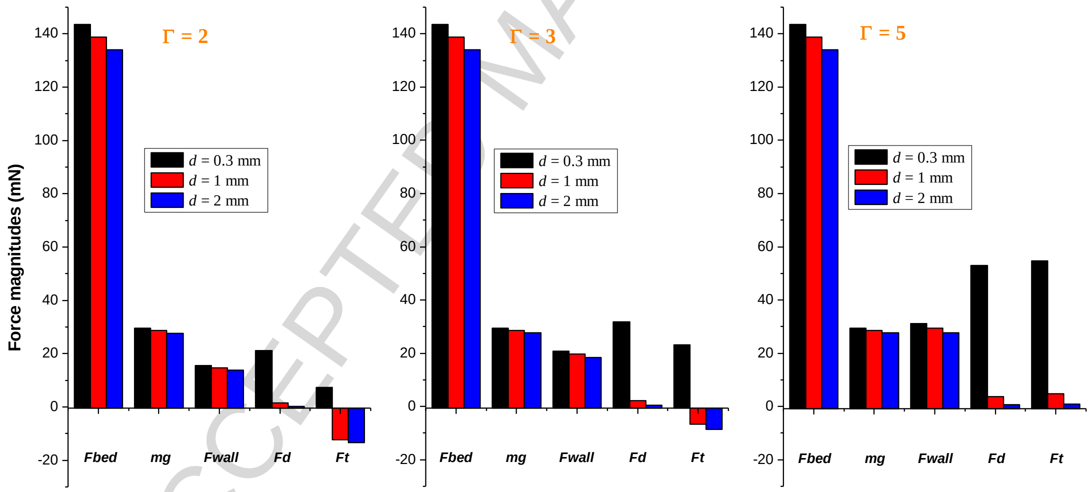

Fig. 11. Forces acting on particles inside the tube for the initial vibration cycle.

Highlights

- The conveying of grains is enhanced when the top of the tube is sealed.
- The enhancement effect works well for particles with smaller size (d < 1mm).
- Particle conveying in sealed tube shows less dependence on tube diameter.
- Sealing the tube top induces an additional upward drag force (F_d) on the particles in the tube.
  - F_d becomes significant for small diameter particles at high levels of vibration