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Effects of vibration parameters and pipe insertion depth on the motion of particles induced by vertical vibration

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ABSTRACT

Granular particles can be induced to move against gravity upwards through a pipe or tube that is partially inserted under the powder free surface while subject to vertical vibration. This offers a new approach for transporting bulk material. In this paper, the effects of both vibration parameters and insertion depth of a pipe on particle motion are experimentally studied. A minimum vibration amplitude (A) and frequency (f) are necessary for particle motion to occur. There is a monotonic increase of the final rise height of the powder (h_{eq}) with increasing amplitude A. However, h_{eq} exhibits a non-monotonic dependence on frequency, f. There is an optimum frequency at which particles climb highest, and any further increase of frequency leads to a diminishment of this upwards motion. A phase diagram of particle movement is presented which shows that different zones of motion exist. This unique finding suggests that the mechanism of particle movement is caused by the creation and filling of voids under the tube. Particles cannot move upwards when the pipe insertion depth, h_{in} is <1.5 mm irrespective of how strong the supplied vibration is. In general, increasing h_{in} can improve climbing, but this effect falls with increasing levels of insertion depth until a saturation level is reached.
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1. Introduction

Granular (Bulk) material is a widely used product form in the food, pharmaceutical and chemical industry. Being markedly different to traditional fluids, granular materials cannot be directly transported by pump as granular material is prone to jamming in pipes. [1–3] Pneumatic conveying is a common method of transferring bulk materials. There are two primary modes of pneumatic conveying; dilute phase where the particles are suspended in high velocity air and dense phase where the air velocity is much lower and the particles are pushed along in slugs [4,5]. However, the air speed must be much larger than particle's entrainment velocity. Because of the high-speed of the gas flow, the energy consumption is usually high and the pipe wall can be seriously abraded for dilute phase pneumatic conveying. This is particularly seen with high gas velocities, and especially at bends [6,7]. In dense phase pneumatic conveying as opposed to dilute phase, there is a higher likelihood of blockages. Dense phase pneumatic conveying system are also not self-cleaning and must be blown empty at regular intervals with a high-velocity pulse of air [8].

Estimates shows that 60% of many industrial plants' capacity is lost due to issues related to conveying of bulk materials from one part of the factory to another [9]. Hence, even a small advancement in transportation technologies of bulk media could have profound impacts for industry. [10] Accordingly, developing a new technology for transporting granular particles is of interest. Rather than using high speed air flow, granular particles can be caused to move in a variety of ways when submitted to vertical vibrations, such as granular convection [11], segregation and mixing [12,13], surface waves [14], arching [15] and fluidization [16]. Recently, based on our work [17,18], by inserting a straight pipe into a particle bed, we found that particles could climb against gravity in the pipe undergoing vertical vibration. The rate of upward movement and final height of the particles can be adjusted by changing vibration strength and the inserted distance of pipe under the powder surface. This novel effect demonstrated a unique approach for transporting granular materials continuously in the vertical direction.

In recent times, much attention has been drawn to investigate this novel phenomenon. Liu et al. [19] established a semi-theoretical mathematical relationship between the height achieved (h) and time (t), and discussed the change of the growth velocity and acceleration with t and h, respectively. By focusing on the effects of pipe geometry and size on particle motion, Zhang et al. [20] illustrated that particle motion

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was more sensitive to the pipe size rather than the shape of the pipe cross-section. Liu et al. [21] found that climbing in a tapered-tip pipe is enhanced because of the strengthened force chain in the assembled hopper compared with a straight pipe. With the help of the discrete element method (DEM), Xu et al. [22] quantified the change in solids volume fraction of particles in a vibrating pipe for each vibration cycle. It illustrated that with sufficiently high vibration strength, the formation of a dense region (high solids ratio) in the middle section of the tube and a low solids volume fraction region close to the lower end of the vibrating pipe occurs and is necessary to achieve particle motion. Also by means of DEM numerical simulations, Fan et al. [23] demonstrated that particle motion is caused by convection of the bulk material in the container. Moreover, they identified two regimes of behavior for the final height of particles depending on the tube-to-particle-diameter ratio.

Due to frictional interactions and inelastic collisions between powder particles and between particles and the pipe wall, the nature of particle motion is complex. The reasons why particles climb and the factors of how to control powder climbing, have not yet been fully understood. During the vibrations of the pipe, powder particles in the pipe are compacted and loosened alternately. The force between the pipe and particles varies periodically. Pipe insertion depth in the powder and vibration parameters (frequency and amplitude) play important roles in the force chain formation in the particle system, which is necessary to achieve motion. In order to apply this novel approach to convey granular material, there are still some issues that need to be clarified, such as how to optimize the vibration conditions for energy efficiency and capacity efficiency. In addition, the relationship between climbing height and time as affected by vibration frequency is less clear than the corresponding relationship for vibration strength up to now. Hence, this experimental work aims at verifying the effects of vibration parameters and pipe insertion depth on particles climbing. It systematically investigates the effects of vibration parameters (frequency, amplitude, and strength) and insertion depth on particle motion in a vibrating tube and interprets the results using a novel phase diagram. In particular, this paper marks the first time that research is focused on the role of frequency alone over a very wide range (10 to 80 Hz) on particle motion in detail. The results presented in this paper should suggest optimal approaches to implement vibratory vertical conveying of bulk material.

2. Experimental setup

The experimental setup (Fig. 1) consisted of a cylinder with 300 mm inner diameter filled with granular materials to an initial height of 200 mm. Specifically the container is filled with glass particles of average diameter (d_m) 0.45 mm with standard deviation of 10%. The sphericity of particles (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. Transparent plexi-glass pipes or tubes with inner-diameter of D (8 mm and 14 mm) are used. As shown in Fig. 1, a pipe is inserted into the bed of glass particles, and then is fixed to an electro-magnetic vibrator (LDS V555) with power amplifier and an acceleration sensor. The vibrator is able to 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 particles layer in the container shows almost no difference as the height of particles in pipe changes.

The pipe is inserted into the particle bed to an initial depth (h_{in}), then vibrates at a given vibration conditions, where the vibration parameters (vibration frequency and vibration amplitude) can be varied. 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 pipe (h) as a function of vibration time (t). Each test is performed three times, and the mean position accuracy is better than 1 mm. After vibration for a sufficiently long time, the height of particle layer in pipe remains unchanged even after at least one additional minute of vibrations (120f vibration cycles). This stabilized height of the particle layer in pipe is denoted as the equilibrium height (h_{eq}).

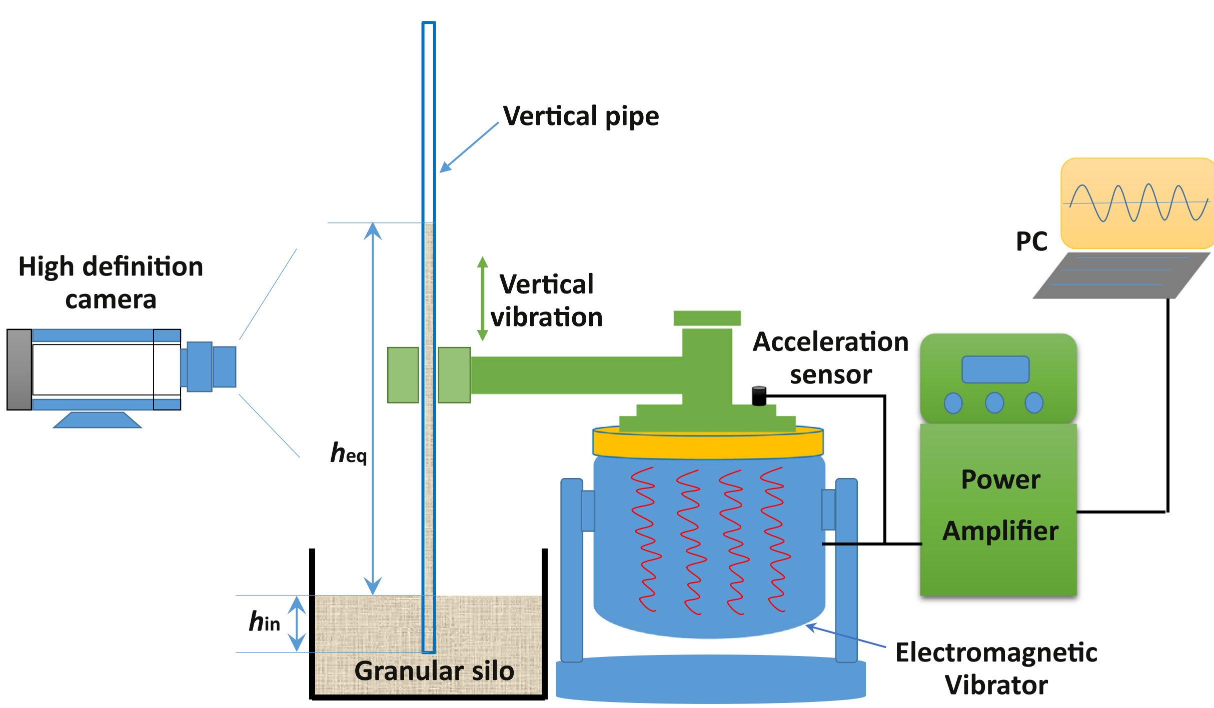

Fig. 1. Schematic diagram of experimental set-up.