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Effect of hoisting tube shape on particle climbing

Chuanping Liu [a], Fuweng Zhang [a], Ping Wu [b], Li Wang [a,c,*]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, China
[b] School of mathematics and physics, University of Science and Technology Beijing, China
[c] Beijing Engineering Research Center for Energy Saving & Environmental Protection, University of Science and Technology Beijing, China

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ABSTRACT

By inserting a vibrating tube in granular silo, particles can climb along the tube, named as "particle climbing". In this study, a hopper is assembled at the bottom of a straight tube that forms in a tapered-tip tube. The particle climbing in both the straight and tapered-tip tubes are studied. Particles can climb only when the vibration strength is large enough ($\Gamma > \Gamma_a$) or some particles are initially filled in the straight tube. By contrast, the climbing in the tapered-tip tube is easier because of the strengthened force chain in the assembled hopper. In addition, the particles can directly climb even when $\Gamma < \Gamma_a$ or without initial filling. In the tapered-tip tube, both the climbing velocity and the equilibrium height increase with the increasing of the vibration strength. As the tube diameter increases, the particles also can climb much higher. However, the climbing in the tapered-tip tube is insensitive to the inserting depth and the slope of the assembled hopper at the tube bottom.

1. Introduction

Granular material is widely used in the processes of metallurgy, mining, chemical industry, pharmaceutical industry, etc. Unlike traditional fluids, the granular material usually jams in pipe [1,2]; therefore, the material cannot be directly transported by pump. Most of the granular material is presently transported discontinuously, which cannot satisfy the modern industry production. With the high-speed gas/liquid flow, the granular material can be entrained and transported continuously, such as in pneumatic conveying [3–5]. However, pneumatic conveying is only proper for the dilute-phase gas-particle flow. For the dense gas-particle and granular flows, this method becomes invalid. The gas/liquid speed must also be larger than the particle's entrainment velocity. With the high-speed gas flow, the energy consumption is usually high and the pipe wall is abraded seriously.

Under vibration, the granular material becomes unstable and exhibit different properties from those of liquids and solids, such as convection [6], heap [7], clustering [8] and size separation [9,10]. When the bottom of two vibration beds (containers) connects, the particles in one bed can move to the other one. There are two main conditions. One is oscillatory [11], which is driven by the asymmetric collision properties between the two types of grains, and another is immigration [12–14], which essentially is an amplification of different force chains between the two beds.

By placing a straight tube in a vibration granular bed, the particles in the tube can rise a distance, which is induced by the air flow among the particles or the friction between the particles and the bed wall. When the tube keeps still, the particle rising [14–16] has a same essence with migration; and while the tube moves up and down freely, the particles can rise only at the condition that the tube-top is closed [17]. Liu et al. [18] insert a straight tube in a granular silo. The granular silo keeps still and the tube vibrates. The particles in the silo can also climb along the tube, which is named as "particle climbing".

Based on the phenomenon of "particle climbing" [18], a vibrating tube can be used as a granular pump for lifting the granular materials. The force chains of the particles in the tube are necessary for particle climbing. If the tube diameter is significantly large or the vibration strength is extremely weak, the particles in the straight tube cannot climb.

This study is based on our previous work [18], and a hopper is assembled at the bottom of the straight tube that forms in a tapered-tip tube. We analyze the differences between the straight tube and the tapered-tip tube by testing the effects of the vibration strength, inserting depth, tube diameter, and shape on particle climbing.

2. Experimental equipment

Fig. 1 shows the sketch of the experimental equipment. The bed is a transparent plexiglass cylinder with 178 mm inner diameter (Φ), filled with 100 mm initial height (H_{layer}) layer of silicate glass beads with 0.3 mm average diameter (d_p), 0.26 mm to 0.34 mm size distribution, 2556 kg/m^3 real density (ρ_p), and 1542 kg/m^3 bulk density (ρ_{layer}). The hoisting tube is made of silicate glass and is fixed on a vibrator (LDS V555), whose vibration parameters can be adjusted continuously.

* Corresponding author at: School of Mechanical Engineering, University of Science and Technology Beijing, China. Tel.: +86 10 62334425; fax: +86 10 62329145.
E-mail address: liwang@me.ustb.edu.cn (L. Wang).

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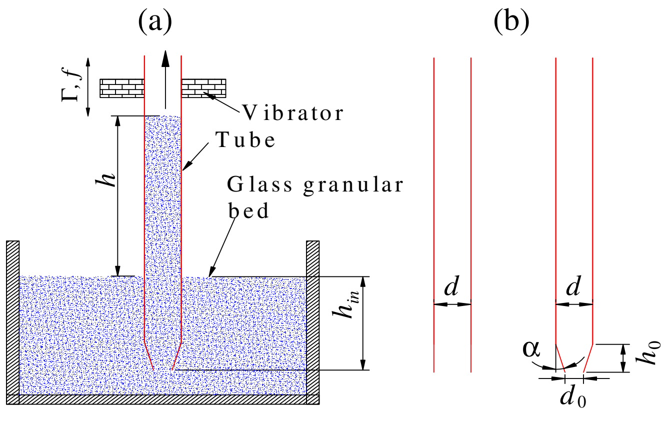

Fig. 1. Experimental equipment, (*a*) the sketch of equipment, where h_{in}—the inserting depth of the tube, and h—the climbing height; (*b*) the left sketch is the straight hoisting tube, where d—the diameter; the right sketch is the tapered-tip tube, where d_0—the diameter of the tube bottom, and α—the slope of the hopper.

Two types of hoisting tubes are used in our experiments, namely, straight and tapered-tip tubes. The tapered-tip tube is composed of a straight tube and a hopper at the bottom, as shown in Fig. 1(*b*), where d is the diameter of the tube, and d_0, h_0, and α are the diameter, height, and slope of the hopper, respectively. The sizes of the hoisting tubes are listed in Table 1.

Before experiments, the hoisting tube is partially inserted into the granular bed, where h_{in} is the inserting depth [Fig. 1(*a*)]. After the tube vibrates, the particles in the tube climb. The particle climbing is recorded by a digital camera, where h is the climbing height [Fig. 1(*a*)].

3. Experimental results

3.1. Particle climbing in hoisting tube

We insert the hoisting tube (Nos. 1 and 3) into the granular silo with 40 mm depth and vibrate the tube at a frequency $f = 12$ Hz. Fig. 2(*a*) and (*b*) show the particle rising/falling in the straight and tapered-tip tubes, respectively.

Straight tube (No. 1):

When the vibration strength (Γ) is 4, the particles in the granular silo climb along the tube gradually and their surface finally stays at 580 mm height (equilibrium height h_{eq}) [hollow diamond in Fig. 2(*a*.1)], where $\Gamma = (2\pi f)^2 / g$, f is the vibration frequency, and g is the gravity acceleration. We initially fill some particles in the tube before vibrating. If the initial filled height is lower than h_{eq}, the particles climb into h_{eq}. If the initial filled height is higher than h_{eq}, the particles finally fall into h_{eq} [solid diamond in Fig. 2(*a*.1)].

When the vibration strength is 2.5, the particles cannot climb directly from the granular silo [hollow circle in Fig. 2(*a*.2)]. However, if some particles are initially filled in the straight hoisting tube and the filled height is slightly higher than the critical value (h_c, about 80 mm), the particles in the tube can climb and finally keep at the corresponding equilibrium height [hollow square in Fig. 2(*a*.2)]. If the filled height is lower than h_c, the initial filled particles fall into the silo [solid circle in Fig. 2(*a*.2)]. If the filled height is higher than h_{eq}, the particles fall into h_{eq} [solid square in Fig. 2(*a*.2)].

When the vibration strength is 2 [Fig. 2(*a*.3)], the particles cannot climb despite the tube's being initially filled. If the tube is initially filled, the filled particles fall into the granular silo.

Tapered-tip tube (No. 3):

When the vibration strength (Γ) is 4, the particles in the silo climb along the tube gradually and their surface finally stays at 570 mm height (the corresponding equilibrium height h_{eq}) [hollow diamond in Fig. 2(*b*.1)]. The climbing in the tapered-tip tube is similar to that in the straight tube. If the initial filled height is higher than the equilibrium height, the particles finally fall into the equilibrium height. Compared with the straight tube, the falling in the tapered-tip tube is very slow and the falling time from 720 mm height to h_{eq} is about 1.1 h.

With the decreasing of the vibration strength ($\Gamma = 2.5$ and 1.5), the particle in the silo can also climb directly. The equilibrium height (h_{eq}) decreases with the decreasing vibration strength [Fig. 2(*b*.2) and (*b*.3)].

Fig. 3 shows the particle rising/falling phase diagram under different vibration strength and initial filled height. Zone I represents the particle rising, and zone II represents the particle falling. When $\Gamma > \Gamma_b (\Gamma_b = 3.5)$, the particle climbing in both the straight and tapered-tip tubes is similar, i.e., the particles can climb from the silo to the equilibrium height. When $\Gamma_a (\Gamma_a = 2.2) < \Gamma < \Gamma_b (\Gamma_b = 3.5)$, a critical height h_c exists for the straight tube. If the initial filled height is higher than h_c, the particles climb or fall. When $\Gamma < \Gamma_a (\Gamma_a = 2.2)$, the particles in the straight tube cannot climb. By contrast, the particles in the tapered-tip tube always can climb from the silo directly even when $\Gamma < \Gamma_b$.

3.2. Effect of inserting depth on climbing

Fig. 4(*a*) shows the particle climbing in a 10 mm straight tube (No. 1) with different inserting depths (h_{in}). When $h_{in} = 25$ mm, the climbing velocity increases at first and then decreases gradually. Finally, the particles climb to the equilibrium height (430 mm) [square line in Fig. 4(*a*)]. When the inserting depth increases from 20 mm to 40 mm, the particles climb faster and the equilibrium height is higher [circle line in Fig. 4(*a*)]. With the increasing of the inserting depth to 60 mm, the effect of the inserting depth on climbing is weakened. As shown by the circle and diamond lines in Fig. 4(*a*), the climbing with 60 mm inserting depth is similar to the climbing with 40 mm inserting depth. Fig. 5(*a*) shows the effect of the inserting depth on the rising/falling phase diagram. With the increasing of the inserting depth, both Γ_a and Γ_b decrease and the climbing zone expands, which indicate that the particle climbing becomes easier.

For the tapered-tip tube, the climbing velocity decreases with the increasing of the climbing height and the climbing equilibrium height is hardly influenced by the inserting depth. With 25, 40, and 60 mm inserting depths, the particles can climb from the silo when the vibration strength is from 1.5 to 5. Fig. 4(*b*) shows the particle climbing in the tapered-tip tube (No. 3) at $\Gamma = 4$, and Fig. 5(*b*) shows the effect of inserting depth on its phase diagram.

3.3. Effect of tube diameter on climbing

By inserting the straight tube into the silo with 25 mm depth and vibrating it at a strength of 4, the particles in the silo can climb along the 10 mm straight tube (No. 1), as shown by the square line

Table 1
Size of hoisting tube.

No.	Type	Diameter of tube d(mm)	Diameter of hopper d_0(mm)	Height of hopper h_0(mm)	Slope of hopper α(°)
1	Straight tube	10	10	–	–
2		20	20	–	–
3	Tapered-tip tube	10	5	15	9.5
4		20	10	5	45
5		20	10	15	18.4
6		20	10	30	9.5
7		30	10	60	9.5