

Dynamics of particulate materials discharged in a granular vibration pumping system

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Abstract. A granular vibration pumping system, which vertically transports particles using a vibrating pipe, offers industrial advantages, such as a compact design, high dust tolerance, and the elimination of pneumatic materials. When the pipe is inserted into particulate materials and vibrated, particles climb inside through a process known as granular capillary action. While earlier studies focused on the height of particle ascent in a pipe, this research emphasizes particle expulsion and transport dynamics, which are more critical for practical applications. High-speed camera observations revealed a unique granular fountain phenomenon at the outlet of a straight pipe. In addition, experiments with a bent pipe were performed to facilitate the collection of transported particles, enabling the evaluation of granular transport rates under various vibration conditions.

1 Introduction

Manufacturing often involves various particulate materials that require suitable handling techniques. Among the many handling processes, one crucial process is the vertical transport of particles against gravity [1]. This study focuses on a granular vibration pumping system, which utilizes only a pipe and a vibration source to vertically transport particulate materials [2]. When a pipe is inserted into the bulk bed of particles and vibrated, the particles climb inside the pipe; this phenomenon is known as granular capillary action [3,4]. Although this resembles liquid capillary action, the underlying mechanisms are fundamentally different. Due to its unique and simple operation, this system provides numerous advantages for industrial applications, including a compact design, high tolerance to dust contamination, and the elimination of pneumatic materials.

Previous studies on this emerging technology have examined the influence of key parameters, including vibration conditions [3], pipe geometry [5], particle size [6], and particle type [7], on the climbing height within a pipe. Moreover, several numerical studies have been conducted to understand the dynamics of particles inside a pipe and sample cell [4,8]. When particles reach the top end of a pipe, they are expelled [2]. For practical applications, the collection of expelled particles is more critical than merely evaluating the climbing height. However, the particle expulsion behavior and particle transport characteristics have not yet been thoroughly investigated.

This study advances the understanding of particle dynamics at the outlet of a granular vibration pumping system. High-speed camera observations were employed to investigate the motion of particles at the outlet of a straight pipe, revealing and characterizing a unique granular fountain phenomenon. Furthermore, experiments using a bent pipe were also conducted to facilitate the collection of transported particles and to evaluate granular transport rates under various vibration conditions.

2 Experimental setup

Fig. 1 (a) shows the experimental setup, which uses an eccentric cam mechanism to convert rotational motion of an AC servo motor (NX975AS-3, ORIENTAL MOTOR) into linear motion to vibrate an acrylic pipe with inner and outer diameters of 8 mm and 16 mm, respectively (see details in the literature [2]). The eccentricity of the cam follower corresponds to the vibration amplitude, and the rotation speed determines the vibration frequency.

A straight acrylic pipe was immersed to a depth of 75 mm into spherical glass beads with diameters of 100–250 μm , which were contained in a cylindrical sample cell (outer diameter: 200 mm, height: 250 mm). When the pipe was vibrated, particles began climbing inside it. The motions of particles reaching the pipe tip were recorded using a high-speed camera (HAS-EF, DITECT). Subsequently, the behavior of expelled particles was analyzed using image-processing software developed based on OpenCV.

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In the following experiments, an acrylic pipe with a bent tip was employed to guide particles to a collection box placed on an electronic scale (GF-6001A, A&D), which enabled the measurement of transported particle weight over time (Fig. 1 (b)). Various vibration conditions were tested, and the flow rate of the transported particles was evaluated.

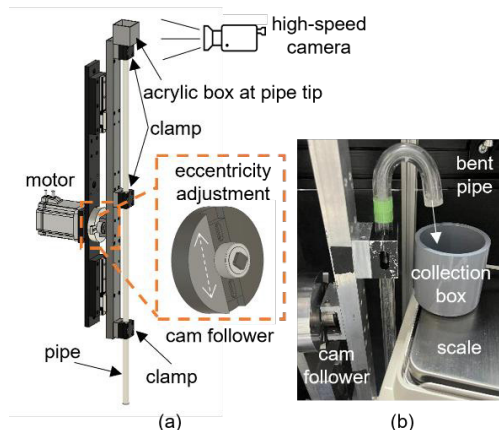


Fig. 1. Experimental setup of the granular vibration pumping system, which employs an eccentric cam mechanism to vibrate (a) a straight pipe for vertical particle transport and (b) a bent pipe for collecting transported particles.

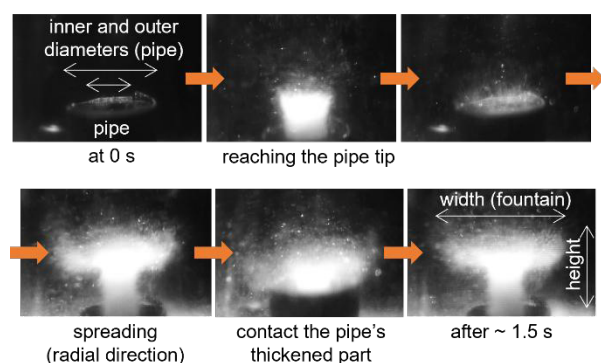


Fig. 2. Overflow of particles reaching the tip of the vibrating pipe. The size of the particle clump gradually increased over time, eventually forming a granular fountain structure (pipe length: 250 mm, insertion depth: 75 mm, vibration amplitude and frequency: 3 mm and 20 Hz, respectively).

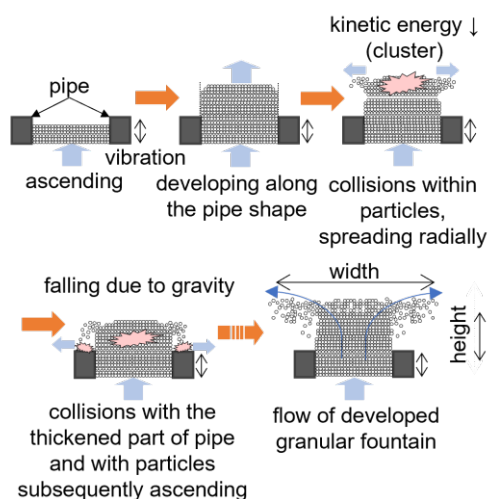


Fig. 3. Schematic showing the development of the granular fountain and its defined dimensions.

3 Results and discussion

3.1 Granular fountain from a straight pipe

When the setup was operated for an extended period, particles reached the top of the pipe and began to overflow, as shown in Fig. 2. Particles near the pipe's upper tip oscillated vertically as they entered and exited the pipe, and the particle clump gradually grew and ascended. As the number of expelled particles increased, they began to form a structure that resembled a liquid fountain. This newly observed phenomenon is referred to as a "granular fountain".

In addition, image processing was applied to the recorded granular fountain, and the temporal variations in its outer dimensions (height and diameter along the radial direction of the pipe) were measured, as shown in Fig. 2. Fig. 3 shows a schematic of the temporal development of the granular fountain, while Fig. 4 shows that the height and diameter of the discharged particle cluster increased periodically in response to the vibration of the pipe and eventually reached a steady state. Initially, the particles rose vertically along the shape of the pipe outlet. However, as the particles reached a certain height, some began to move radially outward due to collisions with other particles, leading to the expansion of the granular fountain. Consequently, the particles came into contact with the thickened part at the pipe tip. These particles acquired kinetic energy directly from the pipe, causing them to float upward and spread radially. The height of these particles gradually increased until reaching a saturation point. This saturation was attributed to cluster formation resulting from energy loss due to gravity and inter-particle collisions. As the particles lost energy, they tended to cluster near the central axis of the pipe, while those located farther outward in the radial direction experienced fewer collisions and continued to move outward.

During this process, the granular fountain initially fluctuated in synchronization with the vibration cycle, as shown in Fig. 4. However, large and small peaks began to emerge over time. The large peaks formed when particles were lifted by the pipe vibration, while the small peaks occurred when the floating particles in the large peaks descended and collided with other particles during the following vibration cycle. Since the particles that reached greater heights required more time to fall, the peak cycles gradually shifted, resulting in a repeating pattern in which the granular fountain exhibited a distinct shape change every two vibration cycles.

Fig. 5 shows the dimensions of the granular fountain after it had sufficiently developed under different pipe lengths. Additionally, the maximum floating heights of individual particles, which were not part of the granular fountain and could be individually identified in the images, were also measured. As shown in Fig. 5, the height and diameter of the fountain decreased as the pipe length increased. This was primarily because the number of particles expelled from the pipe decreased with increasing pipe length. However, the height of

individual particles that did not contribute to the fountain formation increased with the pipe length. This increase in height occurred because the granular fountain became smaller, and most particles floated independently, resulting in less energy loss due to fewer particle collisions. As a result, the individual particles reached higher positions, exceeding the height of the fountain.

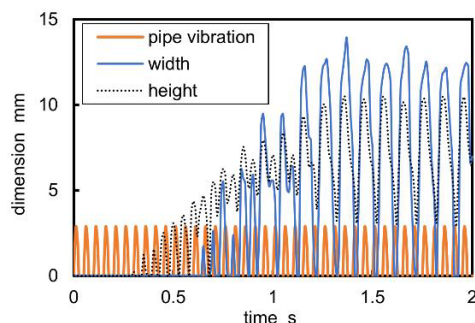


Fig. 4. Time evolution of the granular fountain in synchronization with the pipe vibration (pipe length: 250 mm, insertion depth: 75 mm, vibration amplitude and frequency: 3 mm and 20 Hz, respectively).

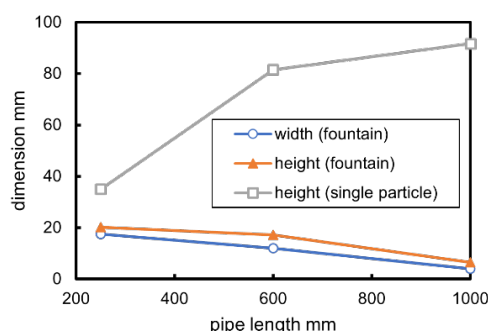


Fig. 5. Dimensions of the granular fountain and maximum floating heights of individual particles not contributing to fountain formation, measured using pipes of different lengths (insertion depth: 75 mm, vibration amplitude and frequency: 3 mm and 17.5 Hz, respectively).

3.2 Transport rate using a bent pipe

In addition to evaluating the behavior of the granular fountain, the particle transport rate was also assessed as a practical performance metric. The bent pipe was used to guide particles to the collection box (Fig. 1 (b)). Figs. 6 and 7 show the weights of particles transported over a period of 60 s, when the vibration frequency and amplitude were varied, respectively. As shown in Fig. 6, the weights of transported particles consistently increased over time at all tested frequencies. Furthermore, the transport rate increased with the vibration frequency. Similarly, as shown in Fig. 7, the transport rate increased with greater amplitude. The increase in transport rate at higher vibration frequencies and amplitudes was attributed to stronger lifting forces acting on the particles. The maximum acceleration of the sinusoidal vibration is proportional to the vibration amplitude and the square of the frequency. Therefore, the particle flow rate can be controlled by adjusting the vibration conditions in the granular vibration pumping system.

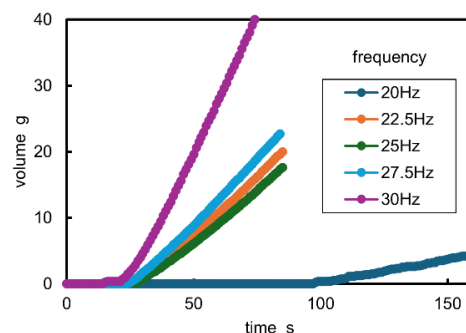


Fig. 6. Weights of transported particles under varying vibration frequencies (pipe length: 850 mm, insertion depth: 75 mm, vibration amplitude: 3 mm).

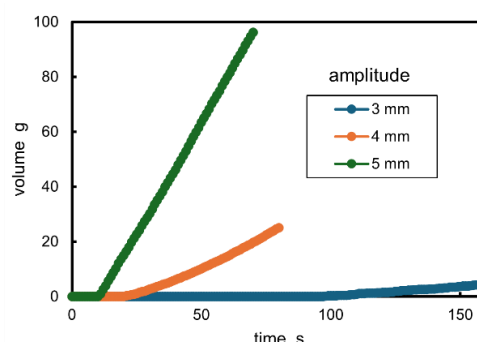


Fig. 7. Weights of transported particles under varying vibration amplitudes (pipe length: 850 mm, insertion depth: 75 mm, vibration frequency: 25 Hz).

Furthermore, the transport rates of particles during long-term operation were investigated. The pipe insertion depth was set to 50 mm, shorter than that used in previous experiments (75 mm), as a shallower insertion depth enabled better observation of changes in the transport state over a shorter time span. As shown in Fig. 8, continuous particle transport gradually reduced the flow rate, and eventually, particle discharge stopped. This phenomenon is attributed to a decrease in particle pressure near the pipe inlet. As particles flowed out, the powder level in the sample cell decreased, even though the pipe inlet remained fully covered by particles. The reduction in particle quantity led to a drop in particle pressure near the pipe inlet, and the upward force exerted by the vibrations became insufficient to overcome the gravitational force acting on the particles inside the pipe, resulting in the cessation of transport.

To address this cessation, an equivalent quantity of outflowing particles was supplied when the flow rate reached zero (Fig. 8). This addition allowed particle transport to resume. From these results, five states during transport were identified: (1) The particles ascend inside the pipe but have yet to reach the pipe tip, during which the flow rate remains zero. (2) Particles begin to flow out (first outflow), causing the flow rate to increase. (3) As the amount of powder in the sample cell decreases and particle pressure drops, the flow rate gradually reduces. (4) The flow rate reaches zero, while the subsequent particles in the pipe no longer ascend. (5) When additional particles are supplied, particle outflow resumes (second outflow). The flow rate gradually decreases again, eventually repeating the cycle described in States 3 and 4.

Fig. 9 shows the flow rate of particles during the first and second outflows, as a function of the dimensionless vibration strength Γ , which is defined as the maximum vibration acceleration divided by gravitational acceleration. As the vibration strength increased, both flow rates increased. This trend was the same as that shown in Figs. 6 and 7. Although an equivalent quantity of outflowing particles was added during State 4 to minimize changes in pressure caused by particles in the sample cell, it was observed that the flow rate during the second outflow (State 5) was slightly lower than that during the first outflow (State 2). This was probably because climbing particles experienced less resistance during the first outflow. During the first outflow, particles ascended through an empty pipe, allowing a greater force to eject particles from the pipe tip. In contrast, during the second outflow, the pipe was already filled with particles, leading to greater resistance and a reduced force for particle ejection from the pipe tip compared to the first outflow. In addition, the variation in particle density could also contribute to the difference in flow rate. When additional particles were supplied, the particle density near the pipe inlet was likely lower than that in the initial state. This lower density may have resulted in fewer particles entering the pipe and a corresponding reduction in particle pressure. However, the difference between the first and second flows was not significant, and both flow rates were effectively controlled by varying the vibration conditions.

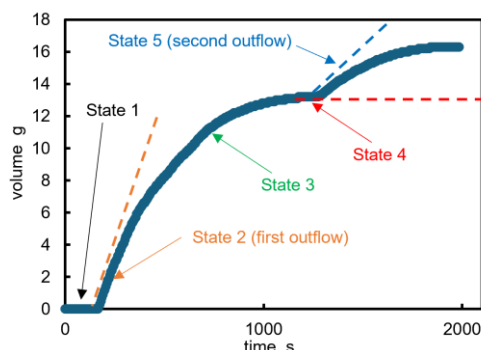


Fig. 8. Temporal variation in the weight of transported particles and the five observed transport states (pipe length: 850 mm, insertion depth: 50 mm, vibration amplitude: 3 mm, vibration frequency: 25 Hz).

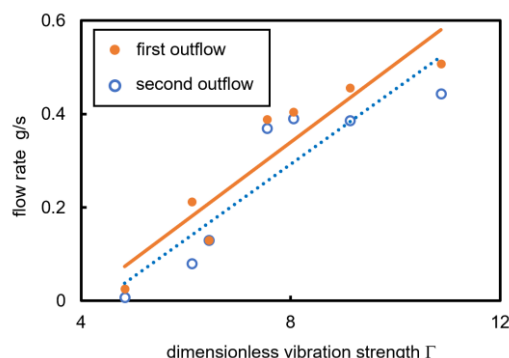


Fig. 9. Flow rates during the first and second outflows under varying dimensionless vibration strengths (pipe length: 850 mm, insertion depth: 50 mm).

4 Conclusion

This study provides fundamental insights into particle dynamics at the outlet of a granular vibration pumping system, which are essential for optimizing its practical applications. A granular fountain was observed when a straight pipe was used, and its time-dependent characteristics were clarified. Additionally, a bent-tip pipe was employed to evaluate the flow rate of transported particles, which was significantly influenced by the state of particles in the sample cell. The resulting flow rate was shown to be controllable under optimized vibration conditions. These findings reveal fundamental properties of the granular vibration pumping system used for practical applications.

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