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Vibration Shear Flow of Fine Particles and Its Application for Micro-feeding

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A novel micro-feeder for fine particles using a vibration shear flow mechanism has been developed. The feeder consists of a cylindrical tube and a bottom, which are both vibrated. Particles in the tube are discharged through a narrow gap between the lower edge of the tube and the bottom surface. In this article, the features of vibration shear flow and the performance of micro-feeding are summarized based on our experimental results. In particular, it is shown that fine particles, including nanoparticles, can be quantitatively discharged as agglomerated particles and are effectively disintegrated owing to vibration shear flow.

1. Introduction

The demand for submicron and nanoscale particles is increasing because of the need to produce highly functional products. However, as adhesiveness increases with decreasing particle diameter, powder handling becomes more complex for these small particles. This is particularly an issue for particles with diameters less than 10 µm. In cases where complications due to adhesiveness are pronounced, it is imperative to develop new techniques to analyze particle behavior and overcome these issues. When fine particles come into contact with other particles or walls, adhesive forces act on the surfaces. In order to reduce the adhesive forces and fluidize the particles without fluid flow, mechanical forces such as vibration must be continuously applied. As an example of application, the micro-feeding of fine particles using a vibrating tube can be cited (Matsusaka et al., 1996). Micron-scale particles were quantitatively discharged by the feeder; however, there were difficulties in quantitatively discharging submicron particles by the feeder. This problem was solved by applying ultrasonic vibrations to the tube wall (Matsusaka et al., 1995). After these pioneering works, relevant studies were conducted. Yang and Evans (2003, 2004) used acoustic vibrations to discharge micron-scale particles. Yang and Li (2003), Lu et al. (2006, 2009) used ultrasonic vibrations to discharge micron-scale and submicron particles. Even though the ultrasonic vibration is applied, the discharge of nanoparticles is still difficult. Therefore, the development of a new method that improves powder flow is required. To achieve this, an experimental study was conducted on micro-feeding by vibration shear flow. (Matsusaka et al. 2012a, b). This mechanism of vibration shear flow was also applicable to characterize powder flow by adding a device with variable vibration amplitude (Zainuddin et al., 2012a, b), whose technique was used to the vibrating tube method (Jiang et al., 2006, 2009; Horio et al., 2013). In this article, the feature of the vibration shear flow of fine particles and its application for micro-feeding are summarized based on our experimental results.

2. Experimental

2.1 Setup

Figure 1 shows the experimental setup. This system consists of a vibrating cylindrical tube, a vibrating bottom, and measurement devices, i.e., a laser vibrometer and a digital balance. The length, inner diameter, and outer diameter of the cylindrical tube are 210 mm, 18 mm, and 22 mm, respectively (or the inner and outer diameters can be 16 mm and 20 mm, respectively). The cylinder was held vertically, and the bottom, which had the same diameter as the outer diameter of the tube, was placed below the vibrating tube with a narrow gap. Particles in the tube are discharged from the narrow gap. As fine particles tend to agglomerate owing to adhesiveness, vibration was applied to prevent the particles from blocking the narrow gap.

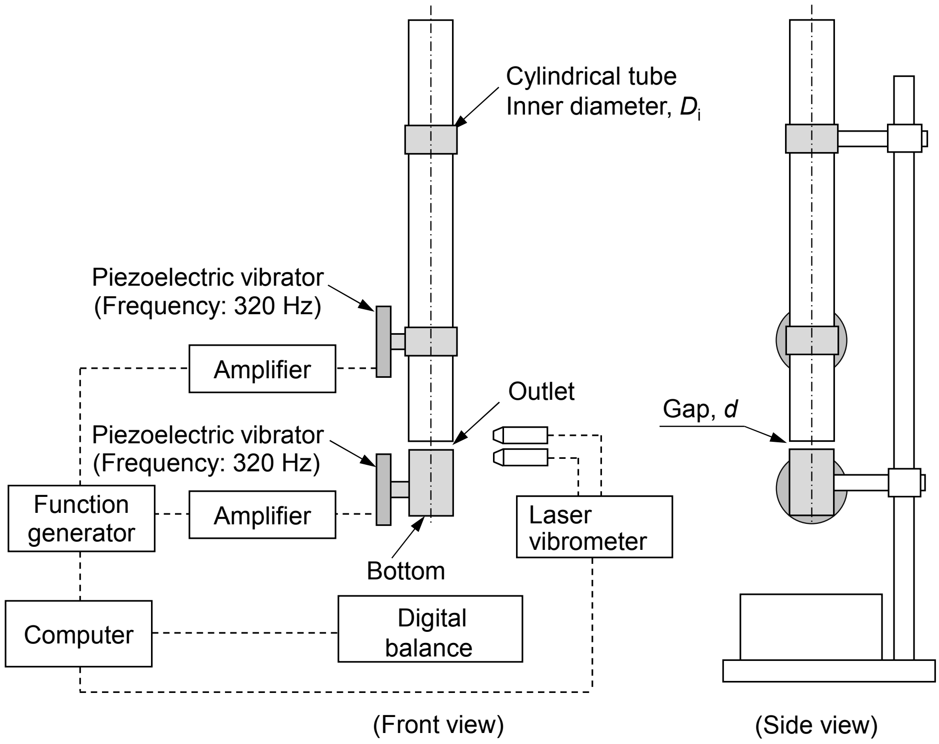


Figure 1: Experimental setup.

The mass flow rate of particles will depend on operation factors, such as the gap distance, vibration acceleration, and powder flow. In this experiment, the gap distance ranged from 0.2 to 3.0 mm. To vibrate the tube and the bottom, two piezoelectric vibrators were fixed to their sidewalls. The shear flow of particles in the gap could take place owing to two horizontal vibrations. The vibration amplitude and phase were controlled by a feedback system (VST-01, IMP Co., Ltd., Japan). In-phase and anti-phase vibrations were applied to the system. The vibration acceleration (α) is expressed by the following equation.

$$\alpha = A\,(2\pi f)^2 \tag{1}$$

where A is the amplitude of vibration and f is the frequency. In this experiment, the frequency was fixed at 320 Hz, and the resonance was taken into account. To measure the mass of the discharged particles, the digital balance with a resolution of 0.1 mg was used.

2.2 Powders

Alumina powders with different mean diameters (D_p = 10 μm and 0.4 μm) and silica nanoparticles with a mean diameter of 12 nm and 7 nm were used. The powders were dried at 120 °C for 24 h and cooled to room temperature in a desiccator. All the experiments were conducted at normal room conditions.

3. Fundamental of vibration shear flow

Figure 2 illustrates the discharge of particles through the narrow gap between the lower edge of the tube and the bottom surface, which is observed by a high speed camera with a zoom lens. In-phase and anti-phase vibrations are shown in this figure. The particles in the gap experience gravity; however, without vibration, the particles do not flow due to adhesiveness and static friction against the tube and bottom surfaces. When the tube and the bottom oscillate horizontally, a shear field is generated under the lower edge of the tube; thus, adhesive and frictional forces are reduced. As a result, the particles in the gap can move horizontally and fall from the bottom surface by gravity. Here, it is worth noting that a pulsating flow occurs in the shear flow. The frequency of the pulsating flow is equal to the frequency of the piezoelectric vibrators. Therefore, the particles in the gap can move in response to quick changes in external forces. Similar features of the vibration shear flow of fine particles were observed by Zainuddin et al. (2012a). The illustrations show that the anti-phase vibration is more effective to disintegrate fine-particle agglomerates than the in-phase vibration.

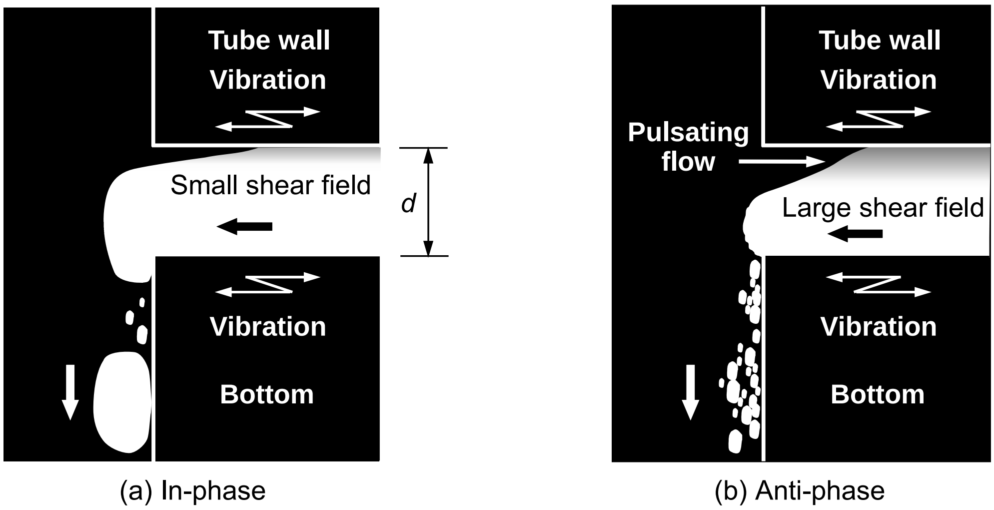


Figure 2: Cross-sectional schematic illustrations of vibration shear flow at the narrow gap, i.e., the outlet slit for powder discharge.

4. Results and discussion

4.1 Powder discharge of micron scale particles

Figure 3 shows the photographs of the discharge of alumina particles (D_p = 10 μm) during in-phase and anti-phase vibrations. The particles are generally agglomerated owing to adhesiveness, but the size of agglomerated particles during anti-phase vibration is smaller than that during in-phase vibration. For the in-phase vibration, the shape and size of agglomerates seems to be determined by the gap distance, while the agglomerated particles were effectively disintegrated due to the vibration of shear flow during anti-phase vibration.

Figure 4 shows the size distribution of the agglomerated particles that discharged from the gap as a parameter of gap distance. The size of the agglomerated particles increases with an increase in the gap distance. The experimental data quantitatively shows that the size of agglomerated particles during anti-phase vibration is smaller than those that occurred during in-phase vibration.

Figure 5 shows the performance of micro-feeding for particles with a mass median diameter of 10 μm and 0.4 μm. The mass flow rate can be controlled by the gap distance. When the gap distance is large, the mass flow rate during in-phase vibration is large compared to the mass flow rate during anti-phase vibration. In addition, it was found that the mass flow rate decreases with a decrease in the mass median diameter of particles.

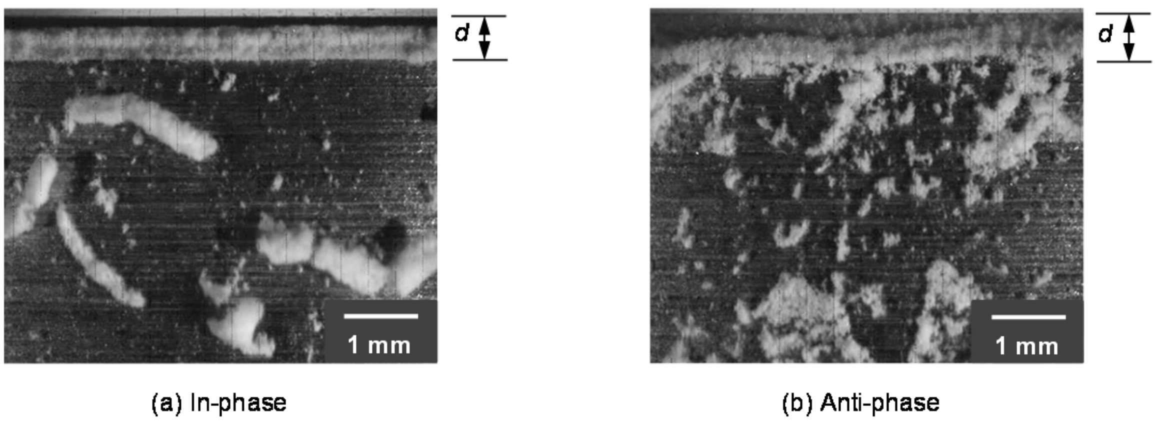


Figure 3: Photographs of powder discharge (Al_2O_3, particle diameter D_p = 10 μm, gap distance d = 0.6 mm, vibration amplitude A = 20 μm).

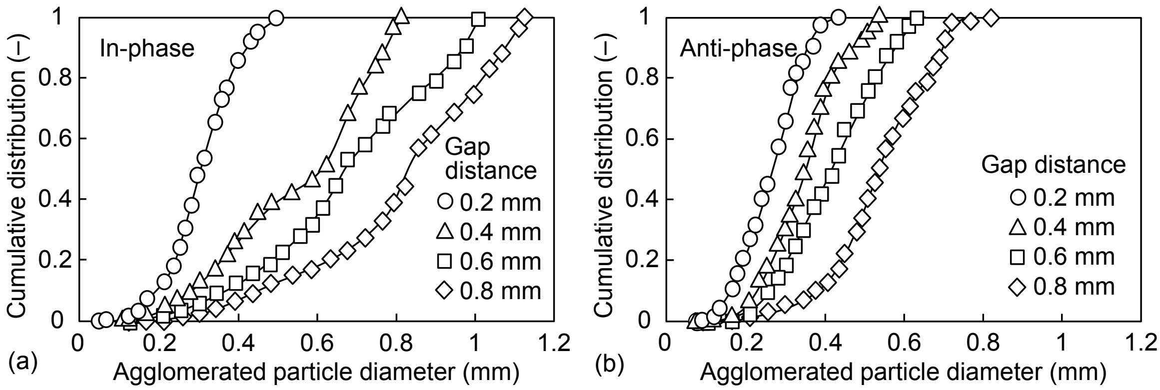


Figure 4: Mass-based agglomerated particle size distribution (D_p = 10 μm (Al_2O_3), A = 20 μm, Tube Inner diameter, I.D.: 18 mm).

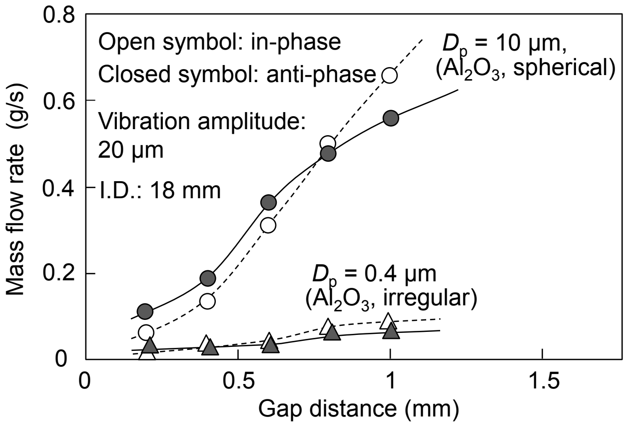
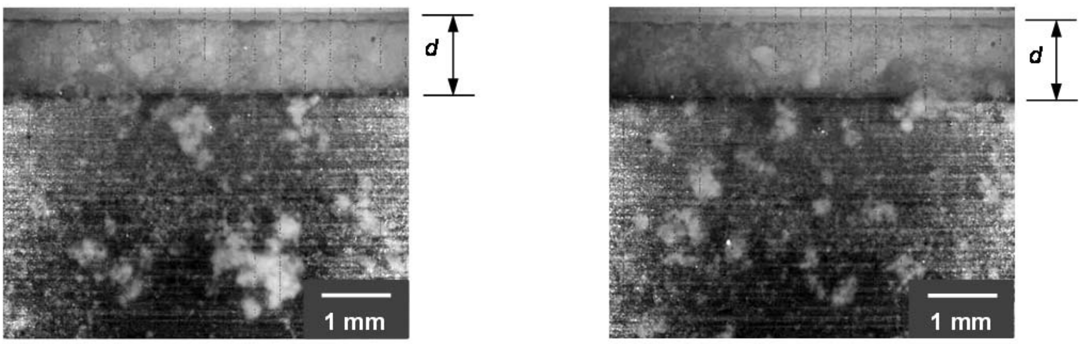


Figure 5: Mass flow rate of powder as a function of gap distance.

4.2 Powder discharge of nanoparticles

Figure 6 shows the photographs of the discharge of silica nanoparticles with a mean diameter of 12 nm during in-phase and anti-phase vibrations. The gap distance is 1.2 mm. Although the nanoparticles are agglomerate owing to adhesiveness, the nanoparticles are constantly discharged. As the void fraction of the agglomerated particles is very large, the outlines of the agglomerated particles are not clear.



(a) In-phase (b) Anti-phase

Figure 6: Photographs of powder discharge (SiO_2, particle diameter D_p = 12 nm, gap distance d = 1.2 mm, vibration amplitude A = 20 μm).

Comparison between two photographs indicates that the agglomerated particles during anti-phase vibration are smaller than those during in-phase vibration, and the agglomerated particles are more effectively disintegrated owing to vibration shear flow.
This tendency is identical to that of micron-scale particles (see Figure 3).
Figure 7 shows the performance of micro-feeding for nanoparticles. The mass flow rate increases with an increase in the gap distance. This tendency is identical to that of micron-scale particles. However, comparing these results with those in Figure 5, the mass flow rate of nanoparticles is very small owing to high adhesiveness and high void fraction. As the gap distance increases (>1 mm), the mass flow rate of particles during in-phase vibration was larger than that during anti-phase vibration.
Considering high-accuracy micro-feeding, large agglomerated particles must not be discharged; i.e., large agglomerated particles must be disintegrated and discharged continuously. Therefore, the anti-phase vibration is better for high-accuracy micro-feeding. However, the mass flow rate of fine particles is lower than that during in-phase vibration.
Figure 8 shows the effect of the vibration amplitude on the mass flow rate of nanoparticles. The mass flow rate increases with an increase in the vibration amplitude of the bottom surface, while the vibration amplitude of the tube is constant at 10 μm. The control of the vibration amplitude is easier than that of the gap distance because the vibration amplitude can be changed by an applied voltage. From these experiments, it was found that the mass flow rate of nanoparticles can be controlled with an accuracy of 1 mg/s.

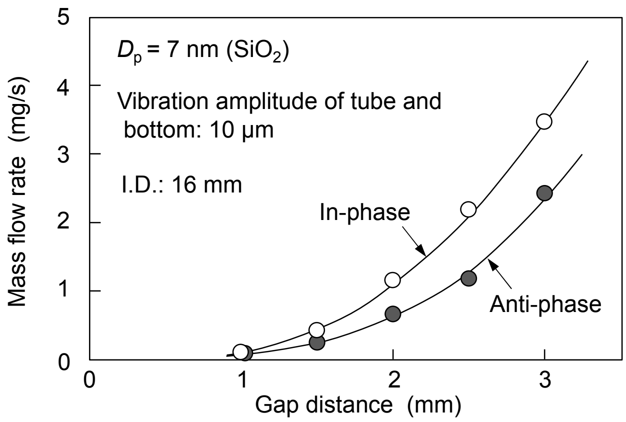


Figure 7: Mass flow rate of powder as a function of gap distance.

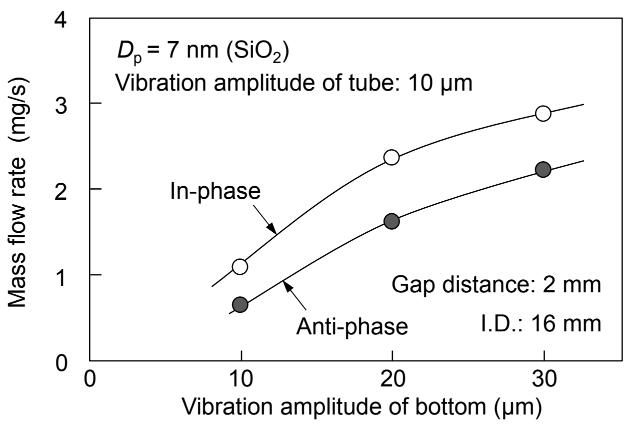


Figure 8: Mass flow rate of powder as a function of vibration amplitude.

In this research, feedback control was not applied. If feedback control by changing vibration amplitude was applied to this system, the performance of the micro-feeder would be substantially improved. The evaluation of the feedback system will be studied as a future work.

5. Conclusions

A novel micro-feeder for fine particles using a vibration shear flow mechanism was developed. The features of the vibration shear flow of fine particles were explained, and the performance of the micro-feeder was evaluated. The results obtained can be summarized as follows:

(1) Agglomerated particles are disintegrated owing to vibration shear flow. This is remarkable for anti-phase vibration compared to in-phase vibration.

(2) Nanoparticles, as well as micron-scale particles, can be continuously discharged.

(3) The mass flow rate of particles increases with an increase in the gap distance and/or vibration amplitude.

(4) The mass flow rate can be controlled to an accuracy of 1 mg/s.

Acknowledgments

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