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Convection induced by vibrating rod in fine-powder bed

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ABSTRACT

In this study, vibration-induced convection was studied experimentally using a fine powder with a mass median particle diameter of 8 μm. A cylindrical rod arranged vertically in a powder container was vibrated horizontally with simple harmonic motion at a frequency of 300 Hz using a piezoelectric vibrator. For a vibration amplitude of 10 μm, particles around the cylindrical rod were consolidated to a certain extent due to gravity; however, for a vibration amplitude of 70 μm or more, a pair of convection rolls formed on both sides of the vibrating rod. The strength of the convection was quantified from the particle velocity distribution in the convection rolls, and the relationship between the convection strength and vibration amplitude was elucidated. In addition, the air-pressure distribution in the powder bed was measured showing that the convection strength correlates with the characteristic positive pressure, i.e., the average value of positive pressure measurements. Elliptical motion and circular motion as well as simple harmonic motion were applied to the cylindrical rod by adding two harmonic motions in directions orthogonally crossing each other with a phase difference of π/2 rad. The convection of the particles varied according to the Lissajous trajectory of the cylindrical rod. Even for simple harmonic motion, heaps of a pair of convection cells overlapped each other. In the case of elliptical motion, the overlapping portion of the heaps became larger. In the case of circular motion, the two heaps were integrated into one circular heap, and there were no effects of the circumferential angle on the particle velocity and the characteristic positive pressure.

1. Introduction

When shaking a container filled with granular material, the solid content can be fluidized owing to the loss of the force balance acting on each solid. As it is known that the vibration-induced fluidization results in unusual behaviors such as convection, segregation, and bubbling, a number of studies have been conducted to elucidate the mechanism of these phenomena under consideration [1–8]. Convection, in particular, has been studied for a long time. In 1831, Faraday's [9] report on the peculiar arrangement and motion of the heaps formed by particles lying on a vibrating surface was a pioneering work in the field. Evesque and Rajchenbach [10] and Laroche et al. [11] analyzed the effect of vibration acceleration on the heap formed by convective motion. Taguchi [12] and Gallas et al. [13] reproduced the convective motion in a numerical simulation and noted that the side wall of the container causes the convection. Aoki et al. [14,15] experimentally demonstrated that multiple pairs of convection rolls are formed by changing the condition of the vibration. Although vibration has generally been applied to containers in the vertical direction, Liffman et al. [16], Tennakoon et al. [17], and Medved et al. [18] studied convection in a horizontally vibrated granular material. Tai and Hsiau [19] quantified the strength of the convection, and Lu and Hsiau [20] analyzed the mixing in a vibrated granular bed while considering the effect of diffusion and convection and using a three-dimensional discrete element method. In addition, the effects of various parameters on the convection were studied, e.g. the effects of the tilted side walls of a container [21], bed height [22], and non-spherical particles [23] on the formation of the convection cells. In recent years, the mechanism of the convection was also studied [24,25]. Most research on vibration-induced convection, however, has focused on larger particles having higher flowability. When using smaller particles, the interparticle adhesive forces such as the van der Waals force, electrostatic force, and liquid bridge force are greater than gravity [26,27]; thus, the movement of the particles is greatly restrained and it is difficult to fluidize these small particles.

Matsusaka et al. [28] and Mizutani et al. [29] reported that a fine powder with a mass median particle diameter of 8 μm

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circulates in a cylindrical container on applying a horizontal vibration of 300 Hz to it. The bubbles generated in the vibrated powder bed play an important role in this phenomenon, i.e., when the vibration is applied, the upper powder layer that has a high void fraction is consolidated and the particles move downward to a certain extent due to gravity. As the space between the particles is reduced, the air is forced out of the space and thus generates small bubbles, which coalesce and become large bubbles near the side wall vibrated in the normal direction and then move toward the top surface of the powder bed. On the other hand, the particles at the center of the powder bed and near the wall that vibrated in a tangential direction move downward; consequently, a pair of convection rolls are formed in the cylindrical container. In addition, it is noted that the bubbles generated at the bottom have a positive pressure but the air pressure in the downflows is negative, and the local pressure in the powder bed approaches the atmospheric pressure as the height increases. Furthermore, their experiments showed that a small opening arranged at the bottom of the container, where the local air pressure is negative, induces the inflow of outside air into the powder bed and forms a vigorously bubbling fluidized bed.

Once the convection rolls are induced in the powder bed, each particle is in a dynamic state; thus, adhesive forces between the particles are significantly reduced compared with those in a stationary state. As a result, the agglomeration in the powder bed will be prevented and stable convection rolls can be maintained. Even though the adhesive powder is stirred with a mechanical agitator, it is difficult to sufficiently disintegrate agglomerated particles. However, on using a vibration-induced convection technique, the powder flowability will be improved and agglomeration will be effectively prevented owing to the steady movement of the particles. This technique is also useful in preventing particles from clogging or in creating ordered mixtures. Moreover, the improvement in the powder's flowability enables the development of new applications using the particle surfaces, such as surface modification and gas–solid reactions.

The studies on vibration-induced convection have been performed by vibrating a container; however, there exists the problem that the scale of the convection is restricted to the size of the container. If convection is induced by a vibrator arranged in a powder bed without vibrating the container, the flexibility of the operation will be enhanced by arranging the vibrators at appropriate positions.

In this research, a cylindrical rod that is arranged vertically in a fine powder bed is vibrated horizontally with a simple harmonic motion using a piezoelectric vibrator, and the behavior of the particles is analyzed. In addition, the air-pressure distribution in the powder bed is measured to investigate the relationship between the particle behavior and the air pressure. Furthermore, to elucidate the effect of motion variation on the particle behavior, elliptical motion and circular motion are applied to the cylindrical rod by adding two harmonic motions generated by two piezoelectric vibrators in directions orthogonally crossing each other.

2. Experiments

2.1. System with a simple harmonic motion mechanism

Fig. 1 shows a schematic of the experimental setup. To facilitate the observation of the behavior of the particles, the container was made of transparent acrylic plates and had a narrow rectangular shape (20-mm wide, 200-mm long, and 60-mm high). The cylindrical rod with a length of 180 mm and a diameter of 16 mm, made of electrically conductive polymer (Nylatron® MC501CD R2: 1–10^2 Ωm, Quadrant Polypenco Japan Ltd) was vertically arranged with its top end as a fulcrum. The bottom end of the rod was set at 5 mm above the bottom plate of the container. The rod was vibrated in the longitudinal direction of the container with simple harmonic motion by a piezoelectric vibrator, which was mounted on the upper side of the rod, i.e. 35 mm from the top end, to secure a work space for filling a container with powder. A controller (VST-01, IMP. Co., Ltd.) was used to control the vibration; the frequency of the vibration was set to 300 Hz considering the resonance of the system, and the amplitude of vibration at the bottom end of the rod was set in the range of 0–120 μm.

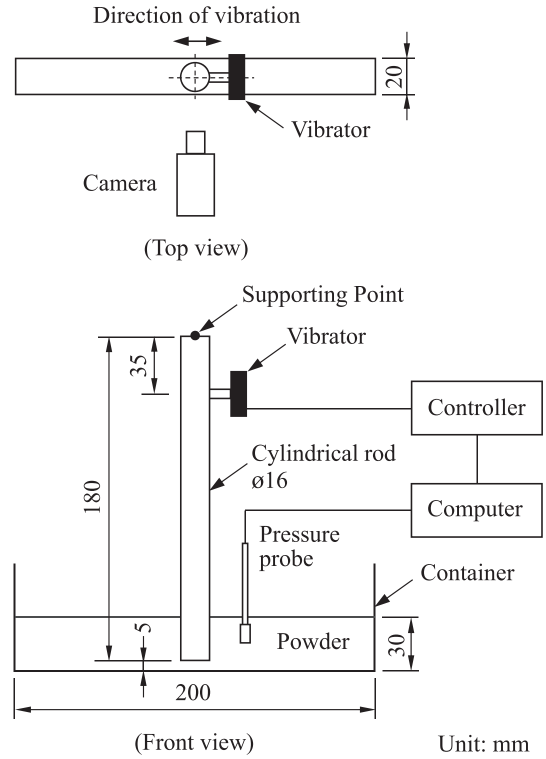

Fig. 1. System with a simple harmonic motion mechanism.

2.2. System with an elliptical or circular motion mechanism

Fig. 2 shows a schematic of the experimental system, where the bottom end of the cylindrical rod can move with an elliptical or circular motion as well as simple harmonic motion. In this system, two piezoelectric vibrators were mounted at 20 mm and 70 mm from the top end of the rod in a direction orthogonally crossing each other. The frequencies of vibration were set to 300 Hz, and each amplitude of vibration was independently controlled; the phase difference between the vibrations was set as π/2 rad to make the bottom end of the rod perform elliptical or circular motion. A container with a square opening of 100 mm on each side was used considering the horizontal spread of the particle movement in two-dimensional vibrations.

2.3. Experimental procedure

The powder used was white fused alumina with a mass median diameter of 8 μm and a particle density of 4000 kg/m^3; the particle shape was irregular. To properly evaluate the behavior of the particles under vibration and to reduce the amount of powder material, the initial bed height was set at 30 mm. To clearly observe the flow of particles in the powder bed, a small quantity of colored particles was added to the powder beforehand. The particle