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Microscopic analysis of particle detachment from an obliquely oscillating plate

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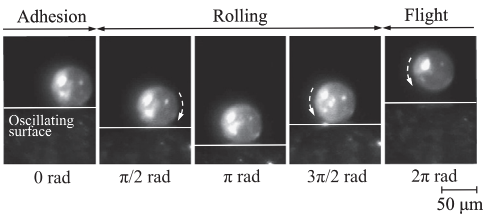
HIGHLIGHTS

- We experimentally study the particle detachment from an obliquely oscillating plate.
- We analyze the motion of micro-sized spherical particles by microscopic observation.
- The particles roll on the plate before detaching from the surface.
- The roll significantly reduces the adhesive force between the particles and surface.
- The particle movement can be explained by the force and moment balance model.

GRAPHICAL ABSTRACT



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ABSTRACT

Particle detachment from an obliquely oscillating plate was studied experimentally and theoretically. The plate was placed in a horizontal position, and vibrations were applied in the horizontal and vertical directions by piezoelectric vibrators. The frequency of vibration was constant at 280 Hz. The amplitude of vibration increased with time and approached a constant value in each experiment. The movement of micrometer-sized spherical particles was analyzed using images captured by a high-speed microscope camera, which showed that the particles rolled on the plate before detaching from the surface, and that the rolling significantly reduced the adhesive force between the particles and surface. Furthermore, the removal efficiency, defined by the number ratio of detached particles to total particles, was analyzed as a function of the horizontal and vertical vibration accelerations. It was found that the removal efficiency was significantly affected by the horizontal vibration acceleration. These experimental results can be explained by the force and moment balance model.

1. Introduction

The external force created by vibration has been used to fluidize particles. Particles under vibration exhibit various unusual behaviors, such as convection (Yang and Hsiau, 2000, 2001; Chung et al., 2013), bubbling (Pak and Behringer, 1994; Zamankhan, 2011a,b), segregation (Rosato et al., 2002; Yang, 2006; Liao et al., 2010), and vibration-induced air inflow (Matsusaka et al., 2013). Particle fluidization under vibration has numerous engineering applications, such as fluidized beds (Tatemoto et al., 2004, 2005; Limtrakul et al., 2007; Quintanilla et al., 2008), conveyors (Gallas et al., 1992; Rademacher and ter Borg, 1994; Sloot and Kruyt, 1996; Simsek et al., 2008), micro-feeders (Matsusaka et al., 1995, 1996) and evaluation methods for powder flowability (Jiang et al., 2006, 2009; Ishii et al., 2011; Zainuddin et al., 2012).

The vibrating conveyor, i.e., an obliquely oscillating trough inducing two-dimensional motion of a particle bed, is one of the simplest systems of particle fluidization under vibration, and has

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been investigated extensively (Gallas et al., 1992; Rademacher and ter Borg, 1994; Sloot and Kruyt, 1996; Simsek et al., 2008). However, in most previous studies of this system, adhesive and cohesive forces and fluid resistance were neglected because the studies have been carried out using non-cohesive, coarse particles with diameters larger than several hundred micrometers.

Particle behavior on an obliquely oscillating plate can be divided into three states: adhesion to the surface, detachment, and saltation. We previously studied the saltation of particles with a range of 0.5–500 μm in mass median diameter (Kobayakawa et al., 2014a, 2014b). However, the process of particle detachment has not been studied.

There are several methods for removing fine particles from surfaces: (i) centrifugal separation (Matsusaka et al., 1997; Salazar-Banda et al., 2007), (ii) vibration separation (Mullins et al., 1992; Theerachaisupakij et al., 2002; Hubbard et al., 2012), (iii) aerodynamic drag separation (Kousaka et al., 1980; Wang, 1990; Tsai et al., 1991; Matsusaka et al., 1991, 1997; Matsusaka and Masuda, 1996; Jiang et al., 2008; Maniero et al., 2012), and (iv) kinetic separation based on the impact of aerosol particles (Theerachaisupakij et al., 2002, 2003; Liu et al., 2011, 2012). Three main mechanisms for removal have been proposed: (i) rolling, (ii) sliding and (iii) lifting. From theoretical analyses using the force and moment balance model, it has been shown that the removal of spherical particles is more easily achieved by rolling, rather than sliding or lifting (Kousaka et al., 1980; Wang, 1990; Tsai et al., 1991; Matsusaka et al., 1991; Soltani and Ahmadi, 1994; Soltani et al., 1995). Although many studies on removal from the surface have been conducted, the process from rolling to detachment is not yet clear. To fully elucidate the mechanism of particle detachment, the phenomenon needs to be observed microscopically.

In this paper, the mechanism of detachment of micrometer-sized spherical particles from an obliquely oscillating plate is presented. In order to clarify the relationship between the phase angle of the oscillating plate and the motion of the particles, the particle behavior, trajectories, and velocities are analyzed from images captured by a high-speed microscope camera, and the experimental results are discussed using a force and moment balance model. Furthermore, the effects of the horizontal and vertical accelerations of the oscillating plate on the particle removal efficiency are elucidated.

2. Materials and methods

Fig. 1 shows a schematic diagram of the experimental setup. A stainless steel plate (SUS304, 15 × 15 mm^2), the surface of which was treated by abrasive blasting to create a homogeneous state, was mounted on a shock absorber. The micro-roughness of the surface was measured by a confocal laser scanning microscope (LEXT OLS4000, Olympus Corporation). The plate was sinusoidally oscillated in both horizontal and vertical directions by piezoelectric vibrators. There was no phase difference between the waves applied in the two directions. The frequency was set at 280 Hz, which corresponds to the natural frequency of the apparatus, so that large vibration amplitudes could be obtained. The amplitude could be adjusted by the applied voltage. The vibrators were controlled by a vibration control system (VST-01, IMP. Co., Ltd.).

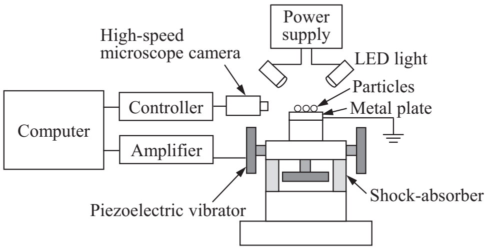

Fig. 1. Schematic diagram of the experimental setup.

Zirconia particles (Tosoh Corporation, particle density $\rho_p = 5900$ kg/m^3) were used in the experiments. The particles were observed through a scanning electron microscope (VE9800, Keyence Corp.). Fig. 2 shows an SEM image of the particles. All the particles are spherical and have smooth surfaces. Fig. 3 shows the number based particle size distribution, in which 100 particles were counted. The particle diameter was in the range of 48–68 μm and the median diameter D_{p50} was 57 μm. The geometry standard deviation σ_g was 1.07, indicating a narrow size distribution. The particles were dried at 120 °C over 24 h and cooled down to room temperature in a desiccator. The particles were distributed on the metal plate through a sieve. To avoid collisions between particles, the area covered by the particles was less than 0.5% of the total surface area.

The plate and the particles were illuminated by LED light (UFLS-75, U-Technology Co., Ltd.), and observed through a high-speed microscope camera with a resolution of 1 μm (Fastcam Mini UX100, Photron, Ltd.). The images were recorded at a rate of 8,0000–12,500 frames per second (fps) and analyzed via digital image processing (Dipp-Motion 2D, Detect Co., Ltd.). The particle removal efficiency was determined by digital counting of the number of particles adhering to the plate before and after each experiment. All the experiments were conducted at 20 ± 2 °C, and the relative humidity was controlled at 30–40% to avoid disturbances caused by liquid bridge forces.

3. Results and discussion

3.1. Two-dimensional vibration of the plate

Fig. 4(a) shows the displacement of the oscillating plate as a function of time; the values were obtained from the images captured by the high-speed microscope camera at a frame rate of 12,500 fps. The experimental results indicate that the amplitude of vibration

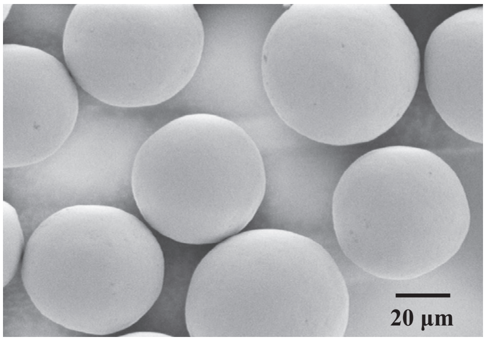

Fig. 2. SEM image of zirconia particles.

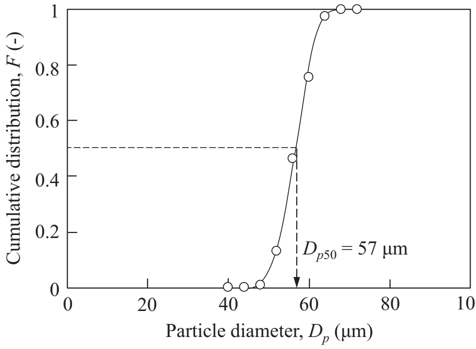

Fig. 3. Cumulative size distribution of zirconia particles.