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Particle dispersion in a horizontally vibrating vessel under microgravity

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ABSTRACT

This paper presents a numerical study on the particle dispersion in a horizontally vibrating vessel with round corners under zero gravity. Such a vessel is specifically designed for particle handling in the outer space. The numerical model is validated by good agreement between the simulated and experimental results. The effects of key variables, including overall particle number concentration and vibration amplitude and frequency, are studied by a series of controlled numerical experiments. The particle flow in the vessel is analyzed by the detailed particle scale information obtained from the simulations. The results are used to reveal the mechanisms and clarify some speculations of the particle flow observed in the experiments. In particular, it is found that the conveying velocity generated by the round corner can be correlated to the velocity amplitude, and so is the overall kinetic energy of the particles inside the vessel. The findings are useful for the optimum design of an effective technique for particle transportation under microgravity.

1. Introduction

Particulate materials are processed extensively on the earth, the amount of which being second only to that of water [1]. Further, they are abundant beyond the earth. With the push for new materials and analyzing out-of-earth materials, collecting soil and rock samples from the moon or other planets will be a primary objective in space research in the years to come [2–4]. However, particles will behave differently when gravity changes [5], and hence the general methods used on the earth for collecting and transporting particles will not be applicable in the outer space due to the microgravity environment. For example, the moon's atmosphere is too dilute for vacuum or pneumatic conveying processes [6]. On the other hand, the low gravity will reduce the friction between particles and walls, which is critical to belt or screw conveying [7]. Therefore, development of a simple and effective method to transport particles under microgravity will be of key importance in handling particulate materials in the outer space.

In this regard, particle motion in a vessel subjected to lateral vibrations under microgravity has recently been investigated by Ohyama et al. [2,3]. A series of experiments were carried out under microgravity generated by free-falling or parabolic flights of an airplane. Based on these tests, a handling unit is expected to develop for the transportation of particles in the outer space [4]. However, achieving microgravity environment is very expensive in such experimental studies, with limited results produced. To date, the mechanisms governing the flow of particles and the effects of key pertinent variables are not understood yet. There is a need to expand such research in a more effective way.

On the other hand, computer simulation of this operation based on the discrete element method (DEM) provides a cost-effective alternative to achieve this goal. DEM can provide detailed dynamic information, including the particle position and velocity, and forces on each particle in a system considered, which is important not only for fundamental understanding but also for engineering application [8,9]. Gravity can be readily controlled in DEM-based numerical studies. In fact, DEM has been applied to investigate the motion of particles under microgravity, and generated some preliminary results in two dimensions (2D) and with simplified vessel geometries [10].

In this work, a three-dimensional (3D) DEM is applied to investigate the motion of particles in a vibrating vessel with round corners under zero gravity. Facilitated by the numerical simulations, the flow dynamics and effects of some key variables are analyzed, aiming to produce some information for general application. The paper is organized as follows. In Section 2, the experimental setup is described, followed by the numerical technique in Section 3. Then, in Section 4, the results are discussed in details. Finally, the major findings from the present work are summarized in Section 5.

2. Experimental setup

Fig. 1 shows schematically the experimental setup for the studied system [3]. Basically, a glass vessel (20 × 20 × 28 mm) is fixed in an aluminum cell holder, which is connected to a controlled vibrator. Particles are placed inside this vessel, which has two round top corners. The vibration is applied along the X-axis only. In each experiment, the

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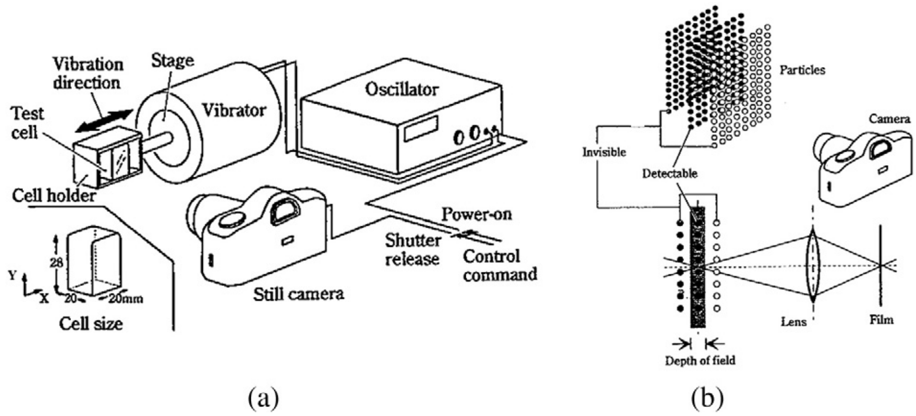

Fig. 1. Schematic illustration of the experimental set up: (a) the whole apparatus, (b) method of particle sampling in the field of depth.

whole apparatus consisting of a still camera and other instruments is set under the microgravity condition generated in Japan Microgravity Center (JAMIC). A near zero gravity environment is sustained for 10 s in the experiments.

The camera is set to take pictures of the vessel continuously every 0.1 s. It is focused at the central region of the cell, with the lens aperture set to f2.8, which gives the shallowest depth of field (0.66 mm). As the particle number concentration is low, particles scattered in front of and behind the focal plane will appear indistinct or entirely invisible in photographs. Only the particles within the field depth will appear distinct. Thus the particles caught on film are considered to be in a 2D section of the cell, and are used to analyze the flow patterns of particles.

3. Numerical simulation

3.1. Governing equations

In DEM, the motion of individual particles is governed by Newton's second law of motion and traced by an explicit numerical scheme. For particle i, its translational and rotational motions are determined by the forces and torques on it, given by:

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \left(\mathbf{F}_{ij}^n + \mathbf{F}_{ij}^s\right) + m_i \mathbf{g} \tag{1}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j \left(\mathbf{R}_{ij} \times \mathbf{F}_{ij}^s - \mu_r R_i \left|\mathbf{F}_{ij}^n\right| \hat{\boldsymbol{\omega}}_i\right) \tag{2}$$

where $\mathbf{v}_i$, $\boldsymbol{\omega}_i$, m_i and I_i are, respectively, the translational and angular velocities, the mass and moment of inertia of particle i; $\mathbf{g}$ is the gravitational acceleration; $\mathbf{R}_{ij}$ is the vector pointing from the center of particle i to the contact point of it with the particle j. $\mathbf{F}_{ij}^n$ and $\mathbf{F}_{ij}^s$ are, respectively, the normal and tangential contact forces from particle j to i, which are calculated by the following equations [8,11,12]:

$$\mathbf{F}_{ij}^n = \left[\frac{2}{3}\frac{Y}{1-\tilde{\sigma}^2}\sqrt{\overline{R}}\xi_n^{3/2} - \gamma_n \left(\frac{3Y}{1-\tilde{\sigma}^2} m^* \sqrt{\overline{R}\xi_n}\right)^{1/2} \left(\mathbf{v}_{ij} \cdot \hat{\mathbf{n}}_{ij}\right)\right] \hat{\mathbf{n}}_{ij} \tag{3}$$

$$\mathbf{F}_{ij}^s = -\mu_s \left|\mathbf{F}_{ij}^n\right| \left[1 - \left(1 - \min\left(\xi_s, \xi_{s,\max}\right)/\xi_{s,\max}\right)^{3/2}\right] \hat{\boldsymbol{\xi}}_s \tag{4}$$

where R_i and R_j are the radii of particles i and j respectively; Y is the Young's modulus; $\tilde{\sigma}$ is the Poisson's ratio; γ_n is the normal damping coefficient; μ_s is the sliding friction coefficient; ξ_s is the total tangential displacement and $\hat{\boldsymbol{\xi}}_s$ is its unit vector; $\overline{R} = R_i R_j / \left(R_i + R_j\right)$; $m^* = m_i m_j / (m_i + m_j)$; $\xi_{s,\max} = \mu_s [(2-\tilde{\sigma})/2(1-\tilde{\sigma})]\xi_n$; and $\hat{\mathbf{n}}_{ij} = \left(\mathbf{R}_i - \mathbf{R}_j\right) / \left|\mathbf{R}_i - \mathbf{R}_j\right|$. The torque also includes the term resulting from the rolling resistance between two contact particles due to elastic hysteretic losses or viscous dissipation, where μ_r is the rolling friction coefficient and $\boldsymbol{\omega}_i = \boldsymbol{\omega}_i / |\boldsymbol{\omega}_i|$ [8].

3.2. Simulation conditions

In the experimental studies [3], the flow in the system is mainly characterized in two dimensions. Therefore, to be comparable with the experiments, a slot model is adopted in the simulation, as shown in Fig. 2(a). The dimensions of the vessel along the x and y axes, and the shape of round corners are the same as those used in the experiments. The dimension along the Z-axis is 6 mm, with periodic boundary conditions applied in this direction. The properties of the particles (lead) and walls (glass) used in the simulations are listed in Table 1. These values are mainly based on the measured data for these two materials, while some calibrations have been done by comparing with the experimental results in terms of the spatial distribution of particles, as will be shown later. Sinusoidal vibration is applied in the X-axis direction, defined by $A \cdot \sin(2\pi f t)$, where A is the vibration amplitude and f the vibration frequency.

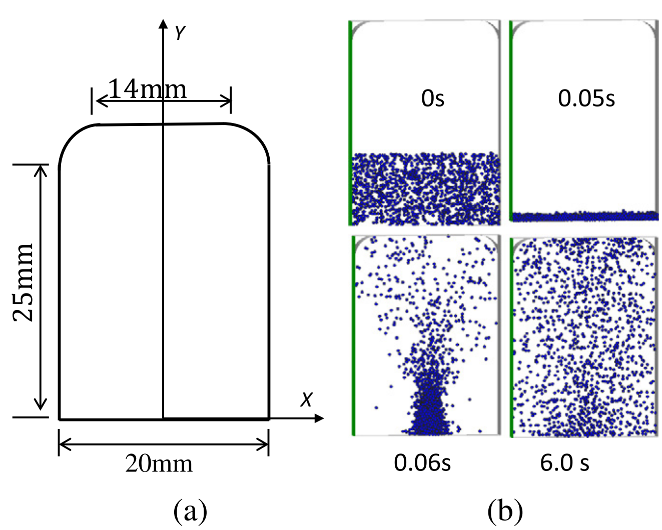

Fig. 2. Schematic illustration of: (a) the coordinate system and the vessel used in the simulation, Z-axis points outwards; and (b) snapshots of a simulation at different times.