Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Numerical study of the motion behaviour of three-dimensional cubic particle in a thin drum

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ARTICLE INFO

Article history:
Received 8 June 2017
Accepted 28 November 2017
Available online xxxx

Keywords:
Drum
Particle
Cubic shape
Filling level
Wall friction

ABSTRACT

The motion of three-dimensional cubic particles in a thin rotating drum is simulated by the SIPHPM method. The drums with frictional or smooth front and rear walls, and the particles of cubic and spherical shapes, and different particle numbers are considered to study the effect of cubic particle shape, end-wall frictions and filling levels. Different flow patterns of cubic particles are observed, which are significantly dominated by the friction from the end-walls. The probability density function of velocity components, the flatness factors are used to analyze the motion behaviour of cubic particle. The Froude number, ensemble mean and time averaged particle velocities are also analyzed. A primary and secondary mode of driving from the end-wall frictions are indicated and the mechanisms on the influences of wall friction, particle shape and filling levels are fully explained.

1. Introduction

As a widely applied mixer for mixing, drying, heating and coating of granular particles, the rotating drum or cylinder mixer has been extensively studied in the past decades on the rich phenomena (e.g. mixing [26], segregations and stratification [2], surface flow [27], granulation [4], axial dispersion [25], cohesion [6]), statistical features (e.g. velocity analysis [7], the Markov process [9] and poly-dispersion [1]). Meanwhile, various influencing effects on the aforementioned phenomena and features have also been explored extensively, including the operating conditions [24], noncircular drum effect [3], non-spherical particle effect [22], internal baffle effect [21], particle density effect [29]), and heat transfer [12]. But, the majority of these studies are based on spherical particles. Compared to the drum filled with spherical particle, the dynamical behaviours of non-spherical particles in the drum have not been well explored, although it is well accepted that particle shape has a significant impact on flow behaviour [10].

Recently, as the particle shape has a strong influence on the dynamics of particulate systems, some studies have been contributed to the non-spherical particles, from theoretical, experimental and modeling, to application aspects [20,19]. In experimental study, Williams et al. [28] analyzed separated and lumped particle images to assess particle shape descriptors through a digital image segmentation technique and implement particle shape parameters into generation of irregular shaped particles. Various particle shape descriptors were obtained using the combinations of image segmentation algorithms, and non-spherical particles were subsequently created in DEM modeling using the particle shape results. Rasouli et al. [22] compared the flow behaviour of cylindrical and spherical particles using the multiple radioactive particle tracking technique to capture the positions and orientations of cylindrical particles simultaneously. The boundary between the active and passive layers and the velocity profile on the free surface were analyzed. Dubé et al. [10] also used the radioactive particle tracking technique (RPT) to follow large non-spherical particles inside a rotating drum, and three crucial aspects of particle: residence time, mixing/segregation, and axial dispersion were studied. It was found that particles of high aspect ratio have significant deviations in velocity profile and residence time. Unexpected core segregation patterns and lower axial dispersion coefficient were also found for non-spherical particles. In simulation [20], using the super-quadric equation, discrete element method simulation was performed to study the cross-sectional flow of non-spherical particles in horizontal rotating cylinders. The effects of the degree of squareness and wall rougheners on flow behaviors were studied. In their work, the typical challenging strategies for non-spherical particle modeling include the orientation representation by using quaternions and the contact

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https://doi.org/10.1016/j.apt.2017.11.033

detection by super-quadric equation [19]. Thus, the composite-sphere method is still an alternative approach frequently applied in non-spherical particle simulation [18,5,8].

Moreover, the effect of drum wall on particle is also an important issue. For example, besides the work by Lu et al. [20], Santomaso et al. [23] also studied the effect of wall roughness on the axial segregation in horizontal rotating drums. They showed that modification of the geometry and roughness of internal surface of mixer could modify the segregation patterns. With regard to the friction effect of walls, Guo et al. [17] studied the angle of internal friction and concerned the particle shape on the angle of internal friction experimentally by powder rheometer. Three regions can be divided for various binary granular systems based on the magnitudes of aspect ratio, and a power function exists between $\Delta \tan \Phi$ and granular shape factors. In addition, although my recent work has indicated the important influence of end-wall on mixing of spherical particles [30], the wall effect on the mixing of non-spherical particle is still unclear.

In particular, we have proposed three kinds of numerical models to simulate the interaction between non-spherical particles. It includes an analytical solution model of non-spherical particle collision of rigid materials (the GHPM model [15,16]), a soft-sphere imbedded pseudo-hard particle model (the SIPHPM model [13]), and a coupled approach of the hard and soft models (the EHPM-DEM [14]). We think the SIPHPM model is particularly suitable for simulating very dense granular flows of non-spherical particles for its robustness, good validation and numerical reliability.

In conclusion, the motion behaviours and characteristics of non-spherical particles (especially under three-dimensional case) in rotating drums are significant to practical applications. The effects of non-spherical shape, filling level and wall friction are also important issues, which are still poorly understood. As a fundamental research, this work is aimed at exploring the mechanisms of cubic particle motion in a thin layer and the effects of cubic shape, filling level and wall friction. To accomplish that purpose, the rotating drums filled with about 400–989 cubic particles with or without frictions on the front and rear walls are simulated by the SIPHPM model, and the results are analyzed in details.

2. Numerical method

2.1. SIPHPM model

The soft-sphere imbedded pseudo-hard particle model (SIPHPM) [13] is applied in this study to simulate the collision between cubic particles. Herein, the cube model (see the inset of Fig. 2a) is composed of 56 sub-spheres and 6 surfaces. The cube-cube interaction is then transformed to the interaction between spheres and surfaces. In SIPHPM, the interactions between the subspheres of the same cube are not needed to be computed, as a pseudo-hard assumption of the material of the cube is always guaranteed. However, the interaction between the subspheres of different cubes must be solved by the discrete element method, as well as the subsphere-surface interaction between different cubes. In addition, the subspheres can oscillate about their equilibrium position within the cube, where the equilibrium position is determined by the position and orientation of the cube. Thus, the governing equations of the cubes and subspheres are coupled and solved respectively as follow:

For sub-spheres:

$$\boldsymbol{F}_{i,s} = k_c \delta \boldsymbol{x}_{i,s} - \eta_c \delta \dot{\boldsymbol{x}}_{i,s}, \text{if} (\boldsymbol{F}_{i,s} \cdot \boldsymbol{t}_{i,s}) > \mu (\boldsymbol{F}_{i,s} \cdot \boldsymbol{n}_{i,s}), (\boldsymbol{F}_{i,s} \cdot \boldsymbol{t}_{i,s}) = \mu (\boldsymbol{F}_{i,s} \cdot \boldsymbol{n}_{i,s}) \tag{1}$$

$$\boldsymbol{T}_{i,s} = \boldsymbol{r}_{i,s} \times \boldsymbol{F}_{i,s} \tag{2}$$

$$\boldsymbol{R}_{i,s} = k_r \Delta \boldsymbol{\zeta}_{i,s} - \eta_r \Delta \dot{\boldsymbol{\zeta}}_{i,s} \tag{3}$$

$$\dot{\boldsymbol{v}}_i = (\boldsymbol{F}_{i,s} + \boldsymbol{R}_{i,s}) / m_s - \boldsymbol{g} \tag{4}$$

where $\delta \boldsymbol{x}_{i,s}, \boldsymbol{r}_{i,s}, \Delta \boldsymbol{\zeta}_{i,m}$ are the deformation displacement, position vector (relative to the cube center), deviation displacement from the equilibrium position of the i^{th} subsphere, respectively. $\boldsymbol{F}_{i,s}, \boldsymbol{R}_{i,m}, \boldsymbol{T}_{i,s}$ are the damping elastic collisional force, restoring force, and the torque generated by the i^{th} subspheres with respect to the cube respectively. $\boldsymbol{n}$ and $\boldsymbol{t}$ are the normal and tangential directions at the collision point, and $\boldsymbol{g}$ is the gravity acceleration. k_c, η_c, k_r, η_r, are the stiffness factor and damping coefficient of collision and restoration, respectively. μ is the friction coefficient for subspheres. $\boldsymbol{v}_i, m_s$ are the velocity and mass of the sub-spheres, respectively. '·' is the inner operator. Note that the self-rotation of sub-sphere is omitted since it may be regarded as an additional degree of freedom within the large non-spherical particle (apart from the most commonly encountered translational, rotational, vibrational degrees of freedom for a large composite particle), which is not true in practice.

For cubes:

$$M_c \dot{\boldsymbol{V}}_{j,c} = \sum_{i}^{N_s} \boldsymbol{F}_{i,s} - \boldsymbol{G} \tag{5}$$

$$\boldsymbol{I_c} \cdot \dot{\boldsymbol{\Theta}}_{j,c} = \sum_{i} \boldsymbol{T}_{i,s} \tag{6}$$

where $\boldsymbol{V_{j,c}}, \boldsymbol{\Theta_{j,c}}, M_c$ and $\boldsymbol{I_c}$ are the translational velocity, rational velocity, mass, and moment of inertia of the cubic particle respectively. $\boldsymbol{G}$ is gravity force of the cube. $N_s = 56$ is the number of subspheres a cube contains.

By solving Eqs. (1)–(6), the collision and motion of both subspheres and cubes can be obtained. In similar manners, the cube-wall and cube-surface collisions can also be transformed into subsphere-wall and subsphere-surface collision, and solved by discrete element method as well.

2.2. Model validation

In our recent work [13], the SIPHPM has been validated through comparison with experimental observations on the arching structures, both in 2D and 3D cases. In addition, as the GHPM model [15,16]) was validated firstly by theoretical consistency and experimental comparison, it was used to validate the SIPHPM for cube-cube collision process. However, in this section, an additional validation on cubic particle discharge is performed according to the experimental work by Fraige et al. [11].

200 cubes of size 12.5 mm in side length are initially set inside a silo of 500 (height) * 200 (width) * 30 (depth) mm, and discharged through the orifice (width B_o = 60, 80, 116 mm) at the bottom center. Notice that the exact positions of all particles cannot be obtained in experiment. Therefore, we just used randomly initial particle velocities in simulation, and let the particles fall freely from some distances from the bottom when the orifice is closed to build similar initial packing states. After that, the orifice is opened, and the discharge starts. The parameters used in current validating simulation are listed in Table 1.

For example, the snapshots of discharge at t = 0.1 s for B_o = 60, 80, 116 mm are illustrated in Fig. 1a–c respectively. When the orifice size is different, the numbers of particles moving downward are different. Then, the corresponding number flow rates are computed and shown in Fig. 1d compared to experimental data. It is indicated that: although the initial packing states are different, the number flow rates in simulation are close to the experimental data or within the range of variation of flow rates in experiment. Therefore, it shows once again the validity of current model for simulation of cubic particle motions.

Please cite this article in press as: N. Gui et al., Numerical study of the motion behaviour of three-dimensional cubic particle in a thin drum, Advanced Powder Technology (2017), https://doi.org/10.1016/j.apt.2017.11.033