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Effect of roundness on the discharge flow of granular particles

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ABSTRACT

The discharge of regular noncircular particles through a hopper orifice is simulated by discrete element method. A novel approach of incorporating distributed sub-spheres around the non-spherical particle borders is developed. The aim of this work is to explore the effect of roundness on the discharge behavior as well as relevant mechanisms of hopper discharge. Seven types of non-spherical particles, i.e. triangular, quadrilateral, pentagonal, hexagonal, heptagonal, octagonal and decagonal shaped particles, are chosen for comparative study. They are respectively discharged freely from the hopper beds of three different base angles, i.e. $\alpha = 65$, 70 and 75°. The discharge process, fraction, flow rate, and voidages are analyzed to show the effect of particle roundness on discharge characteristics.

1. Introduction

Particle flows have rich and interesting unexplored phenomena and complexity [1] and hopper beds are commonly utilized for the storing, diffusing, mixing, feeding and transporting particles in many industries. Thus, particle flow within hoppers is important for both scientific study and industrial application, and many studies have been contributed to this topic.

For example, Janda et al. [2] carried out a systematical study of the flow of granular medium through an orifice placed at the bottom of a two-dimensional silo and found self-similar profiles of velocity in the whole ranges of apertures even in the clogging flow. Zuriguel et al. [3] investigated the process of 2D silo discharged by gravity on silo clogging reduction by the presence of an obstacle. It was interesting to find dramatic changes in the clogging probability when the distance from the silo outlet to the obstacle is changed without changing the flow rate greatly. Zhu et al. [4] presented a DEM study of the steady and unsteady state granular flows in a cylindrical hopper with flat bottom, and indicated the differences in the magnitudes of some physical properties for the unsteady and steady state flows. The results suggested that the distributions of force structures of steady and unsteady discharge flow are similar. But the magnitudes are different, i.e. the unsteady flow has a narrower velocity distribution and larger radial and circumferential normal stresses in the plug flow and transitional zones than the steady flow. Similarly, Xu et al. [5] simulated the discharging of a 3D rectangular hopper by DEM to understand the influence of wall friction on wall stress ratio. The relative density of force chains attaching the wall was found to depend on the wall friction coefficient. Jasion et al. [6] applied the DEM model to simulate a dispensing control method to identify the internal mechanism that allows the particle flow in hoppers to be controlled so precisely. Dreißigacker et al. [7] developed simulation tools to investigate the thermo-mechanical behavior during thermal charging and discharging process of granular packed bed for energy storage. Guo et al. [8] studied the gravity discharge characteristics of biomass and coal particles in a hopper to show the improvement of flowability of the cohesive pulverized coal particles by adding biomass particles. In addition, Albaraki and Antony [9] used digital PIV to probe the spatial and temporal distribution of the velocity fields of pharmaceutical granules in hoppers of different internal angles, and made an agreement between experimental and theoretical estimation on the flow rate. They showed that the free-flowing powder can still experience a significant level of hindrance to flow even passing through smooth hoppers of different internal angles.

Recently, various extensions and applications of the discrete element method have been performed to show the behaviors and

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characteristics of particle flows. For example, Liu et al. [10] studied the effect of ellipsoidal particle shapes on granular flow in cylindrical hoppers. They found that particle shape can make significant effects on flow pattern, mixed region, stagnant region, wall stress, discharge rate etc. The signed distance function (SDF) was applied to create the complicated shape of wall boundaries[11]; the coarse grain model was employed to improve the efficiency of DEM simulation for large scale applications [12]. In particular, a novel open-source work-flow based on "Blender", a rigid-body simulation tool developed for computer graphics applications, was presented and validated to generate realistic packing of particles of different shapes [13].

However, the effect of particle shape on the flow behavior is a very complicated and difficult issue to handle, since shape is a particle-scale property whereas the flow behavior is a bulk flow property and relevant to macroscopic characteristics of granular system. Thus, the effect of particle shape is always neglected in the majority of the past investigations. But, due to the advancement of numerical techniques and high performance computer, especially the DEM-based models for non-spherical particles [14; 15; 16; 17; 18; 19; 20; 21], it becomes a hot issue of research recently. For example, Boon et al. [22] proposed a new contact detection algorithm between three-dimensional non-spherical particles in the discrete element method (DEM) based on the concept of potential particles where an arbitrarily shaped convex particle can be defined. Dong et al.[23] presented a DEM-based method using orientation discretization and pre-calculated databases and applied it to simulate the packing and flow of different shaped non-spherical particles. Pei et al. [24] implemented a sphere-tree multi-sphere method and a contact electrification model into the discrete element method to model the charging process of irregular particles in a rotating drum. Guo et al. [8] observed that the flowability of the blended particles was strongly affected by the aspect ratio and surface roughness of the biomass particles. Liu et al. [10] investigated the shape effect of particles on granular flow in cylindrical hoppers by using ellipsoidal particles. They found that particle shape can make a significant effect on the flow pattern, including the mixed region and stagnant zone, and the discharge rate too. They derived a modified Beverloo equation for ellipsoidal particles as $W^{2/5} = C^{2/5}\rho_B^{2/5}g^{2/5}(D_o - kd_p)$ where C and k are regarded as functions of aspect ratios. Moreover, Höhner et al. [25] conducted an experimental study and DEM simulation of hopper discharge of spheres and polyhedral dices. They showed an approach of polyhedral approximations for dices and found an increased flow resistance to form pile-ups at the bottom of the hopper by the dices. In addition, our group also developed a generalized hard-particle-based model [26; 27] or soft-sphere imbedded pseudo-hard particle model [28] to simulate the 2D and 3D contact/collision between non-spherical particles.

In conclusion, although the hopper discharge has been extensively investigated, some important mechanisms are still poorly understood, especially under the particle scales. The discharge behavior and characteristics of non-spherical particles are relatively even less known. Few researches have been carried out on the effect of roundness of particles on the discharge behaviors within hoppers. Motivated by this consideration, this work aims at showing the particle scale effect of roundness on the macroscopic behavior of flowability, e.g. discharge flow rate. To accomplish that purpose, the discrete element method is incorporated and improved by some extensions to fix the condition of non-spherical particles. The discharges of regular spherical, triangular, rectangular, pentagonal, hexagonal, heptagonal, octagonal and decagonal shapes are compared and analyzed in this work to show the effect of roundness. In addition, the hopper beds with different base angles of $\alpha = 65$, 70 and 75∘are used for each case to show the superposed effect of bed configuration of hopper discharge.

2. Mathematical description

2.1. Discrete element method

The discrete element method-based model, so-called the soft-sphere imbedded pseudo-hard particle model (SIPHPM) [28] is applied in this study to simulate the collision between noncircular particles. In general, as shown in Fig. 1a, let $\partial\Omega$ be the border of a noncircular shape Ω of diameter D_h, and it is covered by a group of small spherical particles S ($S \in \partial\Omega$) of diameter d_s which are arranged one by one on the border. Then the collision between Ω_i and Ω_j can be approximated by the collision between $S_{i,m}$ and $S_{j,n}$, where i,j are indices of the noncircular particles and m,n are indices of the contacting sub-spheres, respectively. Let the collisional force and torque on the subsphere $S_{i,m}$ be $\boldsymbol{F}_{i,m}$ and $\boldsymbol{T}_{i,m}$ respectively, which can be formulated by the discrete element method model:

$$\boldsymbol{F}_{i,m} = k_c\boldsymbol{\delta x}_{m,n} - \eta_c\boldsymbol{V}^c_{m,n} \tag{1}$$

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

where $\boldsymbol{\delta x}_{m,n}$, $\boldsymbol{V}^c_{m,n}$ are the relatively overlapped displacement and relative velocity between $S_{i,m}$ and $S_{j,n}$ respectively. $\boldsymbol{r}_{i,m}$ is the distance vector from Ω_i to $S_{i,m}$. k_c, η_c are the stiffness factor and damping coefficient of collision respectively. The inter-particle friction may take place when

$$\text{If} \quad \langle\boldsymbol{F}_{i,m},\boldsymbol{t}_{m,n}\rangle > \mu\langle\boldsymbol{F}_{i,m},\boldsymbol{n}_{m,n}\rangle, \quad \text{then} \quad \langle\boldsymbol{F}_{i,m},\boldsymbol{t}_{m,n}\rangle = \mu\langle\boldsymbol{F}_{i,m},\boldsymbol{n}_{m,n}\rangle \tag{3}$$

where μ is the friction coefficient and '⟨⟩' is the inner operator. In addition, the noncircular shape Ω is assumed to be pseudo-rigid, which is almost not allowed to be deformed. To achieve this condition, once the small spherical particles $S_{i,m}$ moves away from $\partial\Omega$ at a distance $\boldsymbol{\Delta\zeta}_{i,m}$, a damping elastic restoring force $\boldsymbol{R}_{i,m}$ is generated to drive it back to the right location on the $\partial\Omega$:

$$\boldsymbol{R}_{i,m} = k_r\Delta\boldsymbol{\zeta}_{i,m} - \eta_r\dot{\boldsymbol{\zeta}}_{i,m} \tag{4}$$

where k_r, η_r are the stiffness factor and damping coefficient of restoration respectively.

Then, the motions of the large nonspherical particle 'i' and the small spherical particle 'm' can be governed, respectively by

$$\dot{\boldsymbol{V}}_i = \frac{1}{M_i}\sum_m \boldsymbol{F}_{i,m} - \boldsymbol{g} \tag{5}$$

$$\dot{\boldsymbol{\Theta}}_i = \frac{1}{I_i}\sum_m \boldsymbol{T}_{i,m} \tag{6}$$

$$\dot{\boldsymbol{v}}_m = (\boldsymbol{F}_{i,m} + \boldsymbol{R}_{i,m})/m_p - \boldsymbol{g} \tag{7}$$

$$\dot{\boldsymbol{\theta}}_m = \boldsymbol{T}_{i,m}/I_p \tag{8}$$

where $\boldsymbol{V}$, $\boldsymbol{v}$, $\boldsymbol{\Theta}$, $\boldsymbol{\theta}$, M_i, m_p, I_i, I_p, are the translational velocity, rational velocity, mass, and moment of inertia of the large nonspherical and small spherical particles, respectively. The indices $m \in i$ which means the small sphere 'm'' is imbedded in the large nonspherical particle 'i'. $\boldsymbol{g}$ is gravity acceleration.

2.2. Numerical setup and validation

The different configurations of non-spherical shapes are shown in Fig. 1b. The particles of different shapes have the same area of $|\Omega| = A_p = 6.5$ mm^2. The hopper bed is two-dimensional with 0.2 m wide and 0.65 m high (Fig. 1c). Three base angles of $\alpha = 65^\circ, 70^\circ, 75^\circ$ are

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