Powder Technology 292 (2016) 31–45

Contents lists available at ScienceDirect

Powder Technology

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

Effects of rocking frequency and amplitude on particle discharge in rocking bed: A DEM study

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ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form 23 December 2015
Accepted 14 January 2016
Available online 15 January 2016

Keywords:
Particle
Hopper
Silo
Rocking bed
Discharging flow
Discrete element method

ABSTRACT

A DEM study of a rocking particle bed is performed to show the effects of rocking frequency and amplitude on particle discharge. Six rocking frequencies of $f_r = 0, 0.1, 0.2, 0.3, 0.4, 0.5$ Hz with seven rocking amplitudes of $\theta_r = 5°, 15°, 30°, 45°, 60°, 75°$ are simulated respectively. The particle distributions, discharged fractions, flow rates, particle trajectories and kinetic energies are compared and analyzed in detail to show and explain the features of particle discharging process under different rocking conditions. The rocking frequency is found to be the primary factor to determine the direction of influence on particle discharge, i.e. either beneficial or detrimental, whereas the rocking amplitude is the secondary factor to magnify the primary influence on particle discharge. In addition, the flare angle of the bed can determine the mode of influence on particle discharge, i.e. either a linearly varied discharge or an oscillated variation of discharge. The results are helpful to improve the process control and optimal design of the particle discharge beds in many engineering applications.

1. Introduction

Hoppers and silos are used to store or convey powders in various industrial applications, such as food, pharmaceutical, mining, chemical and process engineering. The discharging particle flows in hoppers or silos have been extensively investigated over decades for its great importance in science and wide applications in engineering. These researches cover many important issues with regard to physics and mechanisms of hopper/silo flows, such as mixing [1], segregation [2,3], optimal design [4], flow dynamics [5], discharge rate [6,7] and pattern [8,9], flow correction [10] and transition [11], flow jam [12–14]. Moreover, the effects of some important parameters have been extensively explored too, such as shape [15,16], angle [17], interstitial air [18], friction [19,20], roughness [21], pressure [22,23], rotation [24] and rotational shear [25], vibration [26–28], and many other material properties [29].

Within these factors, particular attentions have been paid to the effect of vibration. For example, Hunt et al. [26] performed an experimental study on the discharge of glass particles in a horizontally vibrated planar wedge-shaped hopper with 45° sidewalls. The discharge rate was found to increase with the velocity of vibration. An inverted funnel pattern takes place, i.e. the particles along the sides are discharged before the discharge of particles in the core, which is quite opposite to the funnel flow pattern without vibration. Furthermore, Wassgren et al. [27] performed a similar study of hopper flow on the effect of vertical vibration. Particles were found to move up along the inclined walls of the hopper and down at the center line. The discharge rate reaches the maximum point when the dimensionless velocity amplitude is greater than 1. After that the discharge rate will go down due to the decrease in the bulk density under vibration. In addition, Langston et al. [28] studied the effect of point source vibration on the discharge of cohesive particles, where the point source of vibration is used to break the stable arches. They suggested that the vibration source must be located at appropriate height above the hopper outlet to optimize the flow enhancement.

Moreover, the effects of other kind of motions, such as rotating [30–32], shaking [33] and rocking [34], on the behavior of particles have also been studied. For example, Liao et al. [30] implemented an experimental study of particle streak segregation in rotating drums, and found that the density ratio, rotation speed, and fill level play crucial roles in the behavior of streak segregation. Wightman and Muzzio [34] examined the mixing behavior of particles in cylindrical drum under both pure rotation and rotation with vertical rocking motions. Complex patterns of mixing were observed, where large particles are tended to concentrate in segregated cores and migrate to the ends of the cylinder after a long time.

Besides, hopper flows under vibrating, shaking and rocking motions have some specific industrial applications. For example, for microscopic scales, with the assistance of vibration, it can be used for controlling the flow rate of micro-feeding techniques for dispensing milligram dose of

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http://dx.doi.org/10.1016/j.powtec.2016.01.015
0032-5910/

pharmaceutical powders [35] and for depositing thin layers of multiple patterned materials in fabrication of heterogeneous components [36]. On the other hand, for macroscopic scales, the pebble bed high temperature gas-cooled reactor (HTGR) in nuclear engineering utilizes the hoppers to discharge and recirculate fuel and graphite pebbles. The discharge of pebbles from the hopper is a significant issue to the safety of the pebble bed reactor, especially under some emergent conditions, such as seismic shaking and rocking, and oscillating/rocking motion on offshore platforms. As a result, the particle discharge under the rocking conditions is one of the most important issues which has great impact on the design and operation of the pebble bed HTGR.

In conclusion, compared to the effect of rotating, the effect of rocking motion on particle behavior is fairly less understood. Although with extensive applications in engineering, the discharge behavior of particles is far less understood than the behavior of particle mixing and segregation. In addition, accurate prediction, well control and change of the discharge rate are critical for dependable design and optimum performance of the hopper/silo devices. Unfortunately, to date, the effect of rocking motion on the discharge behavior of particles is far from well understood.

In addition, in recent years, the discrete element method (DEM) has been widely utilized to simulate the dynamics of hopper flow at microscopic or particle scales [37-39]. Our group has also employed the DEM method to analyze the particle mixing and flow in mixers and hoppers [31,32,40,41]. These studies take into account the discrete nature of granular materials and allow a good understanding of the fundamental mechanisms of particles flow.

Considered and motivated by the above issues, this study aims at exploring the effect of rocking, including rocking amplitude and frequency, on the discharge behavior of particles in a hopper bed. To accomplish this, the discrete element method was employed to simulate the particle discharging flow in the hopper bed under different rocking amplitudes and frequencies. In addition, the normal bed without rocking was also simulated for reference and comparison.

2. Numerical approach

2.1. DEM collision model

The discrete element method — a soft sphere approach, is used to simulate particle motion in the rocking silo bed. The soft-sphere approach was firstly proposed by Cundall & Strack [42]. It is mainly characterized by modeling particle-particle interaction by three basic collision mechanisms; the incomplete-elastic collision (parameterized by the spring coefficient k and the restitution coefficient e), the viscous damping (parameterized by the damping coefficient η), and the friction or sliding trends (parameterized by a friction coefficient μ):

$$\boldsymbol{f}_c = f_{c,t}\boldsymbol{t} + f_{c,n}\boldsymbol{n} = -k\boldsymbol{\zeta} - \eta\dot{\boldsymbol{\zeta}} \quad (1)$$

$$\text{if}\,|f_{c,t}| > \mu|f_{c,n}|,\,\text{then}\,|f_{c,t}| = \mu|f_{c,n}| \quad (2)$$

where $\boldsymbol{f}_c$ and $\boldsymbol{\zeta}$ are the contact force and inter-particle displacement respectively. '•' denotes the time derivative, and $\boldsymbol{t}$ and $\boldsymbol{n}$ denote the tangential and normal directions between a pair of colliding particles.

Based on the Newton's law of motion, the particle translational ($\boldsymbol{u}_p$) and rotational motion ($\boldsymbol{\omega}_p$) of any particle are governed by:

$$\dot{\boldsymbol{u}}_p = \boldsymbol{F}/m_p + \boldsymbol{g} \quad (3)$$

$$\dot{\boldsymbol{\omega}}_p = \boldsymbol{T}_p/I_p \quad (4)$$

where $\boldsymbol{F} = \Sigma\boldsymbol{f}_c$ is the sum of forces experienced by each particle. m_p, $\boldsymbol{T}_p$, I_p denote the mass, torque and the moment of inertia respectively.

For qualitative validation of the DEM collision model, experimental observations of the discharge of spherical particles from a rectangular hopper (0.4 × 1.4 m in width and height respectively) through an orifice (0.1 m in width) at the bottom are used [43]. According to experimental data, the restitution coefficient $e = 0.55$ and the friction coefficient $\mu = 0.39$ are used in simulation. The numerical results of particle distribution at four time points (t = 0, 1, 1.5 and 8 s) are compared to the experimental counterparts respectively (Fig. 1). After comparison, it is clearly seen that the discharging process can be rebuilt by DEM simulation to a great degree of resemblance. Therefore, this study will use the DEM model to predict the discharging process of particles in the hoppers.

2.2. Simulation conditions

In this work, the hopper bed is 0.8 m × 1.8 m × 0.04 m in width (W), height (H), and depth (D_e) direction respectively. The flare angle of the bed base is 120° (with 30° sidewalls). The orifice width is $D_o = 120$ mm. The bed is filled with 9297 particles of about $H_0 = 1.2$ m pile height (Fig. 2a). The particle diameter is $d_p = 12$ mm. With such kind of bed scales, the constraints of 1). $D_o > 6\,d_p$; 2) $H_0 > D_o$; 3). $W > 2.5\,D_o$ are met. As a result, the discharging rate should be independent of the domain size [27].

The bed is rocking sinusoidally following the governing functions of

$$\theta(t) = \theta_r \sin(2\pi f_r t + \theta_0) \quad (5)$$

where $\theta(t)$ is the rocking included angle between the bed symmetrical axis and the right vertical direction. θ_r is a constant coefficient, namely the rocking amplitude or the maximum included angle of rocking. $\theta_0 = \frac{\pi}{2}$ is the initial phase angle. f_r is the frequency of rocking.

To show the effect of rocking amplitude and frequency on the particle discharging flow, six rocking amplitudes are used ($\theta_r = 5°$, 15°, 30°, 45°, 60°, 75° respectively); and for each amplitude, five frequencies of $f_r = 0.1$, 0.2, 0.3, 0.4 and 0.5 Hz are simulated respectively. The parameters used in current simulation are listed in Table 1.

The initial states of particle in the vertical bed are obtained by a sedimentation process of all the particles, and let them sediment for some time to get stationary states (Fig. 2a). Then, the beds are tilted gradually to reach the angle θ_r of rocking amplitudes, respectively. For example, Fig. 2b shows the initial distribution states of particles in the beds of $\theta_r = 75°$. After that, the bottom orifice of the bed is opened and the particles can be discharged from the orifice.

In addition, it is necessary to mention that, based on the simulation results of the stationary bed without rocking, the particles move downward almost uniformly. The particles near walls do not stay stagnant. Thus, under current flow condition, the flow regime in stationary bed without rocking is a mass flow.

3. Results and discussions

3.1. Discharge process under rocking and flow pattern

At first, for phenomenological comparison, the velocity fields of particles are visualized to show the representative process of particle discharge under rocking. For example, Fig. 3a-f show the particle velocities at $t = 0.1$ s (a), 0.4 s (b), 0.8 s (c), 1.2 s (d), 1.6 s (e), and 2.0 s (f) respectively in the rocking beds with $\theta_r = 60°$ and $f_r = 0.3$ Hz.

At the beginning, only the particles near the orifice begin to discharge (Fig. 3a). After that, the particles near the left-top wall and right-bottom side of the bed begin to move rapidly, forming a large scale "vortex" from the left-top to the right-bottom (Fig. 3b). As a consequence, the particles near the right-bottom side will move to the orifice faster than the particles in the center and near the opposite side wall. When the bed is almost upright (Fig. 3c and d), the particles near the left-bottom wall of the bed get large velocities which are mainly caused by the rebouncing from the wall. As a result, the bulk particle flows from the left-bottom and right-bottom walls converge in the bottom-center, together with the particles from the upside. Therefore,