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Discrete particle simulation of particle flow and separation on a vibrating screen: Effect of aperture shape

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ABSTRACT

This paper presents a numerical study on the effect of aperture shape on particle flow and separation in a vibrating screen process. A three-dimensional discrete element method (DEM) model is developed to simulate vibrating screens with rectangular apertures of different aspect ratios and orientations. Based on the model, the effect of aperture shape on the sieving process is studied through a series of controlled numerical experiments. The sieving performance is analysed in terms of overall percentage passings of different sized particles and the distribution of percentage passings along the screen deck. In addition, the sieving behaviour of individual particles is analysed based on the microdynamics information, particularly the particle-screen interactions. On this basis, the probability of a single attempt and the number of attempts for a particle to pass an aperture are modelled for different shaped apertures, which are linked to the macroscopic sieving performance. The results are useful for developing a fundamental understanding of the effect of aperture shape on screening, which will help design, control and optimise practical processes.

1. Introduction

Screening or sieving is an important unit operation for separating particles according to their sizes, which is normally used for the recovery of product and/or downstream operations [1]. Hundreds of millions of tonnes of particulate materials are subjected to industrial screening each year, in various industrial sectors from traditional resource engineering to food and pharmaceutical engineering [2–5]. However, the understanding on this process is still limited, particularly considering the high number of variables which are related to the screen geometries, operational conditions, and particle properties [5,6]. Previous studies on screening were mainly based on physical experiments, with macroscopic information, such as the percentage passings measured [2,3,7]. Empirical correlations were established based on these experimental data, but they often have limited generality in application due to the phenomenological background. More theoretical models were also developed based on the probability theory [8,9] [10]. These models were dependent on some assumptions on the microscopic information of particles, such as the number of attempts for a particle to pass the mesh. Such information is however difficult to obtain in experiments [8,9].

In recent years, granular dynamic simulations based on the so-called discrete element method (DEM) have been widely used in the studying of granular systems [11,12]. DEM uses first principles to model individual particles, which can provide insight into the complicated particle-particle and particle-wall interactions in the screening processes. In the early studies, Li et al. [13] developed two-dimensional (2D) DEM model to simulate simple sieves. Later, three-dimensional (3D) DEM models have been developed for different screening processes. Simple vibrating screens were studied the most, and the effects of different key controlling variables have been investigated comprehensively. Dong et al. [14] reported a DEM study on the effects of vibration amplitude and frequency and incline angle on the sieving performance of a vibrating screen. Li et al. [15] adopted an advanced regression method to optimise the operational conditions for vibrating screens based on experimental and DEM simulation data. Alkhaldi et al. [16] studied different methods to model meshes of vibrating screens by DEM, while Tung et al. [17] found that the woven wire meshes could more easily cause blocking. Delaney et al. [18] studied the particle shape and flow rate on a vibrating screen, and demonstrated that the modelling of non-spherical particles in DEM could reproduce more precisely the screening of these particles. Yet as aforementioned, screening processes are dependent on various variables, in which particle shape is an important one while others are also interested to researchers [5,7,15]. Therefore, spherical particles are still being used in experimental and numerical studies of screening processes. More recently Elskamp et al. [19]

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benchmarked process models for vibrating screens against various DEM simulations in the literatures, while Jafari et al. [20] studied the wearing of screens by DEM, which demonstrated the other functions of DEM. Other complicated screens have also been investigated by DEM in the literatures. One kind of screens receiving much attention is the banana screens. Dong et al. [21] studied the screening of fine particles in laboratory scale multi-deck banana screens, while Cleary et al. [22,23] modelled the sieving of coarse particles in large scale banana screens by DEM. Fernandez et al. [24] studied the wet banana screens by coupling SPH (smoothed-particle hydrodynamics) to DEM. Later, a single deck banana screen was investigated by Liu et al. [25] and the optimal deck length was recommended. More recently, an open-source DEM package was used to model the double layered banana screens [26]. There are also a few studies on special screening operations involving water flow [27,28]. In all these studies, DEM has not only played as an cost-effective alternative to experiment in generating the data to reveal the effects of different controlling variables on the sieving performance, but also provided the particle scale information, such as the particle bed structure on a screen, the velocity distribution over a deck, and the particle-deck interactions, to improve the understanding of the processes [14,21]. However, how to link the microscopic information with the macroscopic process models still need more attention [14,19].

In previous research, however, the effect of screen aperture shape has not been specifically studied. Most of the studies just used the square apertures although it can be perforated [26] or woven [17]. The macroscopic or process models established in these studies did not consider the effect of aperture shape. Actually, apertures of different shapes are used in the industrial screens [5,29]. The aperture shape is also an important factor that should be considered in optimising the sieving performance [10]. In this paper, we extend our DEM model to study the vibrating screens with rectangular apertures of different shapes and orientations. The effect of aperture shape is then quantified by the simulated percentage passings, including both the overall percentage passings and the distribution of percentage passings at different parts of the screen for different sized particles. In addition, the microscopic information, including particle velocity, the porosity of particle bed, and particle-deck collisions are also analysed and linked with the macroscopic sieving performance. The results will be able to improve the understanding of screening processes and useful to the design and optimisation of screen geometries.

2. Model description

2.1. Governing equations

In DEM, the motions of individual particles are traced by explicit numerical solution of Newton's equation of motion, with various particle-particle and particle-wall interactions considered [11]. For particle i, its translational and rotational motions are determined by:

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

and

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

where $\mathbf{v}_i$, $\boldsymbol{\omega}_i$, m_i and I_i are the translational and angular velocities, and mass and moment of inertia of particle i, respectively; $\mathbf{g}$ is the gravitational acceleration; $\mathbf{R}_{ij}$ is the vector pointing from the centre of particle i to its contact point with particle j; and $\mathbf{F}_{ij}^n$ and $\mathbf{F}_{ij}^s$ are the normal and tangential contact forces respectively, which can be given as [11,30,31]

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

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

where Y is Young's modulus; $\tilde{\sigma}$ is the Poisson's ratio; γ_n is the normal damping coefficient; μ_s is the sliding friction coefficient; $\overline{R} = R_i R_j / (R_i + R_j)$, and R_i and R_j are the radii of particles i and j respectively; $\xi_{s,\max} = \mu_s [(2-\tilde{\sigma})/2(1-\tilde{\sigma})]\xi_n$; $\hat{\mathbf{n}}_{ij} = (\mathbf{R}_i - \mathbf{R}_j)/|\mathbf{R}_i - \mathbf{R}_j|$; and ξ_s is the total tangential displacement during a contact, with $\hat{\boldsymbol{\xi}}_s = \boldsymbol{\xi}_s / |\boldsymbol{\xi}_s|$. The second term of the torque results from the rolling resistance between two contacting particles due to elastic hysteretic losses or viscous dissipation, where μ_r is the rolling friction coefficient and $\widehat{\boldsymbol{\omega}}_i = \boldsymbol{\omega}_i / |\boldsymbol{\omega}_i|$ [32,33]. The DEM model used here has been described in our previous studies in details [14,21]. It has also been validated by good agreement with the experimental results in terms of different parameters, including the mean residence time of the particles, the overall passings of different sized particles, and the distributions of percentage passings along the screen deck [14].

As well established, particle-wall interactions can be calculated according to the same equations, with the radius of a wall assumed to be infinitely large. A complicated boundary is considered to be composed of smooth planes and edges and vertexes shared by two or several planes, with a rigorous protocol to judge particle-vertex, particle-edge and particle-plane collisions. The vibration of the walls are traced and considered in the particle-deck collisions. These treatments are implemented by use of the Object-Oriented Programming (OOP) in the code to facilitate the simulation of complex screen decks vibrated under different conditions, which have been applied in our series of studies on screening processes [14,21,27,28].

2.2. Screen geometries

The geometry of the screen considered is similar to that used in the previous study [14], as shown in Fig. 1(a). The length of the screen (L) is 600 mm. Periodic boundary condition is applied along the X-axis direction to reduce computational effort. Meshes of different rectangular apertures, which are different in dimensions and directions, are used in this work. Fig. 1(b) shows the mesh geometry. Generally a mesh of rectangular aperture can be described by the aperture sizes in the X-axis and Y-axis dimensions, denoted by a_x and a_y respectively, and the distances apart two adjacent apertures along the X-axis and Y-axis, denoted by b_x and b_y respectively. The base case is when $a_x = a_y = 3.5$ mm and $b_x = b_y = 3.0$ mm, corresponding to the square apertures used in the previous study. Aperture shape is changed by increasing either a_x or a_y, while the aperture size in the other dimension should be kept as 3.5 mm to ensure only particles smaller than 3.5 mm can be sieved. In addition, to make the cases comparable, the open areas $(a_x a_y / [(a_x + b_x)(a_y + b_y)])$ of the meshes in different cases are kept as a constant, hence the b_x or b_y is adjusted when a_x or a_y changes. Furthermore, to make the system meet the periodic boundary condition along the X-axis, the length of the screen along the X-axis is also slightly adjusted if a_x and b_x are changed, i.e., the length should equal an integral multiple of $(a_x + b_x)$, as shown in Table 1. Note that the aspect ratio, which is the ratio of the length to the width of a rectangle, is often used to characterize the shape of a rectangle, but it cannot show the orientation of the rectangular aperture. Hence in this study the shape of the aperture is generally quantified in terms of the ratio (a_y/a_x).

2.3. Simulation conditions

A simulation begins with discharging the mixture of particles from the feed end, as shown in Fig. 1(a), and the screen is vibrating under pre-set conditions. The size distribution, feed rate and material properties of the particles are listed in Table 2, which are largely the same as those used in the previous study [14]. The fed particles will fall and hit the vibrating deck, then either pass the deck and report to the

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