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Enhanced axial mixing of rotating drums with alternately arranged baffles

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ABSTRACT

Traditional rotating drums are a popular type of tumbling mixer; however, they generally suffer from poor axial mixing with granular materials. To overcome this weakness, a system of alternately arranged baffles is presented, and its effect on particle mixing is numerically assessed using a GPU-based discrete element method. It is found that this arrangement of baffles displays better axial mixing performance than drums with (or without) traditional baffles, and that maximum mixing efficiency can be obtained through a suitable choice of baffle dimension and number. Essentially, this novel arrangement promotes the bulk movement of particles in the axial direction because of the combined radial scattering and axial guiding effects of the baffles. Together with the enhanced dispersive mixing, axial convective mixing serves to increase the axial mixing efficiency. Moreover, it is found that alternately arranged baffles produce good performance in various granular systems of rotating drums. Thus, the proposed system is a promising approach for industrial applications in more complicated mixers.

1. Introduction

The mixing of granular materials is often encountered in many industries, including pharmaceuticals, plastics, household products, and food processing [1,2]. In general, the quality of the end products is highly dependent upon the degree of mixing of their constituent materials. However, the mixing mechanisms in powder mixers are yet not well understood, because of the complex behavior of dense granular flows [2,3]. Horizontal rotating drums are widely employed to cope with the mixing, drying, and grinding of various powders. Rotating drums display different flow regimes (slipping, slumping, rolling, cascading, cateracting, and centrifuging) at different rotational speeds [4]. Most industrial drums operate in a rolling mode, which is characterized by a dynamic angle of repose with a top active layer and lower passive layer [5]. The mixing/segregation behavior of particles in rotating drums has been extensively studied [6–8] in terms of the particle dynamics and non-equilibrium patterns in the radial and axial directions. Moreover, the scale-up rules of granular flows in rotating drums have also been elucidated [9,10], revealing that the Froude number and particle-to-drum size ratio play crucial roles in this aspect.

Rotating drums belong to the category of so-called tumbling mixers, which generally suffer from the problem of poor axial mixing efficiency because of the slow diffusion of particles [11,12]. To improve the axial mixing of drums, various approaches have been adopted. These include the use of different kinds of blades [13], the exploration of optimum operating conditions [14], and the inclination of the mixer [15]. Each of these approaches enhances the axial mixing of horizontal drums to some extent, but there exists no remarkable change in the flow regimes of particles along the axial direction. That is, no bulk convective flow of particles has been observed. However, this is regarded as the most effective manner of mixing [16]. Regarding the baffles used in the tumbling devices, it has been found that their structure and arrangement are somewhat important [17,18], and may not always improve the mixing efficiency [11,19]. In addition, the symmetric design of mixers can cause symmetrical particle flows in the mixers, prohibiting the axial transport of particles to some extent [20]. Therefore, this paper proposes an axially non-symmetric alternate arrangement of baffles in drums. The proposed system has the potential to instigate the convective mixing of particles in the axial direction.

To understand the mixing mechanisms of baffled drums, the convenience of simulations is preferred to the traditional physical experiments. Generally, granular flows can be simulated by a continuum method [21] or discrete element method (DEM) [22,23]. Although the continuum method can readily cope with large-scale systems containing huge numbers of particles, the general constitutive relations of granular flows that serve as the physical foundation of this technique are still unclear. In contrast, DEM depicts the particle interactions using contact models from classical mechanics, and provides detailed information of the particle dynamics. Due to the advantages of DEM in revealing flow details, it has been widely employed in research into the mixing

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mechanisms of different powder mixers [24], including rotating drums [6,14], V-shaped mixers [25], tote mixers [26,27], and bladed mixers [28,29]. However, the computational cost of DEM simulations is usually quite large, particularly for industrial mixers with large numbers of particles. To alleviate this burden, graphical processing units (GPUs) can be effectively used in powerful parallel implementations of data, leading to a considerable increase in simulation speed compared with traditional CPUs [30]. Indeed, GPUs have recently been applied to DEM simulations of granular flows under different conditions [31–33].

Using GPU-based DEM simulations, the mixing performance of alternately arranged baffles in horizontal rotating drums is fully investigated in this study. Section 2 introduces the nonlinear DEM model and the statistical method of evaluating mixing efficiency. The optimum dimensions and number of baffles are explored in Section 3.1, where the mechanisms underlying enhanced mixing are discussed. Section 3.2 further examines the applicability of this novel baffle arrangement to different granular systems and drum dimensions. Finally, the primary findings of this study are summarized in Section 4, and the implications of our work are also prospected.

2. Simulation method

Particles in industrial mixers may have irregular, non-spherical shapes. Moreover, cohesive systems containing fine particles or wet particles may also be present, and their various non-contact forces play an important role. However, the mixing of spherical dry particles is generally more common, and thus is the focus of the present work. Therefore, the DEM simulations need only consider contact forces and the traditional algorithm of contact detection for spheres. For the statistical analysis of mixing efficiency, some classical functions can be directly employed.

2.1. DEM model

DEM explicitly tracks the motion of individual particles. This motion is governed by Newton's second law as follows:

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

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j \left(\mathbf{T}_{ij} + \mathbf{M}_{ij} \right) \tag{2}$$

where $\boldsymbol{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and angular velocities of particle i, respectively, and m_i and I_i are the mass and moment of inertia. $\mathbf{F}_{ij}^n$ and $\mathbf{F}_{ij}^s$ represent the normal and tangential contact forces imposed on particle i by particle j, respectively. $\mathbf{T}_{ij}$ is the torque on particle i caused by the tangential force $\mathbf{F}_{ij}^s$, and $\mathbf{M}_{ij}$ is the rolling friction torque. Theoretically, the inter-particle contact forces should be given by the Hertz model [34] in the normal direction and the Mindlin–Deresiewicz model [35] in the tangential direction. However, the direct application of these models in DEM is rather complicated, and also computationally expensive (especially for large-scale systems). Thus, a simplified version proposed by Zhou et al. [36] was used in this study. This model includes both conservative and dissipative factors (particularly the rolling friction), giving a suitable balance between accuracy and efficiency in many problems [4,28,37].

The normal and tangential contact forces imposed on particle i by particle j are described by

$$\mathbf{F}_{ij}^n = \left[\frac{2}{3} E \sqrt{\overline{R}} \delta_n^{1.5} - \gamma_n E \sqrt{\overline{R}} \sqrt{\delta_n} \left(\mathbf{v}_{ij} \cdot \hat{\mathbf{n}}_{ij} \right) \right] \hat{\mathbf{n}}_{ij} \tag{3}$$

$$\mathbf{F}_{ij}^s = -\operatorname{sgn}(\delta_s) \mu_s \left| \mathbf{F}_{ij}^n \right| \left[1 - \left(1 - \min\left(\delta_s, \delta_{s,\max} \right) / \delta_{s,\max} \right)^{1.5} \right] \tag{4}$$

where $E = Y/(1-\nu^2)$, with Y and ν being the Young's modulus and Poisson's ratio, respectively; $\overline{R} = R_i R_j/(R_i + R_j)$, with R_i and R_j being the radii of particles i and j; $\delta_{s,\max} = 0.5\mu_s \delta_n (2-\nu)/(1-\nu)$, with μ_s and δ_s being the sliding friction coefficient and total tangential displacement; $\hat{\mathbf{n}}_{ij}$ is a unit vector directed from the center of particle j toward the center of particle i, and γ_n is the normal damping coefficient.

The constant time step (Δt) should be sufficiently small as to guarantee the stability and accuracy of the integral algorithm. According to the energy transfer of Rayleigh waves [38] and the constraints of the Hertz force model [37], there exist two criteria for determining the critical time step:

$$\Delta t = \frac{\pi R}{0.8766 + 0.163\nu} \sqrt{\frac{\rho}{G}} \tag{5}$$

$$\Delta t = 0.1 \sqrt{m / \left(\frac{2}{3} E (0.1R) \right)} \tag{6}$$

where ρ and G denote the density and shear modulus of the particles. The shear modulus can be calculated as $G = Y/[2(1+\nu)]$. In practice, a much smaller time step than that given by Eqs. (5) and (6) is commonly adopted. This accounts for other factors, such as the large relative velocities between particles.

2.2. Simulation conditions

As illustrated in Fig. 1, the baffles are uniformly distributed inside the horizontal drum in a left–right alternate manner. These baffles are arranged so as to lie on the plane passing through the axis of rotation of the drum, and have dimensions of L_b in length and W_b in width. The cylindrical drum rotates around its axis in the counterclockwise direction with angular velocity $\boldsymbol{\omega}$. The radius, diameter, and axial length of the drum are R, D, and L, respectively. The base values of the baffled drum and particles are listed in Table 1. In the base case, the ratios L_b/L and W_b/R are 3/4 and 5/6, and the particle number corresponding to a fill level of 40% is 14,030. A time step of 1.0×10^{-6} s is adopted in the present work. This is sufficiently smaller than the results of Eqs. (5) (9.2×10^{-5} s) and (6) (1.3×10^{-5} s) calculated from the simulation parameters in Table 1. The time integration is performed using the popular leap-frog algorithm [39].

As the initial simulation condition, a collection of spherical particles is arranged in the form of a cylinder with the same axis as that of the stationary drum, and the number of particles is determined by the fill

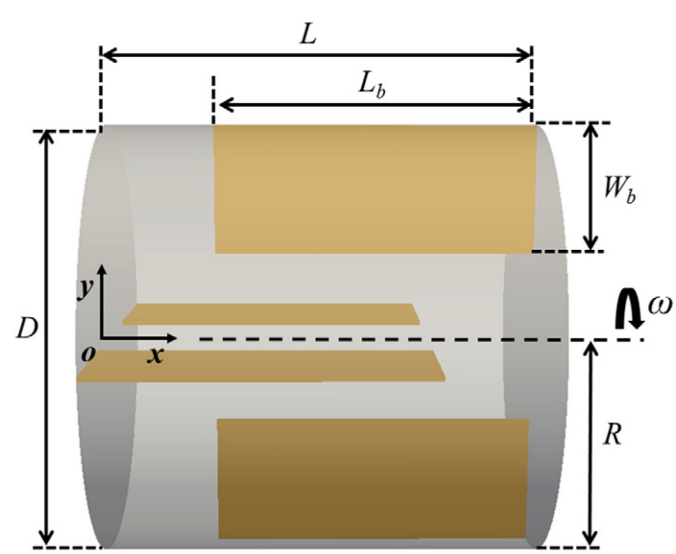

Fig. 1. Schematic illustration of the rotating drum with alternately arranged baffles.