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Numerical study of the mixing efficiency of a batch mixer using the discrete element method

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ABSTRACT

In this study the simulations of granular flow in a batch mixer with independent double axial mixing are presented. The simulated granular flows were used to analyze the mixing efficiency. Such analysis has not been conducted previously for such a batch mixer, because of the complex mixing conditions. The simulations performed in this study use the discrete element method (DEM) with a wall boundary model based on a signed distance function (SDF). Introduction of the SDF allows for an accurate representation of the boundary, which is important for proper analysis of granular flow in the batch mixer. The adequacy of the DEM/SDF approach was validated quantitatively in experiments. The degree of mixing in the batch mixer was evaluated using a mixing index of a binary mixture. The effects of the powder amount, blade speed, initial loading patterns and secondary mixing on the degree of mixing were investigated numerically. In the batch mixer considered in this work, the change in mixing state in the axial direction was found to be much smaller than that in the perpendicular direction. The increase in the mixing speed not only reduces mixing time but also substantially increases the mixing performance if measured per number of rotations. However, the increase in the powder amount reduces the mixing performance. The additional secondary mixing affects the axial-mixing performance. However, the overall mixing performance does not change. In addition, neither the mixing axis position nor the mixing speed appreciably affects the mixing performance. All the mixing differences can be associated with the differences in the granular behavior, irrespective of different speeds, powder amounts or mixing setups.

1. Introduction

The mixing of powders is a critical step in ensuring the quality and performance of various products in food, pharmaceutical and chemical engineering industries. There are many different parameters that are important to mixing e.g., particle sizes and densities, particle surface and air conditions, the mixer design and its fill and the mixing speed and time [1]. A wide variety of industrial mixers exist for different mixture types [2,3], and while mixing dynamics can be evaluated analytically for specific cases [4], experimental approaches are usually taken; e.g., particle sampling, visual tracking, particle image velocimetry, positron emission particle tracking and magnetic resonance imaging [5,6]. However, such approaches cannot track all particles, making it difficult to understand granular flows.

The application of numerical simulations is desirable when investigating mixing because it allows for better control of physical properties and a faster analysis. In addition, numerical simulations based on the discrete element method (DEM) allow for the tracking of all particles in the mixture. The DEM was first proposed by Cundall and Strack [7], and over the years, this method has been improved, modified and coupled with other methods to suit various applications and approaches [8,9]. Solid–fluid interactions can be simulated using the DEM with smoothed particle hydrodynamics [10], the DEM with a moving particle semi-implicit method [11–13], DEM-computational fluid dynamics [14,15] or direct numerical simulation coupled with the DEM [16]. Effects such as agglomeration, breakage and inter-particle bonding can be investigated using the DEM with a more general contact model [17]. Industrial large-scale systems can be simulated using massively parallel DEM approaches [18] or by introducing a coarse-grain model to simplify the system [19–21].

The DEM is also applied to mixing analysis because of its power and flexibility; e.g., the analysis of particle mixing induced by a flat blade [22]. Through the analysis of particle positions, binary mixing can be observed and tracked [23]. The effect of particle size [24] or liquid bonding between particles [25] on the powder mixing performance can also be explored using the DEM. Recently, numerical mixing index calculations were performed to analyze solid particle mixing in a plowshare mixer [26], slant cone mixer [27,28], industrial twin-screw kneader [29] and ribbon mixer [30]. These studies demonstrated the applicability of the

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DEM in analyzing the effects of initial loadings, powder amounts and mixing speeds on the mixing performance.

A batch mixer is a simple mixer that consists of a rotating cylinder. In such a mixer, radial mixing is much stronger than axial mixing, and that the predominant mixing mechanism is diffusion. Many studies have been performed to clarify the powder behavior in a batch mixer. It has been shown that different flow regimes in a rotating drum (i.e., slipping, slumping, rolling, cascading, cataracting, and centrifuging) can be analyzed using the DEM [31]. It has also been shown that the packing density of a powder decreases with an increase in the mixing speed. Another study [32] analyzed cylindrical and horizontal rotating ellipsoidal drums. That study showed that the translational granular temperature increases with an increase in the velocity of the drum wall. Additionally, the highest temperatures were observed at the top of the powder. A similar increase in the granular temperature was reported in another study [33]. Meanwhile, axial dispersion and mixing in the rotating drum decrease with increases in the mixing speed and filling of the cylinder [34]. Transverse mixing also decreases with an increase in the powder amount. This effect can be attributed to the formation and expansion of the dead zone with the powder amount which reduces the mixing efficiency [35]. There are many ways of improving mixing; e.g., blades inside a drum can increase mixing efficiency in the traverse direction for binary particles [36]. The effects of gaps in the side wall [33] or additional paddles [37] have also been analyzed in the study of the granular flow of a binary-particle system. A polydisperse particle system was analyzed in another study [38], which found good agreement between experimental and simulated mixing efficiencies. Good agreement between simulated and experimental granular flows has also been reported in studies on the effects of different particle densities [37] and powder amounts [35]. Although the effects of mixing in a cylindrical vessel subject to a range of motions have been studied by Marigo et al. [39], the behavior of powder in complex mixing has not been fully resolved.

The present study analyzes a cylindrical batch mixer with double axial movement and two interior blades. The blades are applied to improve the mixing performance, while the secondary movement allows achieving a more uniform mixture across different axes. This is an important design element, which reduces the loading effects, thus allowing an easier usage of the device. However, the mixing mechanism in this type of batch mixer has not been fully resolved, owing to the complex double mixing. For example, the degree of mixing and effect of initial loading, powder amount, mixing speed, secondary mixing and granular parameters have not been evaluated in previous studies on such systems.

To clarify the mixing mechanism, dense granular flow in a batch mixer with double axial movement has been simulated using the DEM and a wall boundary model based on a signed distance function (SDF) [40]. In the present study, all analyses were carried out for a mono-dispersed system to reduce the complexity of the analysis. The adequacy of the DEM/SDF approach was validated using simulated and experimental granular distributions in five different cases. The degree of mixing was evaluated using the mixing index of a binary mixture, while the granular behavior was differentiated using the granular temperatures. In the evaluations, the effects of the powder amount, blade speed, initial powder loading and secondary mixing on the degree of mixing in the batch mixer were investigated. It was done by comparing different mixing states that is the different distributions of the mixing ingredients at a specific time, which can be evaluated by visualizing these distributions or by calculating the mixing index of the mixture itself.

Several originalities of this work should be mentioned. First, the novel SDF boundary method was applied for the batch mixer with double-axial movement, while the application of the DEM/SDF to such a system was demonstrated in validation cases. Second, mixing states in a complex batch mixer were numerically investigated for the first time. Finally, different powder behaviors were associated with the different mixing performances.

2. Numerical methods

2.1. DEM/SFD

Solid particle dynamics were calculated using the DEM proposed by Cundall and Strack [7]. The translation and rotation of solid particle i are based on Newton's equations of motion and expressed as

$$m_i \ddot{\vec{r}}_i = \sum_j^{Particles} \vec{F}_{C,ij}^{P-P} + \sum_k^{Walls} \vec{F}_{C,ik}^{P-W} + \vec{F}_G \tag{1}$$

and

$$I_i \dot{\vec{\omega}} = \sum_j^{Particles} \vec{T}_{ij}^{P-P} + \sum_k^{Walls} \vec{T}_{ik}^{P-W} \tag{2}$$

respectively, where m_i is the mass of particle i, which is defined with a position vector $\vec{r}_i$; $\vec{F}_{C,ik}^{P-P}$, and $\vec{F}_{C,ik}^{P-W}$ are the contact forces $\vec{F}_C$ of particle i interacting with particle j (P–P) or wall k (P–W); $\vec{F}_G$ is the gravitational force; $\vec{\omega}_i$ and I_i are the angular velocity and moment of inertia of particle i; and $\vec{T}_{ij}^{P-P}$ and $\vec{T}_{ik}^{P-W}$ are the overall torques $\vec{T}$ of particle i that interacts with particle j or wall k.

The contact force $\vec{F}_C$ between two particles or a particle and a wall was modeled using springs, dashpots and a friction slider. In this model, the stiffness of a spring k, the damping coefficient of a dashpot η and the friction coefficient of a friction slider μ are the free parameters used to describe the normal $\vec{F}_N$ and tangential $\vec{F}_T$ forces. The normal force $\vec{F}_N$ is composed from a spring and dashpot,

$$\vec{F}_N = -k\vec{\delta}_N - \eta\dot{\vec{\delta}}_N, \tag{3}$$

while the tangential force $\vec{F}_T$ is composed from a spring, dashpot, and slider,

$$\boldsymbol{\vec{F}_T} = \begin{cases} -k\boldsymbol{\vec{\delta}_T} - \eta\dot{\vec{\delta}}_T, & \left|\boldsymbol{\vec{F}_T}\right| \le \mu\left|\boldsymbol{\vec{F}_N}\right| \\ \mu\left|\boldsymbol{\vec{F}_N}\right| \dfrac{\eta\dot{\vec{\delta}}_T}{\left|\eta\dot{\vec{\delta}}_T\right|}, & \left|\boldsymbol{\vec{F}_T}\right| > \mu\left|\boldsymbol{\vec{F}_N}\right|, \end{cases} \tag{4}$$

where $\vec{\delta}$ is the displacement of surfaces between two particles. The tangential forces $\boldsymbol{\vec{F}_T}$ were also used to evaluate the torques $\vec{T}$ acting on the particle.

The linear contact model was chosen because a fast algorithm was necessary to evaluate the movement of a large number of particles in a reasonable time. According to the results of our previous studies [11, 13,19], such an approach can be used to simulate realistic particle behavior.

In the present study, a wall boundary based on the SDFs was used [40]. The advantage of the SDF model is that the collision detection algorithm is unaffected by the complexity of the boundary. As an example, the widely used mesh-based wall boundary requires a complex detection algorithm for the analysis of particle–edge, particle–face and particle–vertex interactions. Such a mesh-based model is problematic from a viewpoint of its applicability as more precise boundary representations require more time for the analysis of particle–wall collisions.

The signed distance $\phi(\vec{r})$ is a scalar function defined as the distance to the nearest surface from a position vector $\vec{r}$. Positive values of the SDF indicate that the distance exists outside the boundary whereas negative values indicate that the distance exists inside the boundary. The boundary itself is represented using a zero contour. It has been shown that several SDFs can be used to represent any complex boundary [40].