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

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ABSTRACT

We describe a simulation of granular flow in an industrial ribbon mixer. Such simulations are important to analyze mixing efficiency but they have not been conducted previously in a ribbon mixer, owing to complex boundary conditions. The simulations 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 ribbon mixer. The adequacy of the DEM/SDF approach was validated qualitatively and quantitatively. The degree of mixing in the ribbon mixer was evaluated using a binary mixture mixing index. The effects of the amount of powder, blade speed and initial loading on the degree of mixing were investigated numerically. In the ribbon mixer, the change of mixing state in the axial direction was found to be much smaller than in the perpendicular direction and an increase in the amount of powder and the blade speed generate better mixing. Only the initial loading and amount of powder were found to be critical for good mixing in the ribbon mixer. The mixing mechanism was investigated by DEM/SDF and an optimal initial loading and amount of powder were suggested for better solid mixing.

1. Introduction

The mixing of powders is a critical step to ensure the quality and performance of various products in food, pharmaceutical and chemical engineering industries. A wide variety of industrial mixers exist for different mixture types [1]. Mixing times depend strongly on mixer geometry [2,3] and mixing dynamics can be evaluated experimentally for specific cases [4]. Many experimental approaches can be used to analyze mixing, e.g., sampling, visual tracking, particle image velocimetry (PIV), positron emission particle tracking, magnetic resonance imaging and other techniques [5,6]. However, such approaches may be inaccurate or expensive. The application of numerical simulations is desirable when investigating mixing because they allow for better control of physical properties and a faster analysis.

Numerical simulations of particle behavior are often performed by the discrete element method (DEM), which was first derived by Cundall and Strack [7]. Over the years, the DEM method has been improved, modified and coupled with other methods to suit various applications and approaches [8,9]. Solid–fluid interactions can be simulated by 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 by 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, for example, 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 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] and industrial twin-screw kneader [29]. These researches demonstrated the application of advanced techniques to analyze the effects of initial loading, amount of powder and mixing speed on mixing performance. However, such effects have not been well examined in a ribbon mixer.

A ribbon mixer which has a simple casing but complex blade is commonly used to blend industrial dry powders. Experiments have demonstrated that mixing in the axial direction is not as good as mixing in the perpendicular direction, and that the predominant mixing mechanism in the ribbon mixer is convection [30]. Because of the blade complexity, three-dimensional simulations of particle behavior have only been performed recently, e.g., mixing in a single helical ribbon agitator [31] or

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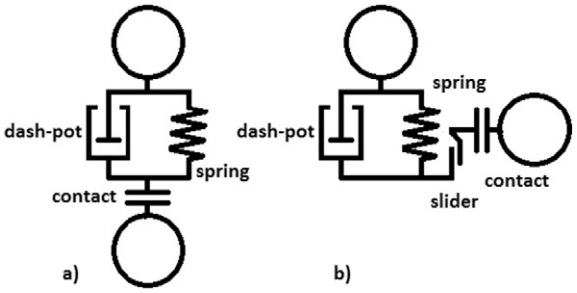

Fig. 1. Springs, dashpots and a friction slider model for the contact force: a) normal force; b) tangential force.

mixer [8]. The mixing mechanism of a complex ribbon mixer has not been resolved. For example, the degree of mixing and effect of initial loading, amount of powder and mixing speed in a ribbon mixer have not been evaluated in previous studies.

To clarify the mixing mechanism, dense granular flow in a complex ribbon mixer has been simulated by the DEM using a signed distance function (SDF)-based wall boundary model [32]. In this study, all analyses are carried out in a mono-dispersed system. Simulations of the DEM/SDF approach were validated using experimental granular flows observed with a high-speed camera and were evaluated using the PIV method. The degree of mixing was evaluated using the mixing index of a binary mixture. In the evaluations, the effects of amount of powder, blade speed and initial powder loading on the degree of mixing in the ribbon mixer were investigated.

2. Simulation method

2.1. DEM

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

$$m_i \vec{r}_i = \sum_{j}^{Particles} \left(\vec{F}_{N,ij}^{P-P} + \vec{F}_{T,ij}^{P-P} \right) + \sum_{k}^{Walls} \left(\vec{F}_{N,ik}^{P-W} + \vec{F}_{T,ik}^{P-W} \right) + \vec{F}_G \quad (1)$$

and

$$I_i \vec{\omega}_{\cdot i} = \sum_{j}^{Particles} \vec{T}_{ij}^{P-P} + \sum_{k}^{Walls} \vec{T}_{ik}^{P-W} \quad (2)$$

respectively, where m_i is the mass of particle i, which is defined with a position vector $\vec{r}_i$; $\vec{F}_{N,ij}^{P-P}$, $\vec{F}_{T,ij}^{P-P}$, $\vec{F}_{N,ik}^{P-W}$ and $\vec{F}_{T,ik}^{P-W}$ are the normal $\vec{F}_N$ and tangential $\vec{F}_T$ forces 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 interact with particle j or wall k. Finally, all contacts that particle i can make are represented by the summations.

The contact force between two particles was modeled using springs, dashpots and a friction slider (Fig. 1). The linear contact model was chosen because a fast algorithm was necessary to calculate a large amount of particles in a reasonable time. Based on our previous studies [11,13,19] such an approach can be used to simulate realistic particle behavior. In the linear contact 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 that are used to describe the normal $\vec{F}_N$ and tangential $\vec{F}_T$ forces:

$$\vec{F}_N = -k\vec{\delta}_N - \eta\vec{\delta}_N \quad (3)$$

Table 1
Simulation parameters and their values.

Parameter	Value	Dimension
Particle diameter d	1.5	mm
Particle density ρ	2500	kg/m^3
Spring constant k	1000	N/m
Particle–particle restitution coefficient e^{P-P}	0.9	–
Particle–wall restitution coefficient e^{P-W}	0.9	–
Particle–particle friction coefficient μ^{P-P}	0.3	–
Particle–wall friction coefficient μ^{P-W}	0.3	–
Integration time step Δt	1×10^{-5}	s

Table 2
Simulation and experimental cases.

Case	Number of particle number (equivalent mass)	Mixing speed	Experimental validation
1–1	400,000 (1767 g)	20 rpm	no
1–2	400,000 (1767 g)	40 rpm	no
1–3	400,000 (1767 g)	60 rpm	no
2–1	700,000 (3092 g)	20 rpm	no
2–2	700,000 (3092 g)	40 rpm	no
2–3	700,000 (3092 g)	60 rpm	no
3–1	1,000,000 (4418 g)	20 rpm	yes
3–2	1,000,000 (4418 g)	40 rpm	yes
3–3	1,000,000 (4418 g)	60 rpm	yes

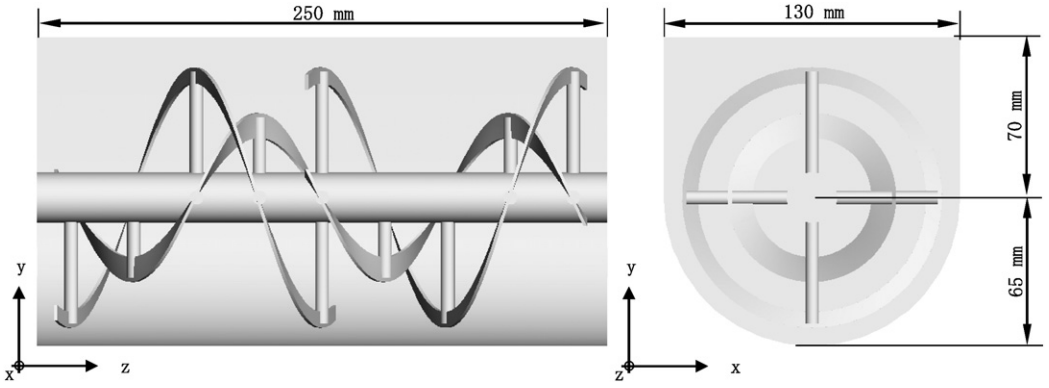

Fig. 2. Geometry of an industrial ribbon mixer with two outer and two inner cylindrical blades (250 mm × 135 mm × 130 mm). The mesh boundary representation as it was used in the simulation. Gravity acts in the direction of the negative y-axis.