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Numerical investigation on particle mixing in a ball mill

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ABSTRACT

Mixing behavior of particles is an essential process for a ball mill. In order to investigate particle mixing, a three dimensional model was established for particle dynamics in a ball mill. Firstly, the Discrete Element Model was adopted to track each particle in the ball mill. Meanwhile, different kinds of collisions, the relative friction for particle movement, and other conventional forces were considered. Then, the bulk movement of particles in the ball mill was explored based on the established model. In addition, the detailed characteristics of particle mixing dynamics in the ball mill were studied with multiple methods, including visual observation, collision detection, and mixing extent. It was found that the contact number of target particles increased fast in the beginning, then collapsed to one unique value when particle mixing became uniform, which finally fluctuated around the unique value periodically with the mill rotation. Moreover, multiple effects of particle size, particle density, uneven granularity and rotational velocity on particle mixing were discussed for particle mixing dynamics. In addition, selected mixing curves were present to provide more mixing information of particles in different areas of the mill. Furthermore, Boltzmann model was found to be available for mixing dynamics with the defined contact number. Additionally, selected stimulation results were compared with relative previous experimental results, and reasonable agreements could be obtained. The present work could provide consults for collision dynamics and mixing behavior of particles in ball mills.

1. Introduction

Ball mills have been widely employed in many industries, such as mineral, cement, food and pharmaceutical industries. During the industrial processes, ball mills are employed not only for grinding, drying and mechanical coating duties, but also for open and closed circuits [1–3]. For example, in the mineral processes, ball mills are often used for grinding duty in a mineral plant. In fact, grinding is an important process since it can directly affect particle size distributions of the final product [4,5]. What's more, the grinding process of particles includes fierce rubbing and contacting and mixing actions of heavy masses in the rotating mill [6,7]. Meanwhile, the mixing process of particles is essential for the ball mill, which could control the secondary phenomena, like chemical reactions and heat transfer between materials [5,8]. Moreover, particle mixing has already been studied with numerous focusing on mixing dynamics, which is usually described in terms of particle contact. This particle contact and the value that described the contacting force acting on ground materials could provide useful signs for the grinding efficiency. Grinding efficiency is regarded as the key factor required to evaluate a grinding process, particularly for its initial grinding stage when compared with other mill types. As a result, the frequency and magnitude of particle mixing is closely related to the grinding rate in the ball mill [9,10]. Additionally, the mixing behavior of particles in the ball mills is of major interest to the energy transfer to the final product. Therefore, precise predictions on particle mixing in a ball mill are of great importance for the grinding process, which can not only meet the need for grinding arrangements but also consume less energy than expected [8, 11].

Mixing dynamics of particles in ball mills have been investigated with various tests and studies. Meanwhile, many relative models have been developed to simulate particle movement in ball mills. However, test studies on particle mixing are very limited based on the present measurement techniques due to the multi-scale complexity of the mill system. Quantitative information, like particle distributions and complete velocities, also cannot be readily accessible via experiments. Consequently, simulation methods, like the Discrete Element Model (DEM), have been put forward to provide insight to further information for particle mixing [7,12–15]. However, particle models and methods on particle mixing are still under development due to this limited availability. And thus, it is still critical to do fundamental work to understand mixing dynamics of particulate systems in ball mills [5,16]. Particle mixing involves multiple processes with complex variables, thus researchers usually identify that particle mixing in a ball mill is in relation to some operating variables, such as particle size, particle type, filling ratio, and rotational velocity [11,17]. Therefore, there are still

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substantial potentials for process investigation with DEM in order to have a more detailed understanding of particle mixing within a ball mill.

The present work aims to obtain further understanding of particle mixing and their contact behavior in a ball mill. Firstly, the DEM method was adopted to establish the three dimensional model for particle movement in the ball mill. At the same time, interactions between particles were estimated in detail with the consideration of the joint action of collision, friction and conventional forces. Then, the whole process of particle movement in a laboratory rotary mill was numerically simulated and presented visually. Particle mixing was investigated in detail with collision detection, in which the contact number of particles was used to find quantitative information for particle mixing. The effects of operating conditions, such as particle size, particle density, uneven granularity and rotational velocity, on particle mixing characteristics were emphatically studied for the ball mill. Furthermore, mixing curves, egression models and comparison with relative results on mixing dynamics were used to find more information for particle behavior in the ball mill.

2. Computational models

In the present work, the DEM method was adopted to simulate particle dynamics in a ball mill, in which particles were assumed to be sphere, homogeneous and anisotropic. The ball mill used for simulation was a laboratory mill, which was essentially a cylindrical shell with six small belly lifters, as shown in Fig. 1. In the mill, particle motion and particle collisions, including particle-particle collision, particle-wall collision and particle-lifter collision, were all considered in detail.

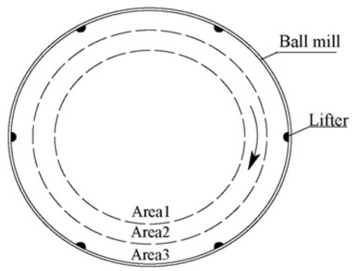
2.1. Particle motion

Each particle was tracked through the whole process. Their locations and velocities were recorded in detail. The relative information on numerical model for sphere particles can be seen in the former work [8,15,18–19]. Particles obey Newton's equation of motion, including translation and rotation, which can be calculated as

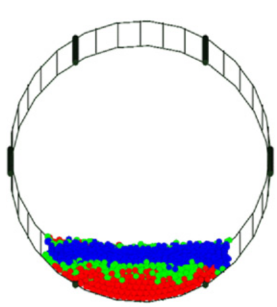
$$\boldsymbol{v} = \frac{\boldsymbol{F}}{m} + \boldsymbol{g} \tag{1}$$

$$\boldsymbol{\omega} = \frac{\boldsymbol{T}}{I} \tag{2}$$

where $\boldsymbol{v}$ is acceleration, $\boldsymbol{\omega}$ is angular acceleration, $\boldsymbol{F}$ is conventional force, like contact force and friction, m is particle mass and $\boldsymbol{T}$ is resultant moment, as well as I is rotational inertia.



(a) Transverse section of the mill



(b) Initial particle bed in the mill

Fig. 1. Configuration of the ball mill.

2.2. Particle collisions

2.2.1. Particle–particle collision

It is necessary to determine particle collision in the first place. Take particle i and particle j for examples, collision was regarded to occur between particle i and particle j when the distance of them is less than the sum of their radius. The collision point was recorded. The force generated at the collision point is called contact force$f_{C,ij}$. $f_{C,ij}$ can be divided into normal component,$f_{cn,ij}$, and tangential component, $f_{ct,ij}$, and can be calculated as

$$f_{C,ij} = f_{cn,ij} + f_{ct,ij} \tag{3}$$

where the subscripts of n and t respectively represent the normal direction and the tangential direction. Moreover, the normal component can make particles deformed, and the tangential component can lead to particle rotation. The two components can be calculated as

$$f_{cn,ij} = -k_n\delta_{nij} - \eta_n \boldsymbol{v}_{nij} \tag{4}$$

$$f_{ct,ij} = -k_t\delta_{tij} - \eta_t \boldsymbol{v}_{tij} \tag{5}$$

where k_n and k_t respectively represent the spring coefficients for the normal direction and the tangential direction. δ_{nij} is the normal displacement of deformation between particle i and particle j, while δ_{tij} is the tangential displacement of deformation between particle i and particle j. η_n and η_t are damping coefficients respectively for the normal direction and the tangential direction.

In the present work, the spring coefficients are regarded as constant, which is 800 according to the early researches [15,19,20,21]. The damping coefficients η_n and $\eta_t$are determined from the equation [22], which is listed as follows

$$\eta_n = \alpha\delta_n^{0.25}\sqrt{mk_n} \tag{6}$$

$$\eta_n = \eta_t \tag{7}$$

where $m$is particle mass, $\alpha$is the sole coefficient deserved from restitution coefficient e. The restitution coefficient can be gained from the experimental fitting curve. However, the detailed information for α and $e$is not presented here, which can be found in early researches [15,20,21,23].

Furthermore, normal loss of kinetic energy and tangential loss of kinetic energy are related to the relative velocity of particle i and particle j, v_{rij}, which can be calculated as

$$\boldsymbol{v}_{rij} = \boldsymbol{v}_i - \boldsymbol{v}_j \tag{8}$$

$$\boldsymbol{v}_{nij} = (\boldsymbol{v}_{rij} \cdot \boldsymbol{n}_{ij})\boldsymbol{n}_{ij} \tag{9}$$

$$\boldsymbol{v}_{tij} = \boldsymbol{v}_{rij} - \boldsymbol{v}_{nij} \tag{10}$$

where $\boldsymbol{n}$ is normal unit vector, $\boldsymbol{v}_t$is the tangential component of relative velocity, and $\boldsymbol{v}_n$ is the normal component of relative velocity.

However, the extreme of tangential component is restricted by the normal component and friction coefficient of particles. Two particles might slide on their contact surface. When the tangential component is greater than the product generated by the friction, namely

$$|f_{ct,ij}| > \mu_f |f_{cn,ij}| \tag{11}$$

Then,

$$f_{ct,ij} = -\mu_f |f_{cn,ij}| \frac{\boldsymbol{v}_{tij}}{|\boldsymbol{v}_{tij}|} \tag{12}$$

where μ_f is friction coefficient of particles.