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# Numerical simulation on mixing kinetics of slender particles in a rotary dryer

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ABSTRACT

The mixing processes of slender particles in a rotary dryer fitted with lifters were simulated in three dimensions. Particle motion was modeled by the Discrete Element Method (DEM) and a three dimensional collision model for slender particles was developed. Contact force, friction force and gravitational force acting on an individual slender particle were considered when establishing mathematics models. The influences of rotational velocity on the mixing of slender particles were discussed and compared with those of spherical particles under identical operating conditions. It was found that the mixing characteristics of slender particles and spherical particles all followed a constant rate until a completely mixed state was encountered. But there were still certain differences between these two kinds of particles. The influences of the lifters with different shapes were further discussed for slender particles. Selected stimulation results were obtained and would provide consults for the further study of slender particles.



## 1. Introduction

Rotary dryers have been extensively employed in the chemical, metallurgical, food, tobacco and mineral processing industries, in which they are used to perform mixing, drying, heating, and chemical reactions. In all of these processes, the mixing of particles is important as this controls the secondary phenomena in the rotary dryer such as heat transfer to the material. The mixing process directly affects the yield and efficiency of the process and is quite commonly a bottleneck [1–4].

Although considerable work has been done in the past in rotary dryers, there is still a lack of fundamental understanding on mixing of particulate systems in rotary dryers [5]. The process of particle mixing in rotary dryers is complex due to differences in particle properties, devices configuration, rotational velocity and the degree of filling. Typically, the particle properties are extremely important factors, especially the particle shapes. Particle shapes are restricted to spheres (with varying radius), considered the most convenient for pharmaceutical, metallurgical and mining applications in rotary dryers [6–8]. However, many other industrial applications are dealing with non-spherical particle mixing in rotary dryers or other rotary devices, such as in drying of biomass stalks, pastures, fibres and cut-tobaccos. Under these conditions, particles are thin and long, and distinctly different from spherical particles. We call them slender particles in this paper. Serious errors would occur if slender particles are approximated as spherical particles in the numerical simulation. Whereas slender particles play a significant role in many processes, it is necessary to study the kinetics of slender particles [9,10].

The aim of this paper is to develop an appropriate model of slender particles for the dynamic simulation on the particle behavior in a rotary dryer. This model can be used to investigate the kinetic characteristics and capture the mixing information of slender particles in a rotary dryer. Since the existing work by DEM (also called discrete particle method), as proposed by Cundall and Strack (1979a,b) [11], does not focus on slender particles, or it was not conducted in a parametric space favorable for our intended comparison, we have decided to track the movement of individual slender particle in a rotary dryer by DEM. The simulation techniques used in the current work are more complex than those typically used for spherical particles due to the following reasons [12]:

- The slender particles are homogeneous, anisotropic and can be treated as cylinders.
- A three dimensional collision model for slender particles is developed.
- Periodic boundaries are considered in the presence of gravity, friction and collision force during the mixing process.
- Particle-to-particle, particle-to-wall and particle-to-lifter collisions are all rigorously modeled.
- Axial motion of particles is taken into consideration for its vigorous mixing [13, 14] and particles distributions in the axial directions are studied.
- The rotary dryer consists of a horizontal rotating drum. The internal shell of the drum is fitted with bars, or lifting flanges, called lifters, to help carry the particles as the drum rotates. In this paper, the case of extended circular lifters and vertical lifters with two segments are considered [15], as shown in Fig. 4 [3,16,17]. The cross-section of a rotary dryer showing lifter arrangement is illustrated in Fig. 5 [18].

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It is important to point that previous works on DEM mostly address these issues for spherical particles, but not for slender particles, as is done in this current work. Moreover, for a narrow drum used in this work, rigorous modeling of the wall collisions and the lifter collisions are preferred as opposed to assuming a no-slip condition at the walls without lifters [12].

In the current paper, DEM simulation and particles counting method are used to study particle motion in rotary dryers. A comparison between the simulation results of slender particles and spherical particles is presented in terms of the mixing extent of particles in a rotary dryer. As shown in Fig. 1, the whole mixing process of slender particles in the rotary dryer is numerically simulated, which is drawn using Auto Lisp. Fig. 2 shows the mixing process of spherical particles according to the previous successful work [3,14,19]. Operating conditions for both slender particles and spherical particles are identical. The effects of rotational velocity as well as lifter configuration on mixing kinetics of slender particles are discussed in detail.

## 2. Computational models

### 2.1. Particle motion

The computational model for spherical particles can be seen in the previous work [19–21]. In the past, most of the modeling and simulation work has focused on spherical particles but this work focuses on a computational model of slender particles instead. According to Newton's equation of motion, the motion of a particle can be calculated as

$$\begin{cases} \sum F = ma \\ \sum M_G = \dot{H}_G \end{cases} \tag{1}$$

where $\boldsymbol{F}$ is the force, $m$ is particle mass, $\boldsymbol{a}$ is acceleration $\boldsymbol{M}_G$ is particle torque and $\dot{\boldsymbol{H}}_G$ is the differential coefficient to time of the momentum torque $\boldsymbol{H}_G$.

### 2.2. Particle collision

Since the model deals with individual slender particle, it is necessary to discriminatingly treat and solve the problems on collisions of particle-to-particle, particle-to-wall and particle-to-lifter.

#### 2.2.1. Particle-to-particle collision

The collisions between slender particles were difficult to decide. This work used the two endpoints of each slender particle to decide the particle's position in the rotary dryer. The knowledge of analytic geometry, such as the distance between two points, coplanar lines, lines in different planes and the distance from a point to a line, etc. were used to decide whether a collision might happen and figure out the collision point if a collision took place. The collision model was used to solve the particle state after collision.

If a collision takes place between particle $i$ and particle $j$, as shown in Fig. 3, the velocities before and after the collision of particle $i$ can be calculated as

$$v_i = u_i + \omega_i \times r_i \tag{2}$$

$$v_i' = u_i' + \omega_i' \times r_i \tag{3}$$

where $\boldsymbol{v}_i$ is the velocity of particle $i$ before collision, which can be determined by the parameters before collision: the translational velocity $\boldsymbol{u}_i$, the rotational velocity $\boldsymbol{\omega}_i$ and the position vector $\boldsymbol{r}_i$ from the particle centroid to the collision point. $\boldsymbol{v}_i'$ is the velocity of particle $i$ after collision, $\boldsymbol{u}_i'$ is the translational velocity after collision, $\boldsymbol{\omega}_i'$ is the rotational velocity after collision.

The impulse caused by the collision may give rise to particle translation and rotation. For the particle centroid, the parameters after collision can be expressed as the following equations

$$u_i' = u_i + \frac{p_n}{m_i} \tag{4}$$

$$\omega_i' = \omega_i + \frac{r_i \times p_n}{I_i} \tag{5}$$

where $\boldsymbol{p}_n$ is the normal impulse at the collision point, $I_i$ is the moment of inertia for particle $i$. As can be seen in the above equations, the velocity at the collision point of particle $i$ after collision can be calculated as

$$v_i' = v_i + \left(\frac{n}{m_i} + \frac{r_i \times n}{I_i} \times r_i\right)|p_n| = v_i + c_i|p_n|. \tag{6}$$

As for particle $j$, it can be calculated as

$$v_j' = v_j + \left(\frac{n}{m_j} + \frac{r_j \times n}{I_j} \times r_j\right)|p_n| = v_j + c_j|p_n| \tag{7}$$

where $\boldsymbol{v}_j$, $\boldsymbol{v}_j'$ and $\boldsymbol{r}_j$ are the velocity at the collision point of particle $j$ before collision, the velocity at the collision point of particle $j$ after collision and the position vector from the particle centroid to the collision point. Here, $\boldsymbol{c}_i$ and $\boldsymbol{c}_j$ are the constant vector for particle $i$ and particle $j$, which are introduced in the computing process.

The normal velocity at the collision point before collision can be described as

$$|v_n| = n \cdot \left(v_i - v_j\right). \tag{8}$$

Based on Eq. (6) and Eq. (7), the normal velocity at the collision point after collision can be described as

$$|v_n'| = n \cdot \left(v_i' - v_j'\right) = n \cdot \left(c_i - c_j\right)|p_n| + |v_n|. \tag{9}$$

The relationship between $\boldsymbol{v}_n$ and $\boldsymbol{v'}_n$ can be described as

$$v_n' = -ev_n \tag{10}$$

where $e$ is the coefficient of restitution, which is a comprehensive concept for describing the loss of energy. It varies from 0 to 1, where 0

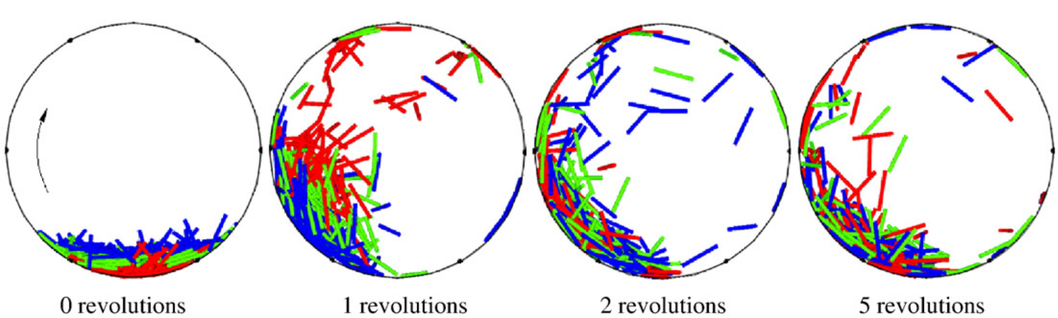


**Fig. 1.** Dynamic mixing of slender particles in a rotary dryer at different revolution numbers.