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Enhancing mixing of cohesive particles by baffles in a rotary drum

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ABSTRACT

A soft-sphere discrete cohesive powder model was used to simulate the transverse mixing of particles in a rotary drum. Using this model, the effect of cohesion strength and baffle length was investigated. Mixing time (t_R) and mixing entropy were used to characterize the mixing behavior. The results showed that increasing particle cohesiveness increases t_R. Baffles enhanced transverse mixing, especially for high-cohesive particles. Moreover, the baffle length played a significant role on mixing. An optimized length of 0.50 (L/R) enhances transverse mixing for high-cohesive particles. Further increases in baffle length only decreases the mixing rate by impeding the surface flow layer. In contrast to high-cohesive particles, low-cohesive particles needed much shorter baffles.

Introduction

Particle mixing using a rotary drum is a common industrial process. Although mixing occurs in both the transverse section and in the axial direction, the former is the dominant process, on which most of the research is focused. The first study was by Hogg and Fuersten (1972) using coupled convection–diffusion kinematics. Khakhar, McCarthy, Shinbrot, and Ottino (1997) developed the model further taking into consideration the surface flow layer. To date, mixing in the transverse section is considered to develop from two main types of mixing mechanisms. One is particle convection which involves macro-scale movements of particle clusters, specifically peripheral rotation, and the other is particle diffusion, which involves the mutual intermingling of particles at the scale of individual particles, similar to molecular diffusion in fluids (Jiang, Zhao, Liu, & Zheng, 2011).

In most studies conducted on mixing in the rotating drum, the particles are regarded as individual particles without any cohesion (Chaudhuri, Mehrotra, Muzzio, & Tomassone, 2006; Herminghaus, 2005; McCarthy, 2003). However, particle cohesion in many industrial materials, such as in pharmaceuticals, semiconductors, food, ceramics, fertilizers, and petrochemicals cannot be ignored. Moreover, from the distinctive properties of industrial materials from diverse sources, the range of cohesiveness is extensive. When dealing with these particles, a parameter giving the degree of cohesiveness must be included in the simulation.

In addition, the mixing efficiency of the final blend depends on many parameters, such as initial loading pattern, percentage fill level, mixing time, component concentration, blender geometry, use of pre-blending, and the presence of baffles (Hill & Kakalios, 1994; Khakhar et al., 1997; Knight, Jaeger, & Nagel, 1993; Ristow, 1994). Baffles in the rotary drum not only change the velocity field of particles in the rotary drum, but also disturb the particle convection and diffusion in the flowing layer. In the design of a reactor, the inclusion of baffles in the drum is a key factor to be considered, especially in regard to high-cohesive particles. Therefore, in our study, the transverse mixing of cohesive particles combined with the inclusion of baffles were studied. Varying particle cohesiveness and baffle properties including length were investigated using the discrete soft-particle model.

Computational models

Discrete element method

The simulations were performed based on the discrete element method (DEM) originally proposed by Cundall and Strack (1979), and implemented in the EDEM software (DEM Solutions). A

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three-dimensional DEM was employed here. In this method the motion of a large number of particles was determined numerically by integrating the equations of motion, using a suitable model, for particle–particle and particle–wall interactions. The motion of a particle of radius R_i and mass m_i in a rotary drum can be described as

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \sum_j (\boldsymbol{F}_{ij}^{\mathrm{n}} + \boldsymbol{F}_{ij}^{\mathrm{s}} + m_i\boldsymbol{g}), \quad (1)$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_j (R_i\boldsymbol{F}_{ij}^{\mathrm{s}} - \mu_{\mathrm{r}} R_i |\boldsymbol{F}_{ij}^{\mathrm{n}}| \boldsymbol{\omega}_i), \quad (2)$$

where $\boldsymbol{v}_i$, $\boldsymbol{\omega}_i$, and I_i are the translational velocity, angular velocity, and moment of inertia of particle i, respectively; $\boldsymbol{R}_i$ is a vector extending from the center of the particle i to the contact point with its magnitude equal to particle radius r_{p}; $\boldsymbol{F}_{ij}^{\mathrm{n}}$ and $\boldsymbol{F}_{ij}^{\mathrm{s}}$ represent the normal contact force and the tangential contact force, respectively, imposed on particle i by particle j.

Tsuji, Tanaka, and Ishida (1992) developed a more accurate mathematical model of particle contact which used the elastic theory of Hertz for the normal contact problem and the no-slip solution of the tangential contact problem, which was solved by Mindlin and Deresiewicz (1953). The elastic constant is a function of the geometrical and physical properties of the particle and wall, which can be expressed as

$$K_{\mathrm{n}} = \frac{4}{3} E_{\mathrm{eq}} \sqrt{R_{\mathrm{eq}}}, \quad (3)$$

where E_{eq} is the equivalent elastic modulus and R_{eq} is the equivalent radius, which could define the equivalent property of particle materials. The relationship between the normal force f_{n} and the normal displacement δ_{n} is expressed as a power law:

$$f_{\mathrm{n}} = -K_{\mathrm{n}} \delta_{\mathrm{n}}^{3/2}. \quad (4)$$

Neglecting micro-slipping, the tangential force is evaluated as

$$f_{\mathrm{n}} = -K_{\mathrm{t0}} \delta_{\mathrm{t}}, \quad (5)$$

where K_{t0} is the initial stiffness constant, which is a function of the equivalent shear modulus G_{eq}, radius R_{eq}, and the actual normal displacement δ_{n}:

$$K_{\mathrm{t0}} = 8 G_{\mathrm{eq}} \sqrt{R_{\mathrm{eq}} \delta_{\mathrm{n}}}. \quad (6)$$

In the absence of micro-slippage, the gross sliding condition provided by Coulomb's law of friction was imposed as a constraint in the tangential force calculation.

The Hertz–Mindlin (no-slip) model provided a better agreement, and more detail at the microscopic scale can be obtained than from any other model, according to a comparison of performance for different contact models (Di Renzo & Di Maio, 2004).

To study the effect of cohesion on particle mixing, a linear cohesion contact model was used as the basic contact model (Herminghaus, 2005). This model was combined with a modified Hertz–Mindlin model by adding a normal cohesion force F, written as

$$F = kA, \quad (7)$$

where k is the energy density and A is the contact area between particles or between particle and wall.

Simulation conditions

A horizontal short kiln was partially filled with spherical particles (Fig. 1). Depending on the rotation speed, different regimes of motion were obtained. With regard to end-wall effect, a periodic boundary condition was employed to simplify the configuration of a long kiln. The length of the rotary kiln L was set to $L = 5.3d_{\mathrm{p}}$ which was validated in a study by Yang, Yu, McElroy, and Bao (2008). The effect of air can be ignored because of the high density of the particle materials. Parameters of the simulation are given in Table 1.

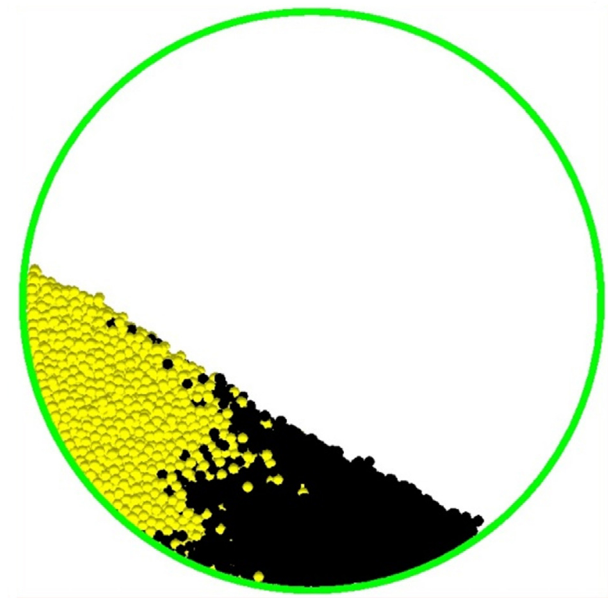

Fig. 1. Geometric model and particle configuration.

Table 1
Parameter values used in simulations.

Parameter	Value
Rotary kiln, R/L (mm)	200/60
Filling degree, f (%)	20
Rotation speed, n (rpm)	10
Particle size, d_{p} (mm)	7
Total number of particles	5500
Particle density (kg/m^3)	90
Shear modulus of particle (N/m^2)	1×10^5
Poisson ratio of particle	0.25
Coefficient of restitution	0.5
Coefficient of static friction	0.5
Coefficient of rolling friction	0.01

Results and discussion

Effect of particle cohesion on transverse mixing

Two main mechanisms, particle convection and particle diffusion, promote transverse mixing in the rotary drum. Particle convection is determined by the active layer where particles are more vigorously mixed; there are more collisions in the active layer than in the passive area. The maximum thickness and average velocity of particles can be used to describe the activity within the active layer. With a larger active layer, particle convection is stronger; given a specified active layer area, the average velocity of particles plays a vital role.

Two simulations were performed of particle mixing in a rotary drum without baffles. Particles with low (energy density of 1500 J/m^3) and high (energy density of 4500 J/m^3) cohesiveness were studied (Fig. 2(a) and (b), respectively). The mixture consisted of particles of the same cohesiveness, but to observe features of mixing they were initially separated into two layers, an upper (yellow) layer and a lower (black) layer. After twelve seconds of mixing, the low-cohesive particles were well mixed, and the particles from the two layers were uniformly dispersed in the drum, whereas