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Using the discrete element method to assess the mixing of polydisperse solid particles in a rotary drum

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ABSTRACT

Despite the wide applications of powder and solid mixing in industry, knowledge on the mixing of polydisperse solid particles in rotary drum blenders is lacking. This study investigates the mixing of monodisperse, bidisperse, tridisperse, and polydisperse solid particles in a rotary drum using the discrete element method. To validate the model developed in this study, experimental and simulation results were compared. The validated model was then employed to investigate the effects of the drum rotational speed, particle size, and initial loading method on the mixing quality. The degree of mixing of polydisperse particles was smaller than that for monodisperse particles owing to the segregation phenomenon. The mixing index increased from an initial value to a maximum and decreased slightly before reaching a plateau for bidisperse, tridisperse, and polydisperse particles as a direct result of the segregation of particles of different sizes. Final mixing indices were higher for polydisperse particles than for tridisperse and bidisperse particles. Additionally, segregation was weakened by introducing additional particles of intermediate size. The best mixing of bidisperse and tridisperse particles was achieved for top–bottom smaller-to-larger initial loading, while that of polydisperse systems was achieved using top–bottom smaller-to-larger and top–bottom larger-to-smaller initial loading methods.

Introduction

Granular materials with different properties are widespread in nature, and they can flow like fluids (e.g., an avalanche, sand flow, and debris flow) under the co-activation of an external force and internal stress (Alexander, Shinbrot, & Muzzio, 2001). One of the differences between particles and fluids lies in the mixing behavior. Granular materials often have a tendency to segregate and even separate owing to differences in particle properties such as the shape, size, and density (Abouzeid & Fuerstenau, 2010). In processing industries, two or more types of solid particles are often required to be mixed to some degree of homogeneity. For example, two drug powders need to be mixed to produce composite drugs in the pharmaceutical field. There are three major mechanisms for mixing, namely, diffusive, shear and convective mechanisms (Poux, Fayolle, Bertrand, Bridoux, & Bousquet, 1991). For industrial processes, at least one of these basic mechanisms is responsible for mixing (Lacey, 1954). If two granular materials are dissimilar (e.g., in size and/or specific weight), it is often difficult to mix them homogeneously owing to size segregation and/or density segregation (Jiang, Zhao, Liu, & Zheng, 2011). Segregation is a continued source of frustration for industries involving granular materials and can cause dramatic revenue loss (Alexander, Shinbrot, Johnson, & Muzzio, 2004).

Depending on the segregation mechanism, researchers have recognized the segregation patterns of fluidization, sieving, percolation, trajectory, rolling, displacement, agglomeration, embedding, push-away, concentration-driven displacement, impact-bouncing, angle of repose, and air current segregations (De Silva, Dyroy, & Enstad, 2000; McGlinchey, 1998; Mosby, de Silva, & Enstad, 1996).

Displacement and percolation segregations are considered as a special case of sieving segregation because the commonality of these patterns is that large particles move upward while small particles move downward. Additionally, these patterns belong to top-to-bottom segregation (Tang & Puri, 2004).

Industrial mixers are classified into six categories: tumbling mixers, pneumatic blenders, gravity silo blenders, high-intensity mixers, high-intimacy or high-shear mixers, and agitating mixers that can be divided into the paddle and plough, fluidizing paddle

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Nomenclature

$C_{n\,rest}$ coefficient of restitution
E_{ef} Young's modulus (N/m^2)
F_n normal force resulting from the contact of particle A with particle B (N)
F_t tangential force resulting from the contact of particle A with particle B (N)
F_{tD} tangential damping force (N)
G_{eq} equivalent Shear modulus (N/m^2)
L distance from center of one particle to the contact plane with the other particle (m)
M_{ef} effective particle mass (kg)
M_A mass of particle A (kg)
M_B mass of particle B (kg)
N normal unit vector
n_M total particle number fraction in cell M
R_{ef} effective radius of the colliding particles (m)
R_A radius of particle A (m)
R_B radius of particle B (m)
$T_{total,S}$ total torque acting on a particle (N m)
T_r rolling resistance torque (N m)
x_j^M number fraction of species j in cell M

Greek letters
Γ degree of mixing of all particle species at a specific time step
δ_n normal overlap
δ_t tangential displacement
$\dot{\delta}_t$ relative tangential velocity (m/s)
μ_R rolling friction coefficient
ν_A Poisson coefficient
ν_B Poisson coefficient
Ψ degree of mixing for poly-disperse systems
ω relative angular velocity of a particle (rad/s)

mixers, ribbon blenders, screw mixers, and the sigma-blade and z-blade mixers (Alian, Ein-Mozaffari, & Upreti, 2015; Muzzio et al., 2004; Tahvildarian, Ein-Mozaffari, & Upreti, 2013).

Tumbling blenders play a significant role in food and pharmaceutical industries. They have many technical advantages that are characterized by their moderate mixing intensity, simple structure, easy sanitization, and the large handling capacity (Jiang et al., 2011). However, serious segregation phenomena might appear especially in the mixing of bidisperse or multidisperse particles with different physical properties inside a tumbler mixer. Inside the tumbler, segregation generally appears at the free surface of granular flow, where the larger or lighter particles rise to the top, and the smaller or denser particles sink inside the total mass of particles (Jiang et al., 2011).

Different types of tumbling mixers such as double-cone, V, Y, and rotary drum blenders have been used in industry (Paul, Atiemo-Obeng, & Kresta, 2004). Rotary drum blenders, which can be used in both batch and continuous processes, are widely used for the mixing of powders in the food industry (Onwulata, 2005), the bioremediation of contaminated soil in environmental applications (Gray et al., 1994; Woo & Park, 1999), the mixing of slurries such as in the hot water extraction of bitumen from Athabasca tar sands (Carrigy, 1963), and drying processes in the mineral industry (Ahmadian, Hassanpour, & Ghadiri, 2011; Renaud, Thibault, & Trusiak, 2000).

Arntz et al. (2008) investigated the fill level effect on the segregation of bidisperse particles, which were initially loaded side by side in a rotary drum. When particles with different sizes are mixed inside a rotary drum, the smaller particles are relocated inside the occupied mass, and the larger particles are pushed away and relocated at the circumference of the occupied mass. This is called the percolation segregation mechanism (Arntz et al., 2008). According to this mechanism, the larger particles move further away from the small particles, and the small particles at the center are surrounded by the larger particles. According to the percolation mechanism, the small particles fall through the voids in the flowing granular bed. It has been shown that the most intense segregation occurred at fill fractions exceeding 65%. Chand, Khaskheli, Qadir, Ge, and Shi (2012) studied the radial segregation for a binary mixture inside a rotary drum. They reported that the radial segregation in a longer drum was higher than that in a shorter drum. Alizadeh, Dube, Bertrand, and Chaouki (2013) investigated the mixing and segregation of polydisperse particles inside a rotary drum according to particle trajectories, which were obtained employing radioactive particle tracking. The radial segregation, axial dispersion coefficients, and velocity profiles for mono- and polydisperse systems were studied as functions of the particle size and rotational velocity.

Faqih et al. (2006) investigated the flow-induced dilation of cohesive granules. The mixing quality inside the rotary blender was a function of the rotational velocity, particle sizes, powder composition, flow-induced dilation of cohesive granular powders, and geometrical parameters of the mixer. Some studies have shown that the mixing quality in rotary drum blenders can be improved using internal blades or baffles (Jiang et al., 2011; Malhotra, Mujumdar, Imakoma, & Okazaki, 1988; Malhotra, Mujumdar, & Okazaki, 1990).

Khakhar, McCarthy, Shinbrot, and Ottino (1997) analyzed the mixing of monodisperse particles in a rotating cylinder to explore the role of flow on the dynamics of the mixing process at rotational speeds ranging 5.0–20 rpm. They reported that the segregation was unimportant if the free surface of the granular particles was nearly flat for identical particles. They also defined two regions of the particle flow. The fixed bed of particles rotated at the speed of the rotary drum and the rapid-flow region of the cascading layer moved at the free surface.

Chen, Ottino, and Lueptow (2011) worked on the axial segregation of binary mixtures (two different particle sizes) within a rotary drum using the discrete element method (DEM). They observed that the axial flow rates of the small and large particles were not the same in different regions of the flowing layer. As a result, the large particles accumulated at the end walls of the mixer while the small particles moved farther from the end walls. In the upstream portion of the flowing layer, both small and large particles flowed away from the wall of the tumbler. However, in the downstream portion of the flowing layer, the large particles fell into the mixture, where the axial flow was weaker, and the small particles flowed back toward the end walls. They found weak axial flow at the segregated bands of the large and small particles.

Our comprehensive literature review revealed that there is a lack of information on the mixing of binary, ternary, and polydisperse particles inside rotary drum mixers. Therefore, the main objective of this study is to explore the mixing features of the mono-, binary, ternary, and polydisperse particles in a rotary drum mixer as functions of the rotational speed of the drum and the initial loading method. To achieve this objective, both experimental and DEM investigations are conducted. Results from the experimental investigation are used to validate the DEM model developed in this study.

Experimental setup and procedures

Fig. 1(a) depicts a schematic of the experimental setup used in this study. The drum was constructed from glass and its length

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