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Evaluation of poly-disperse solid particles mixing in a slant cone mixer using discrete element method

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ABSTRACT

There is a lack of sufficient knowledge regarding mixing of poly-disperse particles. Thus, the main objective of this study was to investigate the mixing of the bi-disperse, tri-disperse, and poly-disperse particles in the slant cone using the discrete element method. DEM results were validated using experimental data obtained from both sampling and image analysis techniques. The effects of initial loading scenarios, particle size, drum and agitator speeds on the mixing efficiency were explored. The mixing metric was utilized to measure the mixing quality for the different mixtures. The mixing index increased to a maximum value and decreased slightly before reaching a plateau for bi-disperse particles for different loading methods and 15 rpm drum speed as a direct result of the trajectory segregation of the particles with different sizes. The highest mixing index for bi-disperse particles was achieved for top–bottom smaller-to-larger initial loading and 45 rpm drum speed. The mixing quality of the bi-disperse particles was improved by the rotation of the agitator compared to that achieved with the stationary agitator at the fill level of 100%. The highest mixing indices were achieved for the tri-disperse and poly-disperse particles under the top–bottom smaller-to-larger loading method at the drum speed of 15 and 55 rpm, respectively.

1. Introduction

Particle mixing is an essential unit operation in many industrial applications such as mineral, polymers, food, ceramic, pharmaceuticals, and cosmetics processing. In chemical industries, two or more types of solid particles are often required to be mixed to some degree of homogeneity. In the pharmaceutical field, two drug powders or fillers require to be mixed in order to produce composite drugs. A key difference between fluids and granules lies in the mixing properties. While fluids might suffer mixing due to the molecular diffusion, turbulence or chaotic advection; granules frequently have a tendency to segregate and even separate due to differences in particle properties such as the density, shape, and size (Abouzeid and Douglas, 2010).

Lacey (1954) specified three major mechanisms for mixing that would be classified into shear, diffusive, and convective mechanism. For industrial processes, at least one of these basic mechanisms is responsible for mixing; if two granules are dissimilar (e.g. in size and/or specific weight), it is often difficult to mix them homogeneously due to the size segregation and/or density segregation (Jiang et al., 2011).

Segregation is a continued source of setback for industries involving granular materials and could cause dramatic revenue loss (Alexander et al., 2004). According to the recent studies, the main reason for segregation of the granular materials is the particle size differences (Remy et al., 2011). Tang and Puri (2004) proposed the following segregation mechanisms: fluidization (fine), agglomeration (cohesive fine), sieving (small particles), and trajectory (large particles).

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Nomenclature

a_k	acceleration for the studied particle (m/s^2)
$C_{n\,rest}$	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)
$F_{total,k}$	total force acting on a particle (N)
F_{tD}	tangential damping force (N)
G_{eq}	equivalent Shear modulus (N/m^2)
g	acceleration of gravity (m/s^2)
I_K	moment of inertia of a particle (kg m^2)
k_n	normal elastic constant (N/m)
K_r	rolling stiffness of the spring (N/m^2)
L	distance from the 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)
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)
S_t	tangential spring stiffness (N/m^2)
$T_{total,k}$	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

α	torsional deformation between particles
β	damping coefficient
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)
ζ_r	rolling damping coefficient
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)
$\frac{d\omega}{dt}$	angular acceleration of a particle (rad/s^2)

Industrial mixers are classified into six categories: gravity silo blenders, pneumatic blenders, tumbling blenders, high intensity mixers, high-shear mixers or high-intimacy, and the agitated mixers that would be divided into the ribbon blenders, plough and paddle, the z-blade and sigma-blade mixers, screw mixers, and fluidizing paddle mixers (Manjunath et al., 2004; Alian et al., 2015b).

Tumbling blenders play a significant role in the household products, food and pharmaceutical industries. The tumbling blender rotates around a horizontal shaft. Inside this blender, the motion of particles is induced by vessel rotation and the gravity force. Different types of tumbling blenders are: v- and y-blenders, double cone, bin blenders, rotating drums, and slant cone mixer (Paul et al., 2004). The double cone mixer might be designed to rotate around two axes, and it is called the biaxial rotary mixer (Cho et al., 2012). It is important to mention that both symmetrical and asymmetrical designs are used in the tumbling mixers. Double cone and v-shape blenders are symmetrical blenders and their axes of rotation is perpendicular to the line of symmetry. v-Shape blenders are commonly used for blending of granules and powders due to their complete discharge of the final mixture, ease of cleaning, efficient blending, and short blending time (Tahvildarian et al., 2013). Tumbling blenders have many technical advantages that are summarized by the moderate mixing intensity, easy to be sanitized, simple structure, and the large handling capacity (Jiang et al., 2011).

Sudah et al. (2005) investigated the mixing mechanisms experimentally and computationally in a tote blender. Simulations were done for mono-disperse and bi-disperse spherical glass beads in a 1:1 scale. During the cascading region, the examination of velocity profiles from DEM simulations delivered information about the mechanisms of mixing. Radial mixing in a tumbling blender was shown to be orders of magnitude faster than axial mixing.

Nonetheless, serious segregation phenomena may become visible especially in the mixing of bi-disperse or poly-disperse solid particles with different physical properties inside a tumbler blender. Inside the mixer, segregation generally appears in the free-surface of granular flow, where the lighter or larger particles rise to the top, and the denser or smaller particles will sink inside the total mass of particles (Jiang et al., 2011).

Arratia et al. (2006) explored the performance of the Bohle (bin) blender and reported that the top–bottom initial loading was more efficient than the back–front loading. They investigated the fill levels of 40%, 60%, and 80% with both top–bottom and side–side initial loading methods at 10 rpm and showed that the mixing efficiency obtained at the lower fill levels was higher than that at the higher fill levels. They also pointed out that the solid particles at the higher fill levels had low velocity and less space to move.

Manickam et al. (2010) studied the double cone blender and concluded that the rotation of the mixer at higher speeds around the horizontal axis resulted in a better mixing efficiency and lower mixing time. They investigated the effect of fill level on the mixing performance of a double cone mixer, and did not examine any changes in the mixing efficiency when the fill level was changed from 10% to 40%.

Two commercial asymmetrical blenders are the slant cone blender and the long leg v-shape design, which has a leg longer than the other. The asymmetrical blenders create the axial flow of the material in the direction of rotation. Indeed, the granules inside the blender are forced across the vertical axis of the tumbler each half revolution, and this leads to increase the quality of granules mixing in a shorter time. The slant cone mixer with an intensifier bar is an advanced type of the powder mixer (Alian et al., 2015a), which is a combination of the tumbling and agitator blenders. It is used for mixtures that may agglomerate or the high intensity blending.

Our comprehensive literature review revealed that there is a lack of adequate information for the mixing of the binary, ternary, and poly-disperse particles inside the slant cone blender. Therefore, the main objective of this study is to explore the mixing quality of the binary, ternary and poly-disperse particles in a slant cone mixer as a function of the drum speed, the initial loading methods, and internal agitator speed through the discrete element method (DEM). DEM is a reliable simulation method for assessing the particulate behavior systems. To validate the model, the simulation results are compared to the experimentally measured values.