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Using discrete element method to analyze the mixing of the solid particles in a slant cone mixer

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ABSTRACT

The slant cone mixer with an intensifier bar is an advanced type of the powder mixer which is a combination of the tumbling and agitator blenders. In this study, the discrete element method (DEM) was employed to investigate the mixing of solid particles in a slant cone mixer. To achieve this goal, the effects of initial loading (side-side, top-bottom, and back-front), drum speed, fill level, and agitator speed on the mixing rate were explored. In addition, the effect of the rotational direction of the agitator in relation to the direction of the drum (co-rotating and counter-rotating) on the mixing performance of the slant cone mixer was studied. In order to provide a mathematical understanding of the mixing rate, Lacey index was utilized. DEM results were validated using experimental data obtained from both sampling and image techniques. DEM simulation results were in good agreement with the experimentally determined data, both qualitatively and quantitatively.

Keywords: Slant cone mixer; Solids mixing; Discrete element method (DEM); Mixing rate; Lacey index; Thief sampling method

1. Introduction

Undoubtedly, powder blending plays a prominent role in several industries that are related to particulate processing. Thus, the efficiency and optimization of the powder mixers are critical issues for food, pharmaceutical, ceramic, metallurgical, and chemical industries. The industrial powder mixers can be broadly classified into the following categories (Paul et al., 2004): tumbling mixers, agitated mixers, pneumatic blenders, gravity silo blenders, high-intensity mixers, and high-intimacy or high-shear mixers. Poux et al. (1991) also classified blenders based on the mixing mechanism in several groups: mixers with moving vessel, mixers with fixed vessel and mobile internal parts, mills and mullers, and fluidized bed mixers.

There are some essential factors that should be considered before any attempt to select a proper powder blender for a specific application. These vital aspects are the specifications of the materials to be mixed, process safety, industry regulations, labor availability, single or multiple operations, the way that the material is transmitted to and from the blender, and the procedure that the mixer will be integrated into the plant.

Multiple industries are using tumbling blenders widely in granular mixing operations, including pharmaceutical, cosmetics, mining, food, energy, polymer, and semiconductor. Tumbling blenders are easy to operate, available in various capacities and are able to operate with shear sensitive or non-agglomerating materials. Their cleaning and emptying procedures are easy. Moreover, tumbling blenders are suitable for blending of dry and free flowing materials (Alexander et al., 2004; Kuo et al., 2005). Finally, the tumbling mixers benefit from simple mixing mechanisms. A closed vessel rotates around the axis in a tumbling mixer. Mixing in this type of the blender is achieved due to the random motions of the particles rolling down from an inclined surface. The counter rotating of the vessel and the installation of the internal baffles would also enhance the mixing of particles (Cullen, 2009). Of course there are some negative points on using the tumbling mixers. One of them is the high chance of the segregation of the particles. Furthermore, mixing is typically confined to the

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Nomenclature

F_c	contact force (N)
F_d^n	normal damping force (N)
F_d^t	tangential damping force (N)
F^n	normal force (N)
F^t	tangential force (N)
G	shear modulus (Pa)
M	mixing index (–)
N	average number of particle in each cell (–)
N_i	number of total particle in cell *i* (–)
P	overall proportion of one type of particles in the system (–)
R	radius (mm)
VAR	variance of the mixture (–)
VAR_R	variance in a perfectly mixed system (–)
VAR_0	variance in a completely segregated system (–)
e	coefficient of restitution (–)
k	number of cell (–)
ns	normal stiffness (N/m)
n_i	number of one type of particle in cell *i* (–)
t_s	tangential stiffness (N/m)
v_{rel}^n	relative normal velocity (m/s)
v_{rel}^t	relative tangential velocity (m/s)
δ_t	tangential overlap (m)
ξ	normal overlap (m)
ϑ	Poison ratio (–)

surface of the powder bed and leaving large regions undisturbed during long periods of the mixing cycle. In addition, tumbling mixers are not suitable for the agglomerating particles (Cullen, 2009; Poux et al., 1991).

Generally, four principal types of tumbling mixers are utilized for powder blending. These four popular blenders are V-shape, double cone, tote, and slant cone (Gemco^{TM}). Both symmetrical and asymmetrical designs are used in the fabrication of the tumbling mixers. V-shape, tote and double cone blenders are symmetrical blenders and their axes of rotation are perpendicular to the line of symmetry. On the other hand, two commercial asymmetrical blenders in the market are the slant cone blender and the long leg V-shape design, where one leg is longer than the other. The asymmetrical blenders superimpose the axial flow of the material in the direction of rotation. In fact, the materials inside the blender are forced across the vertical axis of the unit each half revolution. This enhances the mixing quality in a shorter blend time. One advantage of the slant cone mixers over other asymmetrical mixers is the possibility of installing the internal agitator with an intensifier bar, which is useful for high intensity blending or mixtures that may lump.

Our comprehensive literature review revealed that little information is available regarding the mixing performance of the slant cone mixers. Therefore, the main objective of this study was to analyze the mixing of solid particles in the slant cone mixer through the discrete element method (DEM), which is a reliable simulation method for assessing the particulate systems. In this work, DEM was employed to evaluate the mixing rate of the slant cone mixer as a function of the initial loading, drum speed, fill level, internal agitator speed and rotation mode. To validate the model, the simulation results were compared to the experimentally measured values.

2. Specifications of the mixer and experimental methods

In the present study, a 3.7 L slant cone blender manufactured by Gemco (Fig. 1) was utilized for the mixing of solid particles. Fig. 2 depicts the 3D model of the Gemco slant cone mixer prepared by AutoCAD. Slant cone blenders are classified as tumbling blenders and are asymmetrical in shape. This type of blender can be equipped with the intensifier bars having T-shaped blades as shown in Fig. 3. These intensifier bars are installed for different usages such as the de-lumping packed material, dispersing additives like color, reducing the particle size, and adding liquid such as the binder. Moreover, the installation of these bars will enhance the mixing rate by applying a large amount of energy to the particles, and generating more random and intense flow of solid particles within the mixing vessel. The manufacturer suggested that the agitator is effective only if the fill level is higher than 80 percent. As shown in Fig. 2, the blender vessel and the agitator bar stand on the same center of rotation.

One of the issues for powder mixing is the quality of the mixture. To assess and ensure the homogeneity of the final product, characterization of the mixture plays an important role. Evaluation of the degree of homogeneity and determination of the mixing time in the mixing volume are based on the methods of image and statistical analysis. In the image analysis method, the mixing rate is obtained from digital imaging of the mixture. In the statistical analysis method, a proper sampling technique is applied and a sufficient number of samples must be taken (Daumann and Nirschl, 2008). All the regions of the bed should be included in sampling. Missing the poor mixing regions is unavoidable if sampling is limited to a few locations; this may result in false conclusion (Muzzio et al., 1997). Additionally, the results may change due to the disturbance of the mixture caused by the sampler (Paul et al., 2004). Various statistical analyses such as estimation of intensity of segregation, relative standard deviation (RSD), mixture variance, nearest-neighbors method, Lacey's method, average-height method, and neighbor-distance method have been developed to assess the quality of solid mixing in many different industrial processes (Daumann and Nirschl, 2008; Gotoh et al., 1997). In this study, Thief, a powder sampling tool, was used as a sampler. In order to take a sample from the interior regions, the sampler was inserted into the bed while the mixer was in the static position. Lacey index was used as a factor to find the mixing rate, which is described in next section.

In order to achieve the goal of this study, the spherical non-cohesive "red" and "black" colored glass beads from Metalfini Corporation were used to assess the mixing quality and the flow pattern of the solid particles in the slant cone mixer. The diameter of the glass beads was measured using Microtrac S3500 particle size analyzer. The measured diameter was 3 ± 0.2 mm. A thief sampler (shown in Fig. 4a) was employed for sampling the particles. In order to guarantee that the samples are extracted from the desired positions, a custom-made cardboard template with three holes was put on the top of the particle bed inside the mixer when the samples were taken. The template is shown in Fig. 4b. Each sample had approximately 80–100 particles. The percentage of red and black glass beads in each sample was determined manually by counting the number of each particle. Moreover, a digital camera was employed to capture the mixing of the red and black solid