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Original Research Paper

Numerical analysis of mixing of particles in drum mixers using DEM

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ABSTRACT

Mixing of particles in a rotating drum mixer with filling level greater than 50% has been analysed using Discrete Element Method (DEM). An attempt has been made to understand the mechanism of the dead zone formation and the degree of mixing by varying the mixing parameters. These include the size and packing of particles, speed and shape of the mixer, etc. While the formation of the dead zone is qualitatively analysed, the degree of mixing has been quantified with a suitable mixing index (ψ). It is found that packing arrangement and particle size significantly affect the formation of the dead zone, whereas, the drum speed and geometry has a relatively lesser effect. The effect of various parameters on the dead zone formation is explained on the basis of variation in energy distribution pattern from the wall towards the centre of the mixer. It has been found that the energy required for agitating the particles is transferred from the outer wall to the centre of the mixer. In the process of transfer, a significant amount of energy is expended before reaching the centre, which allows a compacted dead zone to form around the centre. A preliminary attempt has been also made to study mixing in a drum with baffles. The baffles act as the medium of efficient energy transfer by imparting their energy to the particles that come in contact with them thereby resulting in better mixing.

1. Introduction

Mixing and blending of particles is an important process in many industries, such as chemical, pharmaceutical, ceramic, plastic, fertilisers and minerals [1,2]. The primary objective of mixing is to obtain a highly homogenised product, which often becomes difficult due to selective segregation of individual components. Although, different designs of drum mixers with lifters, blades or baffles have been attempted to avoid segregation, the improvements are not satisfactory. It is because of the design considerations that are often made without a fundamental understanding of the factors affecting mixing and segregation.

Rotating drum mixer shows different characteristics of charge motion depending on the mixer speed. The dynamic profile of the granular motion changes from slipping to centrifuging with increasing angle of repose as the speed of drum mixer increases [3]. The angle between the top surface of the rolling bed and the horizontal plane is called the angle of repose. The angle of repose increases with increase in speed of the drum [4], and decreases with the increase in particle size [5]. The transverse section of the rolling bed can be divided into active (also referred as rapid flow layer) and passive layers [6]. Boateng and Barr [6] defined a yield line or an interface surface that separates these two layers. Based on the initial filling pattern and filling level, various patterns are observed during the progress of mixing which also includes the avalanche effect [7]. The rapid flow of particles in the top layer along the slope is identified as the avalanche effect in mixers. Depending on the mixer design and operating conditions, the formation of the dead zone may also take place [7,8]. Metcalfe et al. [7] and McCarthy et al. [8] primarily attribute this observation to static and dynamic angles of friction and to other geometrical variables.

The mixing rate varies in the axial and radial direction of the drum mixer. Convective mixing dominates in the radial direction, and slow diffusive mixing in the axial direction, and, therefore, statistical assessment of mixing based on sampling has been a challenge [9,10]. The degree of mixing at various locations is an important parameter that describes the quality of mixing. Different type of mixing or segregation index based experimental [2,11–15] and numerical studies [16–18] have been proposed by various authors to estimate the homogeneity of mixing. The use of thief probes is limited as they affect the mixing in surroundings of the insertion region [11]. The degree of mixing has been characterised by the methods such as optical imaging [12], online electrical capacitance measurement [13], near-infrared imaging [14], and other image analysis techniques [2,15]. Cleary et al. [16] have proposed a model to describe mixing on the basis of local average

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of desired properties such as colour, mass or density. Moakher et al. [17] have quantified the degree of mixing by dividing the mixer into a number of vertical strips and tracking the axial coordinates of the particles present in each strip. Hill et al. [18] have used the tracer particles to determine the degree of mixing and segregation based on normalised standard deviation.

Baffles or blades are used in drum mixers to improve mixing and to avoid the dead zone formation [19,20]. Design consideration of baffles and level of filling are critical for the improvement in mixing and reduction in the size of dead zone [19]. Jiang et al. [20] have extensively studied the effect of baffles. It was reported that baffles placed at the centre of the drum mixer along the axis results in improved mixing when compared to the baffles placed near the periphery.

Coarse particle mixing can be studied by direct simulation using Discrete Element Method (DEM), but as particle size decreases DEM becomes cumbersome and computationally intensive. Compared to continuum models, DEM treats granular materials as an assembly of discrete particles, each governed by fundamental laws of classical mechanics [21]. Mishra and Rajamani [22] have pioneered the application of DEM for studying the media charge motion in tumbling mills. A review on the applications of DEM techniques has been given by Guo and Curtis [23]. Most of the DEM simulation studies on mixing in rotating drum mixers have been confined to less than half filled mixers [14,15]. The dead zone formation in more than half filled drum mixers have been reported earlier [7,8]. However, the effect of packing on mixing and dead zone formation was not considered by these authors. In a practical scenario, packing fraction which is the ratio of volume occupied by solid to the total cell volume ($\varphi = V_s/V$), depends on the manner of filling/pouring of particles, agitation, surface properties, and moisture content. To represent different packing fractions, packing arrangements namely random packing, body centred cubic packing (BCC) and hexagonal close packing (HCP) have been studied. The present work is a continuation of the preliminary work carried out by Mishra et al. [24] to study mixing and flow behaviour of particles in a drum mixer with filling levels greater than 50%. It is an attempt to investigate on the missing understanding of the physics behind the mixing process and dead zone formation. In this study, detailed 3D-DEM simulations and experiments have been carried out to elucidate the effect of packing arrangement, particle size, speed and shape of drum mixer on the degree of mixing and the size of dead zone. A new method to quantify degree of mixing has been suggested and implemented, which throws light on the formation of the dead zone and variation in mixing pattern.

2. Model development and mixing index

In the present study, soft sphere or time-driven linear contact model based on Hooke's law is used in the DEM simulations to compute the forces between the colliding particles [25,26]. The general force balance equation for colliding particles is given by

$$\vec{F} = (\vec{F}_n - \vec{F}_n^d) + (\vec{F}_t - \vec{F}_t^d) \tag{1}$$

where $\vec{F}_n$, $\vec{F}_n^d$, $\vec{F}_t$ and $\vec{F}_t^d$ are normal, normal damping, tangential and tangential damping force components, respectively. The mathematical expressions for these forces are given below.

$$F_n = \frac{16}{15} E^* \sqrt{R^*} \left(\frac{15 m^* V_{cn}^2}{16 \sqrt{R^*} E^*} \right)^{1/5} \delta_n \tag{2}$$

$$F_n^d = \sqrt{\frac{4 m^* k_n}{1 + \left(\frac{\pi}{\ln e}\right)^2}} V_n^{rel} \tag{3}$$

$$F_t = \frac{16}{15} E^* \sqrt{R^*} \left(\frac{15 m^* V_{ct}^2}{16 \sqrt{R^*} E^*} \right)^{1/5} \delta_t \tag{4}$$

$$F_t^d = \frac{F_n^d}{V_n^{rel}} V_t^{rel} \tag{5}$$

In the above equations, V_{cn} and V_{ct} are the characteristic/initial impact velocity in normal and tangential direction. δ, e, k_n and V^{rel} are overlap between two particles, coefficient of restitution, normal spring constant and relative velocity of interacting particles, respectively. m^* is the effective mass of interacting particles given by $\frac{1}{m^*} = \frac{1}{m_1} + \frac{1}{m_2}$; R^* is the effective radius of interacting particles given by $\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}$; similarly, E^* is the effective Young's modulus expressed by the following equation:

$$\frac{1}{E^*} = \frac{1 - \upsilon_1^2}{E_1} + \frac{1 - \upsilon_2^2}{E_2} \tag{6}$$

where υ, represents the Poisson's ratio. Subscript 1, 2 in notations refer to individual interacting particles, and subscripts n, t refer to normal and tangential directions of collisions, respectively.

A mixing index (ψ) is defined to quantify the extent of mixing throughout the drum mixer. The working space was virtually divided into cubic cells to assess the mixing in different parts of the mixer. The element size selection or discretisation of the domain is based on spatial averaging principle [27]. Cleary et al. [16] suggested that the edge length for the domain discretisation should be an integer multiple of the smaller particle diameter. Also, it should be large enough so that averaging the data inside the cell results in a meaningful value, but small enough to preserve the spatial variation of physical data. In the present work, the cubic cells have the edge length twice the particle diameter. A pictorial representation of the grid subdivision inside the drum mixer is shown in Fig. 1a. The proposed mixing index for i^{th} cubic cell (ψ_i) consisting two types of same size particles in N_1 and N_2 numbers is given by Eq. (7).

$$\psi_i = \frac{2N_k}{N_1 + N_2} \qquad \begin{cases} N_k = N_1, & \text{if } N_1 < N_2 \\ N_k = N_2, & \text{if } N_1 > N_2 \end{cases} \tag{7}$$

In order to estimate the average ψ, concentric radial layers of thickness twice the particle diameter were created as shown in Fig. 1b. The distance of such a radial layer from the cylindrical outer wall can be represented in terms of a number of particle diameters ($N_{p,radial}$) which is given by Eq. (8). These radial layers were further divided into equal parts of 20 mm width in the axial direction. The position of such an axial layer from the front wall of the drum can be represented in a similar manner, and is given by Eq. (9). In this manner, a number of concentric rectangular tubes of thickness equivalent to two-particle diameter in the radial direction and 20 mm wide in the axial direction were obtained as shown in Fig. 1c. The individual mixing index of n cubic cells whose centres fall within a virtual tube were averaged to find the representative mixing index for that tube using Eq. (10).

$$N_{p,radial} = \frac{R_c - R_t}{d} \tag{8}$$

$$N_{p,axial} = \frac{d_a}{d} \tag{9}$$

$$\psi_{ave} = \frac{\sum_{i=0}^{n} \psi_i}{n} \tag{10}$$

where R_c is the radius of the cylindrical mixer, R_t is the radial distance of the tube from the axis of the mixer, d_a is the distance of the tube from the front wall, d is the particle diameter, and n is the number of cubic cells with their centres falling in a tube. Similarly, Eq. (10) was also used to calculate the overall mixing index