G Model
PARTIC-895; No. of Pages 8
ARTICLE IN PRESS
Particuology xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Particuology
journal homepage: www.elsevier.com/locate/partic

Numerical analysis of enhanced mixing in a Gallay tote blender

Xinxin Ren [a], Guangzheng Zhou [a,*], Ji Xu [a], Lijie Cui [b], Wei Ge [a,*]

[a] State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China
[b] School of Chemistry and Chemical Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 11 July 2015
Received in revised form
17 December 2015
Accepted 7 January 2016
Available online xxx

Keywords:
Powder mixing
Tote blender
Granular materials
Discrete element method
Simulation
Baffle

ABSTRACT

The mixing performance of a multi-bladed baffle inserted into a traditional Gallay tote blender is explored by graphic processing unit-based discrete element method software. The mixing patterns and rates are investigated for a binary mixture, represented by two different colors, under several loading profiles. The baffle effectively enhances the convective mixing both in the axial and radial directions, because of the disturbance it causes to the initial flowing layer and solid-body zone, compared with a blender without a baffle. The axial mixing rate is affected by the gap between the baffle and the wall on the left and right sides, and an optimal blade length corresponds to the maximum mixing rate. However, the radial mixing rate increases with the blade length almost monotonically.

Introduction

Efficient mixing of granular materials by mechanical means is of critical importance for a wide range of processes in chemical, pharmaceutical, and food industries (Bridgwater, 2012). Among various kinds of tumbling blenders, the tote blender is frequently adopted because of its simplicity and reliability (Alexander et al., 2004), particularly in the pharmaceutical industry. This blender comprises one bin and one hopper, with two variations, i.e., conical and rectangular bins designed by Bohle and Gallay, respectively (Alexander et al., 2004). However, both types of blenders generally suffer from the common flaw of tumbling blenders, i.e. impeded transport across their symmetry planes, which limits their wider applications (Brone & Muzzio, 2000; Moakher, Shinbrot, & Muzzio, 2000). Inclining the blenders at a certain angle effectively improved the performance of both Bohle (Ren et al., 2013) and Gallay (Sudah, Arratia, Alexander, & Muzzio, 2005) tote blenders, which essentially rendered them asymmetric. However, the dispersive effect is still the dominant mechanism of axial mixing, resulting in a much slower mixing rate in the axial direction than the radial direction. Therefore, this work aims to further improve axial mixing.

Inserting baffles into many types of tumbling blenders to enhance particle mixing has been attempted. Brone and Muzzio (2000) added a stationary deflector plate inclined relative to the symmetry plane of a double-cone blender and found that axial convective mixing was improved remarkably. Shi, Abatan, Vargas, and McCarthy (2007) revealed that short baffles on the wall of a rotating drum were ineffective in reducing segregation but a central baffle had an obvious effect in this regard, because of its influence on the flowing layer. Jiang, Zhao, Liu, and Zheng (2011) further investigated the impacts of two-bladed, four-bladed and six-bladed baffles located on the center of a rotating drum. They found an optimal blade size for the four-bladed and six-bladed baffles, which performed better than the two-bladed baffle. Arratia et al. (2006a) introduced a baffle inclined at 45° to the rotary shaft of a Bohle tote blender but this baffle hindered mixing and promoted the formation of a segregated region at the center of the blender under high filling levels. Sudah, Coffin-Beach, and Muzzio (2002) set a prism-shaped baffle perpendicular to the rotary axis of a Gallay tote blender, resulting in only a slightly enhanced mixing quality. In summary, different internal baffle designs influence particle mixing differently, hence suitable baffle design and optimization are important.

The discrete element method (DEM) (Cundall & Strack, 1979) is advantageous in investigating the mixing mechanisms of granular materials. It tracks the motion of every particle and offers flow and mixing details which are difficult to obtain from physical experiments. Although the industrial-scale three dimensional (3D) DEM simulations are computationally expensive, the compute unified device architecture (CUDA) platform (NVIDIA, 2010) of the graphic processing unit (GPU) effectively alleviates this burden to some extent (Xu et al., 2011; Qi et al., 2015; Yu, Zhou, Xu, & Ge, 2015).

* Corresponding authors. Tel.: +86 10 82544943; fax: +86 10 62558065.
E-mail addresses: gzzhou@ipe.ac.cn (G. Zhou), wge@ipe.ac.cn (W. Ge).

http://dx.doi.org/10.1016/j.partic.2016.01.008

This study uses GPU-based DEM software, DEMms (Xu, Qi, Ge, & Li, 2011), to investigate the effect of a five-bladed baffle on the mixing behavior of a Gallay tote blender for several different loading profiles. The mechanisms behind the enhanced axial and radial mixing of five-bladed and multiple bladed baffles are further elucidated.

Simulation methodology

DEM model

Initially proposed by Cundall and Strack (1979), the DEM method has been applied to a wide range of industrial processes involving granular materials. Normal and tangential forces arising from particle/particle and particle/wall interactions accelerate particle movements. By integrating over small time steps, the velocity and position of each particle are updated according to these forces. For the model of rolling friction suggested by Zhou, Wright, Yang, Xu, and Yu (1999), the motion is governed by (Chandratilleke, Zhou, Yu, & Bridgwater, 2010; Jain, Metzger, & Glasser, 2013; Remy, Glasser, & Khinast, 2010)

$$m\frac{d\mathbf{v}}{dt} = \mathbf{F}_\text{n} + \mathbf{F}_\text{t} + m\mathbf{g} \tag{1}$$

$$I\frac{d\boldsymbol{\omega}}{dt} = \mathbf{R}\times\mathbf{F}_\text{t} - \mu_r R|\mathbf{F}_\text{n}|\boldsymbol{\omega}, \tag{2}$$

where m and I are the particle's mass and moment of inertia, respectively; $\mathbf{v}$ and $\boldsymbol{\omega}$ are the translational and angular velocities, respectively; $\mathbf{g}$ is the gravitational acceleration; $\mathbf{R}$ is a position vector running from the particle's center to the contact point whose magnitude is equal to particle radius R; μ_r is the rolling friction coefficient; $\mathbf{F}_\text{n}$ and $\mathbf{F}_\text{t}$ represent the normal and tangential contact forces, respectively.

Many linear and non-linear contact models already exist (Kruggel-Emden, Simsek, Rickelt, Wirtz, & Scherer, 2007; Zhu, Zhou, Yang, & Yu, 2007) and generally they can be viewed as certain combinations of spring, dash-pot, and slider. Based on the Hertz theory of normal force (Johnson, 1985) and the Mindlin and Deresiewica (1953) theory of tangential force, a simplified contact model proposed by Zhou, Xu, Yu, and Zulli (2002) is adopted in this work, whereby the normal and translational forces include conservative and dissipative components. The two components of the normal force are written as follows:

$$\mathbf{F}_\text{cn} = -\frac{4}{3}Y^*\sqrt{R^*}\delta_\text{n}^{1.5}\mathbf{n}_{ij}, \tag{3}$$

$$\mathbf{F}_\text{dn} = -c_\text{n}\left(6mY^*\sqrt{R^*\delta_\text{n}}\right)^{0.5}\mathbf{V}_{\text{n},ij} \tag{4}$$

where $Y^* = 0.5Y/(1-\upsilon^2)$; Y and υ are the Young's modulus and Poisson's ratio, respectively; $R^* = R_iR_j/(R_i+R_j)$; R_i and R_j represent the radii of particles i and j, respectively; δ_n, $\mathbf{n}_{ij}$, and $\mathbf{V}_{\text{n},ij}$ are the virtual displacement, unit vector, and relative velocity of these two particles in the normal direction, respectively; c_n is the normal damping coefficient.

The two components of tangential force have the following forms

$$\mathbf{F}_\text{ct} = -sgn(\delta_\text{t})\mu_\text{s}|\mathbf{F}_\text{cn}|\left[1-\left(1-\frac{\min(|\delta_\text{t}|,\delta_\text{t,max})}{\delta_\text{t,max}}\right)^{1.5}\right] \tag{5}$$

$$\mathbf{F}_\text{dt} = -c_\text{t}\left(6m\mu_\text{s}|\mathbf{F}_\text{cn}|\frac{\sqrt{1-|\delta_\text{t}|/\delta_\text{t,max}}}{\delta_\text{t,max}}\right)^{0.5}\mathbf{V}_{\text{t},ij}, \tag{6}$$

where μ_s is the slide friction coefficient, and c_t is the tangential damping coefficient; δ_t is the total tangential displacement of two particles during contact, and the maximum of tangential displacement is given by $\delta_\text{t, max} = 0.5\mu_\text{s}\delta_\text{n}(2-\upsilon)/(1-\upsilon)$; $\mathbf{V}_{\text{t},ij}$ is the relative tangential velocity. The normal and tangential damping coefficients account for the energy dissipations during particle interactions and play a similar role to the coefficient of restitution. However, for the non-linear contact model, the relationship between damping coefficients and the coefficient of restitution is rather complex (Malone & Xu, 2008; Tsuji, Tanaka, & Ishida, 1992). A more detailed explanation of the contact model can be found in Zhou et al. (2002).

Simulation conditions

A 14-L Gallay tote blender is commonly employed in experiments (Sudah et al., 2002, 2005) and is used here to investigate the effect of an internal baffle on the mixing performance. Fig. 1(a) and (b) shows a 3D and top view geometric sketch of the blender's dimensions, respectively. The rotary axis is parallel to the x–y plane and perpendicular to the z direction. Based on previous work (Sudah et al., 2005), the rotary axis was offset by 30° to the horizontal direction. Fig. 2 presents the structure of a blender with a five-bladed baffle, where the baffle's supporting shaft is parallel to the blender's rotary axis. To avoid the blades colliding with the wall, the supporting shaft is located half-way up the bin. The thickness and width of each blade are 6 and 50 mm, respectively, while the blades' length is variable in this study.

Table 1 presents the study's simulation parameters, where the material properties are based on those of glass spheres (Lemieux et al., 2008). To increase DEM simulation time steps, a small value of the Young's modulus (2.16×10^6 N/m^2) is adopted, which has been used in a wide range of simulations of particle mixing (Chandratilleke et al., 2010; Zhou, Yu, Stewart, & Bridgwater, 2004). When the Young's modulus is sufficiently large for the corresponding particle velocity range, the general characteristics of

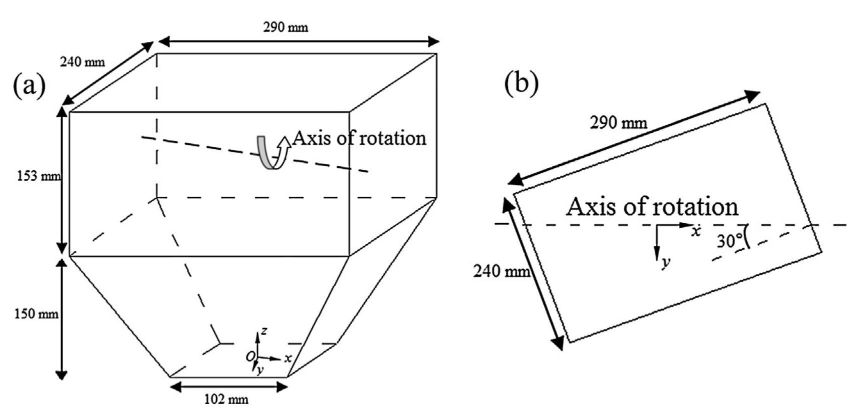

Fig. 1. Geometry and dimensions of the Gallay tote blender: 3D view (a) and top view (b).

Please cite this article in press as: Ren, X., et al. Numerical analysis of enhanced mixing in a Gallay tote blender. *Particuology* (2016), http://dx.doi.org/10.1016/j.partic.2016.01.008