Numerical Investigation of Mixing Performance for a Vertical Turbulence Mixer

Ya MAO*, Di Zhang, Xiong FAN, Yinlei Lv, Zuobing CHEN
School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan, China, 430070

*maoya@whut.edu.cn

Abstract. In this work, discrete element method (DEM) was employed to analyze mixing performance of a vertical turbulence mixer. The lacey mixing index was used to quantify mixing degree while a mixing rate was proposed to evaluate mixing speed. Several typical structural and operating parameters affecting mixing performance was investigated including initial loading pattern, rotational speed of stirring shaft and filling level. Results showed that mixing of top-bottom loading is faster than that of side-side loading. Comparing with another factor, stirring shaft rotating speed and filling level had more significant influence. A nearly linear growth and an almost linear decline relationships with mixing rate was found for the rotary speed and filling level respectively. A higher rotational speed or a lower filling level could help form a more intensive granular turbulent flow, resulting in faster mixing. Application of this work provides instruction to optimization of geometry and parameters of mixing systems to improve the quality of the mixing process.

1. Introduction
Since incomplete mixing will decrease production efficiency and increase cost, mixing is a key process for granular materials in many industrial applications such as pharmacy, chemistry and food[1]. Granular materials are usually mixed in mixers so it is vital to get well understandings to the inside mixing process. It is very difficult to provide an accurate description for mixing process due to the complexity of granular flows[2].

In recent years, particle image velocimetry (PIV) and positron emission particle tracking (PEPT) techniques with fast dynamic response and high measurement precision have been developed and used widely to study flow characteristics of granular materials.[3-5]. For example, PIV was employed by Conway et al.[3] to study dry granular flows in a four-bladed vertical mixer and it was found that particles tended to move inward in the case of sharp blade angle. Stewart [6] used PEPT to explore influence of blade angles on particle velocity field and they concluded that the movement of granular materials in front of the blades was hardly affected by blade angles. However due to experiment limitations, studies for granular flows cannot be further and completed especially in different industrial blenders with complicated structures, like tote(bin)-blenders[7]、V-blenders[8] and double-cones blenders[9].

In this paper, a vertical turbulent mixer, which is applied in ceramsite pellet production, is taken as research object. This mixer has a stirring cylinder with diameter of 2260mm in which a stirring shaft with blades rotates under the drive of motor. The cylinder is installed with an inclination angle to horizontal plane. (a) (b)
Figure 1 shows a 3D structure of the vertical turbulent mixer. Stirring shaft is installed eccentrically with an offset from the cylinder central axis. Mixing process is simulated by discrete element method (DEM). Two common initial loading of materials are compared first and then typical structure and operating parameters are explored.

Figure 1. The 3D model (a) and the simplified schematic (b) of a vertical turbulence mixer.

2. Numerical model description

2.1. DEM model

In a particular system, DEM treats each particle as individual. Every particle has two types of motions, translational motion and rotational motion. The governing equations are given by

\[
m_i \frac{d\omega_i}{dt} = \sum_j (F^N_j + F^T_j + m_i \omega_i)
\]

\[
I_i \frac{d\omega_i}{dt} = \sum_j (R_j \times F^T_j - \mu_i R_i |F^N_i| \omega_i)
\]

Where \(F^N\) and \(F^T\) are respectively total external force in normal and tangential direction. Although several force models have been developed for many cases, Hertz-Mindlin with JKR model has been verified to be appropriate for wet particles with cohesion\[^{[10]}\]. Therefore, Hertz-Mindlin with JKR model has been applied in this work to simulate mixing processes between fly ash and sludge particles with certain humidity. Liquid bridges among particles produce elastic contact forces and damping forces in both normal and tangential direction indicated as \(F^N_c, F^N_d, F^T_c, F^T_d\) and given respectively by

\[
F^N_c = \frac{4E^*}{3R^*} a^3 - \sqrt{16\pi \sigma E^* a^5}
\]

\[
F^N_d = -2\frac{\sqrt{5}}{\sqrt{6\ln^2(e) + \pi^2}} s_n m^* v_n
\]

\[
F^T_c = 8E^* \sqrt{R^* \delta_n \delta_t}
\]

\[
F^T_d = -2\frac{\sqrt{7}}{\sqrt{6}} s_t m^* v_t
\]

Where \(E^*\) is equivalent Young’s modulus and \(R^*\) is equivalent radius. \(\sigma\) is surface energy and \(a\) is contact radius between particles. \(s_n\) is normal stiffness. \(m^*\) is equivalent mass and \(v_n\) is relative velocity of particles in normal direction. \(\delta_n, \delta_t\) are overlaps in the normal and tangential direction. \(s_t, v_t\) are respectively shear stiffness and relative velocity of particles in tangential direction.

2.2. Geometry model and simulation conditions

The vertical turbulent mixer focused in this work is 2260 mm in diameter and 1110 mm in height (see Figure 1). The stirring shaft is 320mm in diameter and the blades are 420 mm in length and there are two scrapers vertically protruding from blades to raise granules for better mixing. Another scraper installed on the wall of mixer can prevent granular accumulation. When the mixer is running, inclined stirring cylinder is rotating at a given speed (usually 12~15 rpm, 15 rpm is set in this work) while...
stirring shaft also rotates in an opposition direction, helping forming turbulent flows in the granular bed. Several parameters including initial loading patterns, rotational speed of stirring shaft and filling level have been investigated via DEM. All calculations stop after 16.0s to ensure complete mixing. The physical and mechanical properties of granular materials are selected according manuals and literatures\cite{11}\cite{12}\cite{13}\cite{14}. These parameters are given in Table 1 and Table 2.

| Table 1. Physical properties of particles (“F” denotes fly ash, “S” denotes sludge and “W” denotes wall) |
| --- |
| Parameter | Unit | F | S | W |
| Particle density | kg·m⁻³ | 780 | 1420 | 7800 |
| Young’s modulus | pa | 1×10⁶ | 1×10⁶ | 7×10¹⁰ |
| Poisson ratio | - | 0.5 | 0.5 | 0.3 |

| Table 2. Mechanical properties of particle-particle |
| --- |
| Parameter | F-F | S-S | F-S | F-W | S-W |
| Coefficient of restitution | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Coefficient of static restitution | 0.60 | 0.35 | 0.45 | 0.40 | 0.30 |
| Coefficient of rolling friction | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

2.3. Mixing performance assessment
Lacey mixing index \( M \) is used to evaluate mixing degree, which is described as\cite{15}:

\[
M = \frac{VAR_0 - VAR}{VAR_0 - VAR_R} \tag{7}
\]

Where \( VAR \), \( VAR_0 \) and \( VAR_R \) are respectively the variances based on current particle location, variances in completely segregate system and variances in perfectly mixed system. They are given respectively by

\[
\frac{1}{N} \sum_{i=1}^{N} \frac{n_i}{N} P^2 \tag{8}
\]

\[
P(\frac{P}{1-P}) \tag{9}
\]

Where \( N \) is total number of particles. \( n_i \) and \( N_i \) are the number of one type of particles and of total particles in sampling cell \( i \). \( P \) is the overall proportion of one type of particle in the system and \( n \) is average particle number over all sampling cells.

3. Results and discussions

3.1. Comparison of two initial loading patterns
Loading pattern determines initial distribution location of two type granular materials. Top-bottom and side-side are two kinds of initial granular distributions. 18000 fly ash particles (black) and 18000 sludge particles (white) are loaded to achieve approximate 60% filling level, while both of equipment inclination angle of stirring cylinder and blade rake angle are 20° and all particles are 20 mm in diameter. Simulations are conducted while rotational speed of stirring shaft is 300 rpm and stirring cylinder rotated at 15 rpm in the opposite direction. Figure shows mixing flows at different time under top-bottom and side-side initial loadings in vertical turbulence mixer.
Figure 2. The mixing patterns at different time under side-side (top) and top-bottom (bottom) initial loading patterns.

Figure 3 gives variations of Lacey mixing indexes for both initial loading patterns. It could be found that mixing processes in side-side loading proceeds more slowly than that in top-bottom loading.

3.2. Effect of stirring shaft rotating speed
Several different rotational speeds including 150 rpm, 300 rpm, 450 rpm and 600 rpm have been explored to reveal effect on mixing. In this compare, blade chamfering angle is 30° and other conditions are same as those in section 3.2. Figure 4 gives particle flows at different time at rotating speed as 150 rpm and 300 rpm. By comparing the particle contours, it can be seen that the mixing under 300 rpm shows more uniform than that under 150 rpm.

Figure a presents variation of mixing index over time and Figure b gives corresponding mixing rates. An almost linear growth relationship occurs between mixing rate and rotating speed. Generally under higher rotary speed, particle movements, contacts and collisions are more intensive, so increasing rotating speed could remarkably improve mixing speed.
Figure 4. The mixing flows at different time under different rotating speeds as 150 rpm (top) and 300 rpm (bottom).

Figure 5. Variation of mixing indexes (a) and mixing rates (b) under different rotating speeds

3.3. Effect of filling level on mixing performance

Filling level is another significant operating parameter for the vertical turbulent mixer. It was believed that mixing will be faster for smaller filling levels under many circumstances such as in a horizontal rotary drum mixer\cite{16}. However mixing may not be same in vertical turbulent mixer. Totally 90000, 18000, 36000, and 48000 particles are respectively filled into the mixer to achieve approximately 15%, 30%, 60%, and 80% of filling levels. The stirring shaft rotary speed keeps 300 rpm while other simulations are the same as section 3.2. Figure gives the particle flows and mixing patterns at different time under different filling levels. Apparently mixing under 15% feeding lever proceeds faster than that under 60%.

Figure a gives corresponding mixing index variation. It can be clearly found that increasing filling levels will decrease the mixing speed and enlarge the mixing time. The mixing speed for each case has been quantified by mixing rates given in Figure b. An almost liner decreasing relationship could be found signifying filling level has prominent influence. For a given rotary speed, lower filling level will lead to higher average particle velocity and higher frequency of particle contact. On the other hand, more space is available for particles to sufficient mixture, which results in a better mixing performance than that at a higher filling level.
4. Conclusions
Mixing performance of an industrial vertical turbulence mixer is numerically investigated based on
DEM. Two industry-used granular materials, fly ash and sludge, are taken as mixing particles in
simulation. The Hert-Mindlin with JKR model has been employed to study the granular flows and
mixing. Several parameters including initial loading patterns, rotational speed of stirring shaft and
filling level have been investigated via DEM. As a conclusion, top-bottom loading pattern is faster
than that side-side loading. The relationship between mixing rate and rotational speed of stirring shaft
is nearly linear growth while relationship between mixing rate and filling level is almost linear reduction.
Among these factors, initial loading patterns, rotational speed and filling level play a significant role in
mixing performance. These results provide instruction to optimization of geometry and parameters of
mixing systems to improve the quality of the mixing process.

Acknowledgements
The enterprise cooperative project of Wuhan University of Technology (Grant No. 20132h0243) is
gratefully thanked for financial support of this work.

5. References
[1] S. Radl, E. Kalvoda, B.J. Glasser, J.G. Khinast. Mixing characteristics of wet granular matter in a
bladed mixer. Powder Technol 2010;200: 171-189.
[2] M. Poux, P. Fayolle, J. Bertrand, D. Bridoux, J. Bousquet. Powder mixing: Some practical rules
applied to agitated systems. Powder Technology 1991; 68:213-234.
[3] S.L. Conway, A. Lekhal, J.G. Khinast, B.J. Glasser. Granular flow and segregation in a four-bladed mixer. Chem Eng Sci 2005;60 : 7091-7107.

[4] A. Darelius, E. Lennartsson, A. Rasmuson, I. Niklasson Bjö rn. S. Folestad, Measurement of the velocity field and frictional properties of wet masses in a high shear mixer. Chemical Engineering Science 2007;62:2366-2374.

[5] A. Lekhal, S.L. Conway, B.J. Glasser, J.G. Khinast. Characterization of granular flow of wet solids in a bladed mixer. Aiche Journal 2006;52: 2757-2766.

[6] Stewart, R. Lorren. Convection and mixing of granular material stirred by a flat blade, University of Cambridge, 2001.

[7] P.E. Arratia, N.-h. Duong, F.J. Muzzio, P. Godbole, S. Reynolds. A study of the mixing and segregation mechanisms in the Bohle Tote blender via DEM simulations. Powder Technology 2006; 164; 50-57.

[8] M. Lemieux, F. Bertrand, J. Chaouki, P. Gosselin. Comparative study of the mixing of free-flowing particles in a V-blender and a bin-blender. Chemical Engineering Science 2007; 62 : 1783-1802.

[9] A.W. Alexander, T. Shinbrot, F.J. Muzzio. Granular segregation in the double-cone blender: Transitions and mechanisms. Physics of Fluids 2001; 13 :578-587.

[10] R.D. Mindlin. Compliance of Elastic Bodies in Contact. J.appl.mech 1949; 16 : 259-268.

[11] Curry D, Favier J, Laroche R D. A Systematic Approach to DEM Material Model Calibration[C], Aiche Meeting. 2009:432-436.

[12] Tahvildarian P, Ein-Mozaffari F, Upreti S R. Circulation intensity and axial dispersion of non-cohesive solid particles in a V-blender via DEM simulation. PARTICUOLOGY 2013; 11:619-626.

[13] B.Y. Liu. Shanghai Fly Ash Application Technical Manual [M]. Shanghai:Tongji University Press, 1995.

[14] Wei Zhu, Fengling Ji. Study on the Relation between Density, Strength and Material Composition of Light Soil. Journal of Geotechnical Mechanics 2007;28 :1411-1414.

[15] Y. Zhou, A. Yu, J. Bridgwater. Segregation of binary mixture of particles in a bladed mixer. Journal of Chemical Technology & Biotechnology 2003; 78: 187-193.

[16] P.Y. Liu, R.Y. Yang, A.B. Yu. DEM study of the transverse mixing of wet particles in rotating drums. Chem Eng Sci 2013; 86: 99-107.