

Proceeding Paper

# Investigation of Mixing Non-Spherical Particles in a Double Paddle Blender via Experiments and GPU-Based DEM Modeling <sup>†</sup>

Behrooz Jadidi <sup>\*</sup>, Mohammadreza Ebrahimi, Farhad Ein-Mozaffari  and Ali Lohi 

Department of Chemical Engineering, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada; mebrahimi@ryerson.ca (M.E.); fmozaffa@ryerson.ca (F.E.-M.); alohi@ryerson.ca (A.L.)

<sup>\*</sup> Correspondence: bjadidi@ryerson.ca

<sup>†</sup> Presented at the 1st International Electronic Conference on Processes: Processes System Innovation, 17–31 May 2022; Available online: <https://sciforum.net/event/ECP2022>.

**Abstract:** In this study, we have investigated the mixing kinetics and flow patterns of non-spherical particles in a horizontal double paddle blender using both experiments and the discrete element method (DEM). The experimental data were obtained using image analysis from a rotary drum containing cubical and cylindrical particles. Then, the experimental data were used in order to calibrate the DEM model. Using the calibrated DEM model, the effects of operating parameters such as vessel fill level, particle loading arrangement, and impeller rotational speed on the mixing performance were examined. The diffusivity coefficient was calculated to assess the mixing performance.

**Keywords:** non-spherical particle; twin paddle blender; discrete element method (DEM)



**Citation:** Jadidi, B.; Ebrahimi, M.; Ein-Mozaffari, F.; Lohi, A. Investigation of Mixing Non-Spherical Particles in a Double Paddle Blender via Experiments and GPU-Based DEM Modeling. *Eng. Proc.* **2022**, *19*, 24. <https://doi.org/10.3390/ECP2022-12661>

Academic Editor: Blaž Likozar

Published: 30 May 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Powder blending is a vital process in different industries, including pharmaceutical, food, and cosmetics [1]. In these industries, batch and continuous solid mixers are widely used. In the food and pharmaceutical industries, however, batch mixers have been the most popular mixers [2]. Among batch mixers, agitated blenders have high processing capacities and are thus the preferred type in the industries [3]. In terms of shape, agitated blenders can be classified as paddle [4], plowshare [5], ribbon [6], or screw blender [7].

Through recent breakthroughs in computer hardware, numerical simulation can be used to evaluate the mixing state [8]. For particle mixing, several computational models have been used in the literature [9–11], including continuum [9], multiscale continuum [12], and discrete element method (DEM) [13–15]. However, most studies relied on DEM since it has been shown to predict particle scale effects effectively [16–20]. Generally, discrete element particle mixing studies have used spherical particle models [21]. However, the shape of particles employed in industry is not always spherical, and these particles are usually complex in structure [8]. In several applications of granular flows, there are particles with sphericity of close to one that can be assumed as spherical particles because of the reduction in the computational cost. On the other hand, this assumption is far from reality for particles with irregular shapes such as cubes, cylinders, ellipsoids, or particles with sharp edges. It should be mentioned that in spite of the high computational cost of the simulation of non-spherical particles via DEM, in comparison to the spherical particles, consideration of the non-sphericity is required for performing a reliable DEM simulation [22]. Experimental [23–25] and discrete element studies [26] have demonstrated that the particle shape directly influences the behavior of the particulate flow. Thus, in this study, the effects of operational parameters on solid mixing in a twin paddle blender containing non-spherical particles were investigated using the actual particles' shapes. This mixing equipment has never been subject to such a thorough investigation for non-spherical particles, to the best of the authors' knowledge.

## 2. Modeling and Simulations

The limitations associated with experimental techniques such as disturbance of the granular flow, cost, and cumbersome implementation have made the discrete element method (DEM) a vital tool to obtain comprehensive particle-level information about mixing systems. However, the DEM technique suffers from high computational time and requires enormous computing power. Some DEM studies have used spherical particle models to address these challenges even though the experimental and numerical studies have demonstrated the pronounced effect of the particle shape on the mixing quality. However, graphics processing units (GPUs) have enabled us to run DEM simulations of mixing systems containing non-spherical particles with less computation time.

In the DEM simulation, the rotational and translation motions of individual particles are calculated by solving Newton's equations, Equations (1) and (2), at each time step, computing the effect of normal and tangential forces, gravity and torque for a particle  $i$  interacting with another particle  $j$  [27]:

$$m_i \frac{d\vec{v}_i}{dt} = \sum_j^{N_c} \left( \vec{F}_{ij}^n + \vec{F}_{ij}^t \right) + \vec{F}_i^g, \quad (1)$$

$$I_i \frac{d\vec{\omega}_i}{dt} = \sum_j \left( \vec{M}_{ij}^t + \vec{M}_{ij}^r \right), \quad (2)$$

where  $m_i$ ,  $I_i$ ,  $\vec{v}_i$ , and  $\vec{\omega}_i$  are the mass, moment of inertia, linear and angular velocity of particle  $i$ , respectively.  $\vec{F}_{ij}^n$ ,  $\vec{F}_{ij}^t$  and  $\vec{F}_i^g$  represent normal contact force, tangential contact force and gravity force on particle  $i$ , respectively.  $\vec{M}_{ij}^t$  and  $\vec{M}_{ij}^r$  are the rotational torque and the rolling resistance torque, respectively. In order to calculate the normal and tangential forces, the Hertz–Mindlin contact model was used [16]. The polyhedral particle representation method was used to simulate the non-spherical particles in the system [28,29].

## 3. Results and Discussion

Firstly, experimental data were obtained using image analysis from a rotary drum containing cubical and cylindrical particles. The EDEM v2021 commercial software was utilized as the GPU-based DEM solver. Then, the DEM model was calibrated using the experimental data. Using the calibrated DEM model, the effects of operating parameters such as vessel fill level, particle loading arrangement, and impeller rotational speed on the mixing performance were examined. The diffusivity coefficient was also calculated to assess the mixing performance.

### 3.1. Calibration

This study used DEM input parameters from the investigation of Hlosta et al. [30] because the shape and material of the particles were similar to those used in their study. Then, the parameters were selected to simulate a dynamic angle of repose test on the non-spherical particles used in this study. By comparing the simulation and experimental results, it was found that the simulation and experimental results were in good qualitative and quantitative agreement. Thus, the DEM simulation results can be used in order to investigate the effects of the shape on particles' behavior in the blender.

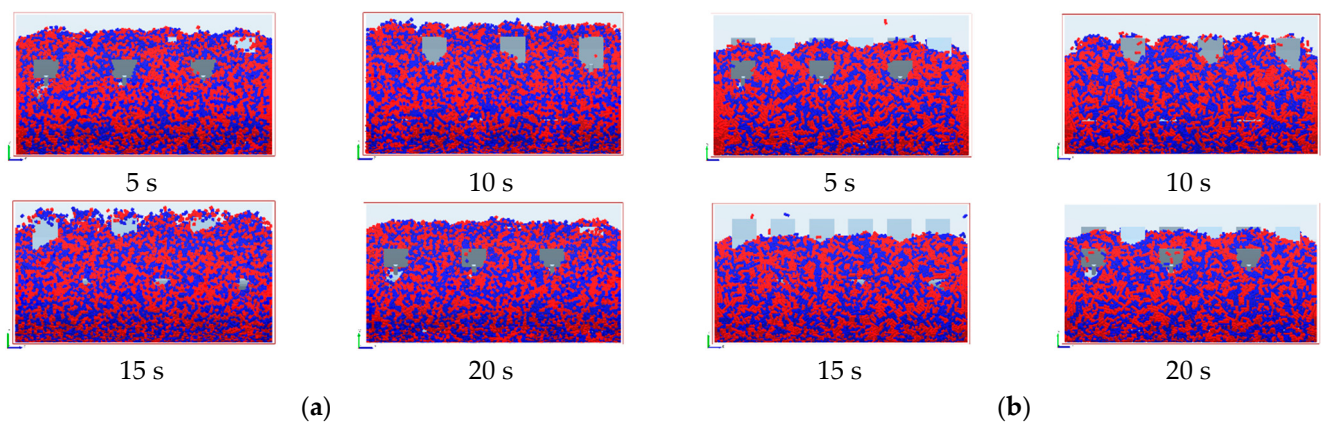
### 3.2. Effect of Particles' Shape on the Mixing Performance

The impact of the particle's shape on the mixing efficiency was examined in this study. To do so, the diffusivity coefficient was calculated for the mixer containing various particle shapes. This coefficient demonstrates the mass flux of particles in the system caused by the random movement of particles. In our previous study [16], diffusion was reported as the dominant mixing mechanism in this mixing system for spherical particles. Thus, the

diffusivity coefficient can be used to analyze the mixing systems' performance. Table 1 summarizes the diffusivity coefficient values in various directions. As can be seen in this table, the shape of the particles significantly influenced the mixer performance, and the spherical particles obtained the highest diffusivity coefficient values in all directions (highest mixing performance). This result is consistent with what was observed in the literature regarding the effect of particles' shape on the mixing quality [8,31,32]. In addition, Figure 1 illustrates the side-view snapshots of the simulated mixer in various times for cubical and cylindrical particles. Based on this figure, between cubical and cylindrical particles, the former reached better mixing since compared to the cylindrical particles, the shape of cubical particles is more similar to that of spherical particles.

**Table 1.** Diffusivity coefficient for various particle shapes.

Particle's Shape	Diffusivity Coefficient		
	$D_{xx}$	$D_{yy}$	$D_{zz}$
Spherical	0.0023	0.0019	0.0003
Cubical	0.0003	0.0004	$5.25 \times 10^{-5}$
Cylindrical	0.0002	0.0003	$6.57 \times 10^{-5}$



**Figure 1.** Snapshots of the mixer for various particle shapes for Top-Bottom initial loading pattern, 40 rpm impeller speed and 40% fill level: (a) cubic (b) cylinder.

#### 4. Conclusions

GPU-enhanced DEM analysis was applied to investigate the effects of particle shape on mixing characteristics such as diffusivity coefficient value in a double paddle blender. The DEM model was calibrated using a dynamic angle of repose test. Then, using the calibrated model, the effects of particles' shape on the solid mixing were investigated, implying that the shape of non-spherical particles is a vital parameter to consider in exploring a real industrial process. By analyzing the DEM results, we can better understand the solid mixing process. Moreover, this study shows that the GPU-enhanced DEM is an applicable tool for simulating non-spherical particles in full-scale operations.

**Author Contributions:** B.J.: Conceptualization, Methodology, Software, Model Development & Validation, Data Analysis, Writing—Original Draft; M.E.: Conceptualization, Methodology, Software, Model Development, Data Analysis, Writing—Review & Editing, Supervision; F.E.-M.: Conceptualization, Resources, Methodology, Writing—Review & Editing, Supervision, Project Administration, Funding Acquisition; A.L.: Conceptualization, Resources, Methodology, Writing—Review & Editing, Supervision, Project Administration, Funding Acquisition. All authors have read and agreed to the published version of the manuscript.

**Funding:** Natural Sciences and Engineering Research Council of Canada (NSERC).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Paul, E.L.; Atiemo-Obeng, V.A.; Kresta, S.M. *Handbook of Industrial Mixing: Science and Practice*; John Wiley & Sons: Hoboken, NJ, USA, 2004.
2. Yaraghi, A. *Mixing Assessment of Non-Cohesive Mono-Disperse and Bi-Disperse Particles in a Paddle Mixer—Experiments and Discrete Element Method (DEM)*; Ryerson University: Toronto, ON, Canada, 2018.
3. Harnby, N.; Edwards, M.F.; Nienow, A.W. *Mixing in the Process Industries*, 2nd ed.; Butterworths: Hong Kong, 1985. [\[CrossRef\]](#)
4. Ebrahimi, M.; Yaraghi, A.; Jadidi, B.; Ein-Mozaffari, F.; Lohi, A. Assessment of bi-disperse solid particles mixing in a horizontal paddle mixer through experiments and DEM. *Powder Technol.* **2020**, *381*, 129–140. [\[CrossRef\]](#)
5. Laurent, B.; Cleary, P. Comparative study by PEPT and DEM for flow and mixing in a ploughshare mixer. *Powder Technol.* **2012**, *228*, 171–186. [\[CrossRef\]](#)
6. Muzzio, F.J.; Llusà, M.; Goodridge, C.L.; Duong, N.-H.; Shen, E. Evaluating the mixing performance of a ribbon blender. *Powder Technol.* **2008**, *186*, 247–254. [\[CrossRef\]](#)
7. Cai, R.; Hou, Z.; Zhao, Y. Numerical study on particle mixing in a double-screw conical mixer. *Powder Technol.* **2019**, *352*, 193–208. [\[CrossRef\]](#)
8. Mori, Y.; Sakai, M. Advanced DEM simulation on powder mixing for ellipsoidal particles in an industrial mixer. *Chem. Eng. J.* **2022**, *429*, 132415. [\[CrossRef\]](#)
9. Khakhar, D.; Orpe, A.V.; Ottino, J. Continuum model of mixing and size segregation in a rotating cylinder: Concentration-flow coupling and streak formation. *Powder Technol.* **2001**, *116*, 232–245. [\[CrossRef\]](#)
10. Christov, I.C.; Ottino, J.M.; Lueptow, R.M. From streamline jumping to strange eigenmodes: Bridging the Lagrangian and Eulerian pictures of the kinematics of mixing in granular flows. *Phys. Fluids* **2011**, *23*, 103302. [\[CrossRef\]](#)
11. Meier, S.W.; Lueptow, R.M.; Ottino, J.M. A dynamical systems approach to mixing and segregation of granular materials in tumblers. *Adv. Phys.* **2007**, *56*, 757–827. [\[CrossRef\]](#)
12. Tartakovsky, A.M.; Redden, G.; Lichtner, P.C.; Scheibe, T.; Meakin, P. Mixing-induced precipitation: Experimental study and multiscale numerical analysis. *Water Resour. Res.* **2008**, *44*. [\[CrossRef\]](#)
13. Cleary, P.W.; Metcalfe, G.; Liffman, K. How well do discrete element granular flow models capture the essentials of mixing processes? *Appl. Math. Model.* **1998**, *22*, 995–1008. [\[CrossRef\]](#)
14. Sen, M.; Karkala, S.; Panikar, S.; Lyngberg, O.; Johnson, M.; Marchut, A.; Schäfer, E.; Ramachandran, R. Analyzing the Mixing Dynamics of an Industrial Batch Bin Blender via Discrete Element Modeling Method. *Processes* **2017**, *5*, 22. [\[CrossRef\]](#)
15. Qi, F.; Heindel, T.J.; Wright, M.M. Numerical study of particle mixing in a lab-scale screw mixer using the discrete element method. *Powder Technol.* **2017**, *308*, 334–345. [\[CrossRef\]](#)
16. Jadidi, B.; Ebrahimi, M.; Ein-Mozaffari, F.; Lohi, A. Mixing performance analysis of non-cohesive particles in a double paddle blender using DEM and experiments. *Powder Technol.* **2022**, *397*, 117122. [\[CrossRef\]](#)
17. Yaraghi, A.; Ebrahimi, M.; Ein-Mozaffari, F.; Lohi, A. Mixing assessment of non-cohesive particles in a paddle mixer through experiments and discrete element method (DEM). *Adv. Powder Technol.* **2018**, *29*, 2693–2706. [\[CrossRef\]](#)
18. Alian, M.; Ein-Mozaffari, F.; Upreti, S.R.; Wu, J. Using discrete element method to analyze the mixing of the solid particles in a slant cone mixer. *Chem. Eng. Res. Des.* **2015**, *93*, 318–329. [\[CrossRef\]](#)
19. Yazdani, E.; Hashemabadi, S.H. The influence of cohesiveness on particulate bed segregation and mixing in rotating drum using DEM. *Phys. A Stat. Mech. Its Appl.* **2019**, *525*, 788–797. [\[CrossRef\]](#)
20. He, S.; Gan, J.; Pinson, D.; Yu, A.; Zhou, Z. A Discrete Element Method Study of Monodisperse Mixing of Ellipsoidal Particles in a Rotating Drum. *Ind. Eng. Chem. Res.* **2020**, *59*, 12458–12470. [\[CrossRef\]](#)
21. Jadidi, B.; Ebrahimi, M.; Ein-Mozaffari, F.; Lohi, A. A comprehensive review of the application of DEM in the investigation of batch solid mixers. *Rev. Chem. Eng.* **2022**. [\[CrossRef\]](#)
22. Norouzi, H.R.; Zarghami, R.; Sotoudeh-Gharebagh, R.; Mostoufi, N. *Coupled CFD-DEM Modeling: Formulation, Implementation and Application to Multiphase Flows*; Wiley: Hoboken, NJ, USA, 2016. [\[CrossRef\]](#)
23. Cleary, P.W.; Sawley, M.L. DEM modelling of industrial granular flows: 3D case studies and the effect of particle shape on hopper discharge. *Appl. Math. Model.* **2002**, *26*, 89–111. [\[CrossRef\]](#)
24. Latham, J.-P.; Munjiza, A. The modelling of particle systems with real shapes. *Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci.* **2004**, *362*, 1953–1972. [\[CrossRef\]](#)
25. Nassauer, B.; Liedke, T.; Kuna, M. Polyhedral particles for the discrete element method. *Granul. Matter* **2012**, *15*, 85–93. [\[CrossRef\]](#)
26. Ji, S.; Wang, S.; Zhou, Z. Influence of particle shape on mixing rate in rotating drums based on super-quadric DEM simulations. *Adv. Powder Technol.* **2020**, *31*, 3540–3550. [\[CrossRef\]](#)

27. Cundall, P.A. A Computer Model for Simulating Progressive, Large Scale Movement in Blocky Rock Systems. In Proceedings of the Symposium of International Society of Rock Mechanics, Nancy, France, 4–6 October 1971.
28. Cundall, P. Formulation of a three-dimensional distinct element model—Part I. A scheme to detect and represent contacts in a system composed of many polyhedral blocks. *Int. J. Rock Mech. Min. Sci. Géoméch. Abstr.* **1988**, *25*, 107–116. [[CrossRef](#)]
29. Nezami, E.G.; Hashash, Y.M.; Zhao, D.; Ghaboussi, J. A fast contact detection algorithm for 3-D discrete element method. *Comput. Geotech.* **2004**, *31*, 575–587. [[CrossRef](#)]
30. Hlosta, J.; Jezerská, L.; Rozbroj, J.; Žurovec, D.; Nečas, J.; Zegzulka, J. DEM Investigation of the Influence of Particulate Properties and Operating Conditions on the Mixing Process in Rotary Drums: Part 1—Determination of the DEM Parameters and Calibration Process. *Processes* **2020**, *8*, 222. [[CrossRef](#)]
31. Govender, N.; Wilke, D.; Wu, C.-Y.; Rajamani, R.; Khinast, J.; Glasser, B.J. Large-scale GPU based DEM modeling of mixing using irregularly shaped particles. *Adv. Powder Technol.* **2018**, *29*, 2476–2490. [[CrossRef](#)]
32. Saeed, M.K.; Siraj, M.S. Mixing study of non-spherical particles using DEM. *Powder Technol.* **2019**, *344*, 617–627. [[CrossRef](#)]