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

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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 was 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)

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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 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 preferred ones 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 reducing 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 high computational cost of the simulation of non-spherical particles via DEM, in comparison to the spherical particles, considering 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]:

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

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

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 Hlosta et al.'s investigation [30] because 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.

Error! Reference source not found. 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 particle's 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	5.25e-05
Cylindrical	0.0002	0.0003	6.57e-05

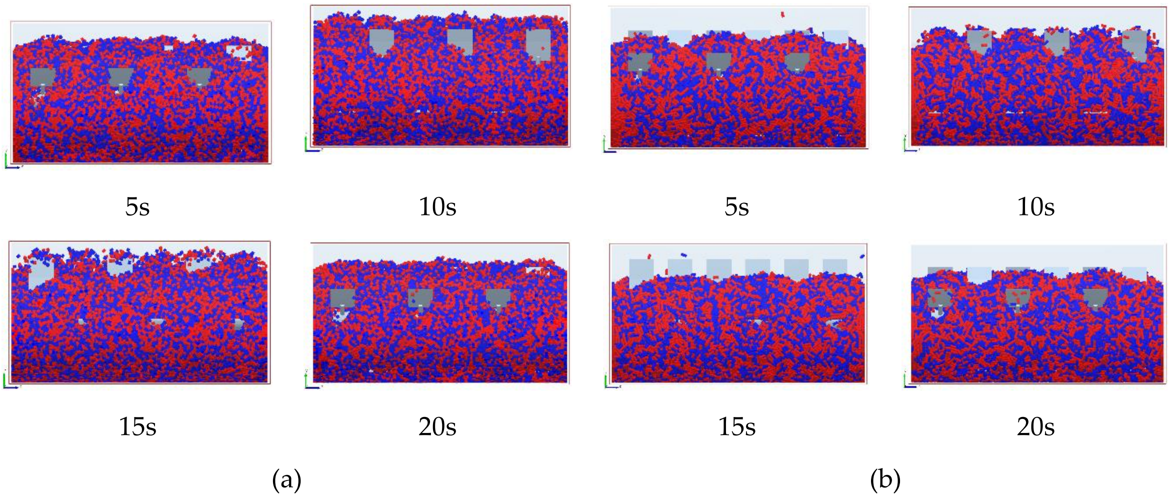

Figure 1. Snapshots of the mixer for various particle shapes for Top-Bottom initial loading pattern, 40 rpm impeller speed and 40% fill level: (a) cubic (b) cylinder.

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 particle's 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.

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