Effect of Agitator Shaft Direction on Grinding Performance in Media Stirred Mill: Investigation Using DEM Simulation

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Abstract

Recently, the discrete element method (DEM) has been widely applied to investigate the influence of operating and design parameters on grinding performances. However, while most studies investigated the effects of such parameters on the fineness of milling products, the relationship between them and the size dispersion of milling products has not been elucidated yet. In this study, we investigated the influence that the direction of the agitator shaft has on grinding performance in a media stirring mill. First, we proved by milling experiments that the media stirring mill with the horizontal direction of the agitator shaft can provide better grinding performances. Then, we further elucidated this experimental evidence by applying DEM simulations to a media stirring milling process in a vertical and a horizontal stirred mill. According to the simulations, in the vertical shaft configuration, the motion of the grinding media in the lower section through the vertical direction was inhibited by a too low velocity. On the other hand, the grinding media in the horizontal stirred mill moved more uniformly but with a lower collision energy. Furthermore, the grinding media in the low sections actively mixed with the grinding media in the upper sections, thereby resulting in a more uniform energy transfer and in a better grinding process. Accordingly, this study demonstrated that not only the collision energy but also the uniformity of the movement of the medium particles should be evaluated in order to investigate the grinding performance in a media stirred mill by DEM simulation.

Keywords: discrete element simulation, grinding, stirred mill, sharpness of particle size distribution

1. Introduction

Milling operations are important unit processes which have been extensively utilized for many years in a wide range of engineering fields such as resource, chemical and the environmental ones.

More recently, due to the improvement of milling technologies, the milling performances improved significantly due to the point where the demand of fine grinding has been increasing in various industries\(^1–3\). In fine grinding, a high control over the sharpness of the particle size distribution and the fineness of milling products is extremely important.

In order to obtain desired milling products, the operating conditions of milling operations must be adequately studied and optimized. However, this is not an easy task because the optimum variables often vary depending on the milling technique, the operating parameters and the specific characteristics of the input material.

Among the numerous milling technologies, the media stirred milling is well known for the fineness of its grinding products. In stirred milling, the characteristics of the milling products strongly depends on the geometry of the agitators in the stirred mill and on operating conditions such as the rotational speed of the agitators and the grinding media\(^4–8\). Although the correlation between operating conditions and milling products characteristics (e.g. fineness and sharpness of particle size distribution) is missing or still limited to empirical approaches, numerical simulations have been recently proven to be a powerful tool to investigate the milling operations. Among them, the discrete element method (DEM)\(^9\), has been utilized to investigate the behavior of particles in mills\(^10,11\). As a matter of fact, because DEM allows for the simulation of the behavior of any single particle at any time in the mill, useful data such as velocity and collision energy of particles, otherwise difficult to retrieve from experiments, can be obtained. The DEM simulations have been also applied to stirred milling to investigate the influence of the apparatus geometry and the operation conditions on the fineness of milling products\(^12–15\). Thus, there are many research works applying DEM to many kinds of mills and it has been known that the behavior of media in mills can be accurately reproduced by DEM simulation. However, only a few studies focused on the effect of these parameters on size dispersion of milling products.

The objective of this study was to investigate the effect of the geometry of the agitation shaft in stirred mills on grinding performance. Two geometries were simulated and analyzed: the vertical agitation shaft and the horizontal agitation shaft. In addition, aiming to a further elucidation of the grinding dynamics, possibly leading to an optimization of the operation, the DEM was also utilized to evaluate the grinding performances, the velocity and the collision energy. From the comparison between experimental and simulation results, we also determined the kinds of grinding media that allows for the lower particle size dispersion of stirred milling products.

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2. Materials and Methods

2.1 Media stirred mill

In this study, two types of stirred mills were used: one with vertical agitation shaft and six agitator arms, namely vertical stirred mill, and one with horizontal agitation shaft four agitator arms, namely horizontal stirred mill. The shaft of the vertical stirred mill was a cylinder whose diameter was 30 mm, and the shaft of the horizontal stirred mill was also a cylinder whose diameter was 60 mm. The edge of each arm in these mills had rounded shape. The diameter and the height of these mills were approximately 200 mm. All devices made of stainless steel. Figures 1 and 2 show respectively the simulation models for the vertical stirred mill and the horizontal stirred mill used in this study.

2.2 Experimental procedure

Grinding experiments were performed to evaluate the grinding performances for later comparison with simulation results. Tests were conducted according to the experimental conditions summarized in Table 1. The grinding media consisted of 10 mm diameter iron balls for a total amount of 18 kg per batch. This amount was determined to be about 70% of filling ratio which is known as best condition for grinding. The grinding sample was silica sand. Before grinding tests, the sample was sieved and ranged from 200 to 300 μm. The input weight of sample in one batch was 0.75 kg, which is sufficient to fill the gap of the filled media balls. The rotational speed of the agitator in these mills was determined by a tradeoff between grinding performance and power consumption and set to 2.31 m/s. The grinding time was set to 30 min, which is the time before negative grinding was occurred.

After milling, the particle distribution was obtained by sieving analysis. Sharpness of the particle size distribution was chosen as index of size dispersion and it was calculated as

$$W = (P90 - P10)/P50,$$

where $W$ is the index of sharpness of the particle size distribution, $P90$, $P50$ and $P10$ are the 90%, 50%, and 10% cumulative weight passing size, respectively. The smaller value of this index means the narrower particle size distribution, while the bigger value of this index means the wider particle size distribution.

2.3 Simulation procedure

In the discrete element method (DEM), the behavior of particles is calculated based on Newton’s second law. The contact force acting between particles or particle and wall are modeled by Voigt model as shown in Fig. 3. In this model, the contact force is divided into normal and tangential directions, and modeled by a spring, a dashpot and a friction slider.

In order to reduce the computational load, just the behavior of grinding media was calculated using DEM in this study. The simulation conditions were determined based on the experimental conditions. The DEM parameters are listed in Table 2. The spring constant was set to be much softer than that estimated from Young’s modulus and Poisson’s ra-

![Fig. 1 Simulation model of vertical stirred mill.](image1)

![Fig. 2 Simulation model of horizontal stirred mill.](image2)

![Fig. 3 Voigt model in DEM simulation.](image3)

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<thead>
<tr>
<th>Table 1</th>
<th>Experimental conditions.</th>
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<tbody>
<tr>
<td></td>
<td>Vertical type</td>
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<tr>
<td>Grinding media:</td>
<td></td>
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<tr>
<td>Material</td>
<td>Iron ball</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>10</td>
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<td>Total weight (kg)</td>
<td>18</td>
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<tr>
<td>Filling ratio (%)</td>
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<td>Grinding sample:</td>
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<td>Operating condition:</td>
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<tr>
<td>Rotational speed (m/s)</td>
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<tr>
<td>Milling time (min)</td>
<td>30</td>
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<table>
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<th>Table 2</th>
<th>Simulation conditions.</th>
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<tr>
<td>Spring constant (N/m)</td>
<td>$5.0 \times 10^5$</td>
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<tr>
<td>Coefficient of restitution (-)</td>
<td>0.36</td>
</tr>
<tr>
<td>Coefficient of friction (-)</td>
<td>0.52</td>
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tio according to previous studies\textsuperscript{9,19,24,25}). The restitution coefficient was obtained from the drop test in the stirred mill. The friction coefficient was a physical property quoted from the Ref. 20). In all simulations, the same parameters were used, and the calculation time was fixed at 5 seconds.

Since this study simulated just grinding media, the size reduction of milling sample could not be directly simulated. Thus, the velocity, the collision energy and the trajectory of the grinding media were calculated for evaluation of the grinding performance. There are models available for the calculation of the collision energy\textsuperscript{21–23}). In this study, the collision energy $E$ is defined as

$$E = \frac{1}{2}mv^2,$$

(2)

where $m$ is mass of grinding media, and $v$ is relative velocity when the grinding media is collided with grinding media or wall. Thus, the collision energy was calculated from magnitude of relative velocity between grinding media and another media or wall.

3. Results and Discussions

3.1 Experimental results

Grinding tests were conducted to evaluate the grinding performances of the two stirred mills. The average particle size, which is the 80\% cumulative weight passing size, through the grinding time for both geometries are shown in Fig. 4. Based on the variation of the average particle size, it appears as the grinding rate in the horizontal stirred mill was faster than that in vertical one.

As for the particle size distribution of milling products, after 30 minutes milling, the horizontal stirred mill produced smaller particles compared to the vertical stirred mill (Fig. 5). From the population of distribution data in Fig. 5, the index of particle size distribution sharpness was calculated based on eq. (1), and results are listed in Table 3. Clearly, the sharpness index of the particle size distribution of milling products from the horizontal stirred mill was significantly smaller than that one from the vertical stirred mill. Such lower size dispersion suggested that in the horizontal stirred mill the grinding sample was more uniformly ground.

In order to elucidate the reason of the better milling performances provided by the horizontal stirred mill, DEM simulations were performed to investigate the behavior of the grinding media in each mill.

3.2 Simulation results

3.2.1 Collision energy of grinding media

To compare the distribution of collision energy for both vertical and horizontal stirred mills, the collision number per unit time in a steady state is shown in Fig. 6. The collision energy in the horizontal stirred mill was distributed in a lower energy area than that in the vertical type stirred mill. Table 3 shows the comparison of the total collision energy per unit time of grinding media. Furthermore, by looking at the total collision energy per unit time in Table 3, the total collision energy per unit time in the horizontal type stirred mill was also smaller. Previous DEM simulation studies reported that collision energy is correlated with the grinding rate\textsuperscript{21,26}). Nevertheless, the grinding performance of the horizontal stirred mill was better. This implies that the grinding performance was not only affected by the collision energy of grinding media but it was affected by the specific behavior
of grinding media in the stirred mill.

3.2.2 Velocity of grinding media

As for the distribution of the average velocity of each grinding media in the mill, while the horizontal stirred mill determined a Gaussian-like distribution, the vertical stirred mill produced a bimodal distribution (Fig. 7). This result clearly highlights that the motion of the grinding media in the horizontal stirred mill was more homogeneous.

To better understand the behavior of the grinding media in each area of the stirred mill, the graphical representations of the velocities of the grinding media through the vertical plane in both vertical and horizontal stirred mills, respectively shown in Figs. 8 and 9. As shown in Fig. 8, the grinding media in the bottom section of the vertical stirred mill had a lower velocity than that one the in upper areas. This result implies that the grinding media in the bottom area was not agitated by the rotation of the agitator. On the other hand, for the horizontal stirred mill (Fig. 9), although the grinding media on the right side (beyond the shaft of the mill) had a relatively low velocity, the grinding media in the bottom section had a larger velocity than the grinding media in the same section of the vertical stirred mill. Consequently, the grinding sample in the bottom section of the vertical type stirred mill could not be efficiently ground by the grinding media. Therefore, we believe that it was such a different behavior of the grinding media in the bottom section of the mills that affected the grinding performances.

3.2.3 Behavior of grinding media in lower area of mill

As mentioned above, there was a difference of grinding performances between the two types of mills due to a different behavior of the grinding media in the bottom section of the mills. To better investigate this aspect, for both milling geometries, we determined the residence time of the grinding media in the bottom section. The portion of grinding media retained in the lowest section of the mills by the grinding time is shown in Fig. 10. The retained portion of grinding media was defined as ratio to the total amount present in the lowest section of the mills at the first second, whilst the lowest section was defined as the volume comprised 20% area from the bottom of the mills. As shown in Fig. 10, in the horizontal stirred mill, the grinding media present in the lowest section of the mill at the first second was completely discharged in 1 second. On the other hand, in the vertical
stirred mill, the discharge was significantly slower as approximately 40% of the grinding media was still retained in the lowest section of the mill even after 5 seconds. These results further indicated that the horizontal stirred mill allows for better stirring performances through the vertical direction.

As for the overall stirring performances, the behavior of the whole grinding media with a cross section parallel to the direction of gravity in the vertical and horizontal stirred mills can be observed respectively in Figs. 11 and 12. The

![Fig. 11](image1.png)

**Fig. 11** Behavior of grinding media in each area (Vertical type).

![Fig. 12](image2.png)

**Fig. 12** Behavior of grinding media in each area (Horizontal type).
iron balls grinding media in these figures were color-coded according to their specific initial position (height) in the mill. As shown in Fig. 11, in the vertical stirred mill, the grinding media in lowest section hardly moved through the vertical direction and, even after 5 seconds, it almost remained in the same place. On the contrary, the grinding media in the upper sections of the mill, actively moved through the vertical direction and mixed. These results indicate that the area below the agitator shaft could not be effectively agitated by the agitator shaft. Consequently, also the grinding sample in the lowest section was not effectively ground due to a lack of vertical mixing. On the other hand, as shown in Fig. 12, in the horizontal stirred mill, the grinding media in lowest area efficiently moved through the vertical direction along the wall of the mill and it actively mixed with the grinding media from other sections. These results suggest that in the horizontal stirred mill, despite the lower collision energy, the grinding media uniformly and efficiently transmitted the energy to the grinding sample due to the better mixing conditions, thereby determining better grinding performances.

4. Conclusion

This study compared the grinding performances of two different geometries of stirred mills: the vertical and a horizontal shaft configuration. Grinding tests and DEM simulations were performed to serve the scope.

Experimental results highlighted the better grinding performances of the horizontal stirred mill as finer and grinding products with a sharper particle size distribution could be produced. Furthermore, DEM simulations revealed that difference between the two geometries was due to the better uniform mixing conditions of the grinding media in the horizontal geometry, which in turn determined a better transmission of the however lower collision energy.

Accordingly, this study demonstrated that not only the collision energy but also uniformity of movement of grinding media should be evaluated in order to understand grinding performance in a media stirred mill by DEM simulation.

REFERENCES