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Research Paper

An Investigation of Various Particle Shapes Load Structure in Tumbling Mills by DEM Method

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Abstract: Load movement in tumbling mills involving spherical particles has been extensively studied with the discrete element method (DEM) in the past. This assumption is legitimized by the added complexity of non-spherical shape representation, contact detection and computational cost. Simulation of particles with realistic shape helps to capture the essential aspects of mechanical behavior of the particulate material. In this research, an in-house developed DEM software called $KMPC_{DEM}^{©}$ was used to simulate the charge movement with spherical and non-spherical particles. At the first to calibrate the model parameters, a model tumbling mill (100 cm diameter and 10.8 cm length) with one transparent end was used. The tests were performed with steel balls and wood cubes. After calibration, a number of mill simulations were performed with the different shape of particles (spherical, cubical, and tetrahedron) to study the effect of particle shape. Comparison of the simulation and experimental results showed that the difference between the measured and predicted impact toe, shoulder angle and bulk toe angles were within 3˚-5˚ of the measured values in the model mill. The amount of in-flight of charge when using spherical and non-spherical particles was significantly different (17%). The marked difference was attributed to higher interlocking of non-spherical particles in comparison to spherical balls. The results showed that the elongation of charge was increased (5o) by considering the non-spherical shape of particles. The simulation computation time increased by 35 times when the shape of particles changed from spherical to cubical.

Keywords: Discrete element method (DEM), Tumbling mills, Simulation, Particle shape, Non-spherical particles.

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INTRODUCTION

Particles could have markedly different mechanical properties on account of a difference in shape. At least 70% of industries consist of granular systems; pharmaceutics, agriculture, mining, environment, civil engineering, geological engineering and segregation and packing of particles are just a few examples [1,2]. The consideration of particles with realistic shape helps capture the essential aspects of mechanical behavior of the particulate material. For example, the strength of the microstructure principally arises from the geometric interlocking of the particles with non-spherical shape [2]. In order to assess and control the performance of various unit operations, it is necessary to obtain a fundamental understanding of the underlying physics of granular systems. The DEM, first proposed by Cundall and Strack [3], is recognized as an effective tool for modelling the flow of granular materials in a variety of industrial applications.

Govender et al. [4] performed a number of ball mill simulations with four additional polyhedral particle systems to study the effect of particle shape. They found that there exist significant differences in charge profiles and force chain networks between the various particle systems. Cleary and Owen [5] studied the effect of particle shape on the structure of the charge in SAG mills by DEM simulations. They showed that when the particles in a mill are non-spherical, the structure of the charge changes.

The present work was carried out to characterize the effect of particle shape on load movement in mill using DEM modeling. The $KMPC_{DEM}^{©}$ software was coded to handle non-spherical particles to be used to simulate the charge trajectory. The calibration was performed through experiments in a model mill using non-spherical shape particles.

METHODS

An in-house developed DEM software called $KMPC_{DEM}^{©}$ has been used to simulate the behavior of spherical particles in different processes. To calibrate the model parameters, a model tumbling mill (100 cm diameter and 10.8 cm length) with one transparent end was used which made accurate photography possible (Figure 1). The tests were performed at filling of 20% and mill speed of 85% of critical speed with steel balls and wood cubes. In the simulation, each cube particle was represented with clusters of spheres (with identical size) by particle packing algorithm for contact detection and contact-force calculation. The tests performed in the model mill were simulated by the $KMPC_{DEM}^{©}$ software at the same conditions (size and shape of particles and operating conditions).

Figure 1. Model mill with control and data acquisition systems

FINDINGS AND ARGUMENT

Simulation results of the $KMPC_{DEM}^{©}$ software were compared with physical experiments to accurately calibrate the model parameters in the software used to simulate non-spherical particles behavior. The structure of charge and the amount of in-flight charge were used to perform this task. This was achieved by comparing the shoulder, toe and charge impact toe of the charge which were measured in degrees starting from the horizontal line passing the mill center (i.e., 3 o'clock position) and moving counter clockwise.

The charge trajectories obtained from the tests and simulations at 20% total filling are shown in Figure 2.

The results showed that the difference between the averages of measured and predicted charge impact toe was 2.8˚. Given the measurement error of 1.8˚ obtained from the repeated tests, the difference was not found significant at 95% confidence level. Comparison of the measured and simulated shoulder angles showed that the simulated positions on average were 3.8˚±2.2˚ (95% confidence level) larger that of the measured shoulder.

Due to the higher lift of the charge in the simulation, the value of simulated bulk toe angle was 4.7˚ higher than the measured angle, but given the standard deviation of 3.1˚ it was believed to be insignificant. It could be concluded that there is a good agreement between the simulated and measured positions of shoulder, bulk toe, and impact toe.

The other important feature that must be considered is the amount of in-flight charge. It was found that the amount of in-flight charge in the DEM simulation and model mill for the cubes was significantly different from that of the spheres (Figure 2). The amounts of in-flight charges were 58.6% and 41.5% for the cubical and the spherical shapes, respectively. It can be seen that the cascading region of the charge became more compact for spherical particles. Cubical shape encourages exposure of more particles to the in-flight region due to interlocking of particles which in turn affects the comminution mechanisms (impact and abrasion).

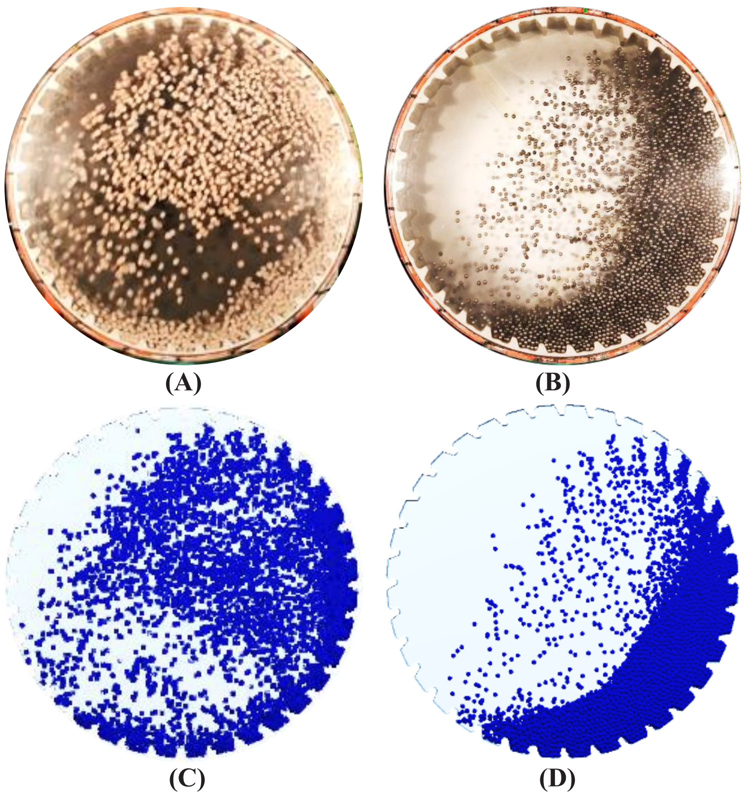

Figure 2. Comparison of the simulated and laboratory charge trajectories at 85% of critical speed and 20% filling (**A and C:** wood cubes, **B and D:** steel balls)

Non-spherical particles were found to change the charge structure, such as head, shoulder, impact toe, and bulk toe. The head of charge is about 13˚ higher for the non-spherical particles. Due to bridging between the non-spherical particles, interlocking of particles, the charge was lifted to a higher point by 16˚. This is a consequence of the interlocking of cubical particles allowing it to be carried higher in the mill by the mill rotation leading to the higher shoulder position. The higher position of shoulder for the non-spherical particles affects the mill power draw and the contribution of various breakage mechanisms in comminution [6]. The higher mill power draw for the non-spherical particles was a result of charge elongation where the shoulder position was higher and the bulk toe position shifted to the left compared to that of the spherical particles.

This moved the charge center of mass further from the center of the mill and increased the moment arm resulting in higher power draw [5,7]. The elongated charge of the non-spherical particles was characterized by a higher shoulder position and the impact toe closer to 9 o'clock position (Figure 2). Changing the mill load from spherical balls to cubes at the same operational conditions at 20% filling decreased the charge impact toe by 29˚ (from 213˚ to 184˚) and the bulk toe by 5˚.

It was found that when considering cubical particles, the computation time increased approximately by 35 times compared to that of spherical particles at identical operating conditions. In other words, for a 20 seconds simulation which included 11887 cubical particles, the required computation time was about 3.5 hours in our system (main board: Asus X99 E WS; CPU: Intel Xeon E5 2650 v3; GPU: Nvidia GTX Titan Xp; RAM: 16 GB DDR4 3000 MHz); whereas for spheres (10198 particles) it reduced to less than 6 minutes.

CONCLUSIONS

- The effect of particles shape on the charge behavior was investigated by using steel balls and wood cubes in a model mill with the diameter of 100 cm.
- The packing density of cubical and spherical particle was found to be 70% and 60%, respectively.
- The $KMPC_{DEM}^{©}$ software was revised by addition of codes to simulate the non-spherical particles flow.
- The effect of particle shape was found to be significant on the load shape. The in-flight charge was found to be 58.6%, and 41.5% (v/v) for cubical and spherical particles, respectively. The non-spherical shape particle essentially exerted an additional force to the layers of charge and increased the amount of particles in free flight zone by 17%.
- The experimental calibration of the simulation results obtained by the $KMPC_{DEM}^{©}$ indicated that the predicted positions of shoulder, bulk toe and impact toe were within 3˚-5˚ of the measured values in the model mill.
- The significant change in the charge movement and structure on account of non-spherical particles was reflected in the amount of in-flight charge (17%), and positions of shoulder (16˚), impact toe (29˚) and bulk toe (5˚). The marked difference was attributed to higher interlocking of non-spherical particles in comparison to spherical balls.
- Investigation of particle shape effects on comminution mechanisms showed the non-spherical particles were mostly located outside of the bulk of the charge (i.e., in the cataracting zone). This indicated that the elongation of charge was increased (5^{o}) by considering the non-spherical shape of particles.
- When the shape of particles was changed from spherical to cubical, it resulted in an increase of the computation time from less than 6 minutes to 3.5 hours for a 20-second simulation. This meant a reduction of 35 times in the computation speed.

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