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Original Research Paper

# The effects of friction characteristic of particle on milling process in a horizontal rice mill

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The physical and mechanical properties of rice are of significant change during milling from brown rice to white rice, especially the friction characteristics. In order to clarify the effects of roughness of rice surface on the milling process and mechanism, in this work, motion of spherical particle in a horizontal rice mill under different static friction coefficients (i.e., between particle and cylinder sieve wall $\mu_{s,pt}$ and between particles $\mu_{s,pp}$) was simulated using the discrete element method. The uniformity of axial motion and circular motion were qualitatively and quantitatively analyzed, which are characterized by introducing the axial dispersion coefficient and uniformity index, respectively. Then, the effects of static fiction coefficients on residence time and collision energy among particles were discussed. The results indicated that the $\mu_{s,pt}$ mainly affects the axial motion while the $\mu_{s,pp}$ primarily influences on the circular motion. The residence time is strongly affected by the uniformity of axial motion while the collision energy is significantly influenced by the uniformity of circular motion. Finally, the relationship between friction characteristics and milling performance can be described based on the method of polynomial fitting. This work is useful for providing essential references to control the quality of milled rice.



## 1. Introduction

Brown rice is commonly comprised of bran, embryo, and endosperm layers [1]. Generally speaking, the handling and processing of brown rice is mainly milling in a rice mill, which is done to strip away the embryo and bran layers by rubbing between particles and finally to obtain silky-white rice [2]. In fact, the rubbing mainly depends on the relatively sliding between the brown rice surfaces [3]. Therefore, the roughness of rice surface plays an important role in rice milling. However, rubbing between particles during milling, not only causes the change in physical and mechanical properties of rice particle [4–7], which manifested in the variation of particle size, shape and roughness etc., but also reduces the rice milling quality, which reflects as the breakage of rice and milling unevenly. Unfortunately, studies on whether there is a connection between the physical and mechanical properties and the rice milling quality have no quantitative information in the published literature. In addition, the existing experiment techniques are difficult to investigate the effect of physical and mechanical parameters on the micro-dynamic properties of particle motion [8]. Therefore, to overcome the above constraints, numerical methods based on discrete element method (DEM) has been generally introduced in particle grinding to realize the visualization of the milling process and further to clarify the milling mechanism [9–12].

To date, the simulated analysis of particle motion in various mill devices, such as IsaMill, tower mill, ball mill and vertical rice mill, has been widely carried out in terms of the mill configurations and operating parameters [13–16]. These researches preliminarily built a relationship between particle motion and milling performance. However, some researches also verified that the friction characteristics of particle have a strong effect on granular dynamic behavior, not only during the process of mixing [17], conveying [18] and discharging [19] but also during the grinding process. In particular, Jayasundara et al. [20,21] suggested that the static friction coefficients have a significant effect on the velocity distribution, porosity distribution, collision frequency, collision energy and power draw in a IsaMill. They also found that the power draw only depends on the static friction between particle and wall. Khanal et al. [22] investigated the influences of particle elastic modulus and coefficient of inter-particle sliding friction on milling of mineral particles in autogenous mill. Summing up above researches, on the one hand, the change in friction characteristics significantly affects particle motion and milling performance. On the other hand, due to

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**Nomenclature**

| | | | |
|---|---|---|---|
| $\mu_{s,pt}$ | static friction coefficients between particle and wall (–) | $SD$ | standard deviation of velocity (–) |
| $\mu_{s,pp}$ | static friction coefficients between particle and particle (–) | $v_{Y,z}$ | average velocity in Y axis at time step $z$ (m/s) |
| $\vec{v}_i$ | translational velocity vector of particle $i$ (m/s) | $v_{Y,ij}$ | average velocity of cell $j$ at layer $i$ in Y axis (m/s) |
| $\vec{\omega}_i$ | angular velocity vector of particle $i$ (rad/s) | $v_{Z,ij}$ | average velocity of cell $j$ at layer $i$ in Z axis (m/s) |
| $m_i$ | mass of particle $i$ (kg) | $N_T$ | total number of time steps (–) |
| g | gravity (m/s$^2$) | $v_{ij}$ | average velocity magnitude of cell $j$ at layer $i$ (m/s) |
| $I$ | moment of inertia (kg m$^2$) | $\bar{v}'_{ij}$ | normalized velocity magnitude of cell $j$ at layer $i$ (m/s) |
| $F^n$ | normal contact force (N) | $\bar{v}'$ | average particle velocity for all cells (m/s) |
| $F^t$ | tangential contact force (N) | $v_{\min}$ | minimum average velocity magnitude in each layer (m/s) |
| $T$ | torque (N m) | $v_{\max}$ | maximum average velocity magnitude in each layer (m/s) |
| RTD | residence time distribution (–) | $N_l$ | total number of layers (–) |
| $E(t)$ | residence time distribution function (–) | $N_c$ | total number of cells (–) |
| $C(t)$ | concentration of tracer as a function of time (–) | $\psi$ | porosity (–) |
| $\Delta t_m$ | sampling time interval (s) | $V_{P,z,j}$ | volume of all particles in cell $j$ at time step $z$ (m$^3$) |
| $\bar{t}$ | mean residence time (s) | $V_m$ | volume of mesh unit (m$^3$) |
| $\sigma^2$ | variance of residence times (–) | $C_r$ | collision rate (J/s) |
| $D$ | axial dispersion coefficient (–) | $C_{e,n}$ | total collision energy of individual tracer particle $n$ (J) |
| $Pe$ | dimensionless Peclet number (–) | $N_{tracer}$ | number of tracer particles (–) |
| $L$ | axial displacement (m) | $t_n$ | total residence time of individual tracer particle $n$ (s) |
| $UI$ | uniformity index (–) | | |

the difference in dominant milling mechanism, particle dynamic behaviors have the different sensitivity to the friction characteristics of particle in the different types of mills. Up until now, nonetheless, no experimental or numerical researches have been reported on the consequent effect of static friction coefficients on the particle motion and even the mill performance during milling.

In this work, the different static friction coefficients (i.e., between particles $\mu_{s,pp}$ as well as between particle and cylinder sieve wall $\mu_{s,pt}$) are used to represent the roughness of rice particle at different time in the process of bran removal. Therefore, the DEM is applied to simulate the spherical particle milling in a lab-scale horizontal rice mill under the different static friction coefficients. Compared with the experiments, the simulation results are first quantitatively validated. Then, the uniformity of axial motion and circular motion are qualitatively and quantitatively analyzed. In addition, the effects of motion uniformity on residence time and collision energy are discussed, respectively. Finally, a relationship between the static friction coefficient and the collision energy as well as residence time is established. The results in this work provide an insight into how the friction characteristics affect particle milling process and mechanism in a horizontal rice mill.

## 2. DEM model

### 2.1. Discrete element method

In order to simulate particles motion in a horizontal rice mill, the DEM model employed in this work has been detailed elsewhere [16,23] and will be briefly described here. In DEM simulation, each collision between particles and particles and their environment is evaluated with a force-displacement equation. Each particle possesses the translational and the rotational motion, which can be described by Newton's second law of motion, given by:

$$m_i \frac{d\vec{v}_i}{dt} = m_i \vec{g} + \sum_{j=1}^{n_i} (\vec{F}^n_{ij} + \vec{F}^t_{ij}) \quad (1)$$

$$I_i \frac{d\vec{\omega}_i}{dt} = \sum_{j=1}^{n_i} (\vec{T}^t + \vec{T}_r) \quad (2)$$

where $\vec{v}_i$ and $\vec{\omega}_i$ are the translational and angular velocity vector of particle $i$, respectively. $m_i\vec{g}$ and $I_i$ are the gravity and moment of inertia. $n_i$ is the number of particle $j$ in collision with particle $i$. $\vec{F}^n_{ij}$ and $\vec{F}^t_{ij}$ are the normal force and the tangential force. $\vec{T}^t$ is the torque caused by the tangential force. $\vec{T}_r$ is the rolling friction torque.

The previous studies verified that the no-slip Hertz-Mindlin contact model in the soft sphere model is effective to calculate the forces and torques of rice particles during discharging, milling and conveying [23–25], respectively. The forces, torques and its detailed definitions were found in the Ref. [16]. The simulations for the particle flow in the laboratory horizontal mill were performed using the professional software EDEM™ (DEM Solution, Edinburgh, UK). With the current configuration, it takes about 8 CPU hours to simulate 1 s of real time. 20% of the critical time step is used as the time step that is $1.35 \times 10^{-6}$ s, which is small enough to ensure the accuracy of the simulations.

### 2.2. Simulation conditions and procedures

Despite rice particle is usually described by the axis-symmetric ellipsoid and constructed by using combined spherical particles to simplify the rice model in simulations [16,26], it increases both of the computational efficiency and cost. Therefore, most researchers adopted the spherical particle to replace the complex shape in simulations. Particularly, as per Markauskas et al. [27], two hundred rice particles were randomly selected to measure its dimension parameters including the length, width and thickness, respectively. Interestingly, the equivalent spheroid diameter distribution of rice particle conforms well to the normal distribution with a mean diameter of 3.03 mm and a standard deviation of 0.086 mm, respectively, as shown in Fig. 1. Hence, rice particle was replaced by the spherical particle which accords with the normal distribution in simulations. Here, the properties of simplified rice is of no breakage, no attrition and no liquid bridge.

The configuration of horizontal rice mill used in simulations includes a feed hopper, a spiral conveyor, a simplified cylindrical rice sieve and a roller shaft, as shown in Fig. 2. Considering the collision and wear among particles generally occur in the annular