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Effects of rotation speed and rice sieve geometry on turbulent motion of particles in a vertical rice mill

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ABSTRACT

Performance optimization of a rice mill is an issue of great significance in the rice milling industry. By means of Discrete Element Method (DEM), this work examines how the turbulent motion of particles in the vertical rice mill is affected by the cross-section shape of rice sieve and the rotation speed of roller shaft. The random motion of particles is analyzed in terms of velocity field and velocity distribution in different directions. In addition, a kinetic analytic method for evaluating the intensity of turbulent motion of particles via average turbulent kinetic energy during a grinding process was investigated. The results showed that the collision rate and average collision energy in a milling chamber increase linearly with the average turbulent kinetic energy for the same type of rice sieve, which confirm the validity and practicability of the average turbulent kinetic energy. Furthermore, an average rate of clearance change is proposed to characterize the cavity shape variation in the milling chamber. It was found that there exists a strong correlation between the average turbulent kinetic energy and the average rate of clearance change, irrespective of the cross-section shape of regular polygon sieve. This revealed that the cavity shape variation, which is determined by the geometric parameters of rice sieve and rotation speed, has a great influence on the turbulent motions of particles in the milling chamber. Overall, the results are useful for developing a fundamental understanding of the kinematic and dynamic characteristics of particle behavior, which will help design and control practical processes.

1. Introduction

Bran removal, a major stage in the complete set of rice milling, is directly related to the quality of final milled rice. In general, this process is accomplished in a milling chamber which mainly consists of a stationary rice sieve and a rotating roller shaft. During the abrasion of rice, not only the outer layers of the rice particles are removed, but also rice particles are broken [1]. Rice is preferably consumed as whole kernels. The primary parameter used to quantify commercial rice milling quality is the head rice yield [2]. In order to improve milling quality, many researches have focused on the interior configuration of the milling chamber.

Previous studies were mainly based on physical experiments. Sun [3] investigated different clearances between roller shaft and rice sieve on the pressure of a milling chamber. Pan and Thompson [4] studied the effects of milling weight on head rice yield and whiteness using a McGill No. 3 mill, while the milling weight is directly related to the interior configuration in the milling chamber. More recently, Firouzi et al. [5] performed the milling experiments to evaluate the influence of blade-rotor clearance on the whiteness and broken rate of rice particles. In recent years, granular dynamic simulations based on the discrete element method (DEM) have been widely used in the studying of granular systems [6,7]. In this regard, Suzuki et al. [8] developed a two-dimensional (2D) DEM model to examine the performance of resistance plates in an abrasive type rice-milling chamber. In essence, the factors investigated in these studies changed the interior configuration of the milling chambers, thus greatly affecting milling quality. However, the effect of the cross-section shape of rice sieve has not been specifically studied, although the cross-section shape of rice sieve is closely linked to the interior configuration in the milling chamber. Actually, rice sieves of different shapes are used in the rice milling industry. The cross-section shape of rice sieve is also an important factor that should be considered in optimizing the milling performance. In addition, to understand the possible mechanisms underlying the influence of the interior configuration of the milling chamber on milling performance, more detailed information at a microscopic level is required. For instance, Xie et al. [9] studied the effect of lifter configuration (straight and arc lifters) in a drum mixer on heat transfer characterized by particle-wall contact area and heat transfer coefficient. And Chandratilleke et al. [10] examined the effect of blade rake angle and blade gap in a cylindrical mixer on particle mixing by velocity fields, Lacey's mixing index and inter-particle forces. In rice milling process, the level of broken kernels is largely determined by the intensity of processing and the intrinsic rice grain properties [11]. A moderate milling strength is required to ensure milling quality since the excessive

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milling strength causing more broken rice. While the strength of rice abrasion is closely related to average individual collision according to our previous work [12]. Thus, by gaining knowledge of how the collision characteristics of particles in the milling chamber are affected by the rice sieve design and operating parameters, the milling quality can be improved.

The collision characteristics of particles are largely determined by the intensity of turbulent motion of particles [13]. Therefore, the intensity of the random motion of particles is one of the most important microscopic characteristics in particle system, whereas it is usually neglected for a specific engineering problem. So far, the intensity of turbulent motion of particles is usually quantified by the granular temperature, which was first introduced by Ogawa [14]. And this concept is the direct analogue of thermodynamic temperature and plays the same vital role in granular dynamics. It generates pressures and governs the transport of material, momentum and energy [15]. However, the granular temperature is strongly grid-size dependent [16,17]. This is because the granular temperature is calculated from the variance of particle velocities in a certain grid cell. When the grid size is reduced, the particle dynamics will become more homogeneous, leading to a lower granular temperature, or vice versa. Besides, Sinclair [18] pointed out that the granular temperature is related to random motion of individual particles rather than the random motion of collections of particles. Moreover, the granular temperature is still not a comprehensive description of the translational and rotational turbulent motion of particles. To avoid these shortcomings, the granular temperature needs to be fully developed and adapted to suit the needs of different conditions.

In this study, we examine the effects of the cross-section shape of rice sieve and the rotation speed of roller shaft by DEM simulations, while the basic conditions for simulation are identical to the previous studies [12,19]. The rest of the paper is organized as follows: the milling geometry, discrete element model, and simulation conditions are introduced in the next section. In Section 3, the simulation results for the 8-sided regular polygon sieve are first compared with experimental results using the dimensionless residence time distribution. Then, the turbulent motion of particles is analyzed in terms of velocity field and velocity distribution in different directions. Furthermore, an average turbulent kinetic energy was developed as a quantitative method for evaluating the random motion of particles in the milling chamber. Finally, this study examines the relationship between the average turbulent kinetic energy and average rate of clearance change which is proposed to quantify the magnitude of cavity shape variation in the milling chamber. While the conclusions are presented in the last section. The results will be able to improve the understanding of milling processes and useful to the design and optimization of the milling chamber.

2. Model description

2.1. Discrete element model

This work uses the DEM model developed in our previous work [12], thus it is only briefly described here. In the model, each particle possesses translational and rotational motions, which can be described by the Newton's second law of motion, given by

$$m_i \frac{dv_i}{dt} = m_i g + \sum_{j=1}^{n_i} \left(F_n + F_n^d + F_t + F_t^d \right) \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n_i} (T_t + T_r) \tag{2}$$

Where v_i and ω_i are, respectively, the translational velocity and angular velocity of particle i. m_i and I_i are the mass and moment of inertia. n_i is the number of particle j in contact with particle i. The normal total force is the sum of normal damping force (F_n^d) and normal contact force (F_n). Similarly, the tangential total force is the sum of tangential damping force (F_t^d) and tangential contact force (F_t). The torque, in turn, includes two terms, arising from the tangential force, T_t, and the rolling friction, T_r.

The no-slip Hertz-Mindlin model, which combines Hertz's theory in the normal direction and Mindlin's no-slip model in the tangential direction, was employed in modeling each contact between particles or particle and geometry within the software EDEM. The equations used to calculate the normal total force, the tangential total force, the tangential torque and the rolling friction torque can be found elsewhere [12], and are not repeated here for brevity. The DEM model used here has been verified by comparing power values of the simulated rice mill with power values of a laboratory scale rice mill with two different outlet openings (0 and 8 mm) in our previous work [12].

2.2. Rice mill geometries

The geometry of the rice mill considered is similar to that used in the previous study [12]. The schematic of the mill is presented in Fig. 1(a). As it shows, the modeled mill is essentially consisted of four parts: a feed hopper, a tubular casing, a rice sieve, and a roller shaft, which is fitted with a screw and two identical spiral convex ribs. The ribs are diametrically opposed (see Fig. 1(c)). Our previous study [19] has focused on the particle conveying in the feed screw section. This work aims to investigate the motional state of particles in the rice sieve section of vertical rice mill.

There are numerous rice sieve designs used in rice milling machine, which are based on the variation of the cross section shape, tubular length and inner diameter of the sieve. In this research, we focus on the effect of the cross-section shape of rice sieve in the milling chamber. The mill was fitted with different shapes of rice sieves: regular polygon sieves and circle sieve, and the edge number of regular polygon sieves ranges from five to twelve. For example, the vertical view of the 8-sided regular polygon sieve and the circle sieve are shown in Fig. 1(b). In addition, to make the cases comparable, each of these rice sieves varied the cross-section shape of rice sieve while keeping the cross-sectional area, which enclosed by the internal edge of rice sieve, and length of rice sieve constant. In this case, all the milling chambers, which consist of different types of rice sieves and the same roller shaft, have the same interior volume. Thus, the influence of the rice sieve geometry on particle behavior can be observed. To ensure that the various types of rice sieves have the same cross-sectional area, the radius of circumcircle of these regular polygon sieve, as shown in Fig. 1(c), are determined according to the following equation:

$$R_s = \left(\frac{2 \cdot A}{\xi \cdot \sin \frac{2\pi}{\xi}} \right)^{\frac{1}{2}} \tag{3}$$

Here R_s is the radius of the circumscribed circle of regular polygon, A and ξ are, respectively, the reference cross-sectional area and edge number of the regular polygon. Note that the formula derivation is implemented according to the geometric attributes of regular polygon. And the reference cross-sectional area is established based on a laboratory vertical mill (SY95-PC + PAE5, Ssangyong Machinery Co., Korea). While the circle can be seen as a regular polygon with an infinite number of sides.

2.3. Simulation conditions

A simulation starts with a randomly packing process in which the roller shaft rest and particles are fed into the hopper to form a stable packed bed, as shown in Fig. 2(a). The roller shaft then rotate at a given speed to brought the rice particles into the milling chamber. Unless otherwise specified, all the results are analyzed after approximately 3 s, when the system reaches the macroscopically steady state, as shown