Powder Technology 297 (2016) 153–164

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Effects of rotation speed and outlet opening on particle flow in a vertical rice mill

Yanlong Han, Fuguo Jia *, Yong Zeng, Longwei Jiang, Yaxiong Zhang, Bin Cao

College of Engineering, Northeast Agricultural University, Harbin, Heilongjiang 150030, China

ARTICLE INFO

Article history:
Received 13 December 2015
Received in revised form 15 March 2016
Accepted 16 April 2016
Available online 19 April 2016

Keywords:
Discrete element method
Rice particle
Vertical rice mill
Particle flow

ABSTRACT

Rice mill is the key equipment to food processing used for milling unpolished rice to milled rice. However, there are few investigations about the flow process on rice particles inside the mill and the role of operation parameters. In addition, the detailed information about particle interaction and mechanisms of milling remains poorly understood. This paper presents a numerical study based on the discrete element method (DEM) to investigate the flow of rice particles in a vertical rice mill. The effects of operation parameters on the hidden flow properties, including particle orientation angle, particle fill level, collision energy and energy efficiency, were analyzed. The results showed that the particle orientations prefer pointing to 0° and 180° and orientation angles fluctuate at U-shaped distributions on a vertical plane. The wear process of particles can be described by the spatial distribution of collision energy. Wear of particles occurs mainly in the upper half of milling chamber, in which is defined as milling area. The effects of outlet opening on flow structure and particle fill level in milling area are more obvious, compared with that of the rotation speed. However, the increase of rotation speed results in higher collision energy, collision number and energy efficiency, which accelerates wear of rice particles. The findings are useful to understand particle flow, wear and milling behavior of the vertical rice mill.

1. Introduction

Rice is mostly consumed in whole milled form. Rice milling is a combination of several unit operations to convert paddy into well-milled silky-white rice [1]. During milling, dried paddy undergoes dehusking, bran removal and whitening stages [2]. In general, corresponding milling machines are used to complete these stages, namely, rice huller, rice mill and rice polisher. The bran removal is a major stage in the complete set of rice milling, which is directly linked to the quality of final milled rice. Improvement of a vertical rice mill to produce white rice in the moisture content range of 15.0–16.5% is needed [3]. Vertical rice mills are often consisting of a milling chamber and a roller shaft. When hulled rice particles revolve inside the milling chamber, the particles coming in contact with each other and with the mill undergo the bran removal. It is also noted that bran removal process is most likely to produce broken rice. The factors affecting milling quality mainly are rice mill characteristics and physical properties of rice particle itself [4].

The objective of bran removal is to obtain maximum possible yield of whole milled rice with desired milling degree. For this purpose, many researchers have already adopted effective methods to improve the performance of rice mills. Takai et al. [5] determined characteristic milling curves and obtained a general view of milling mechanism in a laboratory rice mill. To evaluate and improve the rice mill process, Chung et al. [6] developed a simulation model using a simulation language for alternative modelling. Mohapatra et al. [7,8] also estimated the wear of rice particles and energy utilization by theory modelling, revealing the dynamic abrasion in a rice milling operation. More recently, Yan et al. [9] performed the milling experiments and found that rice milling quality is significantly affected by shaft speed and brown rice moisture content. According to these investigations, parameters, including particle hardness, particle shape, rotation speed and outlet resistance of a rice mill, are closely related to the milling performance. To date, all studies focused on the operating control and optimization in terms of trial and error tests. A key step in optimizing the milling process is to understand the particle kinematic behavior, particularly the particle flow inside the mill. However, no reports regarding the rice particle flow in a rice mill were found. Advances in computer simulation technologies based on discrete element method (DEM) have made it possible to get detailed movement information of rice particles, which is difficult to obtain in experimental approaches. In recent years, the DEM has been widely used in other studies of mills like ball mill [10], conical screen mill [11], stirred mill [12], IsaMill [13], etc. To understand and optimize the particle flow and grinding behavior of IsaMills, Jayasundara et al. [14] analyzed flow properties such as flow velocity, power draw, collision energy and collision frequency. Cleary [15] investigated the mixing of rice grains in a laboratory mixer based on the DEM simulation and PEPT experiment. The results indicated that the validity of DEM simulations can be improved

* Corresponding author.
E-mail address: jiafg301@neau.edu.cn (F. Jia).

http://dx.doi.org/10.1016/j.powtec.2016.04.022

when using a more realistic particle shape. In DEM simulations, the multi-sphere model was employed for the representation of rice particle [16,17], which is the most commonly used techniques to describe complex particle shape. Therefore, by gaining knowledge of how operating parameters affect flow properties of particle that is close to a realistic rice shape based on a numerical method, performance of rice mill and quality of milled rice can be improved.

Summing up research results of predecessors, the DEM simulation approach is used to investigate the particle flow in a vertical rice mill in this study, aiming to give more detailed information of interest at a particle scale and understand the milling behavior. Compared with the experiments, the quantitative validation of simulation results is first discussed. Then, the flow of rice particles will be analyzed in terms of orientation angle, particle fill level, collision energy and energy efficiency. Meanwhile, the effects of operational parameters of the vertical rice mill are investigated.

2. DEM model

The discrete element method model used in this work is based on the soft-sphere model. Dry rice particles were selected to establish the model. It is assumed that there is no cohesive force among particles during milling. Meanwhile each particle interacts with its neighbors or with the wall of the mill through both normal and tangential total forces. In DEM simulations, each particle possesses translational and rotational motion, which can be described by Newton's second law of motion with a force-displacement correlation at the contact point, given by

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \mathbf{g} + \sum_{j=1}^{n_i}\left(\mathbf{F}_n + \mathbf{F}_n^d + \mathbf{F}_t + \mathbf{F}_t^d\right) \tag{1}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{n_i}(\mathbf{T}_t + \mathbf{T}_r). \tag{2}$$

Where $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and angular velocities of particle i, respectively. 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 contact force ($\mathbf{F}_n$) and normal damping force ($\mathbf{F}_n^d$). Similarly, the tangential total force is the sum of tangential contact force ($\mathbf{F}_t$) and tangential damping force ($\mathbf{F}_t^d$). The contact force provides a spring repulsive force that pushes colliding particles back apart and the damping force provides a dashpot to dissipate a portion of the relative kinetic energy. $\mathbf{T}_t$ is the torque caused by the tangential force. $\mathbf{T}_r$ is the rolling friction torque, and is considered to play a significant role in some cases involving the transition between static and dynamic states [18].

Considering the computational efficiency, the most popular no-slip Hertz-Mindlin contact model, which combines Hertz's theory in the normal direction and Mindlin's no-slip model in the tangential direction [19], was selected in the present study to calculate the forces and torques above mentioned. In this contact model, total forces have the characteristics of both elastic and non-elastic, which can be represented by a linear spring-dashpot model [20]. In the normal direction, the spring and dashpot together define the normal total force ($\mathbf{F}_{ntotal}$) given by.

$$\mathbf{F}_{ntotal} = \mathbf{F}_n + \mathbf{F}_n^d = \frac{4}{3}E^*\sqrt{R^*\alpha^3} - 2\sqrt{\frac{5}{6}}\frac{\ln\varepsilon}{\sqrt{\ln^2\varepsilon + \pi^2}}\sqrt{S_n m^*}v_n^{rel} \tag{3}$$

where E^* is the equivalent Young's modulus, R^* is the equivalent radius, and α represent the normal overlap. ε is the coefficient of restitution. $S_n$is the normal stiffness. $m^*$is the equivalent mass. v_n^{rel} is the normal components of the relative velocity between particles.

In the tangential direction, the relative tangential velocity from the relative tangential motions over the collision behaves as an incremental spring that stores energy and represents the elastic tangential deformation of the contacting surfaces. The dashpot dissipates energy from the tangential motion and models the tangential plastic deformation of the contact [21]. Static friction is modeled as a damped linear spring [22], and the magnitude of the tangential total force ($\mathbf{F}_{ttotal}$) is limited by Coulomb's law, giving

$$\mathbf{F}_{ttotal} = \begin{cases} \mathbf{F}_t + \mathbf{F}_t^d = -S_t\delta - 2\sqrt{\frac{5}{6}}\frac{\ln\varepsilon}{\sqrt{\ln^2\varepsilon + \pi^2}}\sqrt{S_t m^*}v_t^{rel}, \text{when} \|\mathbf{F}_t + \mathbf{F}_t^d\| \le \|\mathbf{F}_c\| \\ \mathbf{F}_c = \mu_s \mathbf{F}_n, \text{when} \|\mathbf{F}_t + \mathbf{F}_t^d\| > \|\mathbf{F}_c\|. \end{cases} \tag{4}$$

Where S_t is the tangential stiffness, δ is the tangential overlap. v_t^{rel} is the tangential components of the relative velocity. $\mathbf{F}_c$ is the Coulomb friction force. μ_s is the coefficient of static friction. Based on literature [23] review, some detailed definitions of above parameters are listed in Table 1.

The rotational motion of particles depends on the torques produced on the particles including tangential torque and rolling friction torque. The torques can be considered using the following equations:

$$\mathbf{T}_t = \mathbf{R}_i \times \left(\mathbf{F}_t + \mathbf{F}_t^d\right) \tag{5}$$

$$\mathbf{T}_r = -\mu_r \mathbf{F}_n \mathbf{R}_i \frac{\boldsymbol{\omega}_i}{\|\boldsymbol{\omega}_i\|} \tag{6}$$

where $\mathbf{R}_i$ is the distance of the contact point from the center of mass for object i. μ_r is the coefficient of rolling friction.

In DEM simulations, multi-sphere model was considered for modelling elongated particles of irregular shape. A multi-sphere approach presents the case of composite particle, therewith, a single non-spherical particle is represented by a composition of the overlapping spheres [16]. It is noted that the overlapping spheres in a single non-spherical particle can overlap and no inter-sphere forces are generated. In principle, in order to approximate the actual shape of a non-spherical particle, the number of overlapping spheres should be adopted as much as possible. However, the excessive amounts of overlapping spheres will cause unreasonable computational expenses and can't significantly improve the numerical results.

3. Simulation conditions

In this study, EDEM™ (DEM Solution, Edinburgh, UK) was applied as a platform for simulating the flow of rice particles in an underdriven (SY95-PC + PAE5, Ssangyong Machinery Co., Korea) laboratory vertical mill. The schematic of the vertical rice mill is presented in Fig. 1. As it shows, the modeled mill is essentially consisted of four parts: a feed hopper, an outlet with an adjustable opening size, a milling chamber surrounded by the octagon rice sieve, and a roller shaft, which is fitted with a screw and two identical spiral convex ribs. The ribs are diametrically opposed. The actual dimensions of each part of the mill were measured prior to establishing the DEM model. The detailed geometrical and operational conditions and material properties for the vertical mill

Table 1
The equations of parameters used in the contact model.

	Symbol	Equation
Normal stiffness	S_n	$2E^*\sqrt{R^*\alpha}$
Tangential stiffness	S_t	$8G^*\sqrt{R^*\delta}$
Equivalent Young's modulus	E^*	$\frac{1}{E^*} = \frac{(1-\upsilon_i^2)}{E_i} + \frac{(1-\upsilon_j^2)}{E_j}$
Equivalent radius	R^*	$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j}$

Where G^*: equivalent shear modulus; υ_i, υ_j: Poisson's ratio; R_i, sR_j: radius of each sphere in contact.