THE INFLUENCE OF CIRCULAR SIEVE ON THE MOVEMENT CHARACTERISTICS OF RICE IN INDUSTRIAL HORIZONTAL BALL-BLADE POLISHING MACHINES

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米筛对工业级卧式球筋抛光机内米粒运动特性的影响

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ABSTRACT

The transportation, distribution, and collision dynamics behaviors of rice grains in the polishing machine critically influence the polishing performance. However, existing research has predominantly concentrated on the polishing mechanisms of laboratory-scale polishing machines, where deviations induced by scaling effects are inherently present. This study utilizes the discrete element method to numerically simulate the operational dynamics of industrial-scale rice polishing systems, with subsequent experimental validation confirming the simulation's reliability. The movement characteristics of the particles in the polishing chamber were analyzed, and the influence mechanism of the key components of the sieve on the particle movement was revealed. The simulation results show that as the gap between the polishing roller and the rice sieve increases, the number of particles in the polishing chamber increases, while the axial, tangential and combined velocities of the rice grains as well as their velocity fluctuations decrease, thereby reducing the uniformity of transportation and the collision intensity. Furthermore, influenced by the gravitational force of the rice grains, the movement of the rice grains in the horizontal polishing machine exhibits a certain degree of irregularity. This radial irregularity in the movement promotes the alternation of the rice grains between the inner and outer rings, thereby enhancing the uniformity of the polishing of the rice grains. This research provides theoretical support for the structural design and process optimization of rice polishing equipment.

摘要

抛光机内米粒的输送、分布及碰撞等动态行为对抛光效果起着至关重要的作用。然而，既有研究多聚焦于实验室级抛光机的抛光规律，不可避免地存在规模效应导致的偏差。本研究采用离散元法模拟了工业规模的抛光机工作过程，并通过台架试验验证了仿真的可靠性。分析了抛光室内颗粒的运动特性，并揭示了米筛关键部件对颗粒运动的影响机制。仿真结果表明，随着抛光辊与米筛间隙的增加，抛光室内颗粒数量增加，米粒的轴向、切向和合速度及其速度波动随之减少，从而使其输送均匀性及碰撞强度降低。此外，受米粒重力的影响，米粒在卧式抛光机中的运动呈现出一种不均匀性，这种径向运动的不均匀性促进了米粒在内外圈的交替，促进了米粒的抛光均匀性。本研究为大米抛光设备的结构设计与工艺优化提供了理论支撑。

INTRODUCTION

China, the world's largest producer and consumer of rice. Of this total, food consumption constitutes the primary use, typically representing over 80% (*Yang and Liu, 2019*). Modern consumers increasingly prioritize taste and nutritional value when purchasing rice (*Fang et al., 2024*). The processing of paddy rice into refined white rice involves multiple stages, including drying, threshing, milling, polishing, and grading (*Riaz et al., 2017*). Among these, polishing is a critical procedure that significantly enhances the eating quality and market value by removing surface starch particles and bran layer substances (*Liu et al., 2020; Tamura et al., 2022*). However, an inevitable consequence of this process is the potential for over-polishing, which leads to nutrient loss (including vitamins, minerals, and dietary fibers) and an increased broken-grain rate.

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Thus, a key challenge lies in achieving a desirable polish while simultaneously maximizing nutrient retention and minimizing grain breakage. This is particularly complex because the dynamic behavior of rice grains during polishing is highly variable and influenced by a combination of equipment structural parameters and operational parameters, making the polishing effect difficult to control.

The Discrete Element Method (DEM) has proven to be an effective tool for analyzing the dynamic response within polishing machines and has been widely applied to study materials, operational and structural parameters, and processing techniques (*Zhang et al., 2022; Wakeling and McCarthy, 2009*). For instance, *Li et al. (2022)* analyzed the movement characteristics of rice grains under different filling levels, elucidating the intrinsic mechanism by which filling level affects the degree and uniformity of polishing. They proposed the particle alternation rate as a quantitative indicator for evaluating milling uniformity. *Tajudeen et al. (2023)* analyzed the movement trajectory and collision forces of the grains within the polishing chamber, and obtained the relationship between the contact force and the fragmentation of the grains. *Das et al. (2021)* employed the multi-ball filling method to simulate the fragmentation pattern of rice grains during the polishing process, and reduced the simulation error. In summary, by analyzing the movement, transport, and collision behaviors of rice grains within a polisher, it is feasible to investigate key performance indicators such as the broken-grain rate, polishing degree, and uniformity. The DEM provides an operable means to optimize machine performance by guiding parameter adjustment, with simulation results generally falling within an acceptable error range compared to physical tests. Nevertheless, most existing studies have focused on laboratory-scale polishing machines. While their findings offer some guidance for industrial-scale applications, they are inevitably subject to deviations caused by scale effects.

Therefore, building upon previous research, this study investigates the dynamic behavior of grain particles within an industrial-scale polishing machine. The overall structure, working principle, and key structural parameters of the polisher were first analyzed. The force conditions acting on rice grains in the polishing chamber were investigated to identify the key factors influencing their motion. Subsequently, the DEM was employed to numerically simulate the rice polishing process in a ball-ribbed polishing machine. From a particle-scale perspective, this study provides an in-depth analysis of the distribution, velocity, transport, and collision of rice particles within the machine, clarifying their specific influence mechanisms on polishing performance. The findings of this study provide a theoretical basis for the optimization of structural parameters in industrial-scale rice polishing machines.

MATERIALS AND METHODS

Test Materials

The rice variety selected for the experiment was japonica rice variety Dongnong 429. The rice was processed through husking, milling, and removing broken grains to obtain the test white rice. During the milling and polishing of the rice, the moisture content of the rice had a significant impact on the breakage rate (*Nasirahmadi et al., 2014*). In this study, the moisture content of the white rice was measured using a grain moisture analyzer, which was found to be 12.1% (wet basis).

Structure of the rice Polishing Machine

Structure and Working Principle

Fig. 1 illustrates the structural schematic of the ball-ribbed rice polishing machine. The system primarily comprises a drive unit, an air-blast unit, a feeding unit, a polishing unit, and a collection unit. During operation, rice grains, under the influence of gravity, first descend from the top-mounted hopper into the machine's cavity. The screw conveyor integrated onto the polishing roller is then responsible for steadily transporting the grains into the polishing chamber and ensuring their even distribution. Within the polishing chamber, the high-speed rotation of the polishing roller induces intensive interactions among the rice grains themselves, and between the grains and the polishing roller as well as the screen. These frictional and collisional actions effectively remove surface impurities and minor bran layers, resulting in a smoother grain surface. Following the polishing process, the finished rice is discharged through the outlet into the collection device. Simultaneously, fine rice bran and debris generated during polishing are extracted by an exhaust fan and expelled from the system through the bran outlet.

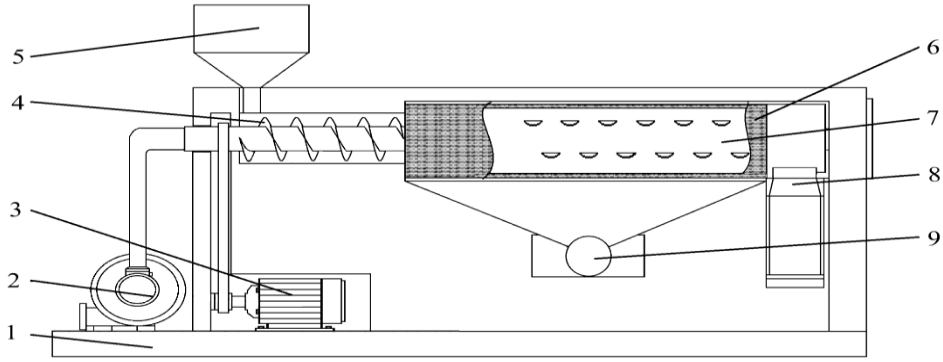
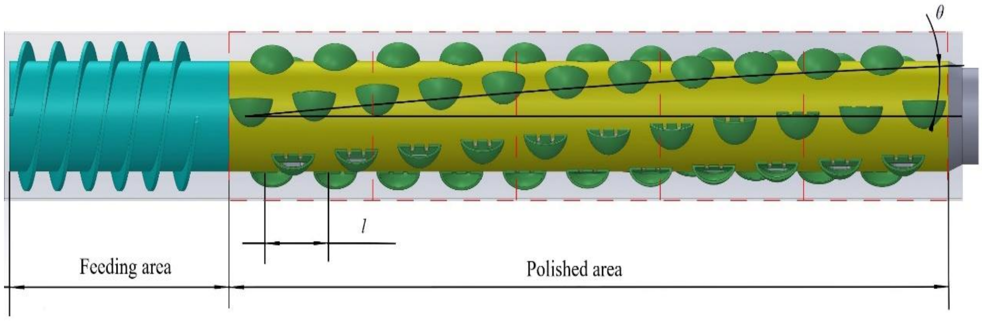


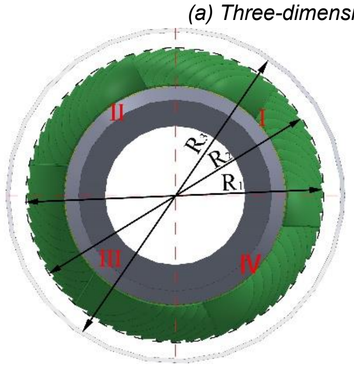
Fig. 1- Schematic diagram of the polishing machine structure
1. rack 2. fan 3. motor 4. spiral blade 5. hopper 6. mill screen
7. polishing roller 8. discharge port 9. bran discharge port

Structure Design of Polishing Chamber

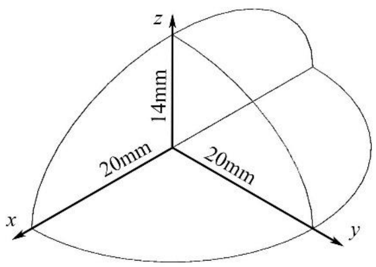
The polishing chamber is among the most crucial components of the rice polishing machine, whose structural parameters directly influence polishing performance, including the broken rice rate, uniformity, and grain smoothness. This chamber, illustrated in Fig. 2, comprises a sieve and a polishing roller, and features a 200-mm long feeding section and a 650-mm long polishing zone. The roller itself is constructed with an 80-mm diameter shaft (R_1) and achieves a 107-mm overall diameter (R_2).



(a) Three-dimensional modeling of the polishing chamber



(b) Three-dimensional modeling of the polishing chamber (axial view)



(c) Diagram of ball-rib

Fig. 2 - Image of the polishing chamber and ball-ribbed structure

(1) Polishing Roller

As the core component, the design and structural characteristics of the polishing roller significantly influence the polishing efficacy and final rice quality. Based on rib shape, polishing rollers are primarily categorized into ball-rib and convex-rib types. The ball-rib roller, featured in this study (Fig. 2a), is equipped with multiple spherical blades evenly and alternately distributed along the shaft. The interlaced gaps between these ribs effectively reduce the pressure exerted on grains during polishing, thereby mitigating the risk of breakage from collisions. To enhance machine performance, previous studies have investigated the influence of parameters in convex-rib rollers—such as the screw conveyor, rib count, and spiral angle—on the particle flow structure within the polishing chamber (*Li et al., 2023; Zeng et al., 2019*). Their findings provide a valuable reference for the optimization design and parametric study undertaken in this work.

(2) Rice Sieve

The rice sieve is another critical component of the polishing chamber (*Cao et al., 2018*), mainly divided into cylindrical and polygonal (or corner) types. As per the *Agricultural Machinery Design Manual (2007)*, a cylindrical sieve is recommended when the polishing roller diameter exceeds 100 mm. The key structural parameter of a cylindrical sieve is its diameter, which directly defines the gap between the roller and the sieve. Following the manual's specifications, this study sets the roller-sieve gap to 3, 4.5, 6, 7.5, and 9 mm. These correspond to cylindrical sieve diameters (R_3) of 112, 115, 118, 121, and 124 mm, respectively, to investigate the influence of sieve diameter on the motion characteristics of rice grains.

Discrete element method

Selection of the contact model

During rice polishing, the moisture content of the grains is typically maintained within 12-15%. Under these conditions, the cohesive and liquid bridge forces between grains are negligible. During the rice polishing process, rice grains are mainly subjected to two types of forces: first, the interaction forces between grains, including the contact pressure between individual grains and the frictional forces generated therefrom; second, the contact forces between rice grains and various components of the polishing machine (e.g., polishing rollers, rice sieves), which consist of the pressure between grains and the machine's geometric structures as well as the corresponding frictional forces. The combined effect of these forces determines the movement trajectory of rice grains, the polishing effect, and the final quality performance of the polished rice. Hence, the Hertz-Mindlin (no-slip) contact model, based on the soft-sphere theory, was adopted to simulate the interactions between particles and with the geometric boundaries (*Li et al., 2022*). This contact model enables the representation of both the translational and rotational motions of particles, thereby accurately simulating their movement processes and force-bearing conditions.

Construction of DEM model

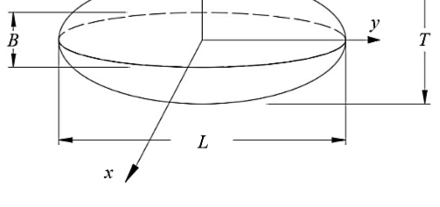
Prior research indicates that for contact detection, representing an ellipsoid with multiple spheres offers superior sensitivity and significantly reduced computational time compared to polyhedral representations (*Hohner et al., 2011*). When employing this multi-sphere approach, the number of contact points increases with the number of constituent spheres. However, a critical compromise exists: beyond a certain point, increasing the sphere count no longer refines accuracy. Instead, due to heightened model complexity, computational instability, and cumulative errors, the simulation error may increase, alongside a substantial rise in computational cost (*Zhang et al., 2020*).

Therefore, drawing on established discrete element models for rice and other grains, this study simplified white rice as an axisymmetric ellipsoid (*Markauskas et al., 2011*) and modeled its geometry via sphere filling. One hundred rice grains were randomly selected, and their three principal dimensions (length L, width B, and thickness T) were measured using a digital vernier caliper with an accuracy of 0.01 mm, as illustrated in Fig. 3(a). In the ellipsoid model, the major axis (D_L) was set equal to the measured length (L), while the minor axis (D_S) was defined as the arithmetic mean of the width (B) and thickness (T), according to Equations (1) and (2). The measurement results are summarized in Table 1.

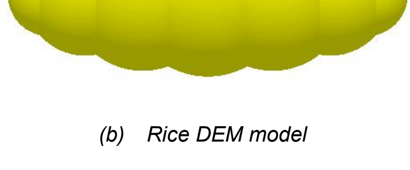
A 3D model based on these simplified dimensions was created in SolidWorks and imported into EDEM software, where the sphere-filling method was applied. The resulting discrete element model of the rice particles is shown in Fig. 3(b). All simulation parameters required for simulating the rice polishing process were determined via literature review (*Xie et al., 2023*), with their specific values presented in Table 2.

$$D_L = L \tag{1}$$

$$D_S = \frac{(B+T)}{2} \tag{2}$$



(a) Dimension measurement diagram



(b) Rice DEM model

Fig. 3- Establishment of the DEM for the rice

Table 1

Three-dimensional geometric parameters of rice grains

	L（D_L） / mm	B / mm	T / mm	D_s / mm
Value	5.59±0.20	2.61±0.12	1.88±0.10	2.45±0.08

Table 2

DEM simulation parameters

Discrete element parameters	Value
Poisson's ratio of grain	0.25
Shear modulus of grain/MPa	2.375
Density of grain/kg m^{-3}	1450
Poisson's ratio of stainless steel	0.3
Shear modulus of stainless steel/MPa	70000
Density of stainless steel/kg m^{-3}	7930
Recovery coefficient of grain-grain	0.4
Static friction coefficient of grain-grain	0.55
Dynamic friction coefficient of grain-grain	0.0258
Recovery coefficient of grain-stainless steel	0.45
Static friction coefficient of grain-stainless steel	0.4
Dynamic friction coefficient of grain-stainless steel	0.055
Rotational speed/r min^{-1}	730
Time step /s	1.5×10^{-6}

Simulation method

In this paper, the discrete element method (DEM) is used to analyze the velocity variation, average residence time, and collision behavior of white rice during the polishing process, with the clearance between the polishing roller and the rice sieve as the variable. The influence of this variable on rice polishing quality, breakage rate, and energy consumption is determined. Polishing quality is mainly evaluated by milling and polishing uniformity, which is determined by the collision characteristics and average residence time of rice grains. The breakage rate is closely related to the impact load and shear load exerted on rice grains during polishing, and the magnitudes of these loads are governed by particle velocity and collisions. The energy consumption of the polishing process is mainly used for the rotation of the motor and overcoming friction between particles and between particles and the equipment, which is directly related to the total dissipated energy of white rice during collisions.

RESULTS

Verification Test

The fundamental differences between industrial and laboratory conditions lie in throughput, geometry size, loading ratio, movement intensity, and actual friction environment. Industrial polishing machines have much larger cavity volume, higher grain flow rate, stronger particle–particle and particle–wall interactions, and more complex force states. In contrast, laboratory devices are small, with low feeding rate and simplified motion. These differences lead to obvious discrepancies in particle motion, force distribution, and polishing results. Most previous DEM models were established based on laboratory-scale equipment or simplified working conditions, which cannot fully reflect the real flow state, force characteristics, and breakage mechanism in industrial polishing. They usually ignore the semi-lubricated friction environment, high-speed continuous feeding, and strong collision characteristics of industrial processes. Therefore, these models are insufficient to accurately predict polishing quality, broken rice rate, and energy consumption under industrial conditions.

To validate the reliability of the simulation, an experimental platform was established, as shown in Fig. 4. The setup featured a polishing roller with 3D-printed nylon ball-ribs affixed to the shaft, and a transparent acrylic rice sieve to facilitate the observation and measurement of grain residence time. Driven by a 1.5 kW single-phase asynchronous motor connected via a V-belt mechanism, the bench allowed for precise speed control through a digital inverter, enabling continuous adjustment from 0 to 2800 rpm. The actual rotational speed was verified using a non-contact laser tachometer. Other calibrated instruments, including a digital power meter and a high-speed camera system, were employed to ensure data accuracy.

A comparison of the residence time distribution curves from the experiment and the simulation at 730 rpm and a 20 mm flow valve opening is presented in Fig. 5. The curves demonstrate a high degree of consistency in their overall trends, with both methods yielding an average residence time of approximately 3 seconds. While minor discrepancies in the specific distribution are evident—potentially attributable to material anisotropy and model simplifications—they do not detract from the overarching agreement. Therefore, it is confirmed that the discrete element simulation possesses considerable accuracy and reliability in modeling the rice polishing process.

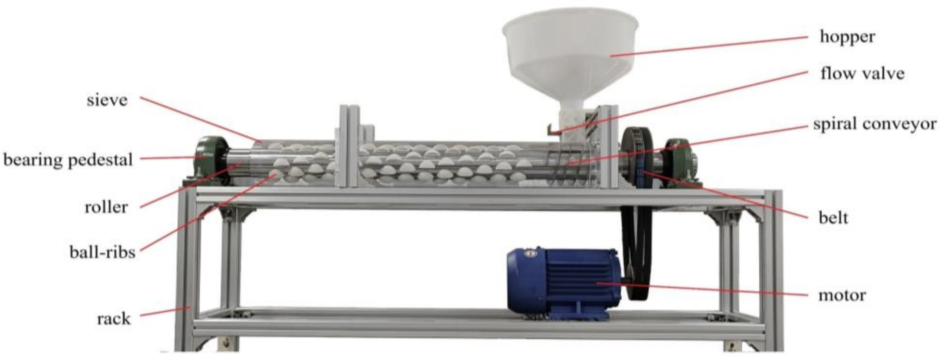


Fig. 4 - Verification test bench

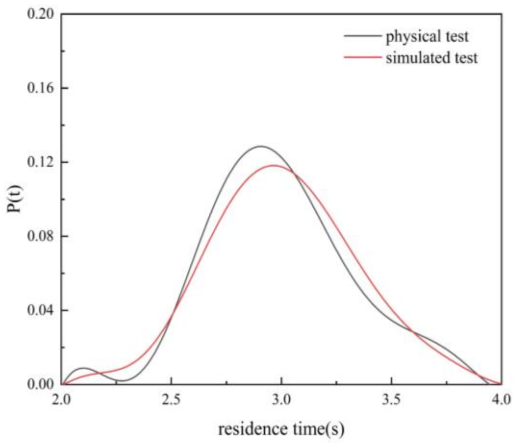


Fig. 5 - Distribution curves of residence time for the bench test and simulation test

Simulation conditions for polishing process

The mixing process in a germinated brown rice machine is critically influenced by the configuration of its straight plate, inclined plate, baffle, and blades, with the primary objective of this study being to analyze the impact of the clearance between the polishing roller and the rice screen on granular motion. As industrial polishing operations involve prolonged continuous operation, this research focuses on the machine's performance after it reaches a stable working state. All subsequent analyses are therefore based on the assumption that the system has achieved a macroscopically steady state.

In the simulation, rice grains were generated at the feed inlet by a particle factory with an initial velocity of 0.5 m s^{-1} to prevent obstruction of subsequently generated particles. The generation rate was set at 1400 particles per second, corresponding to a feed rate of approximately 1 ton per hour.

Fig. 6 illustrates the temporal evolution of the particle count within the polishing machine under different roller-sieve clearances. Employing identical feeding methods, all experimental curves exhibited similar growth trends initially. The number of particles increased until the curve reached an inflection point, indicating that some particles had completed polishing and were exiting the system. A stable state was identified when the mass flow rate of rice entering the machine equaled that leaving it.

As the circular sieve's inner diameter increased, the internal volume of the polishing chamber expanded, resulting in a corresponding significant rise in the steady-state particle count. Consequently, the time required to reach this stable state also increased. Notably, all configurations achieved stability within 5 seconds of the simulation start time.

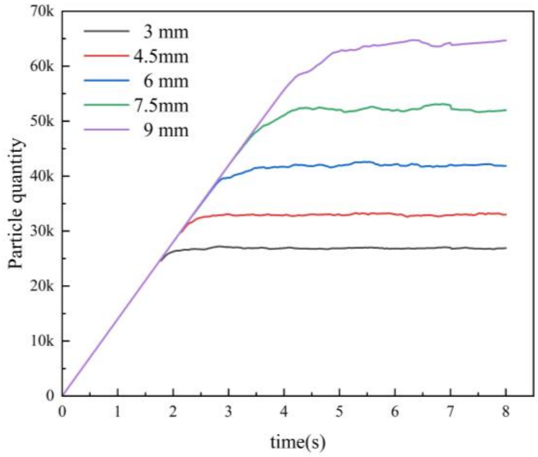


Fig. 6 - Changes in particle quantity during polishing process

The Influence of Gap on the Particle Velocity in the Polishing Chamber

To further analyze the flow structure characteristics of the rice grain group in the polishing chamber, based on Figure 2, this study presents the velocity distribution of rice grains at different positions with the clearance between the polishing roller and the rice sieve set to 3 mm, 4.5 mm, 6 mm, 7.5 mm, and 9 mm. The results are presented in Fig. 7, where each data point represents the average velocity in a corresponding area, and the error bars (denoting standard deviation) visually indicate the magnitude of velocity fluctuations. These fluctuations, independent of the mean velocity, serve as an indicator of inter-particle collision intensity. Notably, the average radial velocity of the grain population is statistically close to zero, where negative values signify motion from the sieve towards the polishing roller.

Analysis reveals that as the roller-sieve gap increases, the tangential, axial, and resultant velocities of the rice grains exhibit a significant declining trend. This is primarily attributed to the reduced friction from the polishing roller, which decreases the kinetic energy imparted to the grains. Concurrently, the velocity fluctuations in all three directions diminish, indicating weakened inter-particle interactions and lower collision intensity. However, it is noteworthy that the number of grains with negative axial velocity (indicating backflow) increases with larger gaps. This backflow can lead to local accumulation of grains, heightening polishing non-uniformity and complicating the control of the process. Furthermore, the tangential velocity component is markedly dominant over the radial and axial components, revealing that the primary motion of the grains is circulatory.

A comparative analysis of different quadrants shows significant variation in motion intensity. The third quadrant exhibits the greatest variability in tangential, axial, and resultant velocities. This can be explained by the role of gravity: in the first and second quadrants, gravity provides a centripetal component, drawing grains toward the roller; conversely, in the third and fourth quadrants, it acts centrifugally, pushing grains away. This dynamic results in a more scattered grain distribution near the junction of the second and third quadrants and a more concentrated distribution near the first and fourth quadrant junction (consistent with Fig. 10). This non-uniform radial motion promotes grain exchange between the inner and outer rings, enhancing polishing uniformity (*Li et al., 2022*). The higher velocity fluctuations in the third quadrant also suggest more frequent collisions, which may lead to localized stress concentration and accelerated wear of machine components, potentially compromising system stability. Finally, velocity distribution along the axial direction shows that as grains approach the discharge outlet, their tangential and resultant velocities gradually decrease, while the average axial velocity increases slightly. This phenomenon may be influenced by boundary effects, as noted by *Han et al. (2015)*, where grain speed typically decreases near the outlet.

Through simulation and physical experiments, it is verified that when the movement velocity of rice grains in the polishing chamber is ≤ 1.2 m/s and the impact angle with the polishing roller is ≤ 60°, the load exerted on the rice grains is lower than their critical breakage force of 15.6 N, and the actual broken rice rate can be controlled within 5%. By comparing the magnitudes of different velocity components, it can be seen that the tangential velocity of white rice is the largest, and its value sometimes exceeds the critical velocity threshold. The radial velocity and axial velocity are not the main causes of breakage of white rice. Therefore, tangential velocity is the dominant factor affecting the breakage of white rice. When the tangential velocity exceeds the critical value, white rice is mainly subjected to impact load and shear load from particles, the polishing roller, and the rice sieve, resulting in breakage under repeated collisions. With an increase in the clearance, the tangential velocity of white rice during polishing gradually decreases. When the clearance is 7.5 mm, the breakage risk of white rice is minimized, and the velocity distribution also tends to be stable.

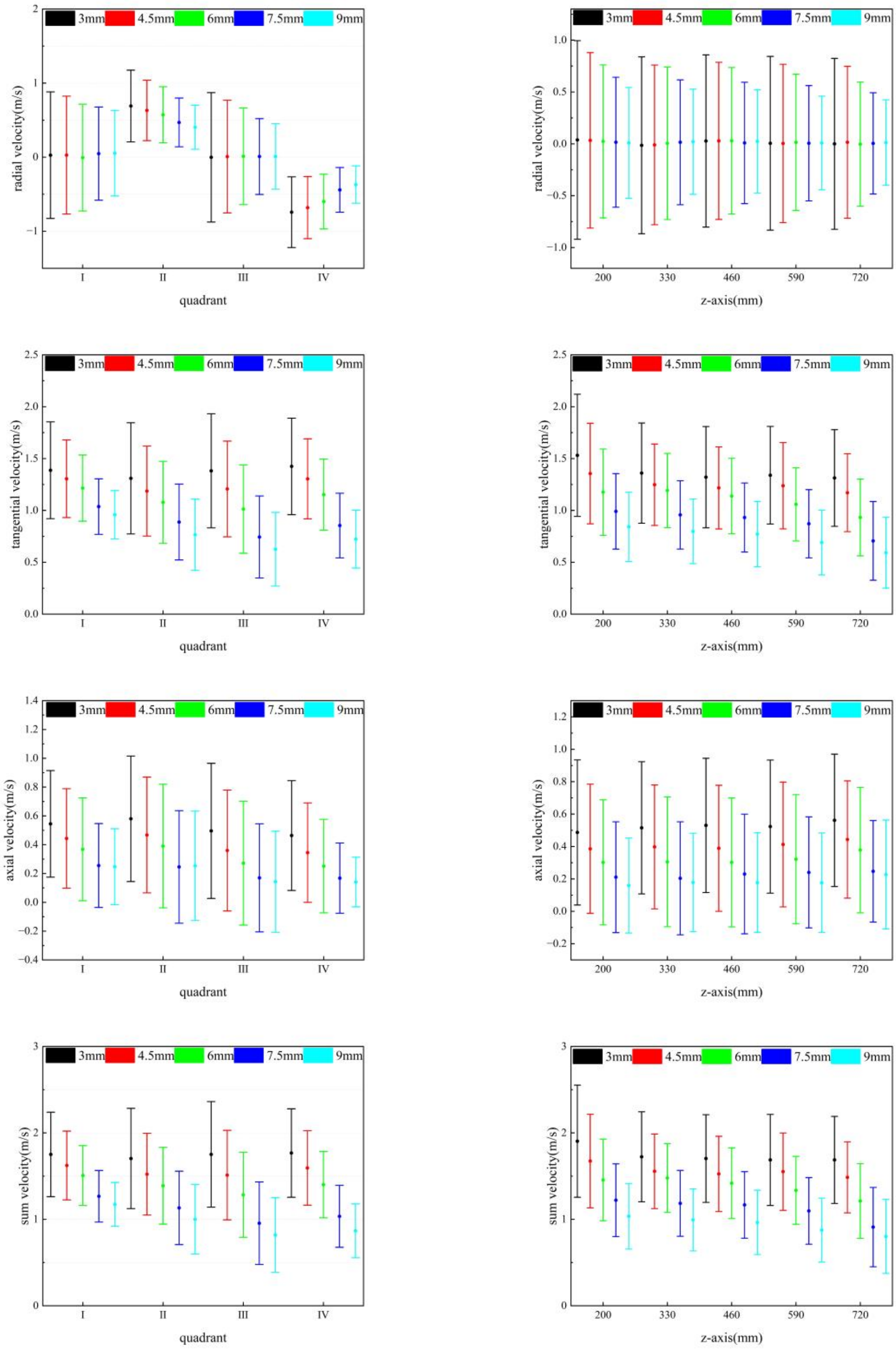


Fig. 7- Particle velocity distribution at different locations

The Influence of the Gap on the Residence Time of Particles

The processing intensity applied to rice grains during polishing is linearly related to their residence time within the chamber, with a longer duration yielding more comprehensive processing (*Ojediran et al., 2020*). The anisotropic nature of grain motion, however, introduces heterogeneity in residence times, consequently causing divergent polishing outcomes. This often manifests as simultaneous over-polishing (and potential damage) of some grains and under-polishing of others, which adversely affects the final product quality.

The Residence Time Distribution analysis has been widely adopted to quantify this temporal heterogeneity and evaluate polishing uniformity (*Zheng et al., 2021*). The RTD function is mathematically expressed as:

$$P(t) = \frac{N(t)}{\int_0^\infty N(t)dt} \cong \frac{N_i}{\sum_{i=0}^{\infty} N_i \Delta t_i} \tag{3}$$

where: $P(t)$ represents the probability distribution of the residence time at a certain time, [s]; $N(t)$ represents the number of grains of rice at time, [s]; N represents the total number of grains of rice over an infinite period of time from 0 to infinity; N_i represents the number of rice grains at the outlet within the time interval from t_i to $t_i + \Delta t_i$; Δt_i represents the sampling time interval, 0.05s.

$$t_m = \frac{\int_0^\infty tP(t)dt}{\int_0^\infty P(t)dt} \cong \sum_{i=0}^{\infty} t_i P_i \Delta t_i \tag{4}$$

$$\sigma^2 = \frac{\int_0^\infty (t-t_m)^2 P(t)dt}{\int_0^\infty P(t)dt} \cong \sum_{i=0}^{\infty} t_i^2 P_i \Delta t_i - t_m^2 \tag{5}$$

where: t_m represents the average value of the retention time of the tracer particles, [s]; σ^2 represents the variance of the grain's residence time, [s^2].

Fig. 8 presents the residence time distribution curves for the rice grains at roller-sieve gaps of 3, 4.5, 6, 7.5, and 9 mm. As the gap widens, the RTD curve exhibits a pronounced rightward shift, signifying a general increase in the mean residence time and a decrease in the conveying efficiency of the polishing roller. This results in more complex grain dynamics within the chamber. Concurrently, the distribution transitions from a single-peak to a multi-peak profile with reduced peak heights. This evolution indicates greater disparity in individual grain residence times and a heightened tendency for particle dispersion under larger gaps, ultimately reducing the uniformity of both grain transport and polishing.

To quantitatively assess the gap's influence, the mean residence time and its variance were calculated for different gaps, as detailed in Fig. 9. Consistent with the qualitative observations, both metrics show a significant upward trend with increasing gap. A larger gap thus prolongs the polishing duration. However, prior findings indicate that the average velocity and velocity fluctuations of the grains weaken as the gap increases, implying a corresponding reduction in collision intensity between grains and with machine structures. Consequently, the polishing duration alone cannot directly characterize the polishing effect. A more comprehensive understanding of the polishing process, therefore, necessitates further investigation into the collision dynamics of the rice grains and their resultant effects.

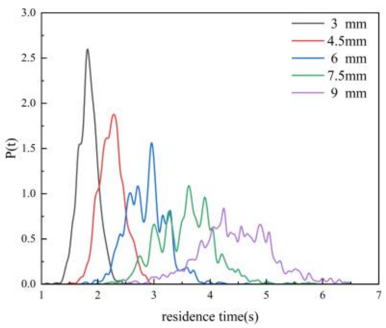


Fig. 8 - Residence time distribution function curve

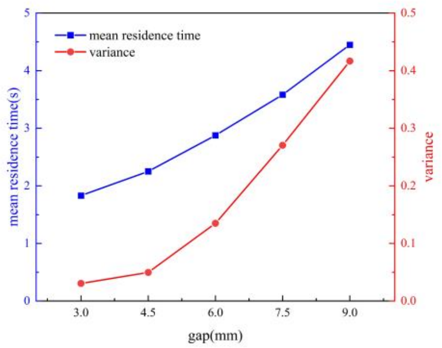


Fig. 9 - Mathematical expectation and variance of residence time

The influence of the gap on particle collisions

In Discrete Element Method simulations, the energy dissipation from individual particle interactions can be directly quantified, providing a powerful tool for elucidating energy conversion and transfer mechanisms within particulate systems. This study calculated the collision energy spectra for two critical event types: grain-to-grain and grain-to-screen collisions. To enhance clarity, the original spectral data were subjected to noise reduction processing to eliminate unnecessary interference.

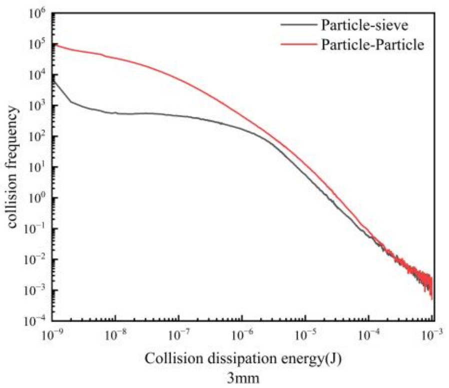
Fig. 10 tracks the collision dissipation energy spectrum of tracer particles—generated and labeled within a 0.1-second time window—throughout their entire trajectory from entry to exit from the polishing chamber. The collision spectrum was measured with an accuracy of 10^{-9} J to better resolve differences in energy dissipation.

Analyzing how these energy spectra vary with the operational parameters and geometric characteristics of the polisher allows for the optimization of collision types, thereby directing more energy toward interactions that are more beneficial to the polishing effect and enhancing overall efficiency.

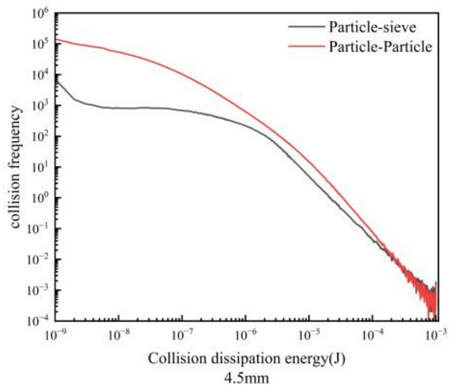
Comparative analysis of the collision energy spectra under different roller-sieve gaps reveals several consistent trends. Specifically, regardless of the gap setting, the frequency of grain-to-grain collisions far exceeds that of grain-to-screen collisions. Furthermore, low-energy collisions are significantly more frequent than high-energy collisions. This indicates that inter-grain collision behavior plays a dominant role during particle motion.

Existing studies classify grain collisions into three distinct types (*Zeng et al., 2022*): non-influential collisions (causing no change in grain strength), weakening collisions (resulting in a strength reduction), and destructive collisions (directly causing grain breakage). Although grain-to-grain collisions are more frequent, most are non-influential and do not significantly affect grain strength. A notable crossover occurs in the energy spectra within the range of 10^{-4} J to 10^{-3} J, where the frequency of high-energy grain-to-screen collisions surpasses that of grain-to-grain collisions. This suggests that high-energy impacts with the sieve surface play a more critical role in the grain fragmentation process. The main factor affecting polishing energy consumption is the friction between particles and between particles and the equipment. This means that the greater the total dissipated energy during the polishing process, the higher the polishing energy consumption. With an increase in the clearance, the energy consumption of the polishing machine also increases. This is because the particle collision frequency in the system shows a significant upward trend as the clearance increases.

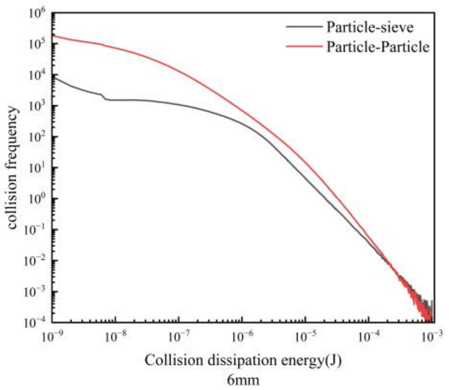
As the gap increases, the overall collision frequency of particles shows a significant upward trend, while the proportion of destructive collisions decreases markedly. However, prior research indicates that excessively large gaps can lead to an increased broken-grain rate (*Firouzi et al., 2010*). This implies that under larger gap conditions, repeated weak collisions become the key factor inducing grain fragmentation. Consequently, the dominant mechanism of grain breakage shifts from direct destructive impact to the cumulative damage from multiple, repeated collisions as the gap widens. As the clearance increases, the average residence time and its variance of rice grains during polishing increase. This leads to an increase in collisions between particles, which raises the polishing intensity but also significantly reduces the polishing uniformity. The increase in average residence time and number of collisions reduces the polishing uniformity, thereby lowering the polishing quality. These findings provide a critical reference and solid theoretical basis for the study of collision behavior in granular material processing.



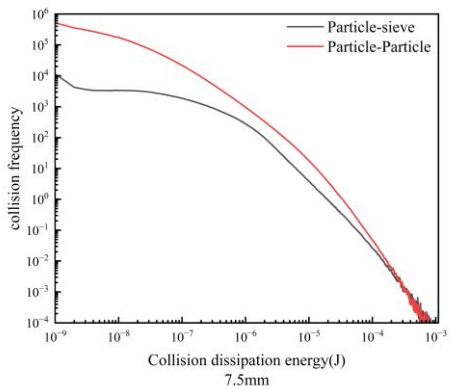
a) 3 mm



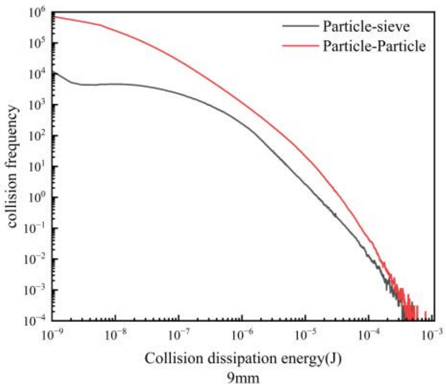
b) 4.5 mm



c) 6 mm



d) 7.5 mm



e) 9 mm

Fig. 10- Rice collision energy spectrum

CONCLUSIONS

In this study, a discrete element numerical model and a parameter model for industrial-scale rice grain polishing were established according to the overall structure and working principle of the polishing machine. The reliability of the discrete element simulation results was verified by conducting physical tests on a built rice polisher experimental platform. Taking the clearance between the polishing roller and the rice sieve as a variable, the variations in particle motion characteristics such as velocity distribution, average residence time and collision behavior of rice grains under different clearances were investigated. Analysis of the simulation results shows that polishing quality, broken rice rate during polishing and energy consumption are affected by particle motion characteristics, with the detailed results as follows:

(1) With the increase in the clearance, the time required for rice grains to reach a stable state during the polishing process is prolonged accordingly, and all attain a stable state successively after 5 seconds.

(2) The speed and speed fluctuations of the grains in different quadrants show significant differences. The grains in the third quadrant of the polishing chamber have a higher speed fluctuation, which directly affects the stability of the entire system. Moreover, the unevenness of radial movement promotes the alternation of grains between the inner and outer rings, thereby enhancing the uniformity of grain polishing. The tangential velocity of rice grains is the primary factor affecting the polishing broken rice rate, and breakage of rice grains will occur when its magnitude exceeds the critical value.

(3) As the gap increases, the distribution function curve of the residence time gradually transforms from a single peak to multiple peaks, and the average residence time and its variance also increase. The rice grains are more likely to disperse in the polishing chamber, thereby reducing the uniformity of rice grain transportation and polishing. An increase in the clearance reduces the polishing quality of rice grains.

(4) The frequency of collisions between particles is much higher than that between particles and the sieve. The frequency of low-level collisions is far greater than that of high-level collisions. As the gap increases, the collision frequency in the particle system significantly rises, while the average collision intensity decreases. This leads to the dominant factor causing the fragmentation of grains gradually shifting from direct destructive collisions to those resulting from multiple repeated accumulation. Polishing energy consumption is primarily governed by interparticle friction and the friction between rice grains and equipment components, and the greater the total collision dissipated energy of rice grains, the higher the polishing energy consumption.

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REFERENCES

[1] Cao B., Jia F., Zeng Y., Han Y., Meng X., Xiao Y. (2018). Effects of rotation speed and rice sieve geometry on turbulent motion of particles in a vertical rice mill. *Powder Technology*, 325: 429-440, https://dx.doi.org/10.1016/j.powtec.2017.11.048

[2] Chinese academy of agricultural mechanization sciences (2007). *Agricultural Machinery Design Manual* (1st ed.). Beijing: Agricultural Science and Technology Publishing House, (Chapter 9). https://max.book118.com/html/2011/0726/434366.shtm

[3] Das A., De T., Kaur G., Kumar J., (2021), An Effective Sphere-based Model for Breakage Simulation in DEM of Rice Polishing, *Powder Technology*, vol.392, pp.891-905, Kolkata/India, https://dx.doi.org/10.1016/j.powtec.2021.06.045.

[4] Fang P., Zhou Z., Wang H., Zhang L. (2024). Consumer preference and willingness to pay for rice attributes in China: results of a choice experiment. *Foods*, 13(17): 2774, https://dx.doi.org/10.3390/FOODS13172774

[5] Firouzi S., Alizadeh M. R., Minaei S. (2010). Effect of the size of perforated screen and blade-rotor clearance on the performance of Engleberg rice whitener. *African Journal of Agricultural Research*, 5(9): 941-946, https://dx.doi.org/10.5897/AJAR09.542

[6] Han Y., Jia F., Zeng Y., Wang A. (2015). Granular axial flow characteristics in a grinding area studied by discrete element method. *Acta Physica Sinica*, 64(23): 176-184, https://dx.doi.org/10.7498/aps.64.234502

[7] Höhner D., Wirtz S., Kruggel-Emden H., Scherer V. (2011). Comparison of the multi-sphere and polyhedral approach to simulate non-spherical particles within the discrete element method: Influence on temporal force evolution for multiple contacts. *Powder Technology*, 208(3): 643-656, https://dx.doi.org/10.1016/j.powtec.2011.01.003

[8] Li A., Jia F., Shen S., Han Y., Chen P., Wang Y., Zhang J., Feng W., Fei J., Hao X. (2023). Numerical simulation approach for predicting rice milling performance under different convex rib helix angle based on discrete element method. *Innovative Food Science & Emerging Technologies*, 83: 103257, https://dx.doi.org/10.1016/J.IFSET.2022.103257

[9] Li A., Jia F., Zhang J., Han Y., Meng X., Chen P., Wang Y., Zhao H. (2022). The effects of filling level on the milling accuracy of rice in the friction rice mill. *Powder Technology*, 398: 117052, https://dx.doi.org/10.1016/J.POWTEC.2021.117052

[10] Li X., Du Y., Liu L., Mao E., Yang F., Wu J., Wang L. (2022). Research on the constitutive model of low-damage corn threshing based on DEM. *Computers and Electronics in Agriculture*, 194: 106722, https://dx.doi.org/10.1016/J.COMPAG.2022.106722

[11] Liu Q., Tao Y., Cheng S., Zhou L., Tian J., Xing Z., Liu G., Wei H., Zhang H. (2020). Relating amylose and protein contents to eating quality in 105 varieties of Japonica rice. *Cereal Chemistry*, 97(6): 1303-1312, https://dx.doi.org/10.1002/cche.10358

[12] Markauskas D., Kačianauskas R. (2011). Investigation of rice grain flow by multi-sphere particle model with rolling resistance. *Granular Matter*, 13:143-148, https://dx.doi.org/10.1007/s10035-010-0196-5

[13] Nasirahmadi A., Emadi B., Abbaspour-Fard M., Aghagolzade H. (2014). Influence of moisture content, variety and parboiling on milling quality of rice grains. *Rice Science*, 21(2): 116-122, https://dx.doi.org/10.1016/S1672-6308(13)60169-9

[14] Ojediran J., Okonkwo C., Olayanju A., Hussain S.; Olaniran A.; Adewumi A. (2020). Effect of polishing duration on physical, milling, cooking, and sensory properties of a novel mix-colored Nigerian parboiled rice. *Cereal Chemistry*, 97(6): 1172-1182, https://dx.doi.org/10.1002/cche.10337

[15] Riaz M., Ismail T., Akhtar S. (2017). Harvesting, threshing, processing, and products of rice. In: Chauhan BS, Jabran K, Mahajan G eds., Rice production worldwide. Cham, *Switzerland: Springer International Publishing*, 419-453. https://link.springer.com/chapter/10.1007/978-3-319-47516-5_16

[16] Tajudeen O.A.A., Ojediran J.O., Okonkwo C., Syed Z., (2023), Development of a Paddy Rice De-husking cum Polishing Machine with Low Breakage Rate, *Agricultural Engineering International: CIGR Journal*, vol.25, no.59, pp.1-16, Abeokuta/Nigeria, https://dx.doi.org/10.1016/10.3970/cigr.2023.025.059.

[17] Tamura M., Kumagai C., Ogawa Y. (2022). Influence of structural changes of brown rice by precise polishing on in vitro starch digestibility of cooked rice grain. *Food Hydrocolloids for Health*, 2: 100077, https://dx.doi.org/10.1016/J.FHFH.2022.100077

[18] Wakeling L., McCarthy C., (2009), Discrete Element Modelling of Grain Polishing and Milling Processes (English), *Computers and Electronics in Agriculture*, vol.67, no.1, pp.45-56, Brisbane/Australia, https://dx.doi.org/10.1016/j.compag.2009.07.006.

[19] Xie B., Bai J., Yan J., Zhao S. (2023). Calibration of white rice simulation parameters based on discrete element method (基于离散元模拟的白米仿真参数标定). *INMATEH-Agricultural Engineering*, 71(3): 205-214, https://dx.doi.org/10.35633/inmateh-71-18

[20] Yang W., Liu Q. (2019). Grain security: projections for rice supply and demand in China. *Research of Agricultural Modernization*, 40(01):44-53. https://dx.doi.org/10.13872/j.1000-0275.2018.0106.

[21] Zeng Y., Mao B., Jia F., Han Y., Li G. (2022). Modelling of grain breakage of in a vertical rice mill based on DEM simulation combining particle replacement model. *Biosystems Engineering*, 215: 32-48, https://dx.doi.org/10.1016/j.biosystemseng.2021.12.022

[22] Zhang R., Jiao W., Zhou J., Qi B., Liu H., Xia Q. (2020). Parameter Calibration and Experiment of Rice Seeds Discrete Element Model with Different Filling Particle Radius. *Transactions of the Chinese Society for Agricultural Machinery*, 51(S1): 227-235. https://dx.doi.org/10.6041/j.issn.1000-1298.2020.S1.026

[23] Zhang Y., Han Q., Xun C., Zhang G. (2022). Discrete element method investigation of the milling characteristic in a rice mill. *Mechanical Sciences*, 13(1): 15-22, https://dx.doi.org/10.5194/MS-13-15-2022

[24] Zheng C., Zhang L., Govender N., Chuan Y. (2021). DEM analysis of residence time distribution during twin screw granulation. *Powder Technology*, 377: 924-938, https://dx.doi.org/10.1016/j.powtec.2020.09.049