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DEM SIMULATION AND EXPERIMENT OF CORN GRAIN GRINDING PROCESS

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KEYWORDS

hammer mill,
feed,
hammer structure,
circulation layer.

ABSTRACT

To improve the working performance of hammer mill, cutting-edge hammer and oblique hammer were designed in this study. The advantages of new hammers were theoretically analyzed. The grinding process of corn grain with different hammers was studied by discrete element method (DEM) and experiments. Discrete element simulation results showed that under same rotor speed conditions, the cutting-edge hammer had highest bond-breaking efficiency in corn grain model. The oblique hammer could reduce the incident angle of corn grain and improve sieving efficiency. The motion trajectory of corn grain in grinding chamber was relatively dispersed and similar when using common hammer and cutting-edge hammer, and the motion trajectory was more concentrated when oblique hammer was used. The experimental results showed that both cutting-edge hammer and oblique hammer could improve the working performance of hammer mill. The productivity of hammer mill could be improved by using cutting-edge hammer, electricity consumption per ton and temperature rise of feed could be reduced by using oblique hammer, and the experimental results were consistent with simulation results and theoretical analysis results. The research results can provide references for the design of new hammer and the grinding process simulation of other agricultural materials.

INTRODUCTION

The grinding of cereal feed can increase its surface area, which is beneficial for improving the digestibility and palatability of feed (Dey et al., 2013; Ghodki & Goswami, 2018). Hammer mills have the widest application due to their advantages of simple structure, good versatility and convenient maintenance (Wang et al., 2020; Bochat et al., 2015; Nakamura et al., 2015). However, hammer mills exhibit low productivity and high energy consumption in production (Polari & Wang, 2019; Tian et al., 2018; Cao et al., 2016). Therefore, improving productivity and reducing the energy consumption of hammer mills have important practical significance for the development of the feed industry.

To improve the working performance of hammer mill, it is necessary to study their grinding mechanism. Because the grinding process of cereal feed is very complex, it is difficult to measure the relevant parameters directly by sensors (Tian et al., 2019; Mugabi et al., 2017). In recent years, with the rapid development of computer simulation technology, the discrete element method (DEM) has been widely used in the study of agricultural materials grinding processes (Weerasekara et al., 2013; Bian et al., 2015; Jiménez-Herrera et al., 2017; Sun et al., 2018).

Ghodki & Goswami (2018) studied the crushing process of black pepper seeds by using discrete element method. Based on the research results, a few suggestions were provided to improve the design aspects of the mill. To improve the accuracy of discrete element simulation, Zhang et al. (2020) imported multiple particle replacement and bonding programs through the application programming interface (API) of a discrete element method model. A discrete element model of corn straw was established, and the grinding process was simulated. Zhang et al. (2019) used the discrete element method to simulate the grinding process of corn straw. The shape classification of broken corn straw was studied and verified by experiments. The results showed that the discrete element method was feasible for simulating the grinding process of corn straw. Xu et al. (2020) used EDEM software to simulate the grinding process of cucumber straw.

Additionally, researchers (Xing et al., 2017; Yang et al., 2019) simulated the grinding process of soybean by using discrete element method. These research results could

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provide reference for the structural optimization design of hammer mill.

Corn grain as the most common cereal feed, but its grinding process was rarely studied. In this study, cutting-edge hammer and oblique hammer were designed. The advantages of new hammers were theoretically analyzed. Discrete element method was used to simulate the grinding process of corn grain, and the grinding performance experiment of new hammers was carried out. The results can provide references for the design of new hammer and the grinding process simulation of other agricultural materials.

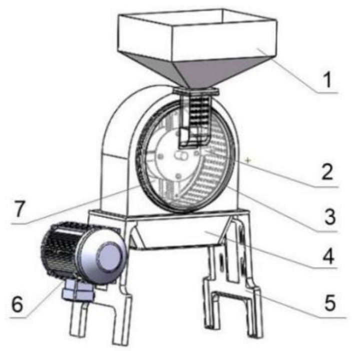
MATERIAL AND METHODS

Experimental material and equipment

Corn grain was used as experimental material in this study and produced in Hohhot, Inner Mongolia. The variety was XIANYU-355 with moisture content of 11.5%. The instruments used in the experiments as follows: TCS-150 electronic scale (accuracy of 0.01 kg), BT223S electronic balance (accuracy of 0.001 g), electric energy meter, frequency converter, stopwatch and drying box, etc. Each group of experiments was repeated three times, and the average value of the experiment results was taken.

Machine structure and working principle

The hammer mill used in this study is mainly composed of a feeding hopper, a sieve, a hammer, an outlet, a frame, and a motor. The overall structure of the hammer mill is shown in Figure 1. The main technical parameters are shown in Table 1.



a. Structure

b. Sample machine

FIGURE. 1 Overall structure of the hammer mill.

1-feeding hopper; 2-hammer; 3-sieve frame and sieve; 4-outlet; 5-frame; 6-motor; 7-grinding chamber

In the working process of hammer mill, corn grain enters grinding chamber through feeding hopper. Corn grain is broken by the high-speed rotating hammer, and then it collides with sieve at a higher speed and is further broken down. Broken particles are repeatedly hit by hammer and sieve until the particle size is sufficiently reduced and flows out through sieve hole to outlet. Hammer is the key part and has an important influence on the working performance of hammer mill. Therefore, to improve the performance of hammer mill, the influence of hammer structure on grinding process of corn grain needs to be studied.

TABLE 1. Main parameters of the hammer mill.

Items	Value
Motor power	3 kW
Size (length×width×height)	850 mm×800 mm×1300 mm
Number of hammers	16
Rotor diameter	370 mm
Grinding chamber width	180 mm
Size of the sieve holes	3 mm

Design of new hammer

To improve the working performance of hammer mill, cutting-edge hammer and oblique hammer were designed, and sample hammers as shown in Figure 2. There were sharp blades on both sides of the cutting-edge hammer, which can enhance the shear force on corn grain (Sun, 2013; Tang et al., 2007). The angle of the end of oblique hammer was 135°, and it has sharp blades. It can enhance the shear force while changing motion trajectory of corn grain.

Force analysis of corn grain

After corn grain entered the grinding chamber, it was hit by hammer. The force analysis diagram is shown in Figure 3. According to impulse theorem and momentum theorem (Wang et al., 2020), the following formulas can be obtained:

$$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v_3 \tag{1}$$

$$v_1 = \frac{\pi n R}{30} \tag{2}$$

$$I = m_2 v_3 = F \Delta t \tag{3}$$

$$v_3 = \frac{\pi n m_1 R}{30(m_1 + m_2)} \tag{4}$$

$$P = \frac{F}{S} \tag{5}$$

Because v_2 is very small relative to the linear velocity of hammer, in this study, v_2=0. We can obtain formula (6):

$$P = \frac{\pi n m_1 m_2 R}{30(m_1 + m_2)\Delta t S} \tag{6}$$

Where:

m_1 is the mass of hammer, kg;

m_2 is the mass of corn grain, kg;

v_1 is linear velocity of hammer, m s^{-1};

v_2 is the velocity of corn grain before being hit, m s^{-1};

v_3 is the velocity of corn grain and hammer at the end of collision, m s^{-1};

n is the rotor speed, r min^{-1};

R is the rotor radius, m;

I is the impulse of hammer and corn grain, N·s;

F is the hitting force of hammer on corn grain, N,

Δt is the hitting time of hammer on corn grain, s;

P is pressure on corn grain, Pa,

S is force area on corn grain, m^2.

a. Common hammer b. Cutting-edge hammer c. Oblique hammer

FIGURE 2. View of the sample hammers.

From formula (6), it could be concluded that under same conditions, the pressure on corn grain was related to force area. The smaller the force area is, the greater the pressure on corn grain. The cutting-edge hammer can reduce the force area of the hammer on corn grain and increase the pressure to improve grinding efficiency.

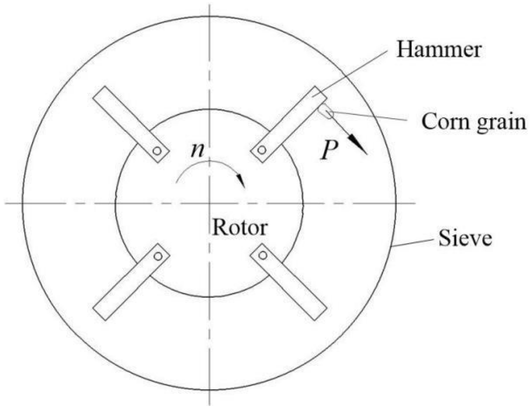


FIGURE 3. Schematic diagram of force analysis.

Analysis on incident angle of corn grain

After corn grain was broken by hammer, due to the influence of circulation layer, the broken particles moved in a circle along sieve. It reduced sieving efficiency of broken particles and intensified abrasion of sieve (Tian et al., 2018). The incident angle is the angle between the motion direction of corn grain after being hit and the normal line of sieve, and a schematic diagram of the incident angle is shown in Figure 4. Formula (7) can be obtained according to momentum theorem.

$$m_3 v_4 \cos\alpha = F_1 \Delta t_1 \tag{7}$$

The impact force between the broken particles and sieve is shown in formula (8).

$$F_1 = \frac{m_3 v_4 \cos\alpha}{\Delta t_1} \tag{8}$$

Where:

F_1 is the impact force between broken particles and sieve, N;

m_3 is the mass of broken particles, kg;

v_4 is the velocity of broken particles before hitting sieve, m s^{-1};

α is the incident angle, °,

Δt_1 is the impact time of broken particles on sieve, s.

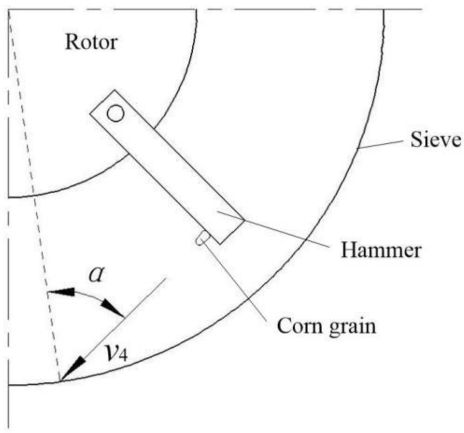


FIGURE 4. Schematic diagram of incident angle.

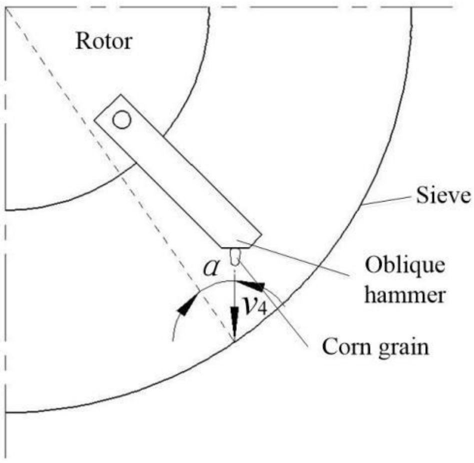
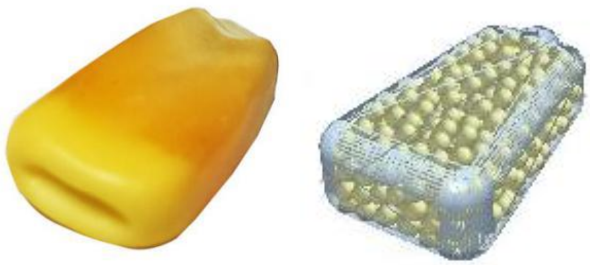


FIGURE 5. Analysis on incident angle of the oblique hammer.

Formula (8) shows that the smaller the incident angle is, the greater the impact force between broken particles and sieve, which is beneficial for improving grinding efficiency and sieving efficiency. Meanwhile, high sieving efficiency is also conducive to reducing energy consumption and temperature rise of feed. In Figure 5, we saw that the incident angle can be reduced because of the special structure the end of oblique hammer.

Corn grain model establishment

The three-dimensional model of corn grain was established by SolidWorks 2017 software, and the model was imported into EDEM 2018 software for particle replacement. The particle factory generated particles with a radius of 0.5 mm to fill the model, with a total of 379 particles. The corn grain and its discrete element model are shown in Figure 6.



a. Corn grain b. Discrete element model

FIGURE 6. Corn grain and its discrete element model.

Simulation parameter setting

To conveniently analyze the simulation results, this study only simulated the grinding process of one corn grain. The rotor speed of hammer mill was set to 3200 r min^{-1}, 3600 r min^{-1}, 4000 r min^{-1} and 4400 r min^{-1}. The time step was set to 5.04×10^{-8}s, and the simulation time was set to 1 s. The physical parameters and contact parameters of corn grain and hammer are shown in Table 2 (Wang et al., 2018; Shi et al., 2020; Wang, 2017).

TABLE 2. Simulation parameters of EDEM.

Items	Parameters	Value
Corn grain	Poisson's ratio	0.40
	Shear modulus (Gpa)	0.14
	Density (kg m^{-3})	1255
Hammer	Poisson's ratio	0.30
	Shear modulus (Gpa)	79.20
	Density (kg m^{-3})	7850
Corn grain-Corn grain	Coefficient of restitution	0.79
	Coefficient of static friction	0.18
	Coefficient of rolling friction	0.05
Corn grain-Hammer	Coefficient of restitution	0.61
	Coefficient of static friction	0.58
	Coefficient of rolling friction	0.06

Performance evaluation of hammer mill

According to the Chinese national standard GB/T 6971-2007, the productivity, electricity consumption per ton and temperature rise were taken as performance evaluation indexes of hammer mill. The calculation formulas are given by formulas (9) - (11).

$$E_c = \frac{Q_c}{T_c} \tag{9}$$

$$G = \frac{G_n}{Q_c/1000} \tag{10}$$

$$T = t_2 - t_1 \tag{11}$$

Where:

E_c is the productivity, kg h^{-1};

Q_c is the mass of the fragmented experimental material, kg;

T_c is the duration of grinding of a single experimental material, h;

G is the electricity consumption per ton, kW·h t^{-1};

G_n is the electricity consumption during grinding of a single experimental material, kW·h;

T is the temperature rise of feed, °C;

t_1 is the temperature of feed before grinding, °C,

t_2 is the temperature of feed after grinding, °C.

RESULTS AND DISCUSSION

Analysis on broken bond

The particles in discrete element model of corn grain were connected by bonds, the total number of bonds was 10806 in the discrete element model of corn grain, and the cyan part in Figure 7 was bonds. When hitting force exceeded the limit normal stress or the limit tangential stress of corn grain model, the bonds broke, and corn grain model was broken into small particles. The number of broken bonds can reflect the grinding ability of hammer. The greater the number of broken bonds is, the higher the grinding efficiency of hammer. The influence of different hammers on the number of broken bonds is shown in Figure 8.

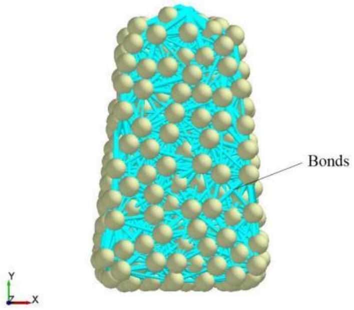


FIGURE 7. Bonds in discrete element model of corn grain.

From Figure 8 we could concluded that with the increase of rotor speed, the number of broken bonds showed an increasing trend, but the growth rate gradually slowed. When the rotor speed was in range of 3200-3600 r min^{-1}, increasing rotor speed had a great influence on the number of broken bonds. When rotor speed was greater than 3600 r min^{-1}, the increase in rotor speed had little influence on the number of broken bonds. Among the three hammers, the cutting-edge hammer had highest efficiency of breaking the bonds, which verified that cutting-edge hammer in theoretical analysis can increase the shear force on corn grain and improve grinding efficiency. The number of broken bonds in the use of oblique hammer was more than that using common hammer. Because oblique hammer can reduce the incident angle of corn grain, increase the impact force of broken particles and sieve, thereby improving grinding efficiency.

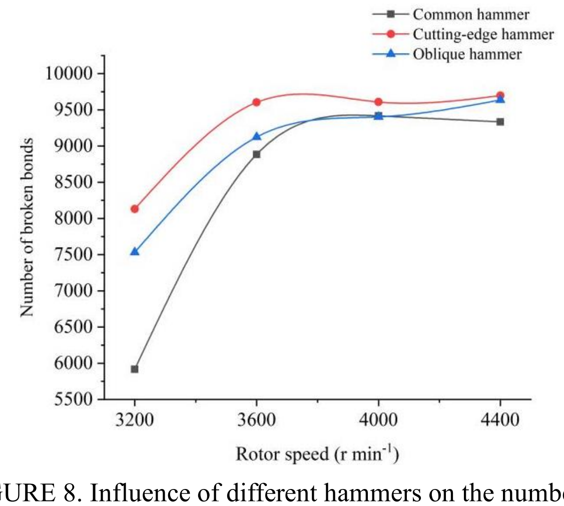


FIGURE 8. Influence of different hammers on the number of broken bonds.

Analysis on incident angle

According to the theoretical analysis results of incident angle of corn grain, when the incident angle is large, there will be a strong friction movement between broken particles and sieve. This not only consumes energy but also increases temperature rise of feed. In contrast, the smaller the incident angle is, the greater the impact force between broken particles and sieve, which is beneficial to improve sieving efficiency and grinding efficiency.

The corn grain model was broken into several broken particles after being hit by hammer. In this study, EDEM software post-processing module was used to count the incident angle of broken particles. The incident angles of different hammers used in hammer mill is shown in Figure 9. When the hammer mill used common hammer and cutting-edge hammer, the average incident angles were 60.74° and 59.59°, respectively, and the incident angle was large. Because the end of common hammer and cutting-edge hammer were right angles, and broken particles moved along the circumferential tangent direction after being hit by hammer. The average incident angle was 48.71° when grinding corn grain with oblique hammer, which was significantly smaller than that of other two hammers. Therefore, under same conditions, the oblique hammer has advantages in sieving efficiency and grinding efficiency.

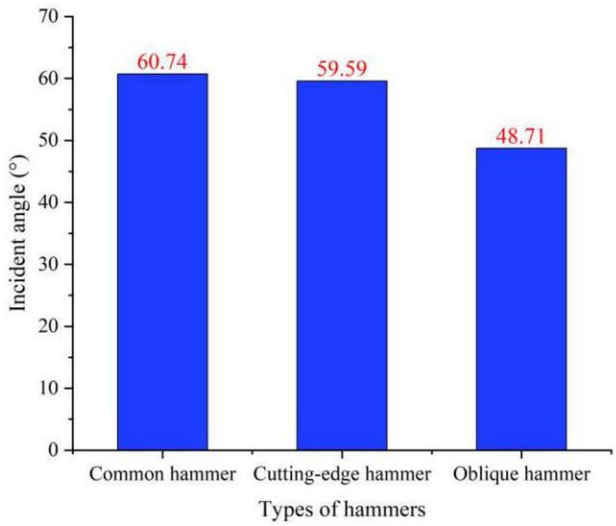
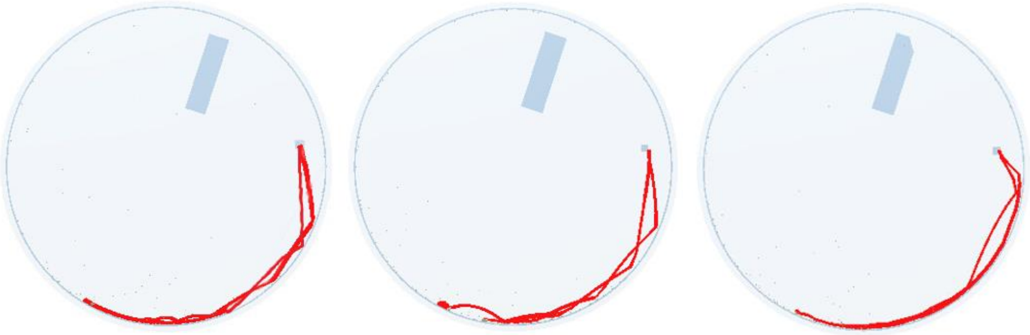


FIGURE 9. Average incident angle of different hammer.



a. Common hammer b. Cutting-edge hammer c. Oblique hammer

FIGURE 10. Motion trajectory of corn grain with different hammers.

Analysis on motion trajectory

The results of discrete element simulation showed that after being hit by hammer, the corn grain model was broken into several small particles, and then the broken particles collided with sieve at different angles. The motion trajectory of corn grain has an important influence on grinding efficiency and sieving efficiency. The motion trajectory of corn grain with different hammers used in the hammer mill is shown in Figure 10.

We saw that the motion trajectory of corn grain in grinding chamber was relatively dispersed and similar when using common hammer and cutting-edge hammer. The incident angle of corn grain was larger, resulting in low sieving efficiency. The motion trajectory of corn grain using oblique hammer was more concentrated. The oblique hammer changed the angle of corn grain collided sieve, improved sieving efficiency, reduced the circulation movement of broken particles in grinding chamber and helped to reduce energy consumption and temperature rise of feed.

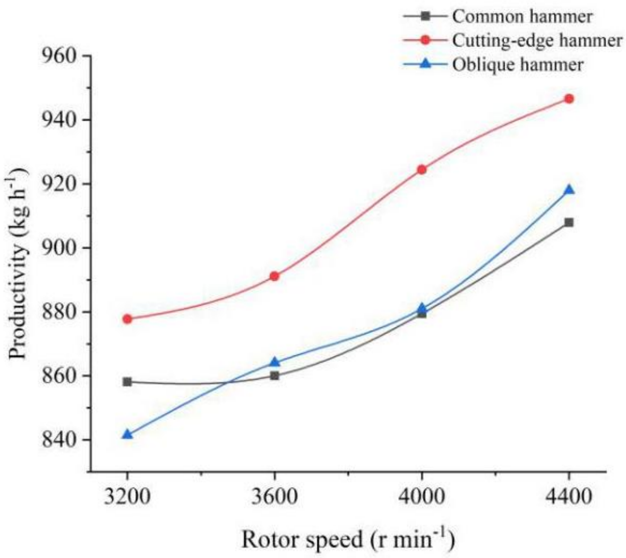


FIGURE 11. Influence of rotor speed on productivity.

Hammer performance experimental results

Analysis on productivity

The productivity increased gradually with increasing in rotor speed, as shown in Figure 11. Because with the increase of rotor speed, the hitting force of hammer on corn grain increased. The productivity of hammer mill using cutting-edge hammer was significantly higher than that of other two hammers. When rotor speed was 4000 r min^{-1}, the productivity of hammer mill with cutting-edge hammer was 4.99% higher than that with common hammer. It was consistent with the results of discrete element simulation and theoretical analysis. When rotor speed was greater than 3600 r min^{-1}, the productivity of hammer mill using oblique hammer was higher than that of common hammer. The reason is that oblique hammer can improve sieving efficiency and grinding efficiency.

Analysis on electricity consumption per ton

Figure 12 shows that the electricity consumption per ton increased with the increase of rotor speed. Because the load power of motor will increase with the increase of rotor speed. The electricity consumption per ton of hammer mill was lowest when using oblique hammer. When rotor speed was 3600 r min^{-1}, the electricity consumption per ton of hammer mill with oblique hammer was 14.07% lower than that of common hammer. This occurs because the oblique hammer can reduce the incident angle of corn grain, improve the sieving efficiency, and thus reducing the electricity consumption per ton of hammer mill.

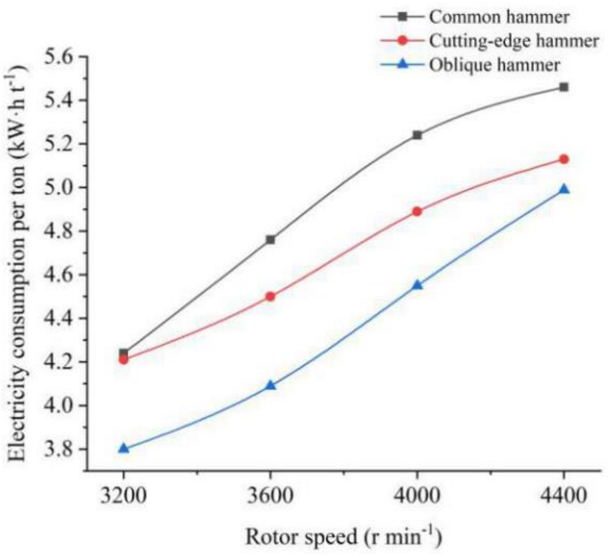


FIGURE 12. Influence of rotor speed on electricity consumption per ton.

Analysis on temperature rise

The temperature rise of feed is an important index to evaluate the performance of hammer mill, which has an important influence on the subsequent processing and storage of feed. In general, we hope that the temperature rise of feed is small. As shown in Figure 13, the temperature rise increased with increasing of rotor speed when the hammer mill used cutting-edge hammer and common hammer. The reason is that with the increase of rotor speed, the friction between broken particles and sieve increased, resulting in the increase of temperature rise. On the contrary, the temperature rise decreased with the increase of rotor speed when using oblique hammer. Because the oblique hammer can improve sieving efficiency, reduce the friction between broken particles and sieve, and reduce temperature rise of feed.

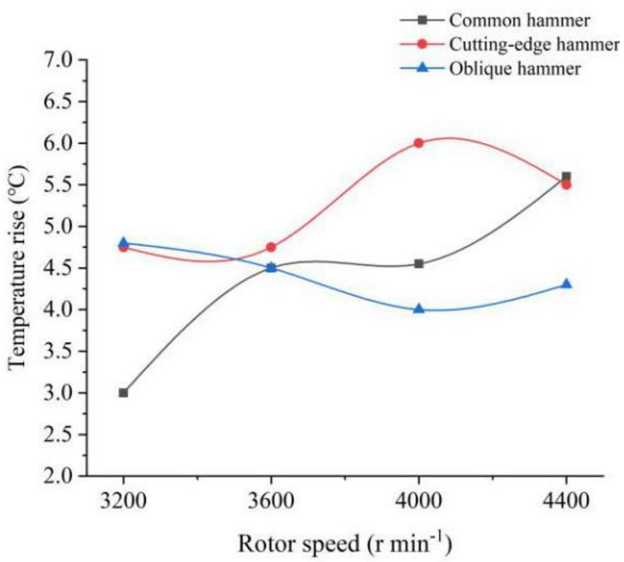


FIGURE 13. Influence of rotor speed on temperature rise.

CONCLUSIONS

In this study, cutting-edge hammer and oblique hammer were designed. The grinding process of corn grain with different hammers was studied by theoretical analysis, discrete element simulation and experiment. The following conclusions were obtained:

According to the results of theoretical analysis, cutting-edge hammer could increase the shear force on corn grain and improve grinding efficiency. Oblique hammer could reduce the incident angle of corn grain and improve sieving efficiency.

Simulation results showed that under same rotor speed conditions, cutting-edge hammer had the highest bond-breaking efficiency in corn grain model. The oblique hammer could reduce the incident angle of corn grain, and the average incident angle was 48.7° when using oblique hammer. The motion trajectory of corn grain in grinding chamber was relatively dispersed and similar when using cutting-edge hammer and common hammer, and the motion trajectory of corn grain was more concentrated when oblique hammer was used.

The experimental results showed that both cutting-edge hammer and oblique hammer could improve the working performance of hammer mill. When the hammer mill used oblique hammer and rotor speed was 4400 r min^{-1}, the comprehensive performance was the best. The productivity, electricity consumption per ton and temperature rise were 918.03 kg h^{-1}, 4.99 kW·h t^{-1} and 4.5 °C respectively, and the three performance indexes were better than the common hammer mill. The experimental results were consistent with simulation results and theoretical analysis results.

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