Effects of typical corn kernel shapes on the forming of repose angle by DEM simulation

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Abstract: Corn kernel shape is an important feature to improve the accuracy of simulation results, also the repose angle is often used to calibrate model parameters in simulation. In this study, the effects of the corn kernel shapes on the behavior during corn kernels accumulation were investigated in detail. Firstly, the DEM models of three typical shapes of corn kernels were developed. Secondly, the influences of the corn kernel shapes on the process of forming repose angle were investigated, such as corn kernels distance change, energy conversion, and the contact number between corn kernels. Results show that the corn kernel shape has a significant effect on the repose angle formation. The irregular shape of corn kernels limit their rolling when adding the corn kernel length in one or two directions. In addition, the irregular shapes of corn kernels increase the contact number and extend simulation time. Regular shape corn kernels need to be mixed with irregular shape corn kernels to improve their flowability. Finally, observation of the trajectory of corn kernel repose angles indicates that spherical corn kernels contact the bottom plate early, and forming small cone first, then the cone becomes bigger to change the direction of other corn kernels from top to bottom.

Keywords: corn kernel shape, energy conversion, repose angle, DEM

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1 Introduction

Particle shape plays an important role in the flow behavior and is every bit as significant as the mechanics of contact[1,2]. Many scholars have conducted related studies. Particle shape is more likely to impact the formation of repose angle with the tangential force than the normal contact force[3]. Increasing sphericity and convexity can significantly decrease the angle of repose. The non-spherical ballast model gives a more realistic angle of repose behaviors compared to simple particle models[4]. Under uniaxial compression, an increase in particle aspect ratio significantly impacted the mechanical response of the specimen. From unity to 1.6 particle aspect ratio, the lateral-to-vertical pressure ratio was predicted to decrease, but after that, it became relatively stable[5]. Numerical investigations on the influence of particle shape and shape approximation as well as hopper design on hopper discharge are conducted, and results show that particles with an increasing angularity reduce the mass flow rate from the hopper[6]. It is essential to build a more precise particle model of corn kernel assemblies. When horse-tooth, spherical cone, and spheroid particles are filled with multiple spheres, respectively, the simulated results are comparable to those obtained experimentally in terms of piling and ‘self-flow screening’[7] and 18 sub-spheres model have higher accuracy of simulation results. The discharge of spheres and polyhedral dices from a hopper is investigated experimentally and numerically using discrete element method (DEM), and angular particles add to the flow resistance and contribute to the creation of pile-ups. Shape approximation has a significant impact on simulation results in DEM[8]. The effects of the number of spheres, shape and angle factors on the simulation accuracy were investigated, and there was a linear relationship between the angle factor and the simulation accuracy[9].

In recent years, discrete element method (DEM) is used to investigate the law of particles movement in measurements, which has been a new trend in recent years[10,11]. Before studying irregular particles flow with DEM, the simulation parameters and model need to be determined firstly, where the contact parameters are very important. The repose angle is often used to calibrate material parameters in agricultural engineering, such as seeds and soil[12,13]. A detailed prediction method to determine the coefficient of rolling friction based on physical and simulation experiments was presented, which significantly improved the accuracy of simulation results[14]. Corn shape also has an important effect on simulation results, while most corn kernels are irregular.

Based on the discrete element model of corn and determination of the coefficient of rolling friction in the previous paper. In this study, the effects of the corn kernel shapes on the behavior during accumulation were observed, three typical shape corn kernels models were established, the corn kernel shapes on the corn kernels distance, energy conversion, the contact number during repose angle forming were investigated.

2 Materials and method

2.1 Materials

In this study, corn kernels (Longdan No.5, China) were selected. Water content was measured by drying method (drying oven, DHG-9013A, Shanghai Yiheng Instruments Ltd., China) was 13.2%. Due to its low water content, inter-particle adhesion can be ignored. It was determined that Hertz-Mindlin (no slip) in the EDEM software was ideal. A total of 1000 corn kernels are randomly selected from the same variety and classified into horse-tooth shape, spherical cone shape, spherical shape, oblate

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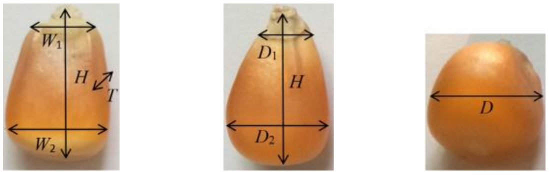
shape, and irregular shape. The statistical results showed that their percentages are 39.7%, 42.7%, 8.7%, 6.0% and 2.9%, respectively. The sum of the horse-tooth shape, spherical cone shape, spherical shape corn kernels accounted for almost 91.1% of the total. The horse-tooth shape corn kernel changes in three directions, and the spherical cone changes from two directions, and the spherical shape from one direction. Compared with the number ratio of spherical and oblate shape, they are close, but the spherical shape is more representative. Finally, horse-tooth, spherical cone, and spherical shape corn kernels are chosen to study. Corn size and its distribution is an important because of effecting modeling basis and influence on corn kernels flow. A more accurate corn model was established, and better verification of simulation results was achieved[10]. However, the simulation time increased accordingly. In this paper, a method was used to establish a more simplified corn model, conveniently estimating corn kernel size distribution. The horse-tooth shape mainly defines the upper base (W_1), lower base (W_2), height (W_2), and thickness (T), as shown in Figure 1a. A spherical cone shape corn kernel is represented by the upper diameter (D_1), lower diameter (D_2), and height (H), as shown in Figure 1b. Spherical shape corn kernels are considered by their diameter (D), as shown in Figure 1c. A digital caliper is used to measure the size with an accuracy of 0.01 mm. By Equations (1)-(3), the corn volume can be calculated to predict the volume distribution. Where, the horse-tooth shape corn consists of the upper half of the capsule body, the middle part of the trapezoid and the lower half of the capsule volume, and the spherical cone corn consists of the upper half of the sphere, the middle part of the dome and the lower half of the sphere volume.

$$V_1=\frac{T}{2}(H-T)(W_1+W_2)+\frac{\pi}{8}T^2(W_1+W_2-2T)+\frac{\pi}{12}T^2 \tag{1}$$

$$V_2=\frac{2\pi}{3}\left(\left(\frac{D_1}{2}\right)^3+\left(\frac{D_2}{2}\right)^3\right)+\frac{\pi}{3}\left(H-\frac{D_1}{2}-\frac{D_2}{2}\right)\left(\left(\frac{D_1}{2}\right)^2+\left(\frac{D_2}{2}\right)^2+\frac{D_1D_2}{4}\right) \tag{2}$$

$$V_2=\frac{\pi D^3}{6} \tag{3}$$

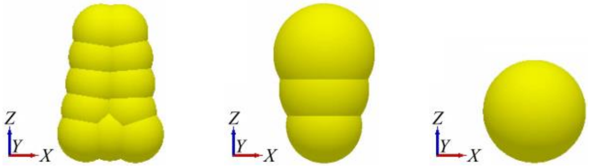
where, V_1 is volume of horse-tooth shape corn kernel, mm^3; W_1 is upper base; W_2 is lower base (height), mm; T is thickness, mm; V_2 is volume of spherical cone shape corn kernel, mm^3; D_1 is upper diameter, mm; D_2 is lower diameter, mm; H is height, mm; V_3 is volume of spherical shape corn kernel, mm^3; D is diameter, mm.



a. Horse-tooth shape b. Spherical cone shape c. Spherical shape

Figure 1 Characteristic sizes of corn kernels

From the calculation results, it can be found that the volume of three shape types of corn kernels follows a normal distribution. The average volume V_1 is 311.11 mm^3 and standard deviation is $0.11V_1$. V_1 is calculated from Equation (1), where H is 12.56 mm, and W_1 is 6.02 mm, and W_2 is 8.44 mm, and T is 4.51 mm for horse-tooth shape corn kernel. For spherical cone shape, the average volume V_2 is 269.75 mm^3 and standard deviation is $0.15V_2$, V_2 is calculated from Equation (2), where D_1 is 5.22 mm, and D_2 is 6.98 mm, and H is 10.96 mm. For spherical shape, the average volume V_3 is 181.37 mm^3 and standard deviation is $0.19V_3$, V_3 is calculated from Equation (3), where D is 7.02 mm. Three types of corn kernels models (horse-tooth, spherical cone, and spherical shape) are constructed using the multi-spheres method with 11 sub-spheres, 3 sub-spheres, and 1 sphere[15], as shown in Figure 2.



a. Horse-tooth shape b. Spherical cone shape c. Spherical shape

Figure 2 Discrete element models of corn kernels

2.2 Model properties

Model parameters for Hertz-Mindlin include the density, Poisson's ratio, the shear modulus, the coefficient of restitution, the coefficient of static friction and the coefficient of rolling friction. By using the drainage method, corn kernels are 1 180 kg/m^3. As reported in literature[16,17], Poisson's ratio is 0.4, the shear modulus is 1.37×10^8 Pa, the coefficient of restitution is 0.37[18,19], and the coefficient of static friction is 0.2[20]. Due to the irregular shape of corn kernels, the coefficient of rolling friction is hard to measure and is needed to calibrate. The rest of the parameters are specified in Table 1. The previous paper has determined the coefficient of rolling friction[17]. The relationship between the coefficient of rolling friction and the repose angle is shown in Figure 3.

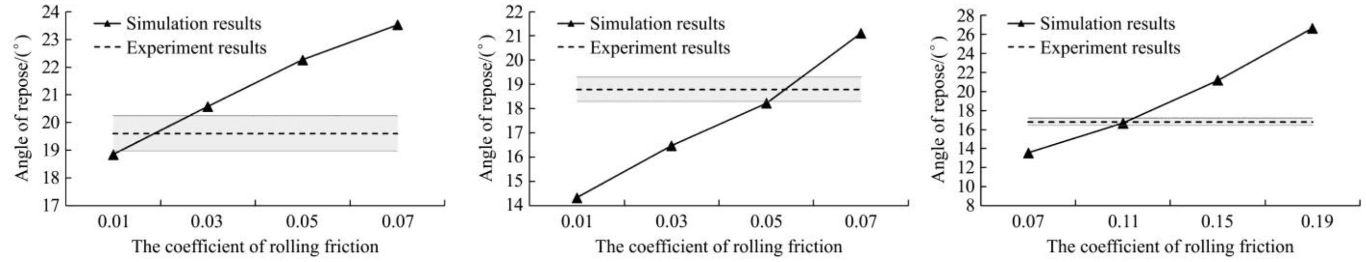
From Figure 3 it can be estimated that the coefficient of rolling friction of horse-tooth shape, spherical cone shape, spherical shape corn kernels is 0.023, 0.062, 0.13, respectively, also that between horse-tooth shape and spherical shape, between spherical cone shape and spherical shape, between horse-tooth shape and spherical cone shape corn kernels is 0.05, 0.17, 0.068, respectively.

Table 1 Contact material parameters used in simulation[21]

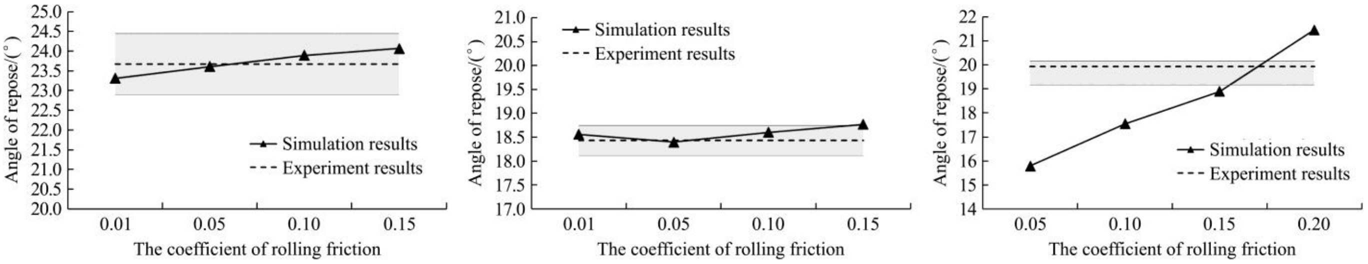
Simulation condition	Parameters	Value
Aluminum	Poisson ratio	0.34
	Shear modulus/Pa	2.5×10^{10}
	Density/kg m^{-3}	2700
Corn and aluminum	Coefficient of restitution	0.729
	Coefficient of static friction	0.342
	Coefficient of rolling friction	0.052

2.3 Device for forming repose angle

900 corn kernels were produced in the aluminum cylinder. To facilitate the study of the variability of the effect of different shapes of corn kernels on the forming process of the repose angle, the corn quantity ratio was generated at 1:1:1 on horse-tooth, spherical cone, spherical shape. The factory radius of particle generation is 25 mm, and the distance from the bottom plate is 270 mm. The generation rate for corn kernels 100/s, and the maximum attempt to place is 5. The formation process of repose angle is as follows: the bottom of the cylinder is fitted to the bottom plate, then the cylinder is pulled up at a speed of 20 mm/s. The corn population naturally accumulates. The angle between the population slope and the bottom plate is the repose angle. The marking process of repose angle is as follows: firstly, the vertical cross-sectional image of repose angle was imported into Photoshop for horizontal correction and clipping, saved in JPG. Then it was introduced into CAXA electronic drawing board. With reference to corn population boundary drawn the horizontal line and the inclined boundary line with the line command, and the angle between the two lines was the repose angle.



a. Horse-tooth shape b. Spherical cone shape c. Spherical shape



d. Horse-tooth and spherical cone shape e. Horse-tooth and spherical shape f. Spherical cone and spherical shape

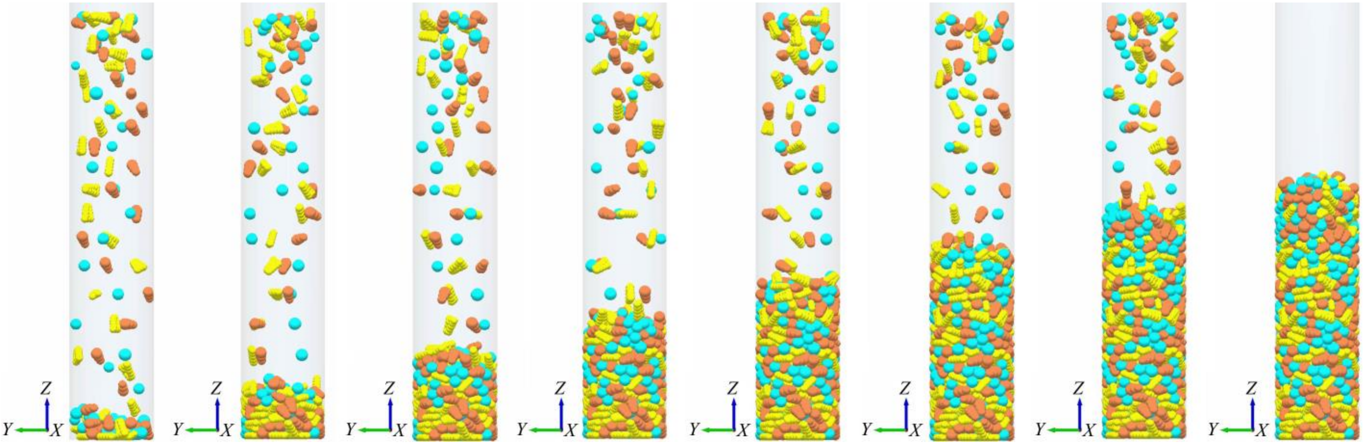
Figure 3 Relationship between the coefficient of rolling friction and the repose angle

3 Results and discussion

To investigate the role played by three typical shape corns in the formation process of the repose angle and provide theoretical basis for the development of corn-related machinery, the effects of the corn kernel shapes on behavior during accumulation were conducted, including the distance of corn kernels dispersion, the energy conversion, and the contact number.

3.1 Formation process for repose angle

Before the formation of the repose angle, it is necessary to fill the container with corn kernels. It is required that three different shape types of corn kernels were mixed adequately to facilitate the study of the effect of corn shape on the formation of the repose angle. It took about 3.2 s for the corn kernels to fill the aluminum cylinder. The observation of 8 time points showed that the corn kernels were mixed sufficiently to form the repose angle, as shown in Figure 4.



a. 0.4 s b. 0.8 s c. 1.2 s d. 1.6 s e. 2 s f. 2.4 s g. 2.8 s h. 3.2 s

Figure 4 Filling process of corn kernels in the container

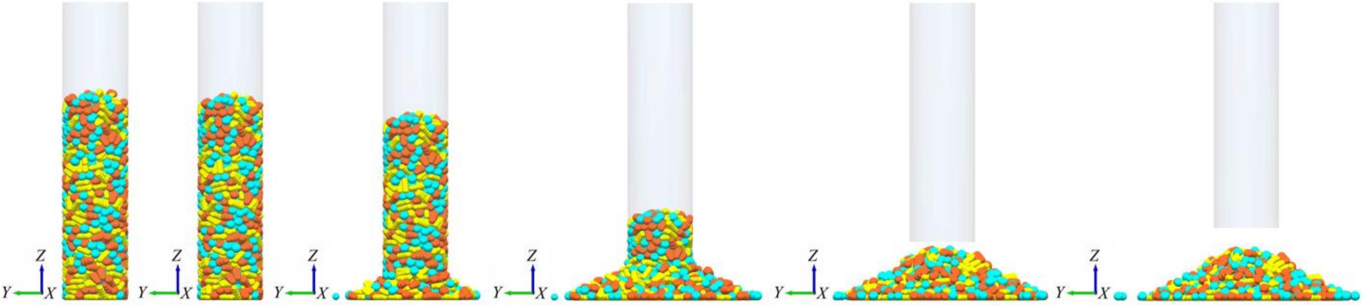
The formation process for repose angle is shown in Figure 5. From Figure 5, it can be seen that different shape types corn kernels play different roles in the formation process. Specifically, spherical corn kernels expands to a larger extent in peripheral direction, while the other two types corn kernels play an important role in the height direction of the repose angle.

From Figure 5, the formation process for repose angle is as follows: at first the gravitational potential energy of corn kernel is larger. When the cylinder is lifted upward, the corn kernels at the bottom of the cylinder spreads around due to the lack of peripheral restriction, and the gravitational potential energy of the corn above is converted into the kinetic energy downward movement due to the partial loss of support, in this process the overall height of corn continues to fall, and the repose range continues to expand. The gravitational potential energy is transformed into the kinetic energy and the rotational kinetic energy, and then finally to the process of equilibrium. The previous corn kernels have formed a more stable accumulation, while the later one continues to decline under the support of the slope continues to be stable. Further, the variations in corn kernels spacing, energy, and the contact number of corn kernels with the bottom plate need to be investigated.

3.2 Effect of corn shape on the range and height of repose angle

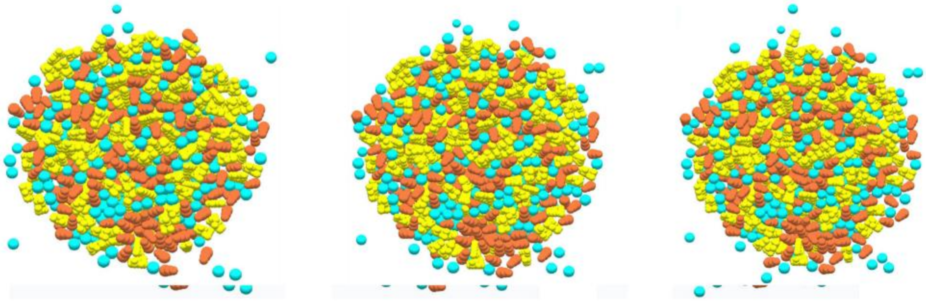
To study the effect of different shape kinds of corn kernels on forming repose angle in the process of corn population falling, three different shape types of the corn popuation after and before accumulation were displayed separately and independently, as shown in Figure 6.

From Figure 6, it was found that the range and height of spherical, horse-tooth, spherical-cone corn kernels in cylinder container were basically the same. However, after a certain period of time corn kernels accumulated the scope expand and the height differed. The results show that after accumulation the distribution range of spherical shape corn kernels has expanded most than other two types of corn, while the horse-tooth shape corn kernels mainly support the height of the repose angle. Moreover, horse-tooth shape corn kernels fill most of the area of the cross section of the repose angle, while there are some vacant areas in the repose angle forming from spherical-cone and spherical shape corn kernels. Further, the repose angle area and height when the corn kernel coefficient of rolling friction is uniformly 0.01 are observed as shown in Figure 7. The comparison results are listed in Table 2.



a. 0 s b. 0.6 s c. 1.2 s d. 1.8 s e. 2.4 s f. 3 s

Main view

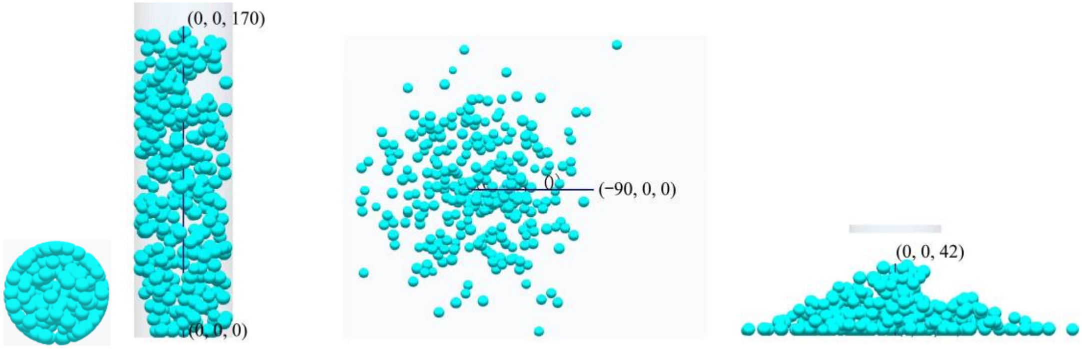


g. 1.8 s h. 2.4 s i. 3 s

Top view

Note: yellow, orange, light blue represent horse-tooth, spherical cone and spherical shape corn kernels, respectively.

Figure 5 Distribution area and height of different shape kinds of corn kernels before and after forming accumulation



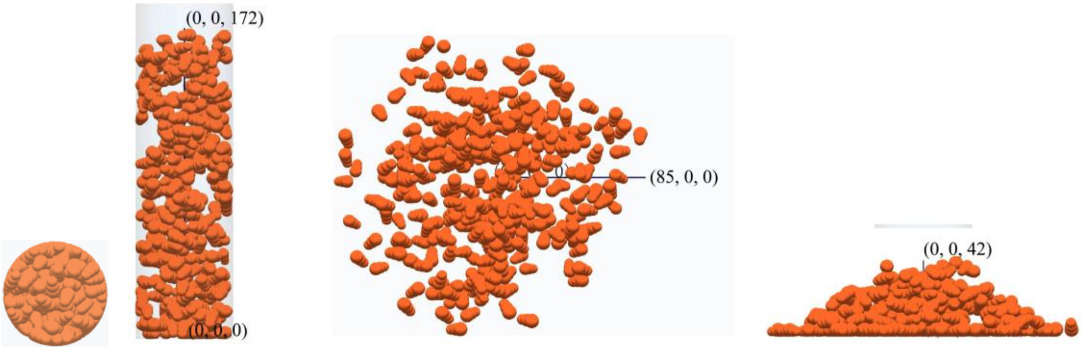
Top view Main view

Before accumulation

Top view Main view

After accumulation

a. Spherical shape



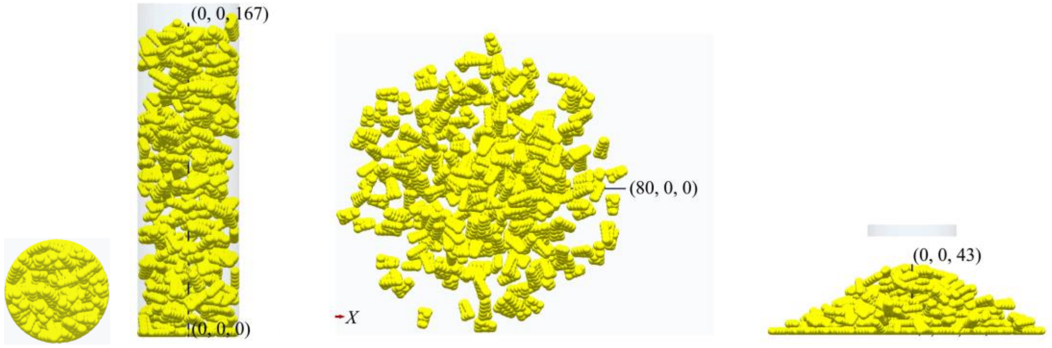
Top view Main view

Before accumulation

Top view Main view

After accumulation

b. Spherical-cone shape

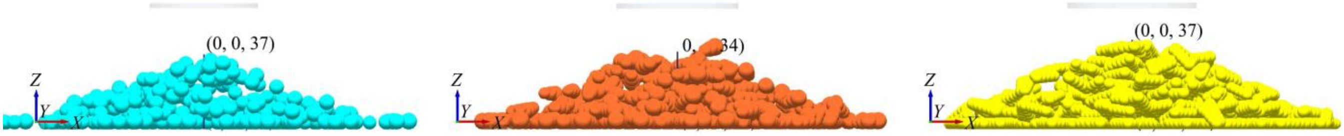


Top view Main view
Before accumulation

Top view Main view
After accumulation

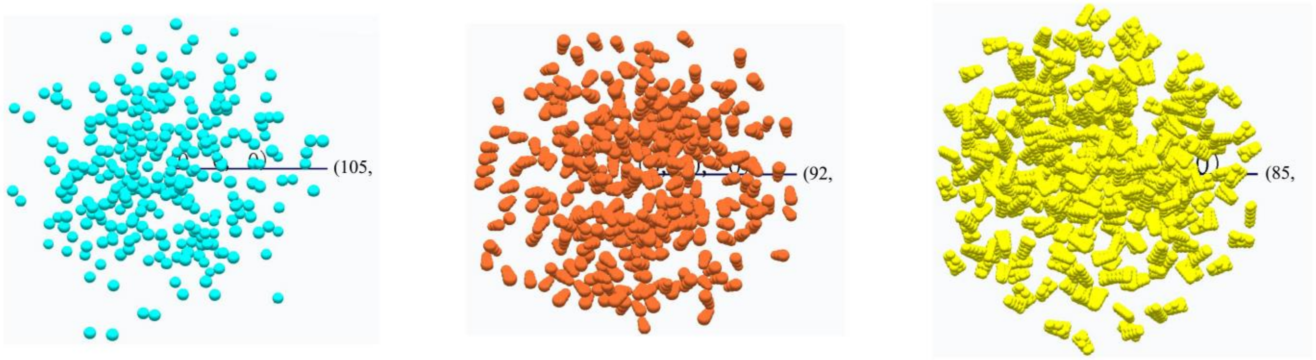
c. Horse-tooth shape

Figure 6 Distribution area and height of corn kernelsbefore and after forming accumulation



a. Spherical shape b. Spherical cone shape c. Horse-tooth shape

Main view



a. Spherical shape b. Spherical cone shape c. Horse-tooth shape

Top view

Figure 7 Distribution area and height of corn kernels after forming accumulation

Table 2 Comparison of the area and height before and after forming repose angle

Corn shape type	Area and height before forming repose angle (mm^2) / Height (mm)	Area and height after forming repose angle (mm^2) / Height (mm)	Change multiple
Horse-tooth	2290/167	22698/37	9.91/4.51
Spherical cone	2290/172	26590/34	11.61/5.06
Spherical	2290/170	34636/37	15.12/4.59

As can be seen from Figure 8 and Table 2, the change of the area after and before forming repose angle from big to small is spherical, spherical cone and horse-tooth shape in turn. It shows that the corn shape effectively limit the flow when increasing the size in one direction, but it is not in a linear relationship. Among them, the spherical seeds have the largest diffusion area, while the horse-tooth shap diffusion area is the smallest. On the other hand, the change multiple of the height after and before forming repose angle from big to small is spherical cone, spherical, and horse-tooth shape in turn, and the ratio difference is small. It indicates that the corn shape does not have a significant effect on the height of forming repose angle. To fully explore the effect of shape on the degree of particle dispersion, the average distance between corn kernels was compared, as shown in Figure 8.

From Figure 8, it can be seen that the average distance between corn kernels during forming repose angle tends to be basically the same. First the distance decrease extremely rapidly, then slowly increase and then stabilize. After the formation of the repose angle the distance between corn kernels from large to small is spherical, spherical conical and horse-tooth in turn. As the spherical corn kernels are weakly constrained in three directions, allowing a large variation in the distance of corn kernels.

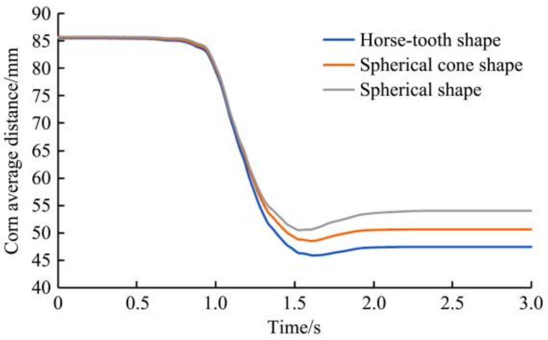


Figure 8 The corn distance between before and after forming accumulation angle

3.3 Effect of corn kernels shape on energy conversion

The process for forming repose angle is actually an energy conversion process. During the process the potential energy of corn kernels will be translated to the kinetic energy that divided into the translational kinetic energy and rotational kinetic energy, leading to increase in the scope area of repose angle. The transformation process of corn potential energy can reflect the function of corn seed shape. Figure 9 shows that the total potential energy of different shape types of corn kernels varies with a function of time.

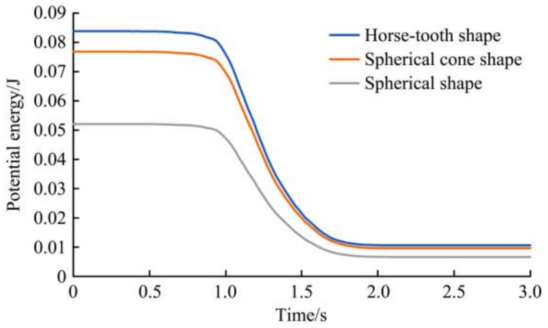
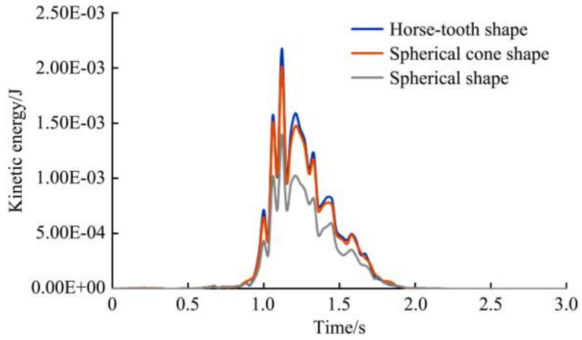
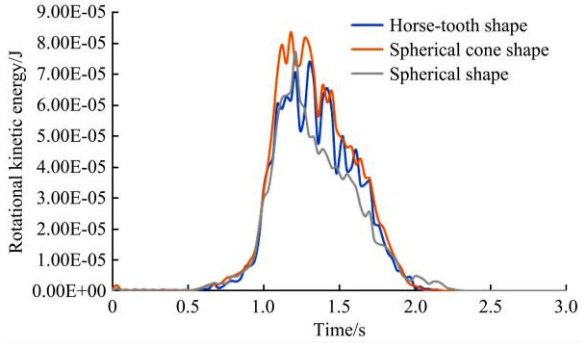


Figure 9 Potential energy conversion during forming repose angle

From Figure 9, it can be observed that between 0 s and 1 s, the potential energy of three shape types of corn kernels all maintain certain, after that period, they start to decrease, in particular, the horse-tooth shape, spherical cone corn kernels falls rapidly. At 1.65 s, the potential energy of spherical shape basically keep level, while that of spherical cone shape corn kernels is at 1.75 s. The results illustrate the height of corn kernels and the bottom plane from big to small is horse-tooth, spherical cone and spherical shape corn kernels. To investigate clearly which form of kinetic energy is relatively important, the translational and the rotational kinetic energy of corn kernels during forming repose angle are ploted with function of time, as shown in Figure 10.



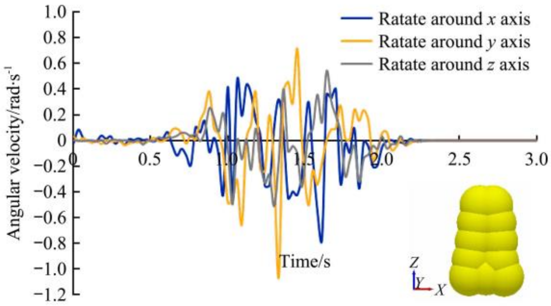
a. Translational kinetic energy



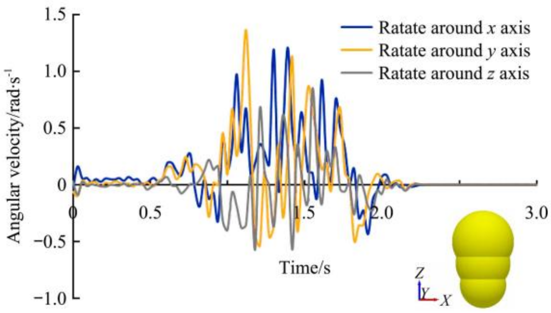
b. Rotational kinetic energy

Figure 10 Kinetic energy conversion during forming repose angle

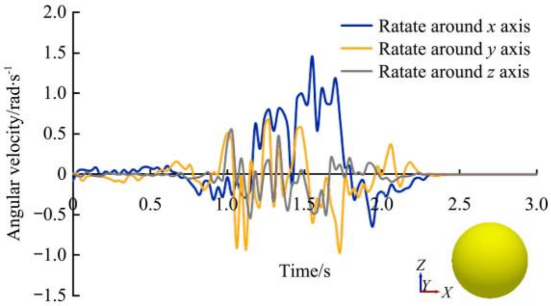
As can be seen from Figure 10, the trend of translational and rotational kinetic energy changes first increases and then decreases to a smooth. The translational kinetic energy transformed from the potential energy from big to small are horse-tooth, spherical cone and spherical shape corn kernels in turn, while the proportion translated into the rotational kinetic energy from the potential energy from large to small is spherical cone, spherical shape, and horse-tooth shape corn kernels in turn. In addtion, the translational and rotational kinetic energy that fluctuated from weak to strong is spherical, spherical cone, and horse-tooth shape corn kernels in turn. The above results prove that the shape of corn kernels is a very important factor in derterminating the flowing of corn kernels, meanwhile the added size of corn seed in one or two direction limit corn kernels rolling further. To investigate the difference in the angular velocity of corn kernel in *x*, *y*, and *z* directions, the angular velocity curves of corn kernels in different directions during repose angle forming were analyzed, as shown in Figure 11.



a. Spherical shape



b. Spherical-cone shape



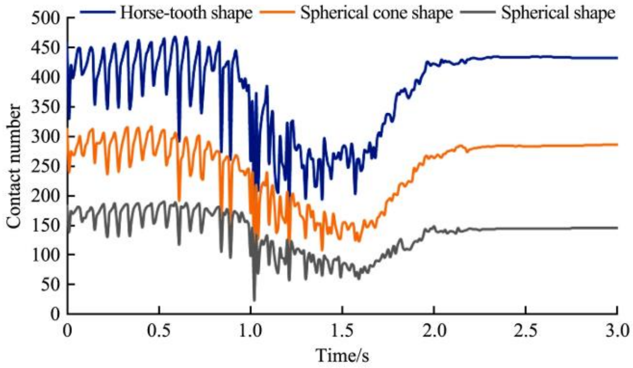
c. Horse-tooth shape

Figure 11 Rotational velocity of corn kernels

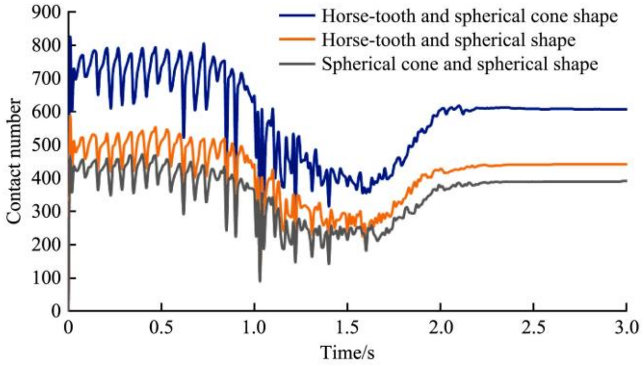
From Figure 11, the frequency of horse tooth corn beating around the *x*-axis is higher than around the *y*- and *z*-axis, and the fluctuation peak of its curve after its maximum peak has been reduced because its size in two directions limit its rolling. The average rotational velocities of spherical cone shape corn kernels around *x*- and *y*-axis fluctuate greatly than that around *z*-axis, and the fluctuation peak of its curve after its maximum peak has been reduced as its length in one direction limit its rolling. The average rotational velocities of spherical shape corn kernels around *x*- and *y*-axis are bigger than that around *z*-axis, which means that spherical shape corn kernels mainly roll toward peripheral direction during accumulation. From the above results, it can be known that the values of the angular velocidy of spherical, spherical cone and horse-tooth shape corn kernels are in a descending order. However, the frequency of peak occurrence are in a descending order as horse-tooth, spherical cone, and spherical shape corn kernels. This means that the more irregular the shape of the corn kernel the more it can restrain its rotation and can accelerate the stabilization of the flow.

3.4 The contact number between different shape corn kernels

Changes in the contact number of corn kernel also reflect its mobility. The contact number of different shape corn kernels during accumulation is plotted as as function of time, as shown in Figure 12.



a. One shape type



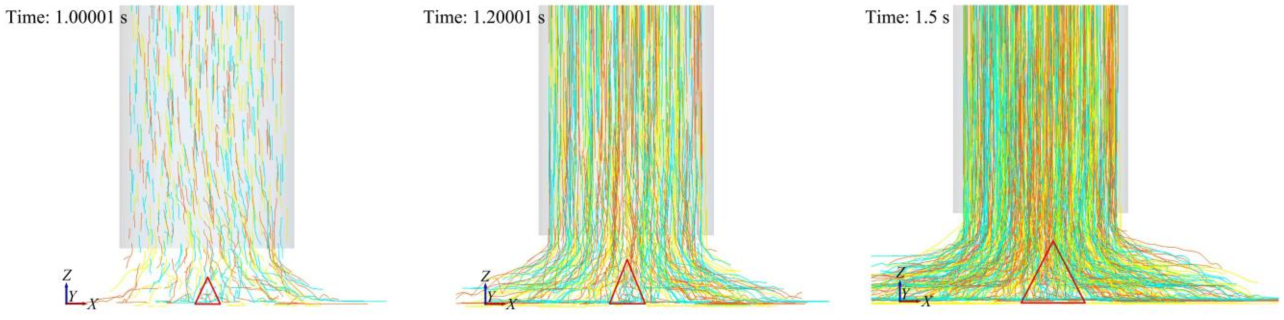
b. Two shape types

Figure 12 Contact number of corn kernels

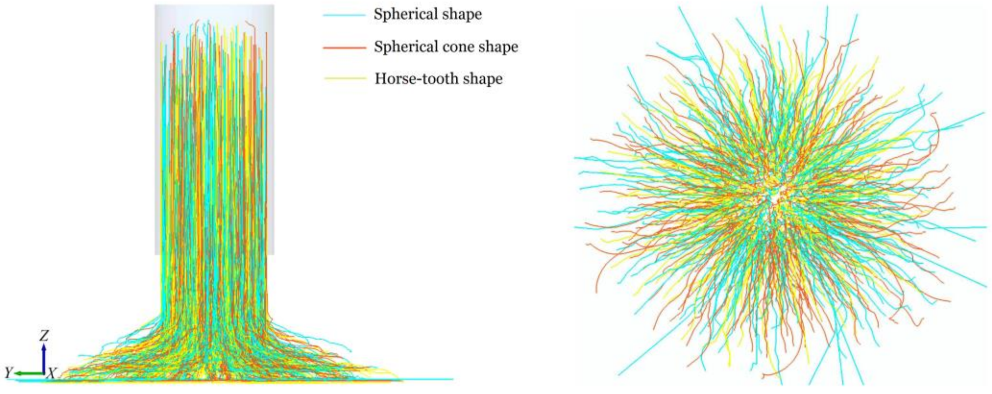
As can be seen from Figure 12, the changing trend of the contact number between single and two types of corn is basically the same. It shows a fluctuating decline first, a slow rise after a trough, and then tends to be stable. The overall number of particle contacts in descending order were horse-tooth and spherical cone, horse-tooth and spherical shape, spherical cone and spherical shape, horse-tooth, spherical cone and spherical shape, respectively. Since horse-tooth corn is made up of 11 spherical particles stacked, spherical cone corn is made up of 3 spherical particles stacked, and spherical is represented by only 1 spherical particle, therefore, horse-tooth and spherical cone corn are higher in the number of contacts than spherical corn. However increasing the number of particle contacts means increasing the simulation time. Also from the number of contacts it was seen that horse-tooth corn spreads in all directions with the help of spherical cone and spherical corn, and spherical cone corn spreads in all directions with the help of spherical corn. To provide a basis for the selection of seed shape type for corn sowing, horse-tooth corn contains more organic matter, favorable for seed germination, but there are certain difficulties in circulation, and the seeds can be mixed with spherical corn to increase the flow of the population and further improve the quality of the row of seeds.

3.5 The function of different shape corn kernels on forming accumulation

The observation of the corn track shows the formation process of the stacking angle. The potential energy of corn kernels is translated into both the height and the contact area of accumulation. Trajectory marking from three key moments in the formation of the repose angle The accumulation behavior of corn kernels is observed in Figure 13.



a. 1 s b. 1.2 s c. 1.5 s



d. Main view e. Top view

Figure 13 Moving track lines of corn kernels during accumulation

From Figure 13a, it can be observed that some spherical shape corn kernels contact with the bottom plate early and form small cone, meanwhile, other corn kernels change directions to slide around under the support of the vertebral body slope, and the vertebral body starts to become larger, and the slope angle becomes progressively larger, and its slope support becomes more obvious, as shown in Figures 13b and 13c. The height of the cone is mostly formed by the horse-tooth and spherical cone due to the weak rolling capacity, as shown in Figures 13d and 13e. This can help to understand how the gravitational potential energy of the corn kernels decreases and part of the energy is converted into kinetic energy of rotation. The initial formation of the small cone and the potential energy plays a key role. The more irregular shape of corn kernels, the more it is likely to form self-locking phenomenon, which is useful to add height and save accumulation time. To increase the flow characteristics of the seeds, it is necessary to deal with both the shape of the seeds and their frictional characteristics.

4 Conclusions

The effects of the corn kernel shapes on repose angle forming were investigated. Firstly, three typical corn kernels were chosen to establish the DEM. An aluminum cylinder container was combined to conduct the experiment of the corn repose angle. Secondly, the effect of different shape types of corn kernels on distance between corn kernels during forming repose angle, energy conversion, and the contact number were investigated. Simulation result show that the shape of corn kernels is a very important factor in determining the flowing of corn kernels, and the irregular shape of corn kernels limit their rolling when adding the size of corn seed in one or two directions. Irregular corn (horse-tooth, spherical cone shape) is stacked by multiple ball particles, increasing the number of contacts and simulation time. Also, irregular corn kernels need to be added with regular shape corn kernels to improve their flowability. Finally, how the repose angle is to form was discussed, and it can be found that spherical corn kernels contact with the bottom plate early, forming small cone first, and this cone becomes progressively larger with the help of the horse-tooth and spherical cone corn kernels, then its cone becomes more capable of changing the corn kernel direction from top to down. In addition, the more irregular shape of corn kernels, the more likely it is to form steady condition which is useful to increase the repose angle and save simulation time.

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