RESEARCH OF SEED GROUP STRUCTURE CHARACTERISTICS OF VERTICAL DISC METERING DEVICE BASED ON DISCRETE ELEMENT METHOD
/
基于离散元法的垂直圆盘侧充排种器种群结构特性研究

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ABSTRACT
The vertical disc seed metering device was selected to study the influence of the structural characteristics of seed group on the filling performance of seed metering device. The working process of seed metering device was simulated by discrete element software to study the influence of seed quantity and structure characteristics of seed chamber on seed movement and filling results. The seed group was divided into four zones: ascending zone, relative static zone, collapse zone and recirculation zone. The number of seeds and the rotation speed of disk have no effect on the inclination angle of the recirculation zone upper surface, which was always about 35°. But they had a significant effect on the filling performance. When the number of seeds was 500-1500, QFI (quality of feed index) decreased, MIS (miss index) increased and MUL (multiple index) did not change significantly. However, when the number of seeds was 2000, the change trend of filling performance was completely opposite. Inner surface inclination angle and axial width of the seed chamber have significant effects on the filling performance. QFI first increased and then decreased with the increase of inclination angle, reaching the maximum at 20° and MIS showed the opposite trend. QFI increases with the increase of thickness and tends to be stable at 40mm. Similarly, MIS has the opposite trend.

摘要
为了了解种子群的结构特性对排种器充种性能的影响规律，选取垂直圆盘侧充排种器为研究对象，利用离散元软件 EDEM 对排种器的工作过程进行仿真试验，研究种群数量及种室的结构特征对种群运动和充种效果的影响规律。离散元仿真显示种群分为上升区、相对静止区、塌落区、回流区。回流区上表面的倾角与种子数量及排种盘的转速无关，始终保持在 35° 左右。种群数量和排种盘转速对充种结果具有显著影响，种子数为 500-1500 时，QFI 随转速增加而降低，而 MIS 逐渐增大，同时 MUL 变化不显著;当种子数为 2000 时，充种性能的变化与 500-1500 时刚好相反。种室的底面倾角和厚度对充种性能具有显著影响，QFI 随倾角的增大先增大后降低，在 20° 时达到最大，MIS 变化与 QFI 相反；合格率随厚度增加而逐渐增大并在 40mm 时趋向稳定，同样 MIS 的变化趋势与 QFI 完全相反。

INTRODUCTION
Sowing is the key link of agricultural production, and the seed metering device is one of the important parts that affect the sowing effect *(Yang et al., 2016)*. Pneumatic seed metering device is the main type of seed metering device in the world *(Correia et al., 2016; Singh., 2007; Jack., 2013; Yu et al., 2014)*. Pneumatic metering device is the main metering device in the world, and it is widely used in developed countries. However, due to its high production cost and complex use and maintenance, mechanical metering device is still used in many countries (*Wang et al., 2017; Yi et al., 2014*).

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Vertical disc seed metering device is a common mechanical seed metering device, which is mainly used for sowing round seeds such as soybean and pea *(Liu et al., 2015; Vianna., 2014)*. The author has carried out the research on the vertical disc metering device, optimized the structure of seed stirring on the disk, and obtained the concave type agitator with better seed stirring effect *(Chen et al., 2021)*. The optimal value of depth and angle of concave type agitator were 3.1mm and 60.5°, respectively.

The discrete element method is often used in the research of seed metering device, because the seed is a typical discrete material *(Khatchatourian, Binelo, & Lima, 2014; Li et al., 2013)*. The movement law of particles can be deeply studied and analyzed by using discrete element software, and EDEM is the most widely used discrete element software *(Wang et al., 2015)*.

At present, the research of seed metering device focuses on the influence of disk on seed movement and seed metering performance *(Kocher et al., 2011; Mao et al., 2015)*. Researchers innovate the structure of seed picking mechanism, optimize the design of seed stirring and seed cleaning mechanism, and improve the detection method of seed metering performance *(Jiang., 2021; Li., 2021; Zhang et al., 2015)*. However, there were few studies on the structure and movement characteristics of seed group in the process of seeding. Therefore, in this paper, the discrete element method was used to research the structure and movement characteristics of the population.

MATERIALS AND METHODS

Vertical disc metering device

The vertical disc seed metering device is mainly composed of shell, flexible seed cleaning part, disk, flange, bearing, base and shaft (Fig. 1). The disk is fixedly connected to the shaft through the flange and rotates with the shaft. The shaft is connected to the shell through the rolling bearing. Seed taking groove and seed agitator are evenly distributed on the outside of the disk, and there are suction holes at the bottom of the seed taking groove.

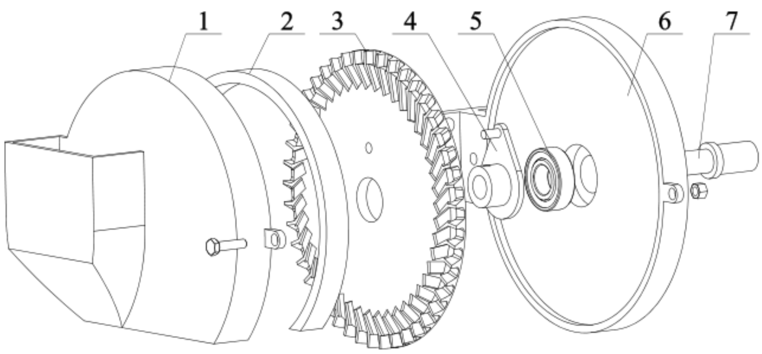


Fig. 1 - Structure diagram of seed metering device

1. Shell; 2. Flexible seed cleaning part; 3. Disk; 4. Flange; 5. Bearing; 6. Base; 7. Shaft; 8. Hole; 9. Seed agitator

The relationship between the rotation speed of disk and the forward speed of planter was shown as follows:

$$n = \frac{v}{60 \cdot k \cdot s} \tag{1}$$

where:

n is the speed of disk, [r/min];

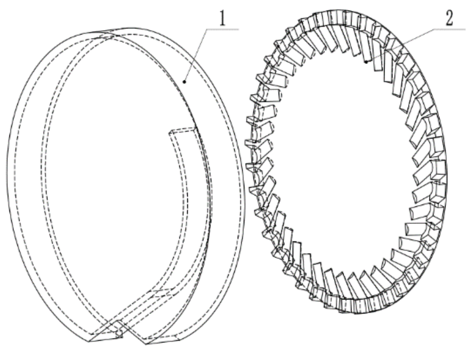
v is the forward speed of planter, [m/s];

k is the number of seed holes on the disk, it is designed as 40;

s is the sowing distance, it is designed as 0.05m.

EDEM is a mature commercial discrete element simulation software (*Wang et al., 2015*) and version 11.0 of EDEM was used for virtual simulation test in this paper.

In the simulation, the vertical disk seed metering device was simplified by removing the shaft, bearing, flexible seed cleaning part and other components, leaving only the shell and disk (Fig. 2). The disk and shell were made of PMMA (polymethyl methacrylate), a transparent material.



1. Shell; 2. Disk

Fig. 2 - Simulation model of seed metering device

Soybean seed used here was Jiyu202 (Table 1), which was widely planted in Northeast, the major soybean production region of China.

Table 1

Physical properties of soybean

Physical property	Mean	Standard error
L [mm]	7.21	0.32
W [mm]	6.11	0.31
T [mm]	6.32	0.44
D [mm]	6.52	
Φ [%]	91.88	
Thousand seed mass [g]	180.55	0.21

Note: *L* average length; *W* average width; *T* average Thickness; *D* means of geometrical diameter and calculated as $D=(LWT)^{1/3}$ respectively. ϕ means of sphericity and calculated as $\phi=\frac{(LWT)^{1/3}}{L}\times 100$.

Hertz-Mindlin non-sliding contact model was adopted in simulation. The global parameters used in the simulation were obtained by reference (*Li et al., 2013; Zhang et al., 2017*) (Table 2).

Table 2

Parameters used in simulation

Property	Soybean	PMMA	Property	Soybean-Soybean	Soybean-PMMA
Poisson's ratio	0.4	0.33	Collision recovery coefficient	0.6	0.5
Shear modulus [Pa]	1.1×10^{7}	8×10^{7}	Static friction coefficient	0.5	0.3
Density [kg/m^3]	1053	1190	Rolling friction coefficient	0.01	0.09

Test plan

There are two factors affecting the structure of seed group. One is the number of seeds entering the chamber from the entrance, which is determined by the size and location of the entrance. Another factor is the structure of seed chamber, which is determined by inner surface inclination angle and axial width. Single factor simulation tests were carried out with seed number n, inner surface inclination angle α, axial width b as factors (Fig. 3).

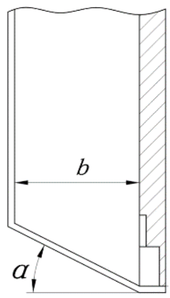


Fig. 3- Schematic diagram of seed chamber structure

The number of seeds was set as 500, 1000, 1500 and 2000 respectively. Inner surface inclination angle was set as 0°, 10°, 20° and 30°, respectively. Axial width was set as 20, 30, 40 and 50 mm, respectively (Table 3).

Table 3

Factors and levels of seed chamber structure

Level	Factors		
	n	*α* [°]	*b* [mm]
1	500	0	20
2	1000	10	30
3	1500	20	40
4	2000	30	50

Measurement and computing method

According to GB/T 6973-2005 test methods for single seed (precision) planter, 250 seeds were collected for statistics in each group of experiments, and the test was repeated 3 times, and the seed metering performance evaluation indexes were *MUL*, *MIS* and *QFI* (*Mao et al, 2015; Zhang et al, 2015*).

$$MUL = N_1 / N \times 100\% \quad (2)$$

$$MIS = N_2 / N \times 100\% \quad (3)$$

$$QFI = (1 - MIS - MUL) \times 100\% \quad (4)$$

where:

N_1 is the number of seed holes containing multiple seeds in the simulation test.

N_2 is the number of seed taking holes that are not filled in the simulation test.

N is the total number of seed holes recorded in the simulation test.

RESULTS AND ANALYSIS

Structural characteristics of seeds

EDEM was used to get the velocity vector of seeds in the working process of vertical disc seeder. According to the velocity size and direction of seed particles, the seed group can be divided into four zones (Fig. 4), ascending zone, relative static zone, collapse zone and recirculation zone。

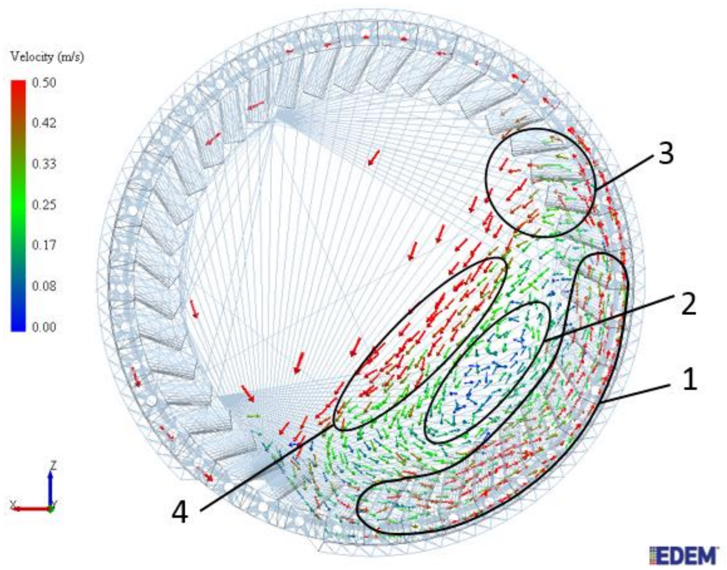


Fig. 4- Simulation diagram of seed movement

1. Ascending zone; 2. Relative static zone; 3. Collapse zone; 4. Recirculation zone

In the lower part of the seed group, seeds near the seed agitator have the highest speed, and the seed move upward from the bottom, so this area was the ascending area. The speed in this area was higher because the seed agitator passes through and drives the seed to move upward from the bottom.

Above the ascending area, seeds carried by the seed hole fall down under the action of gravity and enter into the seed group. This zone was called collapse zone. Seed movement in this area was violent, and the speed direction changes from up to down. The size of the collapse area was related to the rotation speed of the disk.

Seeds in the middle of the seed group only rotate around themselves, and the relative position with the metering device remains basically unchanged. This region was called relative static zone.

Seeds on the surface of the seed group move from the top to the bottom. This area was called recirculation zone. The area was mainly composed of seeds falling back to the group in the collapse zone. Seeds move to the bottom under the action of gravity, and then return to the bottom of the population.

Influence of seed quantity

In the pre-processing of discrete element simulation, the number of particles generated by particle factory was set as 500, 1000, 1500 and 2000 respectively. The forward speed of the planter was set as 2, 4, 6, 8 and 10km/h respectively. The rotation speed of disk was calculated by formula (1), and the corresponding rotation speed is 16.7, 33.3, 50.0, 66.7 and 83.3rpm respectively. The discrete element simulation was carried out (Fig. 5).

500

1000

1500

2000

16.7 rpm 33.3 rpm 50.0 rpm 66.7 rpm 83.3 rpm

Fig. 5- Effect of seed number on movement

With the increase of the rotation speed, the movement of the seeds became more and more intense. But the simulation results show that the number of seeds has no significant effect on the inclination angle of the upper surface of the recirculation zone. When the number changes from 500 to 2000, the inclination angle was maintained at about 35°.

Similarly, the rotation speed has no significant effect on the inclination angle of the recirculation zone when the rotation speed changes from 16.7rpm to 83.3rpm, and the inclination angle was always maintained at about 35°.

Therefore, the inclination angle of the seed group was only related to its inherent characteristics and the structure of the metering device, but not to the seed number and the rotation speed of the disk.

Although the seed number and rotation speed had no significant effect on the seed group inclination, the range of collapse zone increased. Observing the simulation process, it was found that the time required for the seed to leave the hole in the axial direction was increased. The movement time of seeds following the metering tray became longer. More seeds were driven out of the group by seed holes. When the number of seeds reaches 2000 and the rotation speed reaches 83.3 rpm, the seeds separate from the highest part of the upper surface of the seed group and impact on the inner surface of the shell. The scope of the collapse area reached the seed outlet.

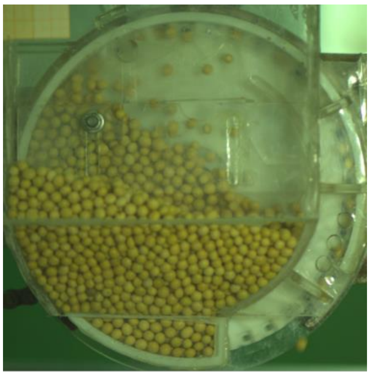


Fig. 6 - High speed photography of seed movement

The movement state of the physical prototype of the seed metering device was recorded by high-speed camera (Fig. 6), and the inclination angle of the seed group was 34.5°, which was consistent with the simulation results. This verifies the reliability of the discrete element simulation test.

The results of seed filling performance under different seed numbers were statistically analyzed (Fig. 7). Results showed that the seed number had a significant effect on the filling performance.

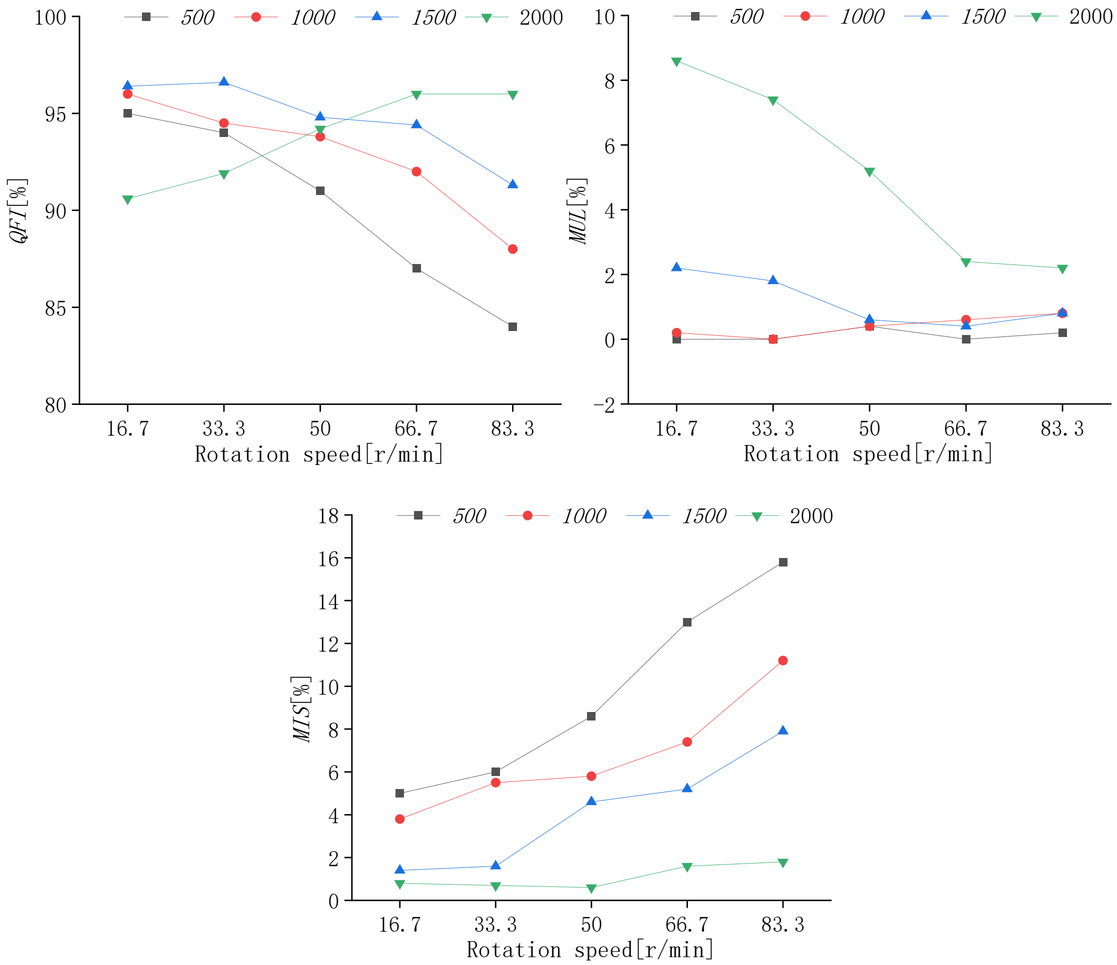


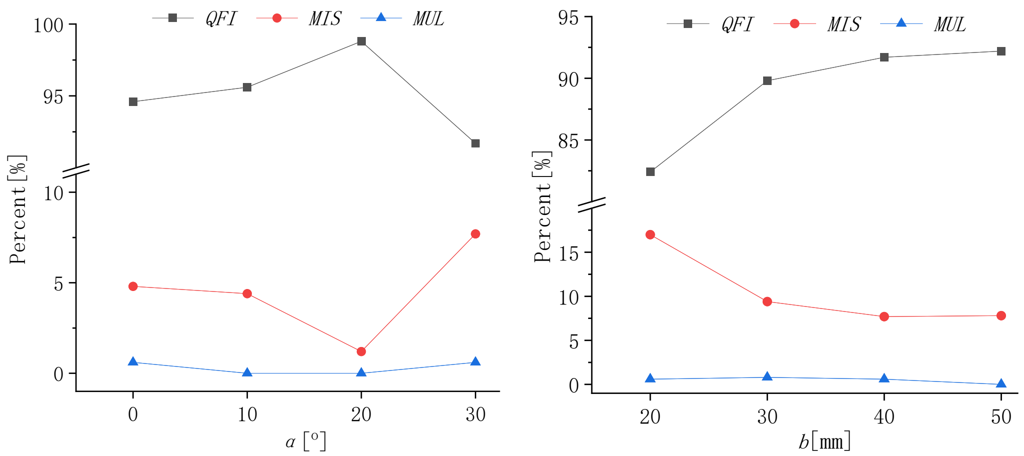
Fig. 7- Effect of seed number on seed filling

When the number of seeds was from 500 to 1500, the change of filling results was similar. With the increase of speed, QFI decreased significantly, MUL did not change significantly, and it was always low. However, MIS and QFI showed the opposite trend, which increased significantly. At 16.7 rpm, QFI of 500 to 1500 was 95.2%, 96.0%, 96.4% respectively. At 83.3 rpm, QFI of 500 to1500 was 84.3%, 88.5%, 91.3% respectively. QFI decreased by 11.4%, 7.8% and 5.3%, respectively. The smaller the number of seeds, the greater the reduction of QFI. The MIS was 4.8%, 3.8% and 1.4% at 16.7 rpm, and increased to 15.5%, 10.7% and 7.9% at 83.3 rpm.

When the number of seeds was 2000, the change of QFI was opposite to that of 500-1500, which increased gradually with the increase of speed. It was 90.6% at 16.7 rpm and tended to be stable at 96.1% after reaching 66.7 rpm. The change of MUL was contrary to that of QFI, which was 8.6% at 16.7rpm and stabilized at 2.4% after reaching 66.7rpm. MIS was 0.8% at 16.7 rpm and 1.8% at 88.3 rpm, with little change.

Influence of seed chamber structure

When the number of seeds was 1500 and the rotation speed was 50.0rpm, the inner surface inclination angle and the axial width of the seed chamber were changed to carry out the simulation experiment. The experiment was divided into two parts. Firstly, the axial width was set to 40mm, the inner surface inclination angle was changed from 0 to 30°, the simulation experiment was carried out, and the statistical results were obtained (Fig. 8.a).



a. Inner surface inclination angle *b. Axial width*

Fig. 8 - Effects of seed chamber structure on seed filling

When the inclination angle changed, the MUL did not change significantly and remained at a low level. The change of QFI and MIS was completely opposite, QFI first increased and then decreased, MIS first decreased and then increased. At 20°, the maximum QFI was 98.8%, and the minimum MIS was 1.2%. According to the simulation analysis, with the increase of inclination angle, seeds attached to the bottom face were subjected to lateral force, which helps the seeds move laterally into the seed hole, resulting in the increase of QFI. When the inclination angle was more than 20 degrees, despite the further increase of lateral force, the smaller angle between the bottom surface and the seed hole resulted in the smaller effective filling area. It was more difficult for the seed to enter the hole, which resulted in the increase of MIS.

The value of axial width was changed when the inner surface inclination angle was the best value of 20° and the simulation test was carried out (Fig. 8.b).

Results showed that the change of axial width also have no significant effect on MUL, and it always kept a low level. The change of QFI and MIS was completely opposite. QFI increased at first and tended to be stable gradually. MIS decreased at first and tended to be stable gradually. The minimum QFI was 82.4% and the maximum MIS was 17.0% when the thickness was 20mm. When the thickness was 40mm, QFI was stable at 91.7% and MIS was stable at 7.7%. Observing the simulation process, it was found that when the thickness was small, there were fewer seeds on the front of the seed hole, fewer chances of filling and higher MIS. With the increase of axial width, the more seeds on the front of the hole, the more chance of filling and the higher QFI. However, when the thickness reached 40mm, the effective driving layer of the seed group reached its maximum. Even if the axial width continues to increase, the effective driving layer would not continue to increase, so QFI and MIS tend to stabilize.

CONCLUSIONS

(1) When the vertical disc seed metering device works, the seed group was divided into four zones: ascending zone, relative static zone, collapse zone and recirculation zone. The inclination angle of the top surface of the recirculation zone was not related to the number of seeds and the rotation speed, but it was always kept at about 35 degrees.

(2) The number of seeds had a significant effect on seed filling performance. When it was between 500 and 1500, the variation of filling performance with speed was similar, QFI decreased gradually, MUL did not change significantly, but MIS increased gradually. When it was 2000, QFI was just opposite to the previous trend, gradually increased and stabilized, MUL gradually decreased and stabilized, while MIS was not significant.

(3) The inner surface inclination angle and axial width of seed chamber have significant effects on seed filling performance. With the increase of inclination angle, QFI first increases and then decreases, reaching the maximum value of 98.8% at 20°. The change of MIS and QFI was just opposite, first decreases and then increases, and the minimum value was 1.2% at 20°, while MUL remains stable at a low level. With the increase of thickness, QFI gradually increases and tends to be stable at 40mm, and the change of MIS and QFI was opposite, while MUL also remains stable at a low level.

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