Optimized design of the pneumatic precision seed-metering device for carrots

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Abstract: The small size, light weight, irregular shape, and impurities that characterize seed groups increase clogging tendencies in the traditional seed-metering device thereby making it difficult to achieve high-speed precision seeding. A pneumatic seed-metering device with good seed-filling performance for carrot was designed in this study. By analyzing the movement state of seeds in the device under the theoretical condition, it was concluded that the minimum critical negative pressure value of air chamber was 0.32 kPa, which provided a theoretical basis for simulation and testing. ANSYS 17.0 Software was used to simulate the shape of the seeding plate hole. By comparing the pressure, air flow stability between the suction surface and the plug removal surface of the convection field, it was concluded that the conical hole was optimal. A bench verification test was conducted on the device. The average qualified rate, missing rate, and replaying rate were 81.48%, 4.07%, and 14.45%, respectively, which provided a strong reference for the design of carrot precision seed-metering device.

Keywords: seed-metering device, carrot, precision seeding, bench verification test
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1 Introduction

As one of the top ten vegetables in the world, carrots are rich in a variety of nutrients that can lower cholesterol and prevent heart disease and tumors[1]. Due to some technical problems in growing carrots in China, the yield per unit is quite poor[2]. At present, the main method of seeding carrots in China is mechanical strip seeding (manual seeding), which results in a lower yield. On the other hand, the cost of planting and harvesting makes up more than 65% of the total labor cost, thereby accounting for 30% of the total production cost[3]. The use of seed-metering devices can greatly improve the efficiency of seeding, reduce the intensity of seeding labor, reduce the cost of artificial labor, and save a lot of seeds as well as increase crop yield[4].

Many scholars have conducted extensive research on precision seeding technology. Singh et al.[5] studied the seeding uniformity of pneumatic seed-metering devices, they found that the displacement of seeds in the field (due to rolling and bouncing) can affect the plant spacing distribution in the field. Han et al.[6] performed the simulation of seed movement based on DEM-CFD coupling approach to improve the working performance of seed-metering device. Gaikwad et al.[7] designed an affordable pneumatic cave plate seed-metering device using existing standard parts and cheap materials. To study the seeding uniformity of air-absorbent monomer seed-metering device, Yazgi et al.[8] determined the uniformity of a number of different types of holes in the seeding plate by conducting a large number of experiments and using high-speed cameras. Kumar et al.[9] designed a new type of single-plant seed-metering device for soybean seeding. It was reported that the seeding performance of this seed-metering device was good, improving the uniformity of seeding, and can be widely used in soybean seeding production. Yatskul et al.[10] investigated the effect of different airflow distribution methods of the pneumatic seed-metering devices on energy loss and seeding accuracy. Lai et al.[11] designed an ultra-narrow-row air-aspiration precision seed-metering device, and used discrete element software to evaluate the seed-metering device. Abdolahzare et al.[12] proposed a test to assess seed spacing uniformity which was applicable in a field situation. In this method, a high-speed camera system was used to detect seed-falling trajectory, which was an effective factor on uniformity of seed spacing in both conditions of laboratory and field. Pandia et al.[13] presented a piece of pneumatic equipment for seeding small seeds in cups. This equipment can be used in narrow spaces, being easy to handle and use. Zhang et al.[14] conducted the single factor and central composite experimental experiments to find out the effects of the main working parameters (rotational speed of seeding cylinder, vacuum degree in vacuum gas chamber, air-blowing velocity and cleaning blockage positive pressure of chamber) on

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seeding performance of the direct seed-metering device. Under the condition of the optimal combination working parameters, the qualified rate, missing rate, cavity rate and replaying rate were 87.73%, 2.93%, 0.53% and 9.34%, respectively.

Many studies have shown that the shape of the suction hole on the seeding plate has a great influence on the seeding performance. Dun et al.[15] found that the ratio of diameter (DI Ratio), and depth (DE Ratio) affect seeding performance.

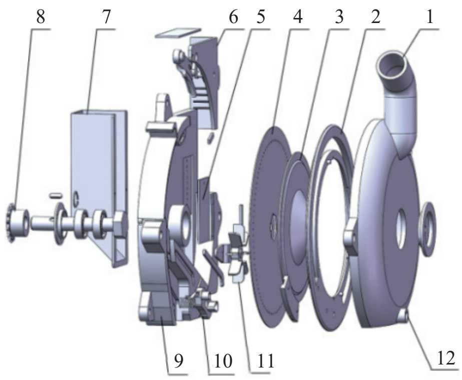
In order to improve seeding performance, this paper used theoretical calculations to design a multi-pore seeding plate and an auxiliary seed-filling device to achieve effective seed-filling. The optimal shape of the suction hole on the seeding plate was determined by simulation. The carrot seed-metering device was validated by the stand test, which provided a powerful reference for the design of a precision seed-metering device for carrots.

2 Materials and methods

2.1 Structure and working principle of the seed-metering device

2.1.1 Structure of seed-metering device

As shown in Figure 1, the precision seed-metering device for carrot was mainly composed of negative pressure outlet, sealing ring, seeding plate, agitating wheel, seed cleaning device, auxiliary seed dropping device, transmission device, box body and seed box. One side of the seeding plate was a positive and negative pressure air chamber, and the other side was a seed box for the seeding device. It was connected to a transmission device and a seed cleaning device.



1. Negative pressure outlet 2. Sealing ring 3. Seal ring fixing 4. Seeding plate 5. Population baffle 6. Seed cleaning device 7. Seed box 8. Transmission device 9. Box body 10. Auxiliary seed dropping device 11. Agitating wheel 12. Positive pressure population

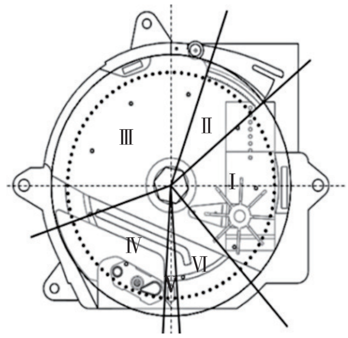
Figure 1 Schematic diagram of seed metering device

2.2 Working principle of the seed-metering device

As shown in Figure 2, the working area of the seed-metering device was divided into seed-filling area I, seed-cleaning area II, seed-carrying area III, seed-dropping area IV, plug cleaning area V, and transition area VI according to different working contents, and the five working processes of auxiliary filling, collision cleaning, single seed carrying, gravity and collision dropping and positive pressure cleaning were realized, respectively[16]. The carrot seeds were filled by the seed churning wheel in the filling area driven by the rotating seeding plate, and the redundant seeds were cleaned by the seed-cleaning device to ensure that there was only one grain in each hole. Carrot seeds are dropped by gravity into the seedbed with the rotation of the seeding plate to reach the seed-dropping area. Some of the holes contained impurities thereby blocking the holes, and positive pressure airflow was used for positive pressure clean plugging of the holes[17].

2.3 Analysis of the movement state of seeds

The process of movement of carrot seeds in different regions of the pneumatic seed-metering device under the oscillatory state can be seen in Figure 3, the direction of arrow indicated the direction of seeds movement in the device. In order to ensure that carrot seeds were adsorbed by the pneumatic seed-metering device, and that the seeding plate rotated to complete the seeding work smoothly so as to match the effective negative pressure value at the air outlet, the critical negative pressure value was analyzed and calculated to ensure that it worked smoothly[18].



Ⅰ. Seed-filling area Ⅱ. Seed-cleaning area Ⅲ. Seed-carrying area Ⅳ. Seed-dropping area Ⅴ. Plug cleaning area Ⅵ. Transition area

Figure 2 Working area division diagram of carrot high-speed precision seed metering device

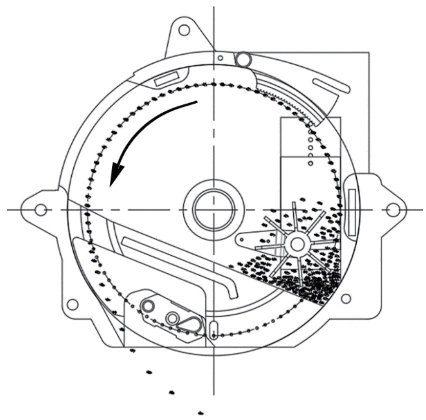


Figure 3 Movement process of carrot seeds in different regions

The main areas where carrot seeds were subjected to negative pressure forces in the seed drains were the filling, cleaning and carrying areas. Ideally, in the seed-filling area, each pore adsorbs a single seed, and the adsorbed seeds are mainly subjected to gravity, centrifugal force, friction between seed and population, and negative pressure adsorption. A large number of studies have shown that the frictional force between the seeds and the population after the seeds are adsorbed by the pore in the seed-filling area is greater than its own gravity, and that the seeds are subjected to the greatest force in the seed-filling area during the whole process of seed movement. Also, the critical negative pressure value of the seeds that can be effectively adsorbed is greater than in other working areas. In order to effectively obtain the critical negative pressure value for the smooth operation of the seed-metering device, a stress analysis study was carried out on the seed-filling area of the pneumatic seed-metering device.

2.4 Suction hole shape

The shape of the seeding plate hole is one of the important conditions to ensure that the carrot seeds are effectively absorbed by the hole[19]. Therefore, a simulation study of the shape of the hole of the seeding plate is needed to obtain the optimal hole shape for seeding carrot seeds. In order to facilitate the description of the airflow field of different positions of suction holes, the first suction hole corresponding to the seeding area is position 1 and the angle is recorded as 0°, and then the positions and angles are numbered in counter-clockwise direction, as shown in Figure 4.

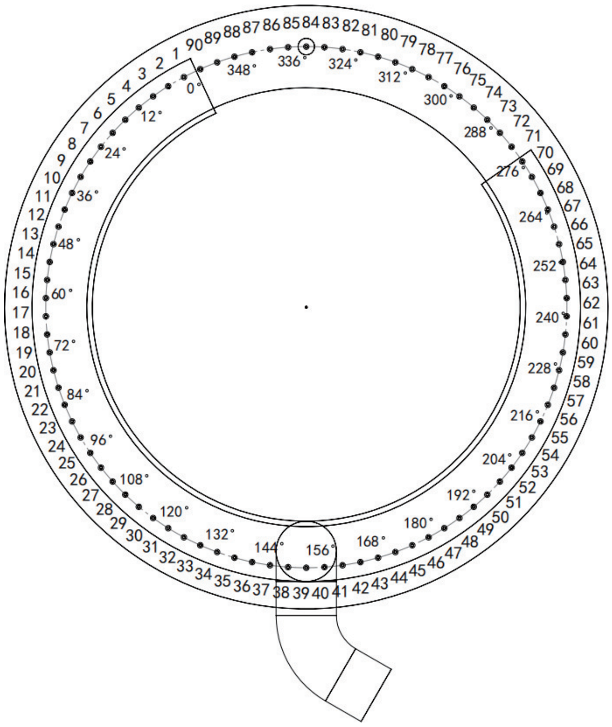


Figure 4 Suction hole number

A large number of scholars have pointed out that the thickness of the seeding plate has a greater influence on the pressure and speed at the suction surface of the hole, such that the smaller the thickness of the seeding plate, the greater the pressure and speed at the suction surface of the hole. The current process of seeding plate fabrication can be laser cut using 1 mm thin steel sheets. In order to determine the optimal hole shape, six different hole shapes were selected for airflow field simulation to investigate the effect of different hole shapes on the pressure of the suction surface, and the effect of different hole shapes on the pressure of the positive plugging area. Six different shapes of the hole were selected for the cylindrical hole, conical hole, countersunk hole, counterbore hole, bowl-shaped hole and bottle-shaped hole for airflow field simulation. The shapes of the holes are shown in Figure 5.

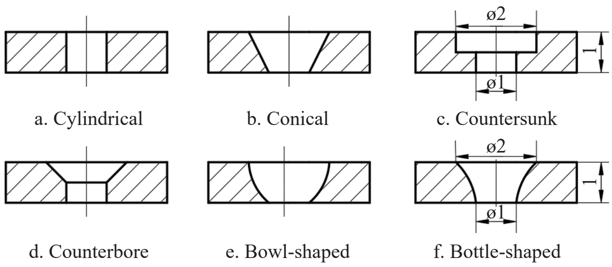


Figure 5 Different shapes of holes

When the number of holes was 90, the negative pressure was 1.5 kPa, the positive pressure was 0.6 kPa, and the rotational speed of the seeding plate was 2 rad/s. Numerical simulation of the airflow field under different shapes of holes on the seeding plate was also performed. The simulation results were analyzed by ANSYS 17.0 Software. The pressure clouds were analyzed at the overall suction surface of the intercepted airflow field $x = 0$ mm, the suction surface of the enlarged hole, the cleaning surface of the positive pressure position, and the axial surface.

2.4.1 Effect of different hole shapes on the pressure distribution

Figure 6 shows that the pressure nephogram of flow field under different hole shapes, the two enlarged parts are pressure nephogram of No.1 hole and positive pressure plugging removal position. It can be seen that the different shapes of the suction holes have a significant impact on the pressure of the seed suction surface and the plug removal surface. It can be seen from the enlarged pressure nephogram at the seed suction surface of No.1 hole with different shapes that the pressure distribution on the seed suction surface of the suction hole was not uniform, but the pressure distribution on the seed suction surface of different shape holes was similar. The pressure at the negative pressure seed suction surface was in the descending order of bottle-shaped hole, countersunk hole, bowl-shaped hole, conical hole, counterbore hole, cylindrical hole. The pressure at the positive pressure plugging removal was in the descending order of conical hole, bowl-shaped hole, counterbore hole, countersunk hole, bottle-shaped hole, cylindrical hole.

As shown in Figure 7, the axial pressure cloud patterns of different shapes of holes were different, whereby the pressure distribution in the air layer was almost hemispherical, and the hemispherical pressure distribution range was approximately the same. From the pressure clouds of cylindrical hole, conical hole and bowl-shaped hole, it can be seen that the maximum pressure in the holes was concentrated in the inner wall of the hole. The pressure distribution in the above three holes in contact with the negative pressure chamber was closer to the negative pressure chamber, the pressure distribution was more uniform. It was easy to stabilize the negative pressure of the suction surface of the above three holes. The negative pressure was concentrated in the central bend of the hole at the countersunk and bottle-shaped hole, which easily lead to the instability of the negative pressure on the suction surface of the hole, such that the countersunk and bottle-shaped holes were unreasonable.

As shown in Figure 8, the axial pressure nephogram of different shape holes were different, some of which did not even form a good positive pressure on the cleaning surface. On the cleaning surface of positive pressure in cylindrical hole, countersunk hole and bottle-shaped hole, the formation of pressure was very small. As such, there was airflow inside the holes to produce a small part of the negative pressure, which could not effectively clean the plugging. Conical holes and bowl-shaped holes exhibited a high pressure on the cleaning surface, and a certain positive pressure was formed on the cleaning surface. Also, an effective positive pressure cleaning range was formed on the air layer.

Through the analysis and comparison of the influence of different shapes of holes on gas flow field, the conical hole had obvious advantages in adsorption and plug removal compared with other shape holes, so the conical hole was adopted in the design of seed-metering device.

2.4.2 Effect of different hole shapes on the velocity distribution

As shown in Figures 9-11, the velocity cloud diagram under the overall and amplified axial cross-sections of the negative and positive cleaning holes was found to have a significant effect on the negative and positive cleaning holes by the different shapes of the

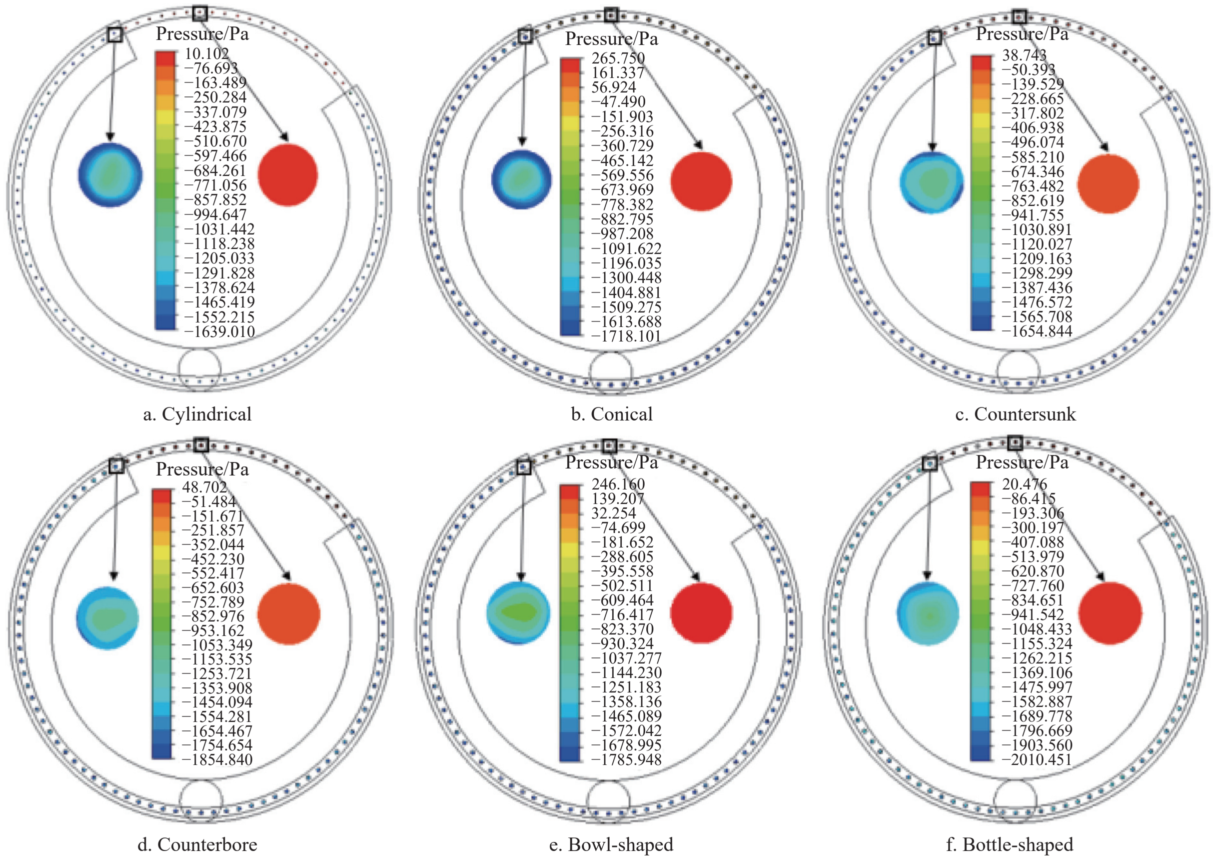


Figure 6 Flow field pressure contour at the suction hole surface with different hole types

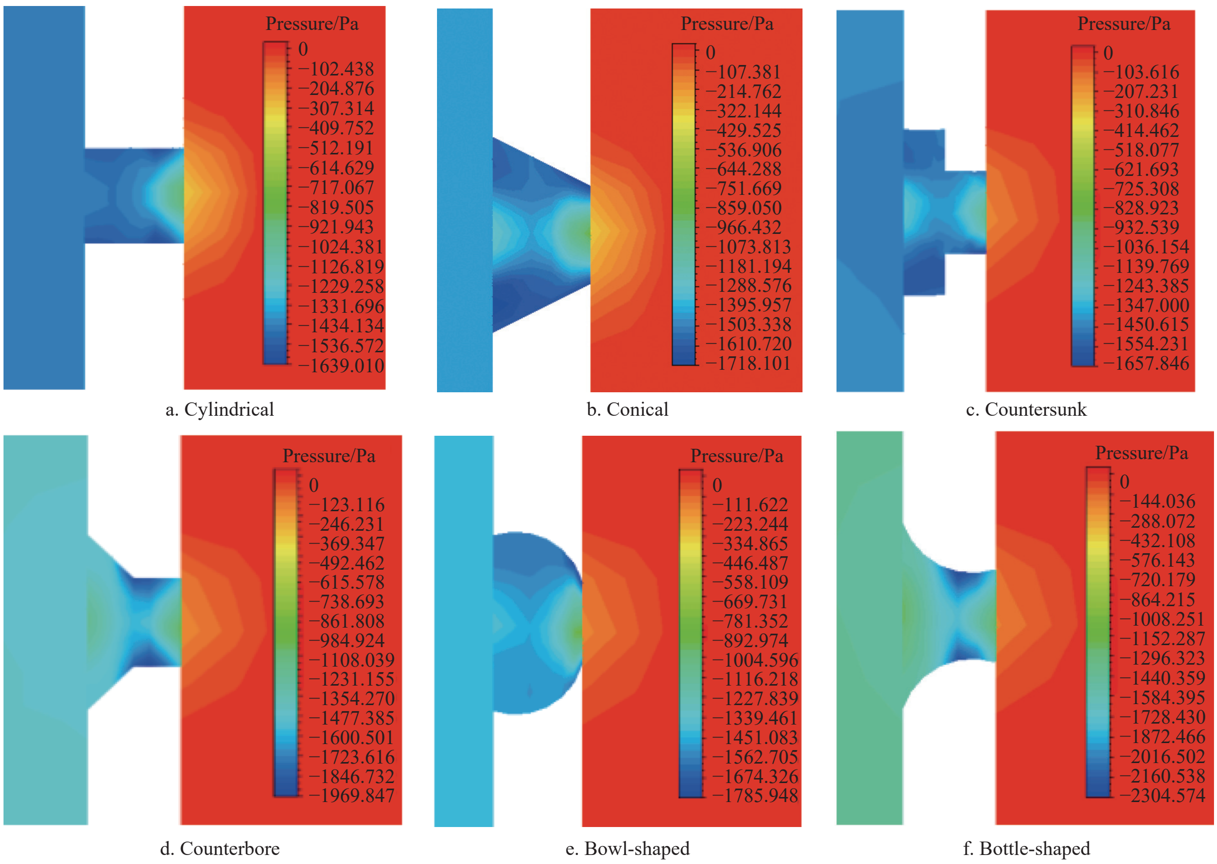
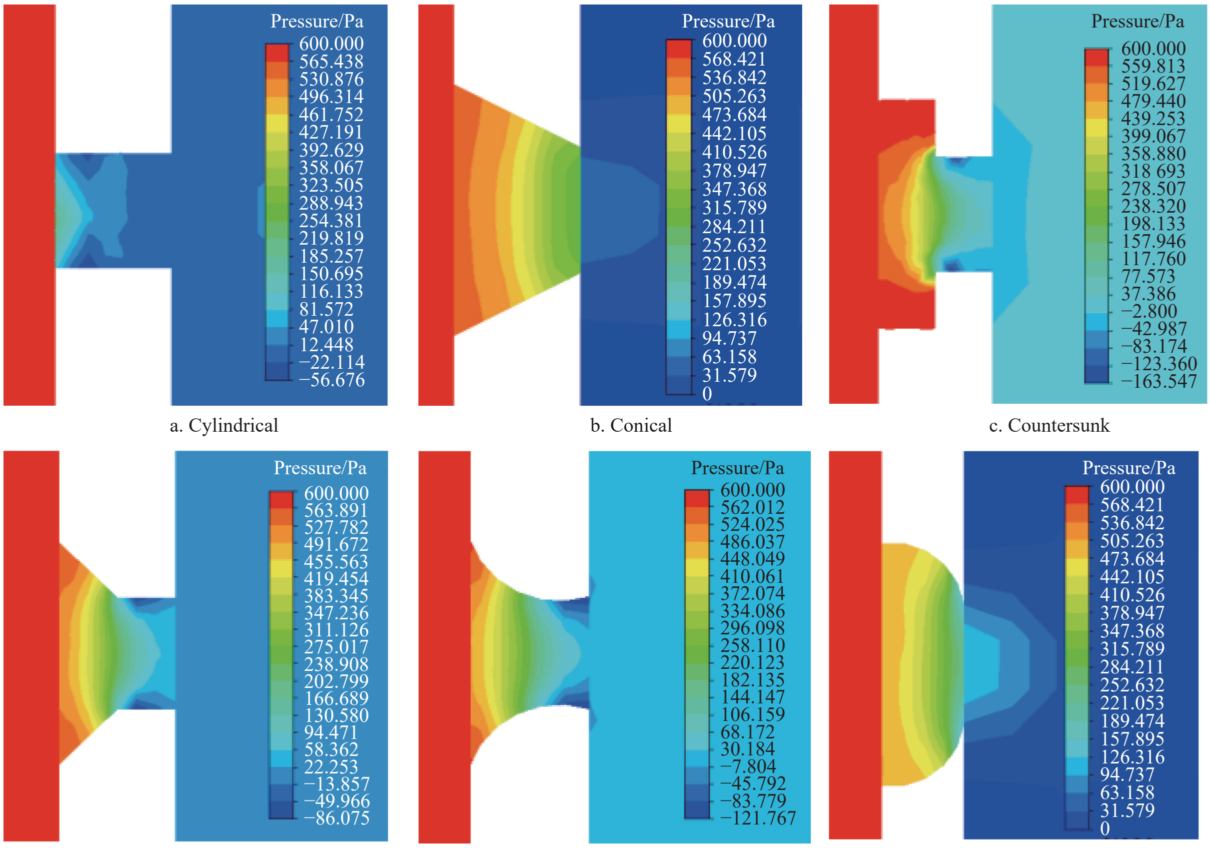


Figure 7 Pressure contour of axial surface of No.1 hole with different hole types

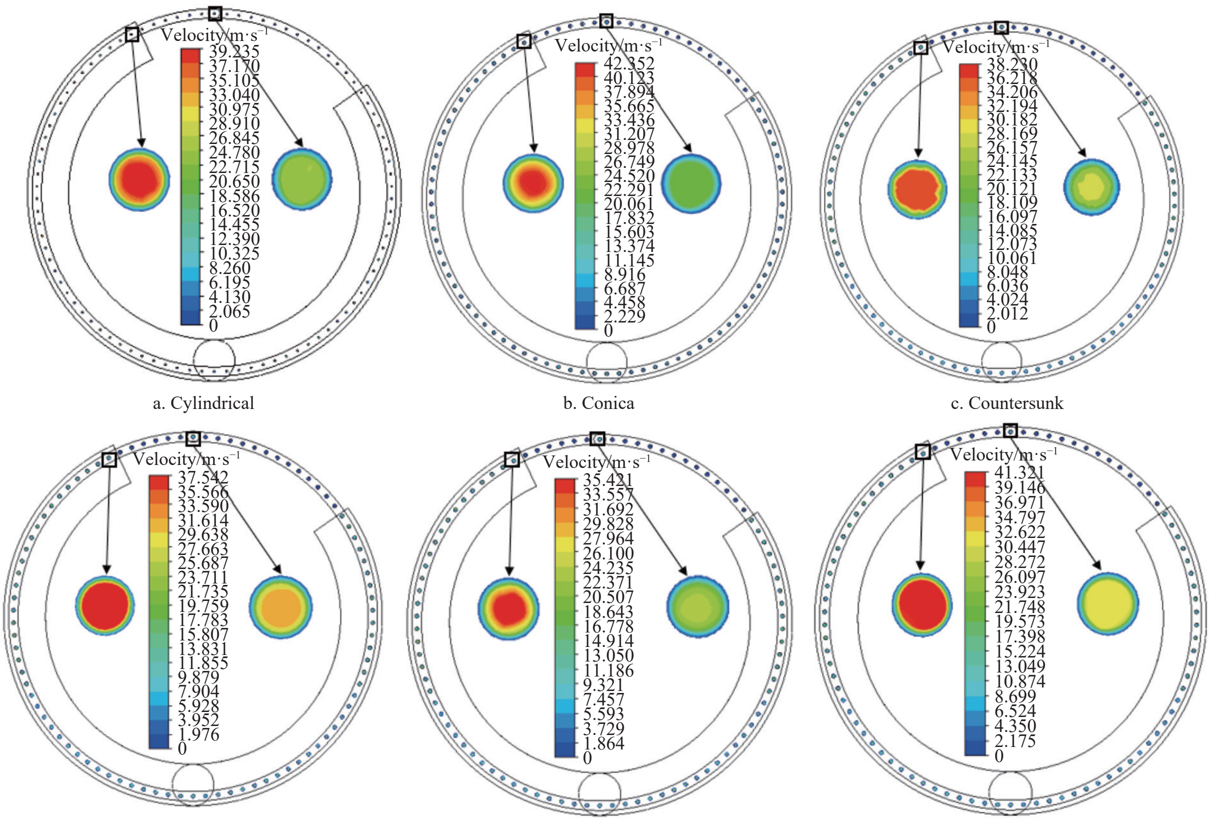
holes. From the overall velocity cloud diagram, it can be seen that the velocity distribution between the suction surface and the cleaning surface of the hole is relatively uniform, and the velocity distribution between the suction surface and the cleaning surface of the hole of different shapes is similar. From the local velocity cloud diagram of the axial cross-section of the negative pressure hole, the



a. Cylindrical b. Conical c. Countersunk

d. Counterbore e. Bowl-shaped f. Bottle-shaped

Figure 8 Pressure contour of axial surface of positive pressure hole with different hole types



a. Cylindrical b. Conica c. Countersunk

d. Counterbor e. Bowl-shape f. Bottle-shaped

Figure 9 Flow field velocity contour at the suction hole surface with different hole types

axial velocity cloud diagram of the different shapes of the hole is basically the same. A velocity distribution approximating the shape of a hemisphere is formed in the air layer, and the hemispherical velocity distribution is approximately the same in extent, with the velocity of the airflow being greater in most areas near the center of the aperture and gradually decreasing near the wall surface. When

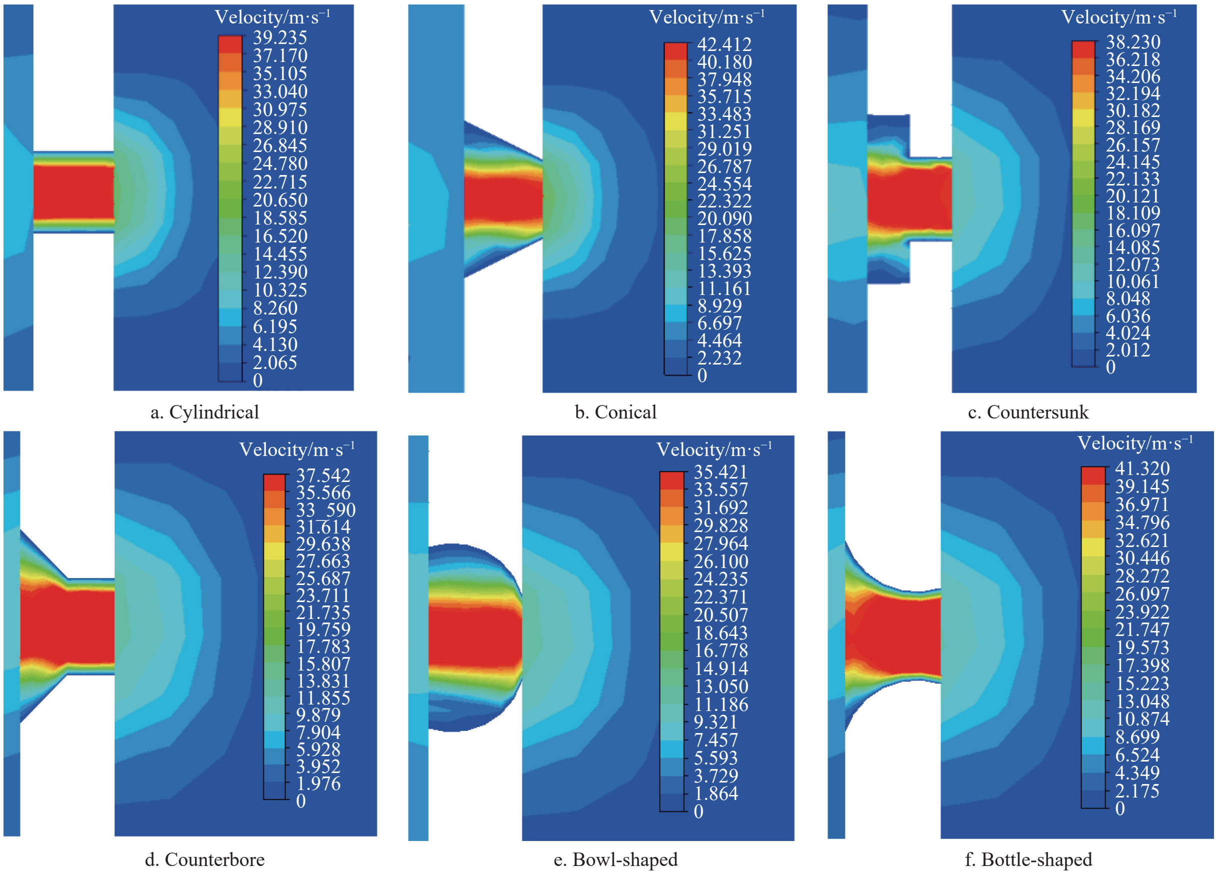


Figure 10 Velocity contour of axial surface of No.1 hole with different hole types

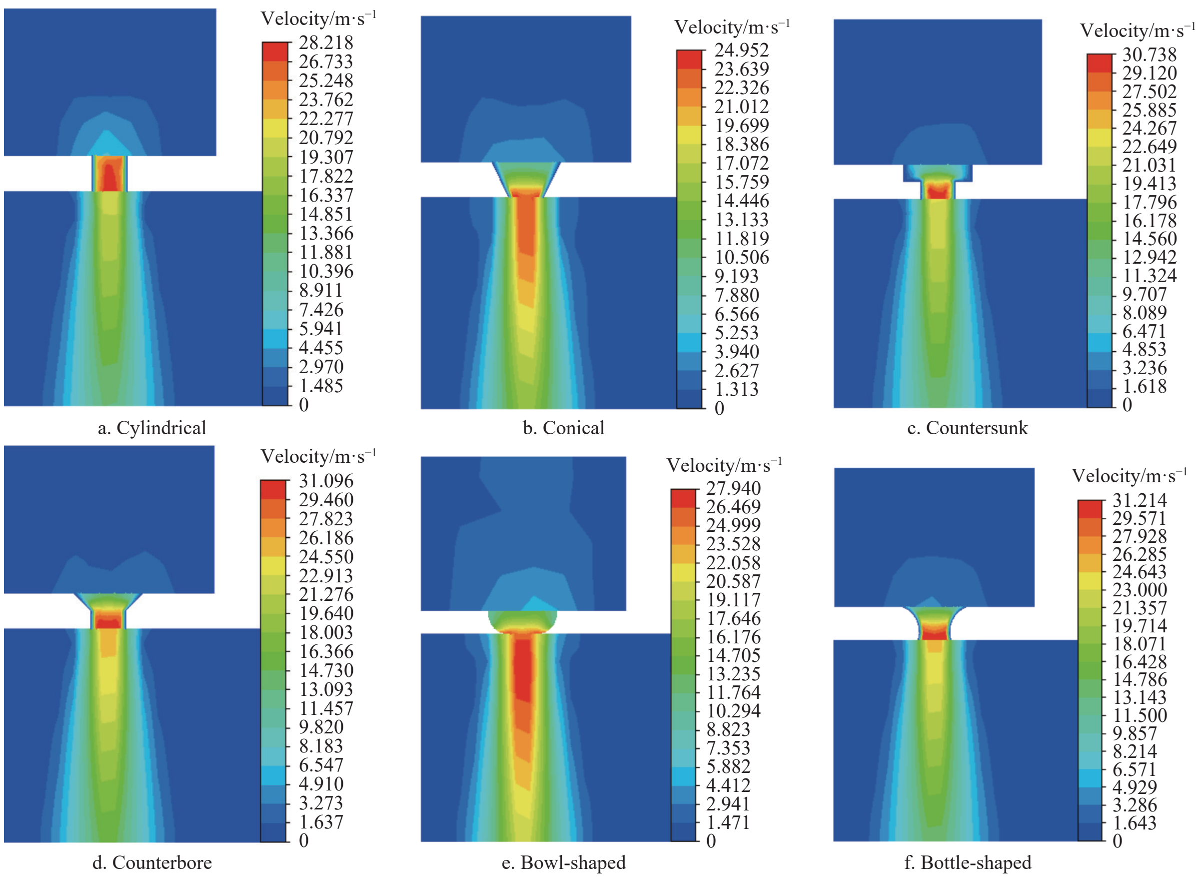
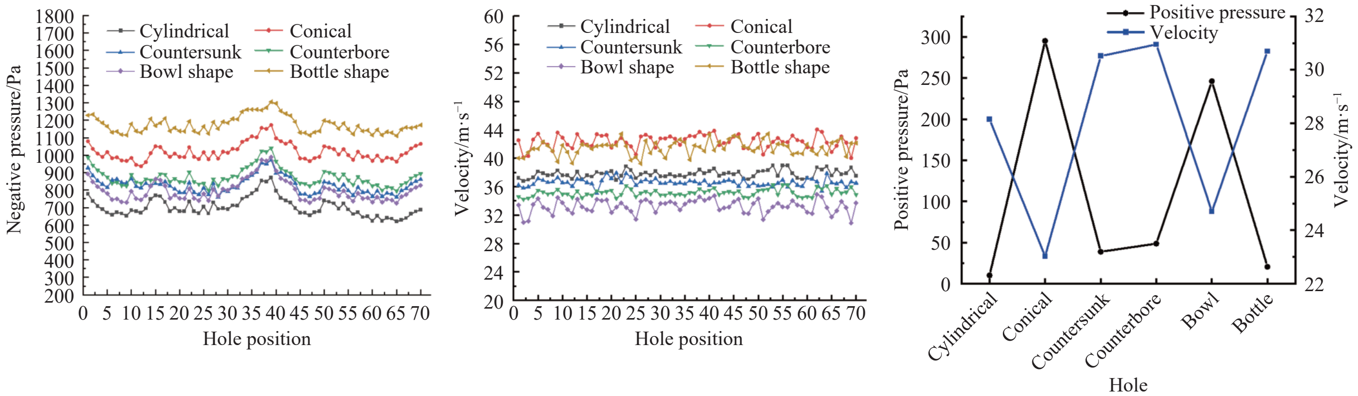


Figure 11 Velocity contour of axial surface of positive pressure hole with different hole types

the airflow passes quickly in the mold hole, the airflow in motion with the increase of the area of the mold hole cannot supplement the increased area in time, resulting in the area with the smallest velocity near the mold hole near the negative pressure air chamber being the largest. From the axial velocity diagram of the positive pressure hole, the axial velocity cloud diagram of different shapes holes are approximately the same, which can form an effective velocity influence range in the air layer. The overall clean speed of different holes is close, especially for conical holes with the bowl-shaped hole in the air layer showing a large red air velocity, it can achieve a better blocking effect.

As shown in Figure 12, in order to further analyze the influence of different shapes on the pressure and velocity of the hole, the pressure and velocity values at the suction surface of each negative pressure hole and the center point of the positive pressure cleaning and plugging hole are extracted for analysis. It can be seen from Figure 12a that there is a large difference in the overall negative pressure of the seed suction surface of different hole shapes. Under the same working conditions, the difference between the seed suction surface of the bottle-shaped hole with the largest overall negative pressure and the cylindrical hole with the smallest overall negative pressure is about 0.4 kPa, but the changing trend of the negative pressure of the seed suction surface of different shaped holes is basically similar. It can be seen from Figure 12b that there is a large gap in the overall speed of seed absorption surface of different hole shapes. Under the same working conditions, the difference between the seed absorption surface of conical hole with the largest overall speed and the bowl-shaped hole with the smallest overall negative pressure is about 10 m/s, and the changing trend of seed absorption surface speed of different hole shapes is different. It can be seen from Figure 12c that there is a large gap in the positive pressure of the cleaning and plugging surface of the holes with different hole shapes, but the speed of the cleaning and plugging surface of the holes with different hole shapes are relatively close. Under the same working conditions, the conical hole with the largest positive pressure is 0.3 kPa larger than the cylindrical hole with the smallest positive pressure, and the counterbore hole with the largest speed of the cleaning and plugging surface is about 8 m/s larger than the conical hole with the smallest speed of the cleaning and plugging surface.



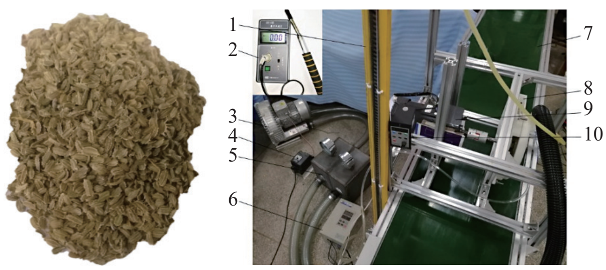
a. Negative pressure b. Velocity c. Negative pressure and velocity

Figure 12 Effect of the different shape hole number on the pressure and velocity of each hole

Through the comprehensive analysis of the influence of different shapes of holes on the airflow field, it can be found that the conical hole and the bottle-shaped hole are better than other holes in the negative pressure and velocity of the airflow field on the seed suction surface of the holes, and the airflow field inside the conical hole and the bowl-shaped hole is more stable; the positive pressure performance of the conical hole and the bowl-shaped hole on the plug removal surface of the holes has greater advantages than other holes; the comprehensive hole seed suction ability and plug removal capacity, the seed-metering device is designed with conical hole.

2.5 Experimental materials and equipment

Carrot seeds of the "Jinhong-6" category produced by the vegetable institute of Inner Mongolia Academy of agriculture and animal husbandry were used in the experiment. The designed seed-metering device was fabricated using mechanical processing and 3D printing technology, and placed on a test bench. The test bench consisted of a conveyor belt, conveyor belt motor, and transformer frequency converter. The speed of the conveyor belt was controlled by adjusting the frequency of the frequency converter. The seed-metering device was equipped with a frequency conversion motor which was controlled by a digital intelligent governor. A high-pressure vortex fan (model HG1500) with power of 1500 W was selected. The vortex machine provided negative pressure and positive pressure which were controlled by a frequency converter. The power of the frequency converter was 2200 W. The range of negative pressure gauge was from −10 to 0 kPa, and the positive pressure was 0-1 kPa. The air pressure at the air outlet was measured by a pressure gauge. The test materials and bench is shown in Figure 13.



a. Carrot seeds b. Test bench

1. U-meter 2. Digital anemometer 3. Fan 4. Fan governor 5. Wind pressure detection system 6. Conveyor frequency regulator 7. Conveyor belt 8. Seed-metering device 9. Motor 10. Regulator

Figure 13 Test materials and bench

2.6 Experimental methods and evaluation indicators

Refer to the national seeding standard GB/T 6973-2005 "Single-grain (precision) seed-metering device test method" which uses the qualified rate, missing rate and replaying rate to evaluate the seeding performance of the designed pneumatic seed-metering device. The seed cleaning degree, the seeding speed and the negative pressure, which have a great influence on the working performance of the seed-metering device, are selected as the test factors, and a better working parameter combination is sought for the quadratic rotation orthogonal combination test[20]. 180 seeds were measured continuously, and the average value was repeated three times in each group.

The performance test of the seed-metering device was duplicated three times under each group of data, and the mean was used as the experimental result[21]. Going by "GB/T6973-2005 Testing Methods of Single Seed (Precision Drills)", the qualified rate, missing rate and the replaying rate were selected as the evaluation index, and the calculation equations follows[22]:

$$\begin{cases} Q = \dfrac{N_1}{N} \times 100\% \\ M = \dfrac{N_2}{N} \times 100\% \\ C = \dfrac{N_3}{N} \times 100\% \end{cases} \tag{1}$$

where, Q is the qualified rate, %; M is missing rate, %; C is replaying rate, %; N_1 is the missing number; N_2 is the qualified number; N is the theoretical seeding numbers. The theoretical spacing is x (40-50 mm), and the distance between adjacent seeds on the conveyor belt is L. When $0.5x<L<1.5x$, it is qualified, and where $L>1.5x$, it is missed seeding.

3 Results and discussion

3.1 Single factor experimental design and analysis

3.1.1 Single factor experimental design

The pneumatic seed-metering device designed in this study has four operating parameters, including seed cleaning degree, seeding speed, negative pressure and the thickness of seeding plate. As the designed seed-metering device has a seed churning wheel, there is no fixed seeding plate thickness when the seed-metering device is in operation, so the three operating parameters of seed cleaning degree, seeding speed and negative pressure are mainly considered in the design of the single-factor test programme, as listed in Table 1.

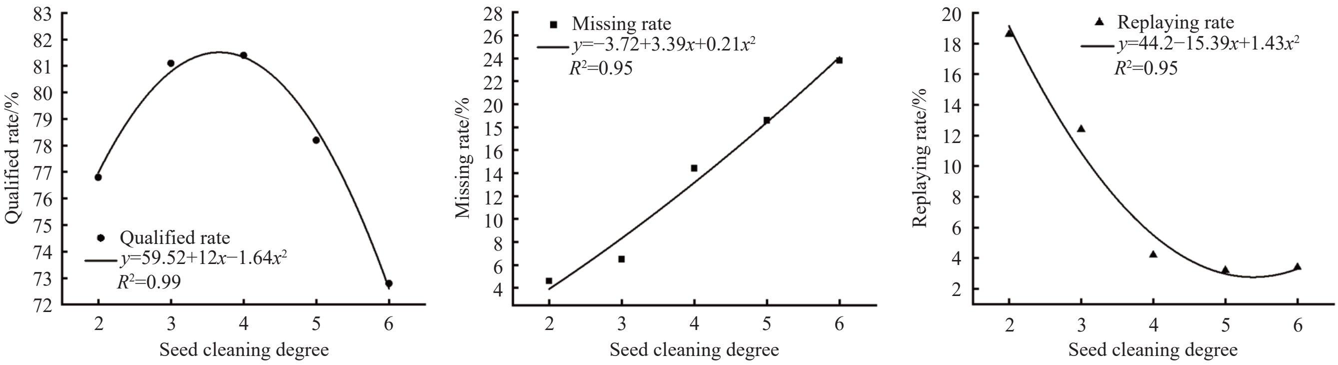
Table 1 Single factor experiment scheme

Level	X_1	X_2/km·h^{-1}	X_3/kPa
1	2	2	0.5
2	3	4	1.0
3	4	6	1.5
4	5	8	2.0
5	6	10	2.5

Note: X_1 is seed cleaning degree; X_2 is seeding speed; X_3 is negative pressure.

3.1.2 The effect of seed cleaning degree on seeding performance

Under the conditions of seeding speed and negative pressure of 6 km/h and 1.5 kPa respectively, different seed cleaning degrees of 2, 3, 4, 5, and 6 were used to test the seeding performance of the pneumatic seed-metering device. From Figure 14a, it can be seen that the qualified rate is increasing and then decreasing with the increase of seed cleaning degree, and when the seed cleaning degree is 4, the qualified rate is the highest, the curve fitting equation is y = 59.52+12x–1.64x^2, R^2 = 0.98. From Figure 14b, it can be seen that the missing rate is gradually increasing with the increase of seed cleaning degree, and when the seed cleaning degree is 6, the missing rate is the highest, the curve fitting equation is y = –3.72+3.39x+0.21x^2, R^2 = 0.95. From Figure 14c, it can be seen that the replaying rate tends to decrease gradually with the seed cleaning degree increases, and when the seed cleaning degree is 4-6, the replaying rate decreases slowly, the curve fitting equation is y = 44.2–15.39x+1.43x^2, R^2 = 0.95.



a. Qualified rate b. Missing rate c. Replaying rate

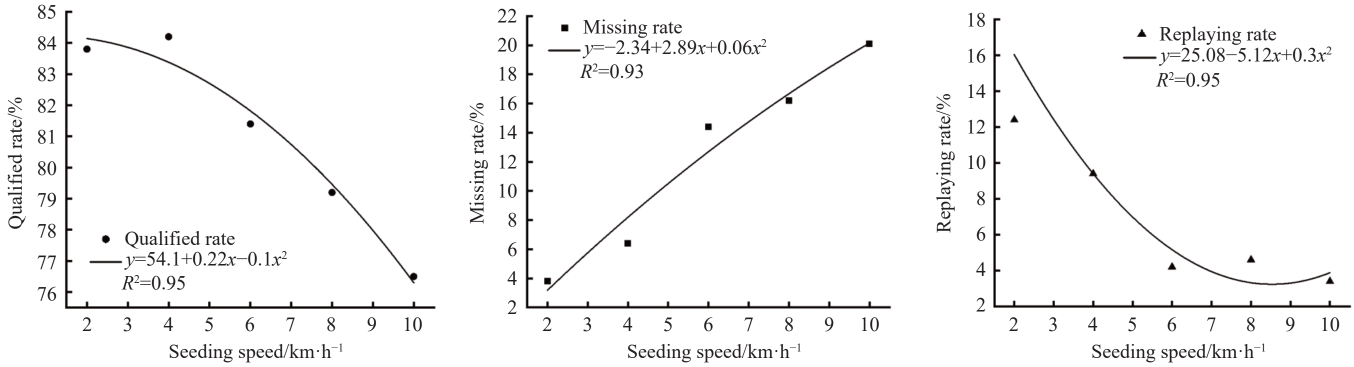
Figure 14 Effect of seed cleaning degree on qualified, missing and replaying rates

3.1.3 The effect of seeding speed on seeding performance

Under the conditions of seed cleaning degree and negative pressure at 4.0 and 1.5 kPa respectively, different seed cleaning speeds of 2 km/h, 4 km/h, 6 km/h, 8 km/h and 10 km/h were taken to test the seeding performance of the pneumatic seed-metering device respectively. From Figure 15a, it can be seen that the qualified rate gradually decreases with the increase of seeding speed, and when the seeding speed is 6-10 km/h, the qualified rate decreases significantly, the curve fitting equation is y = 54.1+ 0.22x–0.1x^2, R^2 = 0.95. From Figure 15b, it can be seen that the missing rate increases rapidly with the increase of seeding speed, and the curve fitting equation is y = –2.34+2.89x–0.06x^2, R^2 = 0.93. From Figure 15c, it can be seen that the replaying rate is gradually decreasing with the increase of seeding speed, and when the seeding speed is 6-10 km/h, the replaying rate is at a low level, the curve fitting equation is y = 25.08–5.12x+0.3x^2, R^2 = 0.95.

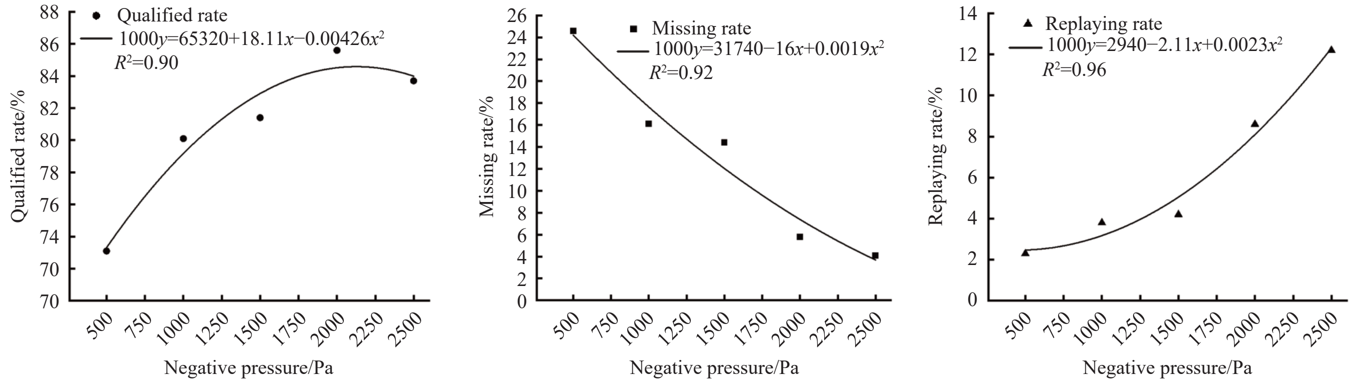
3.1.4 The effect of negative pressure on seeding performance

Under the conditions of seed cleaning and seeding speed at 4 and 6 km/h respectively, different negative pressure of 0.5 kPa, 1.0 kPa, 1.5 kPa, 2.0 kPa, and 2.5 kPa were used to test the seeding performance of the pneumatic seed-metering device. From Figure 16a, it can be seen that the qualified rate increases gradually with the increase of negative pressure, and when the negative pressure is between 1.5-2.5 kPa, the qualified rate increases slowly, the curve fitting equation is 1000y = 65 320+18.11x–0.004 26x^2, R^2 = 0.90. From Figure 16b, it can be seen that the missing rate decreases gradually with the increase of negative pressure, and the curve fitting equation is 1000y = 31 740–16x+0.0019x^2, R^2 = 0.92. From Figure 16c, it can be seen that the replaying rate is gradually increasing with the negative pressure increases, and when the negative pressure is 0.5-1.5 kPa, the replaying rate is at a low level, the curve fitting equation is 1000y = 2940–2.11x+0.0023x^2, R^2 = 0.96.



a. Qualified rate b. Missing rate c. Replaying rate

Figure 15 Effect of seeding speed on qualified, missing and replaying rates



a. Qualified rate b. Missing rate c. Replaying rate

Figure 16 Effect of negative pressure on qualified, missing and replaying rates

3.2 Central composite design experiment

3.2.1 Experimental scheme design

Based on the single-factor results and analyses of seed cleaning degree, seeding speed and negative pressure, the three factors have an influence on the seeding performance of the pneumatic seed-metering device. In order to investigate the interaction between seed cleaning degree, seeding speed and negative pressure, and to find a better combination of operating parameters, a quadratic rotation orthogonal combination test was carried out. The test factors and levels are listed in Table 2.

Table 2 Factors and levels of test

Level	X_1	X_2/km·h⁻¹	X_3/Pa
−1.682	2	2	500
−1	2.81(3)	3.62(3.60)	905.40(910)
0	4	6	1500
1	5.19(5)	8.38(8.40)	2094.60(2100)
1.682	6	10	2500

Note: "()" is revised parameter values; X_1 is seed cleaning degree; X_2 is seeding speed; X_3 is negative pressure.

3.2.2 Experimental design and results

In this study, the experimental results were analyzed using multiple regression fitting using Design-Expert 13.0 Software. A three-factor, five-level experiment was conducted, with the qualified rate、the missing rate and the replaying rate were selected as performance indicators. The experimental design and results are listed in Table 3.

3.2.3 Variance analysis of regression equation

The above date was imported into the Design-Expert 13.0 Software and processed to obtain the variance analysis results of the regression equations of various factors on the qualified rate, missing rate and replaying rate, as listed in Table 4.

Table 3 Experiment design and results

No.	Test factor			Performance indicators		
	X_1	X_2	X_3	Q/%	M/%	C/%
1	−1	−1	−1	78.2	12.3	9.5
2	1	−1	−1	73.6	23.3	3.1
3	−1	1	−1	76.4	16.9	6.7
4	1	1	−1	71.3	22.2	6.5
5	−1	−1	1	83.6	1.6	14.8
6	1	−1	1	78.9	10.7	10.4
7	−1	1	1	81.4	9.8	8.8
8	1	1	1	78.1	16.3	5.6
9	−1.682	0	0	76.8	4.6	18.6
10	1.682	0	0	72.8	23.8	3.4
11	0	−1.682	0	83.8	3.8	12.4
12	0	1.682	0	76.5	20.1	3.4
13	0	0	−1.682	73.1	24.6	2.3
14	0	0	1.682	83.7	4.1	12.2
15	0	0	0	81.4	14.4	4.2
16	0	0	0	82.6	8.4	9
17	0	0	0	85.1	3.4	11.5
18	0	0	0	83.6	12.3	4.1
19	0	0	0	81.5	4.6	13.9
20	0	0	0	82.3	13.1	4.6
21	0	0	0	84.5	11.4	4.1
22	0	0	0	85.7	8.7	5.6
23	0	0	0	83.2	11.5	5.3

Note: Q is qualified rate; M is missing rate; C is replaying rate.

Table 4 Variance analysis of regression model

Index	Source	Sum of square	df	*F*-value	*p*-value
Qualified rate (*Q*)	Model	391.90	9	19.65	<0.0001**
	X_1	43.69	1	19.71	0.0007**
	X_2	27.49	1	12.4	0.0038**
	X_3	119.08	1	53.72	<0.0001**
	X_1X_2	0.10	1	0.046	0.8341
	X_1X_3	0.36	1	0.16	0.693
	X_2X_3	0.15	1	0.068	0.798
	X_1^2	139.52	1	62.95	<0.0001**
	X_2^2	18.25	1	8.23	0.0132*
	X_3^2	45.41	1	20.49	0.0006**
	Residual	28.81	13		
	Lack of fit	9.94	5	0.84	0.5556
	Pure error	18.88	8		
	Cor Total	420.71	22		
Missing rate (*M*)	Model	937.40	9	8.55	0.0004**
	X_1	301.71	1	24.76	0.0003**
	X_2	146.39	1	12.01	0.0042**
	X_3	366.80	1	30.11	0.0001**
	X_1X_2	8.61	1	0.70	0.4157
	X_1X_3	0.06	1	0.01	0.9445
	X_2X_3	13.26	1	1.08	0.3158
	X_1^2	43.59	1	3.58	0.0810
	X_2^2	11.77	1	0.97	0.3434
	X_3^2	46.43	1	3.81	0.0728
	Residual	158.35	13		
	Lack of fit	43.44	5	0.61	0.6993
	Pure error	114.90	8		
	Cor Total	1095.75	22		
Replaying rate (*C*)	Model	281.68	9	2.75	0.0479*
	X_1	115.77	1	10.17	0.0071**
	X_2	47.00	1	4.13	0.0431*
	X_3	67.89	1	5.96	0.0296*
	X_1X_2	6.84	1	0.60	0.4519
	X_1X_3	0.12	1	0.01	0.9181
	X_2X_3	16.24	1	1.43	0.2535
	X_1^2	27.14	1	2.38	0.1465
	X_2^2	0.71	1	0.06	0.8072
	X_3^2	0.01	1	0.00	0.9824
	Residual	147.92	13		
	Lack of fit	40.85	5	0.61	0.6958
	Pure error	107.08	8		
	Cor Total	429.60	22		

Note: * represents significant difference ($0.01<p<0.05$); ** represents extremely significant diffience ($p<0.01$).

Design-Expert 13.0 Software was used to perform variance analysis on the test data table 4, and the regression model equations for the effects of seed cleaning degree, seeding speed and negative pressure on the qualified rate (*Q*), missing rate (*M*) and replaying rate (*C*) were obtained by removing the insignificant factors as shown in Equation (2). The regression model F can be used to derive the seed cleaning degree, seeding speed and negative pressure that affect the qualified rate, the missing rate and the replaying rate.

$$\begin{cases} Q = 37.99 + 14.57X_1 + 14.57X_2 + 17.53\times10^{-3}X_3 \\ -2.10X_1^2 - 0.19X_2^2 - 4.78\times10^{-6}X_3^2 \\ M = 32.50 - 3.03X_1 - 0.35X_2 - 28.12\times10^{-3}X_3 + 1.17X_1^2 \\ C = 29.51 - 11.54X_1 - 1.02X_2 + 10.66\times10^{-3}X_3 \end{cases} \tag{2}$$

3.3 Response surface analysis

3.3.1 Interactive effects of different factors on qualified rate

The experimental data was processed using Design-Expert 13.0 Software to obtain performance indicators in relation to the experimental factors. The effect of the interaction between the experimental factors on the qualified rate was analyzed using the dimension reduction method and the corresponding contour plots and response surfaces were plotted, as shown in Figure 17.

It can be seen from Figures 17a and 17d that when the negative pressure is at the central level of 1.5 kPa, the qualified rate first increases rapidly and then decreases gradually with the increase of seeding speed when the seed cleaning degree is constant. When the seeding speed is in the range of 2-6 km/h, the rotational speed of the seeding plate is relatively small, the contact time between the typed hole and the seed filling area is longer, which is conducive to the seed filling of the typed hole, the qualified rate is higher and the missing rate is lower. When the seeding speed is greater than 6 km/h, the rotational speed of the seeding plate is larger, the contact time between the typed hole and the seed filling area is shorter, which is not conducive to the typed hole filling, the qualified rate gradually decreases and the missing rate increases. When the seeding speed is constant, the qualified rate first increases and then decreases with the increase of seed cleaning degree. When the seed cleaning degree is below 3, the distance between the seed cleaning plate and the typed hole is relatively large, the seed cleaning device cannot effectively clean the re-absorbed hole, resulting in a lower qualified rate and a higher replaying rate. When the seed cleaning degree is in the range of 5-6, the distance between the seed cleaning plate and the typed hole is relatively small, the seed cleaning capacity of the seed cleaning device increases, and it is likely that all the seeds on the typed hole will be cleaned, resulting in a sharp decrease in the qualified rate and a rapid increase in missing rate. The qualified rate is higher than 82% when the seed cleaning degree is in the range of 3-4 and the seeding speed is in the range of 4-6 km/h. The interaction between the seed cleaning degree and the seeding speed has a significant effect on the qualified rate.

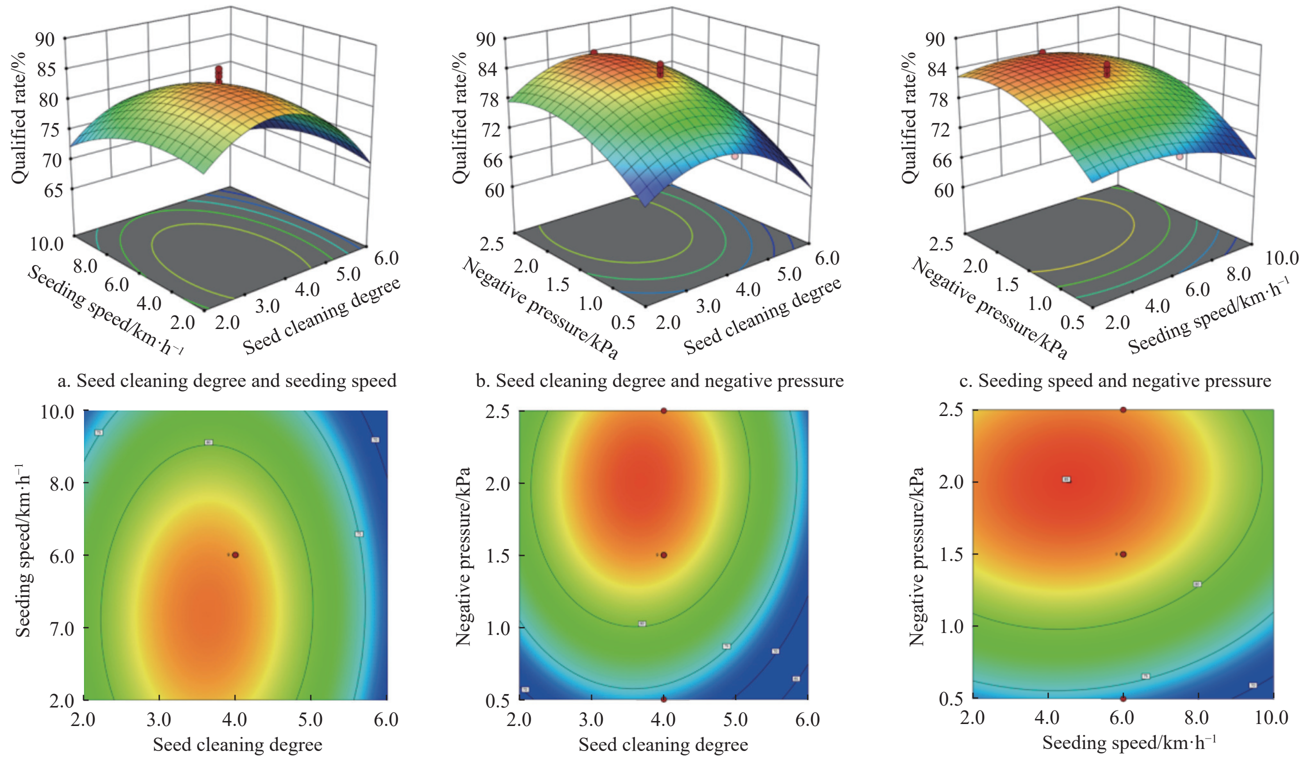
It can be seen from Figures 17b and 17e that when the seeding speed is at the central level of 6 km/h, the qualified rate first gradually increases and then decreases with the increase of the negative pressure when the seed cleaning degree is constant. When the negative pressure is in the range of 0.5-1.5 kPa, the negative pressure on the hole of the seeding plate is relatively small, resulting in the lower qualified rate and the higher missing rate. When the negative pressure is constant, the qualified rate first increases and then decreases with the increase of seed cleaning degree. The qualified rate is as high as 84% when the negative pressure is in the range of 1.5-2.0 kPa and the seed cleaning degree is in the range of 3-5. The interaction between seed cleaning degree and negative pressure has a significant effect on the qualified rate.

It can be seen from Figures 17c and 17f that when the seed cleaning degree is at the central level of 4, the qualified rate first gradually increases and then decreases a little with the increase of the negative pressure when the seeding speed is constant. When the negative pressure is in the range of 1.5-2.5 kPa, the negative pressure on the typed hole of the seeding plate is larger, resulting in the higher qualified rate and the lower missing rate. When the negative pressure is constant, the qualified rate increases first and then decreases rapidly with the increase of seeding speed. The qualified rate can be close to 85% at the highest when the negative pressure is around 2.0 kPa, and the seeding speed is around 5 km/h, The interaction between the seeding speed and the negative pressure has a significant effect on the qualified rate.

3.3.2 Interactive effects of different factors on missing rate

The interactive effect of seed cleaning degree, seeding speed and negative pressure on missing rate of the seeding was analyzed and the corresponding contour plots and response surfaces were plotted, as shown in Figure 18.

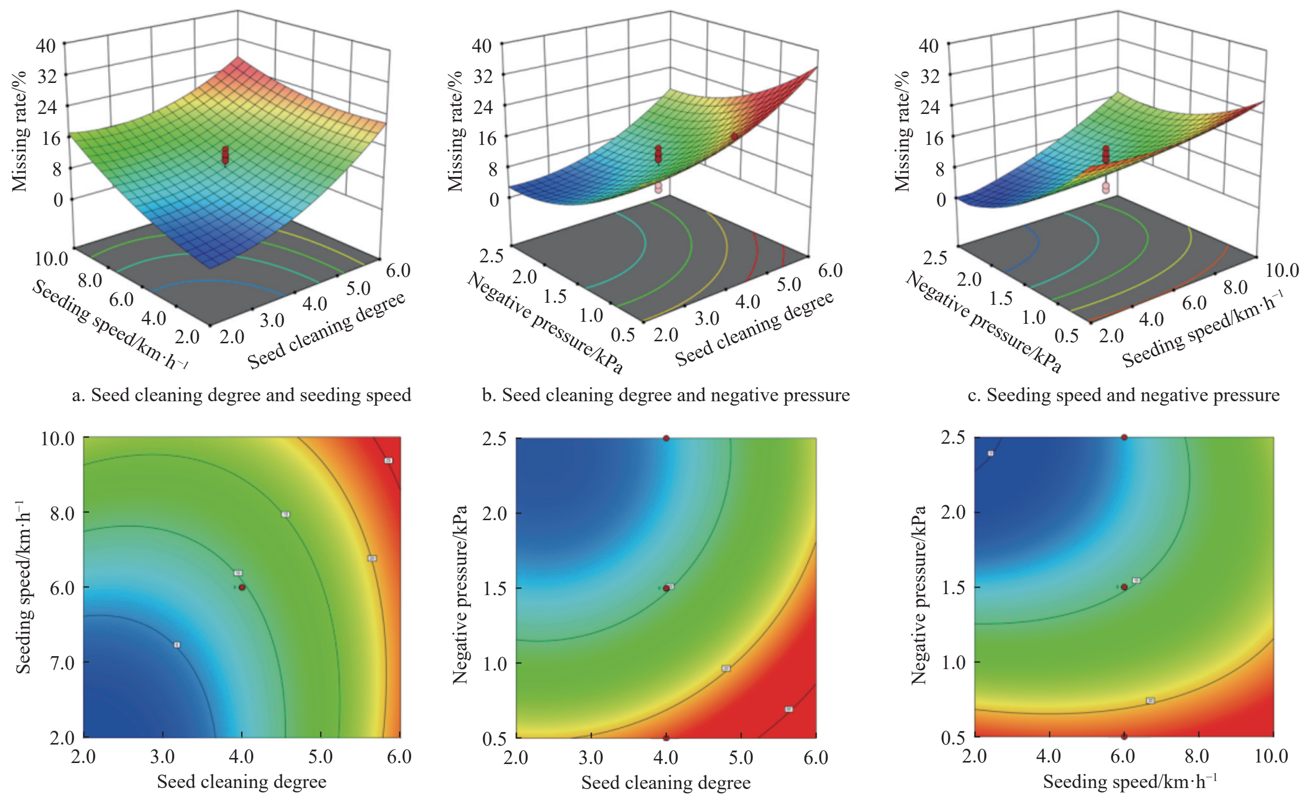
As shown in Figures 18a and 18d, when the negative pressure is at the central level of 1.5 kPa, the missing rate gradually increases with the increase of the seeding speed when the seed cleaning degree is constant. When the seeding speed is constant, the missing rate increases gradually with the increase of the seed cleaning



a. Seed cleaning degree and seeding speed b. Seed cleaning degree and negative pressure c. Seeding speed and negative pressure

d. Seed cleaning degree and seeding speed e. Seed cleaning degree and negative pressure f. Seeding speed and negative pressure

Figure 17 Effects of different parameters on the qualified rate



a. Seed cleaning degree and seeding speed b. Seed cleaning degree and negative pressure c. Seeding speed and negative pressure

d. Seed cleaning degree and seeding speed e. Seed cleaning degree and negative pressure f. Seeding speed and negative pressure

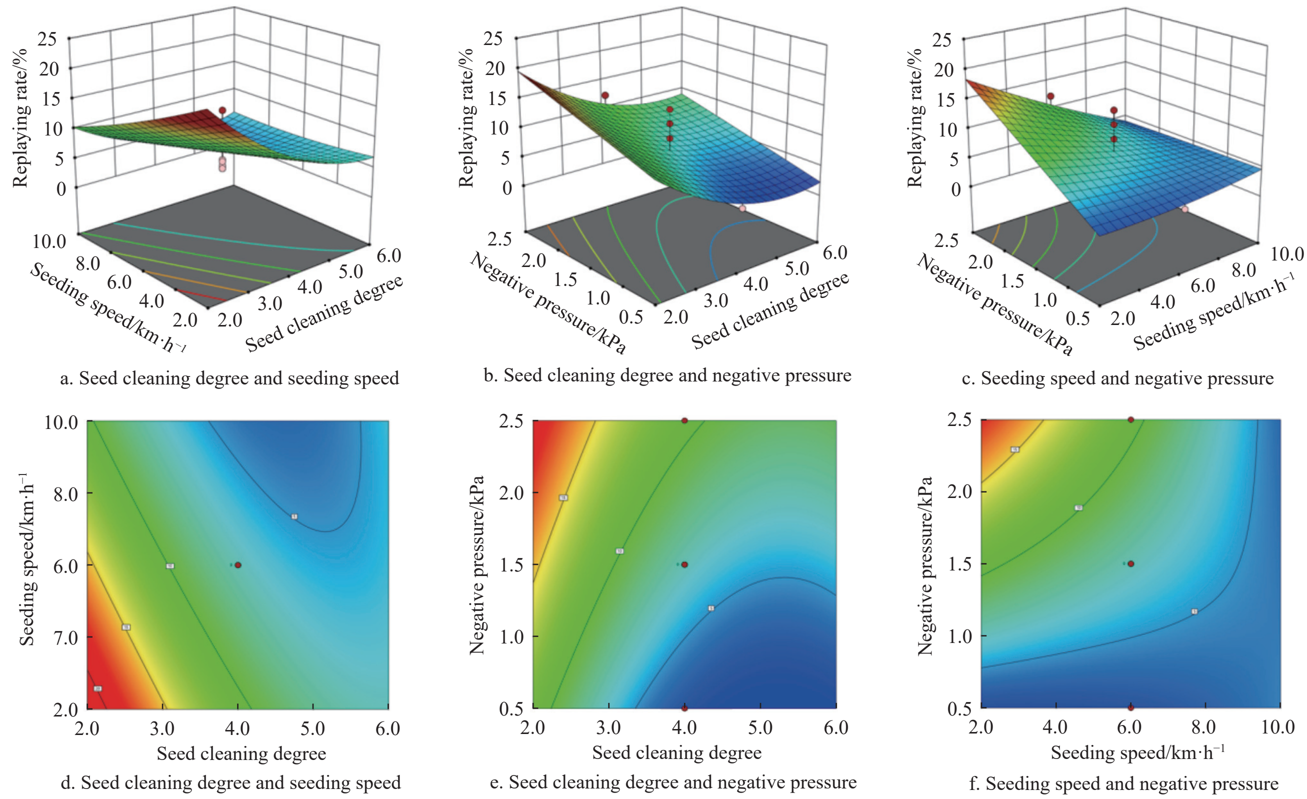
Figure 18 Effect of different parameters on the missing rate degree. The missing rate is low to below 3% when the seed cleaning degree is in the range of 2-3 and the seeding speed is in the range of 2-4 km/h. The interaction between the seed cleaning degree and the seeding speed has a significant effect on the missing rate.

As shown in Figures 18b and 18e, when the seeding speed is at the central level of 6 km/h, the missing rate gradually decreases with the increase of the negative pressure when the seed cleaning degree is constant. When the negative pressure is constant, the missing rate gradually increases with the increase of seed cleaning degree. The missing rate can be as low as 3% when the negative pressure is in the range of 2.0-2.5 kPa and the seed cleaning degree is in the range of 2-3. The interaction between the seed cleaning degree and the negative pressure has a significant effect on the missing rate.

As shown in Figures 18c and 18f, when the seed cleaning degree is at the central level of 4, the missing rate decreases with the increase of negative pressure when the seeding speed is constant. When the negative pressure is constant, the missing rate gradually increases with the increase of seeding speed. The minimum missing rate can be less than 2% when the negative pressure is in the range of 2.0-2.5 kPa and the seeding speed is in the range of 2-4 km/h. The interaction between the seeding speed and the negative pressure has a significant effect on the missing rate.

3.3.3 Interactive effects of different factors on replaying rate

The interactive effect of seed cleaning degree, seeding speed and negative pressure on replaying rate of the seeding was analyzed and the corresponding contour plots and response surfaces were plotted, as shown in Figure 19.



a. Seed cleaning degree and seeding speed
b. Seed cleaning degree and negative pressure
c. Seeding speed and negative pressure
d. Seed cleaning degree and seeding speed
e. Seed cleaning degree and negative pressure
f. Seeding speed and negative pressure

Figure 19 Effect of different parameters on the replaying rate

As shown in Figures 19a and 19d, when the negative pressure is at the central level of 1.5 kPa, the replaying rate decreases slowly with the increase of seeding speed when the seed cleaning degree is constant. When the seeding speed is constant, the replaying rate decreases with the increase of seed cleaning degree. The replaying rate is as low as 5% or less when the seed cleaning degree is in the range of 4-6 and the seeding speed is in the range of 7-10 km/h. The interaction between seed cleaning degree and seeding speed has a significant effect on the replaying rate.

As shown in Figures 19b and 19e, when the seeding speed is at the central level of 6 km/h, the replaying rate gradually increases with the increase of negative pressure when the seed cleaning degree is constant. When the negative pressure is constant, the replaying rate decreases with the increase of seed cleaning degree. The replaying rate can be as low as 3% when the negative pressure is in the range of 0.5-1.0 kPa and the seed cleaning degree is in the range of 4-6. The interaction between the seed cleaning degree and the negative pressure has a significant effect on the replaying rate.

As shown in Figures 19c and 19f, when the seed cleaning degree is at the central level of 4, the replaying rate gradually increases with the increase of negative pressure when the seeding speed is constant. When the negative pressure is constant, the replaying rate gradually decreases with the increase of the seeding speed. The replaying rate can be as low as 3% when the negative pressure is around 0.5 kPa and the seeding speed is in the range of 2-4 km/h. The interaction between seeding speed and negative pressure has a significant effect on the replaying rate.

3.4 Parameter optimization and experiment verification

3.4.1 Parameters optimization

The design of the pneumatic seed-metering device is optimized by means of a quadratic rotation orthogonal combination of tests and analyses, in which the seed cleaning degree, seeding speed, and negative pressure are within a certain range. In order to obtain the optimum test combination parameters, the Design-Expert optimization module[23] was used to optimize the test results. By selecting the constraint interval several times, the final selection constraint is shown in Equation (3). When the seed cleaning degree is a fixed value of 4, the optimization target is the qualified rate of more than 85%, the missing rate of less than 4.3% and the replaying rate of less than 10.8%. As shown in Figure 20, the yellow area is the optimal combination of parameters, the seeding speed in this area is 4.5-4.6 km/h, and the negative pressure is 1.99-2.02 kPa.

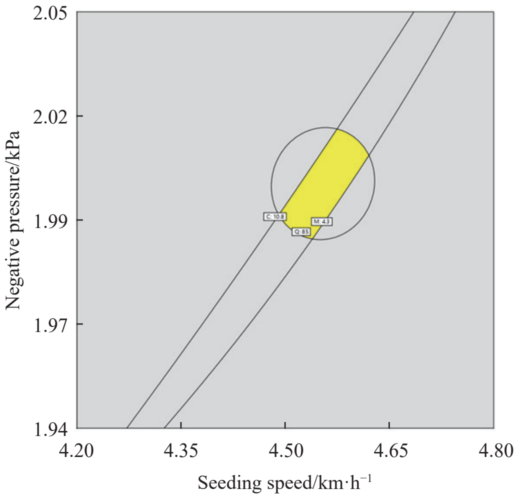


Figure 20 Parametric optimization results.

$$\begin{cases} 85\% \le Q(X_1,X_2,X_3) \le 100\% \\ 0 \le M(X_1,X_2,X_3) \le 4.3\% \\ 0 \le C(X_1,X_2,X_3) \le 10.8\% \\ \text{s.t.} \begin{cases} X_1 = 4 \\ 2\ \text{km/h} \le X_2 \le 10\ \text{km/h} \\ 0.5\ \text{kPa} \le X_3 \le 2.5\ \text{kPa} \end{cases} \end{cases} \tag{3}$$

3.4.2 Experiment verification

According to the obtained optimization parameter results, the seed cleaning degree is 4, the seeding speed is 4.5 km/h, the negative pressure is 2.0 kPa, the experiment is repeated three times, and the average value is taken as the final result of verification, as shown in Table 5. It can be seen from the test results that the average qualified rate is 85.24%, the average missing rate is 2.81%, and the average replaying rate is 11.95%.

Table 5 Test results

No.	Qualified rate/%	Missing rate/%	Replaying rate/%
1	85.52	2.36	12.12
2	85.26	3.24	11.5
3	84.94	2.84	12.22
Average value	85.24	2.81	11.95

4 Conclusions

In this study, a novel pneumatic precision seed-metering device was designed for carrot seeds, a simulation model of gas-solid two-phase flow was established, and the effect of different shapes of suction holes on pressure distribution and velocity distribution in gas-solid two-phase flow coupling simulation was analyzed. The effect of seed cleaning degree, seeding speed and negative pressure on the performance of seed-metering device was investigated. The main conclusions were as follows:

1) Owing to the small size, light weight, irregular shape of the carrot seeds, and the impurities in the population, a pneumatic carrot precision seed-metering device with good seeding performance and suitable for high-speed operation was designed. The overall structure and working principle of the seed-metering device were explained. It had five working processes: auxiliary seed filling in seed-filling area, collision seed cleaning in seed-cleaning area, single seed carrying in seed-carrying area, gravity and collision seed dropping in seed-dropping area, and positive pressure clearing in plug clearing area.

2) The ANSYS 17.0 Software was used to simulate the shape of the seeding plate hole, and the pressure distribution and velocity distribution of different shapes of suction holes on the suction surface and the plugging surface of the flow field were analyzed. It was concluded that the conical hole was better than other types of holes.

3) The single-factor experiments have determined that seed cleaning degree, seeding speed and negative pressure are the main factors influencing the performance of the seed-metering device. The qualified rate, missing rate and replaying rate were selected as the experiment performance indicators and a three-factor, five-level central composite design experiment was carried out.

4) The optimum operating parameters were determined by parameter optimization to be the seed cleaning degree of 4, the seeding speed of 4.5 km/h and the negative pressure of 2.0 kPa. The bench validation tests showed the average qualified rate of 81.48%, the average missing rate of 4.07% and the average replay rate of 14.45%, respectively, which provide a strong reference for the design of carrot precision seed-metering device.

Acknowledgements

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