EFFECT OF SEED FILLING AND RELEASING ANGLES ON THE PERFORMANCE OF COMPOUND VACUUM SEED METERING DEVICE
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充投种角度对复合气吸式排种器作业性能的影响规律

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ABSTRACT
In this paper, taking compound air-suction seed metering device as the subject, the effect rule of seed filling angle and seed releasing angle on the performance of seed filling and seed metering is studied. An indoor test was conducted with a JPS-12 metering test bench and a high-speed camera system. The starting and ending angles of the air chamber were changed by adjusting the regulating plate, that is, the angles of seed filling and seed releasing, and the filling and seed metering performance was taken as evaluation indexes. The test results show that: the seed filling angle has significant effect on the seed filling effect, and the miss fill index decreases with the increase of the quality of fill index. When the seed filling angle exceeds 50°, they will stabilize gradually ending at the multiple fill index of 0%. The negative pressure and operating speed are interactive and have a significant effect on filling performance. The seed releasing angle has significant effect on the metering performance. With the increase of the angle, the quality of feed index increases firstly and then decreases. The multiple index and miss index are opposite to the quality of feed index which is the max at the seed releasing angle of 39.5°. The negative pressure and forward speed are interactive and have a significant effect on metering performance. The quality of feed index under the same condition is lower than that of fill index.

摘要
本文以气吸式复合排种器为对象，研究充种和投种角度对充种性能和排种性能的影响规律。利用 JPS-12 排种试验台和高速摄像系统开展室内试验；通过气室调整盘改变气室的起止角度，即充种和投种的角度，以充种性能和排种性能作为评价指标。结果表明：充种角度对充种效果具有显著影响，充种合格率逐渐增大，漏充率逐渐减小，当充种角大于 50°后，二者逐渐稳定，而重充率始终为 0%，负压和作业速度对充种性能具有显著影响，且二者之间存在交互作用；投种角度对排种性能具有显著影响，随着角度的增大，合格率先升高后降低，重播率和漏播率与合格率呈现相反的变化规律，合格率最大时的投种角度为 39.5°，负压与前进速度对排种性能具有显著影响，且二者之间存在交互作用；相同条件下的排种合格率低于充种合格率。

INTRODUCTION
The seed metering device is a core part of precision seeding which is the main development direction of seeding technologies. By the principles, the seed metering devices can be divided into mechanical and pneumatic type devices, among which, the air-suction seed metering device is a research hotspot at present (*Dylan et al., 2013; Jia et al., 2018; Singh et al., 2007; Wang et al., 2017; Yang et al., 2016*). Most studies on air-suction seed metering device focus on the effect rule of the design of physical dimension of the seed-picking mechanism (*Cujbescu et al., 2019; Liao et al., 2018*), negative pressure value and forward speed and working parameters on the metering performance, or on optimizing seed metering devices for different seeds (*Zhang et al., 2015; Zhang et al., 2020*), such as corn, sunflower seeds, peanuts, rape seeds and millet seeds (*Ding et al., 2018;Yu et al., 2014; Yu et al., 2015; Zhang et al., 2014*).

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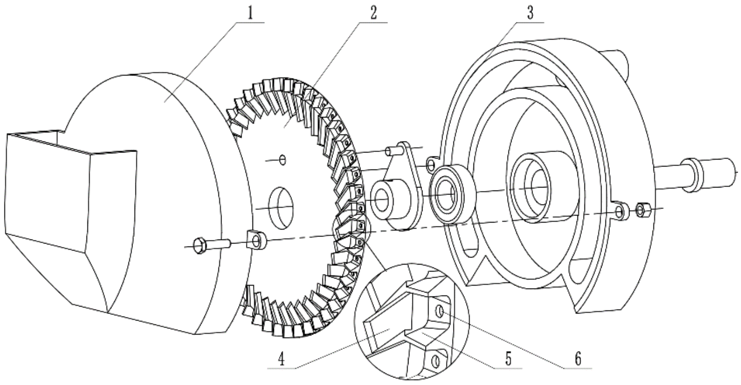
At the same time, some researchers focused on the process of seed falling and touching soil, and optimized the seed releasing angle and the shape of seed tube to improve the consistency of seed spacing (*Abdolahzare et al., 2018; Karayel et al., 2006; Zhao et al., 2016*). In the early stage, the author designed a compound air-suction seed metering device, optimized the seed hole mechanism, and reduced the negative pressure of the air-suction seed metering device (*Chen et al., 2021*).

However, there are few in-depth studies on seed filling and releasing angles. The seed filling angle has significant effect on the filling effect and subsequent seed clearing, and the seed releasing angle has a significant effect on the height, speed and direction when seeds are released from the disk. The design of a suitable seed releasing angle is of great significance to improve the seed-metering performance. Therefore, the seed filling and releasing angles will be studied deeply in this paper by taking the compound air-suction seed metering device as the subject.

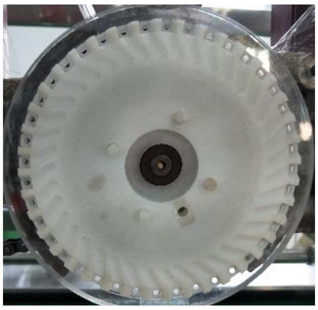
MATERIALS AND METHODS

Vacuum seed metering device

The compound air-suction seed metering device (*Chen et al., 2021*) is equipped with an innovative disk which is a 7 mm thick plastic disk with several seed-stirring slots and seed-picking slots evenly distributed on the periphery (Fig. 1). There is a suction hole at the bottom of the seed-picking slot. The seed-picking structure of the disk is composed of seed-stirring slots, seed hole and suction hole. The seed-stirring slots are used to stir seeds to increase the dispersion degree of seed groups and to guide the movement of the seed hole. When the seed hole passes the seed group, seeds will enter the seed hole under the gravity and the internal force of the seed group, and the suction hole at the bottom of the seed hole will suck seeds under the negative pressure to fix seeds at the bottom of the seed hole. The structure can effectively improve the success rate of seed picking and reduce the negative pressure required during operation.



a. Structural diagram of vacuum seed metering device with composite disc



b. Physical diagram of composite disc

Fig. 1 - Vacuum seed metering device and composite disc

1. Shell; 2. Disc; 3. Base; 4. Seed agitator; 5. Seed hole; 6. Suction hole

Test plan

The test was carried out on the JPS-12 test bench (Fig. 2), which has been widely used in studies of seed metering devices *(Zhang et al., 2015; Zhao et al., 2016)*.

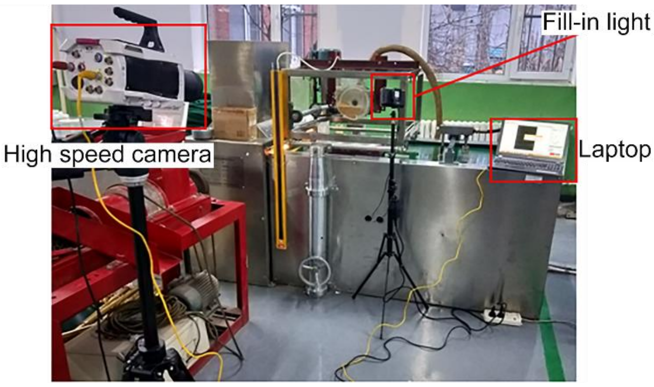


Fig. 2 - Indoor test system

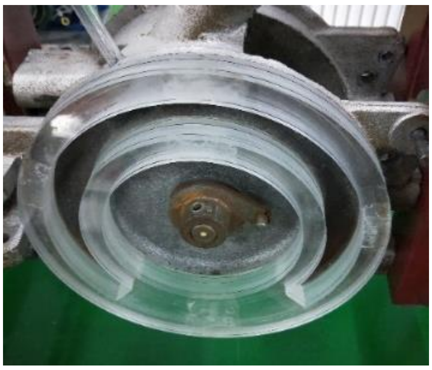


Fig. 3 - Adjustment of vacuum chamber thickness

By recording the position of seeds falling on the seed belt, the seed metering rule was calculated by image processing. However, due to the changes in the position and speed of seeds when they were released from the disk and in the process of falling, the seed metering information recorded by the test bench could not accurately reflect the filling performance of the seed metering device. To study the effect of seed filling angle and working parameters on the filling performance, a high-speed camera was used to record and count the seed filling information of the disk (*Zhang et al., 2015*).

Previous studies have shown that the thickness and range of the air chamber can be changed by installing a regulating plate in the range of the original air chamber (Fig. 3). When the thickness of the regulating plate is 20 mm, the pressure uniformity of all parts within the air chamber is the best and the pressure drop is not obvious. Therefore, the 20 mm-thick regulating plate is used to change the starting and ending angles of the air chamber, then regulating the seed filling and releasing angles during seed metering, and studying the effect rule of seed filling and releasing angles on the seed-metering performance. The seed filling angle is set as 0° in the negative direction of the horizontal line and positive in the downward direction, and is increased by 10° from 0° to 90°. The seed releasing angle is set as 0° in the positive direction of the horizontal line, and positive in the downward direction, and is increased by 10° from 0° to 90°.

Studies at home and abroad have shown that the working parameters have an important effect on the metering performance. The main working parameters of the seed metering device include forward speed and negative pressure. Their effect on the filling and releasing performance was studied at the speed of 6, 8, 10 and 12 km/h, and the negative pressure of 1, 2, 3, 4 and 5 kPa.

Evaluating indicator

In accordance with GB/T 6973-2005 Testing Methods of Single Seed Drills (Precision Drills), each test shall be performed with 250 seeds and be repeated for 5 times, with the metering performance evaluation indexes of quality of feed index *A*, multiple index *D*, miss index *M* and precision index *C*. At the same time, to intuitively evaluate the effect of seed filling, the quality of fill index (*FA*), multiple fill index (*FD*) and miss fill index (*FM*) are set as the evaluation indexes of filling performance (Table 1).

Table 1

Evaluation index of working performance of seed metering device

Seed metering performance	Seed filling performance
$A = n_1/N \times 100$	$FA = h_1/H \times 100$
$D = n_2/N \times 100$	$FD = h_2/H \times 100$
$M = 100 - A - D$	$FM = 100 - FA - FD$
$C = \sigma \times 100$	

In Table 1: h_1 is the number of seed holes with a seed; h_2 is the number of seed holes with two or more seeds; H is the total number of seed holes counted; n_1 is the number of seeds with the seed spacing greater than 0.5 times the theoretical seed spacing and less than 1.5 times the theoretical seed spacing (the theoretical seed spacing herein is 10 cm); N is the number of seeds determined through test; n_2 is the number of seeds with the seed spacing less than 0.5 times the theoretical seed spacing; σ is the standard deviation of seed spacing.

RESULTS AND ANALYSIS

Effect of seed filling angle on filling performance

At first, the seed filling angle was tested, with the original seed releasing angle remaining unchanged. The test was conducted at the negative pressure of 3 kPa and forward speed of 8 km/h. The test results were recorded and counted by a high-speed camera (Table 2).

Table 2

Effect of seed filling angle on seed filling performance

Seed filling angle [°]	*FA* [%]	*FD* [%]	*FM* [%]
0	83.54	0	16.46
10	85.36	0	14.64
20	89.73	0	10.27
30	91.78	0	8.22
40	95.32	0	4.68
50	98.64	0	1.36
60	99.67	0	0.33
70	99.05	0	0.95
80	99.32	0	0.68
90	99.83	0	0.17

With the increase of the seed filling angle, *FA* increased continuously to approximately 100%, and *FM* decreased continuously to approximately 0%. When the seed filling angle increased from 0° to 50°, *FA* and *FM* changed significantly. After the seed filling angle exceeded 50°, *FA* and *FM* became stable gradually. By increasing the seed filling angle, the filling performance can be improved effectively to reduce the misses. In the change process of the seed filling angle, *FD* remained at 0% all along, indicating that the combined structure of seed hole and suction hole had a very obvious quantitative effect on seeds, and there were no multiple seeds filled into the seed hole at the same time, therefore, the clearing parts can be removed to simplify the seed metering mechanism.

After the regression analysis of *FA*, the mathematical models of *FA* and seed filling angle are obtained as below:

$$y_c = 7.19\ln(x) + 68.6, \quad R^2 = 0.96 \tag{1}$$

The effect of working parameters on the filling performance

As *FA* tends to be stable when the seed filling angle is greater than 50°, the forward speed and negative pressure were performed with the dual-factor test at the seed filling angle of 50°. The test results were recorded by a high-speed camera as well (Fig 4).

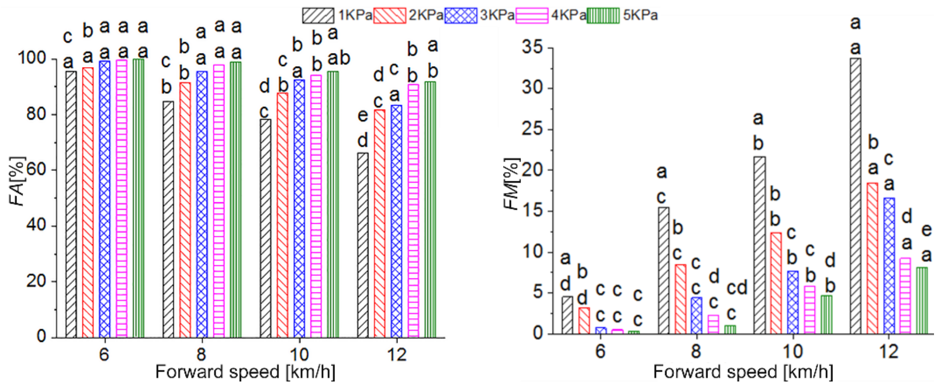


Fig. 4 - Effect of working parameters on seed filling performance

The upper and lower lowercase letters at the top of each group of data in the column chart represent the results of significance analysis of the data. Wherein, the upper letter represents the result of significance analysis of five negative pressures at each speed. If the two groups of data do not contain a same letter, it indicates that the two groups of data are significantly different. The lower letter represents the result of significance analysis of 4 speeds at a negative pressure, the same below.

The negative pressure and forward speed had no significant effect on *FD*. *FD* remained at 0% all along with the change of negative pressure and forward speed, further indicating that single seed quantitative seed picking can be achieved with the seed hole in an appropriate size without additional seed cleaning device.

At different speeds, negative pressure has a significant effect on *FA*. *FA* increases with the increase of negative pressure, with the increased amplitude changing with the increase of speed. At 6 km/h, the *FA* is 95.48% at 1 kPa and 99.60% at 5 kPa, with the increase ratio of 4.3%. At 12 km/h, the FA is 66.30% at minimum at 1 kPa and 91.86% at 5 kPa, with the increase ratio of 27.8%.

Under different negative pressures, *FA* decreases significantly with the increase of forward speed, which is the most significant at 1 kPa. *FA* is 95.48% at 6 km/h, and 66.3% at 12 km/h, with the decrease ratio of 30.6%. *FA* decreases slightly with the increase of negative pressure. Under the negative pressure of 5 kPa, the change of *FA* is the minimum; the *FA* is 99.67% at 6 km/h and 91.86% at 12 km/h, with the decrease ratio of 7.8%, indicating that the negative pressure is interactive with the forward speed.

Since *FD* is 0, *FM* is 100%-*FA*. Therefore, the change rule of *FM* is completely opposite to that of *FA*.

The effect of the seed releasing angle on the metering performance

The effect of the seed releasing angle on the metering performance was studied at the seed filling angle of 50°. The test was performed at the negative pressure of 3 kPa and forward speed of 8 km/h firstly. The data acquisition and processing system of JPS-12 metering test bench was used to record the test results automatically (Table 3).

Table 3

Effect of seed releasing angle on metering performance

Seed releasing angle [°]	*A* [%]	*D* [%]	*M* [%]	*C* [%]
0	81.61	13.14	5.25	21.85
10	86.32	11.27	2.41	21.12
20	92.03	6.95	1.02	18.65
30	93.65	5.67	0.68	15.48
40	98.48	1.01	0.51	11.05
50	97.53	1.34	1.13	13.62
60	92.61	2.96	4.43	19.84
70	85.42	9.48	5.10	21.22
80	76.33	16.37	7.30	24.87
90	73.12	18.28	8.60	25.32

At the seed releasing angle of 0°, *A* is 81.61%, which is low. When the seed releasing angle increases to 40°, *A* gradually increases to 98.48%. When the seed releasing angle is greater than 40°, *A* decreases gradually to 73.12% at 90°.

After the regression analysis of *A*, the regression equation of *A* about seed releasing angle is obtained.

$$y_q = -0.01x_t^2 + 0.79x_t + 80.60, \quad R^2 = 0.95 \tag{2}$$

Through the derivation of the regression equation, the seed releasing angle is 39.5° when A is at its maximum.

Different from *FD*, *D* is no longer 0%, and decreases first and then increases with the increase of the seed releasing angle. *D* is 18.28% (maximum) at 90° and 1.01% (minimum) at 40°.

The change rule of *M* is similar with that of *FD*. *M* decreases first and then increases with the increase of the seed releasing angle. *D* is 8.60% (maximum) at 90° and 0.51% (minimum) at 40°.

To further analyze the effect mechanism of the seed releasing angle on the metering performance, the states of motion of seeds when they are released from the disk at the seed releasing angles of 0, 39.5 and 90° were recorded with a high-speed camera (Fig.5).

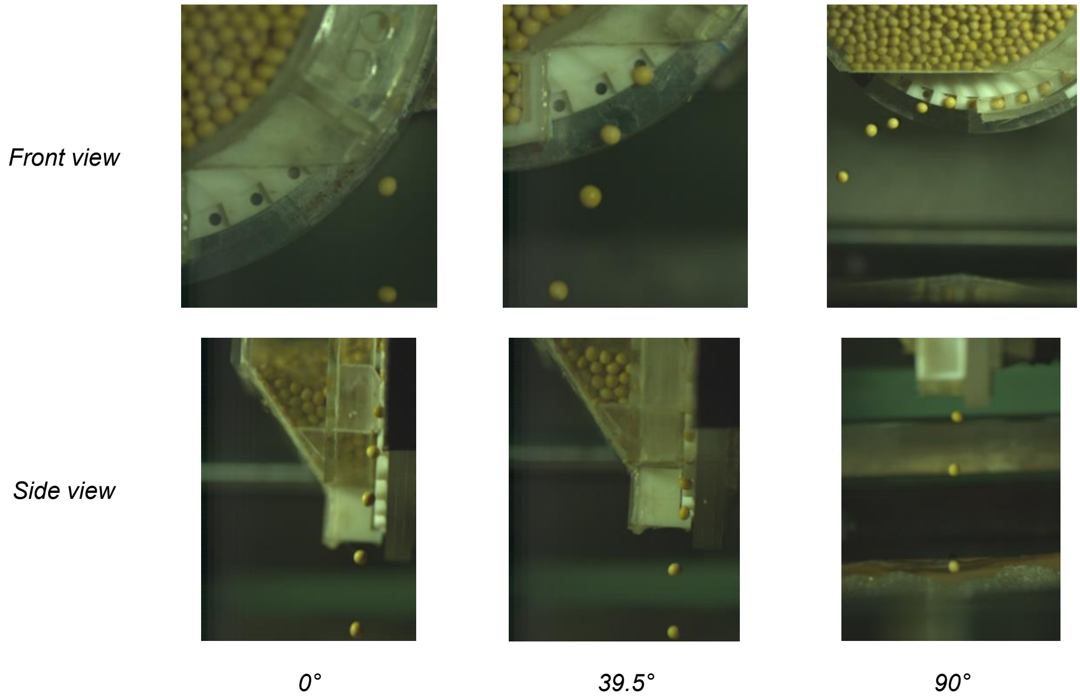


Fig. 5 - High speed photos of seed separation

At the seed releasing angle of 0°, when the speed is 6km/h, the initial speed of seed is vertically downward, and the gravity and speed are in the same direction after the negative pressure disappears. The acceleration of seed is large and the seed speed is greater than the linear speed of the disk. Therefore, the seeds collide with the front wall of the seed hole, and the seeds roll, resulting in the forward deviation of the falling track of seeds. As the front wall is inclined, the seeds have a large axial displacement, which reduces the metering performance and increases the precision index of seeds. With the increase of the speed, the linear speed at the edge of the disk increases, the collision between seeds and the front wall of the seed hole decreases gradually; the falling track of seeds shifts backward gradually, and the axial displacement decreases gradually. At the speed of 10 km/h, the linear speed of the disk is greater than the releasing speed. The seeds contact with the back wall of the seed hole, and then the back wall pushes seeds, resulting in backward deviation of the falling track of seeds. As the back wall is vertical, the axial deviation of seeds is small.

At the seed releasing angle of 39.5°, seeds can be released from the seed hole rapidly as the initial speed of the seeds is oblique to the lower left; the component of the acceleration of gravity in the speed direction is small; the horizontal component of velocity of the seeds is close to the linear velocity at the edge of the disk and the distance that the seeds move with the seed hole simultaneously before the seeds are released from the seed hole is short, after the negative pressure disappears, so that they will not contact with the front wall of the seed hole when being released from the seed hole, resulting in a small axial displacement of the seeds. When the speed varies from 6 to 10 km/h, the seeds don’t contact with the front or back wall of the seed hole. Therefore, at the seed releasing angle of 39.5°, the metering performance is better and the precision index is lower.

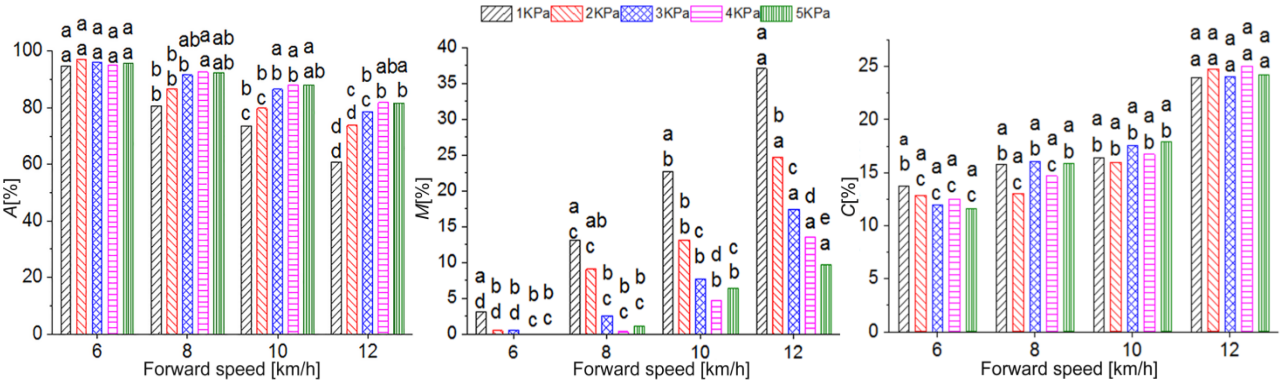
At the seed releasing angle of 90°, the horizontal component of speed of seeds is theoretically consistent with the linear speed at the edge of the disk after the negative pressure disappears. Seeds will not contact with the back wall of the seed hole when they are released from the seed hole. However, actually, the horizontal component of velocity of the seeds is slightly less than the linear seed at the edge of the disk under the impact of friction with the wall of seed hole, air friction and other factors. Therefore, the seeds contact with the back wall of the seed hole. When being pushed by the back wall, with the seed hole moving upward, the seeds contact with the back wall at different points as they are not a standard sphere. As a result, the horizontal displacements of seeds are different when being pushed by the back wall, which reduces the metering performance and increases the precision index. At 6 km/h, the contact time between seeds and the back wall is short, and the difference of falling trajectory of seeds is small. With the increase of the speed, the thrust of the back wall on seeds increases, and the difference in the releasing trajectory of seeds increases. At the same time, as the back wall is vertical, the axial deviation of seeds in the falling process is small.

Effect of working parameters on the metering performance

At the seed releasing angle of 39.5°, forward speed and negative pressure were performed with the dual-factor test; the data processing and variance analysis were conducted; and a column chart was made (Fig.6).

The negative pressure has a significant impact on *A*, and *A* increases with the increase of the negative pressure. At the speed of 6 km/h, the negative pressure has no significant effect on *A*, which remains at about 95%. With the increase of speed, negative pressure has a more and more obvious effect on *A*. At the speed of 12 km/h, the negative pressure has the most significant effect on *A*. *A* is 60.88% at the negative pressure of 1 kPa. *A* increases significantly with the increase of the negative pressure. *A* is 81.62% at 5 kPa, with an increase ratio of 34.1%.

The forward speed has a significant effect on *A*. The lower the negative pressure is, the more significant the effect of forward speed on *A* is. Under the negative pressure of 1 kPa, *A* is 94.85% at 6 km/h and decreases with the increase of the speed. *A* decreases to 60.88% at 12 km/h, with the decrease ratio of 35.8%. When the negative pressure is large, the effect of forward speed on *A* becomes smaller. At the negative pressure of 5 kPa, *A* is 95.83% at 6 km/h and decreases to 81.62% at 12 km/h, with the decrease ratio of 14.8%.



a) A *b) M* *c) C*

Fig. 6 - Effect of working parameters on the metering performance

The negative pressure has a significant effect on *M*, i.e., *M* decreases with the increase of the negative pressure. At the speed of 6 km/h, *M* is 3.16% at the negative pressure of 1 kPa.

When the negative pressure is greater than 2 kPa, *M* does not change significantly and tends to 0%. The effect of negative pressure on *M* becomes more and more significant with the increase of the speed.

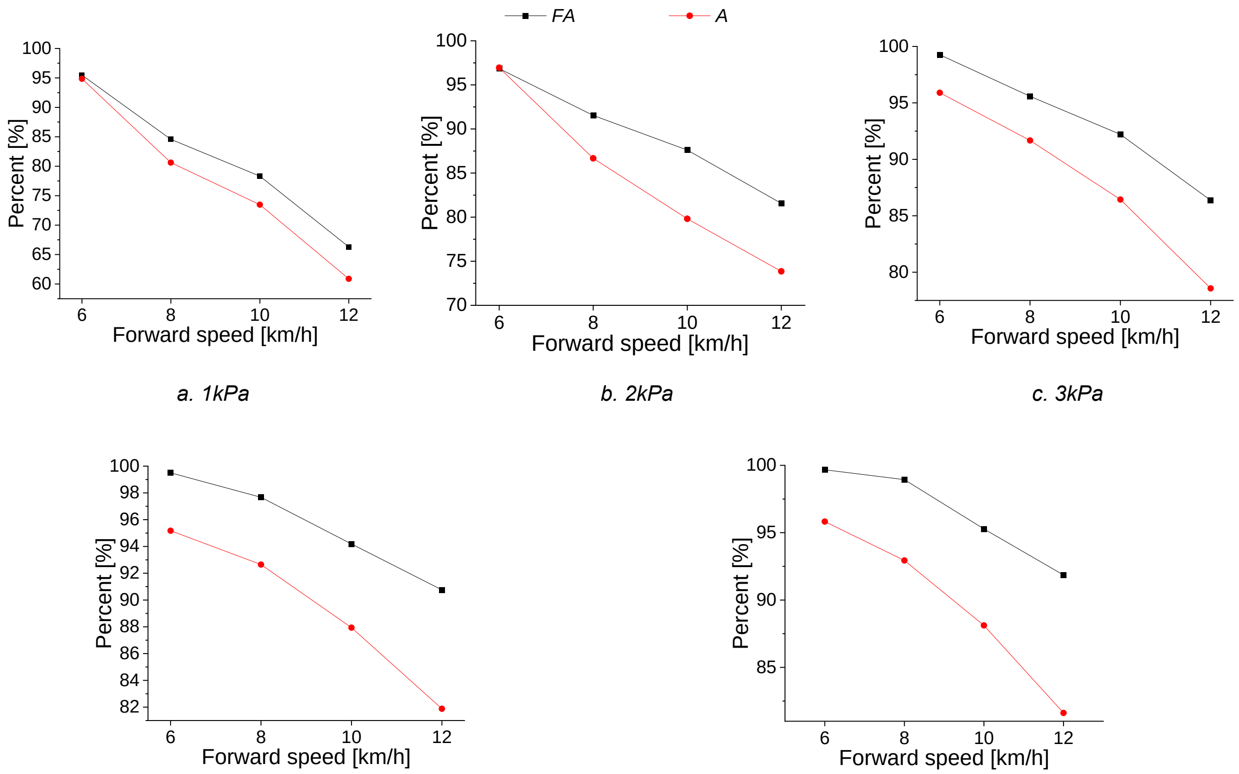
When the speed increases to 12 km/h, *M* is 37.06% under the negative pressure of 1 kPa. *M* decreases significantly with the increase of negative pressure, and is 9.62% at 5 kPa, with the decrease ratio of 74.0%.

The forward speed has a significant effect on *M*, i.e., *M* increases with the increase of the forward speed. The miss index is the largest under the negative pressure of 1 kPa. *M* is 3.16% at 6 km/h and increases to 37.06% when the speed increases to 12 km/h, increasing by 10.7 times. With the increase of the negative pressure, the effect of the forward speed on *M* decreases. Under the negative pressure of 5 kPa, *M* is 0% at 6 km/h and increases to 9.62% at 12 km/h.

The negative pressure has no significant effect on the precision index. The precision index does not change significantly when the negative pressure changes in the range of 1-5 kPa. The forward speed has a significant effect on the precision index. Researchers at home and abroad have come to a similar conclusion that the precision index increases significantly with the increase of the speed.

Comparison of the filling performance and metering performance

The filling performance represents the seed picking capacity of the disk, and the metering performance represents the distribution rule of seeds in seeding ditch. *FA* and *A* under the same negative pressure and speed are compared (Fig.7).

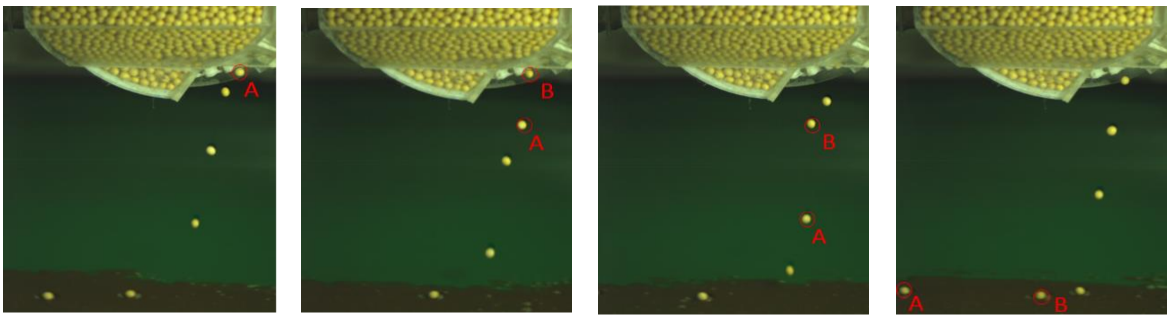


a. 1kPa *b. 2kPa* *c. 3kPa*

d. 4kPa *e. 5kPa*

Fig. 7 - Comparison of the filling performance and metering performance

FA is obviously greater than *A* under the same negative pressure and speed. The difference between *FA* and *A* becomes more and more obvious with the increase of the forward speed.



a. Seed A detachment *b. Seed B detachment* *c. Seed dropping* *d. Seed landing*

Fig. 8 - High speed picture of seed falling process

The state of motion of seeds in the process of falling and touching soil after they were released from the disk was observed with a high-speed camera (Fig.8).

When the seeds on the disk are released from the seed hole, the location and time of releasing of different seeds are different, and the releasing point, initial speed and angle of releasing cannot be kept completely consistent. In the process of falling, the position between seeds changes; the seed spacing in the seedbed decreases or expands, and the positions even change, resulting in the increase of multiple and miss seeds, and the decrease of *A*.

In order to improve the metering performance of the compound seed metering device, the seed releasing location shall be studied next to improve the consistency between the releasing position and time.

CONCLUSIONS

(1) The seed filling angle has significant effect on *FA* and *FM*, which are completely opposite in the change rule. With the increase of the seed filling angle, *FA* increases gradually, while *FM* decreases gradually. After the seed filling angle exceeds 50°, both of them tend to be stable gradually. In the change process of the seed filling angle, *FD* remains at 0% all along, indicating that a significant effect of single-seed picking can be achieved with the combined structure of seed hole and suction hole.

(2) The negative pressure and operating speed are interactive and have a significant effect on *FA* and *FM*. *FA* increases with the increase of the negative pressure and drops significantly with the increase of the forward speed. *FA* and *FM* are completely opposite in the change rule, while *D* remains at 0% all along.

(3) The seed releasing angle has a significant effect on the metering performance. *A* increases first and then decreases with the increase of the seed releasing angle, and reaches 98.48% (maximum) at 40°. The change rule of *D* and *M* is completely opposite to that of *A*. Through the regressive calculation, the seed releasing angle is 39.5° when *A* is at its maximum. Under different seed releasing angles, the positions of seeds colliding with the seed hole when they are released are different, which changes the state of motion of seeds when releasing and has effect on the metering performance.

(4) The negative pressure and forward speed are interactive and have a significant effect on the metering performance. With the increase of the negative pressure, *A* increases and *M* deceases; with the increase of the forward speed, *A* decreases and *M* increases. The negative pressure has no significant effect on the precision index, while the forward speed has a significant effect on the precision index. With the increase of the speed, the precision index increases significantly.

(5) Due to the differences in the time and position of seeds when they are being released from the seed hole, *A* is lower than *FA* under the same conditions. The releasing process shall be further studied next to improve the consistency between the releasing position and time.

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