Design and experiment of an air-suction potato seed metering device

Lü Jinqing*, Yang Ying, Li Zihui, Shang Qinqin, Li Jicheng, Liu Zhongyuan

(*Department of Engineering, Northeast Agricultural University, Harbin 150030, China*)

Abstract: An air-suction potato seed metering device was designed to improve the performance of the large-size seed crops planting equipment and provide a solution for problems on the mechanical potato seeder, such as high multiple-seeding index, high missing-seeding index, low qualified index, and limited versatility. The main structure and operation parameters in terms of rotating speed of the device, seeds height and pickup vacuum pressure were determined by theoretical analysis. Two orthogonal tests, conventional tuber (the triaxial average diameter is about 38-57 mm) test and mini-tuber (the triaxial average diameter is about 12-36 mm) test, were conducted to analyze the influences of these factors on the quality of seeding. The multiple-seeding index, missing-seeding index and qualified index were chosen for evaluating the working performance. The results of conventional tuber test showed that, the multiple-seeding index was 1.1%, the missing-seeding index was 0.8% and the qualified index was 98.1% under conditions of the 30 r/min rotating speed, 25 cm seeds height and 10 kPa pickup vacuum pressure. The results of mini-tuber test showed that the multiple-seeding index was 0.5%, the missing-seeding index was 0.6% and the qualified index was 98.9% under conditions of 35 r/min rotating speed, 17 cm seeds height and 3.5 kPa pickup vacuum. The working performances of the device can meet the requirements of precision seeding.

Keywords: air-suction, seed metering device, mini-tuber, precision seeding, potato, pickup vacuum
DOI: 10.3965/j.ijabe.20160905.2221

Citation: Lü J Q, Yang Y, Li Z H, Shang Q Q, Li J C, Liu Z Y. Design and experiment of an air-suction potato seed metering device. Int J Agric & Biol Eng, 2016; 9(5): 33－42.

1 Introduction

At present, potato planters have already been equipped with mechanical metering devices in China, which generally include picker finger, needle, cup-chain (belt), rotating disc and plate-valve type seeding device. These types of equipment have common problems of high multiple-seeding index, high missing-seeding index, and poor versatility. Part of the equipment is even not fully automated, let alone reaches the precision seeding level. This seriously hampered the development of the potato industry. Therefore, the mechanization level of potato cultivation is at a low level for a long time, far behind the rest crops[1-3].

Many scholars around the world have conducted researches on the development of air-suction metering device. Singh et al.[4] developed a kind of pneumatic type metering device for planting cottonseed. The operational speed of the disc, vacuum pressure and the shape of seed inlet were optimized to ensure precise planting spacing. Liao et al.[5] have done a lot of researches on rapeseed pneumatic precision metering device. The rotating speed, positive and negative pressures were considered as the main factors influencing

Received date: 2015-11-03 **Accepted date:** 2016-04-27
Biographies: Yang Ying, Master student, majoring in potato technology and equipment research, Email: 1378705735@qq.com; **Li Zihui,** Master, Senior Engineer, research interests: potato technology and equipment research, Email: 397843976@qq.com; **Shang Qinqin,** Master student, majoring in potato technology and equipment research, Email: 1510538717@qq.com; **Li Jicheng,** Master, Lecturer, research interests: potato technology and equipment research, Email: 158487225@ qq.com; **Liu Zhongyuan**, Master, Lecturer, research interests: potato technology and equipment research, Email: hitliu2004@163.com.
***Corresponding author: Lü Jinqing,** Master, Researcher, China Potato Research System Post Scientist, supervisor of postgraduate, research interests: potato technology and equipment research. College of Engineering Northeast Agricultural University No.59 Mucai Street, Xiangfang District, Harbin, Heilongjiang Province, China. Tel/Fax: +86-451-55191953, Email: ljq8888866666@163.com.

the performance of the device. A mathematical model was established to describe the relationship between the positive and negative pressure by using a numerical simulation method. The operation parameters of the seeder were adjusted in accordance with the mathematical model, ultimately achieved precision seeding. Deng et al.[6] also carried out a research on rapeseed seeder. The effect of the nozzle's structure and quantity on the sucking-seed process was analyzed in theory and some experiments were conducted to verify the correctness of the theoretical analysis. Many other scholars such as Yang et al.[7,8], Yazgi and Degirmencioglu[9], Onal et al.[10], Karayel et al.[11], Mahl et al.[12] and Zhang et al.[13] all have made series of researches on pneumatic seeding apparatus. At present, the pneumatic seeding apparatus has been successfully applied to many crops, such as maize, wheat, rapeseed, cotton, soybeans, etc. The theoretical and practice researches on these crops' seeders showed that air-suction metering devices have many obvious advantages compared to mechanical equipment, such as high working quality, suitability for high speed operation, which may meet the requirements of precision seeding.

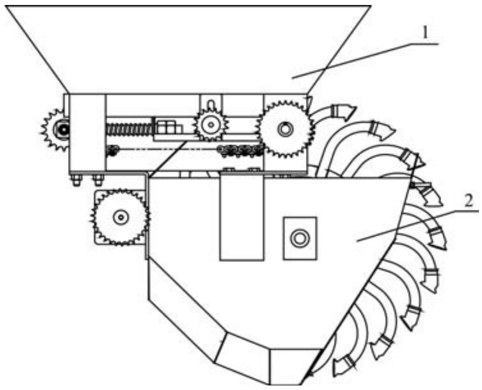
Existed air-suction metering units are usually used for sowing crops of small size seed, for example rice, soybeans, and corn, etc., and also applied to sowing mini-tuber in recent years[14]. However, little information about the air-suction metering units suitable for sowing conventional whole tuber or cut tuber was published.

Based on the mentioned issues above, we proposed a novel design scheme for potato air-suction metering device. Traditional suction holes were replaced by arms and the seed plate was replaced by air distribution valve to make the devices suitable for sowing large-size seed crops. An adopting replaceable suction nozzle was installed at the end of the arm to improve the versatility of the device. Potato is sucked by vacuum pressure and seeds height is controlled by dynamic feeding device to improve the feeding performance. Adjustable release angle of seed throwing enables the users to select the appropriate release position according to working environment. Positive pressure air flow can remove residual impurities inside the arms to extend the service life of the device. The aim of the study is to improve the device's working performance and achieve precision metering.

2 Materials and method

2.1 Whole structural and working principle of the device

The device is composed of a main body and dynamic feeding device. The whole structure is shown in Figure 1.

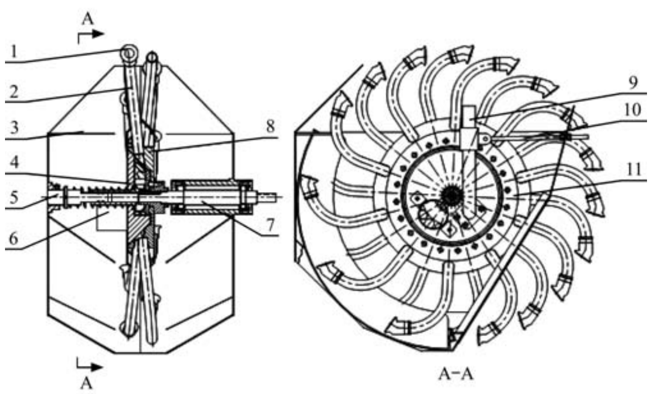


Note: 1. Dynamic feeding device 2. Main body

Figure 1 Whole structure of the device

Dynamic feeding device conveys tubers into the seed box of main body. A switch is installed in the seed box. When seeds height reaches the preset height, the tubers touch the switch and then the dynamic feeding device is stopped. As tubers continually discharge from seed box, seeds height gradually decline. Once the switch is released, the dynamic feeding device is restarted. Seeds height keeps an invariant level in this mode.

The structure of the main body includes suction nozzles, suction arms, a static valve, a rotary valve, an adjusting screw and a seed box, etc. as shown in Figure 2.



Note: 1. Suction nozzle 2. Suction arm 3. Seed box 4. Static valve 5. Static shaft 6. Suction pipe 7. Rotary shaft 8. Rotary valve 9. Blow pipe 10. Adjusting screw 11. Protective shell

Figure 2 Structure diagram of the device's main body

Air distribution valve consists of a static valve and a rotary valve. The interior is divided into two independent air chambers. Suction arms are inserted in the through-holes, which are processed on the exterior surface of the rotary valve. The arms and the interior of the valve are connected. Suction nozzles are installed at the end of the arms and the nozzles can be replaced. The interior of air distribution valve is divided into the suction area, carrying area, metering area and idling area according to its function, as shown in Figure 3. When the device is working, the static valve is stationary, the rotary valve and the arms rotate synchronously. Working process can be divided into four stages as (1) Sucking: the arms suck tubers in the suction area from the seed box under vacuum condition; (2) Carrying: the sucked tubers rotating synchronously with the rotary valve, and then pass through the carrying area; (3) Metering: when the arms are in the metering area, the connection between the arms and the vacuum chamber is blocked and the adsorption force produced by vacuum disappears. Due to the gravity, the tubers fall off the nozzles to the furrow; (4) Idling: in order to prevent accumulation of impurities, valve blockage and corrosion, and ensure the device working properly, the system generated positive pressure in idling area. Any dirt and debris as well as tubers failed to be released would be discharged by the pressure air. After the arms turn back to suction area, a working cycle is completed.

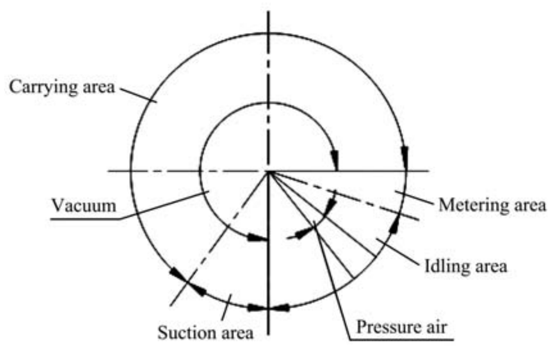


Figure 3 Internal structure description of air distribution valve

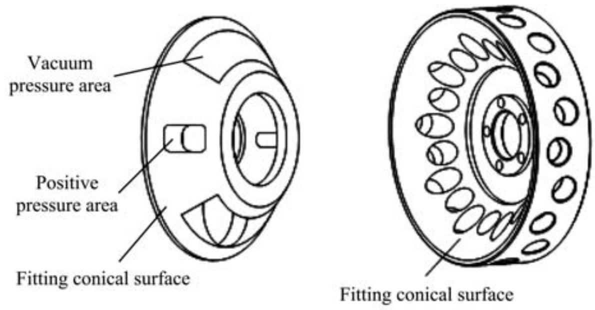
2.2 Main structure design

2.2.1 Air distribution valve

Most of the existed air-suction seeding devices are disc type. A series of holes are processed on the surface of the seed plate. For large-size seed crops, such as potato, if the apparatus needs to suck the tuber and carry the tuber stable rotating, a larger diameter hole is indispensable. Increasing the size of holes would inevitably decrease the quantity of the holes or enlarge the disc's dimension. Decrease of the hole amount may obviously weaken the operating efficiency and performance and a larger plate dimension may result in a bulky whole structure, and high cost and energy consumption. Using an air distribution valve to replace the seed plate may resolve this problem.

The embedded static and rotary valves (Figure 4) constitute the air distribution valve and form independent vacuum chamber and positive pressure chamber. Compared with plane seal, cone connection has many advantages in terms of convenient disassembly, higher assembly accuracy, higher sealing pressure and less hard objects deposited. Therefore, a conical fit was selected between the two valves[15-17].

The static valve with frustum cone was processed into independent vacuum area (occupied 270°) and positive pressure area (occupied 30°). The rotary valve was shaped to flat cylinder. One of the bottom surfaces was processed for inward concave cone, and the outer circumference was processed in series of through-holes uniformly for installing suction arms. The holes were staggered to maximize the quantity.



a. Static valve b. Rotary valve

Figure 4 Air distribution valve

Some impurities like sand and debris would also be inhaled into the air distribution valve during working time. Therefore, the traditional oil or grease lubrication is not fit for it. The surfaces of the two valves are plated by ceramic coating. The hardness of the coating is up to 959.4 HV to realize the valve lubrication-free, balance sealing, abrasion resistance and corrosion resistance.

2.2.2 Suction arm and nozzle

The triaxial average diameter of conventional tuber (including entire tuber and cut tuber) widespread used for sowing in China is about 38-57 mm[18-20]. The diameter of the arm can be determined according to Equation (1)[21]:

$$d = (0.64 - 0.66)b \tag{1}$$

where, d is the diameter of suction arm, mm; b is triaxial average diameter of tubers, mm.

The d calculated should be 24.32-37.62 mm.

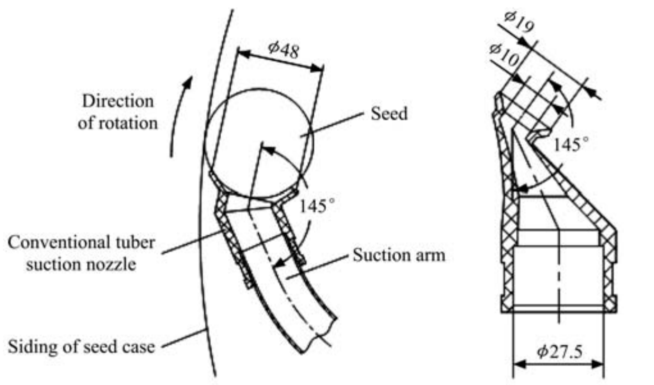
According to Equation (2), the number of the arms (N) can be determined:

$$N = \frac{\pi D(1+\delta)}{iS} \tag{2}$$

where, N is the number of suction arms; D is the diameter of ground wheel, 690 mm; δ is the slip ratio of ground wheel; i is the transmission ratio, 1; S is the theoretical seed spacing, mm.

At present, commonly adopted seed spacing for planting conventional tuber is about 150-450 mm, for mini-tuber is about 150-200 mm[14,22,23]. Referring to the measured value of the existed planter with similar tire size and total weight to the studied machine (2CMF-2 type potato planter), defined δ=12.5%, the calculated result of N is: $N \geq 17$. While the seed spacing and the drive speed are both in the certain values, the more the number of the arms are, the lower the device rotating speed will be. Lower rotating speed can extend the contact time between nozzle and tuber, thereby improve the suction performance. So a larger value of N is suitable. Some structure's dimensions of the arm were determined as: the diameter 25 mm, the number 20, and the tail bent 90°. The arms can play a role to stir the seed pile during working, so this device is stirring free.

Suction nozzle made of Nitrile butadiene rubber (NBR) is installed at the end of the arm. Two types of design schemes were proposed. The first one was used for planting the conventional tuber as shown in Figure 5a. Outward expansive end portion increased the contact area between the nozzle and tuber, and improved the stability of sucking and carrying. According to the preliminary test results and the size of the arm above mentioned, the largest diameter of nozzle's end portion was determined as 48 mm. In order to prevent tuber from being stuck in the space between the nozzle and the siding of seed box, reducing the rotational resistance of the device, the nozzle's end portion was designed to bend 145°. The second one is the mini-tuber nozzle as shown in Figure 5b. The triaxial average diameter is about 12-36 mm for mini-tuber widespread used in China[18,24,25]. For mini-tuber, d should be in the range of 7.68-23.76 mm according to Equation (1). The maximum and minimum diameters of the end portion of mini-tuber nozzle were determined as 18 mm and 10 mm, respectively. And the nozzle's end portion was designed to bend 145°.



a. Conventional tuber suction nozzle b. Mini-tuber suction nozzle

Figure 5 Suction nozzle

2.3 Key operating parameters

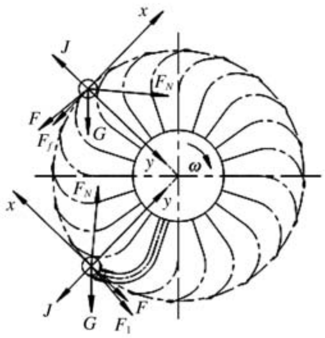
2.3.1 Vacuum pressure

A Cartesian coordinate system was established using the centroid of the tuber as the origin, the tangential direction of rotational linear velocity as the positive x-axis, perpendicular to the x-axis pointing in the direction of rotation center as the positive y-axis. Some assumptions were conducted for further analysis as the rotation angular velocity of the device was constant, the tuber was an ideal rigid sphere, and the tuber would remain relatively stationary with the nozzle after being sucked. Force conditions of tuber in the vacuum pressure area are shown in Figure 6.

In sucking process, compared with carrying process, a bigger suction force is additionally required to overcome the collision and friction between tubers. Therefore, if the vacuum pressure is sufficient for sucking process, carrying process could be successfully completed. Enlarged force diagram of tuber in vacuum pressure area is shown in Figure 7 according which Equation (4) can be obtained.

$$\frac{F_{Nx}}{F_{Ny}} = \tan(\varphi + \frac{\gamma}{2}) \quad (4)$$

where, γ is the angle between the contact surfaces of tuber and nozzle, (°).



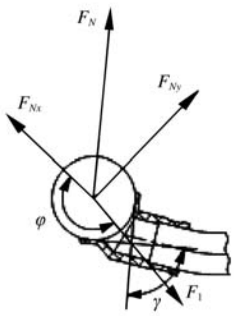
Note: ω is the rotational angular velocity of the device, in a clockwise direction; G is the gravity of the tuber, always in a vertically downward direction; J is the inertia force of rotating tuber, in negative y-axis direction; F_1 is the suction force of the tuber in vacuum area, along the axial direction of the nozzle's end portion; F_f is the frictional force of the sucked tuber, along the tangential direction of the trajectory; F_N is the support force.

Figure 6 Force diagram of tuber in vacuum area

F_f is the frictional force between tubers before the tuber departed from seed pile; after departed, F_f becomes the air resistance. The frictional force between tubers can be defined as following equation:

$$F_f = \lambda G \quad (5)$$

where, λ is a comprehensive coefficient of friction, λ=(6-10) tanθ, θ is the angle of repose, in general, a crop with a smaller angle θ, front constant whichever is greater[26].



Note: F_{Nx} is the component in x direction of support force; F_{Ny} is the component in y direction of support force; φ is the angle between F_1 and positive x-axis; γ is the angle between the contact surfaces of tuber and nozzle.

Figure 7 Enlarged force diagram of tuber

Combine Equation (5) with the following formulas:

$$\begin{cases} P_1 = -\dfrac{F_1}{S} \times 10^3 \\ S = \dfrac{\pi d'^2}{4} \\ J = m\omega^2 R \times 10^{-3} \end{cases} \quad (6)$$

where, P_1 is the vacuum pressure, kPa; S is the force area of the tuber, mm^2; d' is the diameter of the nozzle's end portion, mm; m is the weight of the tuber, g; ω is the rotational angular velocity of the device, rad/s; R is the rotational radius of the tuber, m.

Finally obtain:

$$P_1 = 4\frac{m\omega^2 R \tan\left(\varphi + \frac{\gamma}{2}\right) - mg\left[\tan\left(\varphi + \frac{\gamma}{2}\right)\sin\beta - \cos\beta + \lambda\right]}{\pi d'^2[\cos\varphi - \tan\left(\varphi + \frac{\gamma}{2}\right)\sin\varphi]} \quad (7)$$

If the ω was 4.7 rad/s, setting φ=174°, γ=90°, for conventional tuber, setting m=50 g, d'=25 mm, R=0.37 m, in Equation (5): θ=32°, the constant is 8, calculated λ=5.0, then obtained the desired maximum vacuum pressure P_1=5.21 kPa; for mini-tuber, setting m=15 g, d'=19 mm, R=0.39 m, θ=25°, the constant was 8, calculated λ=3.73, and the desired maximum degree of vacuum P_1=2.07 kPa. During the practical operation, the device was influenced by the natural conditions of tubers (distribution state, collision) and the external environment (vibration, shock, etc.). So for P_1, the actual value should be higher than the calculated value to ensure stabilization of sucking and carrying process. The range of P_1 in the test was determined according to the results of trial test. In the following test, for the conventional tuber, the investigated vacuum pressure was 7-13 kPa; for the mini-tuber, the investigated vacuum pressure was 2.5-4.5 kPa.

2.3.2 Throw angle

Throw angle refers to the angle between the throw position and the vertical direction, as shown in Figure 8. Tubers may collide with the furrow opener if α is too large, and may collide with the device or the seed box if α is too small. In order to avoid the bumping occurrence during the process of falling and damaged the tuber, α was selected as 58°. The α can be adjusted according to the specific operating environment in the actual operation with the range of 44°-75°.

2.3.3 Seeds height

Seeds height refers to the height between the lowest point of the seed box and the top surface of tubers. It reflects the number of tubers inside the seed box. Low seeds height implies small number of tubers inside the seed box. The suction time, namely the contact time between the nozzle and tuber, was shortened. It made the missing-seeding index increased. An excessive seeds height will extend the suction time, which makes the multiple-seeding index, the starting resistance and the device's rotation resistance are added.

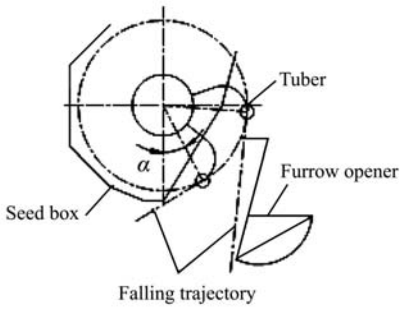


Figure 8 Explanatory drawing of throw angle

2.4 Working performance test

In order to clarify the effect of influencing factors on working performance, a test-bed for orthogonal test was built according to "GB/T 6973-2005 Testing methods of single seed drills (precision drills)" and "GB/T 6242-2006 Equipment for Planting-Potato Planters-Method of Testing"[27,28] in China. A transportation belt was used to simulate the seed bed. The equipment was fixed above the belt, and the forward speed of the belt was same to the seeder operating speed. Ten centimeter thick sand was laid on the belt to prevent the rolling and bounce of dropped potato. Recorded 100 consecutive actual seed spacing when the equipment rotating uniformly. Data were processed to obtain the values of the evaluation indexes.

The rotating speed of the device, pickup vacuum pressure and seeds height were selected as the experimental factors. The evaluation indexes were multiple-seeding index, missing-seeding index and qualified index. The calculated equations are:

Qualified index: $$Q=\frac{n_1}{N'}\times 100 \quad (8)$$

Multiple-seeding index: $$D=\frac{n_2}{N'}\times 100 \quad (9)$$

Missing-seeding index: $$M=\frac{n_0}{N'}\times 100 \quad (10)$$

where, n_1 is the number of seed spacing which is greater than half of the theoretical seed spacing and smaller than 1.5 times of theoretical seed spacing; n_2 is the number of seed spacing which is smaller than half of the theoretical seed spacing; n_0 is the number of seed spacing which is greater than 1.5 times of theoretical seed spacing; N' is the total number of seed spacing measured.

Potato variety Dongnong 303 was selected as the material of conventional tuber test. The tubers were cut into 30-50 g weight blocks with 79.7% moisture content was and greater than 98% seed purity. The theoretical seed spacing was 20 cm.

The experimental factors and levels are shown in Table 1, the actual operation is shown in Figure 9a, and the measurement of actual seed spacing is shown in Figure 9b.

a. Seed metering device operation b. Seed spacing measurement

Figure 9 Actual operation of conventional tuber test

Table 1 Factors and levels of conventional tuber test

Levels	Factors		
	Rotating speed A /r·min^{-1}	Seeds height B /cm	Vacuum pressure C /kPa
1	25	25	7
2	30	20	10
3	35	15	13

Potato variety Kexin 1 was selected as the material for the mini-tuber test, the moisture content was 82.9% and seed purity was greater than 99%. The weight of each mini-tuber was about 5-10 g. The experiment factors and levels are shown in Table 2, the actual operation is shown in Figure 10.

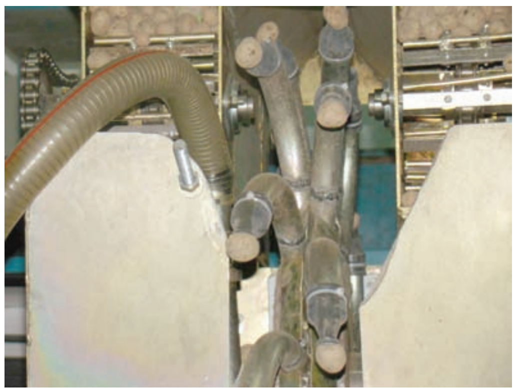


Figure 10 Actual operation of mini-tuber test

Table 2 Factors and levels of mini-tuber test

Factors	Rotating speed A /r·min^{-1}	Seeds height B /cm	Vacuum pressure C /kPa
1	30	17	2.5
2	35	13	3.5
3	40	9	4.5

In the mini-tuber test, the measurement of actual seed spacing and data processing were same to the conventional tuber test.

Test results were analyzed by using Design-Expert 8.05b software. Operating performance of the device was evaluated according to the analysis results.

3 Results and discussion

The orthogonal table $L_9(3^4)$ was used to arrange the experiments. Each of the three factors accounted for a column. A blank column, marked as "error", was added to estimate the test error. Thus the test data can be analyzed by ANOVA[29,30].

The test procedure and results of conventional tuber test are shown in Table 3, and the results of ANOVA and range analysis are shown in Table 4. Table 4 shows that the effect intensity of factors on multiple-seeding index is C>A>B, on missing-seeding index is A>C>B and on qualified index is C>A>B.

With the increase of rotating speed, the multiple-seeding index declined and the missing-seeding index rose. The main reason was that a faster rotating speed shortened the time of the arm through the seed pile, resulting a shorter contact time between nozzle and tuber, and weakened the suction performance. Higher rotating speed resulted in a larger inertia force of tuber, and collisions between sucked tuber and other tubers became fiercer, so the tuber detached from the nozzle easily which meant an unsuccessful suction occurred. Although the A1 corresponded to the minimum missing-seeding index, the multiple-seeding index was large on this point, so A1 was not the most ideal value. Similarly A3 was not suitable for the actual operation. With the increase of rotating speed, the qualified index fell down after a rose. The highest qualified index was in A2 position.

Table 3 Program and results of conventional tuber test

No.	Rotating speed A/r·min^{-1}	Seeds height B/cm	Vacuum pressure C/kPa	Error D	Multiple-seeding index/%	Missing-seeding index/%	Qualified index/%
1	1(25)	1(25)	1(7)	1	4.9	1.3	93.8
2	1	2(20)	2(10)	2	9.8	0.4	89.8
3	1	3(15)	3(13)	3	14.1	0.1	85.8
4	2(30)	1	2	3	1.1	0.8	98.1
5	2	2	3	1	9.8	1.5	88.7
6	2	3	1	2	0.9	6.5	92.6
7	3(35)	1	3	2	6.1	6.6	87.3
8	3	2	1	3	0.2	10.9	88.9
9	3	3	2	1	0.7	10.5	88.8

Table 4 Analysis results of conventional tuber test

Evaluation Index	Factors	ANOVA			Range analysis				Optimum level	Optimal parameter combination
		F-value	P-value	Significance	K1	K2	K3	R		
Multiple	A	200.84	0.0050	**	28.8	11.8	7.0	21.8	A3	A3B1C1
	B	22.72	0.0422	*	12.1	19.8	15.7	7.7	B1	
	C	241.31	0.0041	**	6.0	11.6	30.0	24.0	C1	
Missing	A	213.14	0.0047	**	1.8	8.8	28	26.2	A1	A1B1C3
	B	20.44	0.0466	*	8.7	12.8	17.1	8.4	B1	
	C	33.11	0.0293	*	18.7	11.7	8.2	10.5	C3	
Qualified	A	22.66	0.0423	*	269.4	279.4	265.0	14.4	A2	A2B1C2
	B	19.64	0.0484	*	279.2	267.4	267.2	12.0	B1	
	C	28.17	0.0343	*	274.7	276.7	261.8	14.9	C2	

Note: * indicates significance, (p<0.05); ** indicates highly significance, (p<0.01). A= rotating speed; B= seeds height; C= vacuum pressure. A1 indicates the factor A at level 1; A2 indicates the factor A at level 2, and so on. The same below.

With the reduction of seeds height, the multiple-seeding index increased firstly and then fell, and the missing-seeding index rose gradually. Although a higher seeds height increased the possibility for sucking multiple tubers simultaneously, the tubers amount detached from the nozzle was raised. Because more intense friction and collision happened in tubers are caused by the longer time that the nozzle through the seed pile. Therefore, the multiple-seeding index was not very high. The lower seeds height is, the weaker friction and collision between tubers are. So the multiple-seeding index was risen gradually. When the height was less than 20 cm, the missing-seeding index increased because of the shortened contact time. Also it was found that tubers entrainment between two arms became much more obvious when the seeds height was greater than 20 cm. But the tubers entrained would not be thrown out the seed box, so it does not affect the operational quality. The overall trend is that lower seeds height corresponds to a poor qualified index. Therefore, B1 was a better operating condition.

The multiple-seeding index was proportional to the vacuum pressure, and the change trend of the missing-seeding index was opposite. A higher vacuum pressure generated a larger suction force in the nozzle. When the arm passed the seed pile, the tuber was sucked readily and less likely to detach from the nozzle, even the sucked tuber collided with the other tubers. As a result, the missing-seeding index was low. But, if the suction force was too large, the re-suck phenomenon was seriously. Similar to A, the C1 or the C3 was not the best choice for seeding. The qualified index increased first and then decreased with the rising of vacuum pressure, and reached the maximum value under the C2 condition.

According to the results of ANOVA and range analysis, the optimum operating parameters were obtained as: the device rotating speed 30 r/min, the seeds height 25 cm and the vacuum pressure 10 kPa (A2B1C2). Under this condition, the multiple-seeding index was 1.1%, the missing-seeding index was 0.8% and the qualified index was 98.1%.

The test procedure and results of mini-tuber test are shown in Table 5, and the results of ANOVA and range analysis are shown in Table 6. Table 6 shows that the effect intensity of factors on multiple-seeding index was C>A>B, on missing-seeding index A>C>B and on qualified index C>A>B. When the value of each factor was changed, the changes of the evaluation indexes were basically same to the conventional tuber test. The multiple-seeding index was 0.5%, the missing-seeding index was 0.6% and the qualified index was 98.9% under the conditions of rotating speed of the device 35 r/min, the seeds height 17 cm and the vacuum pressure 3.5 kPa (A2B1C2).

Table 5 Program and results of mini-tuber test

No.	Rotating speed A/r·min^{-1}	Seeds heightB/cm	Vacuum pressure C/kPa	Error D	Multiple-seeding index/%	Missing-seeding index/%	Qualified index/%
1	1(30)	1(17)	1(2.5)	1	3.2	2.5	94.3
2	1	2(13)	2(3.5)	2	5.7	0.6	93.7
3	1	3(9)	3(4.5)	3	12.3	0.3	87.4
4	2(35)	1	2	3	0.5	0.6	98.9
5	2	2	3	1	8.8	1.9	89.3
6	2	3	1	2	0.3	8.3	91.4
7	3(40)	1	3	2	7.5	5.2	87.3
8	3	2	1	3	0.4	11.7	87.9
9	3	3	2	1	1.6	9.4	89.0

Table 6 Analysis results of mini-tuber test

Evaluation Index	Factors	ANOVA			Range analysis				Optimum level	Optimal parameter combination
		F-value	P-value	Significance	K1	K2	K3	R		
Multiple	A	1044.08	0.0010	**	21.2	9.6	9.5	11.7	A3	A3B1C1
	B	89.15	0.0111	*	11.2	14.9	14.2	3.7	B1	
	C	4069.00	0.0002	**	3.9	7.8	28.6	24.7	C1	
Missing	A	216.78	0.0046	**	3.4	10.8	26.3	22.9	A1	A1B1C3
	B	37.92	0.0257	*	7.3	14.2	18.0	10.7	B1	
	C	100.49	0.0099	**	22.5	10.6	7.4	15.1	C3	
Qualified	A	65.11	0.0151	*	275.4	279.6	264.2	15.4	A2	A2B1C2
	B	45.04	0.0217	*	280.5	270.9	267.8	12.7	B1	
	C	79.78	0.0124	*	273.6	281.6	264.0	17.6	C2	

Compared the test results to the predetermined values in “JB/T 10293-2001 Specifications of single seed drill (precision drill)” (multiple-seeding index ≤20%, missing-seeding index ≤10% and qualified index ≥75%)[31], it can be found that the working performance of this potato seed metering device was significantly better than the national standards. So the device could achieve the level of precision seeding.

4 Conclusions

The air-suction metering device for sowing large-size seed crops was achieved by using the structure of an air distribution valve installed with suction arms. Owning the replaceable nozzles, this equipment had the feature of sowing both conventional tuber and mini-tuber. The valve does not need good lubrication even in harsh environments because of the ceramic coating. The seeds height controlled by the dynamic feeding device promoted the sucking performance. The above-described structures contributed to a better working quality, versatility and reliability of the device.

Two orthogonal experiments were carried out on test-bed. Tests results showed that both of the sowing qualities of conventional and mini-tuber were better than those indicated in the national standard. Under the optimized operating conditions, the multiple-seeding index was 1.1%, missing-seeding index was 0.8% and qualified index was 98.1% for planting conventional tuber; and for the mini-tuber, 0.5%, 0.6% and 98.9%, respectively. The apparatus reached the technical level of precision drill.

This research provides solutions for the problems existed in widely used potato planters, such as high multiple-seeding and missing-seeding index, low qualified index, poor versatility, and serious injury on tubers, etc. and gives guidance for air-suction seeding device sowing large-size seed crops, which is benefit for both the developments of air-suction potato seeding apparatus and potato planter.

Acknowledgements

The research was funded by the China Agriculture Research System Special Foundation CARS-10-P22, National Science and Technology Support Project 2014BAD06B03, Yunnan Province Winter Pollution-free Yield Technology System Construction and Application Projects Funded 2014YNC001, and Heilongjiang Province Key Science and Technology Project GA15B401.

[References]

[1] Du H W, Shang S Q, Yang R B, Wang D W. Research and analysis on mechanized potato seed sowing techniques. Journal of Agricultural Mechanization Research, 2011; 33(2): 214–217. (in Chinese with English abstract)

[2] Jia J X, Yang D Q, Li J D, Tao X, Li Y. Investigation summary about potato planting agriculture and mechanical production technique. Journal of Agricultural Mechanization Research, 2010; 11: 1–6. (in Chinese with English abstract)

[3] Lv J Q, Tian Z E, Yang Y, Shang Q Q, Wu J E, Li Z H, et al. The development situation, existing problems and development trend of potato machinery. Journal of Agricultural Mechanization Research, 2015; 12: 258－263. (in Chinese with English abstract)

[4] Singh R C, Singh G, Saraswat D C. Optimisation of design and operational parameters of a pneumatic seed metering device for planting cottonseeds. Biosystems Engineering, 2005; 92(4): 429–438.

[5] Yu J J, Liao Y T, Cong J L, Yang S, Liao Q X. Simulation analysis and match experiment on negative and positive pressures of pneumatic precision metering device for rapeseed. Int J Agric & Biol Eng, 2014; 7(3): 1–12.

[6] Deng X Y, Li X, Shu C X, Huang H D, Liao Q X. Mathematical model and optimization of structure and operating parameters of pneumatic precision metering device for rapeseed. Journal of Food Agriculture & Environment, 2010; 8(3&4): 318－322.

[7] Yang L, He X T, Cui T, Zhang D X, Shi S, Zhang R, Wang M T. Development of mechatronic driving system for seed meters equipped on conventional precision corn planter. Int J Agric & Biol Eng, 2015; 8(4): 1–9.

[8] Yang L, Yan B X, Cui T, Yu Y M, He X T, Liu Q W, Liang Z J, Yin X W, Zhang D X. Global overview of research progress and development of precision maize planters. Int J Agric & Biol Eng, 2016; 9(1): 9–26.

[9] Yazgi A, Degirmencioglu A. Optimization of the seed spacing uniformity performance of a vacuum-type precision seeder using response surface methodology. Biosystems Engineering, 2007; 97(3): 347–356.

[10] Onal I, Degirmencioglu A, Yazgi A. An evaluation of seed

spacing accuracy of a vacuum type precision metering unit based on theoretical considerations and experiments. Turkish Journal of Agriculture and Forestry, 2012; 36(2): 133–144.

[11] Karayel D, Barut Z B, Ozmerzi A. Mathematical modelling of vacuum pressure on a precision seeder. Biosystems Engineering, 2004; 87(4): 437–444.

[12] Mahl D, Furlani C E A, Gamero C A. Efficiency of pneumatic and horizontal perforated disk meter mechanism in corn no-tillage seeders in soil with different mobilization reports. Engenharia Agricola, 2008; 28(3): 535–542.

[13] Zhang G Z, Zang Y, Luo X W, Wang Z M, Zhang Q, Zhang S S. Design and indoor simulated experiment of pneumatic rice seed metering device. Int J Agric & Biol Eng, 2015; 8(4): 10–18.

[14] Xie J B. Design and experiment study on disease-free mini-tuber metering device. ME dissertation. Wuhan: Huazhong Agricultural University, 2012. 70p. (in Chinese with English abstract)

[15] Wu H J, Guo B Z, Ding Y R. Theoretical discuss on selecting valve sealing angle. Fluid Machinery, 1992; 20(9): 22–24. (in Chinese with English abstract)

[16] Wang H S, Zhu W B, Huang Z P, Zhang C N, Zhang J K. Research on the cone angle and clearance of main pump seal. Journal of Mechanical Science and Technology, 2015; 29(7): 2939–2947.

[17] Zhang L Q, Feng Q. Application of cone extruding face elements in high efficiency and precision machining. Aerospace Shanghai, 2014; 31: 56–59. (in Chinese with English abstract)

[18] Shi Y. Seed potato production in Heilongjiang Province. Chinese Potato Journal, 2004; 18(5): 282–286. (in Chinese with English abstract)

[19] Liu W P. Study on development present status and countermeasure of virus free seed potato in Heilongjiang province. MS dissertation. Beijing: Chinese Academy of Agricultural Sciences Dissertation, 2013. 65p. (in Chinese with English abstract)

[20] He W, Paul C Struik, Hu J J, Zhang Y, Zhang Z Y, Lu X L, et al. Effects of seed tuber weight on potato as influenced by other factors under different ecological conditions in Sichuan. Southwest China Journal of Agricultural Sciences, 2007; 20(3): 458–461. (in Chinese with English abstract)

[21] Chinese Academy of Agricultural Mechanization Sciences: Agricultural Machinery Designing Handbook (Ⅰ). Beijing: China Machine Press. 1990. (in Chinese)

[22] Yan Z S. Study on planting techniques of early maturing potato for high-efficient in suburb of Harbin. MS dissertation. Beijing: Chinese Academy of Agricultural Sciences Dissertation, 2006; 12. 37p. (in Chinese with English abstract)

[23] Lin T R, Yin Y H, Hu B, Han S E, Xing J, Li H C, et al. Effect of mini-tuber planting density on yield under condition of mechanization planting mode. Chinese Potato Journal, 2014; 4: 76–79. (in Chinese with English abstract)

[24] Li Y. Effects of tuber size of pre-elite seed potato on agronomic traits, propagation coefficient and yield of potato. Chinese Potato Journal, 2014; 28(1): 21–26. (in Chinese with English abstract)

[25] Fu Y C. Effects of Different Sizes of Pre-elite Seed and Density on the Growth and Yield Formation of Potato. MS dissertation. Wenjiang: Sichuan Agriculture University, 2012. 53p. (in Chinese with English abstract)

[26] Li L. A preliminary study on the theory and experimentation of the suction-type metering device for precision drill. Transactions of the CSAM, 1979; 10(3): 56–63. (in Chinese with English abstract)

[27] GB/T 6973-2005 Testing methods of single seed drills (precision drills). National Standards of the People's Republic of China. (in Chinese)

[28] GB/T 6242-2006 Equipment for planting-Potato planters-Method of test. National Standards of the People's Republic of China. (in Chinese)

[29] Maghsoodloo S, Ozdemir G, Jordan V, Huang C H. Strengths and limitations of Taguchi's contributions to quality, manufacturing, and process engineering. Journal of Manufacturing Systems, 2004; 23(2): 73–126.

[30] Ballantyne K N, van Oorschot R A, Mitchell R J. Reduce optimisation time and effort: Taguchi experimental design methods. Forensic Science International: Genetics Supplement Series, 2008; 1(1): 7–8.

[31] JB/T 10293-2001, Specifications of single seed drill (precision drill). Machinery Industry Standards of the People's Republic of China. (in Chinese)