Simulation analysis and match experiment on negative and positive pressures of pneumatic precision metering device for rapeseed

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Abstract: Positive and negative pressures determine the performance of pneumatic precision metering device for rapeseed. In order to investigate the relationship between positive and negative pressures of nozzles, fluid models of chamber were developed to simulate the airflow, and the k-ε turbulence model was conducted to capture the pressure and velocity of nozzles. Through these efforts linear models were achieved. Meanwhile, the three-factor factorial split-split experiment was designed with negative pressure, positive pressure and the rotating speeds varying from -1 000 to -4 500 Pa, 50 to 250 Pa and 10 to 45 r/min, respectively. The mathematical models were developed through employing the stepwise regression method. The sequence of influential factors on the quality of feed index was positive pressure, negative pressure and rotating speed. To obtain the match regulation of negative and positive pressures with "good" performance, the ratio coefficient K of negative and positive pressures was introduced to build mathematical models. Models relating ratio coefficient K with positive pressure were fitted in different rotating speeds. The results showed that the ratio coefficient was matched $\Gamma\in[f_1(x), f_2(x)]$ from the fitting equations with the rotating speed of 10 - 30 r/min; while the rotating speed has greater influence when it was 35 - 40 r/min and the sets $\Lambda\in[g_1(x), g_2(x)]$ were achieved, where $x\in[100, 250]$. This study could be conducted to adjust the rotating speed of the pneumatic system to optimize the ideal performance of the seeder.

Keywords: precision metering device, pneumatic device, simulation, positive and negative pressures, stepwise regression, fitting, rapeseed

DOI: 10.3965/j.ijabe.20140703.001

Citation: 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.

1 Introduction

Rapeseed is an important oil plant, and China has become one of the largest rapeseed cultivation countries in the world with 7.35 thousand ha and a production of 13.43 million tons in 2011 (National Bureau of Statistics of China, 2011). Despite high production, the large consuming demand necessitates result in importation from other countries every year, thus rapeseed plays an essential role in our daily lives, especially in Yangtze River area (P.R. China).

In China, there are various methods to cultivate rapeseed including transplantation of seedling, manual broadcasting and direct sowing. While transplantation is the most traditional method for farmers, it is labor-intensive, time-consuming, expensive in operation and strict in environmental requirement. If these conditions are not met, non-uniform distribution and low yields will be resulted. What's more, nowadays the

Received date: 2013-05-12 **Accepted date:** 2014-06-12

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migration of people from the production areas to urban cities results in a smaller labor force in the villages to cultivate rapeseed. Moreover, various land environments and fewer seeders for rapeseed make the difficulties of cultivation become more prominent for farmers. It is urgent to develop the mechanization for rapeseed production in China.

Rapeseed (*Huaza* No.4) is small in size with an average diameter of 1.9 mm. Skins can be easily damaged and gathered to block the nozzle of the metering device, causing poor seeding performance[1]. According to the basic parameters of rapeseed, pneumatic precision metering device[2] with negative and positive pressures[3,4] had been invented by the Group Liao Qingxi in the College of Engineering of Huazhong Agricultural University. As a result of its great advantages, this pneumatic precision metering device could overcome the problem of small-size plant in sowing, and is applied in the 2BFQ-6 combined direct seeders for rapeseed[5-7].

In precision agriculture, pneumatic metering device has been widely developed for sowing different seeds, such as rapeseed, wheat[8], maize, soya, sugar beet[9], cotton[10], etc, and it is expected to place the single seed in the soil at a desired plant position for precision planting. However, there are many factors to influence the performance in the field, so many researchers aim to achieve desirable performance of metering device in experiments.

Many experimental studies of metering devices have been conducted to optimize the structural and operational parameters in achieving ideal performance. A. özmerzi[11] investigated the effects of different depths of sowing maize in precision vacuum seeder; the optimum sowing depth was 60 mm according to uniformity of sowing depth and maximum emergence rate index. Zeliha Bereket Barut[12] designed a factorial completely randomized vertical metering unit for seeding maize to analyze the relationship between the seed holding ratio and the shapes of holes, peripheral velocities, vacuum pressure, the hole area on the seed plate, as well as thousand grain weight. D. Karayel[13] developed mathematical models with physical properties of seeds such as one thousand kernel mass, projected area, sphericity and kernel density in maize, cotton, soya bean, watermelon, melon, cucumber, sugar beet and onion seeds, and achieved an optimum vacuum pressure in the laboratory tests, which showed that the vacuum pressure was related with thousand kernel weight with the model efficiency of 0.99. R. C. Singh[14] investigated the pneumatic planter for cottonseed with entry cone angles of the hole at between 90° and 150°, speeds at between 0.29 and 0.69 m/s, and the vacuum pressure at between 1 and 2.5 kPa to evaluate the performance. Their results revealed that the metering disc achieved the quality of feed index of 94.7% when entry cone angle, disc speed, vacuum pressure were 120°, 0.42 m/s and 2 kPa, respectively. M.R. Maleki[15] introduced a new index designated as the coefficient of uniformity U_c for the evaluation of seed distribution uniformity of grain drills; and it was proved to be repeatable and insensitive to outlying values. Arzu Yazgi[16,17] optimized the vacuum pressure, the diameter of seed holes and peripheral speed of seed plate on precision planter for cottonseed using response surface methodology, and the optimum vacuum pressure and the diameter of seed holes were found to be 5.5 kPa and 3 mm, respectively. D. Karayel[18] compared the performance of furrow openers in the distribution of sowing depth and lateral seed scatter for the precision vacuum seeder, and ellipse and integral criteria were calculated in the distribution area of seeds. B.B. Gaikwad[19] developed a precision plug tray seeder for sowing capsicum and tomato, the suction pressures of 4.91 kPa and 3.92 kPa and nozzle diameters of 0.46 mm and 0.49 mm were achieved, respectively. M. Anantachar[20,21] conducted the artificial neural network to predict the performance of an inclined plate seed metering device for the peanuts.

The studies of pneumatic precision metering device for rapeseed had been conducted for many years. Wu Futong[22,23] designed this metering device and determined the parameters including the vacuum pressure, the diameters of holes, the number of holes and rotating speeds, the optimal structural parameters of the vessel and air chamber were studied to simulate the airflow using ANSYS/FLOTRA. Li Jibo[24,25] simulated the airflow of negative pressure region in different parameters on ANSYS/CFX, and verified the performance of metering device with negative pressure, positive pressure and the rotating speeds of the metering disc. Xiaoyan Deng[26,27] focused on the sucking-seed process of a pneumatic metering device and developed mathematical models to optimize the operating parameters. Yang Song[28] studied the distribution of rapeseed seedling for 2BFQ-6 precision seeder, and the results indicated the exponential distribution was formed in different parameters. Xu Li[29] obtained mathematical models for the vacuum metering device in the theoretical analyses, and simulated the airflow of negative pressure region using ANSYS/CFX.

The reasons of this study were as follows: i) the prototype had been developed through the studies years ago before it was applied to the seeder. It is necessary to investigate the relationship between negative pressure and positive pressure on the newest type of metering device; ii) previous experiments had been conducted to prove that negative and positive pressures affected the performance greatly; iii) the core of 2BFQ combined seeder for rapeseed was pneumatic precision metering device. Negative and positive pressures changed over the load of tractor when the seeder completes many operations including furrowing, plough, planting, fertilizing, earth covering etc; iv) the turbulence of air chamber would affect negative and positive pressures. The research results could be conducted to recommend the match of negative and positive pressures. It is beneficial to maintain the performance of the metering system in the seeder and optimize the structural parameters of pneumatic metering device.

To avoid poor seeding space and low yields for the seeder, it is essential to study the relationship between negative and positive pressures. The objectives of this study were to:

1) simulate the fluid region of chamber and find the influence of pressures;

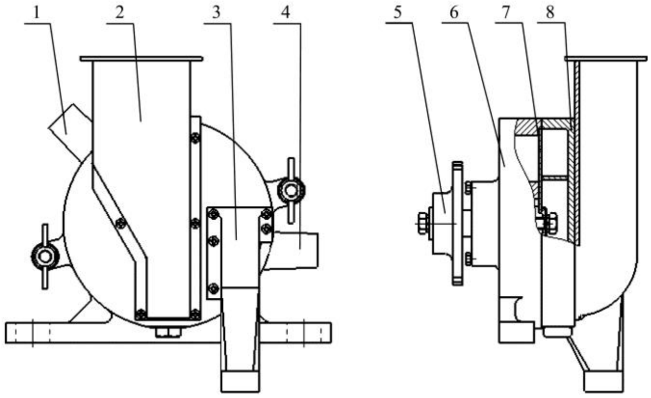
2) build the mathematic models of negative and positive pressures ratio coefficient K; and

3) achieve the match of negative and positive pressure at different rotating speeds.

2 Materials and methods

2.1 Pneumatic precision metering device for rapeseed

As shown in Figure 1, the components of the pneumatic precision metering device included a shell, an air chamber, a seed box, a seed spout, a seed plate, as well as a sprocket, etc.



1. Outlet of negative pressure 2. Seed box 3. Seed spout 4. Inlet of positive pressure 5. Sprocket wheel 6. Shell 7. Seed plate 8. Air chamber

Figure 1 Schematic diagram of pneumatic precision metering device

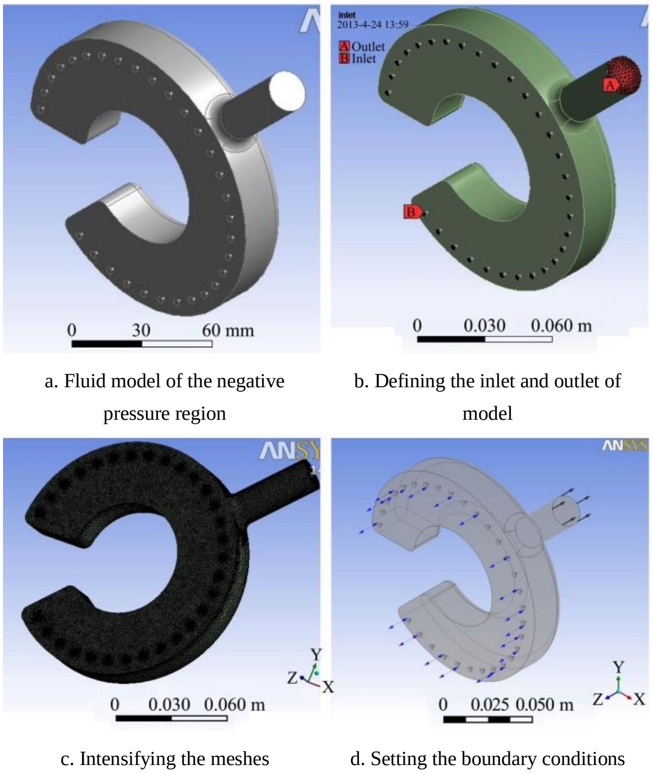
Negative and positive pressures could be created in the air chamber region by the air fan. The sprocket wheel drove the metering unit to rotate. When rapeseeds from the seed box flowed into the shell, they were attached into the cone nozzles on the seed plate, and carried by the seed plate through the negative pressure region into the positive pressure region. Meanwhile rapeseeds were injected from the nozzle into the seed spout under the force of positive pressure and gravity. The seeds dropped from the tube into the field to realize precision planting.

2.2 Simulation models of metering device

Studies showed that the pressures of air chamber could directly affect the performance of metering device. In order to find out the relationship between the chamber pressures of nozzles, ANSYS/CFX was conducted to simulate the airflow, and achieved the pressure and velocity of nozzles in the results. There were assumptions to simplify the fluid models during the simulation of ANSYS/CFX: 1) the temperature of air always kept at 25℃; 2) the negative pressure region and the positive pressure region were independent without interaction; and 3) the seed plate and air chambers contacted tightly without air leakage[29].

2.2.1 Fluid model of negative pressure region

The fluid model of negative pressure region was built according to the structural parameters in the geometry section of ANSYS/CFX as Figure 2a, and defined the nozzles plane and the negative pressure tube as the inlet and outlet as Figure 2b. The others were wall. In order to capture the change of pressure near the nozzles and the negative pressure tube, the meshes were intensified and the minimum size in the fluid model was controlled as Figure 2c. The boundary conditions were set in the CFX-Pre as Figure 2d. The inlet was opening with the pressure 0 Pa, while the outlet was set at -1 000 Pa (test in the experiment). Navier-Stokes equations were solved to select the standard k-ε turbulence model in the CFX-Solver. The time step was 2 s and the convergence was 10^{-4}. The solver ran to simulate after initialization.



a. Fluid model of the negative pressure region

b. Defining the inlet and outlet of model

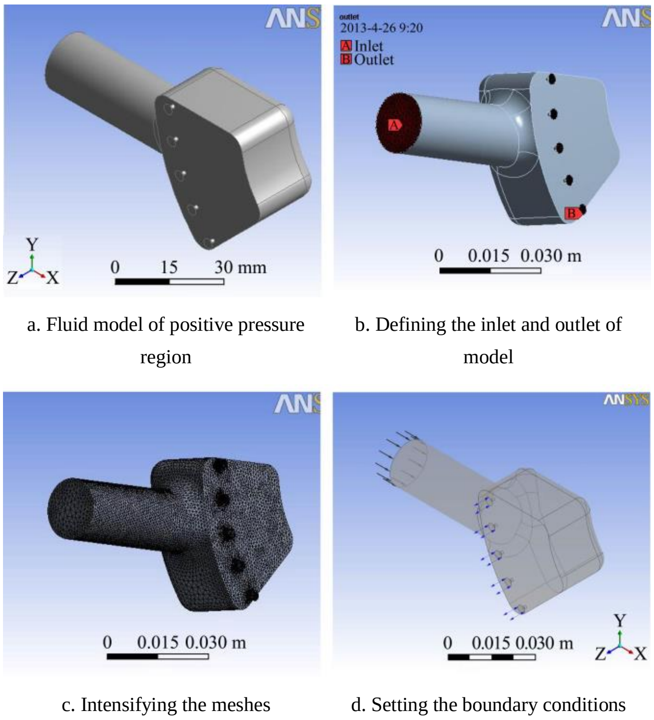
c. Intensifying the meshes

d. Setting the boundary conditions

Figure 2 Fluid model of negative pressure region

2.2.2 Fluid model of positive pressure region

The fluid model of the positive pressure region was built as Figure 3a. The nozzles and the positive pressure tube were defined as the outlet and inlet. The other parts were defined as the wall as Figure 3b. The meshes were intensified and controlled at the minimum element size as Figure 3c. The boundary was defined in the CFX-Pre. The inlet was set at 50 Pa (test in the experiment), the outlet at 0 Pa. The standard k-ε turbulence model was selected to solve Navier-Stokes equations in the CFX-Solver. The convergence was defined as 10^{-4}, and calculated after initialization.



a. Fluid model of positive pressure region

b. Defining the inlet and outlet of model

c. Intensifying the meshes

d. Setting the boundary conditions

Figure 3 Fluid model of positive pressure region

2.3 Experimental equipment

The laboratory experiments involved testing seeding uniformity of pneumatic precision metering device in different positive pressures and negative pressures at various rotating speeds. Positive and negative pressures were located based on the previous experiments in the range of 50 - 250 Pa and -1 000 − -4 500 Pa, respectively. The rotating speeds were defined between 10 - 45 r/min. The data were collected in the grease belt stand as was shown in the Figure 4 and a three-factor factorial split-split experiment was designed (Table 1) with three replicates for each treatment. The quality of feed index, miss index, and multiple index were analyzed to estimate the performance of precision metering device.

They were calculated following Experimental Methods of Single-seed or Precision Seeder in China National Standard (GB/T 6973-2005), where the corresponding equations are:

Quality of feed index: $$A=\frac{n_1}{N'}\times 100 \quad (1)$$

Miss index: $$M = \frac{n_0}{N'} \times 100 \qquad (2)$$

Multiple index: $$D = \frac{n_2}{N'} \times 100 \qquad (3)$$

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

1. CCD detector 2. Manometer 3. Pneumatic precision metering device for rapeseed 4. Air fan 5. JPS-12 test stand of the precision metering device

Figure 4 Picture of test stand on metering device

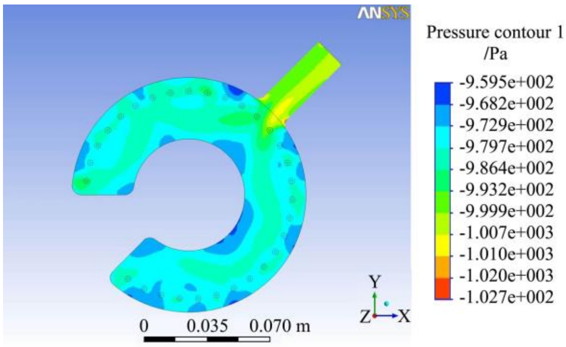
Table 1 Experimental factors and levels

Code	Factors		
	Positive pressure /Pa	Negative pressure /Pa	Rotating speed /r min^{-1}
1	50	-1 000	10
2	100	-1 500	15
3	150	-2 000	20
4	200	-2 500	25
5	250	-3 000	30
6	-	-3 500	35
7	-	-4 000	40
8	-	-4 500	45

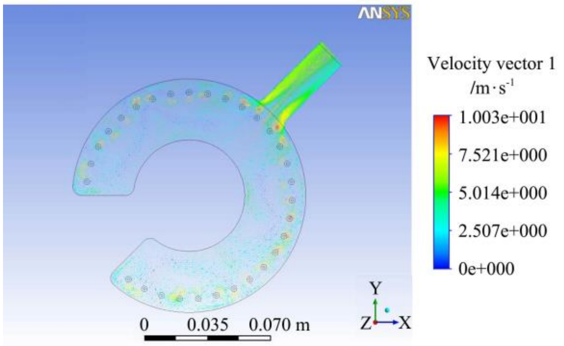
3 Results and discussion

3 1 Results of negative pressure fluid model

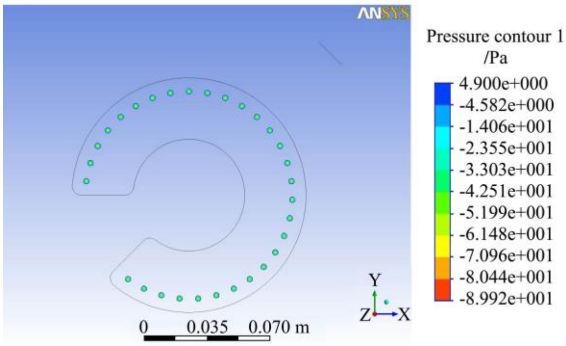
The pressures and velocity contours were captured in CFX-Post as Figure 5. The pressure contour and velocity vector were observed through building a plane in the Figure 5a and 5b. It was easy to know that the pressure and velocity of negative pressure region were uniform except the nozzles and the negative pressure outlet as Figure 5c and 5d.



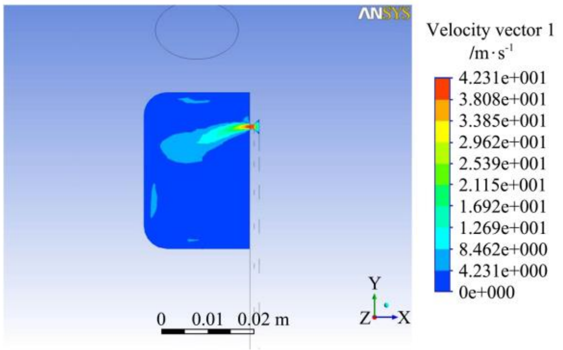
a. Pressure contour of negative pressure region



b. Velocity vector of middle plane



c. Pressure contour of nozzles



d. Velocity of nozzles

Figure 5 Pressure and velocity of air flow in negative pressure region

The reason was that structures of nozzles and negative pressure outlet were contracted section. When the airflow passed through them, the pressure and velocity changed greatly, so pressure showed in the contour. While the pressure of nozzles would influence the performance, in order to find the relationship between the negative pressure outlet and nozzles, the pressure and velocity of nozzles were analyzed from the results as Table 2.

Table 2 Pressures and velocities of nozzles in the negative pressure region

Pressure of outlet/Pa	Pressure of nozzles/Pa	Velocity of nozzles/m s^{-1}
-1 000	-954.55	6.73
-1 500	-1 431.73	8.28
-2 000	-1 907.41	9.58
-2 500	-2 384.55	10.74
-3 000	-2 861.74	11.78
-3 500	-3 338.41	12.74
-4 000	-3 816.10	13.64
-4 500	-4 293.23	14.48

It was concluded that pressure of nozzles rose as the increase of pressure in negative pressure outlet. Thus the high pressure would increase the probability of sucking seeds. The velocity of nozzles either increased. The pressure gradient increased to make the rapeseed accelerate in the sucking process.

The mathematical model between pressure of nozzles and pressure of negative pressure outlet was developed as the equation:

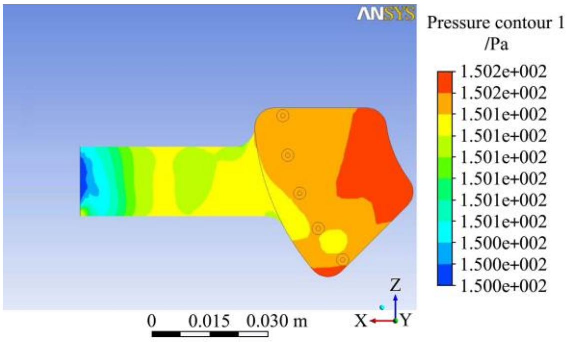
$$y_n=0.9539x_1-0.3055 \qquad (4)$$

where: y_n is pressure of nozzles, Pa; x_1 is pressure of the negative pressure outlet, Pa.

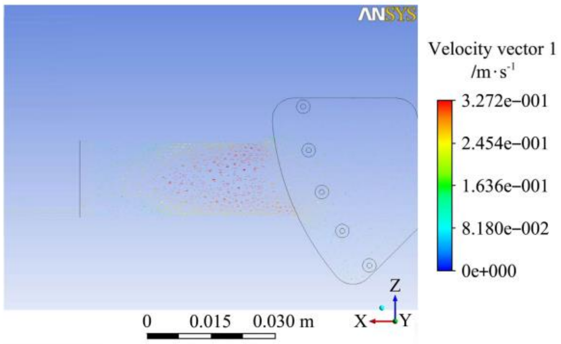
The results showed that the relationship between pressure of the negative pressure outlet and pressure of nozzles in the pneumatic precision metering device was linear.

3.2 Results of positive pressure model

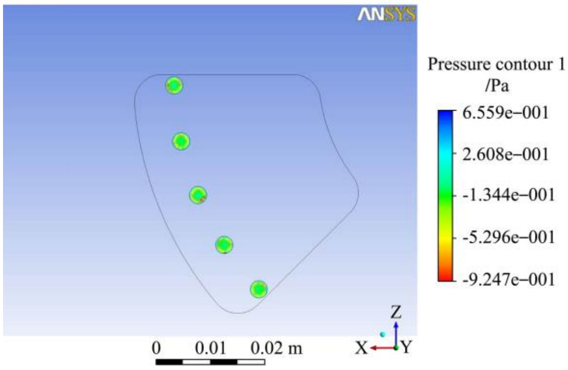
The pressure contour and velocity vector of positive pressure region were achieved from the fluid model in the CFX-Post. Figure 6a showed the pressure contour was large enough, while velocity of positive pressure inlet was larger than it was in the air chamber as Figure 6b, because the air in positive pressure inlet was pushed into air chamber, only flowed out from the nozzles, so the pressure would increase. The structure of positive pressure inlet was an expanding tube, when the air passed through the tube into the air chamber and velocity decreased. Meanwhile positive pressure of cone nozzles was jet, so the pressure and velocity of nozzles were changed greatly as Figure 6c and 6d.



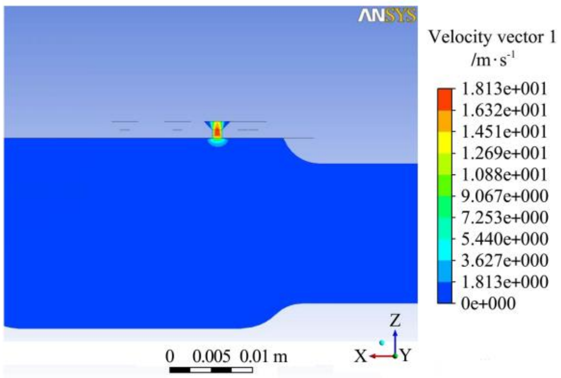
a. Pressure contour of positive pressure region



b. Velocity vector of middle plane



c. Pressure contour of nozzles



d. Velocity of nozzles

Figure 6 Pressure and velocity of air flow in positive pressure region

The pressure and velocity of nozzles in the positive pressure region were collected from the simulation as showed in Table 3. The pressure of nozzles changed with pressure of positive pressure inlet, it was known when pressure of nozzles was large, the displacement of rapeseed increased; and the airflow velocity of nozzles increased with the increase of pressure in positive pressure inlet.

Table 3 Pressures and velocities of nozzles in positive pressure region

Pressure of inlet /Pa	Pressure of nozzles/Pa	Velocity of nozzles/m s^{-1}
50	47.04	1.92
100	94.24	2.79
150	141.64	3.42
200	188.43	3.97
250	235.58	4.45

The mathematical model was fitted according to the results in Table 3:

$$y_p=0.9426x_2+0.001163 \tag{5}$$

where: y_p is pressure of nozzles, Pa; x_2 is pressure of the positive pressure inlet, Pa.

The equation showed that the relationship between pressure of positive pressure inlet and pressure of nozzles was linear.

The results showed that pressure of nozzles in the positive pressure region changed with pressure of the positive pressure inlet, and the relationship was linear. The pressure of nozzles in positive pressure region would affect the performance of metering device, so pressure of positive pressure inlet determined the performance.

It was observed that pressure of air chamber would affect pressure of nozzles to result in poor performance. When pressure of the negative pressure region was large enough, the multiple index increased. While pressure of nozzles in the positive pressure region increased, the trajectories of rapeseed increased in the seed spout, and resulted in the worse uniformity of seed spacing. So it was essential to maintain the match of negative and positive pressures for pneumatic precision metering device.

3.3 Relationship between negative and positive pressures

According to Equations (1), (2) and (3), the sum of three abovementioned performance indexes of metering device was 100%. Quality of feed index and miss index were more important than multiple index for rapeseed. Thus in evaluating the changes of performance in different experimental conditions, all the results were only reported in terms of quality of feed index and miss index, as was in Figure 7.

Positive pressure and negative pressure were verified to be the more important factors from the results. In order to figure out the relationship between quality of feed index and the operational parameters including positive pressure, negative pressure and rotating speed, stepwise regression was applied to develop mathematical models. The regression equation for the quality of feed index I_{qf} with negative pressure x_1, incorporating the positive pressure x_2, and the rotating speed x_3 in r/min was calculated as (6):

$$\begin{aligned} I_{qf} &= -0.027x_1+0.52x_2+1.32x_3-6.39\times10^{-6}x_1^2- \\ &0.001x_2^2-0.0344x_3^2-0.0045x_1x_2-3.23\times10^{-4}x_2x_3 \end{aligned} \tag{6}$$

Where the determination coefficient R^2 was 0.98.

Analysis of variance showed that the effect of operational parameters on quality of feed index was significant (P<0.01). Table 4 showed that negative pressure x_1, positive pressure x_2 and rotating speed x_3 influenced quality of feed index in different ways with $x_2>x_1>x_3$.

Table 4 Parameters of stepwise regression equations

Parameters	Estimate of regression coefficient	Standard error	Value t	Pr>|t|	Standard regression coefficient
x_1	-2.695E-02	3.07E-03	-8.76	<0.0001	-0.97
x_2	0.52	5.11E-02	10.28	<0.0001	1.06
x_3	1.32	0.29	4.59	<0.0001	0.48
x_1^2	-1.00E-03	1.65E-04	-6.06	<0.0001	-0.42
x_2^2	-6.39E-06	5.75E-07	-11.12	<0.0001	-0.85
x_3^2	-3.44E-02	5.75E-03	-5.99	<0.0001	-0.46
x_1x_2	-4.53E-03	8.25E-04	-5.49	<0.0001	-0.27
x_1x_3	-3.23E-04	4.95E-05	-6.53	<0.0001	-0.35

Based on the obtained results, the performance of metering device could be judged as “insufficient”, “sufficient”, “good”, and “excellent”, which was in compliance with the classification reported in the ENAMA Test Protocol for the seeding machinery.

Figure 7 clearly showed that the rotating speed would affect the results: when the rotating speed varied from 10 to 30 r/min, the quality of feed index would decrease at positive pressure of 50 - 100 Pa. While the rotating speeds changed from 35 to 45 r/min, quality of feed index changed greatly, and only a few points resulted in “sufficient” at the rotating speed of 45 r/min. Also it was found that different positive and negative pressures could be combined to ensure the quality of feed index in “good”.

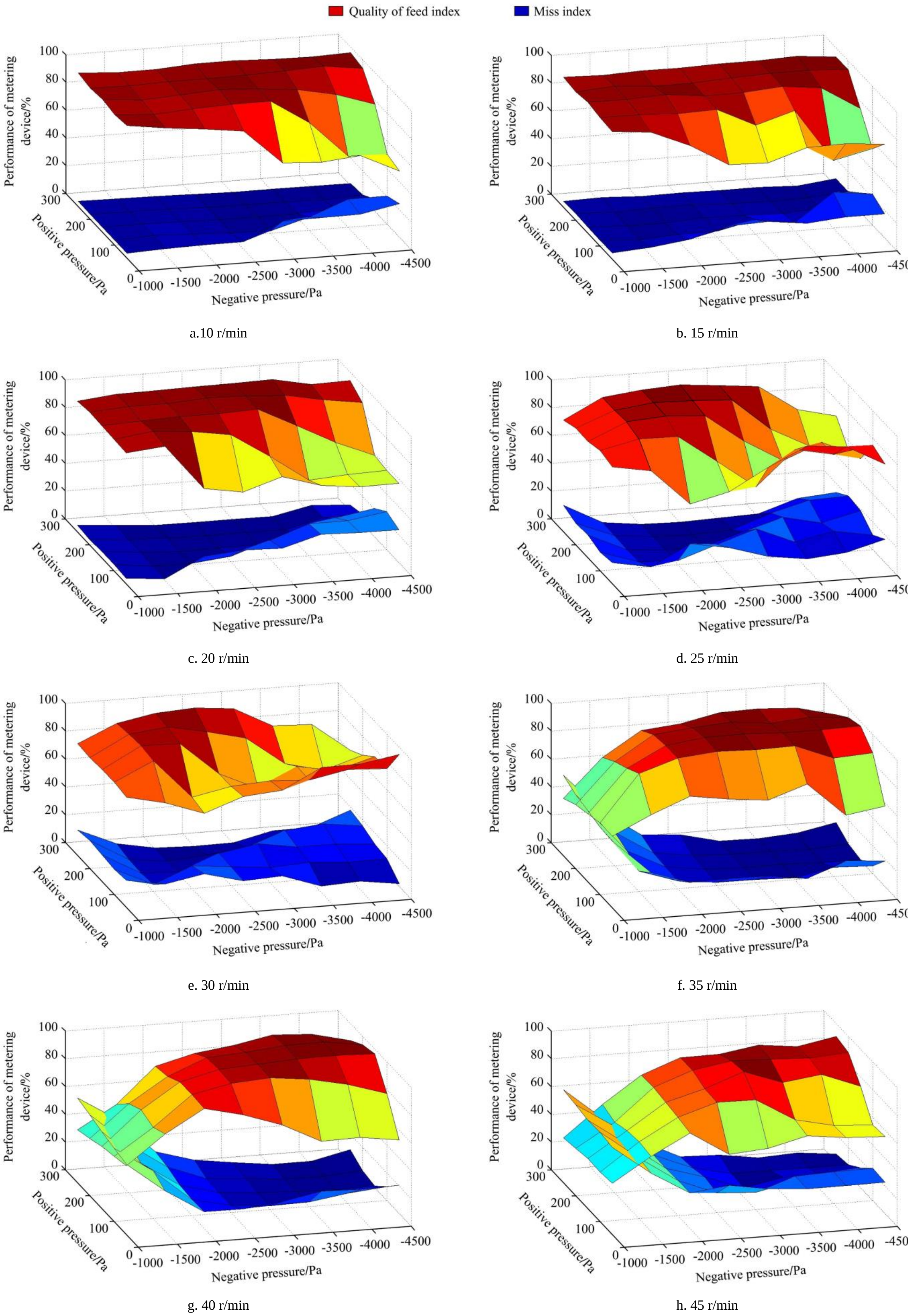


Figure 7 Performance of metering device at different rotating speeds

Table 5 gave the statistics of quality of feed index in the rotating speeds of 10 - 45 r/min with negative pressure -1 000 − -1 500 Pa. When negative pressure was -1 000 Pa and the rotating speed varied from 10 to 20 r/min, the performance remained "good" with positive pressure 50 - 250 Pa, and "sufficient" at the rotating speed of 25 r/min, but "insufficient" when the rotating speed changed from 30 - 45 r/min; while negative pressure was -1 500 Pa, the rotating speed switched from "good" to "insufficient" with the rotating speed varying from 10 to 45 r/min.

Table 5 Results of different rotating speeds with negative pressure -1 000 − -1 500 Pa

Negative pressure/Pa	Rotating speed /r min^{-1}	Positive pressure /Pa	Quality of feed index/%	Evaluation
-1000	10	50-250	≥90.4	Good
-1000	15	50-250	≥90.4	Good
-1000	20	50-250	≥90.4	Good
-1000	25	50-200	≥82.3	Sufficient
-1000	30	50-250	≤82.3	Insufficient
-1000	35	50-250	≤82.3	Insufficient
-1000	40	50-250	≤82.3	Insufficient
-1000	45	50-250	≤82.3	Insufficient
-1500	10	50-250	≥90.4	Good
-1500	15	50-250	≥90.4	Good
-1500	20	100-250	≥90.4	Good
-1500	25	100-250	≥90.4	Good
-1500	30	100-200	≥90.4	Good
-1500	35	100	≥82.3	Sufficient
-1500	40	50-250	≤82.3	Insufficient
-1500	45	50-250	≤82.3	Insufficient

The main reasons for the above finding were: a block (6 mm in width) divided the chamber into two regions: positive and negative pressure regions. There was a slit between the seed plate and the block. A rapeseed in the shell was sucked by the seed plate transferring between the two regions. When the seeds passed through the slit into positive pressure region but with a low pressure, the rapeseed could not drop immediately. This would result in the decrease of performance for metering device in the greased belt. When the value of positive pressure from the air fan was sufficient, there could be a wide range of matching negative pressure that could be employed to maintain "good" quality of feed index at the same rotating speed.

3.4 Development of negative and positive pressure ratio coefficient models

To maintain the great performance in the field, it was essential to study the relationship between positive and negative pressures. Positive and negative pressure ratio coefficient K was introduced to describe the relationship, and the mathematic models were developed in different rotating speeds. The statistics of operational parameters resulted in "good" were applied from the experiments, and the range of ratio coefficient was calculated according to the experimental results in Table 6.

Table 6 Range of ratio coefficient K at different rotating speeds

Rotating speed /r min^{-1}	Positive pressure /Pa	Negative pressure /Pa	Ratio coefficient /K
10	50	-1 000−-1 500	20−30
10	100	-1 000−-3 000	10−30
10	150	-1 000−-3 500	6.67−23.33
10	200	-1 000−-4 500	5−25
10	250	-1 000−-4 500	4−15
15	50	-1 000−-1 500	20−30
15	100	-1 000−-2 500	10−25
15	150	-1 000−-4 500	6.67−30
15	200	-1 000−-4 500	5−22.5
15	250	-1 000−-4 500	4−18

To describe the relationship clearly, the mathematical models were established where positive pressure was taken as the independent variable x. Negative and positive pressures ratio coefficient K was considered as the dependent variable y. Figure 8 indicated the area of ratio coefficient K by the upper and lower boundaries at different rotating speeds.

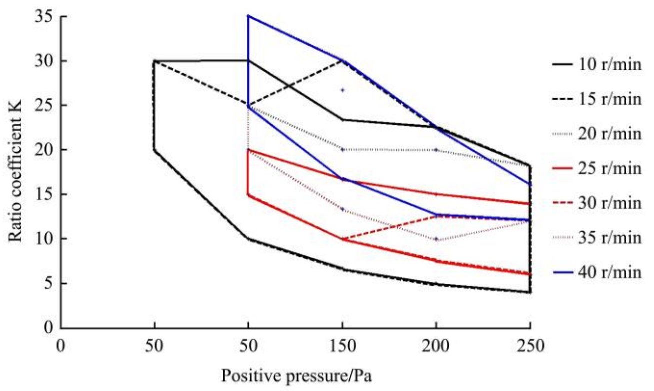


Figure 8 Ratio coefficients of negative and positive pressures at different rotating speeds

To develop the relationship between the ratio coefficient K and positive pressure, the ratio coefficient K_i was defined in different ways where i (i = 10, 15, 20…, and 40) denoted the rotating speed (in r/min), and the fitting equations were determined as follows (7):

$$
\begin{aligned}
&K_{10} \in [-4.0\times10^{-6}x^3+2.362\times10^{-4}x^2-0.4786x+38.47,\\
&\quad -0.063x+34.22],\ x\in[50,\ 250]\\
&K_{15} \in [-4.0\times10^{-6}x^3+2.362\times10^{-4}x^2-0.4786x+38.47,\\
&\quad -7.095\times10^{-4}x^2+0.1999x+11.97],\ x\in[50,\ 250]\\
&K_{20} \in [-4.0\times10^{-6}x^3+2.362\times10^{-4}x^2-0.4786x+38.47,\\
&\quad 3.143\times10^{-4}x^2-0.1523x+36.8],\ x\in[50,\ 250]\\
&K_{25} \in [3.5\times10^{-4}x^2-0.1815x+29.58,\ 2.333\times10^{-4}x^2-\\
&\quad 0.121x+29.72],\ x\in[100,\ 250]\\
&K_{30} \in [3.5\times10^{-4}x^2-0.1815x+29.58,\ -1.4\times10^{-5}x^3-\\
&\quad 0.0078x^2-1.385x+89.5],\ x\in[100,\ 250]\\
&K_{35} \in [8.667\times10^{-4}x^2-0.358x+47.23,\ -6.5\times10^{-4}x^2+\\
&\quad 0.1285x+24.08],\ x\in[100,\ 250]\\
&K_{40} \in [7.833\times10^{-4}x^2-0.3605x+53.19,\ 1.0\times10^{-4}x^2-\\
&\quad 0.169x+51.45],\ x\in[100,\ 250]
\end{aligned}
\tag{7}
$$

When the rotating speeds varied from 10 r/min to 20 r/min, the minimum value of ratio coefficient K_i was applied to fit the curve of the lower boundary in the figure, and the same equation $K_i = -4.0\times10^{-6}x^3+2.362\times10^{-4}x^2-0.4786x+38.47$ was obtained. While it came to 25 r/min and 30 r/min, the area became smaller and the upper boundary descended, but sharing the same lower boundary. The equation was $K_i = 3.5\times10^{-4}x^2-0.1815x+29.58$. When the rotating speed reached 35 - 40 r/min, the whole area moved upwards. No "good" results could be achieved at 45 r/min in the experiments.

All the fitting curves and equations had the same expression as those in Figure 3. If the rotating speed was not greater than 25 r/min. The ratio coefficient determined the performance. When it rose to 30 r/min, the performance would be affected by the rotating speed as well. While the seed plate ran between 35 r/min and 40 r/min, it became the main factors. Therefore, the quality of feed index can be concluded as two parts with a threshold of rotating speed at 30 r/min.

Moreover, when the rotating speed was confined within 30 r/min, the ratio coefficient had a great influence on the performance; when it came to 35 r/min and 40 r/min, the rotating speed became more important to the performance than the ratio coefficient.

Therefore, the sets were concluded from the equations (8). When the rotating speed varied from 10 - 30 r/min, the set $\Gamma\in[f_1(x),\ f_2(x)]$ was conducted, where $x\in[100,\ 250]$, $f_1(x)$ and $f_2(x)$ were as follows:

$$
\begin{cases}
f_1(x) = 3.5\times10^{-4}x^2-0.1815x+29.58\\
f_2(x) = -1.4\times10^{-5}x^3-0.0078x^2-1.385x+89.5
\end{cases}
\tag{8}
$$

While it was tested within the range 35 - 40 r/min, the set $\Lambda\in[g_1(x),\ g_2(x)]$ was concluded, where $x\in[100,\ 250]$, and $g_1(x)$ and $g_2(x)$ were as follows:

$$
\begin{cases}
g_1(x) = 7.833\times10^{-4}x^2-0.3605x+53.19\\
g_2(x) = 1.0\times10^{-4}x^2-0.169x+51.45
\end{cases}
\tag{9}
$$

When the rotating speed was adjusted within the effective range, positive and negative pressures were matched according to the mathematic models, and thus the performance would be "good"; the structural parameters could be optimized by the results. Moreover, the tractor's working power could be as low as possible to save energies, and the suggestion of positive pressure was to maintain within the range from 100 Pa to 250 Pa.

4 Conclusions

The fluid models of pneumatic precision metering device were built to obtain the pressure and velocity of nozzles in the chamber in ANSYS/CFX. The linear models were developed between the air chamber and the nozzles, which showed that negative and positive pressures could directly affect the pressure of nozzles. In the laboratory tests, factors including rotating speed, positive and negative pressures were introduced to investigate the performance in the respective range of 10 - 45 r/min, 50 - 250 Pa and -1 000 − -4 500 Pa. Stepwise regression was conducted to develop mathematical models. The results showed that three factors had a significant effect on the performance of the metering device (P<0.01), and the performance was influenced greatly by negative and positive pressures. The increase of the rotating speed would result in "insufficient" performance.

According to the experimental results, the data corresponding to "good" quality of feed index were calculated to develop mathematical models at different rotating speeds, where negative and positive pressure ratio coefficient K was introduced to investigate the performance, and two sets were concluded from the fitting equations $\Gamma \in [f_1(x),\ f_2(x)]$ and $\Lambda \in [g_1(x),\ g_2(x)]$ with the rotating speeds of 10 - 30 r/min and 35 - 40 r/min, respectively, where $x \in [100, 250]$. The recommended positive pressure was 100 - 250 Pa in the application. Therefore when the combined seeder for rapeseed works in the field, negative and positive pressures should match each other to achieve "good" performance; it is beneficial to reduce the power and to optimize the structural parameters.

Acknowledgements

The research was funded by the National Science Foundation of China under grant 51275197, National Rapeseed Industrial System Special Foundation CARS-13, National Science and Technology Support Project 013BAD08B02, and High School Science Research Foundation 2014PY033.

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