Research on Characteristics of Airway Pressure Loss in Seeding-Wheel-Type Pneumatic Seeder

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Abstract: In order to optimize the parameters of the mechanism, reduce the pressure loss and improve the efficiency of pneumatic utilization, the principles and types of pneumatic loss in different areas were defined, and the key parameters, including the diameter of the horizontal air pipe, the angle of the air pipe, and the diameter of the negative pressure aperture, which affect the pressure loss, were analyzed. In addition, an orthogonal simulation experiment was carried out using Fluent software, and determined the best parameter combination, which is as follows: the diameter of the horizontal air pipe must be 15 mm, the angle of the air pipe must be 105°, and the diameter of the negative pressure aperture must be 34 mm. It can be concluded from the simulation results that the average airflow velocity of the seed-sucking hole is 102.59 m·s⁻¹, the minimum airflow velocity of the seed-sucking hole is 101.58 m·s⁻¹, and the airflow velocity standard deviation of the seed-sucking hole is 0.54 m·s⁻¹. The trend of the test results was consistent with the simulation results, which verified the reliability of the numerical analysis. These results will provide theoretical guidance for research on the obstruction effect of complex airways on airflow.

Keywords: pneumatic seeder; pressure loss characteristics; complex airway; airway optimization

1. Introduction

Single-seed precision seeding refers to a type of seeding technology that separates crop seeds one by one and controls their distribution position precisely on the seedbed. This technology encounters difficulties in the separation of seeds and in preventing the formed uniform seed flow from being re-dispersed on the inner wall of the seed pipe and seedbed [1–3]. To solve the above problems, a seeding-wheel-type pneumatic seeder that works via pneumatic single-grain separation and orderly and stable casting in a low position was designed. However, its internal airway structure is complex with many branches, has a dense arrangement, variable cross-sectional areas, and displays long and narrow bending, which will inevitably cause pressure losses, and lead to further problems, such as low pneumatic utilization efficiency and energy waste [4].

Scholars have conducted extensive research on the airflow field associated with the pneumatic seed-metering mechanism [5–8]. For example, Yazgi et al. [9,10] used the CFD method to study the effect of a vacuum plate with different numbers of holes on the uniformity of seed spacing. The highest performance was reported when 26 and 36 holes were used for cotton and corn, respectively. Ghafori et al. [11] analyzed the pressure drop function during the suction and transport of corn and barley. The lowest pressure drop for corn and barley occurred at the air velocity of 20 m·s⁻¹ and 15 m·s⁻¹, respectively. Yang Shandong et al. [12–14] used the large eddy simulation method with Fluent software to analyze the flow field of the positive-pressure air chamber inside a seed-metering device, and studied the variation law of the internal flow field of the seed-metering device under different parameters. It was shown that the seeding performance
was better when the plate speed was lower than 18 r·min\(^{-1}\). Zhao Zhan et al. [15–17] used Fluent software to calculate the force of seeds in the real seed suction airflow field and high-speed photography technology to obtain the seed transient adsorption and falling trajectory. The results showed that the average seed-spacing interval error reached its minimum value at 1.5 kPa pressure and a \(-5^\circ\) angle and that the error increased almost linearly with increasing cylinder rotational speed. Xiaolong Lei et al. [18,19] carried out a numerical simulation of seed motion in the distribution head and tracked the seed migration trajectory and distribution behavior. The simulation results showed that, when the streamlined angle increased from 10\(^\circ\) to 50\(^\circ\), the variation coefficient of seed distribution decreased initially and then increased for an inlet diameter of 20 mm and an airflow velocity of 20 m·s\(^{-1}\). Song shi et al. [20] calculated the gas-solid two-phase flow of a seed-metering device by introducing the pressure gradient force model into the coupled analysis of EDEM-CFD. The results were given as follows: the curvature coefficient of the seed guide groove curve was 0.265, the depth of the seed guide groove was 2.57 mm, and the slope angle of the seed guide groove was 15.33\(^\circ\).

The above scholars all used the computational fluid dynamics method to simulate the internal flow field that is difficult to measure, and the simulation results were similar to the experimental results, which shows that it is an effective method to study the pneumatic seed-metering mechanism. However, the above research mainly focuses on the large-diameter pneumatic and intensive conveying air duct or the cylindrical chamber inside the seed-metering device, which is characterized by a spacious air duct and simple structure. There is no relevant research on long, narrow and complex air ducts with variable diameters.

Therefore, we focused on the fluid domain of seeding-wheel-type pneumatic seeders and used the computational fluid dynamics method to explore the types and principles of the pressure loss in each area. The key parameters that affect the pressure loss were identified and the airflow field distribution and the airflow motion law in the seed-placing device were defined to determine the best structure and working parameters. The results show that it is possible to weaken the obstruction of the complex airway structure to the airflow, reduce the pressure loss, and improve pneumatic utilization and the effect of sowing. The results will also provide theoretical guidance for pressure drop analysis of complex airways.

2. Structure and Fluid Analysis

2.1. The Structure and Working Principle of Seeding-Wheel-Type Pneumatic Seeder

Seeding wheels are the main carriers used for picking seeds, transporting seeds, and casting seeds. Their structure and installation are shown in Figure 1 [21]. Several seed-sucking holes are evenly distributed along the edge of the seeding wheel and are connected to the internal pneumatic distribution center through a long and narrow airway with variable diameters. The upper-end face of the pneumatic distribution center is connected to a rubber sealing ring fixed with a pneumatic distribution cover, and they are press-fitted and sealed. The inner air cavity of the rubber sealing ring is connected to the negative pressure aperture to provide negative pressure force for the seed-sucking hole. During operation, the pneumatic distribution cover remains stationary, the seeding wheel rotates with the ground wheel, and the two are connected by thin-walled bearings. A spring in the locking mechanism is used to press the seed wheel and air distribution cover together. The outer wall of the seeding wheel, which is installed on both sides of the edge of the seeding wheel, flattens the soil with a certain force, which makes a difference to the depth limit and level of flattening. The seed-sucking boss can extend to the lower soil layer to complete the casting of seeds at a suitable position.
Figure 1. Schematic diagram and three-dimensional modeling of seeding wheel structure. (a) Schematic diagram of seeding wheel structure: (1) seed-sucking hole; (2) airway; (3) thin-walled bearing; (4) negative pressure aperture; (5) rubber sealing ring; (6) seeding axle; (7) locking mechanism; (8) positive pressure aperture; (9) outer wall; (10) seed-sucking boss; (b) three-dimensional modeling of seeding wheel structure.

2.2. Fluid Domain Modeling

The function of the airway inside the seeding wheel is to transport the fan’s pneumatic supply to the seed-sucking hole, and try to reduce the pressure loss during conveying [16,17,22], so that the seed-sucking hole has enough airflow velocity and negative pressure to perform its function. In addition, the airway should demonstrate good pneumatic distribution, making the difference between negative pressure and airflow velocity in each seed-sucking hole small, which is not significantly related to their location.

The negative pressure fluid domain inside the seeding device is the inner space enclosed by the seeding wheel, rubber sealing ring, and pneumatic distribution cover. The seeding wheel and the pneumatic distribution cover will rotate during operation, thereby dividing the entire negative pressure fluid domain into two parts, the static part and the moving part. The static part is the upper fluid domain surrounded by the pneumatic distribution cover, which is the green part shown in Figure 1b. The moving part is the under-fluid domain surrounded by the seeding wheel, which is the blue part shown in Figure 1b. The seeding wheel has 16 sub-airways that are not connected, as shown in Figure 1a. Because the inner pneumatic distribution cover is divided into areas with air and areas without air, the seed-sucking hole at the end of the sub-airway has negative pressure only when the sub-airway is connected to areas with air. These two parts will rotate during operation, which contributes to the airflow’s on–off control by switching the corresponding position. Using Space Claim software to extract the fluid domain, a simplified 3D model of the seeding device was imported into the workbench of ANSYS, as shown in the central part of Figure 2.
2.3. Analysis of Pressure Loss in Airway

2.3.1. Aerodynamic Analysis of Variable-Section Panhandle Area

The energy loss of the fluid can be divided into the along-path loss and the local loss [23] according to the difference in the airway geometrical boundary that causes the fluid energy loss. The airflow velocity inside the airway is much less than the sound velocity, so air can be regarded as an incompressible fluid. The pneumatic input is negative pressure. The entire pneumatic system’s inlet is the 12 seed-sucking holes, and the outlet is a negative pressure aperture. The analyses of the four areas were conducted using the airflow inlet. The cross-sectional view of the variable-section panhandle area is shown in Figure 3.

![Figure 2. Fluid domain division.](image)

According to Figure 2, there are 12 lower sub-air channels connected to the upper air chamber, and there is a lower sub-air channel at the edge of the domain (only about half of this is connected to the upper air chamber at the top). The analysis below focuses on the airway in the connected position only. The structure of the negative pressure fluid domain is complex, involving various forms of airway structural changes, and it is difficult to conduct an overall analysis. Therefore, the negative pressure fluid domain is divided into the following four areas according to the different types of aerodynamic changes: the variable-section panhandle area, the bending area of the air pipe, the air chamber confluence area, and the connection area of the negative pressure aperture and air chamber. These are shown in Figure 2.

![Figure 3. Sectional view of the variable-section panhandle area: (a) the section with an unequal diameter; (b) the section with an equal diameter.](image)

The airway structure in this area is shown in Figure 3a. There are three cylindrical cavities arranged from small to large. The first cavity is the seed-sucking hole, which is also the executed structure for the terminal, and its cross-sectional area is mainly related to the
performance of seed absorption. Its structure is not studied in this paper. The second cavity is the airway section I, which is contained in the seed-sucking boss. Its cross-sectional area is limited by the size of the seed-sucking boss and has a maximum size of 10 mm. The third cavity is the airway section II, and its cross-sectional area is adjustable. When the diameters of airway section I and airway section II are equal, the airway structure shown in Figure 3b can be observed.

The variable-section panhandle area mainly involves two forms of pressure loss. When the air passes from the seed-sucking hole to the airway section I and from the airway section I to the airway section II (unequal diameter), the type of aerodynamic change that occurs is the sudden expansion of the pipe. It is mainly caused by the local pressure loss; while in the airway section I and II, it is caused by the pressure loss along the path.

2.3.2. Aerodynamic Analysis of Variable Diameter Transition

The type of aerodynamic change in the variable diameter is caused by diffusion flow [24], which can be divided into the following two forms: sudden and gradual expansion. The space with a variable diameter is narrow, and it is difficult to make a tapered airway with a small angle and a long lead. Therefore, this is regarded as the sudden expansion type. After the cross-sectional area of the sudden expansion pipe changes, the fluid will move away from the wall and form a vortex, resulting in the loss of airflow energy. This part of the local energy loss can be calculated as follows [25]:

\[ p_{j1} = (1 - \frac{A_1}{A_2}) \rho \frac{v^2}{2} \]  

(1)

where \( p_{j1} \) is the energy loss per unit volume of the gas in the form of sudden expansion (pressure loss), Pa; \( \rho \) is the medium density, kg \( \cdot \) m\(^{-3} \); \( A_1 \) is the inlet cross-sectional area, m\(^2 \); \( A_2 \) is the outlet cross-sectional area, m\(^2 \); \( v \) is the inlet airflow velocity, m \( \cdot \) s\(^{-1} \).

It can be observed from Equation (1) that the pressure loss here is mainly related to the cross-section ratio and the velocity in the inlet. Under the condition of a given inlet with negative pressure, the velocity in the inlet can be regarded as constant. Moreover, because the diameter of the seed-sucking hole and the cross-sectional area of the airway section I are not variable, \( A_1 \) can be regarded as invariable. Therefore, the pressure loss of this part is mainly related to the outlet cross-sectional area \( A_2 \) (the cross-sectional area of the airway section II). When the cross-sectional areas of airway section I and section II are equal, local pressure loss occurs once. Otherwise, it will occur twice.

2.3.3. Aerodynamic Analysis of Long and Narrow Air Pipe

The size, shape, and direction of the flow cross-sections inside airway section I and section II remain unchanged, so the fluid encounters only the frictional resistance provided by the airway wall, which is the loss that occurs along the path [26,27]. The resistance loss coefficient along the path (\( \lambda \)) is related to the fluid flow state and often is calculated using the Reynolds number (\( Re \)). The Reynolds number calculation formula [28] is as follows:

\[ Re = \frac{\rho \bar{v} d_0}{\mu} \]  

(2)

where \( \mu \) is the dynamic viscosity of the fluid, Pa \( \cdot \) s; \( d_0 \) is the characteristic length of the airflow section, m; \( \bar{v} \) is the average flow velocity of the airway section, m \( \cdot \) s\(^{-1} \).

Air is the fluid object studied in this paper and by taking the parameters under normal pressure at 20 °C, \( \rho \) can be calculated as 1.205 kg \( \cdot \) m\(^{-3} \) and \( \mu \) as 1.79 \times 10^{-5} \) Pa \( \cdot \) s. The characteristic length of the airflow section, which is also the diameter of the air pipe, is 0.02 m. The average velocity of the airway section II after stabilization is calculated by pre-simulation to be about 2 m \( \cdot \) s\(^{-1} \). The Reynolds number (\( Re \)) is solved at 2692, which is greater than the critical value of 2300. Therefore, at this time, the fluid flow state in the airway is turbulent, but the value is less than 4000, indicating that the fluid in the airway is in the
transition state between laminar flow and turbulent flow \cite{29,30}. Therefore, the resistance loss coefficient (\(\lambda\)) along the path in the area increases with the increase in Reynolds number (\(Re\)) and has a weak relationship with the relative roughness of the wall \cite{31}.

\[
p_{f1} = \frac{l_g \rho^2 Q^2}{800 d_g^2 \mu^2}
\]  

(3)

where \(l_g\) is the length of the pipe, mm; \(Q\) is the flow rate, \(m^3 \cdot s^{-1}\); \(d_g\) is the diameter of the pipe, mm. \(p_{f1}\) is the pressure loss along the path of the long and narrow airway part.

It can be observed from the formula that the pressure loss (\(p_{f1}\)) in the airway part is mainly related to the length of the pipe (\(l_g\)), the diameter of the pipe (\(d_g\)), and the flow rate (\(Q\)). The length of the pipe (\(l_g\)) is the pneumatic conveying distance, which is determined by the size of the seeding wheel. The flow rate (\(Q\)) is mainly related to the given negative pressure. Therefore, in order to reduce air resistance in design, one must adjust the diameter of the pipe (\(d_g\)). The larger the diameter of the pipe, the smaller the pressure loss along the path in the long and narrow airway.

Therefore, according to the above research, there are three kinds of design schemes in this area, which are as follows:

Scheme 1. The diameter of airway section II is equal to the diameter of section I, that is, the diameter of airway section II is 10 mm, so there is only one instance of local pressure loss in this area, but the pressure loss along the path is higher.

Scheme 2. The diameter of the airway section II is unequal to that of section I, so this will result in twice the local pressure loss. However, due to the larger diameter of the airway section II, the pressure loss along the path will be lower.

Scheme 3. The optimal value can be found between Scheme 1 and Scheme 2. However, based on theoretical analysis alone, it is impossible to determine which scheme is better, and numerical analysis and experimental methods are still needed for research.

2.3.4. Aerodynamic Analysis of Bending Area of Air Pipe

The direction of the airway shifts from horizontal to longitudinal in the bending area of the air pipe, as shown in Figure 4.

![Figure 4. Bending area of the air pipe.](image)

When the air goes flows through the connection, there is a velocity difference between the inner and outer airflows, which generates eddy currents, resulting in a large local energy loss. Due to space constraints, this is in the form of a sharp bend. The pressure loss in the bending area of the air pipe \cite{32} can be calculated as follows:

\[
p_w = \left[0.946 \sin\left(\frac{\theta}{2}\right) + 2.05 \sin^4\left(\frac{\theta}{2}\right)\right] \frac{\rho \sigma^2}{2}
\]  

(4)

where \(p_w\) is the local pressure loss in the bending area of the air pipe, Pa; \(\theta\) is the angle between the two air pipes, (°).
It can be observed from the formula that the pressure loss in this part is related to the angle ($\theta$) between the two air pipes. The larger the angle, the smaller the pressure loss. However, when the position of the air-passing aperture is fixed, the larger the angle is and the larger the horizontal length of the inclined section is. The relationship of the angle ($\theta$) between the horizontal length and the two air pipes is as follows:

$$\theta = 180^\circ - \arctan\left(\frac{h_f}{l_c - R}\right)$$  \hspace{1cm} (5)

where $h_f$ is the vertical distance from the center of the outermost air pipe to the plane where the air-passing aperture is located, mm; $l_c$ is the horizontal length of the distribution center, mm. $R$ is the distance between the center of the longitudinal airway and the center of the sowing wheel, mm.

Restricted by the structure and thin-walled bearings, the horizontal length of the distribution center should not be greater than 150 mm. The vertical distance should be less than the width of the outer wall of the seeding wheel (100 mm). It can be solved by formula 5 that the angle ($\theta$) between the two air pipes should be less than $122.6^\circ$, meaning that the horizontal value range of the air pipes’ angle is $90^\circ$–$120^\circ$.

2.3.5. Aerodynamic Analysis of Air Chamber Confluence Area

The air chamber confluence area is shown in Figure 5.

![Figure 5. Air chamber confluence area.](image)

This area is the air chamber space formed by the air afflux from the longitudinal air pipes of each lower sub-airway to the rubber sealing ring in the pneumatic distribution cover [33], which is essentially the flow form of multiple small-section pipes that transform into large-section cavities. The energy loss that occurs is mainly local pressure loss, which mainly depends on the cross-sectional area on both sides, but it is difficult to change, and therefore optimize.

2.3.6. Aerodynamic Analysis of Connection Area of Negative Pressure Aperture and Air Chamber

The connection area of the negative pressure aperture and air chamber is shown in Figure 6. The geometry of the airway in this area is transformed from an arc-shaped air chamber to a cylindrical negative pressure aperture. The aerodynamic change that occurs is in the form of a sudden reduction in the cross-sectional area, and the reported energy loss is mainly local pressure loss [34].

$$p_s = 0.5(1 - \frac{A_2}{A_1} \frac{\rho v^2}{2})$$  \hspace{1cm} (6)

where $p_s$ is the local pressure loss in the connection area of the negative pressure aperture and air chamber, Pa.
the pressure was 0 Pa. The solution method used was the SIMPLE method. The simulation results are shown in Table 2.

It can be observed from the formula that the local pressure loss in this area is mainly related to the cross-sectional area of the negative pressure aperture, and the larger the negative pressure aperture, the lower the pressure loss. However, the space of the pneumatic distribution cover is limited, and it is necessary to leave space for the connection with the frame, so the maximum inner diameter of the negative pressure aperture is 34 mm. In addition, the maximum diameter of the fluid domain of the negative pressure aperture in order to maintain a complete circle is 21.5 mm under the structural limitations, as shown in Figure 6b. If it increases continually, the rubber sealing rings will block the two sides, and the bottom section of the negative pressure aperture will change from a circle to a rectangle-like shape, as shown in Figure 6a. It is difficult to determine the optimal inner diameter of the negative pressure aperture only by theoretical analysis, and further experimental research is needed.

3. Simulation Analysis
3.1. Flow Field Static Simulation Analysis of Seeding Device

The fluid domain was imported into ANSYS FLUENT, and the hexahedral meshing method was used to mesh the nine groups of the fluid domain in the experiment scheme. Since there was no need to solve the viscous bottom layer, we used the wall function method to solve the simulation [35–37]. The divided fluid domain contained about 1 million meshes under the simulation parameter of five boundary layers and a 1.2 mesh growth coefficient. The mesh quality was good, with a minimum orthogonal quality is above 0.5 and a maximum aspect ratio of less than 10. The fluid domain is shown in Figure 7.

![Figure 6. Connection area of negative pressure aperture and air chamber. (a) Diameter of negative pressure aperture is 34 mm; (b) diameter of negative pressure aperture is 21.5 mm.](image)

![Figure 7. Fluid domain meshing: (a) overall meshing diagram; (b) meshing diagram for seed-sucking hole.](image)
According to the above theoretical analysis, it can be concluded that the diameter \(d_h\) of the horizontal air pipe, the angle \(\theta\) of the air pipe, and the diameter \(d_z\) of the negative pressure aperture have a significant influence on the pressure loss in the airway. Taking the above three parameters as the experimental factors, a three-factor three-level orthogonal simulation experiment was designed. The experiment factors and levels are shown in Table 1.

Table 1. Experiment factors and levels.

<table>
<thead>
<tr>
<th>Level</th>
<th>Factor</th>
<th>A Diameter of Horizontal Air Pipe (d_h/\text{mm})</th>
<th>B Angle of Air Pipe (\theta)</th>
<th>C Diameter of Negative Pressure Aperture (d_z/\text{mm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>10</td>
<td>90</td>
<td>21.5</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>15</td>
<td>105</td>
<td>27.75</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>20</td>
<td>120</td>
<td>34</td>
</tr>
</tbody>
</table>

The airflow velocity at the seed-sucking hole was used as the core index to measure the performance of the seed sucking, so the seed-sucking holes’ average airflow velocity, the minimum airflow velocity, and the airflow velocity standard deviation were selected as the experiment indicators. There were 12 sets of data on seed-sucking holes for each set of simulations. The airflow velocity at the center of the seed-sucking hole was taken as the experiment results. The standard three-factor three-level orthogonal table was selected and simulations were carried out. The method of steady-state calculation and the model of standard k-epsilon turbulence in Fluent were used. The pressure inlet boundary was set at \(-7\) kPa, the outlet boundary condition was the pressure outlet boundary, and the pressure was \(0\) Pa. The solution method used was the SIMPLE method. The simulation results are shown in Table 2.

Table 2. Simulation experiment results.

<table>
<thead>
<tr>
<th>Number</th>
<th>Factor</th>
<th>A Diameter of Horizontal Air Pipe (d_h/\text{mm})</th>
<th>B Angle of Air Pipe (\theta)</th>
<th>C Diameter of Negative Pressure Aperture (d_z/\text{mm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>10</td>
<td>90</td>
<td>21.5</td>
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<td>2</td>
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<td>27.75</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>20</td>
<td>120</td>
<td>34</td>
</tr>
</tbody>
</table>

3.2. Analysis of Simulation Results

3.2.1. Analysis of Variance and Range

The range analysis of the simulation experiment results [21] is shown in Table 3. The selection of the optimal parameter combination is based on the following information: the larger the average airflow velocity and the minimum airflow velocity of the seed-sucking hole, the lower the airway resistance and pressure loss and airflow velocity standard deviation of the seed-sucking hole; the smaller the difference in seed sucking performance, the better the sucking stability. According to this information, it was concluded that the optimal parameter combination of the airway structure parameters for the three experiment indicators is \(A_2B_2C_3\), which is the fifth level of the orthogonal simulation experiment. The simulation results show that the average airflow velocity of the seed-sucking hole is \(102.59\) m \(\cdot\) s\(^{-1}\), the minimum airflow velocity of the seed-sucking hole is \(101.58\) m \(\cdot\) s\(^{-1}\), and the airflow velocity standard deviation of the seed-sucking hole is \(0.54\) m \(\cdot\) s\(^{-1}\), which are the best values in every group. Therefore, the optimal airway structural parameters can be
determined as follows: the diameter of the horizontal air pipe must be 15 mm, the angle of the air pipe must be $105^\circ$, and the diameter of the negative pressure aperture must be 34 mm.

Table 3. Range analysis.

<table>
<thead>
<tr>
<th>Items</th>
<th>Average Airflow Velocity of Seed-Sucking Hole /$(\text{m} \cdot \text{s}^{-1})$</th>
<th>Minimum Airflow Velocity of Seed-Sucking Hole /$(\text{m} \cdot \text{s}^{-1})$</th>
<th>Airflow Velocity Standard Deviation of Seed-Sucking Hole /$(\text{m} \cdot \text{s}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>$K_1$</td>
<td>102.06</td>
<td>101.87</td>
<td>101.61</td>
</tr>
<tr>
<td>$K_2$</td>
<td>102.08</td>
<td>102.25</td>
<td>102.15</td>
</tr>
<tr>
<td>$K_3$</td>
<td>101.96</td>
<td>101.87</td>
<td>102.34</td>
</tr>
<tr>
<td>$R$</td>
<td>0.12</td>
<td>0.38</td>
<td>0.73</td>
</tr>
<tr>
<td>Optimal level combination</td>
<td>$A_2B_2C_3$</td>
<td>$A_2B_2C_3$</td>
<td>$A_2B_2C_3$</td>
</tr>
</tbody>
</table>

Further variance analysis was conducted on the experimental data to determine the significance of each factor. The variance analysis is shown in Table 4.

Table 4. Variance analysis.

<table>
<thead>
<tr>
<th>Source of Difference</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average airflow velocity of seed-sucking hole</td>
<td>A</td>
<td>0.02</td>
<td>2</td>
<td>0.01</td>
<td>11.75</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.23</td>
<td>2</td>
<td>0.17</td>
<td>118.91 **</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.87</td>
<td>2</td>
<td>0.43</td>
<td>442.65 **</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>0.00</td>
<td>2</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>1.13</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum airflow velocity of seed-sucking hole</td>
<td>A</td>
<td>0.03</td>
<td>2</td>
<td>0.01</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.55</td>
<td>2</td>
<td>0.78</td>
<td>72.45 *</td>
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<tr>
<td></td>
<td>C</td>
<td>1.01</td>
<td>2</td>
<td>0.5</td>
<td>47.05 *</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>0.02</td>
<td>2</td>
<td>0.01</td>
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</tr>
<tr>
<td></td>
<td>Sum</td>
<td>2.61</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airflow velocity standard deviation of seed-sucking hole</td>
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<td>0.03</td>
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<td>0.01</td>
<td>2.9</td>
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<td>0.03</td>
<td>5.87</td>
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<tr>
<td></td>
<td>C</td>
<td>0.00</td>
<td>2</td>
<td>0.00</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>0.01</td>
<td>2</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>0.09</td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: In the table, the critical value of significance judgment is $F_{0.001 (2, 2)} = 999$, $F_{0.01 (2, 2)} = 99$, and $F_{0.05 (2, 2)} = 19$. ** indicates that the influence is very significant. * indicates that the influence is significant. The data in the table were rounded up, but in order to ensure accuracy, the calculation was based on the original value.

From the analysis of variance results, it can be observed that the angle of the air pipe and the diameter of the negative pressure aperture have a significant influence on the average airflow velocity index of the seed-sucking hole. The diameter of the horizontal air pipe does not influence the average airflow velocity of the seed-sucking hole. For the minimum airflow velocity of the seed-sucking hole, the angle of the air pipe and the diameter of the negative pressure aperture have less significant influence, while the diameter of the horizontal air pipe has no influence on the experiment results, and the degree of influence on the average airflow velocity of the seed-sucking hole is ranked as follows: angle of air pipe > diameter of negative pressure aperture > diameter of horizontal air pipe. From the results of the variance analysis for the airflow velocity standard deviation index of the seed-sucking hole, it can be observed that three factors do not influence this index. By analyzing the simulation experiment data, it was found that there is little difference in airflow velocity between the 12 seed-sucking holes, resulting in a small standard deviation value, indicating that the distribution of airflow in the air chamber is very uniform, which is beneficial for the collection of seeds.
3.2.2. Analysis of Airflow Velocity Difference of Various Seed-Sucking Holes

Taking the optimal parameter combination as the research object, the airflow velocity at the center of the 12 seed-sucking holes with negative pressure was calculated, as shown in Figure 8. It can be found from the figure that the position of the seed-sucking hole has no significant influence on the airflow velocity of the seed-sucking hole. The deviation in the airflow velocity value of the seed-sucking hole compared with the average value is less than 1%, which shows that the air pressure stability of the seeding-wheel-type seed precision placing device is higher.

![Figure 8. The line chart of the airflow velocity of seed-sucking holes with the optimal parameter combination.](image)

Figure 8. The line chart of the airflow velocity of seed-sucking holes with the optimal parameter combination.

3.2.3. Airflow Trajectory Analysis

Taking the airflow inlet (seed-sucking hole) as the starting point, it is possible to study the airflow trajectory of air that enters the negative pressure fluid domain and flows out the airflow outlet (negative pressure port). A streamlined diagram of the fluid domain is shown in Figure 9.

![Figure 9. Streamline diagram of fluid domain.](image)

Figure 9. Streamline diagram of fluid domain.

It can be observed from the streamlined diagram that after the airflow flows in from the seed-sucking hole, the flow velocity gradually decreases after diffusion occurs twice. When entering the vertical air pipe, most of the airflow flows into the air chamber after a 90° turn, but a vortex composed of a small amount of airflow is formed near the wall, and the streamline is chaotic, resulting in a large local pressure loss. After entering the arc-shaped air chamber, the airflow flows to the negative pressure aperture. In this trajectory, a clear light blue area to the right of the negative pressure aperture can be observed, indicating
3.3. Study on Negative Pressure Characteristics of Locally Connected Seed-Sucking Holes

During operation, a seed-sucking hole that is locally connected can be observed, but its airflow velocity does not significantly differ from other seed-sucking holes. Therefore, it can be determined that when more than half of the air-passing aperture of the longitudinal air pipe is connected to the air chamber, the seed-sucking hole’s performance will not be affected. However, this phenomenon will lead to a certain deviation in the seeding position compared with the design value, making it impossible to cast the seed precisely at the designated position. To compensate for this deviation, it is necessary to further determine when the air-passing aperture of the longitudinal air pipe and the air chamber are in any of the connection states, as the airflow velocity of the seed-sucking hole will drop significantly, thus triggering seeding.

A dynamic simulation was carried out that gradually reducing the connected part of the air-passing aperture, and the time when the negative pressure of the seed-sucking hole dropped significantly and sharply was determined as the trigger time of seed casting. According to the actual working situation, we simulated the rotation of the seeding device, set the fluid domain of the upper air chamber to remain static, and the lower fluid domain to rotate, and studied the variation law of the negative pressure of the seed-sucking hole in the lower sub-fluid domain. Separate fluid domain extraction was performed for each sub-airway, obtaining 14 fluid domain units, as shown in Figure 10a.

![Diagram of simulation process and results](image)

**Figure 10.** Diagram of simulation process and results: (a) fluid domain flow diagram; (b) interface setting; (c) dot–line graph of experiment results.

To observe the spatial position changes in rotating objects in real time, the sliding mesh method [38–41] was adopted. The surface of the air-passing aperture of the lower sub-airway and the lower surface of the fluid domain of the upper air chamber were set as the interfaces, and data exchange could be performed, as shown in Figure 10b. The rotational speed of the lower sub-airway was set to 2.31 rad·s⁻¹, and the time step was 1.5 × 10⁻⁴ s. The simulation time was 0.141 s, which could cover the complete process of lower sub-airway separation. We plotted the experimental data as a dot–line graph, as shown in Figure 10c. We recorded the significant negative pressure changes in the seed-sucking holes for groups 41–48, and calculated the corresponding opening angles of
the air-passing aperture according to the structural parameters. The results are shown in Table 5.

Table 5. Sliding mesh simulation results for groups 41–48.

<table>
<thead>
<tr>
<th>Group</th>
<th>Simulation Time (s)</th>
<th>Opening Angle of Air-Passing Aperture (°)</th>
<th>Negative Pressure of Seed-Sucking Hole (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>0.12</td>
<td>2.518</td>
<td>−6101.03</td>
</tr>
<tr>
<td>42</td>
<td>0.123</td>
<td>2.121</td>
<td>−5974.7</td>
</tr>
<tr>
<td>43</td>
<td>0.126</td>
<td>1.723</td>
<td>−5768.42</td>
</tr>
<tr>
<td>44</td>
<td>0.129</td>
<td>1.326</td>
<td>−5179.11</td>
</tr>
<tr>
<td>45</td>
<td>0.132</td>
<td>0.929</td>
<td>−3831.63</td>
</tr>
<tr>
<td>46</td>
<td>0.135</td>
<td>0.532</td>
<td>−1072.76</td>
</tr>
<tr>
<td>47</td>
<td>0.138</td>
<td>0.135</td>
<td>−5.13</td>
</tr>
<tr>
<td>48</td>
<td>0.141</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

It can be observed from Figure 10c and Table 5 that the air pressure of the seed-sucking hole remains stable for most of the time, fluctuating only slightly. However, there is a certain decline after 0.12 s, but the range is not large, and after 0.129 s (the corresponding opening angle of the air-passing aperture is 1.326°), it falls sharply, and the negative pressure of the seed-sucking hole is only −5.13 Pa until 0.138 s. The negative pressure distribution of groups 41–48 is shown in Figure 11.

On the whole, when only a small part of the air-passing aperture is connected to the upper air chamber, the seed-sucking hole still retains the ability to maintain seed adsorption. The trigger of seed casting may be associated with the period when the negative pressure of the seed-sucking hole drops sharply, but it is difficult to judge its exact time. However, the period in which the negative pressure of the seed-sucking hole sharply drops is very short and only lasts about 0.01 s, so the setting error is small.
4. Prototype Test Verification

4.1. Prototyping and Testing Methods

Three-dimensional printing technology was used to process complex key components, such as the seeding wheel and pneumatic distribution cover, with a Stratasys F900 3D printer (Stratasys Ltd., Rehovot, Israel) and 8000 photosensitive resin, and the rest of the components were processed using metal. The prototype is shown in Figure 12a. The measuring equipment included a DN2000 intelligent anemometer (Beijing Instrument Equipment Factory, Beijing, China), as shown in Figure 12b. Its measuring range of wind speed was 1.00–365.00 m·s⁻¹ with an accuracy of 0.01 m·s⁻¹, its wind pressure range was ±80 kPa, with an accuracy is 0.01 kPa, and its air volume range was <999,999 m³·h⁻¹.

Figure 12. Test prototype and measuring equipment: (a) the prototype; (b) DN2000 intelligent anemometer; (c) the Pitot tube.

The prototype was fixed according to the relative position of the pneumatic distribution cover and the seeding wheel in the simulation experiment, and the airflow velocity of the airway at this position was measured by an anemometer. When the seeding wheel was processed, a measuring slot hole in an air pipe was created to facilitate the insertion of the Pitot tube. During the measurements, the front end of the Pitot tube was inserted into the hollow airway and then hot-melt adhesive was used to seal the measuring hole to ensure air tightness. In addition, it is necessary to ensure that the extended part of the Pitot tube is concentric with the pipe. The negative pressure fan was turned on, and the vacuum degree of negative pressure was 7 kPa during the test. After the working state was confirmed as stable, the value on the DN2000 intelligent anemometer was read, the airflow velocity of this group was recorded, the measurement was repeated 3 times, and the average value was recorded. After one measurement was completed, the seeding wheel was rotated to the next position and the steps above were repeated to derive the actual airway wind velocity at the same location as in the simulation.

However, because of the small diameter of the seed-sucking hole, it was difficult to use an anemometer to measure air velocity accurately at this position. It would also affect flow field distribution if it was too close to the seed-sucking hole. Therefore, the measurement position was adjusted by 20 mm. From the simulation results, it can be concluded that the airflow velocity trend at this position is consistent with the results for the seed-sucking hole.

4.2. Results and Analysis

Figure 13 shows the simulated and tested values of the airflow velocity in the air pipe.
A functional model of pressure loss in variable-section panhandle areas, the bending would have affected the measurement results. Third, the inserted part of the Pitot tube should be concentric with the air pipe during the measurements. However, it was hard to ensure this during the actual measurements, which would have affected the airflow in the airway. Third, the inserted part of the Pitot tube should be concentric with the air pipe during the measurements.

In fact, the results of the anemometer fluctuated in a narrow range due to the uncertainty of the flow field during the measurement, and the recorded value was taken as the fluctuation center. The analysis of the readings obtained from the three groups of tests showed that there was little difference in the values measured, so it was reasonable to characterize the values using averages. The dot–line graph shows that the test results were generally lower than the simulation results. There are three main reasons for the results. First, the prototype processing could not guarantee absolute air tightness as in the numerical analysis, resulting in additional pressure loss. Second, the detection head of the anemometer inserted into the air pipe inserted an artificial obstacle, which would affect the airflow in the airway. Third, the inserted part of the Pitot tube should be concentric with the air pipe during the measurements. However, it was hard to ensure this during the actual measurements, which would have affected the measurement results.

However, both the simulation results and the test results show a trend of narrow fluctuations around the mean value, and the airflow velocity of each airway shows little difference, which can verify the accuracy of the simulation.

5. Conclusions

In this paper, an evaluation scheme for internal complex airway pressure loss was formulated, the influence of airway structure on pressure loss under different parameter combinations was explored, the internal flow field distribution and airflow movement law of a precision seeding device were defined, the drag reduction and efficiency increase were analyzed, and a new method was provided for the research of the pneumatic characteristics of complex narrow airway groups. The specific conclusions are as follows:

1. A functional model of pressure loss in variable-section panhandle areas, the bending area of the air pipe, air chamber confluence area, and connection area of the negative pressure aperture and air chamber were established and it was concluded that the airway structural factors that may have a significant influence on the pressure loss are the diameter of the horizontal air pipe, the angle of the air pipe, and the diameter of the negative pressure aperture.

2. It was concluded that the optimal parameter combination was as follows: the diameter of the horizontal air pipe was 15 mm, the angle of the air pipe was 105°, and the diameter of the negative pressure aperture was 34 mm. Under these parameters, the average airflow velocity of the seed-sucking hole was 102.59, the minimum airflow velocity of the seed-sucking hole was 101.58, and the airflow velocity standard
deviation of the seed-sucking hole was 0.54. The position of the seed-sucking hole has no significant influence on its airflow velocity.

3. A dynamic simulation test was carried out and it was concluded that there is a sharp decline when the opening angle of the air-passing aperture is 1.326°. In addition, it triggers the casting action of seeds when the opening angle of the air-passing aperture is 0.929°.

4. Compared with the simulation results, the tested measurement results are generally lower, but the difference is not significant, which proves that the position of the seed-sucking holes has little influence on the airflow velocity, and the overall pneumatic distribution is uniform.

5. This paper mainly explores the distribution law of the internal flow field when the seed-sucking hole is open, and the interaction between the flow field and the seeds can be further explored by CFD-DEM coupling technology in the future, which will help us to study the mechanism and effect of the flow field on seeds more accurately.

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