DESIGN AND ATOMIZATION CHARACTERISTICS OF ELECTRIC CENTRIFUGAL NOZZLE FOR PLANT PROTECTION UNMANNED AERIAL VEHICLES
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植保无人机电动离心喷嘴设计及雾化特性研究

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ABSTRACT
In order to reduce the drift loss of small droplets sprayed at low altitudes and low volume, a two-channel two-phase electric centrifugal nozzle was designed. The three-dimensional full-size numerical simulation of the flow field in the nozzle was carried out using Fluent software, and the radial distribution characteristics and axial variation of the flow field were studied. The relationships between the motor voltage and the atomizing disc's speed, between the nozzle's inlet pressure and its flow rate were determined. The variations of the droplet size and the droplet spectrum width with the atomizing disc and flow rate were revealed. The results showed that the rotation speed and flow rate were the important factors affecting the droplet's middle diameter and spectrum width. When the rotation speed of atomizing disc was 4000 r/min, the droplet spectrum width exhibited the narrowest, and the middle diameter of the droplet volume was 231.9 μm. The droplet coverage density was higher, meeting the requirements of low-volume aviation spraying control. This study provides a theoretical basis for optimizing nozzle configuration and developing variable spray devices.

摘要
为了减少低空低量喷洒中小雾滴的飘移损失，本文设计了一种双流道两相电动离心喷嘴。通过 Fluent 软件对喷嘴内流场进行三维全尺寸数值模拟，研究了喷嘴稳定喷雾时内流场径向分布特性及轴向变化规律。通过试验明确了电机电压与雾化盘转速、喷嘴入水口压力与其流量间的关系，揭示了雾滴粒径和雾滴谱宽度随喷嘴流量、雾化盘转速的变化规律。结果表明，该电动离心喷嘴可有效改善雾化盘底部液膜分布及喷雾均匀性，提高药液雾化效果。转速和流量是影响雾滴体积中径和雾滴谱宽度的重要因素。当雾化盘转速为 4000r/min 时，雾滴谱宽度最窄，此时雾滴体积中径为 231.9μm，雾滴覆盖密度较高，可满足航空低量喷洒的防治要求。该研究为优化喷嘴构型，研发变量喷雾装置提供了理论基础。

INTRODUCTION
With the development of unmanned aerial vehicles (UAV) technology, agricultural aviation has attracted intense attention *(Wang J. et al., 2019; Huang X. et al., 2020).* UAV have been widely used in crop remote sensing, agricultural monitoring, agricultural plant protection and other fields *(Lan Y. et al., 2017; Sun G. et al., 2018; Dash J. et al., 2017; Tian J. et al., 2017).* Aviation spray application is widely used because of its good operation effect as well as it is not limited by terrain. The plant protection nozzle is one of the key parts of the aviation application system playing a key role in pest control. The efficiency and effect of UAV plant protection can be significantly improved by designing suitable plant protection nozzles and setting reasonable operation parameters.

Low-altitude and low-volume spraying were usually adopted in plant protection UAV. However, the droplet size is small in the case of low-capacity spraying, which might cause drift loss *(Yan X. et al., 2021)*. Intense investigations are focused on UAV's anti-drift loss reduction technology to overcome this problem. *Chen et al.* and *Qi et al.* illustrated the significant impact of flight altitude and flight speed on the average

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deposition amount of fog droplets in the target area, so the flight altitude and speed can be used to study the drift reduction strategy further *(Chen D, et al., 2016; Qi H. et al., 2019)*. *Qin et al.* examined the influence of spraying parameters on the deposition distribution of fog droplets in the corn canopy. They believed that when the flight height was 7 m and the transverse spraying range was 5 m, the deposition characteristics and spraying effect of fog droplets were better, and the drift loss was smaller *(Qin W. et al., 2018). Li* revealed the influence of multi-rotor plant protection UAV operation parameters on fog droplet deposition and drift, established a statistical analysis model of fog droplet deposition and drift, and improved the effective utilization rate of pesticides *(Li H. et al., 2021)*.

The above studies focused only on the parameter tuning of the plant protection operation process, while less research has been conducted on spray devices and their characteristics. Electric centrifugal nozzles form mist droplets of different sizes by adjusting the motor voltage and the water outlet pressure to change the velocity and flow of the centrifugal nozzles. The atomization spray is widely used in low-altitude UAV plant protection operations due to its wide width, non-obstinate spray holes, and convenient parameter tuning. However, the application has some problems, such as uneven distribution of droplets, inconsistent atomization, broad droplet spectrum, and easy drift. In this direction, this study focuses on designing a two-channel, two-phase electric centrifugal nozzle, and the spray performance of the nozzle is examined through numerical simulations and solid-state tests for practical applications.

MATERIALS AND METHODS

The structure design of electric centrifugal nozzle for plant protection UAV

In this study, a two-phase, two-channel electric centrifugal nozzle for UAV planting and maintenance was designed to address the above issues. Its overall structure (a) and 3D model (b) are shown in Fig. 1. The nozzle mainly consists of a shell, a gas passage, a steady flow passage, a liquid flow passage, a motor, a mixed flow passage, an atomizing disk, a diverter, a swirling chamber, and other components. The main body of the centrifugal nozzle is connected to the UAV by mounting bracket. The upper end of the steady-state flow chamber is connected to the liquid medicine box by a pipe, and the lower end is connected to the liquid channel. The mixed flow channel and the diverter form a swirl chamber, and the outer part is equipped with an atomization plate. The spinning power of the atomizing disc comes from a motor mounted vertically in the housing.

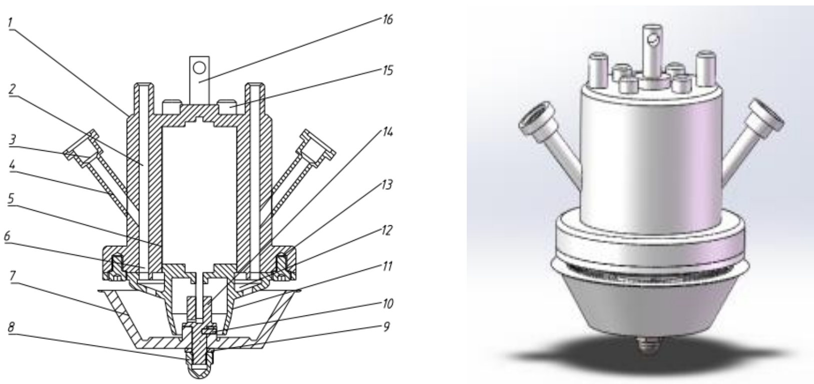


Fig. 1 - Structure diagram and 3D model of centrifugal nozzle

a. Structural diagram b. Three-dimensional model

1. Cover shell; 2. Gas channel; 3. Steady flow chamber; 4. Liquid flow channel; 5. The motor; 6. Mixed channel; 7. Atomization; 8. Cover lock nut; 9. Flat gasket; 10. Cylindrical pin; 11. The shunt; 12. Swirling chamber 13. Cylindrical head screws 14 Sleeve 15 Terminal 16 Installing Supports

Principle of Operation

When the centrifugal nozzle is in operation, the power for the nozzle and the liquid pump is provided by the UAV's DC power generation system. Under the liquid pump action, the liquid flows through the two-sided steady flow chamber into the symmetric tangential flow channel. The airflow under the UAV rotor enters the gas channel. The liquid medicine and air enter the mixing channel, where the liquid is mixed with air, the droplet is broken up. Then they flow into a vortex chamber composed of a tangential flow channel and a diverter. On the one hand, the liquid drug rotates in the vortex chamber, and on the other hand, it advances towards the atomized disk with a certain axial velocity. The motor drives the atomization rotation, and the liquid is ejected under centrifugal action.

Flow field analysis

The flow field of the designed nozzle was analysed by the modern eddy current theory and Computational Fluid Dynamics (CFD). The chosen fluid domain is shown in Fig. 2, and the grid is divided. The VOF and the standard *k-ε* models of the multiphase flow model were selected according to the working conditions of the nozzle. The gas density and viscosity were set to 1.225 kg/m^3 and 1.79e-05 Pa·s, respectively, after the first phase. The second phase liquid density and viscosity were 998.2 kg/m^3 and 0.001003Pa·s, respectively. The gas inlet was set as the pressure inlet, and the total boundary pressure was 101235 Mpa. The liquid inlet was a velocity inlet with a velocity of 1 m/s. The fluid domain of the entire atomized disk was set to a velocity of 3200 rpm.

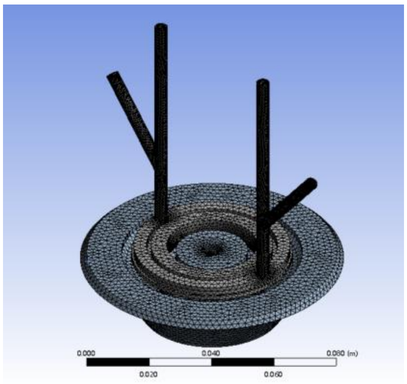


Fig. 2 - Grid division

Nozzle atomization characteristics

In order to solve the problem of the mismatch between the speed, flow rate and nozzle during the application of an electric centrifugal nozzle which is easier to cause the droplet spectrum width, numerical simulations were performed to optimize the nozzle's internal structure. The nozzle was customized based on the optimization results. Combined with the actual production, the experiments were designed to clarify the relationship between the motor voltage and the speed of the atomizing disc, the inlet pressure and the flow rate. It reveals the change in the droplet size and the droplet spectrum width with the flow rate and the atomizing disc speed. It identifies a regular working interval for the designed electric centrifugal nozzle to guide production.

Optimization of nozzle internal structure parameters

The nozzle structure directly affects the spray quality. The velocity at which the nozzle droplet exits directly affects the horizontal displacement of the droplet. Therefore, the drop exit velocity is chosen as the evaluation metric for spray performance. Considering the liquid passage diameter (factor A) and the swirling chamber outlet diameter (factor B) as the main influencing factors, a numerical simulation method was used to optimize the nozzle's internal structure parameters. The nozzle's gas channel diameter was set to 4 mm during the simulation test. Orthogonal tests were performed at 3 levels for factors A and B, respectively, and the resulting test permutations are shown in Table 1. The other parameters were set using the nozzle flow field analysis.

Table 1

Test factors and levels

level	Liquid channel diameter A (mm)	Diameter of swirling chamber outlet B (mm)
1	3	4
2	4	5
3	5	6

Study of atomization properties of the nozzle

Nozzle velocity and flow rate

The velocity and the flow rate are two important parameters in the atomization of an electric centrifugal nozzle. According to the design principle, adjusting the motor's power supply voltage can change the motor's speed, which is the speed of the atomized disk. The flow rate can be changed by adjusting the nozzle inlet pressure. Because of a mismatch problem between speed, flow rate and nozzle, a strobe tester (SW-6500, accuracy 0.001%) was used in the plant protection spray test bed to examine the corresponding voltage when the speed of the nozzle atomizing disc was 2000, 3000, 4000, 5000, 6000, 7000 r/min, and the relationship between voltage and speed was analysed. The nozzle's inlet pressure was set to 0.2, 0.3, 0.4, 0.5 and 0.6 MPa to measure the nozzle's current flow. The dependence of the flow rate on the inlet pressure was analysed, and a reference was given for using the nozzle.

Droplet size and distribution law

The particle size and the distribution law are the two most important parameters in spray techniques. Particle size refers to the size of each spray droplet forming the spray shape of the nozzle, which is usually measured by the median volume diameter (Dv_{50}). The particle size distribution refers to the fraction of droplets of various sizes in the total number of droplets. It is usually described by the particle size distribution curve or the particle size distribution table. The accurate measurements of the droplet size and the droplet size distribution are important for better control of the spray quality.

This study used a real-time high-speed spray particle size meter (Marvin Spraytec, Fig. 3) to measure the particle size distribution of fog droplets at different speeds and flows. A stable operating range for the centrifugal nozzle was found based on trends in the droplet size and the width of the droplet spectrum. The partial measurements are shown in Fig. 4. The obtained data were used to analyse and calculate the particle size of the droplet forming the scattering spectrum. The test schemes are listed in Table 2.

Fig. 3 - Real-time high-speed spray particle size analyser

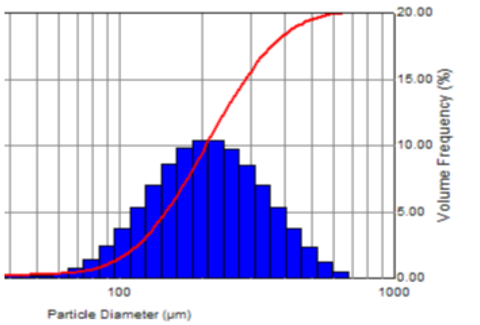


Fig. 4 - Distribution curves of volume diameter and particle size

Table 2

Volumetric medium diameter test scheme of electric centrifugal nozzle

Nozzle flow rate / mL·min^{-1}	800，1000，1200
Speed of motor / r·min^{-1}	2000，3000，4000，5000，6000，7000，8000

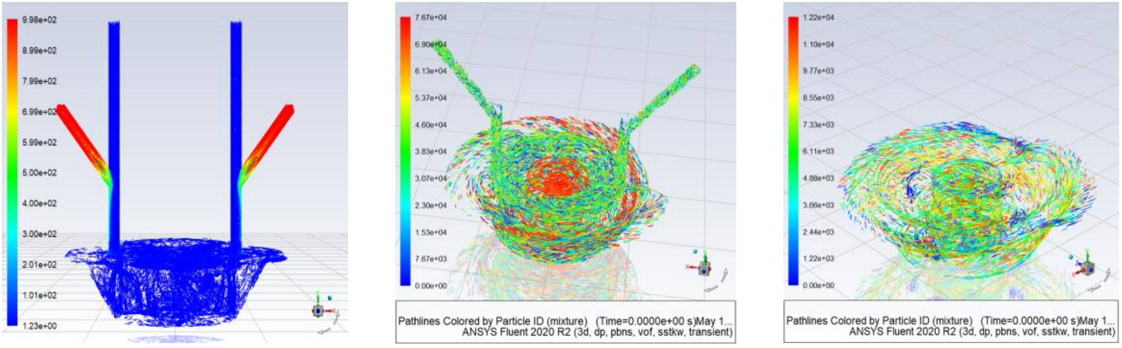
RESULTS AND ANALYSIS

Simulation of fluid inside the nozzle

The trajectory of the fluid motion is shown in Fig. 5. It is clear from Fig 5a that the liquid phase flows close to the wall. Near the outlet of the liquid channel, the liquid exists as a thin film. The liquid film flows into the vortex chamber under inertial forces and surface tension, as well as the rotor air flow. It is then ejected from the edge of the atomized disc by the centrifugal action of the atomized disc. The flow field's radial distribution exhibits a forced eddy structure at the vortex chamber's profile. The tangential and axial velocities reach their maximum values throughout the basin, as shown in Fig. 5b. Fig. 5c shows the motion path of the fluid in the atomized disk. Under the rotating centrifugal action of the rotating atomization disk, the flow velocity of the droplets increases and presents a helical distribution.

In addition, the horizontal velocity directly affects the spray amplitude. The horizontal velocity of the droplet decreases rapidly to 0 m/s from the initial velocity at which it leaves the atomized disk. Under gravity, the vertical velocity of the droplet increases rapidly from 0 m/s to a certain velocity and then drops at a constant velocity. The droplet's trajectory can reflect the droplet's settling process in the flow field, and the horizontal displacement of the droplet landing site can be obtained. Further analysis shows that the horizontal displacements of mist droplets with different particle sizes differ. At the same height and with the same horizontal initial velocity, the larger the droplet size, the further the droplet moves horizontally.

Depending on the trajectory of the fluid, the entire atomization region is approximately distributed as a hollow conical table, with relatively uniform atomization properties and droplet distribution. It can be seen that the structure can effectively improve the liquid film distribution and spray uniformity, and the atomization effect to a certain extent.



a. Fluid motion trajectory *b. Fluid inside the nozzle* *c. Fluid movement track in atomizing disc*

Fig. 5 - Flow trace diagram of nozzle

Optimization of nozzle internal structure

The nozzle's internal structure was optimized by orthogonal experiments with two factors and three levels. 9 groups of tests were arranged, and the test results are shown in Table 3. The largest speed of fog drops on the edge of the atomizing disc was obtained by test combination A (4 mm), B (5 mm) in No.5, and the test group is preferred. The range analysis shows that the diameter of the nozzle liquid passage and the diameter of the swirling chamber outlet impact the droplet exit velocity, and the influence of the diameter of the swirling chamber inside the nozzle on the droplet exit velocity is significantly greater than the liquid passage diameter.

Table 3

Results and range analysis of the orthogonal test

No.	**Factors**		**The speed of the droplets on the edge of the atomizing disc**
	A (mm)	B (mm)	(m/s)
1	3	4	18.4
2	3	5	19.7
3	3	6	18.7
4	4	4	17.9
5	4	5	20.8
6	4	6	17.6
7	5	4	16.6
8	5	5	19.5
9	5	6	17.5
K_1	18.93	17.63	-
K_2	18.76	20.00	-
K_3	17.86	17.93	-
R	1.07	2.37	-

In order to more intuitively reflect the influence law and trend of each diameter on the nozzle exit velocity, the factor level was taken as the horizontal coordinate, and the average droplet velocity on the edge of the atomizing disc was taken as the vertical coordinate to obtain the trend diagram of factors and indicators (Fig. 6). The graphical analysis shows that when B2 is taken, the effect on the exit velocity of the droplet is the greatest. At the same time, A1 and A2 have roughly the same effect on the exit velocity of the droplet. Combining with the test results, the optimal scheme B2A2 is selected, i.e., the diameter of the flow chamber is 5 mm, and the diameter of the liquid channel is 4 mm.

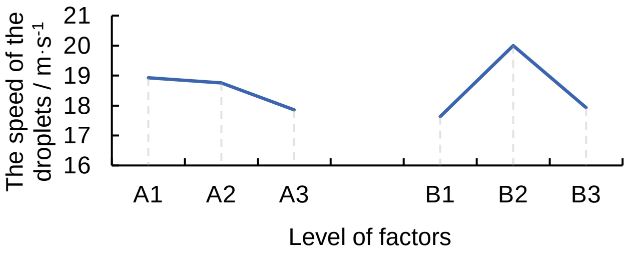


Fig. 6 - Trend chart of factors and indicators

Relationship between atomizing disc speed and voltage, nozzle flow and spray pressure

The strobe was used to test the rotational velocity of the centrifugal nozzle. The voltages corresponding to different rotational velocities were recorded, and the plots of voltage versus rotational velocity were made, as shown in Fig. 7. A positive linear correlation exists between the rotary speed and the voltage. The motor speed increases with the voltage. The spray pressure as a function of the flow rate is shown in Fig. 8. The nozzle flow rate and spray pressure are also approximately linearly and positively correlated with the nozzle flow rate increasing with spray pressure.

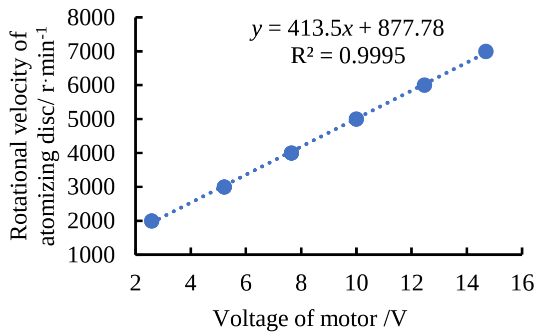


Fig. 7 - Relation between motor speed and voltage

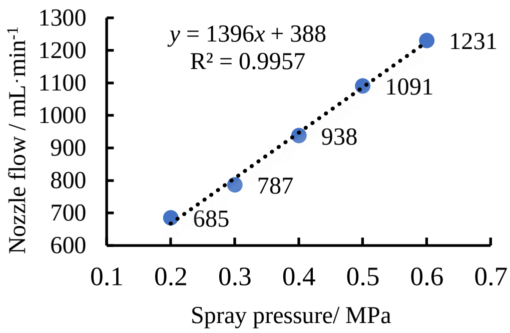


Fig. 8 - Relation between nozzle flow and spray pressure

Droplet size

Fig. 9 shows the atomization disk velocity versus droplet volume diameter for different flow conditions.

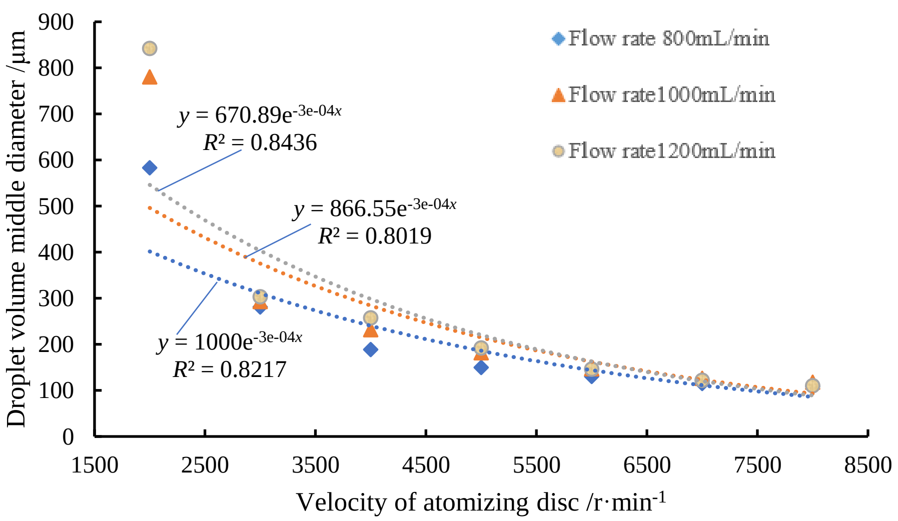


Fig 9 - Relation between atomizing disc speed and droplet volume median diameter under different flow conditions

It shows that at the same flow rate, the droplet size decreases with increasing rotational velocity and exhibits an exponential decline. As the rotational velocity gradually increases from low to high, the droplet size decreases rapidly. The droplet size decreases slowly when the rotational speed increases to a certain value (above 7000 rpm). At the same rotational speed, droplet size increases with the flow rate, but the range for the change is small. With an increase in the rotational velocity, the particle sizes of fog droplets with different flow rates gradually tend to be the same, indicating that the rotational velocity of the atomizing disc is the main factor affecting the median diameter of the volume of fog droplets.

Distribution law of droplet spectrum width

Table 4 shows the droplet spectrum width under different nozzle flow rates and atomizing disc speeds. It can be seen that under the same flow rate of the nozzle, the droplet spectrum width decreases rapidly at first and then increases slowly with the increase of rotational speed. The spectral droplet width reaches its minimum at a rotation velocity of 4000 r/min. At the same rotational velocity, the spectral width of the droplet increases with the flow rate. However, as the three flow rate levels are similar, the variation of droplet spectrum width is not divided into three obvious levels. Therefore, both the rotation speed and flow rate significantly influence the fog drop spectrum width, and within the flow range of 800~1200 mL/min, the fog drop spectrum width is the minimum when the rotation speed is 4000 r/min.

Table 4

Fog droplet spectrum width of electric centrifugal nozzle

Velocity of motor / r·min^{-1}	Nozzle flow rate / mL·min^{-1}		
	800	1000	1200
2000	1	1.12	1.2
3000	0.89	0.97	0.92
4000	0.76	0.74	0.82
5000	0.77	0.8	0.9
6000	0.8	0.89	0.93
7000	0.85	0.97	0.96

Determination of working parameters of electric centrifugal nozzle

The above analysis shows that the rotation speed and flow rate are the important factors affecting the droplet middle diameter and the droplet spectrum width. The ideal spectral width of droplet size can be obtained by adjusting the speed and flow rate of the atomizing disc. Regulating the motor speed and nozzle flow changes only the motor voltage and spray pressure. According to pest control requirements, the working parameters can be easily adjusted to achieve the best control effect.

If the droplet's particle size is known, the coverage density per unit area can be calculated based on Eq.(1) *(Lan Y. B. et al., 2021)*.

$$f=\frac{6\times10^{-11}}{\pi d^3}\times q \tag{1}$$

Where f is the droplet coverage density (droplets/cm^2); q is the dosage (L/hm^2); d is the droplet particle size (m). According to Eq. (1), the dosage and droplet size directly affect the coverage density. Under low altitude and low dosage, the dosage of rotary wing UAV is generally required to be 15~30 L/hm^2. Due to the influence of plant canopy density, it has a certain vegetation index, and the back of the leaves also requires good coverage. Therefore, the droplet size should not be too large to ensure a good coverage density.

In addition, the aviation low-volume spray volume is small, and the flight height is high; the particle size is too small, easy to evaporate, and easy to produce drift. Droplets with a particle size of less than 100 μm tend to evaporate and drift under high temperatures, humidity, and air flow disturbance. Droplets with a particle size of 300 μm or more have fast settling speed, considerable kinetic energy and are not easy to attach to the leaf surface, resulting in pesticide loss. According to the Biological optimum particle size (BODS), the control effect is the best when the droplet size is between 100 and 300 μm *(Yuan H. et al., 2015)*.

When the droplet size is between 100 and 300 μm, the droplet can be deposited on the target as soon as possible with the rotor downwash air flow to reduce drift.

As shown in Table 4, when the rotation speed is 4000 r/min, the fog droplet spectrum width is the narrowest, and the middle diameter of the fog drop volume is 231.9 μm. If the dosage is 15 L/hm², the atomizing disk speed is 4000 r/min, and the droplet volume diameter is 231.9 μm, the fog droplet coverage density can be calculated as 22.95 droplets /cm². The droplet coverage density is higher, which meets the requirements of low-volume aviation spraying control.

CONCLUSIONS

(1) The symmetrical two-channel two-phase electric centrifugal nozzle for aviation was developed in this study. This structure can effectively improve the distribution of the liquid film and the uniformity of the spray at the bottom of the atomizing disk and avoid the inhomogeneous and incomplete atomization caused by the one-sided tilt of the water.

(2) The speed of atomizing disc and the nozzle flow rate are the important factors affecting the median diameter and spectrum width of droplet volume. The ideal droplet size and spectral width can be obtained by adjusting the speed and flow rate. When the rotation speed is 4000 r/min, the fog drop spectrum width is the narrowest, and the median diameter of the fog drop volume is 231.9 μm. The fog drop coverage density is higher, meeting the requirements of low-volume aviation spraying control.

(3) The droplet's horizontal velocity directly affects the nozzle's spray amplitude. The trajectory of droplet movement in the air is similar to parabolic motion. At the same height and initial horizontal velocity, the larger the droplet size is in a certain range, the larger the nozzle spray amplitude is.

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