OPTIMIZATION STUDY OF STRUCTURE AND OPERATING PARAMETERS OF DOUBLE-LAYER CENTRIFUGAL ATOMIZING NOZZLE BASED ON RESPONSE SURFACE METHODOLOGY
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基于响应面法的双层离心式雾化喷头结构与工作参数的优化研究

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ABSTRACT
In view of the problems such as the lack of comprehensive analysis of working parameters and structural parameters and the imperfection of the atomization model in existing studies, a dual-layer centrifugal atomizing nozzle was designed to optimize the droplet volume median diameter and droplet spectrum width. The key influencing factors, including atomizing disc speed, flow rate, and the number of atomizing teeth, were selected for optimization. Both single-factor and three-factor, three-level response surface optimization experiments were conducted to determine the optimal number of atomizing teeth for different combinations of disc speed and flow rate. Furthermore, with the spray width as the objective function, a Box-Behnken experimental design was employed to investigate the effects of atomizing disc speed, flow rate, and spray height on the atomization performance of the centrifugal nozzle. A multiple quadratic response surface regression model for spray width was also developed. The results indicated that both individual factors and their interactions had a significant impact on the droplet volume median diameter, droplet spectrum width, and spray width. The optimized number of atomizing teeth was found to be 50, and the adjusted R-squared values for the above three regression equations were 0.9977, 0.9893, and 0.9485, respectively. This study provides a theoretical basis for optimizing the nozzle structure and improving the quality of plant protection operations.

摘要
针对现有研究中喷头工作参数和结构参数综合分析不足、雾化模型不完善的问题，本文设计了一种基于响应面法的双层离心式雾化喷头，旨在优化雾滴体积中径和雾滴谱宽度。研究选取雾化盘转速、流量和雾化齿个数作为关键影响因素，通过单因素和三因素三水平响应面优化试验，得到了不同转速和流量组合下雾化齿的最佳数量。进一步，以优化后的喷幅为目标函数，采用Box-Behnken 试验分析了雾化盘转速、流量和喷雾高度对离心喷头雾化性能的影响，并构建了喷幅的多元二次响应面回归模型。结果表明，单因素及各因素间交互作用对雾滴体积中径、雾滴谱宽度和喷幅均具有显著影响。优化后的雾化齿数量为50，雾滴体积中径、雾滴谱宽度、喷幅的校正决定系数分别为0.9977、0.9893、0.9485，表明模型拟合效果良好。本研究为喷头结构优化和提升航空植保作业质量提供了理论依据和指导。

INTRODUCTION
Throughout the growth cycle of crops, chemical control has become the primary choice for controlling diseases, pests and weeds in China due to its high efficiency and rapidity *(Zhang et al., 2014)*. As a large agricultural country, China has problems such as excessive pesticide application and low pesticide utilization, leading to environmental pollution and agricultural product quality and safety problems *(Li et al., 2012)*. With the development of agricultural science and technology, plant protection UAVs (Unmanned Aerial Vehicle) are more and more widely used in crop application by virtue of their advantages such as high efficiency, high speed and excellent application effect *(Lan et al., 2018; Lan et al., 2019)*. As the core component of the drone spraying system, the plant protection spraying nozzle plays a crucial role in determining the quality of spraying *(Deng et al., 2020)*. Among them, the rotary disk centrifugal atomizing nozzle belongs to the ultra-low-volume atomizing nozzle, such nozzle atomization uniformity is better, can be adjusted through the rotational speed

and flow rate to control the liquid particle size. In recent years, the application in the field of plant protection has become widespread *(Chen et al., 2018)*.

In recent years, in order to enhance the uniformity of liquid spraying and improve the atomization performance of droplets, many scholars at home and abroad have carried out a large number of experimental studies on centrifugal atomizing spray nozzles. *Liu et al., (2012)*, used a high-speed camera to observe the specific forms of three atomization modes, namely droplet atomization, ribbon atomization, and film atomization, and found that they can transform into each other under different flow rates and atomizing disk speed. *Ru et al., (2012)*, designed a remotely controllable centrifugal atomized spraying system with the help of a German multi-purpose unmanned helicopter, and investigated the effects of the atomizing disk speed and flow rate on the spray nozzle atomization performance. *Yang et al., (2023)*, in order to analyze the impact of flow rate changes in the application system on the spraying effect, designed a three-layer intelligent centrifugal variable spray nozzle that can satisfy four levels of flow rate adjustments, realizing the variable and controllable spraying of the medicinal liquid. *Zhou et al., (2016)*, studied the influence of the diameter, number of teeth and groove shape of the rotary cup on the atomization performance of the nozzle and optimized the structural parameters of the rotary cup through the analysis of the atomization mechanism of the rotary cup centrifugal nozzle. Most of these studies are aimed at optimizing the operating parameters of existing centrifugal atomizing spray nozzles, or improving the structure of centrifugal atomizing spray nozzles under fixed operating parameters. However, the structural optimization of centrifugal atomizing spray nozzles and atomization performance under different operating parameters have not been systematically studied.

In order to realize the comprehensive matching of nozzle structure and working parameters and improve the atomization performance, this research designs a double-layer centrifugal atomizing nozzle, which completes the secondary atomization of the liquid to obtain finer droplets. Design and construction of variable spray test system, combined with one-factor test and Box-Behnken response surface method, systematically studied the impact of different atomizing disc structure and working parameters on the atomization effect of the spray nozzle, and analyzed and came up with the best combination of parameters for atomization effect, aiming at realizing the “optimal bioparticle size”, and providing theoretical support for the application of plant protection drone spraying technology. The aim is to realize the “optimal biological particle size” and provide theoretical support for the application of plant protection UAV drug application technology.

MATERIALS AND METHODS

Double-layer centrifugal atomizing nozzle structure design and working principle

In this study, a centrifugal atomizing nozzle with a double-layer atomizing disc was designed. Compared with the traditional rotary disc centrifugal atomizing nozzle, a lower atomizing disc with atomizing teeth was coaxially added below the original atomizing disc, and both of them realized the secondary atomization of the liquid through the coaxial reversal movement of the transmission part.

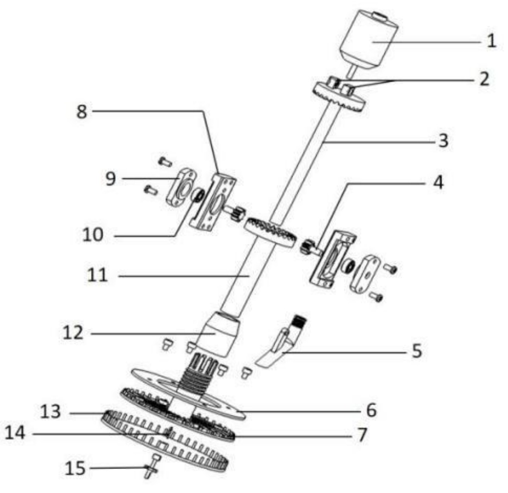


Fig. 1 – Structure diagram of double-layer centrifugal atomizing nozzle

Fig. 2 – Physical picture of double-layer centrifugal atomizing nozzle

1 - Motor; 2 - Motor connector; 3 - Input end gear; 4 - Cylindrical gear; 5 - Liquid inlet pipe; 6 - Upper atomization plate cover; 7 - Upper atomization plate; 8 -Support frame; 9 - Bearing end cover; 10 - Bearing; 11 - Output end gear; 12 - Locking ring; 13 - Lower atomizing disc; 14 - Spring; 15 - Remove parts

As shown in Fig. 1, the nozzle is mainly composed of DC motor, transmission part (end face gear and cylindrical gear), liquid inlet pipe, upper atomizing disk, lower atomizing disk, quick release parts and other structures. The motor is connected to the power supply, high-speed rotation, driven by the transmission structure consisting of end face gear and cylindrical gear. When the motor rotates clockwise, through the connection of the quick-release components, the input face gear drives the upper atomizing disk to rotate clockwise, while the output face gear drives the lower atomizing disk to rotate counterclockwise, thus realizing the coaxial reverse rotation of the upper and lower atomizing disks. The liquid enters the cavity of the upper atomizing disk through the inlet pipe. The surface of the upper disk is equipped with diversion grooves, which guide the liquid flow. As the upper atomizing disk rotates at high speed, the centrifugal force propels the liquid along the grooves. At the edge of the disk, the liquid comes into contact with the lower atomizing disk and collides with the atomizing teeth. This collision generates intense shearing forces, breaking the liquid into smaller droplets *(Gong et al., 2019).* The picture of the double-layer centrifugal atomizing nozzle is shown in Fig. 2.

Test Methods

Control program and materials

Variable pressure-regulated, flow-regulated and liquid concentration-regulated are the three most widely used variable application methods in agricultural production *(Feng et al., 2021)*, in which the flow-regulated type outperforms the other two in terms of transient response. For the purpose of effectively controlling the impact of specific factors on the atomization performance of spray nozzles, a variable spraying system with adjustable flow rate and speed is built in this research, see Fig. 3.

Among them, the speed control system is mainly composed of PWM signal generator, DC power supply, motor drive module and brushless motor. The PWM signal generator generates different output control signals by constantly adjusting the width of each pulse signal, thus realizing the precise control of the voltage of the nozzle motor and the adjustable control of the rotational speed. Liquid part mainly includes sprayer tank, pump, one-way throttle valve, flowmeter and hose, etc. By adjusting the valve handle of the one-way throttle valve, the circulation area of the liquid circuit is controlled, so as to control the flow of the whole liquid circuit. The real-time flow rate of the liquid circuit is presented via the digital display of the flowmeter.

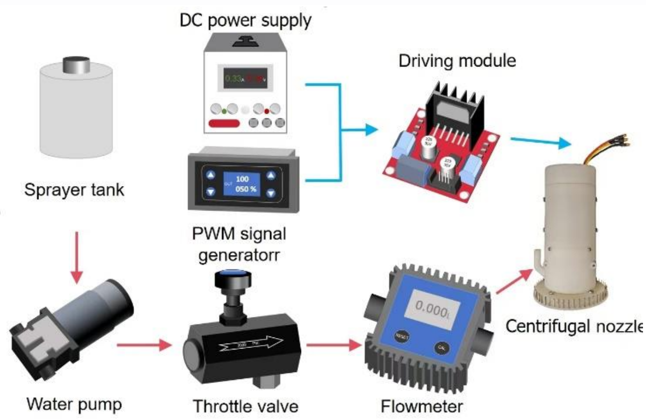


Fig. 3 – Diagram of variable spray system

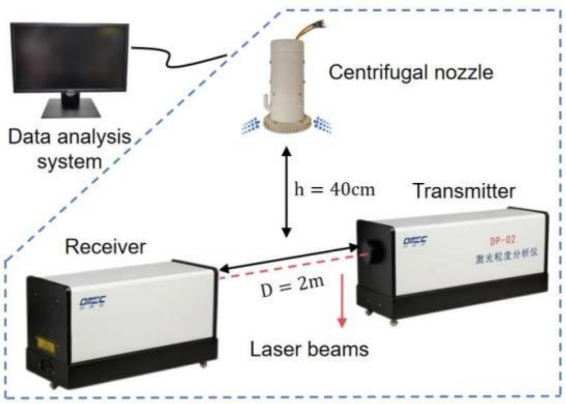


Fig. 4 – Droplet size test system

Droplet size test system

The droplet size testing system mainly consists of variable spray system, aluminum alloy support frame, laser particle size analyzer and data analysis system, in which the sending port of the laser particle size analyzer maintains a horizontal distance of 2m from the receiving port. As shown in Fig. 4, the centrifugal nozzle was installed vertically downward on the support frame, and the vertical distance from the laser beam was maintained at 40 cm. Its central axis was kept perpendicular to the laser beam of the laser particle sizer and the ground to ensure that the laser beam passed through the spray at the maximum cross-section of the spray, and the centrifugal nozzle spray was stabilized, which in turn was used to measure the particle size of the medicinal liquid.

Spray width test system

The spray nozzle comprehensive performance precision test device includes three parts: spraying system, droplet collection tank and control system.

As shown in Fig. 5, the spray nozzle is installed vertically downward, and after starting the power supply, the spraying system is first opened to wet the droplet collection tank. When it is completely wet, the deflector plate is put down to keep the centrifugal spray nozzle spraying steadily. In the test bench, if one of the collected liquids reaches 90% of the capacity of the cylinder, the spraying system is immediately closed, and the deflector plate is put away. The spray volume collected in each cylinder is measured and the spray width of the double-layer centrifugal atomizing nozzle is obtained through the output of the control system.

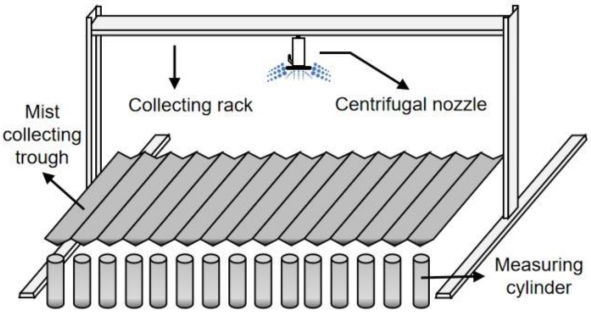


Fig. 5 – Sprinkler comprehensive performance precision test device

Atomization performance evaluation index

In the actual farmland operation, by selecting the appropriate range of liquid particle size, the desired pest control effect is then obtained, in which the median particle size of the volume of droplets can reflect the range of most of the droplet size, and the droplet size distribution width (RS) can better show the uniformity of the distribution of droplets. The smaller the droplet size distribution width, the better the uniformity of the droplet particle size distribution *(Lan et al., 2016)*. This is typically calculated using Equation (1),

$$RS=\frac{D_{v90}-D_{v10}}{D_{v50}} \tag{1}$$

where D_{v10}, D_{v50} and D_{v90} denote 10%, 50%, and 90%, respectively, of the total volume of the entire system for droplets smaller than this particle size value.

In addition, the spray width can provide certain technical references for path planning in plant protection operations, which plays a vital role in improving spraying efficiency and operation quality. In summary, the above three features were selected as the evaluation indexes of centrifugal spray nozzle atomization performance in this experiment.

Response surface method optimization of nozzle structural parameters

Response surface methodology as an optimization tool, through a series of steps of screening tests, determining key factors, modeling and model testing, the key factors are tested at different levels of combinations, and through regression analysis of the whole process, the response values under the corresponding levels of factors are simulated, and the optimal way of combining factors is predicted, and this method has been widely used in many fields in practice *(Wang et al., 2005; Hanrahan et al., 2006).*

Single factor test

Taking the volume median diameter of droplets and the droplet size distribution width as evaluation indicators, the effect of various factors on the atomization capability of spray nozzle was studied and analyzed.

Table 1

Single-factor experimental design

Factors	Values
Atomizing disk speed	3000, 4000, 5000, 6000, 7000, 8000, 9000
Flow rate	600, 700, 800, 900, 1000
Number of teeth	0, 5, 25, 50, 75, 100

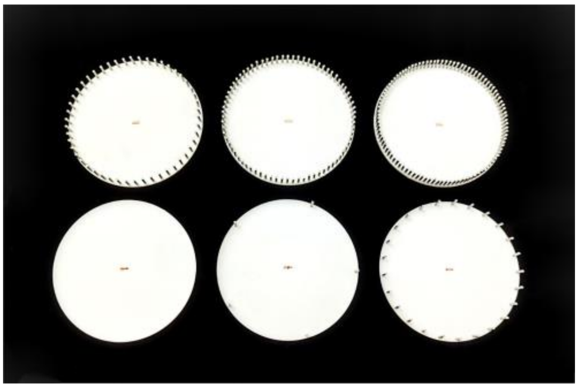


Fig. 6 – Lower atomizing disk with different number of teeth

A constant flow rate of 800 ml/min was set, and the atomization disk speed was maintained at 6000 r/min. The atomization disk had 50 teeth, and the spray medium used was water. The physical structure of different teeth under the atomization disk is illustrated in Fig. 6. The test factors and their corresponding values are summarized in Table 1. Each group of tests was repeated three times to ensure accuracy.

Box-Behnken test

Based on the analysis of the results of single-factor experiments, using Design-expert 13.0 software, the atomizing disk speed (A), the flow rate (B), and the number of atomization teeth (C) were identified as key factor, and the volume median diameter of droplets and the droplet size distribution width were set as dependent variables. Then, the Box-Behnken experiment analysis and design with three factors and three levels were carried out. Tables 2 and 3 respectively show the levels of the response surface experiment factors and the experiment design and results.

Table 2

Box-Behnken test factors and horizontal coding for structural optimization

Factors	Values		
	Atomizing disk speed (r/min)	Flow rate (ml/min)	Number of teeth
-1	3000	600	25
0	6000	800	50
1	9000	1000	75

Table 3

Design and results of Box-Behnken test for structural optimization

Group	Values			D_{v50}	RS
	Atomizing disk speed	Flow rate	Number of teeth		
1	9000	1000	50	81.46	0.98
2	6000	600	25	76.36	1.26
3	6000	600	75	79.94	1.42
4	6000	800	50	79.17	0.94
5	6000	800	50	80.64	0.96
6	3000	600	50	124.49	1.31
7	3000	1000	50	146.72	1.14
8	6000	1000	75	101.14	1.23
9	6000	800	50	79.23	0.93
10	9000	800	75	75.21	0.94
11	3000	800	25	134.96	1.14
12	6000	800	50	80.84	0.93
13	9000	800	25	73.37	0.82
14	3000	800	75	136.32	1.17
15	6000	1000	25	96.33	1.23
16	6000	800	50	80.94	0.97
17	9000	600	50	67.94	0.99

According to Table 3, it can be seen that the maximum value of the volume median diameter of droplets is 146.72 μm, the minimum value is 67.94 μm, and the droplet size distribution width ranges from 1.42 to 0.82. This result indicates that all the three variables selected in the test have a significant effect on the atomization performance of the double-layer centrifugal atomizing nozzle.

Model fitting analysis

Multivariate regression fitting and analysis were carried out on the experimental data obtained in Table 3. Using Design-expert 13.0 software, the multivariate quadratic response surface regression equations of the target functions, namely the volume median diameter of droplets ($Y1$) and the droplet size distribution width ($Y2$), with factors A, B, and C were established. The expressions are shown in Equation (2) and Equation (3), and the analysis of variance results of $Y1$ and $Y2$ were obtained, as shown in Table 4.

$$Y1=80.16-30.56A+9.62B+1.45C-2.18AB+0.12AC+0.3075BC+20.76A^2+4.23B^2+4.05C^2 \quad (2)$$

$$Y2=0.946-0.1287A-0.05B+0.0388C+0.04AB+0.0225AC-0.04BC-0.0543A^2+0.2132B^2+0.1257C^2 \quad (3)$$

Table 4

Regression model analysis of variance

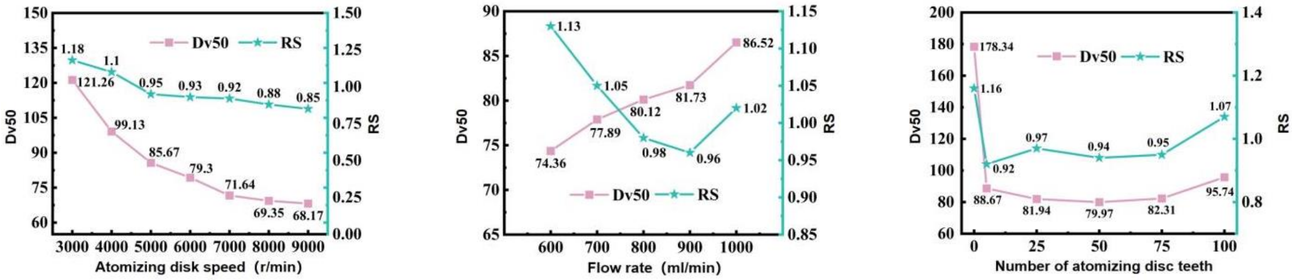
Source	Sum of squares		Mean of squares		F-value		P-value	
	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2
A	7473.14	0.1326	7473.14	0.1326	5086.64	432.77	< 0.0001	< 0.0001
B	739.59	0.0200	739.59	0.0200	503.40	65.27	< 0.0001	< 0.0001
C	16.79	0.0120	16.79	0.0120	11.43	39.20	0.0117	0.0004
AB	18.97	0.0064	18.97	0.0064	12.91	20.89	0.0088	0.0026
AC	0.0576	0.0020	0.0576	0.0020	0.0392	6.61	0.8487	0.0370
BC	0.3782	0.0064	0.3782	0.0064	0.2574	20.89	0.6275	0.0026
A^2	1813.86	0.0124	1813.86	0.0124	1234.61	40.44	< 0.0001	0.0004
B^2	75.45	0.1915	75.45	0.1915	51.35	624.86	0.0002	< 0.0001
C^2	68.91	0.0666	68.91	0.0666	46.90	217.28	0.0002	< 0.0001
Model	10307.57	0.4555	1145.29	0.0506	779.55	165.15	< 0.0001	< 0.0001
Lack of fit	7.14	0.0008	2.38	0.0003	3.03	0.8333	0.3614	0.5413
Residual	10.28	0.0021	1.47	0.0003				
Pure Error	3.15	0.0013	0.7865	0.0003				
Cor Total	10317.85	0.4576						
Y1: R^2_{Adj}=0.9977; R^2=0.9990				Y2: R^2_{Adj}=0.9893; R^2=0.9953				

Note: P<0.01 (indicates highly significant),; P<0.05 (indicates significant), same below.

The P-values in both of the above regression models are less than 0.0001, which means that the models have an extremely significant impact on both the volume median diameter of droplets and the droplet size distribution width. The misfit terms > 0.05 are all non-significant, which means that the experimental errors are small. Where, R^2 is the coefficient of determination and R^2_{Adj} is the corrected coefficient of determination, equal to 0.9977 and 0.9893, indicating that 99.77% and 98.93% of the test data, respectively, are applicable to the above fitted equations. Therefore, all the above regression models showed good reliability and fitting accuracy.

RESULT ANALYSIS

The impacts of a single factor on D_{v50} and RS.



(a) Atomizing disk speed (b) Flow rate (c) Number of atomization teeth

Fig. 7 – Influence of a single factor on the objective function

(1) The atomizing disk speed

As can be seen in Fig.7(a), both the volume median diameter of droplets and the droplet size distribution width are negatively correlated with the atomizing disk speed. This means that as the rotation speed of the atomization disk increases, the obtained droplet size becomes smaller and the droplet distribution becomes more uniform. This is mainly due to the fact that the centrifugal force on the liquid is gradually rose along with the growth of the atomizing disk speed, which further stretches the liquid into finer filaments, increases the friction with the surrounding air in the process, and achieves a second atomization when contacting the nebulizing teeth at the edge of the lower nebulizing disk, and thus it is rapidly broken into finer droplets.

(2) Flow rate

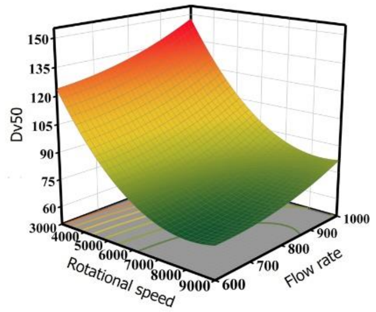
As can be seen in Fig.7(b), with the increase of flow rate, the volume median diameter of droplets increases gradually, and the experimental value increases gradually from 74.36 μm to 86.52 μm, while the droplet size distribution width decreases and then increases, and reaches a minimum value of 0.96 when the flow rate is 900 ml/min. When the flow rate is increased to 1,000 ml/min, the nozzle is unable to break the excess liquid completely, which leads to the non-uniformity of droplet size, and the droplet size distribution width increases to 1.02, but still meets the conditions of low-volume spraying for UAV plant protection operations. The width of droplet spectrum increased to 1.02, but it still meets the condition of low volume spraying for UAV plant protection operation.

(3) The number of atomization teeth

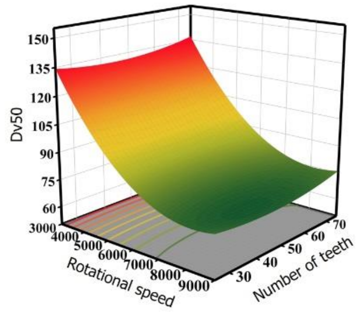
From Fig.7(c), it can be seen that the volume median diameter of droplets and the droplet size distribution width show a tendency of decreasing and then increasing with the increase of the number of atomizing teeth. When the number of teeth increases from 0 to 5, the decreasing rates of the volume median diameter of droplets and the droplet size distribution width are relatively large, which indicates that the atomization teeth have an obvious impact on the fragmentation of the liquid medicine. When the number of teeth is 50, the volume median diameter of droplets and the droplet size distribution width reach their minimum values of 79.97 μm and 0.94 respectively, and as the number of teeth continued to increase to 100, the narrow spacing of the teeth prevented the liquid from being thrown out smoothly, which in turn prevented it from being broken completely, resulting in an increasing trend in the volume median diameter of droplets and the droplet size distribution width.

The impacts of the interactions of various factors on D_{v50} *and* RS.

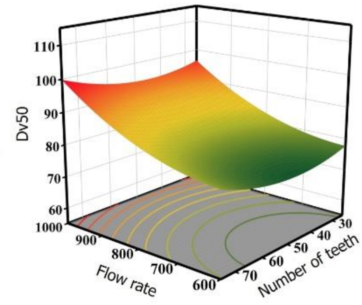
According to the analysis of variance in Table 4, the influences of the interactions of various factors on the volume median diameter of droplets and the droplet size distribution width are shown as AB > BC > AC and AB = BC > AC, respectively, which is consistent with the results of the response surface plots in Fig. 8. As shown in Figs. 8(a) - 8(c), the volume median diameter of droplets was negatively correlated with the atomizing disk speed, while positively correlated with the flow rate, and the volume median diameter of droplets decreased and then increased with the increase in the number of atomization teeth, which was consistent with the results of the one-factor analysis. From Fig. 8(d), it can be seen that when the flow rate is at a low value, the size of the rotational speed has a greater effect on the droplet size distribution width. From Fig. 8(f), it can be observed that the droplet size distribution width first decreases and then increases with the increase in the flow rate and the number of teeth. At this time, the lowest point of the response surface curve falls within the test area, which can be seen that the response surface test can achieve the best structural parameters of the acquisition of the spray nozzle atomization performance to achieve the optimization.



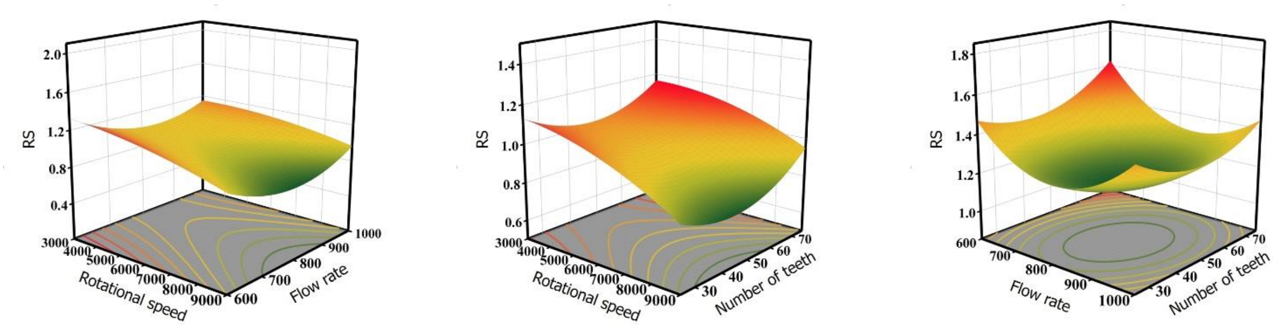
(a)



(b)



(c)



(d) (e) (f)

Fig. 8 – Response surface diagram of the influence of interaction of various factors on the middle diameter of droplet volume and the droplet spectral width

Based on the response surface curves and the actual test conditions, when atomizing disk speed is 8500 r/min, the flow rate is 750 ml/min, and the number of atomization teeth is 50, the structural parameters of the centrifugal spray nozzle are optimal. At this time, the volume median diameter of droplets is 67.4 μm, and the droplet size distribution width is 0.82, both of which can meet the requirements of low-volume spraying for unmanned aerial vehicle pesticide application.

Spray width response surface method optimization test

Table 5

Spray width Box-Behnken test factor and level coding

Factors	Values		
	Atomizing disk speed(r/min)	Flow rate(ml/min)	Height(m)
-1	3000	600	1
0	6000	800	1.5
1	9000	1000	2

Table 6

Spray width Box-Behnken test design and results

Group	Factors			Spray width(cm)
	Atomizing disk speed	Flow rate	Height	
1	6000	600	2	144.66
2	6000	1000	2	154.87
3	3000	600	1.5	111.34
4	6000	800	1.5	149.36
5	6000	1000	1	164.97
6	9000	800	1	163.35
7	3000	1000	1.5	122.29
8	9000	1000	1.5	146.93
9	6000	800	1.5	146.79
10	6000	800	1.5	140.31
11	9000	600	1.5	142.39
12	3000	800	1	107.64
13	9000	800	2	139.36
14	6000	800	1.5	147.06
15	6000	600	1	153.14
16	3000	800	2	125.37
17	6000	800	1.5	144.98

Spray height refers to the vertical distance between the nozzle and the crop canopy, the flight height of the UAV in actual operation has a significant impact on the application effect, according to the actual operational specifications and indoor conditions to determine the spray height of the value range of 1-2m *(Hu et al., 2005)*. Using Design-expert 13.0 software, spray width was set as the response variable, and the atomizing disk speed (A), the flow rate (B), and the spray height (D) were selected as the independent variables, and three-factor, three-level response surface tests and analyses were designed and conducted. Table 5 and Table 6 show the response surface test factor levels and experimental design and results, respectively.

Model fitting analysis

The experimental data obtained in Table 6 were imported into Design-expert 13.0 software to carry out the fitting and analysis, and the multivariate quadratic response surface regression equations of the objective function spray width (Y3) with the factors A, B, and D, respectively, with the expressions as shown in Eq. (4) were established, and the analysis of variance (ANOVA) results of Y3 were obtained, as shown in Table 7.

$$Y3=145.7+15.67A+4.69B-3.1D-1.6AB-10.43AD-0.405BD-17.72A^2+2.76B^2+5.95D^2 \quad (4)$$

Table 7

Analysis of variance of spray width regression model

Source	Sum of squares	Mean of squares	F-value	P-value
A	1965.33	1965.33	145.01	< 0.0001
B	176.06	176.06	12.99	0.0087
D	77.13	77.13	5.69	0.0485
AB	10.27	10.27	0.7579	0.4128
AD	435.14	435.14	32.11	0.0008
BD	0.6561	0.6561	0.0484	0.8321
A^2	1322.29	1322.29	97.56	< 0.0001
B^2	32.05	32.05	2.36	0.1680
D^2	149.13	149.13	11.00	0.0128
Model	4111.98	456.89	33.71	< 0.0001
Lack of fit	48.87	16.29	1.42	0.3614
Residual	94.87	13.55		
Pure Error	46.00	11.50		
Cor Total	4206.85			
R^2_{Adj}=0.9485; R^2=0.9774				

The P-values in the above regression models are well below the significance level of 0.0001, indicating a highly significant difference between the models. The misfit term > 0.05 is not significant, indicating that the error generated in the test is at a low level. Where, R^2 =0.9774, R^2_{Adj} =0.9485, indicating that the above regression model has good reliability and accuracy. Thus, it is feasible to predict and analyze the change in spray width by this regression model.

Response surface analysis

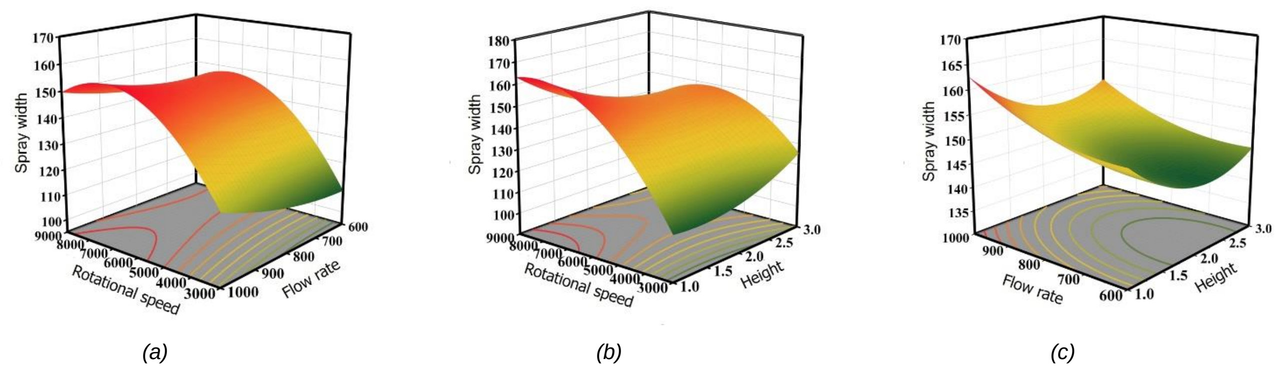


Fig. 9 – Response surface diagram of the influence of interaction of various factors on the spray width

From Fig. 9(a) and (b), it can be seen that when other factors remain constant, the spray width shows a tendency to increase and then decrease with the increase in rotational speed. This is because with the increase of the atomizing disk speed, the fog droplets obtain a greater initial velocity, the spray width increases; however, as the rotational speed continues to increase, the particle size of the droplets decreases, which leads to the liquid being more susceptible to the influence of the external environment and drift, the impossibility of being deposited on the surface of the test bench, resulting in a decrease in the spray width. As shown in Fig. 9 (a) and (c), when the rotational speed and height are certain, the spray width and the size of the flow rate are positively correlated, and the number of droplets will continuously increase with the increase of the flow rate in the liquid circuit, and the larger the droplet particle size, the larger the spray width. From Fig. 9(b), it can be seen that at low rotational speeds, the spray width increases with the increase in height, whereas at high rotational speeds the trend of the spray width is the opposite. This may be due to the fact that the increase in rotational speed decreases the droplet size, and the liquid is more prone to drift and loss, resulting in a decrease in spray width. In summary, it can be seen that this regression model can provide some reference value for the selection of working parameters of UAV in aerial plant protection operation.

CONCLUSIONS

This research proposes a double-layer centrifugal atomizing nozzle that can realize the secondary atomization of liquid medicine, combining single-factor experiments and the response surface method, and systematically exploring the effect of the structural parameters and working parameters of the double-layer centrifugal atomizing nozzle on its atomization performance.

(1) According to the single-factor experiments, within the test range, the volume median diameter of droplets and the droplet size distribution width of the centrifugal nozzle show the same trend with the increase in the number of atomization teeth, that is, they first decrease and then increase. Meanwhile, both of them are negatively correlated with the atomizing disk speed. On the other hand, the volume median diameter of droplets increases linearly with the increase in the flow rate, while the droplet size distribution width first decreases and then increases.

(2) In the response surface optimization experiment, three key factors that have significant effects on the volume median diameter of droplets and the droplet size distribution width are selected: the atomizing disk speed, the flow rate, and the number of atomization teeth, and a Box-Behnken analysis experiment with three factors and three levels is carried out. Through the analysis of variance of the obtained regression models, the R^2_{Adj} values of the two are 0.9977 and 0.9893 respectively, indicating that the models have good fitting performance. Finally, the optimized number of atomization teeth is 50.

(3) The response surface method is used to establish a quadratic polynomial regression model of the atomizing disk speed, the flow rate, and the spray height with the spray width. The results show that R^2_{Adj}=0.9485and R^2=0.9774, and the regression model has high accuracy and fitting degree, indicating that the response surface method has certain feasibility and theoretical guiding significance for the prediction and control of the spraying width in aerial plant protection operations.

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