Optimization and test for structural parameters of UAV spraying rotary cup atomizer

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Abstract: Small unmanned aerial vehicle (UAV) pesticide application technology is developing rapidly in China. However, the spray efficiency of UAV sprayer is not stable, one important reason is that the lack of specialized aviation nozzle. Rotary cup atomizer is not easily to be blocked and has broad application foreground in UAV spray. In order to obtain good spraying quality and narrow droplet spectrum aviation spraying centrifugal nozzle, the impacts of rotary cup atomizer structural parameters on atomization property were studied. In this research, a centrifugal atomization test device was designed, on which a frequency converter was used to adjust the rotary speed, and a return valve was used to stabilize the flow rate and pressure of spray liquid. The droplet volume medium diameter (VMD) and droplet spectrum relative width (SRW) were tested by using laser particle analyzer and particle analysis system. The analysis results of variance and quadratic regression orthogonal test were used to optimize the structural parameters of rotary cup atomizer. The influences of rotary cup atomizer structural parameters on atomization property, such as groove shape, diameter, teeth number, cone angle and height were evaluated and analyzed by conducting single-factor test. The results showed that: the best optimized rotary groove shape was square, diameter and teeth number had significant effects on droplet VMD and SRW, while cone angle had no effect on the droplet VMD and SRW, height affected droplet VMD but did not affect droplet SRW. Therefore, diameter and teeth number were selected as the variables of quadratic regression orthogonal test, droplet VMD and SRW regression model was established by using response surface analysis method. The optimized structural parameters respectively were: groove shape square, cone angle 60°, height 20 mm, diameter 61.5 mm and teeth number 149. Droplet VMD and SRW simulation value respectively were 200 μm and 0.562. The differences between simulation value and test value were 0.68% and 9.90% respectively, indicating that the regression model is accurate. The research result can provide a reference for further optimizing the structure parameters of rotary cup atomizer to meet the requirement of UAV spraying.

Keywords: rotary cup atomizer, atomization, droplet VMD, droplet SRW, optimization, mathematical model, response surface
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1 Introduction

Small unmanned aerial vehicle (UAV) pesticide application technology is developing rapidly in China because of its high working efficiency and easy operation. However, the spray efficiency of UAV sprayer is not stable for its uneven deposition distribution and high drift risk of aviation spraying. Pesticide drift and uneven deposition distribution lead to the low pesticide usage, terrible environmental pollution and high pesticide residues[1-3]. The atomization performances of nozzle, especially droplet size and droplet distribution, directly impact the distribution of droplet deposition and drift performance[4,5]. Large droplets are easy to drop, while small droplets are easy to drift, the narrow droplet distribution can reduce the ratio of maximum and minimum droplets. Therefore, the narrow droplet

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distribution is easier to control the droplet deposition and will also improve the utilization of pesticides[6,7]. Since centrifugal atomizing nozzle can atomize viscous liquid and is no easily to be blocked, it is currently widely used in low volume applications of aviation spraying field[8-11]. Therefore, optimizing the rotary cup structure parameters to obtain the narrow droplet spectrum can provide a way to increase the amount of spray deposition and reduce drift.

Some scholars analyzed atomization principle of centrifugal atomizing nozzle theoretically[12]. The atomization process was revealed and some theoretical formulas were obtained. Some scholars researched the atomization performance of centrifugal atomizing nozzle by conducting experiments. Hooper and Spurgin[13] used laser particle size analyzer (one of the most widely recognized tools in testing particle size) to study the influences of speeds and flow volumes in the wind tunnel test chamber on wind-wheel-drive cage nozzle droplet diameter curves. Malvenrn 2600/3600 droplet laser analyzer was used to study droplet volume distribution and droplet number distribution of nozzle[14]. Craig et al.[15] used high-speed camera and laser particle size analyzer to study the atomization of rotary nozzle, and found that the nozzle outer edge of the tines could increase the consistency of droplet size. Ahmed and Youssef[16] used a phase Doppler particle analyzer (PDPA) to get a solution that rotary cup atomizer's atomization performance was superior than rotary disk.

Most articles focused on the optimization of rotary speed and flow rate parameters. Rotary speed and flow rate do have a significant effect on the atomization performance. But in the fixed rotary speed and flow rate circumstances, the structural parameters of the centrifugal atomizing nozzle have not been studied systematically.

The rotary atomizer used in UAV currently is Micron's production, mainly for hand-held ultra-low volume spray. The flow rate is less than 200 mL/min, speed is about 5000 r/min, and the droplet diameter is about 100 μm. It cannot completely meet the requirements of UAV spraying, since UAV spraying is a high-altitude, high-speed and low-volume application. Aviation low volume spray requires 100-300 μm droplet size[11,17], and the narrower droplet spectrum, the better. The working conditions are flow rate 700 mL/min and rotating speed 3600 r/min. The indicators are droplet volume medium diameter (VMD, D_{50}) and droplet spectrum relative width (SRW, $(D_{90}–D_{10})/D_{50}$). In this research, firstly, the groove shape was changed and optimized by using variance analysis. Secondly, the diameter, number of teeth, cone angle and height were changed individually based on optimized groove shape, the influence of droplet VMD and SRW were studied. Finally, the structural parameters that had significant influences on droplet VMD and SRW were selected as quadratic regression test factors. At last the droplet VMD and SRW regression models were obtained. Rotary atomizer structure optimization can obtain the narrow droplet spectrum rotary atomizer and provide reference for improving the quality of aviation spray.

2 Structure and working principle of rotary cup atomizer

2.1 Structure

Rotary cup atomizer is different from rotary disk atomizer nozzle, it is a conical nozzle that has a certain height and cone angle, the model is ULVA +, produced by the British micron sprayers Limited (Micron Sprayers Ltd.). Rotary cup is the main working part of the rotary cup atomizer, its reference structural shape is shown in Figure 1, the shape of groove and tooth tip is equilateral triangle, cup diameter is 50 mm, the teeth/grooves number is 180, rotor cone angle is 60°, and the height is 20 mm. In the following optimization test, the change of rotary cup structure is on the basis of the reference rotary cup structure. These cups were made by using 3D printer, the material is photosensitive resin and manufacturing precision is 100 μm.

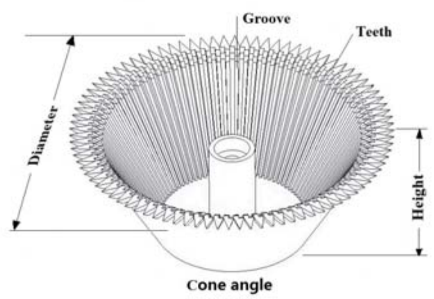


Figure 1 Structural parameters of rotary cup atomizer

2.2 Calculation of film thickness

The process of centrifugal nozzle's liquid silk spray is divided into three steps: firstly, liquid is spread into thin film on the rotating cup, then the liquid filaments form on the edges of sharp teeth, finally liquid filaments break and form droplet[16,18]. The liquid flow of rotary cup surface is an axisymmetric swirl flow. According to polar coordinates hydrodynamics incompressible, Newtonian fluid quality conservation and momentum conservation laws, the following Equations (1) and (2) can be given[19]:

$$\rho\frac{u_r}{r}+\rho\frac{\partial u_r}{\partial r}+\frac{1}{r}\frac{\partial}{\partial\theta}(\rho u_\theta)=0 \quad (1)$$

$$u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial\theta}-\frac{u_\theta^2}{r}+u_z\frac{\partial u_r}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+\frac{\mu}{\rho}\left[\frac{\partial}{\partial r}\left(\frac{u_r}{r}+\frac{\partial u_r}{\partial r}\right)+\frac{\partial^2 u_r}{\partial z^2}\right] \quad (2)$$

where, ρ is the liquid density, kg/m^3; r is the radius of the rotary cup, m; u_r is the radial velocity, m/s; u_z is the axial velocity, m/s; u_θ is the tangential velocity, m/s.

Since the flow pattern of liquid on surface of the rotary cup is not slip flow, boundary condition is liquid-gas, interface pressure is approximately 0, joint rotary cup nozzle flow calculation Equation (3), we can get the rotary edge film thickness as Equation (4):

$$Q=\int_0^{2\pi}\int_0^{\delta}u_r r d\theta dz=2\pi\int_0^{\delta}u_r r dz \quad (3)$$

$$\delta=\left(\frac{3}{2}\frac{Q\mu}{\pi r^2\omega^2\rho}\right)^{1/3} \quad (4)$$

where, δ is film thickness, m; μ is fluid kinematic viscosity coefficient, N·s/m^2; Q is flow rate, m^3/s. Liquid parameters and rotary cup parameters are shown in Table 1.

Table 1 Fluid parameters and rotary cup parameters

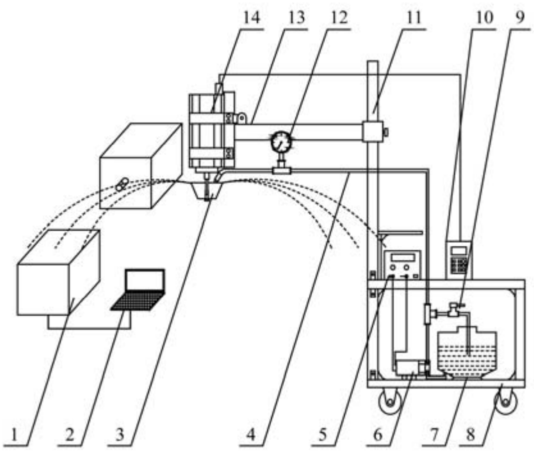
Name	Value	Name	Value
Liquid viscosity μ/N·s·m^{-2}	0.001	Liquid density ρ/kg·m^{-3}	1000
Rotating speed ω/rad·s^{-1}	376.8	Flow rate Q/m^3·s^{-1}	11.67×10^{-6}
Radius r/mm	25		

The impacts of the groove, teeth, cone angle, height and other parameters on the atomization performance are ignored in simplified hydrodynamic model. The groove and the sharp teeth have the function of draining and diversion liquid, so they can increase the adhesion of liquid inside the rotor. Cone angle and height can influence the contact length of liquid with the rotor wall, thus affect the atomization performance. Therefore, studying the atomization performance influenced by rotor groove shape, diameter, number of teeth, and the height of the cone angle, can give a technical support to improve the rotary atomizing fluid model.

3 Atomization quality test

3.1 Test instruments and equipment

In this research, the centrifugal atomization test platform was designed, the motor speed was adjusted by using a frequency modulator, and the spray liquid flow rate and pressure were steadied by using a return valve. The test equipment is shown in Figure 2. The centrifugal atomization test platform consists of a centrifugal atomization device, a liquid supply system and a droplet size testing system. Centrifugal atomization device includes a spindle motor (Model: TDK65-0.8F-24k, maximum zero-load speed 24 000 r/min), a frequency modulator (model: FC300-2.2G-T4-B3, output frequency 0-1000 Hz), a support platform. Liquid supply system consists of a diaphragm pump (rated pressure 12 V, maximum flow rate 2800 mL/min), DC power supply (voltage adjustable range 0-30 V, current measurement range 0-3 A), return valve, pressure gauge (measurement range 0-1 MPa). Droplet size test system consist of a laser particle size analyzer (Model: DP-02, measuring range 0.1-1500 μm, Zhuhai OMC Instrument Co., Ltd.) and laser particle size analysis system.



Note: 1. Laser particle size analyzer 2. Laser particle analyzer system 3. Rotary cup atomizer 4. Pipeline 5. DC power 6. Diaphragm pump 7. Tank 8. Support platform 9. Return valve 10. Frequency modulator 11. Lifter 12. Pressure gage 13. Rail 14. Spindle motor

Figure 2 Droplet test device diagram

3.2 Atomization performance evaluation

Droplet SRW is the reaction of the droplet size concentration degree, the narrower droplet spectrum, the more concentrated droplet size distribution is, which means that the droplet differential distribution is steeper. Narrow droplet spectrum, which is called controllable droplet, will improve deposition rate and reduce drift in spraying. Droplet VMD (D_{50}) represents the sum of all the droplet volumes that smaller than this droplet diameter, which takes up 50% of the total volume of the sample droplet particles, it can be used to characterize droplet diameter. Droplet SRW ((D_{90}–D_{10})/D_{50}) indicates the degree of differential droplet size distribution concentration, the smaller the value, the better[13]. Since sample droplets accumulate form small to large, D_{10} and D_{90} respectively present the sum of all the droplet volumes that smaller than this droplet diameter, which take up 10% and 90% of the total volume of the sample droplet particles. In this paper, the droplet VMD (D_{50}) and droplet SRW ((D_{90}–D_{10})/D_{50}) are indicators of atomization quality, and the droplet SRW is the main assessment indicator.

3.3 Test methods and conditions

Laser particle analyzer outputs D_{50}, D_{10}, D_{90} and the particle size differential distribution curves. Under most UAV spray operating conditions, application liquid amount is 15 L/hm^2, flight speed is about 3 m/s, UAV spray width is about 5 m, there are two nozzles installed on the aircraft. So the rotary cup atomizer's flow rate is set to 700 mL/min[8,11], the rotary speed is 3600 r/min, under these working conditions, the droplet differential distribution is stable unimodal distribution. The rotary cup was installed horizontally, and rotary cup outlet edge is 300 mm horizontal far from the laser, and is 20 mm vertically above the laser. Since the droplet size changes with the direction of the droplets tangent motion[21-23], according to the droplet trajectory analysis, the number of droplets measured at this sample point is larger, so we can get more accurate droplet size. Laboratory average temperature is (25±5)°C, relative humidity is (70±5)%, and the measure medium of experiment is water.

3.4 Experimental design

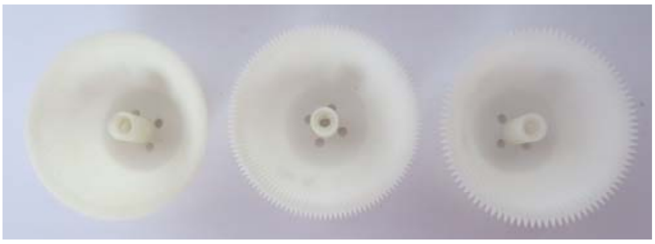
3.4.1 Effects of groove shape on atomization performance

On the basis of reference rotary cup structure, the shape of the groove was changed and six rotary cups with different groove shapes were designed, the groove shapes respectively are triangular, square, oblique, cylindrical, only with the teeth tip and smooth disk.

3.4.2 Effects of rotary cup structural parameters on the atomization performance

On the basis of the determined shape of the groove, according to the analysis of section "4.1 Optimization of the groove shape", the groove shape is square. On the basis of rotary cup reference structure, the other structure parameters were fixed, and single structure parameter was varied one by one. For example, on the basis of teeth number 180, cone angle 60°, height 20 mm, change the rotary cup diameter, and design three cups with different diameters. Four sets of rotary cups were designed, the parameters were: diameter of 50 mm, 60 mm and 70 mm; teeth number of 180, 120 and 90 and the teeth number was equal to the groove number; cone angle of 60°, 45° and 30°; height of 20 mm, 15 mm and 10 mm, as shown in Figure 3.

a. Different diameters



b. Different teeth numbers

c. Different cone angles

d. Different heights

Figure 3 Rotary cups with different structure parameters

3.4.3 Atomization model test

According to the analytical results of atomization performance effected by rotary cup structural parameters, in order to obtain a narrow droplet spectrum rotary cup atomizer, diameter and teeth number, which have significant effects on droplet VMD and SRW, were chosen as two impact factors of quadratic regression design, i.e., on the basis of the square groove shape and basic taper angle 60°, basic height 20 mm, changed the diameter and teeth number. Nine rotary cups with different diameters and teeth number were designed. The factor level encoding parameters of quadratic regression experiment are shown in Table 2.

Table 2 Factors and levels of quadratic regression experiment design (*p*=2)

Level	Factors	
	Diameter/mm	Teeth number
–1.414	50	80
–1	53.8	95
0	63	130
1	72.2	165
1.414	76	180

4 Test results and analysis

4.1 Optimization of groove shape

The droplet VMD (D_{50}) and the droplet SRW ((D_{90}–D_{10})/D_{50}) of six rotary cups with different groove shape are reported in Table 3. The analysis of variance was done by using SAS 9.2 statistical analysis software. The mean comparison was done by using the least significant difference method, and the significance level P is 0.05, the results of variance analysis and mean comparison of droplet VMD and SRW are shown in Table 4. The droplet VMD and SRW variance analysis and means comparison of different diameter, teeth number, cone angle and height are shown in Table 5.

According to the results of variance analysis and mean comparison, the droplet VMD in ascending order are: square, triangle, cylindrical, oblique, only with teeth tip and smooth disk. Droplet SRW in ascending order are: square, triangle, oblique, only with teeth tip, smooth disk and cylindrical. This indicates that the grooves and tooth tip play a role of drainage and diversion, and impact the droplet VMD and SRW. The square groove shape has the narrowest droplet SRW. Finally the optimizing result of groove shape is square.

4.2 Effects of rotary cup structure parameters on atomization performance

According to test report of laser particle size analyzer, the particle size differential distribution curves of rotary cups with different structure were obtained. The particle size differential distribution was graded with step of 50 μm, the droplet size frequencies of each 50 μm step within 0-600 μm particle size range were recorded, and the differential distribution curve was drawn again. The droplet size distribution curves are shown in Figure 4.

Table 3 Droplet VMD and SRW of six rotary cups with different groove shapes

Level	D_{50}/μm				$\overline{x_{i.}}$ Mean value	(D_{90}–D_{10})/D_{50}				$\overline{y_{i.}}$ Mean value
A_1	277.99	272.54	276.67	279.16	276.59	0.964	0.917	1.019	0.990	0.973
A_2	286.05	288.39	286.53	286.71	286.92	0.993	0.983	0.916	1.041	0.983
A_3	333.1	339.58	343.07	352.96	342.18	1.654	1.635	1.503	1.500	1.573
A_4	345.47	346.95	34326	342.98	344.66	1.094	1.161	1.111	1.090	1.114
A_5	375.64	374.68	376.48	374.73	375.38	1.179	1.115	1.124	1.117	1.134
A_6	446.58	447.99	441.83	451.49	446.97	1.153	1.187	1.102	1.195	1.159

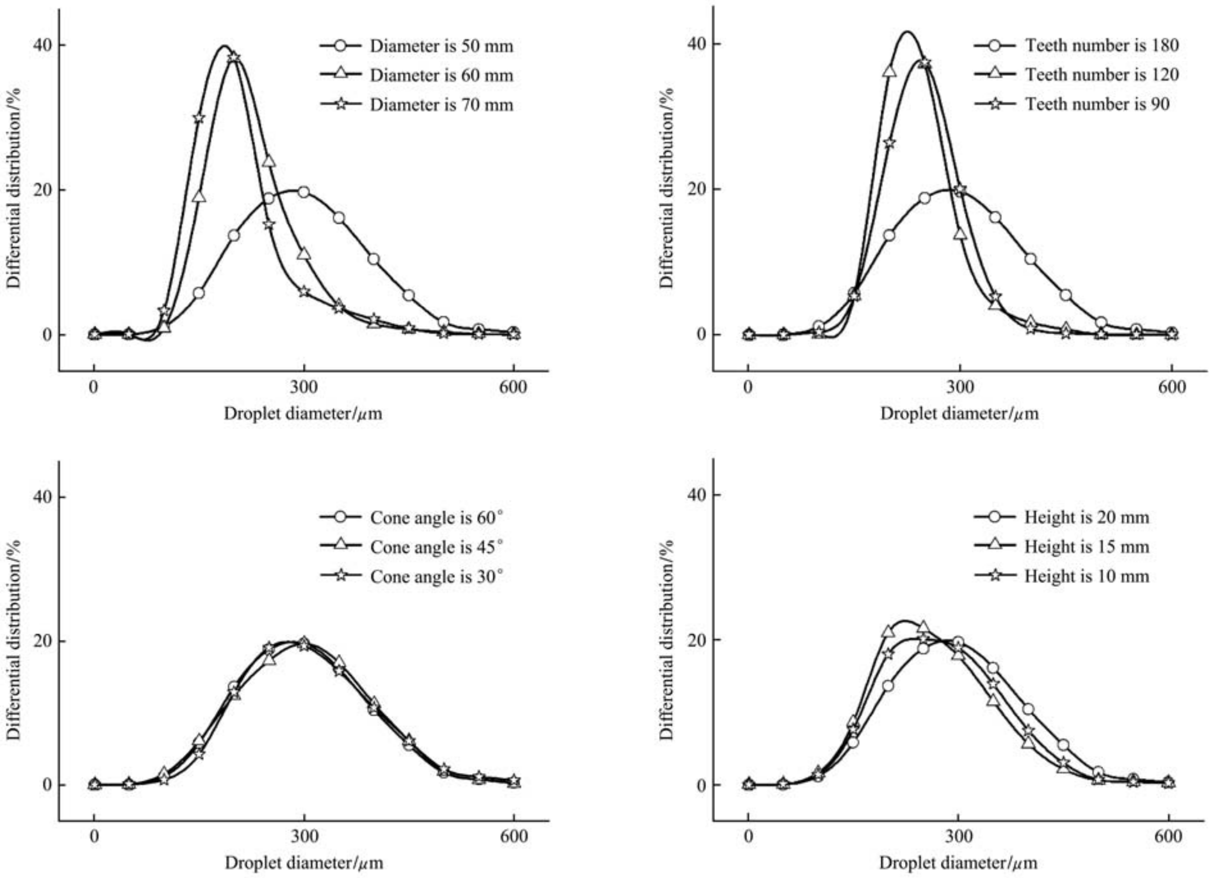
Note: A_1-A_6 are triangle groove, square groove, cylindrical groove, serrated groove, only have teeth and smooth cup respectively, the same as below.

Table 4 Variance analysis and mean value comparison

Source	D_{50}/μm					(D_{90}–D_{10})/D_{50}				
	Sum of Squares	Freedom	*F* value	Significant level *p*	Mean value comparison	Sum of Squares	Freedom	*F* value	Significant level *p*	Mean value comparison
Factor *A*	77526	5	945.41	<0.0001**	A_6>A_5>A_4= A_3> A_2>A_1	0.959	5	75.78	<0.0001**	A_3>A_6=A_5= A_4> A_2= A_1
Pure Error	295.2	18				0.045	18			
Cor. Total	77821	23				1.004	23			

Table 5 Variance analysis and mean value comparison

Structure	Source	$D_{50}/\mu m$					$(D_{90}-D_{10})/D_{50}$				
		Sum of squares	Freedom	F value	Significant level p	Mean value comparison	Sum of squares	Freedom	F value	Significant level p	Mean value comparison
Diameter	Factor	26639.5	2	2471	<0.0001**		0.095	2	41.1	<0.0001**	
	Error	48.5	9			$D_1>D_2>D_3$	0.010	9			$D_1>D_3>D_2$
	Total	26688	11				0.105	11			
Teeth number	Factor	10073	2	460.8	<0.0001**		0.374	2	75.85	<0.0001**	
	Error	98.4	9			$T_1>T_3>T_2$	0.022	9			$T_1>T_3>T_2$
	Total	10171.4	11				0.396	11			
Cone angle	Factor	110.3	2	2.2	0.1647		0.011	2	1.47	0.194	
	Error	223.8	9			$C_3=C_2=C_1$	0.032	9			$C_3=C_2=C_1$
	Total	334.1	11				0.043	11			
Height	Factor	2304.9	2	32.6	<0.0001**		0.087	2	4.61	0.065	
	Error	318.3	9			$H_1>H_3>H_2$	0.085	9			$H_2=H_3=H_1$
	Total	2623.2	11				0.154	11			



Note: D_1-D_3 are rotary cup with diameters of 50 mm, 60 mm and 70 mm, respectively; T_1-T_3 are rotary cup with teeth numbers of 180, 120 and 90, respectively; C_1-C_3 are rotary cup with cone angles of 60°, 45° and 30°, respectively; H_1-H_3 are rotary cup with heights of 20 mm, 15 mm and 10 mm, respectively, the same below.

Figure 4 Droplets distribution of rotary cup atomizers with different diameters, teeth numbers, cone angles and heights

According to the droplet size differential distribution curve, analysis of variance and mean comparison, the diameter and teeth number had a significant influence on droplet VMD and SRW, while cone angle and height had a smaller impact. Droplet VMD and SRW decreased with the increase of diameter, the droplet SRW was stabilized when the diameter increased to a certain value. Droplet VMD and SRW decreased with the decrease of teeth number, the droplet SRW was stabilized when the teeth number decreased to a certain value. Height only affected droplet VMD, and did not affect droplet SRW. Cone angle affected neither droplet VMD nor droplet SRW.

4.3 Atomization model

In order to obtain a narrow droplet spectrum centrifugal nozzle, regardless of cone angle and height, diameter and teeth number were chosen as two factors of quadratic regression analysis. Each factor had five levels in quadratic regression test, the total test points were nine, each test point was repeated three times, and the center test point was repeated 21 times. The test results of droplet VMD and SRW are reported in Table 6.

Response surface analysis was done by using SAS 9.2 statistical analysis software, quadratic regression models of droplet VMD Y_1 and droplet SRW Y_2 were obtained. Two regression models' significant determination coefficient R^2 were 0.803 and 0.897 respectively, it means that the regression equations fit well. The significance of regression coefficient are shown in Table 7, it is obvious that the cross term between diameter and teeth number is very significant, indicating that there is a strong interaction between the two factors.

Table 6 Experimental levels and results of quadratic

Test number	Diameter	Teeth number	D_{50}/μm	$(D_{90}–D_{10})/D_{50}$
1	1	1	173.43/166.98/172.28	0.618/0.655/0.649
2	1	–1	184.94/182.6/186.47	1.086/0.968/0.866
3	–1	1	236.27/240.41/236.24	0.722/0.729/0.679
4	–1	–1	251.51/243.89/252.16	0.554/0.592/0.525
5	1.414	0	185.75/190.33/191.84	1.062/1.008/1.108
6	–1.414	0	252.46/244.31/250.36	0.519/0.579/0.518
7	0	1.414	168.54/167.52/167.17	0.541/0.539/0.538
8	0	–1.414	220.26/219.53/221.35	0.668/0.678/0.593
9	0	0	206.23/204.81/207.64	0.588/0.592/0.586
10	0	0	204.95/204.36/205.56	0.595/0.593/0.596
11	0	0	199.36/198.1/200.61	0.601/0.607/0.595
12	0	0	202.77/204.73/200.84	0.621/0.610/0.630
13	0	0	209.66/209.26/210.05	0.578/0.574/0.582
14	0	0	201.62/201.72	0.603/0.609
15	0	0	204.04/209.79	0.595/0.579
16	0	0	210.92/208.62	0.572/0.586

Table 7 Significance test for regression coefficient of droplet size

Source	D_{50}/μm				$(D_{90}–D_{10})/D_{50}$			
	Coefficient Estimates	Freedom	*t* value	Significant level *p*	Coefficient Estimates	Freedom	*t* value	Significant level *p*
Intercept	205.03	1	123.60	<0.0001**	0.595	1	52.36	<0.0001**
d	–38.14	1	–17.38	<0.0001**	0.191	1	12.74	<0.0001**
n	–17.63	1	–8.04	<0.0001**	–0.059	1	–3.89	0.0004**
d^2	16.13	1	5.11	<0.0001**	0.216	1	10.00	<0.0001**
$d^* n$	–1.11	1	–0.25	0.8011	–0.243	1	–8.08	<0.0001**
n^2	–8.98	1	–2.84	0.0071**	0.010	1	0.47	0.6422

Note: $p<0.01$ (highly significant, **: $p<0.05$ (significant, *).

The regression results are shown as Equations (5) and (6).

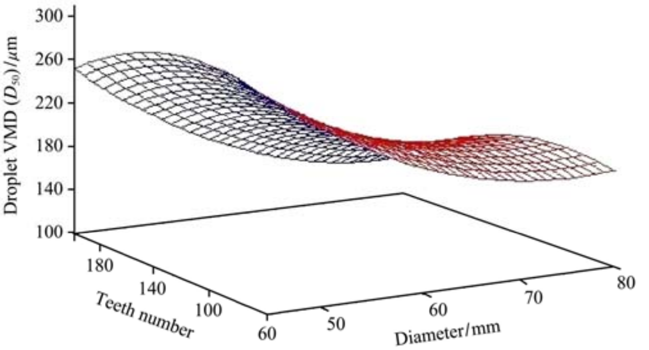
$$Y_1=205.03-38.14d_c-17.63n_c+16.13d_c^2-1.11d_c\cdot n_c-8.98n_c^2 \tag{5}$$

$$Y_2=0.595+0.191d_c-0.059n_c+0.216d_c^2-0.243d_c\cdot n_c-0.01n_c^2 \tag{6}$$

where, d_c, n_c are the coded values of rotary cup diameter d and the teeth number n.

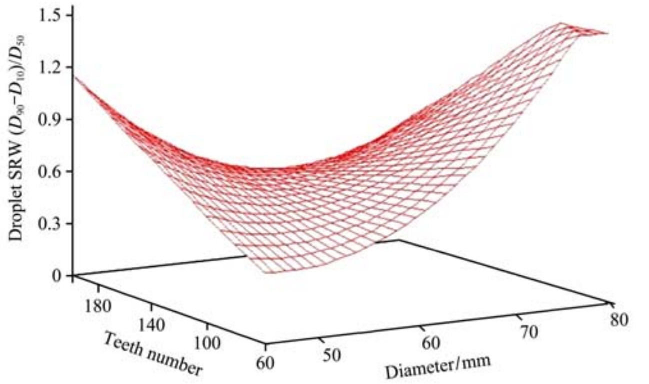
The response surface of the droplet VMD and SRW are shown in Figures 5 and 6, the quadratic regression response surface of droplet VMD and SRW were saddle.

To meet the low volume spray requirements of UAV spraying, the droplet size should be in range of 101-300 μm[11,17]. Fmincon function was called in Matlab software, to search the minimum constrained optimization functions. Subject conditions were: Y_1 equal to 200 μm, d_c, n_c within the [–2, 2] interval, to solve the minimum value Y_2. The results were d_c= –0.169, n_c = 0.537, Y_2 = 0.5621. So the optimized diameter was 61.5 mm, teeth number was 149. This cup was made by using 3D printer, and the optimized rotary cup's atomization performance was measured by the laser particle size analyzer. The average droplet VMD was 198.65 μm and droplet SRW was 0.624. The differences between simulation value and test value were 0.68% and 9.90%, respectively, therefore the developed models can be regarded as a reliable representative of the experimental results.



Note: Red is the top of response surface, blue is the bottom of response surface.

Figure 5 Droplet VMD quadratic regression response surface



Note: Red is the top of response surface, blue is the bottom of response surface.

Figure 6 Droplet SRW quadratic regression response surface

5 Conclusions

We could get the conclusion that the diameter and teeth number of rotary cup have significant effects on droplet VMD and SRW by using the method of variance analysis and mean comparison. By combining the diameter and the number of teeth correctly, a centrifugal nozzle with narrow SRW could be obtained. The quadratic regression model of the droplet VMD and SRW that obtained by the orthogonal rotation design verified the reliability of the regression model.

The groove shape had a significant effect on droplet VMD and SRW. Grooves and teeth played a role in drainage and diversion, square groove shape had the smallest droplet VMD and the narrowest droplet SRW, so square groove is the best.

The diameter and teeth number had significant influences on droplet VMD and SRW, while cone angle and height had smaller effect. The droplet VMD and SRW decreased with the increase of diameter and the decrease of teeth number. When diameter increased to a certain value, the width of the droplet spectrum tended to be stable. When teeth number decreased to a certain value, the droplet VMD increased while the droplet width stabilized. The height of rotary cup affected the droplet volume median diameter while had no effect on droplet SRW. The cone angle neither influenced droplet VMD nor droplet SRW.

Under the working conditions of rotational speed of 3600 r/min, flow rate of 700 mL/min, the regression model of droplet VMD and SRW were obtained. The coefficients of determination R^2 were 0.803 and 0.897 respectively. The optimized structural parameters respectively were groove shape square, cone angle 60°, height 20 mm, diameter 61.5 mm and teeth number 149. Droplet VMD and SRW simulation value respectively were 200 μm and 0.562. The difference between simulation value and test value were 0.68% and 9.90% respectively, therefore the developed models can be regarded as a reliable representative of the experimental results.

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[References]

[1] He X K. Improving severe draggling actuality of plant protection machinery and its application techniques. Transactions of the CSAE, 2004; 20(1): 13–15. (in Chinese)

[2] Qiu B J, Wang L W, Cai D L, Wu J H, Ding G R, Guan X P. Effects of flight altitude and speed of unmanned helicopter on spray deposition uniform. Transactions of the CSAE, 2013; 29(24): 25–32. (in Chinese)

[3] Kilroy B. Aerial application equipment guide. United States Department of Agriculture Forest Service, 2003; pp. 3–17.

[4] Yan Y f, Zhang L, Gao Z Y, Pu G. Atomization performance of low pressure swirl atomizing nozzle. CIESC Journal, 2009; 60(5): 1141–1147.

[5] Liao J, Zang Y, Zhou Z Y, Luo X W. Quality evaluation method and optimization of operating parameters in crop aerial spraying technology. Transactions of the CSAE, 2015; 31(Supp.2): 38–46. (in Chinese)

[6] Yuan H Z, Wang G B. Effects of droplet size and deposition density on field efficacy of pesticides. Plant Protection, 2015; 41(6): 9–16.

[7] Mao Y J, Wang X, Ma W. Numerical analysis method for predicting droplet size distribution of nozzles. Transactions of the CSAE, 2009; 25 (Supp.2): 78–82. (in Chinese)

[8] Qin W C, Xue X Y, Zhou L X, Zhang S C, Sun Z, Kong W, et al. Effects of spraying parameters of unmanned aerial vehicle on droplets deposition distribution of maize canopies. Transactions of the CSAE, 2014; 30(5): 50–56. (in Chinese)

[9] Zhang S C, Xue X Y, Qin W C, Sun Z, Ding S M, Zhou L X. Simulation and experimental verification of aerial spraying drift on N-3 unmanned spraying helicopter. Transactions of the CSAE, 2015; 31(3): 87–93. (in Chinese)

[10] Zhou L X, Xue X Y, Sun Z, Zhang S C, Kong W, Zhang T, et al. Experimental study on electrical-driven centrifugal nozzle of aerial sprays. Chinese Agricultural Mechanization, 2011; (1): 107–111. (in Chinese)

[11] Fan Q N. The research on the pesticide spray system using for the mini unmanned helicopter. Nanjing: Nanjing Forestry University, 2011. (in Chinese)

[12] Ledebuhr R, Hetherington M H. Rotary atomizer drip control method and apparatus. CA 2763916 A1 [P]. 2013.

[13] Hooper G H S, Spurgin P A. Droplet size spectra produced by the atomization of a ULV formulation of fenitrothion with a Micronair AU5000 rotary atomizer. Crop Protection, 1995, 14(1): 27–30.

[14] Dong H M, Zhu Z P, Tao X P, Zhao L, Yan H R. Distribution characteristics of fog droplets from air-cooling fan. Transactions of the CSAE, 2004; 20(2): 118–121. (in Chinese)

[15] Craig I P, Hewitt A, Terry H. Rotary atomiser design requirements for optimum pesticide application efficiency. Crop Protection, 2014; 66:34–39.

[16] Ahmed M, Youssef M S. Influence of spinning cup and disk atomizer configurations on droplet size and velocity characteristics. Chemical Engineering Science, 2014; 107(14): 149–157.

[17] Ru Y, Jin L, Zhou H P, Jia Z C. Performance experiment of rotary hydraulic atomizing nozzle for aerial spraying application. Transactions of the CSAE, 2014; 30(3): 50–55. (in Chinese)

[18] Liu J, Yu Q, Guo Q. Experimental investigation of liquid disintegration by rotary cups. Chemical Engineering Science, 2012; 73(19): 44–50.

[19] Ellwood K R J, Tardiff J L, Alaie S M. A simplified analysis method for correlating rotary atomizer performance on droplet size and coating appearance. Journal of Coatings Technology & Research, 2013; 11(3): 1–7.

[20] Ahmed M, Youssef M S. Characteristics of mean droplet size produced by spinning disk atomizers. Journal of Fluids Engineering, 2012; 134(7): 3412–3427.

[21] Rahimi-Gorji M, Pourmehran O, Gorji-Bandpy M, Ganji D D. An analytical investigation on unsteady motion of vertically falling spherical particles in non-Newtonian fluid by collocation method. Ain Shams Engineering Journal, 2014; 59(2): 531–540.

[22] Mohebi M M, Evans J R G. The trajectory of ink-jet droplets: Modelling and experiment. Chemical Engineering Science, 2005; 60(13): 3469–3476.

[23] Colbert S A, Cairncross R A. A discrete droplet transport model for predicting spray coating patterns of an electrostatic rotary atomizer. Journal of Electrostatics, 2006; 64(3): 234–246.