EXPERIMENT ON SPRAY FLOW FIELD CHARACTERISTICS AND DEPOSITION PERFORMANCE OF CONICAL WIND FIELD ANTI-DRIFT SPRAY
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锥形风场式防飘喷雾流场特性及沉积性能试验研究

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ABSTRACT
Conical wind field anti-drift spray is an innovative form of anti-drift operation using auxiliary air flow, which can resist the generation of vortex, and has the characteristics of reducing the droplets loss with wind at the vertical height. In order to explore the characteristics of spray flow field and droplet deposition performance under conical wind field, the structure and working principle were analyzed based on the basic principle of proton dynamics. Spraytec and PDPA system were used to explore the distribution characteristics of spray flow field. Box-Behnken experimental design was used to analyze the droplet deposition performance. The optimum combination of the working parameters with spray height is 0.46 m, the spray pressure was 0.34 MPa, the conical wind speed was 16.16 m/s, and the droplet deposition amount was 3.39μL·cm^{-2}. The droplet deposition amount was optimal.

摘要
锥形风场式防飘喷雾是利用辅助气流进行防飘作业的一种创新形式，可以抵御绕流涡旋的产生,具有减少雾滴在纵向高度上随风飘失的特性。为探究锥形风场作用下的喷雾流场特性及雾滴沉积性能，基于质子动力学基本定律对其结构和工作原理进行了分析。利用 Spraytec 和 PDPA 系统探究了喷雾流场的分布特点。采用 Box-Behnken 实验设计法分析了各影响因素对雾滴沉积率的影响。最优工作参数为喷雾高度 0.46m，喷雾压力为 0.34MPa，锥风风速为 16.16m/s 时，雾滴沉积量为 3.39μL·cm^{-2}。雾滴沉积量最优。

INTRODUCTION
Atomizing pesticides into fine droplets for spraying is a key link in pesticide application technology (*Zhang et al., 2015; Yang et al., 2012; Zhang et al., 2017*). Droplet size is a key indicator to measure the effect of atomization (*Fritz et al., 2009; Ahmed et al., 2014*). The specific performance is that the smaller the particle size of the droplets, the greater the number, and the more uniform distribution on the leaves, but the risk of evaporative drift and wind drift also increases (*Li et al., 2019*). Therefore, selecting droplets with appropriate particle size is one of the important ways to ensure spray quality. There are many methods to improve the spatial distribution of droplet size, such as electrostatic spray, air-assisted spray, variable spray, etc. (*Liang et al., 2020*). Air-assisted spraying technology improves droplet distribution through directional airflow, increases its deposition rate on the target, and reduces drift (*Yuan et al., 2012*). Currently, air-assisted spraying is mostly used in orchard spraying operations, and air curtains are used in field spraying operations (*Qi et al., 2010*).

The variation law of droplet size, motion characteristics and spatial distribution in gas-liquid two-phase flow field is closely related to droplet drift and deposition behavior (*Zhang et al., 2012; Oliveira et al., 2015*). The mechanism research on the interaction between auxiliary airflow and mist droplets has become a research hotspot in the field of plant protection. The Malvern Spraytec laser particle size analyzer is often used to test the droplet size of agricultural nozzles and analyze their atomization characteristics (*Tang et al., 2016*). *Ru et al.,* (*2016*) also used Spraytec to analyze the droplet size distribution gap between GP-81A series aviation nozzles under wind tunnel conditions and flight conditions. *Yan et al.,* (*2014*) used the Phase Doppler Particle Analyzer (PDPA) to determine the influence of the wind speed and distance at the outlet of the air curtain on the particle size and velocity distribution of the droplets. *Guler et al.,* (*2007*) used PIV to compare the velocity field distributions of standard fan nozzle and the air induction nozzle under wind tunnel conditions. *Sinha et al.,* (*2015*) used PDIA to characterize the spray characteristics from the droplet cone angle and droplet size distribution.

The conical wind field anti-drift spray device has been proved to be a kind of air-assisted auxiliary spray method with excellent anti-drift performance (*Liu et al., 2021*). However, the interaction law between the conical wind field generated by the device and the droplet is still unclear. The size, trajectory and deposition effect of droplets in air-assisted spray are affected by air flow, so the deposition characteristics of droplets affected by air flow should be paid special attention (*Gupta et al., 2012*).

In this paper, according to the theory of proton dynamics, the force model of a single droplet in the moving air medium is established, which is used to describe the action law of the conical wind field on the droplet. The Spraytec Laser Particle Size Analyzer and PDIA were used to establish the droplet spatial size spectrum and reveal the relationship between droplet size distribution and velocity. The optimum combination parameters of droplet deposition were obtained by orthogonal test. This study provides a reference for the application of air-assisted spray technology in the field of plant protection.

MATERIALS AND METHODS

Theoretical analysis of conical wind field anti-drift spray

In order to clarify the anti-drift mechanism of the conical wind field, a Cartesian coordinate system is introduced to establish a schematic diagram of the force of a single droplet under the action of the crosswind and the conical wind field (Fig. 1), and the force of a single droplet is analyzed (without considering the internal force of the droplet group).

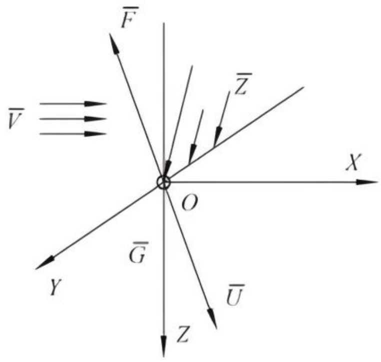


Fig. 1 - The force analysis of droplet under the action of natural wind and conical wind field

Under the combined action of cross wind and conical wind, a moving air medium is formed. The mass and size of a single droplet in it are relatively small, and the interference of the surrounding fluid medium on the droplet can be ignored. Therefore, according to the basic law of proton dynamics, the dynamic equation of the droplet relative to the moving air medium is obtained as

$$m\bar{a} = \bar{F} + \bar{G} \rightarrow m\frac{d\bar{U}}{dt} = \bar{F} + m\bar{g} \tag{1}$$

Where:

a is the droplet acceleration in the flowing air, [m/s^2];
m is the droplet mass, [kg];
U is the relative drift velocity vector, [m/s];
g is the acceleration of gravity, [m/s^2].

According to Euler's method, the resistance F generated by droplet movement in the air medium has a quadratic relationship with the droplet speed (*Pascuzzi et al., 2013; Bulgakov et al., 2018*):

$$F = \frac{mg}{V_{so}^2} \cdot \bar{U}^2 \tag{2}$$

Where: V_{SO} is the average rising speed of droplets, [m^2/s^2].

Equations (1) ~ (2) are combined:

$$\frac{d\bar{U}}{dt} = -\frac{g}{V_{SO}^2} \cdot \bar{U}^2 \cdot \frac{\bar{U}}{|\bar{U}|} + g \tag{3}$$

In the Cartesian coordinate system, the simplified differential equations for the motion of a single droplet are obtained:

$$\begin{cases} \dfrac{d^2x}{dt^2} = -\dfrac{g}{V_{so}^2} \cdot \left|\overline{U}(t)\right| \cdot U_x(t) \\ \dfrac{d^2y}{dt^2} = -\dfrac{g}{V_{so}^2} \cdot \left|\overline{U}(t)\right| \cdot U_y(t) \\ \dfrac{d^2z}{dt^2} = -\dfrac{g}{V_{so}^2} \cdot \left|\overline{U}(t)\right| \cdot U_z(t) + g \end{cases} \tag{4}$$

It can be seen from Equation (4) that the speed of droplets in each direction depends on their relative drift vector when moving in the air. By applying conical wind field, the velocity of droplet in target direction is increased and the ability of resisting crosswind is improved. The purpose of spray operation is to prevent and reduce drift through the above measures. The combined wind field formed by the conical wind and the side wind can reduce the longitudinal height of the vortex generation position and reduce droplet drift when the left side wind intrudes into the spray fan to form a surrounding vortex (Fig. 2).

Fig. 2 - Drift state of droplet group before (a) and after (b) conical wind field is applied in crosswind

Structure and flow field distribution of anti-drift spray device

The conical wind field anti-drift spray device connected with HARDI F-110-03 fan nozzle (Fig. 3) was selected for the experiments.

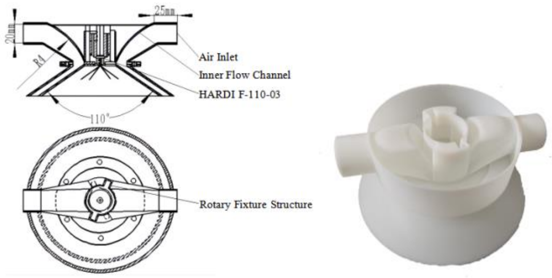


Fig. 3 - Conical wind field anti-drift spray device

The application form of the auxiliary airflow has a significant influence on the droplet motion characteristics (*Hu et al., 2020*). The flow field distribution of the conical wind field anti-drift spray device was simulated (Fig. 4) with the method described in the research of Liu et al., (*2021*).

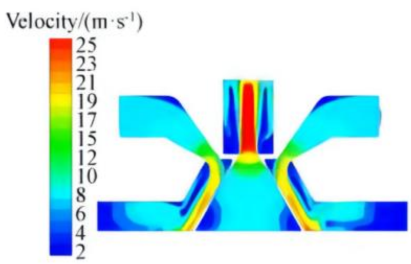


Fig. 4 - Flow field distribution of the conical wind field anti-drift spray device

In order to ensure the stable deposition of droplets on the target, the airflow should meet the final velocity principle (*Hu et al., 2020*). According to the velocity field at the outlet of the device, the conical wind speed is set as five gradients: 0 m/s, 10 m/s, 15 m/s and 20 m/s.

Experimental instruments and conditions of spray flow field

In order to verify the theoretical analysis and explore the influence of conical wind field on droplets, spray experiments were carried out in the Research Center of Plant Protection Machinery and Application Technology (CCAT) of China Agricultural University, Beijing, China. The Laser Particle Size Analyzer Spraytec by Malvern Co., Ltd was used to measure the droplet spatial particle size spectrum (Fig. 5a), and the Droplet Image Analyzer VisiSize P15 (PDIA) by Oxford Lasers Co., Ltd was used to measure the droplet velocity distribution (Fig. 5b).

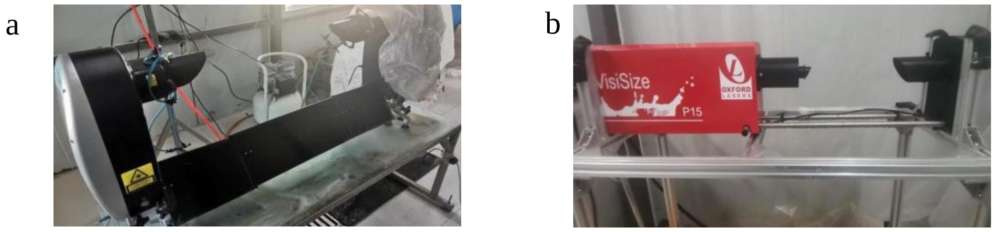


Fig. 5 - Malvern Laser Particle Size Analyzer Spraytec (a), Droplet Image Analyzer VisiSize P15 (b)

The experiment was conducted on November 23, 2020. The temperature was 23°C, and there was no wind during the experiment.

Experimental method design of spray flow field

As the pretest showed that the effective range of the conical wind field acting on droplets effectively was 200 mm beyond the nozzle, the droplets were measured by the method shown in Figure 6.

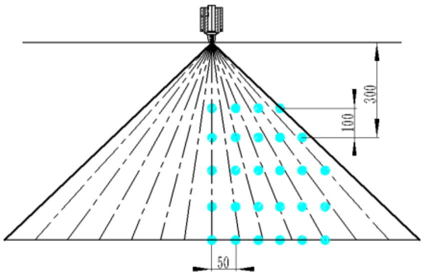


Fig. 6 - Sampling point of spray flow field

For the particle size distribution test, the test nozzle was selected as HARDI F-03-110 fan nozzle, the air supply device was a KOMAX Fan (with duct), the spray liquid was tap water, the spray pressure was 0.3 MPa, and the test index was Dv50. Dv50 also called Volume Median Diameter (VMD), is the droplet diameter when 50% of the spray volume is contained in droplets of lesser diameter. The position where the droplets are easy to drift away is concentrated at the central axis 300-500 mm away from the nozzle (*Song et al., 2011*). For the velocity distribution test, the spray height is selected from 300 mm, 400 mm, 500 mm below the central axis of the nozzle, the spray pressure is 0.3 MPa, 0.4 MPa, and the conical wind speed is 0 m/s, 10 m/s, 15 m/s, 20 m/s. To ensure the accuracy of the test results, each test was repeated 3 times and the average value was taken as the final test result.

Experimental method design of spray deposition test

The conical wind field anti-drift spray device was mounted on the self-propelled plant protection spray truck for orthogonal test, as shown in Fig. 7.

Fig. 7 - Outdoor test of conical wind field anti-drift spray device

The rectangular area formed by soybean plants was selected as the test area, in which the water-sensitive paper was distributed on the top and bottom and overlapped on the soybean plants as far as possible, with a spacing of 300 mm. Model of nozzle was HARDI F-03-110 fan-shaped nozzle; Spray liquid: tap water; Spray pressure: According to the experimental conditions of each group; The amount of droplet deposition (μL·cm^{-2}); Ambient wind speed: 3 m/s (The average wind speed during the test and the wind direction during the test period is generally consistent); Locomotive speed: 2 m/s (Keep constant).

RESULTS

The effect of droplet spatial particle size spectrum

The VMD of the droplets under each conical wind speed obtained according to the test plan are shown in Table 1, and the spatial particle size spectrum of the droplets are shown in Fig. 8.

Table 1

VMD of the droplets under different conical wind speed

Conical wind speed v/(m·s^{-1})	y/mm	x/mm					
		0	50	100	150	200	250
		VMD/μm					
0	200	148.4	157.3	165.4	169.6	-	-
	300	155.5	162.8	172.3	180.1	188.2	-
	400	159.6	171.8	180.4	189.2	197.4	205.4
	500	165.3	179.7	188.3	196.4	203.6	211.7
	600	176.2	189.3	196.5	202.5	213.7	220.6
10	200	146.9	155.6	163.1	166.6	-	-
	300	150.3	158.3	167.4	178.1	186.1	-
	400	156.4	165.4	174.0	182.2	191.0	198.3
	500	160.7	169.2	179.3	186.0	194.6	203.4
	600	169.8	176.7	187.5	193.6	204.5	212.6
15	200	144.0	152.3	161.0	164.4	-	-
	300	148.1	155.5	165.5	175.6	181.0	188.2
	400	153.4	161.1	168.2	178.5	185.7	192.4
	500	156.3	165.2	173.7	181.7	188.0	198.3
	600	165.5	172.4	182.3	188.2	195.8	208.2
20	200	143.1	153.4	162.4	163.2	-	-
	300	146.3	154.3	163.0	175.3	180.2	187.3
	400	152.7	162.5	166.6	176.4	184.6	193.2
	500	154.4	164.1	175.5	180.6	186.4	197.1
	600	163.6	171.2	183.0	187.1	193.6	206.0

It can be seen from Fig. 8 that under the same spray pressure (0.3 MPa), the VMD of droplets are negatively correlated with the conical wind speed. At 500 mm below the nozzle, the mean VMD of droplets decreases by 8.63 μm when 10 m/s conical wind is applied. The VMD of droplets decreased by 5.00 μm on average when the conical wind speed increased from 10 m/s to 15 m/s. But the VMD of droplets decreases only by 1.45 μm, which remains basically unchanged when the conical wind speed increased from 15 m/s to 20 m/s.

Since the nozzle used in this paper is a liquid pressure type, without applying auxiliary wind field, the droplet size distribution and flow velocity are determined by the nozzle aperture and spray pressure, that is, the liquid pressure is the dominant driving force for the atomization. The conical wind field applied in this paper provides additional aerodynamic force for liquid atomization and aggravates the atomization of droplet fragmentation by overcoming the droplet surface tension. An excessively large conical wind field will cause the droplets to collide or even merge, which explains the VMD of droplets located certain areas increase in Table 1.

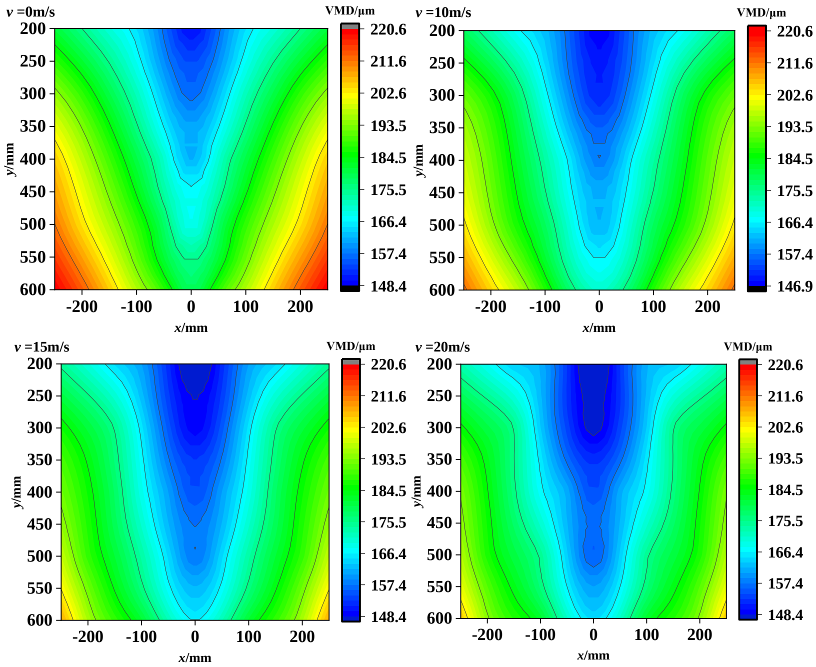


Fig. 8 - The spatial particle size spectrum of the droplets

It can be seen from Table 2 that the overall trend of the change of the average velocity of the droplets decreases with the increase of the spray height, which is caused by the resistance of the droplets during the falling process, and the velocity is constantly attenuated. At the same spray height, the average velocity of droplets increases with the increase of spray pressure, which is due to the large initial kinetic energy of droplets generated under the conditions of high spray pressure.

Table 2

Experiment factor level and coded value

Coded value	The spray height (m)	The spray pressure (MPa)	The conical wind speed ($m \cdot s^{-1}$)
-1	0.450	10	0.2
0	0.475	15	0.3
1	0.500	20	0.4

Under the influence of the conical wind field, the decrease of the average velocity of the droplets show a downward trend with the decrease of the spray pressure. At the distance of about 350 mm from the spray height, the influence of the conical wind on the average velocity of the droplets exceeds the spray pressure.

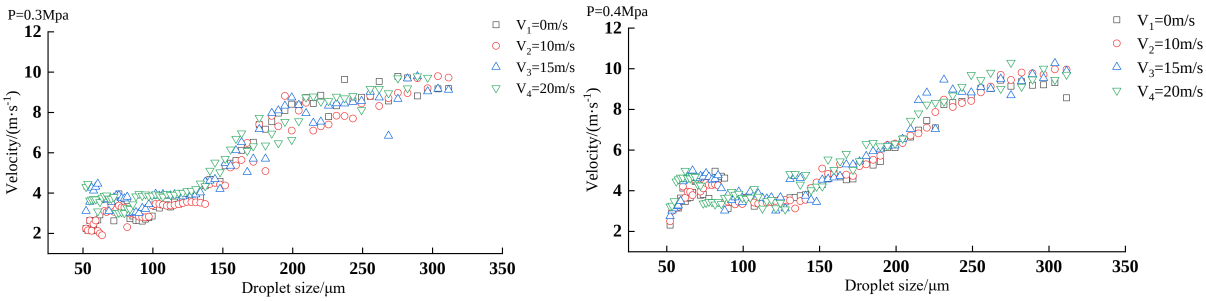


Fig. 9 - Velocity distribution of the droplets under different conical wind speed and spray pressure

The droplet movement speed in the range of 50-150 μm particle size increases obviously with the application of the conical wind field when the spray pressure is 0.3 MPa, which indicates that the droplet speed in this part of the particle size range is related to the conical wind field. The acceleration effect of the conical wind field on this part of the droplets is not obvious when the droplet size is in the range of 150-200 μm. The main body of the conical wind field acting on the movement of the droplet group is 50-150 μm. This is similar to the data law when the spray pressure is 0.4 MPa.

The experiment method and result

This paper uses Box-Behnken as a test method, the amount of droplet deposition as the assessment index. The paper sets out a series of experiments on the spray height (the level value X_1, the coded value x_1), the spray pressure (the level-value X_2, the coded value x_2), the conical wind speed (the level-value X_3, the coded value x_3). The level-value and the coded value of the experiment elements are shown in Table 2. The experimental scheme and the results are shown in Table 3.

Table 3

Experiment factor level and coded value

No.	The spray height, x_1 (m)	The spray pressure, x_2 (MPa)	The conical wind speed, x_3 (m·s^{-1})	The amount of droplet deposition, Y（μL·cm^{-2})
1	-1	-1	0	2.71
2	1	-1	0	2.51
3	-1	1	0	3.32
4	1	1	0	2.87
5	-1	0	-1	3.01
6	1	0	-1	2.68
7	-1	0	1	3.39
8	1	0	1	3.01
9	0	-1	-1	2.01
10	0	1	-1	3.03
11	0	-1	1	2.94
12	0	1	1	2.87
13	0	0	0	3.24
14	0	0	0	3.25
15	0	0	0	3.23
16	0	0	0	3.12
17	0	0	0	3.17

The regression model

This research imports the experimental data in Design-Expert 10.0 to make a regression fit, which sets up the regression model of the broken-tea ratio and the assessment index of the sensory evaluation score from different elements, as shown in Eq.(5).

After getting rid of the non-distinctive regression items, the regression model of the broken-tea ratio and the sense assessment index is shown in Eq.(6):

$$\begin{aligned} Y &= 3.20 - 0.17x_1 + 0.24x_2 + 0.19x_3 - 0.063x_1x_2 \\ &+ 0.013x_1x_3 - 0.27x_2x_3 - 0.020x_1^2 + 0.33x_2^2 - 0.16x_3^2 \end{aligned} \tag{5}$$

$$\begin{aligned} Y &= 3.20 - 0.17x_1 + 0.24x_2 + 0.19x_3 \\ &- 0.27x_2x_3 + 0.33x_2^2 - 0.16x_3^2 \end{aligned} \tag{6}$$

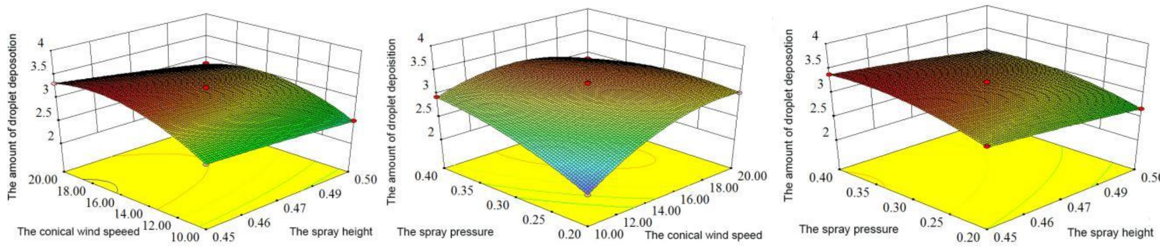
Analysis of the effect of experimental factors

In the regression equation, one element with the factor level o is randomly selected, and the remaining two elements are studied to find out their influence on amount of droplet deposition. The software Design-Expert 10.0 is used to make an analysis to get the response hook face affected by the interaction factors, as shown in Fig. 10.

In Fig. 10 a), this paper finds that if the spray pressure is fixed, the amount of droplet deposition increases first and then decreases with the increase of conical wind speed. With the increase of spray height, the amount of droplet deposition is more suitable in the range of conical wind speed 14 ~ 18 m/s and spray height 0.45 ~ 0.47 m.

In Fig. 10 b), if the spray height is fixed, the amount of droplet deposition increases with the increase of conical wind speed and spray pressure. The amount of droplet deposition is more suitable in the range of conical wind speed 14 ~ 18 m/s and spray pressure 0.27 ~ 0.35 MPa. In this case, the contour lines of the response surface are closed ellipses, indicating that the interaction between conical wind speed and spray pressure is strong and has a maximum value.

In Fig. 10 c), if the conical wind speed is fixed, the droplet deposition increases first and then decreases with the increase of spray pressure. With the increase of spray height, the amount of droplet deposition is more suitable in the range of conical wind speed 14 ~ 18 m/s and spray pressure 0.27 ~ 0.35 MPa. The above analysis is consistent with the significance shown in Eq.(6).



a) $Y=f(x_1, 0, x_3)$ b) $Y=f(0, x_2, x_3)$ c) $Y=f(x_1, x_2, 0)$

Fig. 10 - Response surfaces of interactive factors influence on test indexes

The optimization model and the experimental verification

Based on the working performance demand and the actual working condition of the conical wind field anti-drift spray device, this work plans to succeed in the lower conical wind speed, the higher amount of droplet deposition. According to the different elements having different effects, this paper needs to optimize all results. This paper regards amount of droplet deposition as an objective function, makes the optimization design to 3 experimental elements, including the rotating speed of conical wind speed, the spray height and the spray pressure.

The optimization constraint conditions can be conducted as follows:

$$\begin{cases} \max Y \\ s.t. \begin{cases} X_1 \in (0.43, 0.49) \\ X_2 \in (0.25, 0.35) \\ X_3 \in (14.00, 18.00) \end{cases} \end{cases} \tag{7}$$

The influence laws of three experimental factors affecting the amount of droplet deposition is comprehensively considered to get the best parameter combination, using Design-Expert 10.0 software to make an optimization solution. This research gets the optimum working parameter combination, the spray height being 0.46 m, the spray pressure being 0.34 MPa, the conical wind speed being 16.16 m/s, the amount of droplet deposition being 3.39 $\mu L \cdot cm^{-2}$.

In order to use the optimum parameter combination in the actual spray operation, this paper makes the round number of them, the spray height is 0.45 m, the spray pressure is 0.35 MPa, the conical wind speed is 16.00 m/s, 3 repetitive tests are made to get the average value, the amount of droplet deposition is 3.36 $\mu L \cdot cm^{-2}$ which means the experimental results keep an accord with the theoretical results substantially, thus the regression model is good.

CONCLUSIONS

In this paper, the characteristics of spray flow field and droplet deposition of the conical wind field anti-drift spray device are investigated experimentally. The results clearly show that the conical wind field can significantly improve the spatial distribution of droplets, and the optimal combination obtained from the experiment can provide a basis for field spraying operation.

(1) The conical wind field improves the spatial distribution of droplets by intensifying droplet fragmentation and suppressing the entrainment of small droplets. However, when the conical wind speed increases to a certain extent, its effect on the particle size of the droplets to promote the fragmentation will become small or even have no effect.

(2) The conical wind field has a significant effect on the droplet group of 50-150 μm. The average velocity of droplets is positively correlated with spray pressure and conical wind speed, and it decreases continuously with the decrease of height. The research results shows that the conical wind field can supplement the kinetic energy of the small droplets that are easy to drift away, which is helpful for the droplets to settle.

(3) The Box-Behnken was introduced to design the experimental methods, regarding the spray height, the spray pressure, the conical wind speed as the experimental elements, and regarding the amount of droplet deposition as the test indexes, making the series experiments on the operation parameter of the conical wind field anti-drift spray device, finding out that the optimum working parameter combination is the spray height of 0.45 m, the spray pressure of 0.35 MPa, the conical wind speed of 16.00 m/s, and the amount of droplet deposition being 3.39μL·cm^{-2} .

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