Wind tunnel experimental study on droplet drift reduction by a conical electrostatic nozzle for pesticide spraying

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Abstract: Droplet drift wastes pesticide, pollutes the environment, and has become one of the focus issues of agricultural crop protection. Electrostatic spray technology reduces drift to a certain degree. In order to investigate the droplet drift pattern of a conical electrostatic nozzle, the droplet drift mass center distance was defined as an experimental index and used to conduct experimental wind tunnel studies on droplet drift. A mathematical model of the droplet drift mass center distance versus electrostatic voltage and wind speed was created via the regression method. The test results showed that the electrostatic voltage had an insignificant effect on droplet drift, the wind speed and its interaction with the electrostatic voltage had significant effects on droplet drift. When the wind speed was less than 3 m/s and stable, the crop adsorbability of a droplet had a dominant effect on the droplet drift; the droplet drift decreased with the increase of electrostatic voltage. When the wind speed exceeded 3 m/s and was stable, the reduced droplet particle size had a dominant effect on droplet drift, where droplet drift increased as the electrostatic voltage increased. When the wind speed was 0 m/s and the electrostatic voltage was 12 kV, the minimum droplet drift mass center distance was 35.5 mm, which was 56 mm less than that of conventional nozzle droplet drift. Therefore, a conical electrostatic nozzle is inapplicable for operation in an environment where wind speeds exceed 3 m/s. This study provides a reference for optimizing operational parameters of conical electrostatic nozzles and improving the anti-drift capability of droplets.

Keywords: pesticide spraying, conical electrostatic nozzle, droplet drift, wind tunnel, experimental study, electrostatic sprayer
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1 Introduction

During pesticide spraying, movement of pesticide particles or droplets toward non-target areas driven by airflow is called drift. Droplet drift not only wastes pesticide and affects the prevention effect[1,2] but also pollutes the environment[3,4]. Currently, the government requires "pesticide reduction" for agricultural crop protection operation. Therefore, droplet drift has become an important issue in agricultural crop protection operation and requires attention[5].

Currently, the wind tunnel test is widely used in studies on droplet drift worldwide. A wind tunnel test can simulate field operation and accurately control

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parameters, such as the wind speed. Additionally, the test results provide excellent references for practice[6].

There are numerous factors that cause droplet drift, such as the droplet particle size, pesticide solution concentration, nozzle type, spray pressure, and climatic condition[7-9]. Researchers worldwide have conducted a large number of studies on droplet drift. Fritz et al.[10] obtained droplet drift patterns for various types of nozzles in a wind tunnel via tests. To reduce droplet drift and the application dosage of pesticides, Qiu et al.[11] developed a targeting air-assisted (TAA) sprayer and compared it with conventional air-assisted (CAA) sprayers. The results showed that the sizes of droplet increased at opening and closing moments during TAA spray, which could reduce droplet drift. Hewitt et al.[12] integrated geographic information system (GIS) technology with an aviation drift model to reduce the number of pesticide droplets being deposited in a non-target area. In the area of aviation crop protection technology research, Salyani[13] created a mathematical model to calculate the drift distance of spray droplets from a fixed wing airplane under different wind speeds. Nuyttens et al.[14] created a droplet drift forecast model that contains meteorological parameters, which provided a reference for research on droplet drift. Currently, the particle size of a droplet produced by low-drift nozzles developed in other countries, e.g., the front hole and mixed-flow chamber nozzles from the United States, is approximately 40% larger than that produced by a standard fan-shaped spray nozzle, which significantly reduces droplet drift[15,16]. Wang et al.[17] studied the effect of different additives and concentrations on nozzle droplet drift, the results showed that when the anti-drift additives Silwer SRS-60, Break-thru Vibrant, and Greenwet 360 were mixed at volume fractions of 0.8%, 0.6% and 0.3%, respectively, the corresponding anti-drift effect was optimal, these provided a theoretical evidence for the development of new anti-drift additives. Xue et al.[18] studied the drift and deposition of low volume and ultra-low application by an unmanned aerial vehicle (UAV) in paddy field. The results showed that the 90% drifting droplets were deposited within a range of 8 m of the target area.

Huang et al.[19] investigated droplet size and deposition characteristics of a low drift CP flat-fan nozzle at different application altitudes. Jiang et al.[20] studied the influencing rules of fan frequency, nozzle angle, and vertical and horizontal distances between the nozzle and air curtain outlet on air curtain sprayer drift in an enclosed, spacious indoor environment, the results showed that the nozzle spray angle had a significant effect on the drift rate, whereas the fan frequency and the vertical and horizontal distances between the nozzle and air curtain outlet had insignificant effects on the drift rate. To investigate pesticide droplet drift under airflow, Dong et al.[21] performed a three-dimensional numerical simulation on the spray field under air flow via FLUENT software and analyzed the effects of different air flow directions on droplet drift.

The above researches demonstrated that although droplet drift could not be avoided, droplet drift could be reduced via certain methods, such as changing the nozzle type, applying airflow, or using an air curtain. However, these methods also led to larger-sized droplet particles and wider spray spectra[22,23]. By comparison, electrostatic spray technology has the advantages such as small-sized droplet particles and a uniform distribution of the spray group[24]. He et al.[25] installed an electrostatic nozzle on orchard sprayers and performed field tests, the test results showed that electrostatic spray technology could reduce pesticide consumption by 50%-70%. Kirk et al.[26] performed a field test using electrostatic spray technology and demonstrated that compared with conventional spray technology, electrostatic spray technology reduced droplet drift by 20%-30%. Hu et al.[27] reported that the electrostatic conical spray nozzle had a uniform distribution of the spray group and less than 10% errors in the flow rate and spray angle. Zhang[28] reported that the charge-mass ratio of a droplet from a conical electrostatic nozzle could reach 0.79 mC/kg. Electrostatic droplets from a conical electrostatic nozzle exhibit crop adsorbability, which reduces droplet drift in theory. However, compared with a conventional nozzle, droplets from an electrostatic nozzle are small, and the small size will increase droplet drift. Therefore, this paper investigates the effects of electrostatic voltage and wind speed on the conical electrostatic nozzle drift rule via a wind tunnel test bed, which provides reference for the application of a conical electrostatic nozzle.

2 Materials and methods

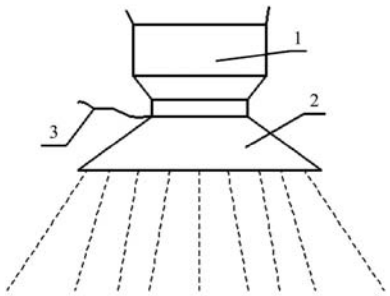
2.1 Test condition

In the test, for safety reasons, pesticide solution was replaced by water for the drift tests. During the tests, the indoor temperature was 20°C, and the humidity was 70%. The conical electrostatic nozzle rated pressure was 0.3 MPa at a flow rate of 0.47 L/min, and the nozzle spray duration in each test was 5 min.

2.2 Test equipment and measurement devices

The test and measurement system includes an electrostatic spray system, a wind tunnel test bed, a wind temperature/speed meter, and an electronic scale. The wind tunnel test bed (Haiguang Enterprise Corporation, Shanghai, China) can generate a stable airflow field with an internal test space of 3.38 m (length)×0.76 m (width)× 0.80 m (height). The wind temperature/speed meter (model AS836, Smart Sensor Co., Ltd.) can test the wind speed and lab temperature with a measuring accuracy of ±2% at minimum scale of 0.01 m/s and 0.1°C. The electronic scale (model 2204, Shanghai Zhuojing Electronics Co. Ltd.) can measure the mass of collected spray with a measuring accuracy of 0.1 mg at a range of 0-220 g.

The conical electrostatic nozzle was primarily composed of a TR80-015C conical spray nozzle (LECHLER, Germany) and conical charge electrodes, as shown in Figure 1.



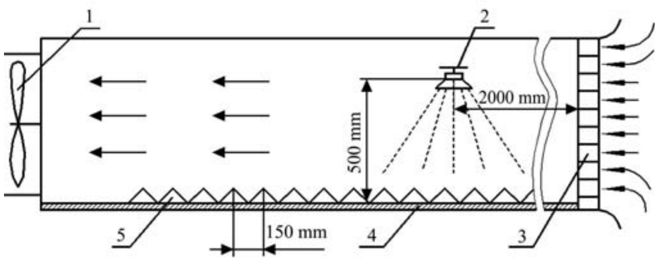
1. TR80-015C nozzle 2. Conical electrostatic electrode 3. Electrode wire

Figure 1 Electrostatic spraying nozzles

2.3 Test procedure and index

2.3.1 Test procedure

The test layout is shown in Figure 2. To prevent errors caused by droplet splash, the wind tunnel bottom was covered with a layer of artificial grass[29]. The nozzle was positioned 2 m from the honeycomb air inlet horizontally and 0.5 m from the artificial grass blanket[30]. A V-shaped polyvinyl chloride (PVC) spray collector is installed under the nozzle to collect the spray droplets. Each V-shaped spray collector was leaned slightly against the horizontal plane to ensure that the spray droplets are collected at one side of each V-shaped spray collector[31]. At the collecting side of each V-shaped spray collector, open circular plastic bottles (from left to right, the numbers are 1,2,3…20) were installed to collect the spray droplets, and the spray droplet mass in each bottle was measured. Each test was repeated three times, and the average was used as the final test result.



Note: 1. Fan 2. Electrostatic nozzle 3. Honeycomb air inlet 4. Artificial grass blanket 5. Droplet collector

a. Wind tunnel experimental layout

b. Site layout of droplet drift experiment

Figure 2 Droplet drift experiment

2.3.2 Test index

In the case of the droplet drift test index, according to existing research results, the droplet drift mass center distance reflects the droplet mass center and overall droplet drift. Therefore, based on the method by Li et al.[32] in their study of the anti-drift effect of a vineyard vertical tube air-carrier sprayer, the droplet drift mass center distance was selected to represent the droplet drift intensity. The following formula is used to calculate the droplet drift mass center distance:

$$D = \frac{\sum_{i=1}^{n} m_i \cdot d_i}{\sum_{i=1}^{n} m_i} \quad (1)$$

where, D is the droplet drift mass center distance, mm; i is the spray collector identifier (i=1, 2, 3, 4…20); n is the total number of spray collectors; m_i is the spray droplet mass in the i^{th} spray collector, g; di is the horizontal distance between the center of the i^{th} spray collector and the nozzle, mm.

Equation (1) shows that a smaller droplet drift mass center distance D indicates a shorter droplet drift distance and better nozzle anti-drift capability.

2.4 Test design

To study the effects of electrostatic voltage and wind speed on droplet drift for a conical electrostatic nozzle during a spray process, tests were performed based on the quadratic orthogonal rotational regression method. Based on the actual meteorological condition of operation, crop protection operation requires a temperature less than 26°C, a humidity level exceeding 65%, and a wind speed less than 4 m/s. Because electrostatic droplets exhibit crop adsorbability, to ensure the accuracy of the test result, the wind speed was set to 0-6 m/s, and the electrostatic voltage was set to 0-12 kV. The factor levels are listed in Table 1.

Table 1 Factors and levels of the test design

Canonical variables	Electrostatic voltage X_1/kV	Wind speed X_2/m·s^{-1}
Upper asterisk arm 1.414	12	6
Upper level 1	10.2	5.12
Zero level 0	6	3
Lower level –1	1.8	0.88
Lower asterisk arm –1.414	0	0
Varying spacing	4.2	2.12

3 Results and analysis

Based on the quadratic orthogonal rotational regression combination design, 16 groups of factor tests were performed, which included eight groups of zero-level tests[33]. The test scheme and results are listed in Table 2.

3.1 Regression model construction

The regression analysis of Table 2 was performed via the "enter" approach in SPSS software to obtain the analysis results of the equation coefficients as shown in Table 3.

Table 2 Experimental scheme and results

No.	X_1	X_2	Electrostatic voltage/kV	Wind speed /m·s^{-1}	Droplet drift mass center distance Y/mm
1	1	1	10.2	5.12	573.75
2	1	－1	10.2	0.88	243.58
3	－1	1	1.8	5.12	494.36
4	－1	－1	1.8	0.88	318.54
5	1.414	0	12	3	511.36
6	－1.414	0	0	3	438.33
7	0	1.414	6	6	618.39
8	0	－1.414	6	0	68.57
9	0	0	6	3	483.28
10	0	0	6	3	484.48
11	0	0	6	3	483.64
12	0	0	6	3	481.90
13	0	0	6	3	479.53
14	0	0	6	3	479.01
15	0	0	6	3	480.16
16	0	0	6	3	481.59

Table 3 Analysis results of the equation coefficients

Model	Unstandardized coefficient		Standardized coefficient	t	*Sig.*
	B	Standard error	trial version		
(constant)	445.029	8.093		54.986	0
X_1	13.464	11.447	0.074	1.176	0.267
X_2	160.454	11.447	0.886	14.017	0
X_1'	–3.828	11.446	–0.021	–0.334	0.745
X_2'	–69.511	11.446	–0.384	–6.073	0
$X_1 X_2$	38.587	16.187	0.151	2.384	0.038

The equation coefficient analysis result shows that when the significance level is α=0.05, the wind speed, wind speed quadratic term, and interaction between electrostatic voltage and wind speed have a significant effect on the droplet drift mass center distance, whereas the effect of the electrostatic voltage on the droplet drift mass center distance is insignificant.

Therefore, based on Table 3, the standard regression equation for the significant factor is

$$Y = -69.511X_2' + 38.587X_1X_2 + 160.454X_2 + 445.029 \quad (2)$$

Table 4 (analysis of variance for Equation (2)) was obtained via regression analysis.

Table 4 shows that Equation (2) is significant when α=0.05. Equation (2) is subjected to dimensional transformation to obtain the dimensional regression equation as follows:

$$\hat{y} = -15.466x_2^2 + 4.334x_1x_2 - 13.002x_1 + 142.478x_2 + 191.545 \quad (3)$$

Lack-of-fit verification for the regression equation leads to F_{Lf}=0.384<$F_{0.1}$(3,7)=3.07. The test result showed that the lack-of-fit was insignificant; the regression equation fit the actual situation well.

Table 4 Analysis of variance (ANOVA) for Equation (2)

Model	Quadratic sum	*df*	Mean square	*F*	Sig.
Regression	252 108.937	5	50 421.787	48.109	0a
Residual	10 480.687	10	1 048.069		
Sum	262 589.625	15			

Note: a. predictor variable: (constant), X_1X_2, X_2^2, X_1^2, x_2, x_1; b. dependent variable: droplet drift mass center distance *Y*.

3.2 Analysis of the single-factor effect

3.2.1 Analysis of the effect of electrostatic voltage on drift

Regression Equation (3) is subjected to the dimension reduction process. With a wind speed of 0 m/s, the regression equation of electrostatic voltage versus drift is:

$$\hat{y} = -13.002x_1 + 191.545 \quad (4)$$

The variation curve of the droplet drift mass center distance versus electrostatic voltage plotted via MATLAB software is shown in Figure 3.

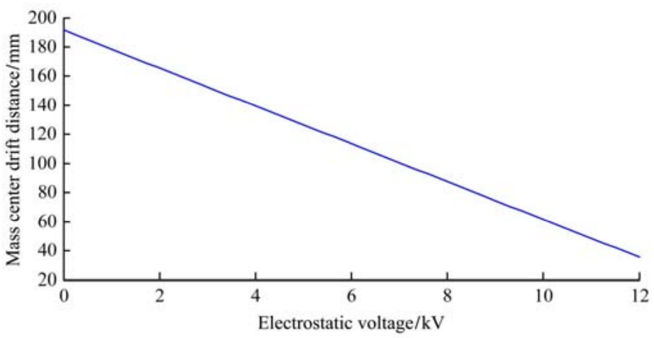


Figure 3 Effect of electrostatic voltage on droplet drift

Figure 3 shows that when the wind speed is 0 m/s, the droplet drift mass center distance decreases as the electrostatic voltage increases because with the increase in electrostatic voltage, the droplet charge-mass ratio increases, and the electrostatic interaction with the target crop increases, which reduces droplet drift.

3.2.2 Analysis of the effect of wind speed on drift

Regression Equation (3) is subjected to the dimension reduction process. With the electrostatic voltage set to 0 V, the regression equation for wind speed versus drift is:

$$\hat{y} = -15.466x_2^2 + 142.478x_2 + 191.545 \quad (5)$$

The variation curve of droplet drift versus wind speed plotted using MATLAB software is shown in Figure 4.

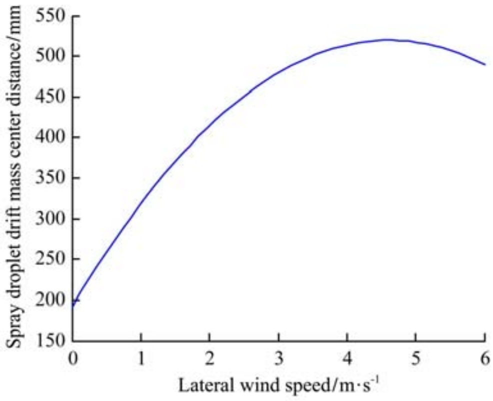
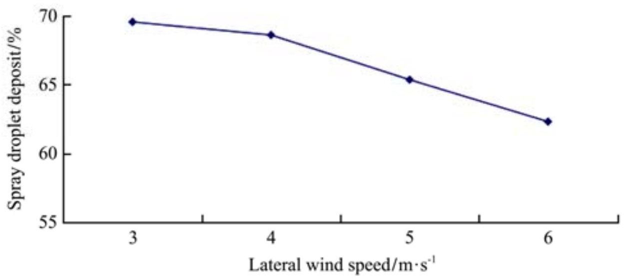


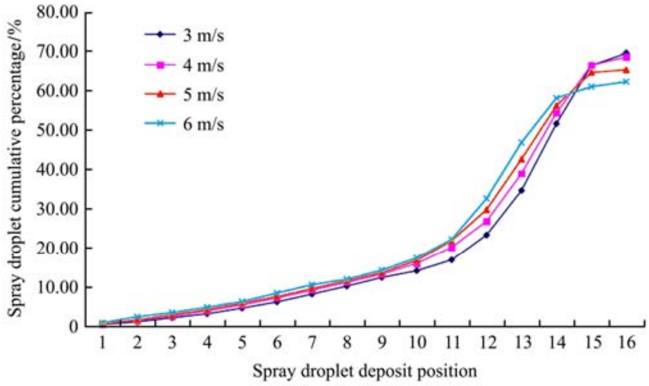
Figure 4 Effect of wind speed on droplet drift

Figure 4 shows that when the electrostatic voltage is 0 kV, the droplet drift mass center distance increases as the wind speed increases when the wind speed is less than 4.6 m/s; however, when the wind speed exceeds 4.6 m/s, the droplet drift mass center distance decreases as the wind speed increases. Considering the constraint of the test bed spatial dimension, the hypothesis is that when the wind speed exceeds 4.6 m/s, the drift distance of a large number of droplets under that particular wind speed exceeds the test bed dimension, which decreases the droplet drift mass center distance. To verify this hypothesis, an additional test is performed. The method measured the number of droplet deposits in the test table after 5 min under an electrostatic voltage nozzle of 0 kV with wind speeds of 3 m/s, 4 m/s, 5 m/s and 6 m/s. The test results are shown in Figure 5.

Figure 5a shows that when the wind speed is less than 4 m/s, the droplet deposits in the test bed vary slightly, and the droplet drift variation for the conical electrostatic nozzle is insignificant. When the wind speeds are 5 m/s and 6 m/s, the number of droplet deposits in the test bed reduces significantly. This result indicates that a large number of droplets drift away from the test bed when the wind speed increases, and the droplet drift of the conical electrostatic nozzle begins to increase. Figure 5b shows that when the wind speed at the left end increases, the number of droplet deposits in the test bed also increases; furthermore, the number of droplet deposits gradually reduces as the wind speed increases, which proves that the aforementioned hypothesis is correct.



a. Droplet deposits in the test bed under different wind speeds



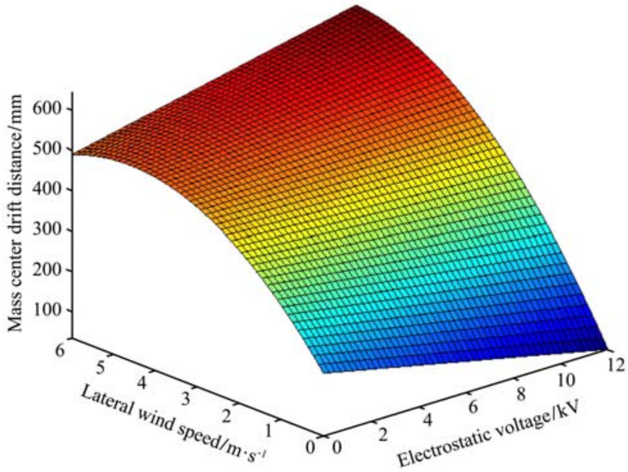
b. Droplet cumulative percentage at different positions

Figure 5 Effect of wind speeds on deposition

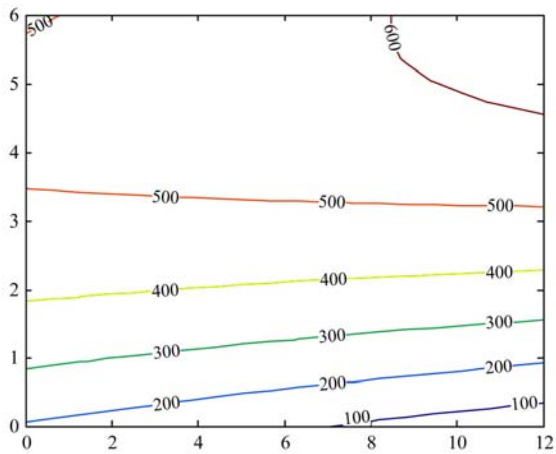
3.3 Dual-factor effect analysis

To analyze the effect of the interaction between the electrostatic voltage and wind speed on droplet drift, a dual-factor response surface is created using MATLAB software, as shown in Figure 6.

Analysis of Figure 6 shows that wind speed is the primary influencing factor of droplet drift, whereas the effect of electrostatic voltage on droplet drift is insignificant. However, the interaction between the two factors has a significant impact on droplet drift, and when the wind speed is 3 m/s, the electrostatic voltage has no effect on droplet drift. As the electrostatic voltage increases, the droplet charge-mass ratio, adsorbability, and anti-drift capability all increase, and furthermore, an increase in the electrostatic voltage also results in a smaller droplet particle size that may lessen the anti-drift capability. When the wind speed is fixed at a value less than 3 m/s, the droplet drift intensity decreases as the electrostatic voltage increases. This shows that at this moment, the effect of a droplet's crop adsorbability on droplet drift exceeds the effect of droplet particle size on droplet drift; the effect of a droplet's crop adsorbability on droplet drift is dominant. When the wind speed is a fixed value greater than 3 m/s, the droplet drift intensity increases with the increase of the electrostatic voltage, the droplet particle size shrinks, and the effect of wind speed increases. These results demonstrate that at this moment, the effect of droplet particle size on droplet drift exceeds the effect of a droplet's crop adsorbability on droplet drift; the effect of decreased droplet particle size on droplet drift is dominant.



a. Response surface of droplet drift to electrostatic voltage and wind speed



b. Isoclines of droplet drift

Figure 6 Effects of electrostatic voltage and wind speed on droplet drift

4 Model verification and model solution

To verify the validity of the above regression equation, a verification test was performed. Each test was performed three times, and the results were averaged. The obtained theoretical results and test results are listed in Table 5.

Table 5 Comparison of theoretical versus test results

No.	Electrostatic voltage/kV	Wind speed /m·s^{-1}	Theoretical result	Test result	Relative error
1	7	2	384.30	394.35	2.55%
2	8	3	479.78	485.34	1.14%
3	9	4	553.17	551.94	0.19%

Table 5 shows that the relative error between the theoretical results from the regression model and test results does not exceed 3%. Therefore, the regression model is reliable.

To ensure minimum electrostatic droplet drift, an optimal solution for the regression equation is obtained via a planning solution: when the wind speed is 0 m/s and the electrostatic voltage is 12 kV, the droplet drift mass center distance is 35.5 mm. When the wind speed is 3 m/s, the electrostatic voltage has no effect on droplet drift. At this moment, the droplet drift mass center distance is 478.8 mm. When the wind speed exceeds 3 m/s, an increase in the electrostatic voltage increases the droplet drift mass center distance. Therefore, the conical electrostatic nozzle is inapplicable for operation in any environment where the wind speed exceeds 3 m/s.

Based on the above analysis, electrostatic droplets from a conical electrostatic nozzle exhibit reduced drift and enhanced crop adsorbability under certain conditions. This aligns with the result of a pneumatic electrostatic sprayer performance test performed by Jia et al[34].

5 Conclusions

In this study, to investigate the effects of electrostatic voltage and wind speed on the drift of droplets from a conical electrostatic nozzle, the droplet drift mass center distance was defined as an index; a quadratic orthogonal rotational regression test was performed in a wind tunnel test bed. The following conclusions are obtained:

(1) A regression model of the electrostatic voltage and wind speed versus droplet drift mass center distance is obtained via regression. The effect of the electrostatic voltage on droplet drift is insignificant, whereas the effects of wind speed and its interaction with the electrostatic voltage on droplet drift are significant.

(2) When the wind speed is a fixed value of less than 3 m/s, the effect of a droplet's crop adsorbability on droplet drift is dominant; droplet drift decreases as the electrostatic voltage increases. When the wind speed is a fixed value greater than 3 m/s, the effect of reduced droplet particle size on droplet drift is dominant, where droplet drift increases as the electrostatic voltage increases.

(3) When the wind speed is 0 m/s and the electrostatic voltage is 12 kV, the droplet drift mass center distance reaches a minimum of 35.5 mm, which is 65 mm smaller than the droplet drift of a conventional nozzle. When the wind speed exceeds 3 m/s, droplet drift increases with increasing electrostatic voltage. Therefore, the conical electrostatic nozzle is inapplicable for operation in any environment where the wind speed exceeds 3 m/s.

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