The Effects of Lateral Wind and Droplet Size on the Droplet Drift Characteristics of Fan-shaped Nozzles for Aerial Spraying

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Abstract: To investigate the effects of lateral wind speed and droplet size on the deposition of droplets sprayed by aviation-specific fan-shaped nozzles in aerial spraying operations, this paper takes the Teejet series 01, 03 and 05 aperture fan-shaped pressure nozzles as the research objects, and studies the drift distribution of droplets when the lateral wind speed is 2, 4, 6 m/s and the droplet volume median diameter (D_{V50}) is 100, 150, 200 μm respectively, and builds a nozzle drift model based on the experimental results. The results show that the lateral wind speed and droplet size have significant effects on the horizontal and vertical drift distribution of the nozzle droplets, and the droplet drift rate increases with the increase of lateral wind speed and the decrease of droplet size. In addition, the droplet drift distance also increases significantly with the increase of lateral wind speed, and when the wind speed increases from 2 m/s to 6 m/s, the 90% drift distance of droplets increases from about 9 m to about 12 m; and when the lateral wind speed is 4 m/s, the droplet drift is more serious, exceeding 40%; and with the increase of wind speed, the droplet drift will also increase. Therefore, it is suggested that plant protection unmanned aerial vehicle (UAV) should choose to operate under the condition of wind speed less than 4 m/s as far as possible in field operations, and increase the droplet size appropriately when necessary to reduce the degree of droplet drift. The research results provide theoretical and data support for optimizing the drift distribution characteristics of aviation fan-shaped nozzles, and have certain guiding significance for practical spraying operations.

Keywords: fan-shaped nozzle; droplet; wind speed; droplet size; drift
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1 Introduction

In agricultural production, increasing yield is the main goal for human beings, and the invention and use of pesticides are the key means; according to statistics, the use of pesticides can reduce the loss of 45% of grain crop yield[1-2]. However, with the improvement of modern living quality, the impact of pesticides on environmental pollution and crop residues has become a problem that people pay close attention to. In recent years, the agricultural aviation industry has developed rapidly, and has been highly valued by the plant protection industry. It has become a powerful means to reduce pesticide use, lower pesticide residues, and improve pesticide efficacy[3]. Aerial spraying operations have good atomization effect, high work efficiency, low cost, strong assault ability, and are conducive to eliminating outbreak pests and diseases; and compared with ground machinery field operations, aerial operations are not limited by crop growth, and can solve the problem of ground machinery being difficult to operate in the field during crop growth[4-5]; in addition, aerial spraying uses low or ultra-low volume spray, which can save 15%-20% of pesticides, and can be used as an important technical support for "reducing fertilizer and pesticide use". Therefore, aerial spraying operations are favored by a large number of users and the market, and its large-scale application has become a trend[6-7].

The ideal effect of aerial spraying is that all pesticide agents are deposited on the target pests or crops in the target area. However, due to the fast speed and high altitude of aerial spraying operations, and the susceptibility of liquid droplets to the operating environment, aerial spraying droplets are prone to drift[8-9]. Wang et al.[10] conducted aerial spraying experiments with a single-rotor plant protection drone and found that under the condition of lateral wind speed of 0.76~5.5 m/s, the cumulative drift rate of droplets reached 14.3%~75.8%. Some of the liquid drifted into the non-target environment, which not only wasted a lot of pesticides, but also caused problems such as phytotoxicity to sensitive crops, poisoning of humans and animals, and environmental pollution[11]. Therefore, the problem of aerial spraying droplet drift has become a bottleneck for the application and promotion of aerial spraying operations, and strengthening the research on aerial spraying droplet drift is of great significance for the application of plant protection drones.

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At present, the methods for studying droplet drift are field experiments, wind tunnel experiments and simulation[12]. Due to the poor controllability of environmental variables in field experiments and the difficulty in ensuring the accuracy of simulation results, wind tunnel experiments have high data reliability and repeatability, so they are widely used in droplet drift research. In recent years, domestic and foreign scholars have done a lot of research on wind tunnel droplet drift experiments. Zhang et al.[13] conducted wind tunnel experiments at the University of Queensland, and studied the effects of wind speed, nozzle type, adjuvant and sampling distance on droplet drift from horizontal and vertical directions, and established a multivariate nonlinear droplet drift characteristic model that includes the above four factors, which helps to select spraying parameters and predict droplet drift deposition. Ru et al.[14] established a test system for the influence of lateral wind on droplet drift, and used the aerosol particle mass concentration test method to carry out experimental research on the law of droplet drift under different wind speed and particle size conditions. The experimental results show that droplets smaller than 200 μm are more likely to drift under lateral wind. Wang et al.[15] put drones on top of the wind tunnel, and studied the droplet deposition law of hovering drones spraying variables, which is more in line with the operating environment of plant protection drones, and provides some reference. Martin et al.[16] used the aerial spraying wind tunnel of the Agricultural Aviation Research Center of the United States Department of Agriculture to study the droplet distribution law of fixed-wing aircraft-mounted electrostatic spray under different wind speed conditions. Ellis et al.[17] based on a large amount of field experiment data, theoretically established a distance-drift model, and further modified it by computer simulation, showing that spray drift decreases with downwind distance, and wind tunnel measurements can be used to estimate at least 20 m downwind distance.

As can be seen from the above studies, the current research on droplet drift based on wind tunnel experiments mainly focuses on ground plant protection machinery and agricultural manned aircraft; while plant protection drones, as a new type of plant protection equipment, most of their droplet drift research is concentrated on field experiments[18], and there are few studies that use wind tunnel experiments to study their drift characteristics. Therefore, this paper selects different aperture plant protection drone-specific aviation nozzles, and conducts spraying experiments under different wind speed conditions in the wind tunnel of the National Precision Agricultural Aviation Spraying Technology Research Center, to evaluate the drift characteristics of aviation fan-shaped nozzles, and provide data support for the scientific application of plant protection drone aerial spraying.

2 Materials and Methods

2.1 Experimental instruments and equipment

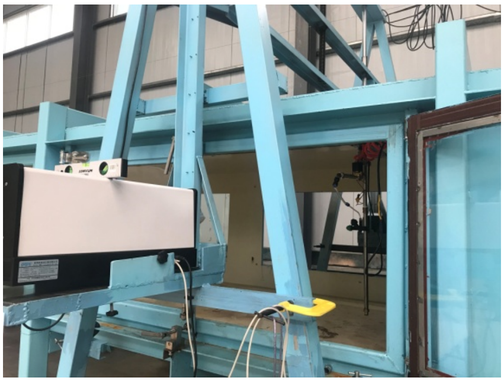
This experiment used the agricultural wind tunnel laboratory of the National Precision Agricultural Aviation Center of South China Agricultural University. The wind tunnel adopted a direct current open design, which mainly included six parts: power section, transition section, diffusion section, stabilization section, contraction section and test section, as shown in Figure 1. The detailed design indicators of the wind tunnel are shown in Table 1.

The fixed spraying system used in the experiment was designed by the Nanjing Agricultural Mechanization Research Institute of the Ministry of Agriculture. The system consists of six parts: a delay relay, a water tank, a booster pump, a pressure relief valve, a pressure gauge, a spraying pipeline and a nozzle. By adjusting the pressure of the pressure relief outlet, the spraying pressure can be precisely controlled, and by adjusting the relay mode, timed spraying can be realized. The droplet size distribution measurement device uses the DP-02 laser particle size analyzer produced by Zhuhai OMEC Instruments Co., Ltd., as shown in Figure 2, which measures particle sizes in the range of 1~1500 μm. The working principle of the instrument is that a beam of laser is emitted from the emission end and passes through the spray area, and according to the different scattering angles of different particle size particles to the laser, photosensitive films are arranged in different areas of the receiving end to collect and obtain the scattering light intensity, and finally the spray droplet size distribution ratio is obtained by computer calculation. The fluorescence detection device is the FP-8300 fluorescence spectrophotometer and its supporting software produced by JASCO Corporation of Japan.

Figure 1 Appearance of the wind tunnel laboratory

Table 1 Technical indicators of the wind tunnel

Main parameters	Values
Test section size/m×m×m	20×2.0×1.1
Wind speed range/m·s^{-1}	2~52
Turbulence/%	<1
Axial static pressure gradient	<0.01
Dynamic pressure stability coefficient/%	<1
Average airflow deflection angle/(^{o})	<1



a. Wind tunnel droplet size test photo

b. Laser particle size analyzer

Figure 2 Laser particle size analyzer test droplet experiment

2.2 Spray parameters and treatment

The droplet size parameters can be directly read out by the DP-02 laser particle size analyzer and its supporting software. For the droplet drift characteristics, they are indirectly obtained by the droplet deposition mass on the polyethylene collection line.

The specific method is as follows:

First, prepare the standard stock solution to fit the standard curve. According to the calculation before the experiment, prepare five different concentration levels of rhodamine-B solution, which are 5×10^{-5} g/L, 1×10^{-4} g/L, 2×10^{-4} g/L, 5×10^{-4} g/L, 2×10^{-3} g/L respectively, and put the prepared stock solutions into the FP-8300 fluorescence spectrophotometer separately. Use light with a wavelength of 552 nm to excite, and measure the emission light intensity with a wavelength of 575 nm as the basis for the rhodamine-B concentration in the solution. The fitted curve is y=201341x+4.83142, and the fitting degree is 99.958%, which meets the accuracy requirements of the experiment. Then, when processing the samples, use a 10 mL pipette to inject 40 mL of deionized water and shake well to wash, and take about 2 mL and put it into a quartz dish, and put the quartz dish into the fluorescence spectrophotometer test tank. By testing its emission light intensity through the instrument and its supporting software, the concentration value of rhodamine-B solution can be measured. Finally, import the original data obtained by the FP-8300 fluorescence spectrophotometer and its supporting software into Excel 2010, and calculate the droplet deposition mass and droplet drift rate.

The total amount of droplets deposited on the collection line is represented by A_d:

$$A_d = \sum_{i=1}^{n} d_i(\frac{s}{w}) \tag{1}$$

where, n is the number of collection lines, and the sum is taken separately for the horizontal and vertical directions; d_i is the deposition of the tracer on the i-th collection line; s is the distance between the collection lines; and w is the diameter of the collection line.

$$T_a = v \times c \tag{2}$$

where, T_a is the total amount of spray tracer; v is spray volume; c is tracer concentration.

$$S = \frac{A_d}{T_a} \times 100\% \tag{3}$$

where, S is the drift rate, which is the percentage of the droplet deposition mass on the collection line to the total amount of the spraying tracer. To better analyze the maximum drift distance of the droplets, the 90% drift position is defined as follows:

$$\mathrm{D}_t(\%) = \int_2^{14} f(x)dx \tag{4}$$

$$\mathrm{D}(\%) = \int_2^{i} f(x_i)dx / \mathrm{D}_t \tag{5}$$

where, $\mathrm{D}_t(\%)$ is cumulative horizontal drift in drift zone; D(%) is cumulative horizontal drift rate at position i; $f(x_i)$ is drift rate at position i. The 90% drift distance is located at the distance (m) when cumulative horizontal drift rate reaches 90%.

2.3 Experimental design

2.3.1 Droplet size test experiment

To analyze the influence of droplet size on droplet drift under wind tunnel conditions, the droplet size test was first performed on the operating environment of the experiment, to determine the operating parameters during the experiment. The droplet size is represented by, D_{V50} , which refers to the volume of droplets with a diameter smaller than this droplet diameter accounting for 50% of the total volume of droplets, also known as the volume median diameter (VMD).

This paper uses the Teejet110-01, Teejet110-03 and Teejet110-05 nozzles from the American Teejet company as the research objects. During the experiment, the two lenses of the laser particle size analyzer were placed symmetrically on the horizontal brackets on both sides of the nozzle at a distance of 1.5 m, and the distance between the nozzle and the laser beam of the laser particle size analyzer was 0.35 m. The spray plume of the nozzle was perpendicular to the laser line and parallel to the observation window of the wind tunnel. The average particle sizes measured by the three nozzles under the standard pressure of 0.3 MPa were 106.23 μm, 140.16 μm and 189.17 μm respectively, and the data could not meet the three particle size requirements required by the experiment well. Therefore, we changed the spraying pressure of the fixed spraying system to continuously approach the experimental target. When the adjusted pressure size was close to the required droplet size, each test experiment was repeated three times to determine that it met the experimental requirements.

The experiment used the Testo512 differential pressure wind speed meter produced by the German Detu company. The wind speed of the wind tunnel during the experiment was between 2-6 m/s, which belonged to low wind speed, so the influence of wind speed on droplet size was ignored. The droplet size test results of the three nozzles under the selected spraying pressure are shown in Table 2. As can be seen from Table 2, the average value of Lechler 110-01 nozzle diameter was 99.90, with a standard deviation of 1.31; the average value of Teejet-110-03 nozzle diameter was 149.58, with a standard deviation of 1.01; and the average value of LICHENG110-05 nozzle diameter was 197.07, with a standard deviation of 1.11. The experimental results met the experimental requirements (100, 150, 200 μm), and the pressures of the three nozzles were 0.35 MPa, 0.20 MPa, and 0.25 MPa respectively, which were used as the operating parameters for the later droplet drift experiment.

Table 2 Test results of droplet size under selected pressure

Nozzle type	Droplet size (D_{V50})/μm		
Lechler 110-01	101.75	99.10	98.86
Teejet-110-03	148.22	150.64	149.88
LICHENG110-05	198.45	195.74	197.02

2.3.2 Droplet drift test experiment

During the experiment, the nozzle was fixed at the center position 0.8 m above the wind tunnel floor, and the droplet deposition was collected by polyethylene lines with a diameter of 1 mm. In the downwind direction, at a position 2 m away from the nozzle, four collection lines with a spacing of 0.2 m were placed from the wind tunnel floor to 0.1-0.7 m above it. These collection lines were used to detect the droplet deposition through the vertical plane of air, and were named V1, V3, V5 and V7 respectively. In addition, along the horizontal direction, 13 collection lines with a spacing of 1 m were placed at a height of 0.1 m above the ground, to detect the horizontal drift of the spray from 2 m to 14 m, and were named H2, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H13 and H14 respectively (where H2 is the same as V1). The wind tunnel floor was covered with turf carpet to prevent the solution sprayed on the wind tunnel floor from bouncing back to the collection lines. The principle of the experimental arrangement is shown in Figure 3, and the actual arrangement is shown in Figure 4.

The spraying time of the nozzle was controlled by a timer relay, ensuring that the spray time of each test was fixed at 10 s. Rhodamine B (Aladdin, green, R104961) fluorescent tracer was selected and mixed with water at a ratio of 5 g/L as the spray medium. Each experiment was repeated three times, and the average value was taken as the final data. After the spraying was finished, the droplets attached to the line were collected with disposable rubber gloves after they were fully dried, and the collection lines were placed in sealed bags and brought back to the laboratory for dark and low-temperature preservation.

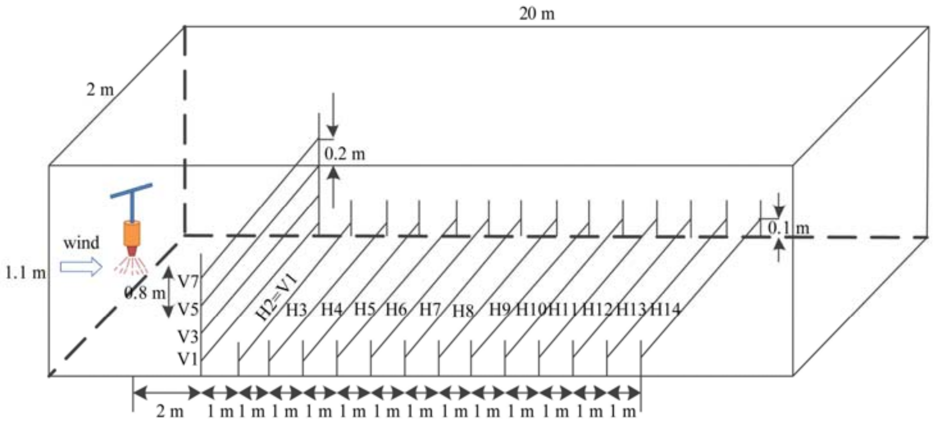


Figure 3 Schematic diagram of wind tunnel test system

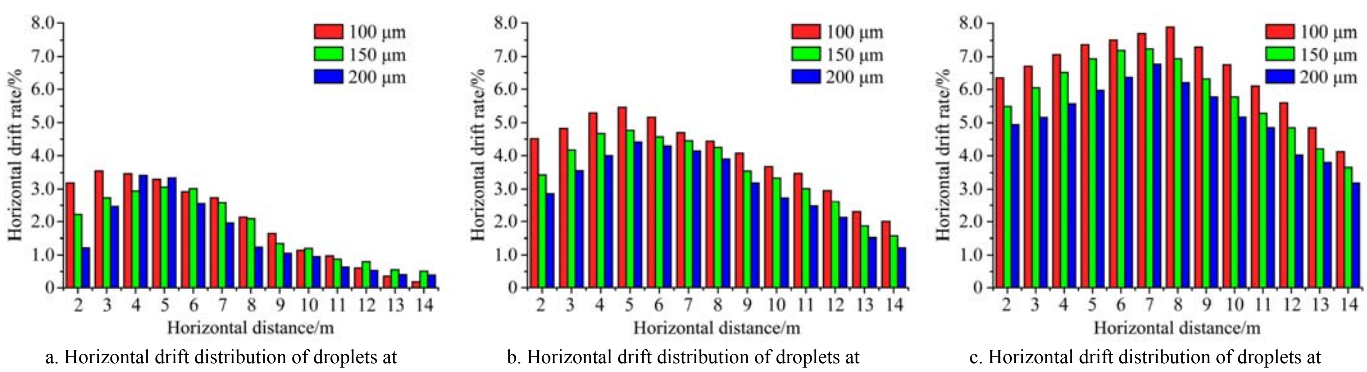
Figure 4 Layout of wind tunnel experiment

To analyze the specific situation of vertical and horizontal drift in the wind tunnel, the drift rates of each collection line in the vertical and horizontal planes are displayed in sequence, to obtain the influence law of wind speed and particle size on droplet drift in the wind tunnel. The final experimental data were analyzed by the two-factor repeated variance analysis method on SPSS V22.0 software, and the experimental results were plotted by OriginPro 9.1 software.

3 Results and Analysis

3.1 The influence of droplet size on droplet drift distribution

Figure 5 shows the horizontal drift distribution of droplets in the range of 2-14 m under different wind speed conditions. As can be seen from the figure, the larger the droplet size, the smaller the horizontal drift rate. Taking the collection line 3 m away from the nozzle as an example. When the wind speed was 2 m/s, the horizontal drift rate of the droplet size 100 μm treatment was 3.55%, while the horizontal drift rate of the droplet size 200 μm treatment was only 2.46%; when the wind speed was 4 m/s, the horizontal drift rate of the droplet size 100 μm treatment was 4.82%, while the horizontal drift rate of the droplet size 200 μm treatment was only 3.56%; when the wind speed was 6 m/s, the horizontal drift rate of the droplet size 100 μm treatment was 6.7%, while the horizontal drift rate of the droplet size 200 μm treatment was only 5.16%. Overall, for the same horizontal position, the drift rate of larger droplet size was smaller than that of smaller droplet size.



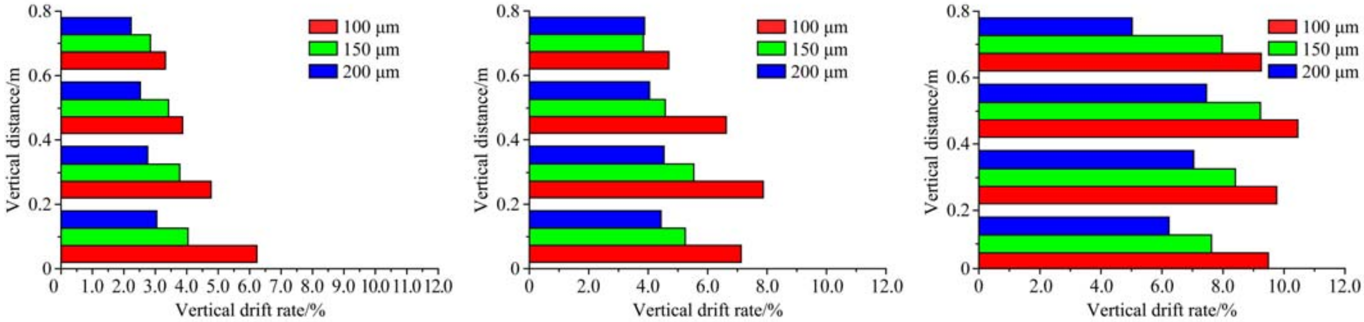
a. Horizontal drift distribution of droplets at wind speed of 2 m/s

b. Horizontal drift distribution of droplets at wind speed of 4 m/s

c. Horizontal drift distribution of droplets at wind speed of 6 m/s

Figure 5 Horizontal drift distribution of droplets under different wind speed conditions

Figure 6 shows the drift rate distribution of droplets at the vertical plane 2 m downwind. As can be seen from the figure, the larger the droplet size, the smaller the vertical drift rate. Taking the collection line 0.1 m above the ground as an example, when the wind speed was 2 m/s, the drift rate of the droplet size 100 μm treatment was 6.2%, while the drift rate of the droplet size 200 μm treatment was only 3.0%; when the wind speed was 4 m/s, the drift rate of the droplet size 100 μm treatment was 7.1%, while the drift rate of the droplet size 200 μm treatment was only 4.4%; when the wind speed was 6 m/s, the drift rate of the droplet size 100 μm treatment was 9.3%, while the vertical drift rate of the droplet size 200 μm treatment was only 5.0%. Overall, for the same vertical height position, the drift rate of larger droplet size treatment was smaller than that of smaller droplet size treatment.



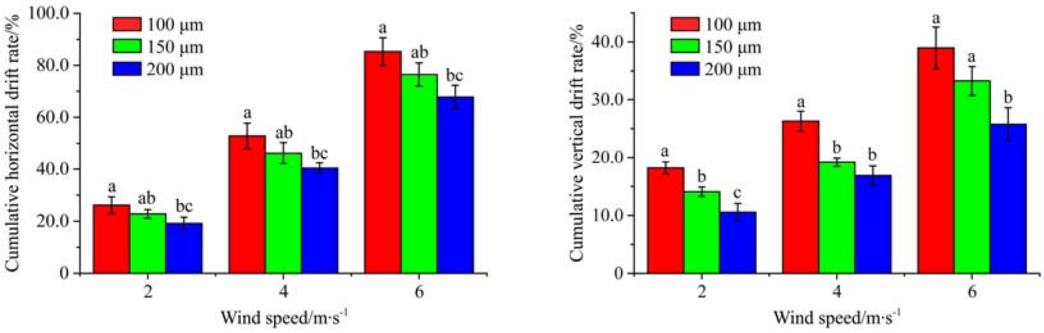
a. Vertical drift distribution of droplets at wind speed of 2 m/s

b. Vertical drift distribution of droplets at wind speed of 4 m/s

c. Vertical drift distribution of droplets at wind speed of 6 m/s

Figure 6 Vertical drift distribution of droplets under different wind speed conditions

The effects of droplet size on the cumulative horizontal and vertical drift rates of droplets under different wind speed conditions are shown in Figure 7. As shown in Figure 7a, droplet size has a significant effect on the cumulative horizontal drift rate of droplets under wind speeds of 2 m/s, 4 m/s, and 6 m/s. When the droplet size is 200 μm, the horizontal drift rate of droplets is the lowest, and significantly lower than the treatment with droplet size of 100 μm, but there is no significant difference (P>0.05) between the treatment with droplet size of 150 μm. At the same time, under different wind speed conditions, droplet size also has a significant effect on the cumulative vertical drift rate of droplets. When the droplet size is 200 μm, the vertical drift rate of droplets is the lowest, and significantly lower than the treatment with droplet size of 100 μm. Only under the wind speed of 4 m/s, there is no significant difference between the treatment with droplet size of 150 μm and the treatment with droplet size of 200 μm in terms of vertical drift rate of droplets, while there are significant differences among other treatments. The results show that both the cumulative horizontal and vertical drift rates of droplets decrease with the increase of droplet size, indicating that increasing the droplet size appropriately can reduce the droplet drift rate of aerial spraying to some extent.



a. Cumulative horizontal drift rate

b. Cumulative vertical drift rate

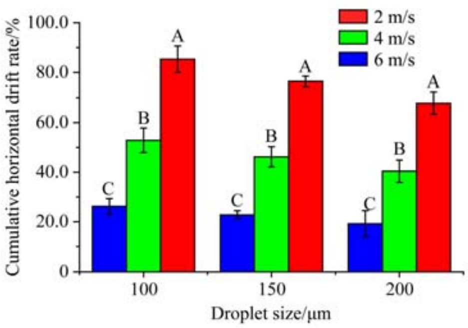
Figure 7 The effect of droplet size on the overall drift of droplets

3.2 Analysis of the influence of wind speed on droplet drift distribution

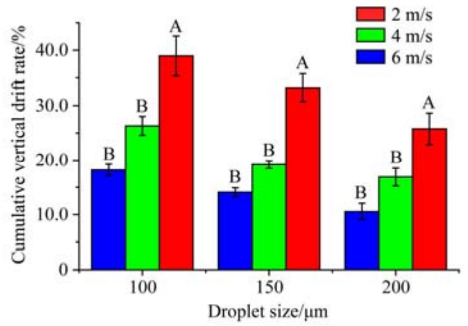
Comparing Figure 5 and Figure 6, it can also be seen that the cumulative horizontal and vertical drift rates of droplets increase with the increase of wind speed. From the horizontal drift situation of droplets within the range of 2 m to 14 m, it can be known that the higher the wind speed, the higher the horizontal drift rate of droplets, and it shows a trend of increasing first and then decreasing with the increase of distance, and some droplets with wind speed of 6 m/s have exceeded the range of 15 m. In addition, wind speed also affects the position of the maximum cumulative horizontal drift rate of droplets. As shown in Table 3, when the wind speed is 2 m/s, 90% of the droplet drift distance is at the position of 9.4-10.2 m, when the wind speed is 4 m/s, 90% of the droplet drift distance is at the position of 11.3-11.7 m, when the wind speed is 6 m/s, 90% of the droplet drift distance is at the position of 12.1-12.4 m. This indicates that the larger the wind speed, the farther the droplet drift distance, and the more serious the droplet drift.

For the cumulative vertical drift of droplets, taking the collection line at 0.1 m above the ground as an example, under the condition of droplet size of 100 micrometers (μm), the cumulative vertical drift rate of droplets is 6.2% when the wind speed is 2 meters per second (m/s), and the cumulative vertical drift rate of droplets reaches 9.3% when the wind speed is 6 m/s; under the condition of droplet size of 150 μm, the cumulative vertical drift rate of droplets is 4.0% when the wind speed is 2 m/s, and the cumulative vertical drift rate of droplets reaches 8.0% when the wind speed is 6 m/s; under the condition of droplet size of 200 μm, the cumulative vertical drift rate of droplets is 3.0% when the wind speed is 2 m/s, and the cumulative vertical drift rate of droplets reaches 5.0% when the wind speed is 6 m/s. At the same vertical height position, the cumulative vertical drift rate of droplets under larger wind speed conditions is larger than that under smaller wind speed conditions. In addition, wind speed also affects the position of the maximum vertical drift rate. When the wind speed is 2 m/s, the drift rate decreases with the increase of height; when the wind speed is 4 m/s and 6 m/s, the drift rate increases first with the increase of height, and then decreases after reaching the peak at heights of 0.3 m and 0.5 m respectively. This indicates that when the wind speed is low, the drift rate decreases with the increase of sampling height; when the wind speed is high, the sampling height where the maximum drift rate is located increases. The reason may be that when the wind speed is low, droplets are affected by their own mass, and the drift distance is not very far, so they are easily deposited at lower positions; when the wind speed is large, droplets drift farther, and in the vertical plane at 2 m downwind, the main droplet passing plane height increases, and so does the sampling height where the maximum drift rate is located.

The analysis of the effects of wind speed on the cumulative vertical and horizontal drift rates of droplets under different droplet size conditions is shown in Figure 8: As shown in Figure 8a, wind speed has a very significant effect on the cumulative horizontal drift rate of droplets, and when the wind speed is 6 meters per second (m/s), the cumulative horizontal drift rate of droplets is the highest, all exceeding 70%, and very significantly higher than the treatments with wind speeds of 4 m/s and 2 m/s. As shown in Figure 8b, wind speed also has a very significant effect on the cumulative vertical drift rate of droplets. There is a very significant difference between the treatment with wind speed of 6 m/s and the treatments with other wind speed conditions, but there is no very significant difference between the treatment with wind speed of 4 m/s and the treatment with wind speed of 2 m/s. In summary, both the cumulative vertical and horizontal drift rates of droplets increase with the increase of wind speed, and the larger the difference of wind speed, the higher the degree of droplet drift.



a. Cumulative horizontal drift rate



b. Cumulative vertical drift rate

Figure 8 The effect of wind speed on the overall drift of droplets

3.3 Establishment of droplet drift model

To further analyze the effects of wind speed and droplet size on the horizontal drift rate of droplets, the regression equations and the 90% drift distances of the horizontal drift rate (y) and the horizontal distance (x) under different conditions of the nine treatments are shown in Table 3: From the fitted equations, it can be seen that except for the experimental treatment with wind speed of 2 m/s and droplet size of 100 μm, whose functional relationship is exponentially decreasing and the coefficient of determination is only 0.74, the rest of the treatments are polynomial functions with overall decreasing and coefficients of determination greater than 0.86. The former has a low coefficient of determination, which may be due to a large error during the treatment. For the other treatment groups, the cumulative horizontal drift rate of droplets at a position close to the nozzle has a slight increase first, and then decreases with the increase of distance. This result is consistent with the rule that the horizontal drift rate of droplets decreases with the increase of distance during field spraying operations.

Table 3 Fitting equations and 90% drift positions

Wind speed /m·s^{-1}	Droplet size/μm	Fitting equation	Determination coefficient R^2	90% drift distance/m
2	100	$y=-0.0001x^2-0.0013x+0.0394$	0.96	9.4
2	150	$y=-0.0002x^2+0.0008x+0.0268$	0.86	10.2
2	200	$y=0.0467e^{-0.169x}$	0.74	10.0
4	100	$y=-0.0004x^2+0.0031x+0.0434$	0.96	11.7
4	150	$y=-0.0005x^2+0.0051x+0.0303$	0.94	11.3
4	200	$y=-0.0005x^2+0.0057x+0.0234$	0.92	11.5
6	100	$y=-0.0007x^2+0.0087x+0.0476$	0.98	12.4
6	150	$y=-0.0006x^2+0.0082x+0.0427$	0.96	12.2
6	200	$y=-0.0006x^2+0.0081x+0.0349$	0.93	12.1

It is known from the above that wind speed and droplet size have a significant effect on the horizontal drift rate of droplets. Now, the effects of wind speed (A) and droplet size (B) on the cumulative horizontal drift rate (P) are examined, and the stepwise regression method of SPSS is used to analyze and establish the multiple linear regression equation as follows:

$$y=0.133591*\mathrm{A}-0.00123*\mathrm{B}+0.137816 \quad (R^2=0.979) \tag{6}$$

This indicates that the fitted equation can well express the correlation among the three variables. From the equation, it can also be seen that wind speed can increase the horizontal drift rate of droplets, droplet size can reduce the horizontal drift rate of droplets, and the influence weight of wind speed is larger than that of droplet size. It is known from the above analysis that droplet size and wind speed have a significant effect on the horizontal drift rate of droplets at different positions, and the horizontal drift rate at different positions is a quadratic polynomial function relationship, droplet size and wind speed have a linear relationship with the horizontal drift rate. The SPSS multivariate nonlinear fitting is performed for the drift rates at different positions and the sampling distance, wind speed and droplet size of 27 groups of data:

$$D_p=(-a*D_t^2+b*D_t+c)\times(d*W_s-e*D_s+f) \tag{7}$$

where, D_p is the horizontal drift rate (%); D_t is the distance from the downwind to the nozzle (m); W_s is the wind speed (m/s); D_s is the droplet size (μm). However, the fitting result does not converge. The main reason for the analysis is that the b value in the polynomial function relationship is not fixed, which makes it impossible to use the polynomial function relationship for fitting. When the fitting function is changed to a power function, the optimal solution appears after 14 iterations, and the fitting result is as follows:

$$D_p=\exp(-0.042D_t)\times(0.014W_s-1.29\times10^{-4}D_s+0.017) \tag{8}$$

In the above fitting model, R^2 can reach 0.828, which indicates that the fitting effect is good, but it also shows that the control of irrelevant variables in the previous experiment is not very good, and further optimization should be done in the later experiment. From the fitting model, it can be seen that the horizontal drift rate of droplets has a positive linear function relationship with wind speed, and a negative function relationship with droplet size. This result is basically consistent with the conclusion of drift ratio and 90% drift position.

4 Conclusion

This paper studies and analyzes the droplet drift situation at different positions under different droplet size and wind speed conditions in the wind tunnel, and the conclusions are as follows:

1) Lateral wind speed and droplet size have a significant effect on the horizontal and vertical drift distribution of droplets from the nozzle, and the droplet drift rate increases with the increase of lateral wind speed and the decrease of droplet size.

2) The droplet drift distance also increases significantly with the increase of lateral wind speed, and when the wind speed increases from 2 m/s to 6 m/s, the 90% drift distance of droplets increases from 9 meters (m) to about 12 m.

3) When the lateral wind speed is 4 m/s, the droplet drift is more serious, exceeding 40%; with the increase of wind speed, the droplet drift will also increase. Therefore, it is recommended that plant protection drones should choose to operate in the field under the condition of wind speed less than 4 m/s as much as possible, and increase the droplet size appropriately when necessary to reduce the degree of droplet drift.

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[References]

[1] Lan Y B, Chen S D. Current status and trends of plant protection UAV and its spraying technology in China. Int J Agric & Biol Eng, 2017, 10(3): 1–17.

[2] Lan Y B, Chen S D. Current status and trends of plant protection UAV and its spraying technology in China. International Journal of Precision Agricultural Aviation, 2018, 1(1): 1–10.

[3] Zhan, Y., Chen, P., Xu, W., Chen, S., Han, Y., Lan, Y., & Wang, G. Influence of the downwash airflow distribution characteristics of a plant protection UAV on spray deposit distribution. Biosystems Engineering, 2022, 216: 32–45.

[4] Chen S D, Lan Y B, Li J Y, Zhou Z Y, Liu A M, Xu X J. Comparison of the pesticide effects of aerial and artificial spray applications for rice. Journal of South China Agricultural University, 2017, 38(4): 103–109. (in Chinese)

[5] Chen S D, Lan Y B, Li J Y, Xu X J, Wang Z G, Peng B. Evaluation and test of the effective spraying width of aerial spraying on plant protection UAV. Transactions of the CSAE, 2017, 33(7): 82–90. (in Chinese)

[6] Chen S D, Lan Y B, Zhou Z Y, Ouyang F, Wang G B, Huang X Y, et al. Effect of Droplet Size Parameters on Droplet Deposition and Drift of Aerial Spraying by Using Plant Protection UAV. Agronomy, 2020; 10, 195. Doi: 10.3390/agronomy10020195

[7] Zhou Z Y, Yuan W, Chen S D. Current status and future directions of rice plant protection machinery in China. Guangdong Agricultural Sciences, 2014, (5): 178–183. (in Chinese)

[8] Gong Y, Zhang X, Wang G, Chen X. Study on drift characteristics of pesticide droplets based on simulating environment factors of farmland. Jiangsu Agricultural Sciences, 2018, 46(11): 205–208. (in Chinese)

[9] Chen P, Douzals J P, Lan Y, Cotteux E, Delpuech X, Pouxviel G and Zhan Y. Characteristics of unmanned aerial spraying systems and related spray drift: A review. Front. Plant Sci., 2022, 13: 870956.

[10] Wang X N, He X K, Wang C L, Wang Z C, Li L L, Wang S L, et al. Spray drift characteristics of fuel powered single-rotor UAV for plant protection. Transactions of the CSAE, 2017; 33(1): 117–123. (in Chinese)

[11] Fritz B K. Meteorological effects on deposition and drift of aerially applied sprays. Trans ASABE, 2006, 49(5): 1295–1301.

[12] Richardson B, Thistle H W. Measured and predicted aerial spray interception by a young pinus radiate canopy. Trans ASABE, 2006, 49(1): 15–23.

[13] Zhang H C, Gary D, Zheng J Q, Zhou H P, Yu J. Wind tunnel experiment and regression model for spray drift. Transactions of the CSAE, 2015, 31(3): 94–100. (in Chinese)

[14] Ru Y, Zhu C Y, Bao R. Spray drift model of droplets and analysis of influencing factors based on wind tunnel. Transactions of the CSAM, 2014, 45(10): 66–72. (in Chinese)

[15] Wang L, Lan Y B, Hoffmann W C, Bradley K F, Chen D, Wang S M. Design of variable spraying system and influencing factors on droplets deposition of small UAV. Transactions of the CSAM, 2016, 47(1): 15–22. (in Chinese)

[16] Martin D E, Carlton J B. Airspeed and Orifice Size Affect Spray Droplet Spectrum from an Aerial Electrostatic Nozzle for Fixed-wing Applications. Applied Engineering in Agriculture, 2013, 29(1): 5–10.

[17] Ellis M C B, Alanis R, Lane A G , et al. Wind tunnel measurements and model predictions for estimating spray drift reduction under field conditions. Biosystems Engineering, 2017, 154: 25–35.

[18] Wang, G., Lan, Y., Qi, H., Chen, P., Hewitt, A., & Han, Y. Field evaluation of an unmanned aerial vehicle (UAV) sprayer: effect of spray volume on deposition and the control of pests and disease in wheat. Pest management science, 2019, 75(6): 1546–1555.