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Research Article

DEPOSITION EXPERIMENT OF AIR-BLAST VARIABLE-RATE SPRAY WITH CONSTANT-PRESSURE CONTROL IN ORCHARD

Wei Deng*[1,2,3,4], ChunjiangZhao[1,2,3,4], Liping Chen[1,2,3,4], Min Xu[1,2,3,4], Gang Xu[1,2,3,4]

[1]Beijing Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China
[2]National Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China
[3]Key Laboratory of Agri-informatics, Ministry of Agriculture, Beijing 100097, China
[4]Beijing Key Laboratory of Intelligent Equipment Technology for Agriculture

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A B S T R A C T

The traditional sprayers adopt large-area uniform pesticide application, resulting in a low effective utilization of pesticide and a harmful effect to the natural environment. Variable-rate spray is the key point to precision chemical application. However, it is inevitable that the spray pressure sharply fluctuates during variable-rate spray, which will definitely influence the spray characteristics, such as spray droplet sizes, spray angles, spray droplet velocities, etc., and reduce the efficiency of pesticide applications. Therefore, the research on how to keep the spray pressure constant during the process of variable-rate spray has practical significance to Precision pesticide Applications. In order to achieve the stability of spray pressure for variable-rate spray, a sprayer with constant-pressure control was set up using a closed-loop PID controller of constant-pressure water-supply which employed the techniques of single-phase AC Chopper Variable-Voltage Control and PID Feedback Regulation. Using hollow-cone nozzles, the spray volume was changed by adjusting spray pressure, frequency, and duty cycle of electromagnetic valve switching. An air-assisted variable-rate sprayer with the constant pressure control was set up and its deposition feature and spray-field simulation were studied in the research. The conclusions are as follows: (1) By the factorial experiment of spray droplet deposition, combination of influence factors in the test which the smallest coefficient of variation is: the travelling speed of 1.1 m / s, the frequency 5, and the duty cycle 0.5. (2) Set the pressure of the constant pressure controller at 0.3MPa, the spray distributions on the front side, the back side, and the shadow of canopy were compared in two conditions of the open nozzle unilateral and bilateral operations. The results indicated that the spray pressure kept constant with the different number of open nozzles and the regional distribution of spray deposition was consistent. (3) The simulation of spray field with CFD showed that the wind speed in the middle region was obviously larger than that in the upper and lower regions of spray field and the wind speed in upper region was larger than that in the lower region. Therefore, the spray droplets in the middle of the spray field are apt to penetrate into the center of the thickest part of the canopy so as to increase the deposition rate in central and lower parts in the tree. The more, the droplets in the upper spray field can easily be sent to the top of the fruit trees so as to improve the uniformity and coverage of the spray droplet distribution.

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INTRODUCTION

In the spraying process of traditional pest control, uniform applications of agro-chemicals were utilized in large area, neither considering the differences of plant covers and row spacing in pesticide spraying area, nor thinking about the diverse degree of pest and disease disasters in different plots, which led to serious issues of excessive uses and low effective utilization rate of chemical pesticides (Praice *et al*., 1996; Yang S. and Yang K., 2002; He, 2004). Off-target deposition of pesticide will cause severe problems of environmental pollution and pesticide waste (Chen and Zheng, 2005). Precision farming machineries based on variable-rate spraying can effectively improve the utilization rate of pesticides and reduce the environmental pollution of chemical pesticides (Escolà *et al*., 2013), in which the core technology is to vary the spray volume according to the different pesticide needs in different field parcels using technologies of information

Corresponding author:* **Deng Wei
Beijing Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China

positioning like photoelectric detection technique (Deng *et al*., 2008b; Zhai *et al*., 2012), ultrasonic detection technique (Alexandre *et al*., 2011; Zhang *et al*., 2010), laser detection technique (Yu *et al*., 2013; Joan *et al*., 2009), and image processing detection technique (Shen *et al*., 2013; Gui and Xu, 2014) and variable-rate spray like PWM-based (Pulse-Width Modulation) intermittent variable-rate spray (Giles *et al*., 1990 and 1992), PWM-based continuous variable-rate spray (Deng *et al*., 2008a and 2011), injection spray (Sudduth *et al*., 1995), and so on.

Although it is in a situation of a given liquid pressure, variable-rate spray will cause dramatic fluctuations of spray pressure which will alter the atomization features and result in significant changes in spray droplet size so that spray deposition characteristics and chemical application effect are severely influenced (Deng *et al*., 2008a, 2008b, and 2011; Giles 1990 & 1992). For the sophisticated requirements of precision chemical application, the problem of the pressure stability during variable-rate spraying has been noticed in recent studies. A constant-pressure controller has been set up using a closed-loop PID controller of constant-pressure water-supply which employed the techniques of single-phase AC Chopper Variable-Voltage Control and PID Feedback Regulation and its performance has been tested as well. Using hollow-cone nozzles, the spray volume was changed by adjusting spray pressure, frequency, and duty cycle of electromagnetic valve switching. The spray features concerning the spray angle and the spray volume distribution were studied in laboratory (Deng, 2016).

In this research an air-assisted variable-rate sprayer with constant-pressure control was set up and the spraying deposition feature (and spray-field simulation) was studied.

Apparatus and methods

Air-assisted Variable-rate sprayer with constant pressure control

The air-assisted variable-rate orchard sprayer with constant-pressure control is mainly composed of PWM-based variable flow-rate control system, constant-pressure control system for variable flow-rate (Deng, 2016), tractor, and blast system. On the control interface of PWM-based variable flow-rate control system the frequency and the duty cycle can be set to regulate the spray flow-rate. On the control interface of constant-pressure controller spray pressure can be set to realize automatic control of spray pressure to be constant around the setting pressure and reduce the pressure fluctuation due to the changing of variable-rate flow-rate. The qualitative filter paper was fixed on sampling devices or on the tree to collect the spray droplet deposition.

The overall arrangement for experiments

The overall thought of the experiments was to implement in two steps. The first step was to do Factorial Design experiment, namely two-factor and three-level test, on the test-bed of spray droplet deposition. There were two types of influence factors, one type was frequency and duty cycle and the other was vehicle speed. In each type there were three levels. Whether there were interactions between the two types of factors was tested and then the combination of factors and levels which could contribute the most uniform spray droplet distribution was selected. The second step was to do constant-pressure control test in orchards. Setting the factor at the level selected at the first step, two tests were done on the orchard separately under the conditions of unilateral and bilateral nozzles open. For the two tests the spray droplet depositions on the same sampling points were compared. The flow chart of the experiment is shown in Figure 2.

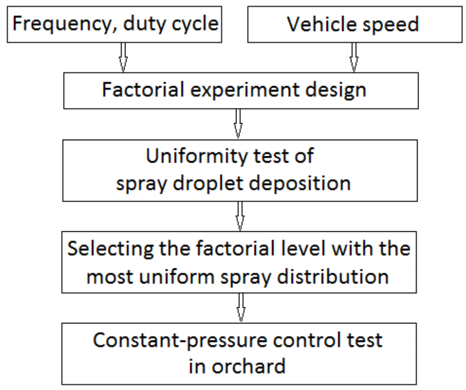


Figure 2 The flow chart of the experiment of spray droplet deposition test

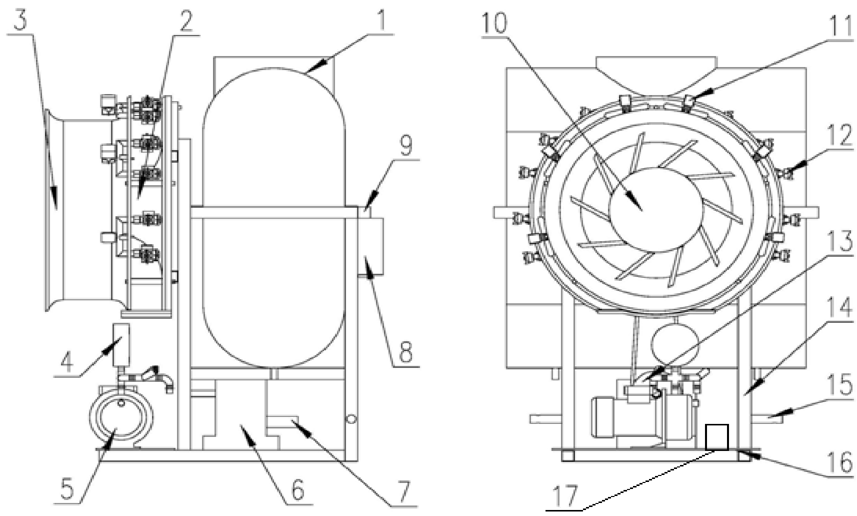


Figure 1 The structure drawing of the sprayer

1. Tank; 2.Air outlet; 3. Air inlet; 4. Transmissible pressure gauge; 5. Water pump; 6.Speed reducer; 7. Prime power shaft (From the tractor); 8. PWM-based variable-rate flow-rate controller; 9. Upper suspension point; 10. Fan; 11. Electromagnetic valve; 12. Spray nozzle; 13. Belt wheel; 14. Rack; 15.lower suspension point; 16.Mounting plate of water pump; 17. Constant-pressure controller for variable-rate flow-rate

The uniformity test of spray droplet deposition

2.3.1 Collecting devices and the layout of sampling points

Generally, for a 1.2 m wide and 2.2 m high fruit tree, the upper level of sampling points are arranged about 2.00 m above the ground on the tree canopy, the middle level of sampling points are about 1.6 m above the ground on the tree canopy, and the bottom level of sampling points are about 1.2 m above the ground on the tree canopy. Accordingly, the collecting device for testing the uniformity of spray droplet deposition was designed as 2.2 m high and 4.0 m wide. The rectangular device was divided as small 10-width square grids using fishing threads in order to fix the sampling filter paper. Three lines of filter paper were fixed at the height of 1.2 m, 1.6 m, and 2.0 m with lateral interval of 40 cm. The total number of the filter paper is 27 with 3 lines and 9 columns. The layout of the collecting points in the test is shown in Figure 3.

The circular qualitative filter paper, with 9 cm diameter and manufactured by Hangzhou Special Paper Industry Co. Ltd., can separates the water and the solutions in the spray droplets falling on the paper. Therefore, the filter paper which has collected the spray droplets can be used to test and quantify the ago-chemicals after evaporation of the water in the spray droplets.

Figure 3 The layout of the collecting points in the test on the collecting device

Factorial experiment

A factorial experiment is an experiment whose design consists of two or more factors, each with discrete possible values or "levels", and whose experimental units take on all possible combinations of these levels across all such factors. A full factorial design may also be called a fully crossed design. Such an experiment allows the investigator to study the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. For the vast majority of factorial experiments, each factor has only two levels. For example, with two factors each taking two levels, a factorial experiment would have four treatment combinations in total, and is usually called a 2×2 factorial design. If the interaction effect exists between or among the factors, it indicates that the factors are not independent and the level change of one factor will accordingly cause changes of other factors. On the contrary, if there is no interaction between each factor, it shows that the factors are independence and the level change of one factor will not affect other factors.

As to the one type of factor, frequency and duty cycle, according to the degree of their influence on the flow-rate change, three levels are determined as A1 (frequency is 1 Hz and duty cycle is 0.1), A2 (frequency 5 Hz and duty cycle 0.5), and A3 (frequency 10 Hz and duty cycle 0.9). For another type of factor, according to the gear setting vehicle speed is divided into three levels, B1 (0.8m/s), B2 (1.1m/s), B3 (1.7m/s). The level combinations in the test scheme are shown in Table 1.

Table 1 The test scheme

Test number	Level combination	Influence factor	
		Frequency, duty cycle	Vehicle speed（m/s)
1	A_1B_1	1, 0.1	0.8
2	A_1B_2	1, 0.1	1.1
3	A_1B_3	1, 0.1	1.7
4	A_2B_1	5, 0.5	0.8
5	A_2B_2	5, 0.5	1.1
6	A_2B_3	5, 0.5	1.7
7	A_3B_1	10, 0.9	0.8
8	A_3B_2	10, 0.9	1.1
9	A_3B_3	10, 0.9	1.7

Test method

The spray pressure was set at 0.3 MPa, the spray nozzles were 1.2 m away from the frame for collecting the spray droplets, the wind speed of the fan was 0.8 m/s, and all the nozzles were open. On the different test conditions, the sprayer traveled from one side to the other side of the collecting frame and then the pieces of filter paper which have collected the spray droplets with fluorescent agent were separately immersed in 100 mL quantitative water in small bottles for 0.5 – 1.0 hour. The resulting solution in separate small bottles will be used as sample solution measured by the fluorescence detector and 9 test data can be achieved respectively at the top, middle, and bottom layer. Accordingly the average value, standard deviation, and coefficient of variation (CV) at each layer can be calculated.

There are diversities between each set of the data of the deposition amount at top, middle, and bottom layer so that the average value and the standard deviation cannot be used to accurately compare the homogeneous degree of the deposition amount among difference layers. Therefore, coefficient of variation (CV) was introduced to measure the variability and the dispersion degree of different types of data with different measurement scales and dimension, which cannot be done by standard deviation. CV is defined as the ratio of standard deviation and average and its calculation formula is shown as Formula (1). When the difference of the measurement standard between two groups of measuring data is very big or when data dimension is different, the coefficient of variation is required to compare the difference and discrete degree of measurement data with different levels and variability.

$$V_x = \frac{\sigma_x}{E_x} \tag{1}$$

Where, E_x is average value, whose expression is $E_x = \frac{1}{n}\sum_{i=1}^{n} x_i$. σ_x is standard deviation, whose expression is $\sigma_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - E_x)^2}$.

The test was done outdoors in the in Xiaotangshan Scientific Observation and Experimental Field Station of Precision Agriculture in Beijing. During the experiment the outdoor wind speed was 1 m/s, the temperature was 30 ^{o}C.

Deposition experiment on fruit tree

Layout of sampling points

The sampling filters were arranged in three regions, namely on the external surface of the tree canopy, within the canopy, and on the ground of the canopy shadow. Total of 12 sampling points (3 lines and 4 columns) were arranged on the external surface of the tree canopy, shown as in Figure 4. 4 sampling points were arranged inner the canopy (two points respectively on left and right side in the middle of the inner canopy and two points respectively on upper and lower side of the inner canopy). 9 sampling points (3 lines and 3 columns) were laid out on the ground of the tree shadow, putting the main trunk as the center line and the three isometric columns laying out symmetrically. For each sampling point, two pieces of filter paper were clipped together on the front and back of the branch leaves.

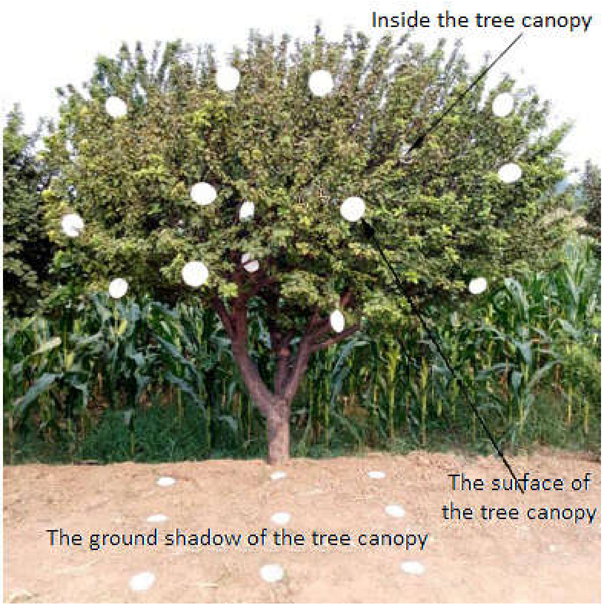


Figure 4 The layout of the collecting points in the test on the fruit tree

Experimental methods

In practice, according to the actual need the flow-rate of orchard sprayers will be changed, which will cause the fluctuations of spray pressure and further influence the spray characteristics and spray quality. In order to verify the stability of constant-pressure control in the orchard sprayer with variable-rate flow-rate, two times of tests were done, for one time one side of nozzles (total of 6 nozzles) open and for another time two sides of the nozzles (total of 12 nozzles) open. All of the collecting filter paper was collected after each test and each filter paper was separately stored in a small bottle. Then all of the filter paper was uniformly washed using quantitative water and the concentration of washed water was measured using a fluorescence detector. The distribution features of droplet deposition accordingly on three regions were compared for the two tests so as to judge the stability of the constant-pressure control system in the sprayer. In the process of the tests, the relevant parameters were as follows, the spray pressure was 0.3 MPa, the distance between nozzles and fruit trees was 1.2 m, and the wind speed of the fan was 0.8m/s.

Recovery rate test

During the tests a small residue of Rhodamine tracer will be left on the filter paper after the filter paper which has collected the spray droplets was washed. Therefore, the recovery rate should be estimated through tests in order to improve the accuracy of obtaining the amount of Rhodamine depositing on the filter paper. 50 mL Rhodamine was diluted with 500 mL pure water and the resulting solution was regarded as the mother liquor in the follow-up tests. First, 0.5-mL Rhodamine mother liquid was extracted using a micropipettor and dropped into a volumetric container with 100-mL pure water. The concentration of Rhodamine in the resulting diluent was measured. Then, 0.5-mL Rhodamine mother liquid was again extracted and dropped on a piece of filter paper. After the dropped filter paper drying, it was washed in another volumetric container with 100-mL pure water and the concentration of Rhodamine in the cleaning solution was measured. The test was repeated for 3 times.

RESULTS AND DISCUSSION

Recovery rate

The experimental data of recovery rate is shown in Table 2, from which the average recovery rate was worked out to be 84.94%.

Table 2 The results of the recovery ratio test

Test	Concentration (μg/L)			Average
	Repeat 1	Repeat 2	Repeat 3	
Mother liquor	50.62	51.02	51.25	
Cleaning solution of dropped filter paper	42.80	43.51	43.55	
Recovery rate (%)	84.55	85.28	84.98	84.94

The results of factorial experiment

The test data of spray droplet deposition on the top, in the middle, and at the bottom layer of the droplet collecting device are shown in Table 3, 4, and 5. It can be seen from Table 3 that for the spray deposition on the top layer the CVs of three tests (the test number is 1, 9, and 5) are the smallest, namely 0.20, 0.27, and 0.28. From Table 4 it can be seen that the three CVs of the spray deposition in the middle layer (the test number is 5, 9, and 4) are the smallest, namely 0.19, 0.22, and 0.26. In Table 5 the three CVs of spray deposition at the bottom layer (the test number is 5, 4, and 9) are the smallest, namely 0.27, 0.28, and 0.34. From the above results, it shows that No.5 test (Level combination is A_2B_2) can provide the smallest CV of the droplet deposition on the top, middle, and bottom layers. That is to say, when frequency, duty cycle, and vehicle speed are respectively 5 Hz, 0.5, and 1.1 m/s (A_2B_2), the droplet deposition uniformity on the top, middle, and bottom layers of the collecting device is higher than that of other level combinations for variable-rate spray with constant-pressure control. Therefore, the level combination of No.5 test is the optimal combination of factors.

The data of No.5 test on the top, middle, and bottom layers were input to EXCEL and the distribution plot of spray droplet deposition was drawn using "Curved Surface " method in EXCEL and shown in Figure 5. It can be seen from

Figure 5 that the deposition volume on the middle layer is obviously more than that on the top and bottom layers. The deposition volume gradually increases from the top and the bottom to the middle layer. Around the center of the middle layer the deposition volume reaches its maximum. The overall deposition uniformity of the three layers is all well, however the uniformity of the bottom layer is better than that of the top.

Spray deposition on the fruit tree

The distribution of the droplet deposition on the front side of leaves on the tree canopy is shown in Figure 6. When the flow-rate was changed through opening unilateral nozzles or bilateral nozzles, the distribution feature of spray droplet deposition on the front side of leaves of the tree canopy surface essentially remains consistent.

Table 3 The droplet deposition on the top line of the collecting device

Test number	Deposition volume (μg/L)											
	Filter-paper number									Mean value	Standard deviation	CV
	1	2	3	4	5	6	7	8	9			
No. 1	3.70	1.08	2.24	2.56	3.02	3.66	5.18	4.48	2.05	3.11	1.28	0.41
No. 2	3.96	0.19	0.66	0.82	0.62	11.86	0.70	0.30	4.20	2.59	3.80	1.47
No. 3	1.07	2.72	1.90	11.97	0.94	0.42	5.50	0.98	0.57	2.90	3.75	1.29
No. 4	17.55	15.08	13.13	16.84	8.78	16.57	13.63	18.20	12.76	14.73	2.98	0.20
No. 5	3.00	2.88	5.62	5.02	6.12	6.23	7.01	6.83	5.93	5.41	1.52	0.28
No. 6	2.89	4.45	5.04	2.30	3.10	5.56	5.03	5.80	4.95	4.35	1.26	0.29
No. 7	31.99	24.02	14.90	17.69	17.01	13.18	23.40	16.10	22.12	20.05	5.89	0.29
No. 8	18.11	11.05	20.79	11.08	14.62	13.74	8.08	9.36	14.41	13.47	4.10	0.30
No. 9	7.33	8.50	8.83	6.90	6.30	12.80	8.87	7.12	5.44	8.01	2.14	0.27

Table 4 The droplet deposition on the middle line of the collecting device

Test number	Deposition volume (μg/L)											
	Filter-paper number									Mean value	Standard deviation	CV
	1	2	3	4	5	6	7	8	9			
No. 1	7.44	6.19	5.85	3.11	10.09	9.32	7.77	6.18	7.17	7.01	2.05	0.29
No. 2	3.22	1.13	0.71	2.41	5.01	2.09	0.96	0.61	2.13	2.03	1.42	0.70
No. 3	0.20	5.67	8.13	2.07	9.17	0.71	4.47	9.88	2.58	4.76	3.66	0.77
No. 4	22.61	21.52	15.49	19.78	31.03	19.64	17.65	15.59	29.29	21.40	5.53	0.26
No. 5	7.33	8.31	7.61	9.58	10.18	12.12	7.48	8.34	11.19	9.13	1.73	0.19
No. 6	7.00	13.96	4.96	6.19	9.13	6.45	25.67	9.14	5.10	9.73	6.59	0.68
No. 7	15.11	22.07	53.79	15.69	34.52	24.76	19.97	28.71	22.46	26.34	11.95	0.45
No. 8	20.12	32.45	29.93	19.29	13.89	15.04	21.51	22.18	13.11	20.84	6.75	0.32
No. 9	10.84	11.46	10.54	13.02	13.08	6.58	11.79	11.03	7.05	10.60	2.32	0.22

Table 5 The droplet deposition on the lower line of the collecting device

Test number	Deposition volume (μg/L)											
	Filter-paper number									Mean value	Standard deviation	CV
	1	2	3	4	5	6	7	8	9			
No. 1	6.39	2.39	6.51	4.58	2.52	4.04	5.32	6.65	2.29	4.52	1.82	0.40
No. 2	2.33	0.60	0.10	1.41	1.02	2.03	1.32	0.12	0.77	1.08	0.78	0.72
No. 3	1.55	3.81	1.97	0.46	3.34	4.84	1.35	2.34	0.68	2.26	1.47	0.65
No. 4	11.20	8.72	9.36	10.83	10.19	16.44	17.86	13.35	8.91	11.87	3.32	0.28
No. 5	3.17	3.39	3.41	4.31	5.33	3.39	4.33	5.87	6.29	4.39	1.18	0.27
No. 6	2.63	4.76	3.42	3.41	4.53	5.39	10.01	4.18	4.07	4.71	2.15	0.46
No. 7	22.22	23.10	9.07	8.96	17.41	12.04	8.64	7.85	18.26	14.17	6.12	0.43
No. 8	11.83	11.93	8.06	7.01	7.94	7.20	22.13	12.38	11.06	11.06	4.68	0.42
No. 9	5.25	5.65	9.30	9.49	5.56	7.05	8.51	4.65	3.18	6.52	2.20	0.34

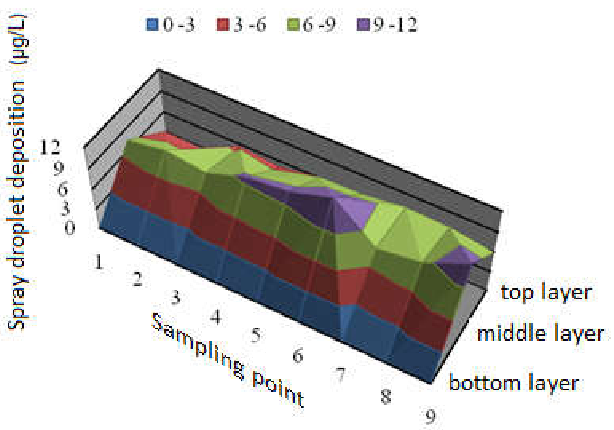
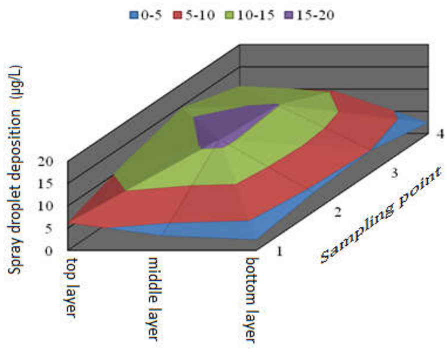
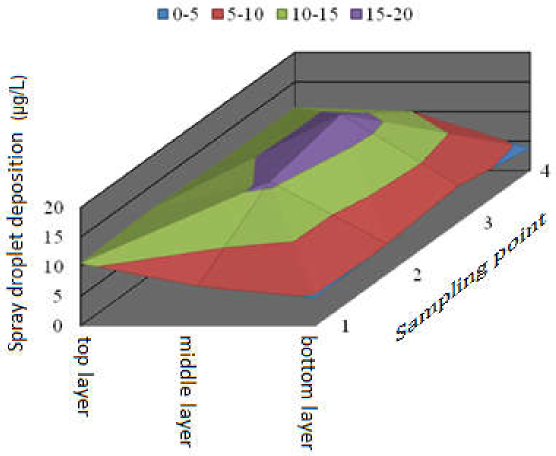


Figure 5 The distribution of the droplet deposition on the collecting device of test No. 5

Namely, the deposition volumes on the top, middle, and bottom layers all gradually increase from both sides to the center, the area with the highest deposition volume which is about 15-20 μg/L is in the center of the whole measuring field.



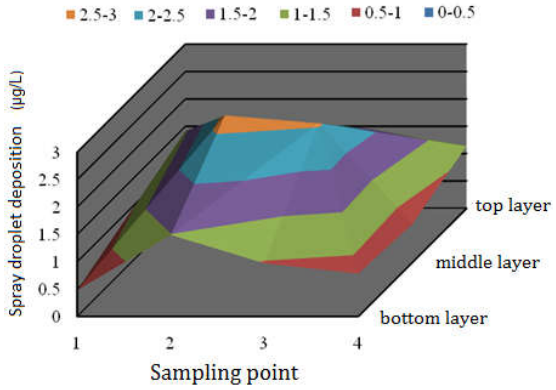
1 unilateral nozzles open



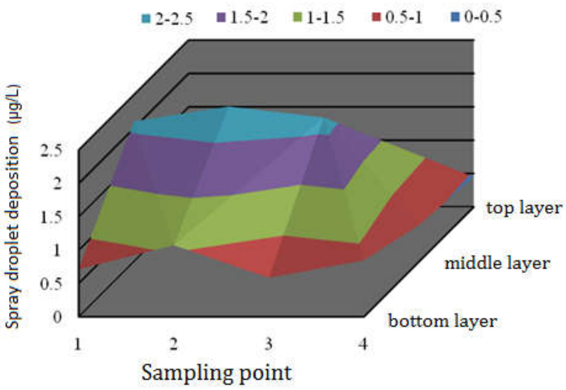
2 bilateral nozzles open

Figure 6 The distribution of the droplet deposition on the front side of leaves on the surface of the tree canopy

The distribution of the droplet deposition on the back side of leaves of the tree canopy is shown in Figure 7. When the flow-rate was changed through opening unilateral nozzles or opening bilateral nozzles, the distribution feature of spray droplet deposition on the back of leaves of the top and bottom layers basically remains the same, while the area with the highest deposition volume in the center is larger for opening unilateral nozzles.



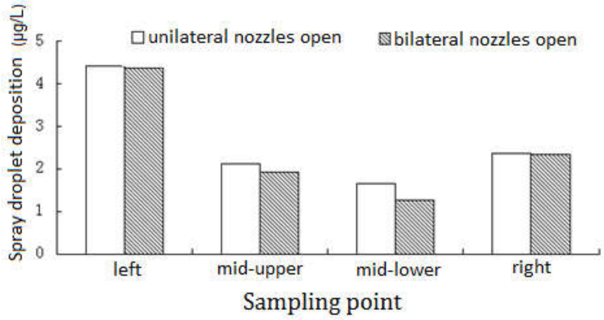
1 unilateral nozzles open



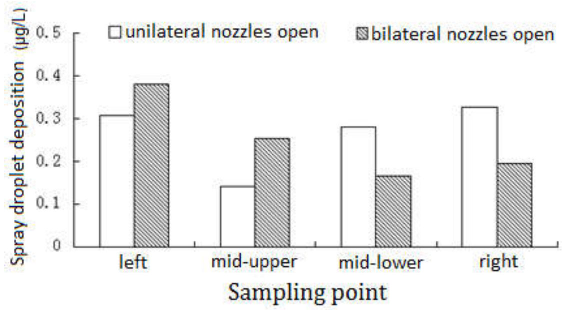
2 bilateral nozzles open

Figure 7 The distribution of the droplet deposition on the back side of leaves of the tree canopy

The distribution of the droplet deposition inside the tree canopy is shown in Figure 8. It is obvious that the deposition volume on the front side of leaves is greater than that on the back side of leaves. The deposition on the front side of leaves inside the tree are basically the same for the four locations of the left, the right, the upper, and the lower sampling point when opening unilateral nozzles or opening bilateral nozzles, which indicates a good pressure stability. The reason that the deposition on the both sides is greater than that on the center position of the tree is probably because the foliage density in the center of the canopy is greater that on the sides of the tree. It is also shown in Figure 8 that the deposition uniformity on the back side of the leaves is less than that on the front side of the leaves for the four locations of the left, the right, the upper, and the lower sampling point when opening unilateral nozzles or opening bilateral nozzles. On the whole, the deposition uniformity on the front side of leaves is better than that on the back side.



1 The deposition on the front side of leaves

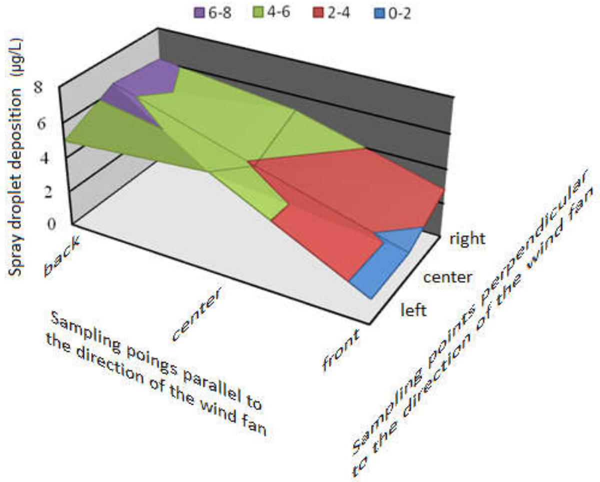


2 The deposition on the back side of leaves

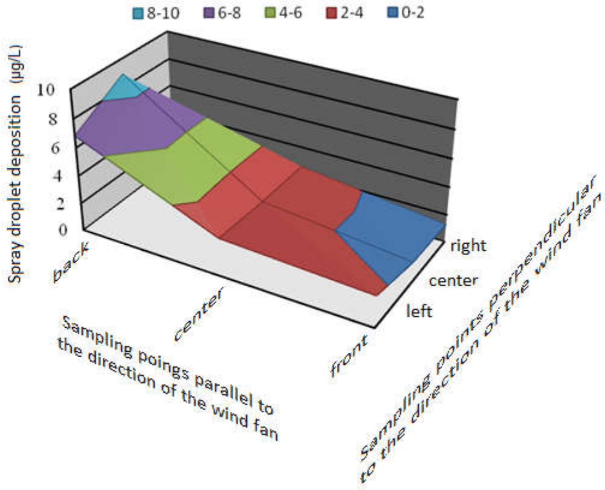
Figure 8 The distribution of the droplet deposition inside the tree canopy

The distribution of the droplet deposition on the ground shadow of the tree canopy is shown in Figure 9. It is shown in Figure 9 that the deposition of spray droplets gradually decreases outward from the tree. The trend basically remains consistent when the flow-rate was changed through opening unilateral nozzles or bilateral nozzles, which further indicates that the stability of the spray pressure is satisfying.

The test result of the variable-rate spray with constant-pressure control on the fruit tree indicated that the volume and the feature of spray droplet distribution on both the front and the back sides of the leaves on the canopy surface was basically not influenced by the change of the number of the open nozzles. The spray droplet distribution on the front side of the leaves inner the tree canopy was less susceptible to the changing number of open nozzles, while the spray distribution on the back side of the leaves inner the tree canopy was greatly affected by the number of open nozzles. The reason is probably related to the droplet penetration weakening gradually from the canopy surface to the inside of the tree. The deposit volume of the spray droplet inner the tree was far less than that on the canopy surface. The more, the deposit volume on the ground shadow of the tree canopy progressively decreased from the main trunk of the tree to external shadow. And the deposition distribution was not affected by the change number of open nozzles.



1 unilateral nozzles open



2 bilateral nozzles open

Figure 9 The distribution of the droplet deposition on the ground shadow of the tree canopy

CONCLUSIONS

1. Through the factorial experiment of spray droplet deposition with constant-pressure control, the combination of experimental influence factors with the smallest CV of the droplet deposition was found out to be No.5 test (Level combination is A_2B_2), namely frequency, duty cycle, and vehicle speed are respectively 5 Hz, 0.5, and 1.1 m/s.
2. Under the experimental factor of No.5 test and the pressure of constant-pressure controller was set at 0.3 Mpa, when the spray flow-rate in orchard was changed through opening unilateral nozzles or bilateral nozzles, the distribution feature of spray droplet deposition respectively on the front and back sides of leaves of the tree canopy surface, inner the tree, and on the ground shadow of the tree essentially remains consistent, which indicated that the stability of spray pressure was not influenced by the variable-rate spray.

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