Spray drift characteristics of pulse-width modulation sprays in wind tunnel

Longlong Li[1,2,3], Liping Chen[4,5], Ruirui Zhang[1,3*], Qing Tang[4,5], Tongchuan Yi[4,5], Boqin Liu[6], Wei Deng[1,3]

(1. *Research Center of Intelligent Equipment, Beijing Academy of Agricultural and Forestry Sciences, Beijing 100097, China*; 2. *Qingyuan Smart Agriculture and Rural Research Institute, Qingyuan 511500, Guangdong, China*; 3. *National Research Center of Intelligent Equipment for Agriculture, Beijing Academy of Agricultural and Forestry Sciences, Beijing 100097, China*; 4. *National Center for International Research on Agricultural Aerial Application Technology, Beijing Academy of Agricultural and Forestry Sciences, Beijing 100097, China*; 5. *Beijing Key Laboratory of Intelligent Equipment Technology for Agriculture, Beijing Academy of Agricultural and Forestry Sciences, Beijing 100097, China*; 6. *College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, Shaanxi, China*)

Abstract: Pulse-width modulation (PWM) sprays can improve flow accuracy by adjusting duty cycle and frequency signal which accurately controls the relative proportion of opening time of solenoid valve. The objective of this research was to determine the impacts of PWM duty cycle and frequency on spray drift characteristic. Spray tests were conducted in a wind tunnel with a PWM variable-rate spraying system. The airborne drift and sediment drift were determined with tracer method, and the drift potential reduction (*DPR*) compared with reference condition of 100% duty cycle at vertical profile and horizontal planes were calculated, respectively. The results show that, at a given frequency, droplet size decreases with the increase of duty cycle, the main reason is that the liquid does not reach full pattern development at lower duty cycle. Duty cycle has a greater impact than the frequency on spray drift, the influence weights of duty cycle on airborne drift and sediment drift were 88.32% and 77.89%, respectively. At a lower PWM frequency, in addition to the droplet size, the spray drift may be affected by the pulsed spray pattern. From the perspective of reducing spray drift, it is recommended that the PWM duty cycle should be set in the range of 20%-70% to reduce the potential drift in PWM sprays. This research provides a pesticide drift reduction scheme for variable spraying technology, which can serve as a theoretical basis for PWM parameter selection.

Keywords: nozzle, spray drift, pulse-width modulation, drift potential reduction, droplets spectral
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1 Introduction

Pesticides play an essential role in preventing and controlling serious plant pests and diseases and ensuring national food security. During spraying, 20%-30% of the fine droplets drift into non-target areas because of the wind. This situation not only causes pesticide waste, but also leads to crop phytotoxicity and water and air pollution, threatening the safety of humans and animals[1,2]. The reduction of such drift during spraying has become an important research topic in the field of pesticide application[3].

The variable-rate spraying technique is an important method of achieving high-efficiency low-volume pesticide application. Among the available variable-rate spraying techniques, pulse-width modulation (PWM) has been favored because of its precise pesticide application and fast response[4]. This technology can realize real-time adjustment of the nozzle flow rate by regulating the PWM duty cycle and frequency. This technology enables the pressure of the spray system to remain unchanged during operation and has little effect on the spray characteristics. It can effectively solve the problems of pressure-output-control technologies, such as droplet deformity and system pressure instability, while addressing the problem of inserting variable-rate technologies. Additionally, it ensures the uniformity of the spray droplet deposition and a wide adjustment range for the flow rate[5,6]. Given these advantages, numerous variable-rate spraying systems, such as variable-rate boom, variable-rate knapsack, and variable-rate air-assisted orchard systems, have been developed based on PWM technology and applied to various sprayers[7-12]. These methods can effectively control the pesticide dose and achieve the desired spraying effects.

To improve understanding of the working performance of PWM variable-rate sprays, many studies have been carried out on droplet size, nozzle tip pressure and deposition distribution. Butts et al.[13] explored the effects of the PWM duty cycle on the droplet spectrum and pressure at the nozzle tip in a wind tunnel, suggesting that Venturi nozzles should not be used in PWM variable-rate spraying systems. Lebeau et al.[14] and Jiang et al.[15] examined the uniformity of the dynamic droplet deposition n distribution under different PWM working conditions. Li et al.[16] constructed a PWM variable-rate spray system using a high-frequency solenoid valve and tested its effects on the flow rate, droplet size, atomization process, and vertical deposition distribution. Further, Zhang et al.[17] measured the droplet deposition distribution of a PWM

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Biographies: Longlong Li, PhD, research interests: plant protection machinery and chemical application technology, Email: lill@nercita.org.cn; **Liping Chen**, Professor, research interests: intelligent agricultural technology, precision agriculture, Email: chenlp@nercita.org.cn; **Qing Tang,** PhD, research interests: agricultural aviation application, Email: tangq@nercita.org.cn; **Tongchuan Yi**, Engineer, research interests: electrics and electronics, Email: yitc@nercita.org.cn; **Boqin Liu**, Master candidate, research interests: agricultural engineering, Email: boqinliu_lbq@163.com; **Wei Deng**, PhD, research interests: precision agriculture, Email: dengw@nercita.org.cn.
*__Corresponding author: Ruirui Zhang__, Professor, research interests: agricultural aviation application and precise spraying. Beijing Nongke Mansion, No.11 Shuguang Huayuan Middle Road, Haidian District, Beijing 10097, China. Tel: +86-10-51503991, Email: zhangrr@nercita.org.cn.

variable-rate spray by using a dot-matrix droplet deposition sensor. Zhai et al.[18] and Wei et al.[19] constructed models to compute the spray flow of different nozzles, providing corresponding pesticide application control algorithms for developing precise variable-rate spraying systems. In addition, Deng et al.[20] used a flat fan spray nozzle and investigated the variation patterns of the spray amount, distribution, spray angle, droplet velocity, and dynamic properties of PWM. These researches enhance understanding of the characteristics of PWM variable-rate sprays. However, studies on the influence of different PWM working conditions on the droplet drift have not been reported. During the application of PWM variable spraying, the regulation of both the flow rate and drift caused by the changes in the PWM parameters should be considered.

In this study, a PWM variable-rate spraying system was designed, and spray-drift experiments were conducted in an IEA-II wind tunnel at the National Research Center of Intelligent Equipment for Agriculture in China. The drift-potential reduction (*DPR*) was calculated as the evaluation parameter to explore the spray drift characteristics under various PWM duty cycles and frequencies under controllable environmental conditions. The results are expected to serve as a theoretical basis for PWM parameter selection and spraying system optimization.

2 Materials and methods

The experiments were conducted at the Beijing Xiaotangshan National Experiment Station for Precision Agriculture. The test equipment included a PWM variable-rate spraying system, a laser particle size analyzer (HELOS-VARIO, SYMPATHEC GmbH, Germany), a wind tunnel, and an ISO F110-03 nozzle (Hardi International, Denmark). An aqueous solution concentration of 2.5‰ silicone additives (Runhebao Biotechnology Co., Ltd, China) was used to simulate the pesticide solution. The spray pressure was set as 0.3 MPa for all tests.

2.1 PWM variable-rate spraying system

The PWM variable-rate spraying system consisted of a tank, diaphragm pump, surge tank, flowmeter, PWM controller, solenoid valve, and pressure gauge (Figure 1). The controller was designed to modulate the PWM frequency and duty cycle using an electric signal. Upon receiving the signals, the solenoid valve immediately acted to change the flow rate. The solenoid valve is the main control element of the spraying system, and its performance determines system execution. At present, the frequencies of PWM spraying systems are generally less than 10 Hz[19,21], and a few studies have reached 16 Hz[14]. To improve the response speed, a new solenoid valve (Tengwang Auto Parts Co., Ltd., China) with a maximum operating frequency of 167 Hz and a response time of 0.9 ms was assembled for the system. In reference [16], the technical parameters of this solenoid valve were described in detail, and spray characteristics on pulse-width modulation sprays with the solenoid valves were studied. In this study, the PWM frequencies were set to 5 Hz, 10 Hz, and 15 Hz, and the duty cycle was set from 10% to 100% in 10% intervals.

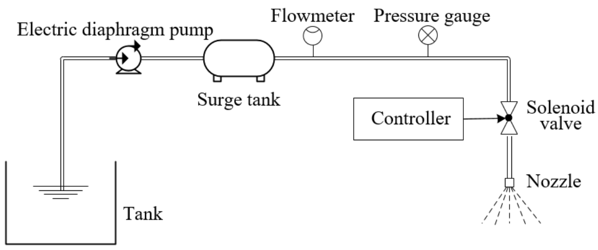


Figure 1 PWM variable-rate spraying system

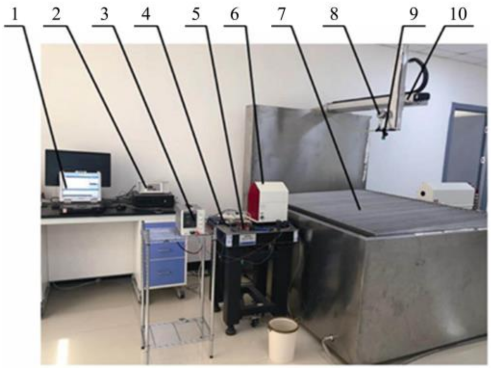
2.2 Measurement of nozzle parameters

2.2.1 Flow rate

The nozzle flow rate is related to PWM frequency and duty cycle[21,22]. To determine the flow rate of the spraying system, a weighing method was used to measure the nozzle flow rate under various PWM conditions. For each measurement, the spray mixture spout within 30 s was collected and the flow rate (L/min) was calculated. The measurements were repeated five times for each set, and the average values were calculated.

2.2.2 Droplet spectrum analysis

A HELOS-VARIO/KR laser particle size analyzer was used to measure the droplet spectra. The analyzer can measure particle sizes from 0.1 to 3500 μm. The analyzer used an R7 lens; the laser transmitter and detector were held along the same axis, and the nozzle was installed 0.5 m above the laser beam. During the tests, the flat-fan atomization plane remained perpendicular to the laser beam. A typical cumulative droplet spectrum was adopted to characterize the droplet size distribution for different PWM working parameters of the ISO 110-03 nozzle. D_{V10}, D_{V50}, and D_{V90} represent the diameters for which smaller droplets constituted 10%, 50%, and 90% of the total volume, respectively. Additionally, the proportional characteristics V_{100}%, V_{150}%, and V_{210}% represent the volume percentages of droplets with diameters smaller than 100 μm, 150 μm, and 210 μm, respectively[23]. Generally, the atomization parameters of V_{100}%, V_{150}%, and V_{200}% were used to characterize spray drift potential. Unfortunately, there is no V_{200}% in the output result of this instrument, so in this study, the adjacent V_{210}% is used to replace V_{200}%. The droplet spectrum test platform is shown in Figure 2.



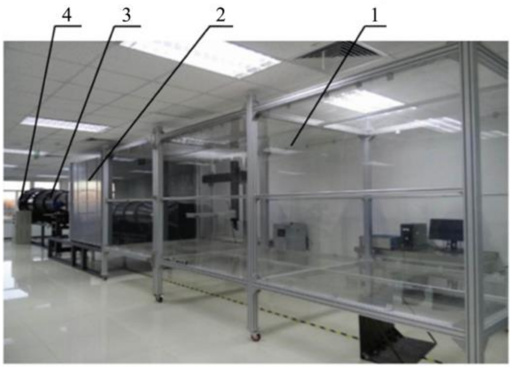
1. Computer 2. Mechanical arm controller, 3. Power supply 4. PWM controller 5. Solenoid valve 6. Laser particle size analyzer 7. Droplet collection device 8. Pressure gauge 9. Nozzle 10. Motor driving two-dimensional arm

Figure 2 Droplet size testing setup

2.3 Drift measurement in wind tunnel

Spray drift tests were performed in an IEA-II wind tunnel[17]. The wind tunnel was designed as a direct-current opening self-priming type, which consisted of a centrifugal blower, contraction section, steady section, and test section. The test section, with dimensions of 6 m×2 m×2 m, was used to conduct the drift test under controlled environmental conditions. This tunnel produces a uniform wind field (turbulence intensity less than 0.3% and uniformity less than 0.5%) with a working air speed range of 0.5-7.0 m/s. The wind tunnel structure is illustrated in Figure 3.

The tests were conducted in the test section of the wind tunnel. To eliminate the influence of the tunnel floor on the wind flow turbulence and spray droplet bouncing and to prevent passive collectors from touching the floor, an artificial ground was set at a height of 0.1 m above the tunnel floor. The nozzle was installed 0.5 m above the artificial ground, with the spray fan orientated at a right angle to the wind direction. Polyethylene lines with a diameters of 2.0 mm were used as passive collectors to collect the droplets. In the vertical plane, five polyethylene lines (V_1-V_5) were placed vertically across the wind tunnel 2 m downwind from the nozzle at heights from 0.1 m to 0.5 m in 0.1 m intervals. These vertical collection lines were used to determine the airborne spray profiles. Nine lines (H_1-H_9) were placed in a horizontal array at distances of 2.0-6.0 m in 0.5 m intervals. With these horizontal collecting lines, the sediment drifts at different distances were determined. V_1 and H_1 are the same collection lines. An ultrasonic anemometer was fixed above the nozzle to obtain the real-time wind speed[24,25]. The PWM duty cycles and frequency settings were the same as those discussed in Section 1.2. In the drift tests, tartrazine (8 g/L) was added as a tracer to the aqueous solution of silicone additives[26]. The spraying time was strictly controlled to be 10 s using a timer. When the droplets on the line surface had completely dried, the collection lines were collected in a plastic zipper bag and stored in a dark box. The wind speed in the wind tunnel was set to 2.0 m/s, and each test was repeated thrice. For drift deposit measurements, the polyethylene lines were washed with 20 mL of deionized water. An ultraviolet-visible spectrophotometer (752N, INESA Co., Ltd.) was used to measure the absorbance of the tracer solution at a wavelength of 426 nm, and the deposit volume was subsequently calculated. During the tests, the temperature in the wind tunnel was 23 ℃, and the relative humidity was 38%.



1. Test section 2. Steady section 3. Contraction section 4. Centrifugal blower

Figure 3 Structure of the IEA-II wind tunnel

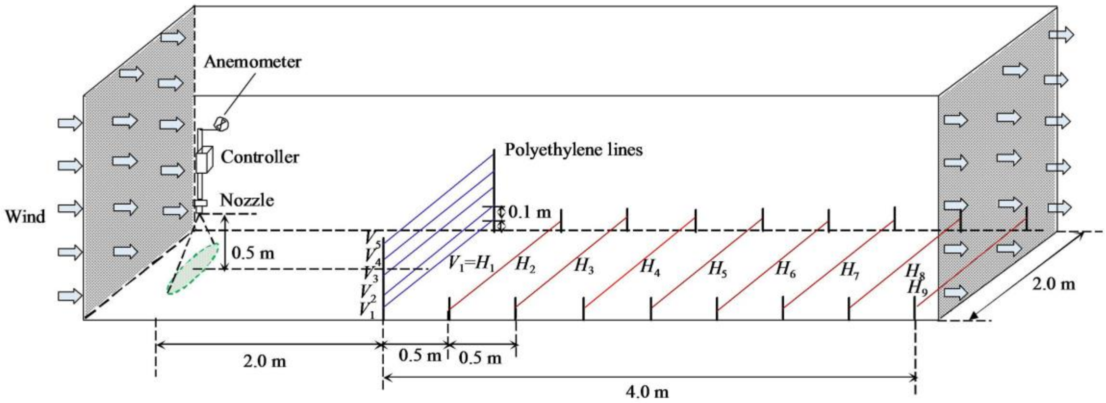


Figure 4 Schematic layout of the collecting line arrangement in the wind tunnel

2.4 Data analysis and processing

2.4.1 Drifting deposit measurement

According to the absorbance value of the tracer solution, the drifting droplets on each polyethylene line were determined using the following equation[27]:

$$V'_{i/j}=\frac{V_w\times FL_s}{N\times FL_a}\times 1000 \tag{1}$$

where, $V'_{i/j}$ is deposit volume attached to a vertical or horizontal polyethylene line, μL. Here, i represents a polyethylene line arranged vertically, which takes values of 1, 2, 3, 4, and 5 from the bottom to the top; j indicates a polyethylene line that is set horizontally and takes values of 1, 2, 3, 4, 5, 6, 7, 8, and 9 in the downwind direction; V_w is the volume of the elution liquid, mL; N is the dilution factor of of spraying solution; FL_s is the absorbance value of the eluent; FL_a is the absorbance of spraying solution.

2.4.2 Calculation of normalized deposit

The drifting deposit is directly related to the pesticide dosage, and the nozzle spout varies with the PWM working conditions. The drifting deposit volumes obtained in Section 2.4.1 were normalized[28]. Thus, the drifting deposits obtained at different nozzle flow rates could be directly compared. The normalization equation can be expressed as follows:

$$V_{i/j}=\frac{V'_{i/j}V_w\times 60}{10\times V_N} \tag{2}$$

where, $V_{i/j}$ represents the normalized volume of on the vertical or horizontal polyethylene line, μL/L; V_N is the nozzle flow rate, L/min.

2.4.3 Drift evaluation

Spray drift evaluation is important for chemical application techniques, and it serves as a positive guide for pesticide dosage reduction by selecting the appropriate spraying parameters and optimizing the spraying system. Herbst[29] proposed the drift-potential index in 2001 and tested the total droplet volume flux in the vertical profile to evaluate nozzles and spray equipment. Nuyttens et al.[30] proposed a reduction percentage using the Hardi ISO F110-03 nozzle as a reference to clarify the drift reduction performance by comparing accumulated drift deposits. In this study, passive collectors were arranged in the vertical and horizontal directions in a wind tunnel, and the *DPR* was adopted to evaluate the PWM variable-rate spray drift performance. A 100% PWM duty cycle was adopted as the reference working condition.

The total droplet volume fluxes in the vertical and horizontal planes can be determined as follows:

$$DP_V=\sum_{i=1}^{i=5}V_i\times\frac{\Delta d_C}{D_C}\times 10^6 \tag{3}$$

$$DP_H=\sum_{i=1}^{i=9}V_j\times\frac{\Delta d_C}{D_C}\times 10^6 \tag{4}$$

where, DP_V denotes the drift potential in the vertical profile; Δd_C is the distance between the corresponding collecting lines in the vertical direction, the corresponding value of the highest and lowest lines is half of the spacing, where i takes values of 1, 2, 3, 4, and 5, and the corresponding Δd_C values are 0.05 m, 0.1 m, 0.1 m, 0.1 m, and 0.05 m, respectively; DP_H is the drift potential value in the horizontal plane; for j values of 1, 2, 3, 4, 5, 6, 7, 8, and 9, the corresponding Δd_C values are 0.25 m, 0.5 m, 0.5 m, 0.5 m, 0.5 m, 0.5 m, 0.5 m, 0.5 m, and 0.25 m, respectively; D_C is the diameter of the polyethylene line, m.

Subsequently, the drift potential reduction under the setting condition was calculated and compared with the reference 100% duty cycle. If the DPR value is positive, a larger DPR value corresponds to a better drift-reduction performance. Conversely, a negative DPR value indicates that the set working condition is more likely to cause spray drift than the reference condition.

$$DPR = \frac{DP^{rs} - DP^{os}}{DP^{rs}} \times 100\% \tag{5}$$

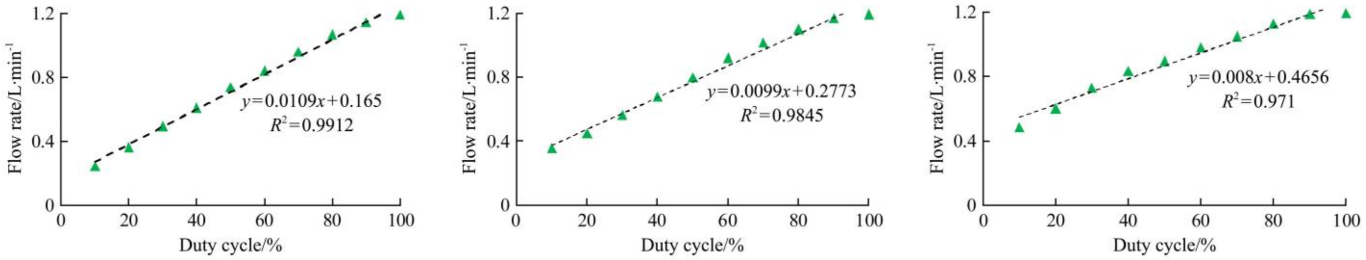
where, DP^{rs} is the reduction percentage under the reference condition of a 100% PWM duty cycle, this data is calculated based on Equations (3) and (4); DP^{os} is the percentage reduction under the tested working conditions.

3 Results

3.1 Measurement of nozzle parameters

3.1.1 Flow rate

Understanding the correlations between the nozzle flow rate and the PWM frequency and duty cycle is the key to controlling the chemical output precisely. The flow rates of the ISO 110-03 nozzle at different PWM frequencies and duty cycles are shown in Figure 5. It can be observed that the flow rate and PWM duty cycle are positively correlated, and the flow rate gradually increases with increasing duty cycle. Moreover, the flow rate growth slows when the duty cycle exceeds 90%. The main reason for this tendency is that the response speed of the mechanical components of the solenoid valve is not as high as that of the electronic signal. At a given frequency, the relationship between the flow rate and duty cycle can be well described by a linear equation[31,32], and the corresponding R^2 values at 5 Hz, 10 Hz and 15 Hz conditions are 0.99, 0.98, and 0.97, respectively. For different PWM spraying systems, the nozzle flow rate does not maintain a linear relationship in the range of 0%-100%, which is related to the structure of the solenoid valve, response time of the solenoid valve, and control circuit. Reference [14] explored the relationship between the duty cycle and flow rate in the PWM frequency range from 0.5 to 35 Hz and found that a better linearity with a larger bandwidth of the linear zone was observed at lower frequencies. Generally, in PWM sprays, the working PWM duty cycle range with a good linear correlation should be selected to establish a mathematical function to improve the control accuracy of the nozzle spout. To this end, a high-frequency high-speed solenoid valve was adopted, which restrained the bandwidth reduction for the working frequencies of 5 Hz, 10 Hz, and 15 Hz. The experiment proves that the PWM variable-rate spraying system used in this study exhibits good flow regulation performance.



a. Frequency = 5 Hz b. Frequency = 10 Hz c. Frequency = 15 Hz

Figure 5 Nozzle flow rates with different PWM frequencies and duty cycles

3.1.2 Droplet spectrum analysis

The droplet size is affected by the PWM operating parameters[33]. Before conducting the wind tunnel test, the droplet spectra were measured under different PWM working conditions, as listed in Table 1. At frequencies of 10 Hz and 15 Hz, as the duty cycle increases, D_{V10}, D_{V50}, and D_{V90} decrease gradually. Taking the working frequency of 10 Hz as an example, comparison between the 100% and 10% duty cycle cases shows that D_{V10}, D_{V50}, and D_{V90} decrease by 21.4%, 22.13%, and 67.3%, respectively. With increasing duty cycle, the percentages of the volume of droplets with diameters smaller than 100 μm, 150 μm, and 210 μm (V_{100}%, V_{150}%, and V_{210}%, respectively) tend to increase. At 10 Hz frequency, V_{100}%, V_{150}%, and V_{210}% at a 100% duty cycle increase by 6.98%, 11.28%, and 15.32%, respectively, compared with the 10% duty cycle. These increases mainly occur because the liquid does not reach full pattern development before the flow is terminated and creates coarser droplet sizes at a lower PWM duty cycle. Previous studies have shown that the droplet spectrum is an important factor affecting spray drift[34]; in particular, droplets smaller than 200 μm are a concern for potential drift[35,36]. The above results are consistent with the conclusions reported in the literatures[13,37], that is, the droplets diameter increases as the flow decreases.

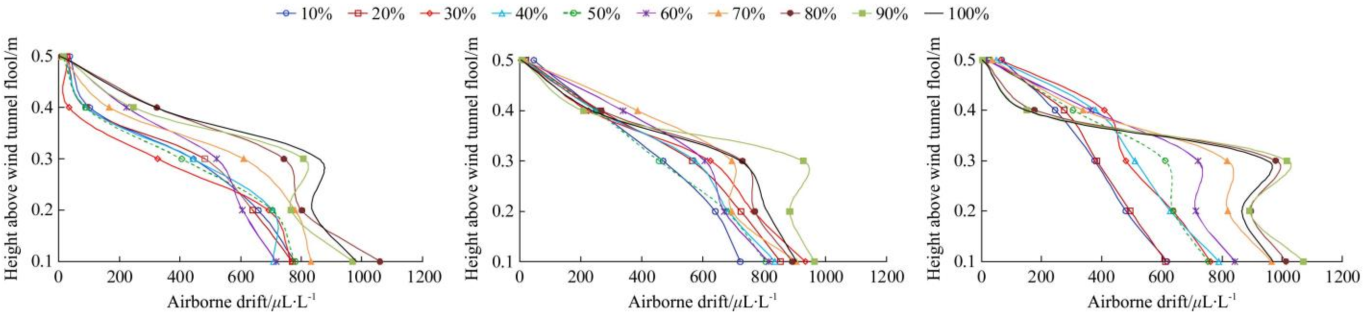
3.2 Airborne drift and sediment drift

Tracer drifting deposits on the collecting lines were measured using a spectrophotometer. The spray drift distributions in the vertical and horizontal directions are shown in Figures 6 and 7, respectively. In the vertical profile, the maximum value of airborne drift occurs at 0.1 m height above the tunnel floor, this is consistent with the airborne drift results of conventional sprays in the wind tunnel[30]. As the height increases, spray drift differs with the duty cycle. At a frequency of 15 Hz, in the 10%-40% duty-cycle range, spray drift decreases gradually as the height increases, whereas in the 50%-100% duty-cycle range, the drifting deposits at 0.3 m height is greater than that at 0.2 m. Miller et al.[38] noted that deposit height is positively correlated with drift potential and that a greater deposit height means worse drift performance. Based on this principle, it can be qualitatively concluded from the drift curve in the vertical profile that a higher duty cycle increases the drift potential. Based on this principle, it can be qualitatively concluded from the drift curve in the vertical profile that a higher duty cycle increases the drift potential in the pulse-width modulation sprays.

In the horizontal plane, the sediment drift are the greatest at 2.0 m away from the nozzle. As the distance continues to increase, the drifting deposits gradually decrease. When the distance is increased to 6.0 m, drifting deposits decrease to approximately 100 μL/L for all sets of conditions.

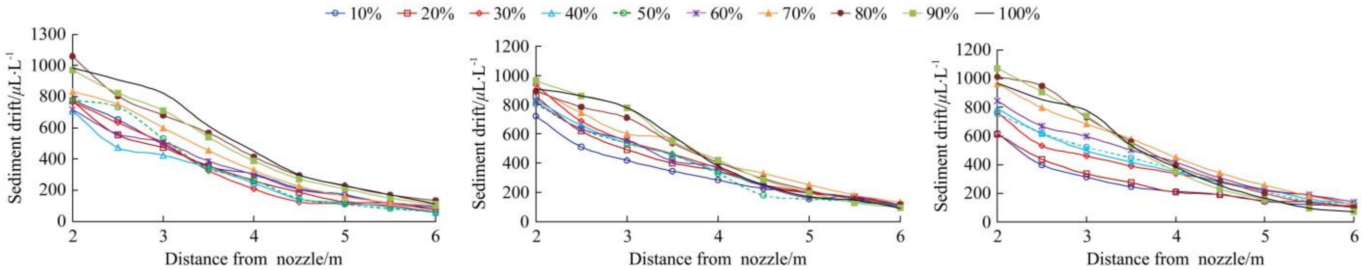
Table 1 Droplet spectrum of the ISO F110-03 nozzle under the set working conditions

Duty cycle/%	5 Hz						10 Hz						15 Hz					
	D_{V10}/μm	D_{V50}/μm	D_{V90}/μm	V_{100}%	V_{150}%	V_{210}%	D_{V10}/μm	D_{V50}/μm	D_{V90}/μm	V_{100}%	V_{150}%	V_{210}%	D_{V10}/μm	D_{V50}/μm	D_{V90}/μm	V_{100}%	V_{150}%	V_{210}%
10	88.18	194.54	429.69	13.34	32.77	55.37	124.73	259.19	1141.93	3.31	17.84	37.84	120.1	247.86	819.13	5.76	18.9	39.35
20	85.88	192.11	451.22	14.26	33.94	56.04	114.13	237.04	724.93	6.00	21.74	42.54	102.1	221.61	488.34	9.42	25.21	46.65
30	86.91	192.05	437.40	14.04	33.96	56.09	108.11	249.59	1291.06	7.75	22.47	40.62	96.22	209.94	461.66	10.94	28.02	50.02
40	94.71	223.49	456.24	11.28	27.70	46.90	102.56	223.43	595.53	9.22	25.81	36.35	89.06	200.91	428.95	12.96	30.87	53.24
50	93.82	222.49	447.29	11.50	27.61	46.99	101.32	216.10	500.85	9.58	26.83	48.28	82.80	187.00	390.57	15.35	35.2	58.32
60	92.06	212.56	422.12	11.99	28.85	49.35	102.61	215.53	515.63	9.18	26.52	48.41	79.71	181.58	374.40	16.55	37.05	60.2
70	85.20	193.60	404.44	14.35	33.29	55.83	104.93	227.19	1156.38	8.56	24.71	45.32	77.87	177.03	356.67	17.43	38.62	62.15
80	84.68	191.29	373.33	14.50	33.69	56.87	101.61	208.16	424.34	9.47	27.52	50.69	80.01	180.65	359.34	16.51	37.23	60.73
90	82.87	187.78	364.58	15.26	34.94	58.15	99.15	204.55	390.2	10.23	28.70	52.04	80.27	181.41	353.28	16.46	37.06	60.52
100	81.76	188.07	361.87	15.66	35.15	57.92	98.97	201.82	373.81	10.29	29.12	53.16	82.00	188.02	365.29	15.57	35.12	57.92



a. Frequency = 5 Hz b. Frequency = 10 Hz c. Frequency = 15 Hz

Figure 6 Airborne drift curves in the vertical profile under various PWM working conditions



a. Frequency = 5 Hz b. Frequency = 10 Hz c. Frequency = 15 Hz

Figure 7 Sediment drift curves in the horizontal plane under various PWM working conditions

The average spray drift in the vertical and horizontal planes were calculated (Tables 2 and 3, respectively). It can be observed that the drifting deposits increase with increasing duty cycle for a given PWM frequency. A correlation analysis was performed between the drifting deposit volume and the droplet spectrum parameters of D_{v50}, V_{100}%, V_{150}%, and V_{210}%. Table 4 lists the values of the correlation coefficient R under different PWM working conditions. The results show that D_{v50} is negatively correlated with the drifting deposit volume ($R < 0$), whereas V_{100}%, V_{150}%, and V_{210}% are positively correlated ($R > 0$). The drift characteristics of PWM sprays are consistent with those of conventional spray methods, that is, increasing the droplet size and reducing the proportion of fine droplets reduce spray drift. Previous studies have considered 100 μm[39], 150 μm[40], and 200 μm[41] as the critical droplet sizes prone to drift. In the results of this study, the relationship between D_{v50}, V_{100}%, V_{150}%, V_{210}% and both airborne drift and sediment drift at a frequency of 15 Hz are extremely significant. Significantly correlation is observed between the four parameters and the sediment drift in the horizontal direction at a frequency of 10 Hz. However, only V_{100}% shows a significant correlation at a frequency of 5 Hz, because when the frequency is lower, the solenoid valve performs the opening and closing actions relatively slowly, and the spray pattern shows contraction and expansion changes, which indirectly affect the spray drift. When the frequency is higher, owing to the shortening of the solenoid valve action period, the spray pattern is less affected by the solenoid valve pulse; thus, the correlation between the droplet spectrum and drifting deposits is enhanced.

Table 2 Average airborne drift under the various PWM working conditions

Frequency/Hz	Airborne drift/μL L^{-1}									
	Duty cycle/%									
	10	20	30	40	50	60	70	80	90	100
5	404.11	402.06	369.90	393.63	398.33	417.04	479.82	587.51	561.04	600.86
10	426.51	486.27	512.42	472.31	441.89	489.61	539.86	533.07	598.59	536.33
15	357.43	358.07	470.40	471.80	466.02	530.65	594.77	613.67	626.93	587.14

Table 3 Average sediment drift under the various PWM working conditions

Frequency/Hz	Sediment drift/μL·L^{-1}									
	Duty cycle/%									
	10	20	30	40	50	60	70	80	90	100
5	351.09	323.36	314.35	289.43	338.12	338.74	396.64	483.40	463.60	509.30
10	329.46	380.90	413.08	388.40	371.88	387.17	457.34	456.06	475.42	463.87
15	262.20	273.15	366.45	385.11	385.76	432.38	486.24	485.40	461.69	456.25

Table 4 Coefficient of correlation *R* between droplet spectrum and spray drift

`	5Hz				10 Hz				15 Hz			
	D_{v50}	V_{100}%	V_{150}%	V_{210}%	D_{v50}	V_{100}%	V_{150}%	V_{210}%	D_{v50}	V_{100}%	V_{150}%	V_{210}%
Airborne	–0.547	0.709^{*}	0.565	0.592	–0.566	0.589	0.602	0.597	-0.875^{**}	0.887^{**}	0.887^{**}	0.888^{**}
Sediment	–0.611	0.754^{*}	0.622	0.651^{*}	-0.675^{*}	0.709^{*}	0.717^{*}	0.704^{*}	-0.932^{**}	0.941^{**}	0.940^{**}	0.940^{**}

Note: Significance level at α=0.05. ** represents very significant, and * represents significant.

The effects of the PWM frequency and duty cycle on the airborne drift in the vertical and horizontal sediment drift were analyzed, and a regression analysis was performed using SPSS software (Table 5). The results show that the *P* values corresponding to the PWM duty cycle and frequency in the vertical direction are both less than 0.05, indicating that both parameters have significant impacts on airborne deposits, whereas only the duty cycle has a significant effect on sediment drift. The influence weights of the duty cycle and frequency on the spray drift were calculated based on standardized coefficients (*Beta* in Table 5). The PWM duty cycle has greater effects than the frequency on airborne drift and sediment drift, with influence weights of 77.89% and 88.32%, respectively (Figure 8).

Table 5 Influence of PWM frequency and duty cycle on drift deposits

Direction	*R*	*F* value	Variable	*Beta*	*p*
Vertical	0.708	36.226	Duty cycle	0.821	0.000
			Frequency	0.233	0.028
Horizontal	0.696	34.140	Duty cycle	0.839	0.000
			Frequency	0.111	0.287

Note: Significance level at α=0.05.

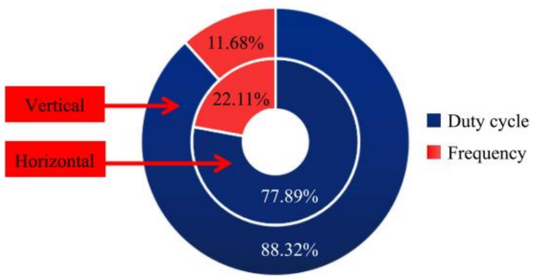


Figure 8 Influence weights of the PWM duty cycle and frequency on spray drift

3.3 Drift potential reduction

DP_V and DP_H, representing the drift deposit volume flux in the vertical and horizontal planes, respectively, were calculated according to Equations (3) and (4). The results are presented in Table 6. In general, *DP* increases with the duty cycle, which is consistent with spray drift curve. Taking the condition of a 10 Hz frequency as an example, at a 50% duty cycle, DP_V and DP_H are 0.090 and 0.722, respectively. When the duty cycle is 100%, DP_V and DP_H increase by 23.3% and 27.28%, respectively.

Based on the *DP* values in Table 6, the drift potential reduction relative to the reference condition was calculated using Equation (5). The *DPR* values under various PWM working conditions are shown in Figures 9 and 10. In the vertical direction, DPR_V exhibits a decreasing trend with increasing duty cycle, indicating that the drift reduction performance gradually decreased. A comparison among the three PWM frequencies shows that the frequency of 5 Hz produces the best drift reduction performance, where all DPR_V values are positive for all duty cycles. This is followed by 15 Hz, which provides effective drift reduction at duty cycles of 10%-70%. Under the same duty cycle condition, a frequency of 10 Hz has the worst drift reduction capability, with a minimum DPR_V of –12.6% at a 90% duty cycle. Similar to the results observed in the vertical direction, at 5 Hz, all the DPR_H values are positive, and the drift reduction capacity is the best among the three frequencies. At the frequency of 15 Hz, 10% and 20% duty cycles have the best drift reduction capacity, and the corresponding DPR_H values are 44.37% and 41.47%, respectively. When the duty cycle increases in the range of 30%-60%, DPR_H begins to decrease gradually with increasing duty cycle. At 10 Hz, DPR_H does not change abruptly when the duty cycle is below 60%. However, when the duty cycle exceeds 70%, DPR_H decreases significantly. Generally, at a given frequency, *DPR* exhibits a decreasing trend with increasing duty cycle, which means that the drift reduction capacity is weakened, and the drift potential is enhanced.

Section 3.2 demonstrated that the duty cycle has a considerable impact on drift. In order to clarify the difference in the impact of the duty cycle on *DPR*, covariance analysis was performed using SPSS software. The frequency was set as a covariate, duty cycle was set as a fixed variate, and *DPR* values under each duty cycle were compared in pairs. The results are presented in Table 7. A larger mean difference value indicates that duty cycle (I) has a better anti-drift performance than duty cycle (J). In the horizontal direction, the *DPR* values under 10%-50% duty cycles are significantly different from those of 70%-90% cycles, and the mean difference ranges from 17 to 34. In the vertical direction, the *DPR* of the 10% and 20% duty cycles is significantly different from those of the 70%-90% duty cycles, and the *DPR* of the 30%-50% duty cycles is significantly different from those of the 80% and 90% duty cycles. The above results show that when the duty cycle exceeds 60%, the drift reduction effect is significantly reduced, increasing the drift risk. For the comprehensive *DPR* values (Figures 9 and 10) in PWM sprays, the duty cycle is recommended to be below 70%.

Table 6 DP_V and DP_H for the different PWM working conditions

Frequency /Hz	DP_V										DP_H									
	Duty Cycle/%										Duty Cycle/%									
	10	20	30	40	50	60	70	80	90	100	10	20	30	40	50	60	70	80	90	100
5	0.081	0.081	0.072	0.080	0.080	0.086	0.099	0.120	0.116	0.125	0.682	0.622	0.604	0.555	0.656	0.660	0.776	0.939	0.908	1.009
10	0.087	0.100	0.104	0.097	0.090	0.102	0.112	0.111	0.125	0.111	0.639	0.736	0.799	0.755	0.722	0.755	0.899	0.900	0.937	0.919
15	0.072	0.074	0.097	0.097	0.097	0.111	0.124	0.128	0.130	0.122	0.499	0.525	0.714	0.752	0.758	0.850	0.958	0.953	0.856	0.897

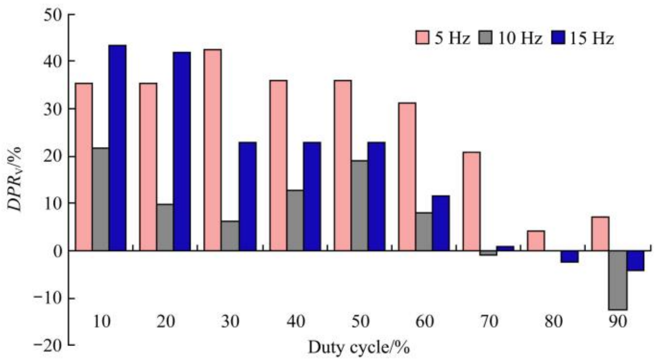


Figure 9 DPR_V for different PWM frequencies and duty cycles

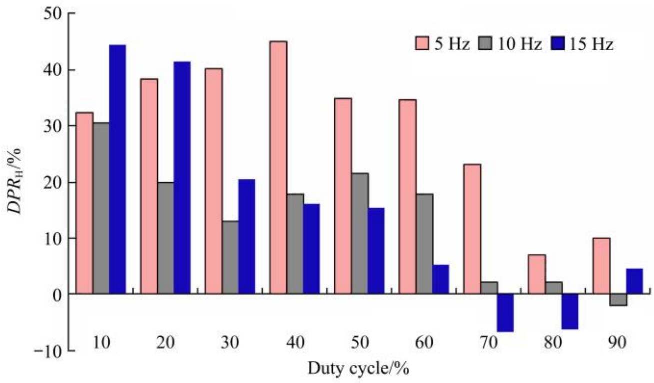


Figure 10 DPR_H for different PWM frequencies and duty cycles

Table 7 Analysis of covariance of PWM duty cycle on drift potential reduction

(I) Duty cycle/%	Horizontal			Vertical		
	(J) Duty cycle/%	Mean difference (I-J)	*P*	(J) Duty cycle/%	Mean difference (I-J)	*P*
10	70	29.592781	0.001704	70	26.515158	0.012289
	80	34.828118	0.000411	80	32.907754	0.002892
	90	31.541432	0.001002	90	36.591739	0.001243
20	70	27.090441	0.003371	70	22.064806	0.032347
	80	32.325778	0.000809	80	28.457402	0.007956
	90	29.039092	0.001982	90	32.141387	0.003446
30	70	18.376586	0.033724	—	—	—
	80	23.611922	0.008627	80	23.372047	0.024466
	90	20.325236	0.020512	90	27.056033	0.010894
40	70	20.179173	0.021301	—	—	—
	80	25.414510	0.005312	80	23.340816	0.024631
	90	22.127824	0.012801	90	27.024802	0.010970
50	70	17.816524	0.038792	—	—	—
	80	23.051861	0.010018	80	25.442918	0.015580
	90	19.765175	0.023698	90	29.126904	0.006840
60	80	18.303960	0.034345	90	20.098164	0.048751

4 Discussion

PWM sprays are important for achieving precise chemical applications. In this study, spray drift tests were conducted in a wind tunnel with controllable environmental conditions, airborne drift and sediment drift in the downwind direction were measured, and the effects of frequency and duty cycle on drift reduction characteristics were analyzed.

Firstly, the relationship between the duty cycle and flow rate at frequencies of 5 Hz, 10 Hz, and 15 Hz was measured. It is confirmed that the nozzle flow rate and duty cycle exhibited an excellent linear relationship under the test conditions (Figure 5), which confirmed that the PWM variable-rate spraying system used in this study is feasible for flow regulation. Furthermore, the droplet spectra under different PWM working conditions were measured (Table 1), and the results showed that with increasing duty cycle, the size of the droplets gradually decreased, and the proportion of fine droplets increased. The reason for this phenomenon is that when the duty cycle was lower, only part of the way developed and droplets failed to form an incomplete pattern before the flow was terminated, resulting in reduced efficacy and inefficient applications. Therefore, PWM solenoid valves should avoid using duty cycles of 20% or lower[42,43].

The spray drift curves in the vertical profile and horizontal planes were measured using a spectrophotometer (Figures 6 and 7), and it was confirmed that, at a given frequency, a higher duty cycle significantly increased the drift potential. A greater deposit height was observed at a frequency of 15 Hz, indicating that the possibility of drift pollution increased. Correlation analysis was conducted on the drift deposits and droplet spectrum parameters (D_{v50}, V_{100}%, V_{150}%, and V_{210}%) under different PWM conditions (Table 4), and the correlations between the four parameters and drifting deposits at the same frequency did not show regular differences. However, at 15 Hz frequency, the droplet size parameter had an extremely significant correlation with drift deposits. For PWM variable-rate sprays, the spray drift performance is not only affected by the droplet spectrum, but also by the special spray pattern caused by the solenoid valve pulsed action. In reference [16], the authors used high-speed photography technology and found that, in the PWM variable-rate spraying process, instantly opening and closing the solenoid valve could break up the atomization zone, affecting the atomization of the nozzle and altering the diffusion performance of the spray plume.

Based on the drifting deposit volume on the passive collectors and taking the duty cycle of 100% as the reference condition, the drift potential reduction (*DPR*) under different PWM conditions was calculated (Figures 9 and 10). It is observed that at the same frequency, as the duty cycle increases, the *DPR* value decreases. Furthermore, the influence weights of the PWM frequency and duty cycle on drift were analyzed (Figure 8), and the results showed that the effect of duty cycle was more heavily weighted than frequency, and the potential drift risk was significantly increased when the duty cycle exceeded 60%.

Frequency and duty cycle are the main parameters affecting PWM sprays. In this study, wind tunnel drift tests confirmed that the PWM duty cycle affected the droplet spectrum, which in turn affected the spray drift characteristics. To achieve precise flow regulation, reducing drift pollution as much as possible and improving spray quality are the ultimate goals of PWM spraying, and choosing the appropriate PWM parameters is the key to realizing these objectives. The literatures[13,38] showed that the duty cycle minimally impacted the nozzle tip pressure trends, which were similar to the electrical square-wave PWM signals. These can affect the spray pattern and cause pressure loss, which in turn affects the droplet deposit distribution. It is recommended that the spray PWM duty cycle be greater than 40%. A previous study[44] confirmed that as the duty cycle decreased, the spray pattern uniformity decreased, and the 20% duty cycle caused severe losses in spray pattern uniformity compared to other duty cycles. In addition, the deposition distribution uniformity in the driving direction is related to the PWM duty cycle; the larger the PWM duty cycle, the more uniform the deposition distribution[16,45]. From the perspective of reducing the drift in PWM variable spraying, we suggest that the PWM duty cycle should be less than 70% to improve the spray drift reduction potential.

5 Conclusions

In this study, a variable-rate spraying system was designed using PWM technology. An ISO 110–03 nozzle was used as the research target, and a series of drift tests were conducted in a wind tunnel. At PWM frequencies of 5 Hz, 10 Hz, and 15 Hz, the spray drift in the vertical profile and horizontal plane were measured at different duty cycles. Using a 100% duty cycle as the reference condition for each frequency, the *DPR* under different setting conditions was calculated and compared. The conclusions can be summarized as follows:

1) The linear correlation between the nozzle flow rate and duty cycle is significantly improved by using a high-frequency solenoid valve in the designed PWM variable spraying system rather than compared to the solenoid valves adopted by previous researchers. At PWM frequencies of 5 Hz, 10 Hz, and 15 Hz, the nozzle flow rate exhibits a linearly increasing trend with the duty cycle, and the linear section ranges from 10% to 90%. Under the three frequency working conditions, the coefficients of determination are 0.99, 0.98, and 0.97, respectively.

2) The droplet spectrum is related to the PWM working condition parameters. At a given frequency, with increasing duty cycle, D_{V50} gradually decreases, whereas V_{100}%, V_{150}%, and V_{210}% gradually increase. The main reason for this behavior is that the liquid does not reach full pattern development before the flow is terminated at a lower-PWM duty cycle.

3) In the wind tunnel test, the PWM duty cycle has a greater impact than the frequency on drifting deposits; the deposit volume increases gradually with increasing duty cycle. At a lower PWM frequency, in addition to the droplet size, the spray drift may be affected by the pulsed spray pattern.

4) In terms of drift reduction potential, a frequency of 5 Hz produces the best drift reduction performance. At a given frequency, the nozzle exhibits a better drift reduction capacity at duty cycles below 70%. In general, as the duty cycle increases, the *DPR* value decreases, indicating that the possibility of the drift potential increasing.

In summary, PWM parameters can change the droplet size, affecting the drift characteristics. In addition to the effect of droplet size, the drift reduction performance is also affected by the unique pulse-modulation mode of the PWM system. In actual applications, the flow regulation range, droplet size, and spray drift characteristics should be comprehensively considered to determine the appropriate PWM frequency and duty cycle. Based on the present experimental results, it is recommended to operate the PWM variable-rate spraying system at a duty cycle below 20%-70% to improve atomization quality and enhance the drift reduction capacity.

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