Droplet size and spray pattern characteristics of PWM-based continuously variable spray

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Abstract: A Pulse-Width-Modulation-based (PWM-based) continuously variable sprayer was developed using a proportional regulating solenoid valve. Variable flow-rate was obtained by varying the duty cycle of the actuating signal with 24 kHz frequency. Flow-rate regulating ranges of the PWM-based continuously variable spray (i.e. the turndown ratio responding to 100%-40% duty cycle) are 7.14:1, 3.57:1, and 3.70:1 for flat-fan, hollow-cone and solid-cone nozzles, respectively. The purpose of the study was to evaluate the PWM-based continuously variable spray. The method was to quantify the effects of flow-rate control on spray characteristics in terms of droplet size spectra, spray distribution patterns, and spray angle for flat-fan, hollow-cone, solid-cone nozzles. For all nozzles tested, spray distribution concentrated on the center of the spray field with the decrease of flow-rate. But the spray shape is still symmetrical. The sensitivities of the spray angles to flow-rate were 0.83, 0.67, and 0.58 (^{o})/% respectively for flat-fan, hollow-cone and solid-cone nozzles. Compared with the sensitivities of spray angle for PWM-based intermittent variable spray, they are somewhat larger. As flow-rate was reduced from the maximum (100% flow-rate) to the minimum controllable rate, the observed median diameter of spray droplets decreased by 5.4%, 9.8%, and 9.9 % for flat-fan, hollow-cone and solid-cone nozzles, respectively. This indicates that spray droplet size was affected slightly by flow-rate control.

Keywords: Pulse Width Modulation (PWM), continuously variable spray, droplet size, spray distribution pattern, spray angle

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1 Introduction

For responding to the changing conditions in fields in terms of the control-based spatial variable, precise variable spray has been an issue of common concern in modern agricultural study and plant production[1-3]. Utilizing a well-designed spatial variable atomizer, such as the direct-injection sprayer[4,5], or the compressed air (type) sprayer with the ground speed control[6], a planter can change the discharge rate rapidly and accurately in the forward direction (namely longitudinally). However, the effective methods to change the discharge rate and spray area via the width-space variation (namely widthwise) are still lacking[7]. Therefore, in order to meet the spray requirement to a complex field, it is essential to develop and study alternative variable spray equipment with wide regulating ranges and different spray characteristics, especially for adjustable space-width applications.

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PWM-based intermittent pulse variable spray has been extensively discussed by Giles[8-10]. A kind of PWM-based continuously variable spray equipment was developed, in which an electromagnetic proportional regulating valve was used to adjust flow-rate continuously. Based on PWM technology, the continuously variable spray flow was achieved by using a square signal with 24 kHz frequency and a tunable duty cycle to drive the valve, and control the flow through the valve and the nozzle continuously. Only a dedicated screw jointer was needed to connect the nozzle as close as possible to the valve. The traditional nozzle needn't be changed or improved. And the performance of this alternative method of spray nozzle flow control was investigated. Some of the work has been reported partially and briefly in reference [11]. The detailed information and results are introduced here. The purpose of this article was to evaluate PWM-based continuously variable spray in terms of spray distribution pattern, spray droplet size, and spray angle for flat-fan, hollow-cone and solid-cone nozzles.

2 Equipment

2.1 Definition of pulse width modulation

PWM technology is one of the modulation methods of the electrical pulse signal. The process in which the switch cycle T is unchanged and the switch turn-on time t_{on} is adjusted is called Pulse-Width Modulation (PWM), where t_{on} is the turn-on time of the output voltage, t_{off} is the turn-off time of the output voltage, T is the switch cycle, $\alpha = t_{on}/T$ is the conduction duty cycle, or duty cycle for short[12].

2.2 Principle of flow-rate control

The principle of continuous spray flow control based on PWM control technology is shown in Figure 1. The square signal $v(t)$ is the output in the PWM control circuit, whose load is the electromagnetic proportional regulating valve, an inductive load. The square signal with three segments of differing duty cycles is shown in Figure 1. When the square signal is at a high level (the t_{on} segment in Figure 1), the power is supplied by a control circuit to the load and the load current rises gradually with the discharge process of the inductive load, shown as Figure 1(b). When the square signal is at a low level (the t_{off} segment in Figure 1), no power is supplied to the load, so that the inductive load will back discharge via the diode which is reversely connected parallel to the crossover load. This back discharge is due to the reverse electromotive force, and an after current flow is formed which makes the load current continuous, shown as the t_{off} segment in Figure 1(b). Generally, in a PWM control circuit, the diode is called a fly-wheel diode, and it makes the load current continuous. If the inductance in the inductive load is large enough, namely wL»R, the load current $i_o(t)$ will approach and even become constant flow, shown as the I_o in Figure 1. By adjusting the duty cycle of the PWM square signal, the charge and discharge time of the inductance and the output current I_o are all changed, so that the output power and the valve opening are controlled, and the control of the spray flow is realized.

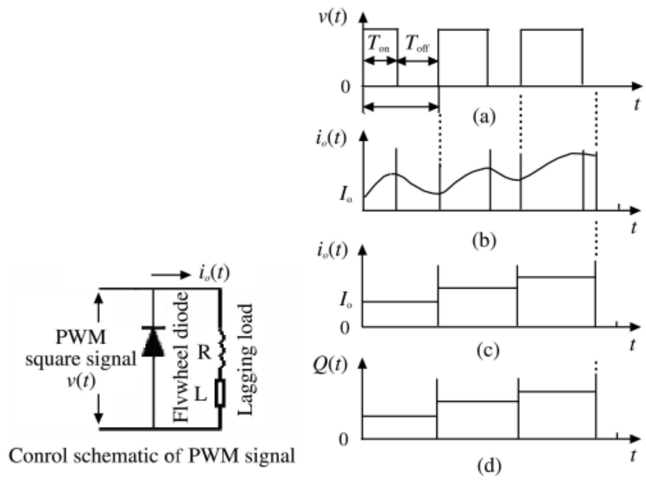


Figure 1 Principle of continuous spray flow control based on PWM technology

2.3 Test-bed

Frame diagram of test-bed for spray flow control is shown in Figure 2. The laser generator, laser shot set, optical receiving set, and computer make up Phase-Doppler Particle Dynamic Analyzer (PDA), which is manufactured by Dantec Dynamics Company and was used to measure spray droplet diameter and velocity using spot measurement method. The advantages of this device are high precision, undisturbed measurement. Its measurement principle is to calculate droplet velocity according to the frequency of doppler signal and calculate droplet diameter according to the phase difference of doppler signals received from different places. Therefore PDA can measure droplet velocity and diameter simultaneously. Liquid supply system is composed of liquid container, electric motor and pump, overflow mechanism, fluid delivery tube, flow meter, and pressure guage. Spray flow control equipment was set up in the study, which is composed of PWM electromagnetic proportional regulating valve and its actuating circuit. Spray distribution was measured using a spray sample table, including groove patternator with some V-shape liquid collecting troughs, cubical measuring cup, cup bracket, and supporting frame of the patternator.

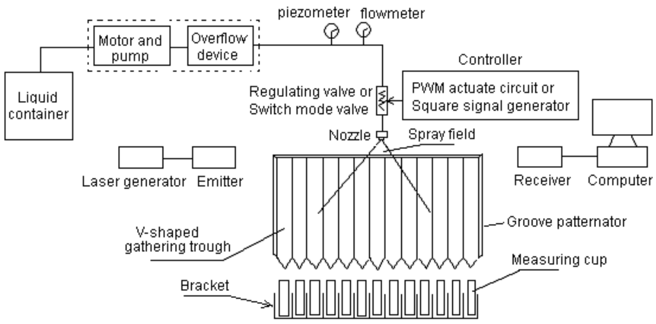


Figure 2 Diagram of nozzle spray flow control test-bed

2.3.1 Control circuit

1) Electromagnetic proportional regulating valve

An electromagnetic proportional regulating valve produced by Burdert Company in Germany was selected—model 6023. It is a direct-acting, two-way, normally-closed solenoid valve. The working pressure was 0-4 bar, and the acting lag was slight. The valve body was constructed of brass, and the valve orifice diameter was 4mm. The coil was designed for 24 V DC operation with a rated holding power of 15 W. The valve ports were nominal 3/8″ female fittings. The electromagnetic proportional valve would shut off when the electric power was cut off. When power was supplied, the valve opening would be adjusted and controlled continuously according to the different duty cycles of the 24 kHz PWM electrical signal output by the control circuit. In order to connect the nozzle tip closely to the valve, a screw jointer was custom-made. One side of the jointer was 3/8″ NPT male thread, the other side was M18×1.5 male thread and was connected to the spray nozzle directly. This kind of electromagnetic proportional valve must be controlled with a PWM control signal.

2) Actuate circuit of PWM electromagnetic solenoid

A key part of the driver control circuit for PWM electromagnetic valve was a chipset with Model No. DRV101. The DRV101 driver provides adjustable PWM signals making the output power on the load adjustable and provided high reliability[13]. It comprises PWM output circuit, an internal 24 kHz oscillator, PWM modulator, digital control input, external delay and duty cycle adjustment. It provided a high driving current output (2.3A) and a wide range of power voltage (+9 V～+60 V). The input (pin 1) was compatible with standard TTL levels. An input voltage of +2.2 V～+5.5 V can provide a low voltage output (0 V～+1.2 V) which can close the valve. A capacitor C_D was connected between pin 2 and the ground, and adjustment of C_D can change the delay time of PWM signal output. A resistor R_{PWM} was connected between the duty cycle adjustment pin (pin 3) and the ground, and the duty cycle of the PWM output signal was adjusted between 10%～100% by tuning the value of R_{PWM}. The load (electromagnetic proportional valve) was connected between the power supply pin (pin 5) and the output pin (pin 6). The output on pin 6 was the PWM square signal. For inductive loads, a diode was connected across the load for external inverse discharging. All mentioned above are shown in Figure 3.

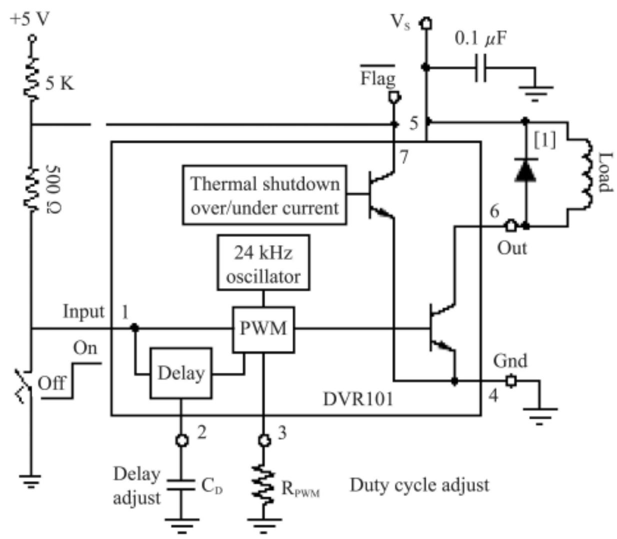


Figure 3 Control circuit of PWM proportional regulating solenoid valve

The PWM control circuit of the electromagnetic proportional valve is shown in Figure 2. When switch K is closed, the control input (pin 1) is set to zero volts and the drive circuit of PWM electromagnetic valve inoperative. When switch K is open, the control input is set to 5 volts and the drive circuit of PWM electromagnetic valve sends out a PWM square control signal with a frequency of 24 kHz. By adjusting the duty cycle, the opening of the electromagnetic proportional valve was controlled, and the volume of spray was adjusted.

2.3.2 Nozzle selection

Three typical nozzles were tested.

Flat-fan nozzle: No. N11012 flat-fan nozzle of the N110 series was selected, under standard working pressure of 0.3MPa.

Hollow-cone nozzle: No.30HCX10 hollow-cone nozzle of the 30HCX series from the LURMARK Company was selected, under standard working pressure of 0.3 MPa.

Solid-cone nozzle: No. NY05 solid-cone nozzle of the NY series was selected under standard working pressure of 0.3 MPa.

3 Test methods and results

3.1 Test conditions

The actuating signal of the electromagnetic proportional solenoid was a square signal which had a duty cycle adjustable continuously between 10%～100%. The various tested spray conditions were obtained by adjusting the duty cycle. The relative flow-rate (%) of the tested condition could be obtained when the flow of the tested spray condition was divided by the full flow which was the flow when the valve was opened completely. The pressure of all the tested spay conditions was 0.3 MPa. The designed test conditions and the corresponding relative flow-rates of the used nozzles are shown in Table 1.

3.2 Flow-rate regulating range

The flow-rate regulating range of the continuous spray based on PWM technology was obtained experimentally. The spray behaviors were observed while the duty cycle was adjusted from the upper limit to the lower limit. Although the duty cycle of the PWM square signal was adjusted from 100% to 10%, but in the tests the electromagnetic proportional solenoid valve would almost shut down when the duty cycle was tuned down to 35% below due to the weak driving power and the serious distortion of the spray pattern. Therefore the actual practical range of the duty cycle was 100%～40%. The flow-rate at 100% and 40% duty cycle was measured as shown in Table 2. The flow regulating ranges for flat-fan, hollow-cone and solid-cone nozzles were 7.14:1, 3.57:1, and 3.70:1, respectively.

Table 1 Excitation duty cycles and resulting relative flow for flat-fan, hollow-cone and solid-cone nozzles

Flat-fan nozzle		Hollow-cone nozzle		Solid-cone nozzle	
Duty cycle /%	Flow-rate /%	Duty cycle /%	Flow-rate /%	Duty cycle /%	Flow-rate /%
100	100	100	100	100	100
90	89	90	98	90	90
80	85	80	97	80	88
75	83	75	95	75	65
70	81	70	94	70	63
65	68	65	92	65	61
60	52	60	72	60	53
55	42	55	56	55	48
50	27	50	53	50	42
45	16	45	37	45	35

Table 2 Three nozzles' flow measured at the upper and lower limits of duty cycle under 24 kHz

Nozzle type	Upper limit of duty cycle/%	Relative flow-rate /%	Lower limit of duty cycle /%	Relative flow-rate /%	Flow regulating ranges
flat-fan nozzle	100	100	40	14	7.14
hollow-cone nozzle	100	100	40	28	3.57
solid-cone nozzle	100	100	40	27	3.70

3.3 Spray distribution pattern

The spray distribution pattern from the nozzles operating under the test conditions was measured by using a simple spray table as shown in Figure 4. The variable spray controller was positioned 500 mm above the surface of the table. Each V shaped trough in the table and corresponding cubical sample cup collected spray liquid from a 50 mm segment of the spray pattern. The nozzle was operated until at least one of the sample cups was filled. Then the amount in each sample cup was recorded. Each test was replicated twice, from which the average was calculated.

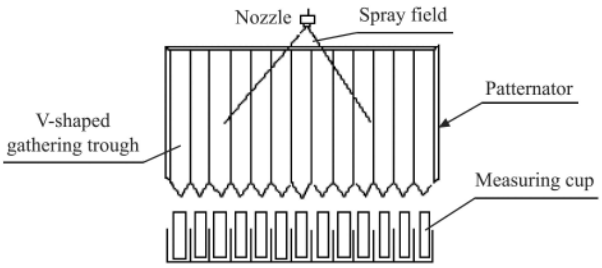


Figure 4 Apparatus used for characterization of spray distribution pattern.

It was observed in the tests that the spray contribution patterns of the three kinds of nozzle converged just below the nozzles when the flow-rates were reduced by reducing the duty cycle. The spray pattern narrowed greatly after the duty cycle was reduced below 75%. Especially for the hollow-cone and the solid-cone nozzle, the spray pattern distorted seriously when the duty cycle was reduced to below 40%. After each pattern test, the spray volume collected in all sample cups was summed. The volume in each sample cup was then divided by the collected total flow. The fraction of total nozzle flow in each sample cup was the spray distribution pattern proportion of the flow in each V shape trough and was used as the response variable in all statistical analysis.

The observed spray pattern data for the flat-fan nozzle and statistical analysis appear in Table 3. Example pattern data are shown graphically in Figure 5. The spray pattern proportion histogram is shown in Figure 4a. This way made the spray distribution patterns of the various flow shown in a unified coordinate system so that the relative spray patterns under different flow could be compared. The spray distribution pattern histograms of the various flows are shown separately in Figure 4b. The spray pattern of the flat-fan nozzle was influenced significantly by the PWM continuously variable spray controller. As the flow rate decreased, pattern was more concentrated about the center of the nozzle. Accordingly, the bilateral spray distribution decreased. The spray divergence was reduced, and the spray transverse span also reduced. But the spray shape had little distortion and was nearly symmetrical.

The observed spray pattern data for the hollow-cone nozzle and statistical analysis appear in Table 4. Example pattern data are shown graphically in Figure 5a in the way of histogram. It was shown that the effect of flow control on the spray pattern of the hollow-cone nozzle was significant. With the flow decreased, the pattern was more concentrated about the center below the nozzle and the reduction of spray divergence was apparent. As the flow rate was reduced to 40% of the full flow, the distortion of the pattern was so dramatic that the other spray characteristics parameters could not be measured. Compared with the spray pattern without PWM continuous spray controller, the collected flow in the No.6 sample cup directly underneath the nozzle increased up to twice the collected flow from the uncontrolled nozzle.

Observed spray pattern data, statistical analysis and example spray pattern histogram for the solid-cone nozzle appear in Table 5 and Figure 6b. The spray pattern of solid-cone nozzle was similar to that of hollow-cone nozzle, but much more observable.

Table 3 Spray distribution proportions for flat-fan nozzle

Duty cycle /%	Flow rate /%	Percentage of the collected flow at each position on spray table in the total nozzle flow/%										
		1	2	3	4	5	6(center position)	7	8	9	10	11
100	100	3.2	7.5	10.0	12.7	12.4	14.1	13.2	11.4	9.3	5.1	1.1
90	89	0.7	6.9	10.2	12.2	12.5	14.8	13.3	12.5	10.1	6.4	0.4
80	85	0.6	6.1	10.8	12.4	12.9	15.2	13.2	12.1	10.6	5.8	0.3
75	83	0.5	5.7	11.0	12.3	13.2	15.4	13.5	12.2	10.5	5.4	0.3
70	81	0.3	5.6	10.7	12.3	13.5	15.9	13.8	12.6	10.3	4.9	0.1
65	68	0.1	4.5	8.9	13.2	14.8	17.6	15.2	13.4	9.1	3.2	0
60	52	0	1.7	8.1	14.0	16.9	19.1	16.6	15.0	7.6	1	0
55	42	0	0.3	7.4	13.8	18.6	22.3	17.9	14.7	5.0	0	0
50	27	0	0	2.3	14.9	20.3	27.5	21.1	13.3	0.5	0	0
45	16	0	0	0	8.3	25.4	34.2	24.8	7.3	0	0	0

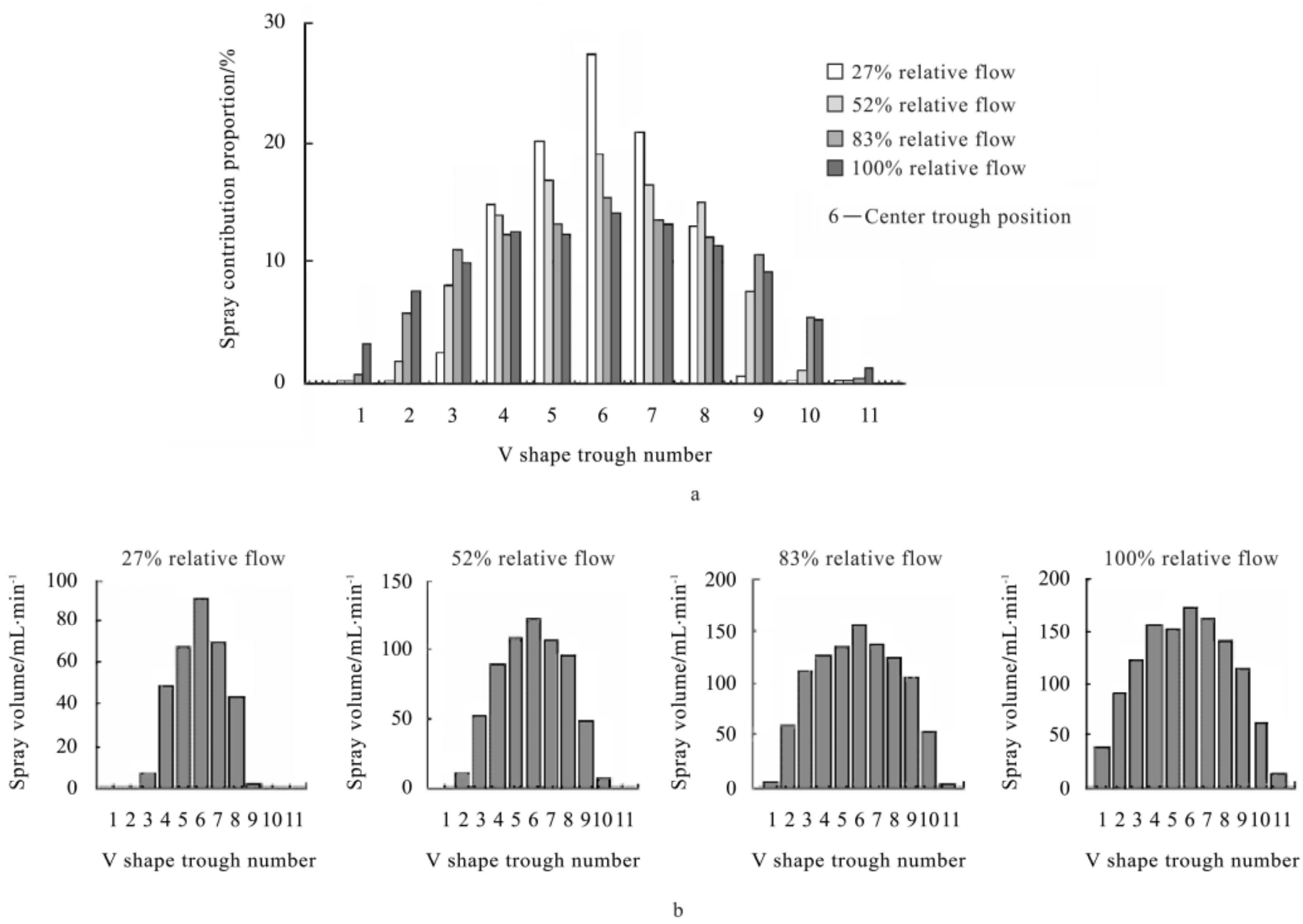


Figure 5 Spray distribution pattern for flat-fan nozzle

Table 4 Spray distribution proportions for hollow-cone nozzle

Duty cycle %	Flow rate %	Percentage of the collected flow at each position on spray table in the total nozzle flow /%										
		1	2	3	4	5	6(center position)	7	8	9	10	11
100	100	0.9	5.1	13.6	14.5	11.2	10.4	10.9	14.7	12.9	4.9	0.9
90	98	0.8	5.1	13.5	14.6	11.3	10.5	11.0	14.6	13.0	5.0	0.6
80	97	0.6	5.2	13.6	14.7	11.1	10.6	11.3	14.8	12.8	4.9	0.4
75	95	0.3	4.9	13.4	14.8	11.9	10.9	11.5	14.4	13.1	4.8	0.3
70	94	0.2	4.3	13.2	15.0	12.1	11.5	12.3	14.9	13.1	3.9	0.1
65	92	0.1	4.2	13.0	14.7	12.5	11.7	12.6	14.5	13.2	3.4	0.1
60	72	0	0.8	7.7	16.3	15.4	20.3	15.6	16.7	6.8	0.4	0
55	56	0	0	0.7	15.9	19.6	28.9	18.9	15.6	0.4	0	0
50	53	0	0	0.2	14.0	21.4	29.8	20.7	13.7	0.2	0	0
45	37	0	0	0	3.6	28.3	38.6	27.4	2.1	0	0	0

Table 5 Spray distribution proportions for solid-cone nozzle

Duty cycle %	Flow rate %	Percentage of the collected flow at each position on spray table in the total nozzle flow /%										
		1	2	3	4	5	6(center position)	7	8	9	10	11
100	100	1.6	3.6	7.6	11.1	14.9	16.7	16.6	13.9	8.9	3.8	1.5
90	90	0.5	3.5	7.6	12.9	15.3	17.5	16.4	13.8	8.8	3.4	0.3
80	88	0.4	2.9	7.3	12.8	16.3	17.8	16.7	14.0	8.6	3.1	0.1
75	65	0	0	2.0	11.9	21.4	28.6	21.9	12.6	1.6	0	0.3
70	63	0	0	1.8	12.1	21.5	29.3	21.1	13.2	1.0	0	0.1
65	61	0	0	0.6	8.9	23.1	36.2	22.9	7.8	0.5	0	0
60	53	0	0	0.3	7.5	24.8	33.6	24.6	8.9	0.3	0	0
55	48	0	0	0	2.1	29.6	37.4	28.9	2.0	0	0	0
50	42	0	0	0	1.0	23.5	47.9	27.0	0.6	0	0	0
45	35	0	0	0	0	22.4	51.5	26.1	0	0	0	0

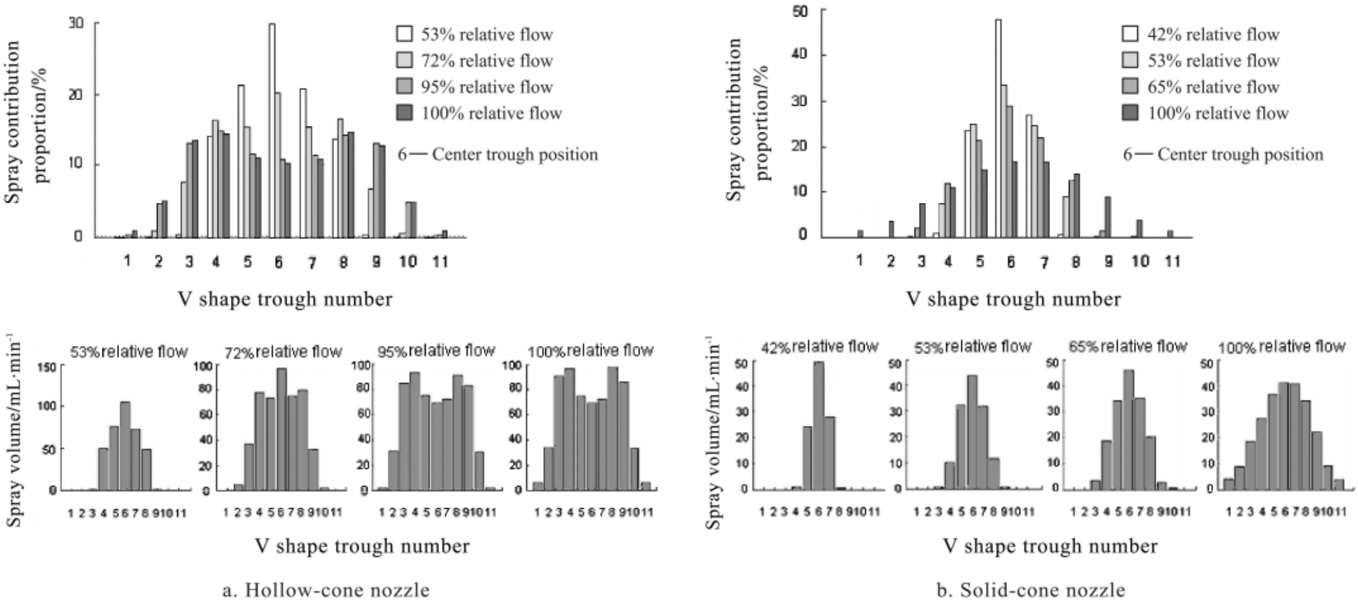


Figure 6 Spray distribution pattern for hollow-cone and solid-cone nozzle

3.4 Spray angle

A piece of black cloth was put behind the spray field and a beam of light was set close to the nozzle. The spray field of each tested condition was photographed twice. Then the two photos were transferred to the computer. The spray angle was determined using the method in document[14].

The observed spray angle data and statistical results for each nozzle operating at the conditions in Table 1 are shown in Table 6. The relationship between spray angle parameters and flow was quantified by least squares fit of a first order model to the observed data at different flow-rates as shown in Figure 7.

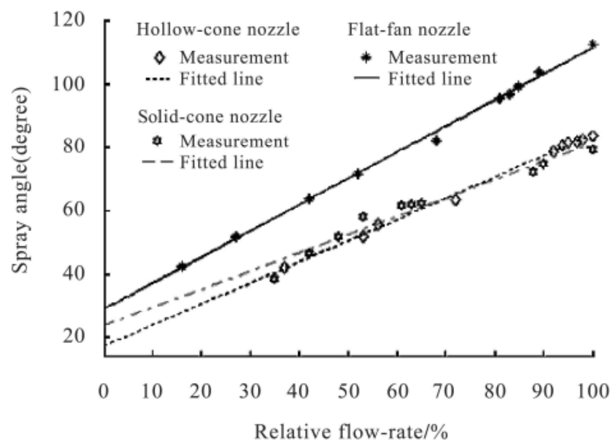


Figure 7 Spray angle data for various relative flow rates and their changing trends

Table 6 Spray angle measurement and analysis results

Flat-fan nozzle			Hollow-cone nozzle			Solid-cone nozzle		
Duty cycle/%	Flow-rate /%	Spray angle	Duty cycle/%	Flow-rate /%	Spray angle	Duty cycle/%	Flow-rate /%	Spray angle
100	100	112.3°	100	100	83.1°	100	100	79.6°
90	89	103.7°	90	98	82.2°	90	90	74.5°
80	85	99.2°	80	97	81.7°	80	88	72.1°
75	83	96.6°	75	95	81.1°	75	65	62.4°
70	81	95.1°	70	94	80.4°	70	63	62.1°
65	68	81.8°	65	92	78.5°	65	61	61.6°
60	52	71.3°	60	72	63.3°	60	53	57.9°
55	42	63.7°	55	56	55.6°	55	48	51.7°
50	27	51.9°	50	53	51.7°	50	42	46.4°
45	16	42.3°	45	37	42.0°	45	35	38.3°
Sensitivity of spray nozzle to flow changement (°/%)		0.8254	Sensitivity of spray nozzle to flow changement (°/%)		0.6681	Sensitivity of spray nozzle to flow changement (°/%)		0.5761

The effects of the PWM continuously variable spray on the spray angles for all the three nozzles were significant. With the decrement of the duty cycle and flow, the spray angles were reduced obviously. The spray angle sensitivities to the flow-rate change, namely the angle decrement for the each per cent of flow decrease, for flat-fan, hollow-cone and solid-cone nozzle were respectively 0.83, 0.67, and 0.58%. Compared with the sensitivities of the spray angle to the flow under PWM intermittent flow control method, the sensitivities of the spray angle to the flow under PWM continuous flow control method increased greatly. This indicated that the effect of the PWM continuous flow control on the spray angle was significant. With the decrease of flow, the spray angles of the three kinds of nozzles decreased greatly.

3.5 Spray droplet size

Droplet size and velocity produced by each nozzle operating at the conditions in Table 1 were measured 4 mm below the nozzle using PDA.

The descriptive parameters of the spray droplet size spectrum for each test condition were calculated from the observed spectral data. The descriptive parameters were: (1)Volume Median Diameter (VMD), namely $D_{V0.5}$, defined as the droplet diameter such that 50% of the spray volume is contained in droplets larger than the VMD and 50% is contained in droplets smaller than the VMD; (2)$D_{V0.1}$, the diameter indicating that 10% of the spray volume is contained in droplets of a smaller diameter; (3)$D_{V0.9}$, the diameter indicating that 90% of the spray volume is contained in droplets of a smaller diameter. In all statistical analyses, the independent variable was the normalized (0～100%) flow-rate through each nozzle and response variables were $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$. The relationship between droplet size parameters and flow-rate was quantified by least squares fit of a first order model to the observed data. The model[9] is

$$Y = a + b(X-10\ 0) \tag{1}$$

where Y is droplet size; $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$ (μm); X is nozzle flow-rate, %; a is the estimated Droplet size statistic value at full nozzle flow (μm); b is sensitivity of droplet size statistic to flow- rate ((μm)/%).

Applying the measured flow-rate data (the measured relative flow-rate and corresponding droplet size statistics) to equation (1), the relationship between droplet size and flow-rate for a nozzle was obtained and quantified by least squares fit. Shifting the pivot of the line from the zero flow to the full flow value resulted in the a parameter estimates having the physical meaning of full flow-rate (100%) droplet size. Experimentally observed full flow-rate droplet size was directly compared to the a estimates. Model parameter estimates, observed droplet size and estimates of the b (sensitivity of the droplet size to the flow-rate) parameter for all nozzles appear in Tables 3-5. The observed and predicted values are in close agreement.

The observed droplet size data and estimated results for flat-fan nozzle appear in Table 7 and Figure 8, respectively. It can be seen that droplet sizes diminished with the decrease of flow-rate. Effects of flow-rate control on $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$ were statistically significant. The physical effect, however, was extremely small. $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ were reduced 0.063, 0.349, and 0.529 μm, respectively for each percent of flow-rate decrement. Therefore, over a continuous flow-rate range of 100 to 40%, reduction in $D_{V0.1}$ was 3.78(0.063×60) μm, representing 1.7% of estimated full flow $D_{V0.1}$ of

Table 7 Parameter estimates and sensitivities of droplet size to flow-rate for flat-fan nozzle

Paramete r	Measurement of a/μm	Evaluated value of a/μm	Evaluated value of b /μm • $\%^{-1}$
$D_{V0.1}$	233.4	228.9	0.063
$D_{V0.5}$	413.3	385.3	0.349
$D_{V0.9}$	896.8	878.4	0.529

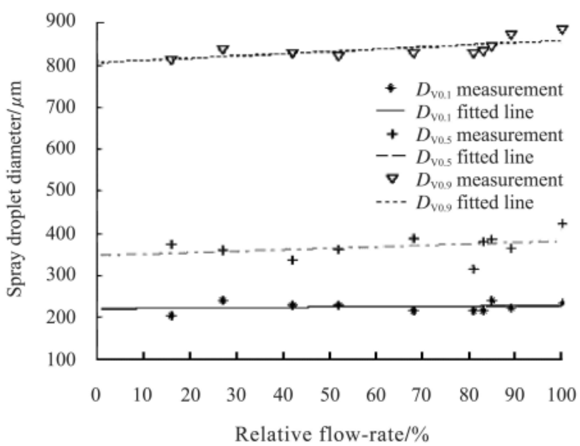


Figure 8 Droplet diameter vs. relative flow-rate for flat-fan nozzle

228.9 μm; in $D_{V0.5}$ is 20.94(0.349×60) μm, representing 5.4% of estimated full flow $D_{V0.5}$ of 385.4 μm; in $D_{V0.9}$ was 31.74(0.529×60) μm, representing 3.6% estimated full flow $D_{V0.9}$ of 878.4 μm.

The observed droplet size data and statistical results for hollow-cone nozzle appear in Table 8 and Figure 8a, respectively. It can be seen that the droplet sizes diminished with the decrease of flow-rate. The effects of flow-rate control on the $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ were statistically significant. The physical effect was also very slight. The sensitivities of $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ to the flow control were 0.232, 0.584, and 0.343 μm/%. Over the continuous flow control rang of 100% to 40%, the diminishment in $D_{V0.1}$ was 13.92(0.232×60) μm, representing 10.2% of estimated full flow $D_{V0.1}$ of 136.5 μm; in $D_{V0.5}$ was 35.04(0.584 × 60) μm, representing 9.8% of estimated full flow $D_{V0.5}$ of 358.6 μm; in $D_{V0.9}$ was 20.58(0.343 × 60) μm, representing 4.1% of estimated full flow $D_{V0.9}$ of 504.7 μm.

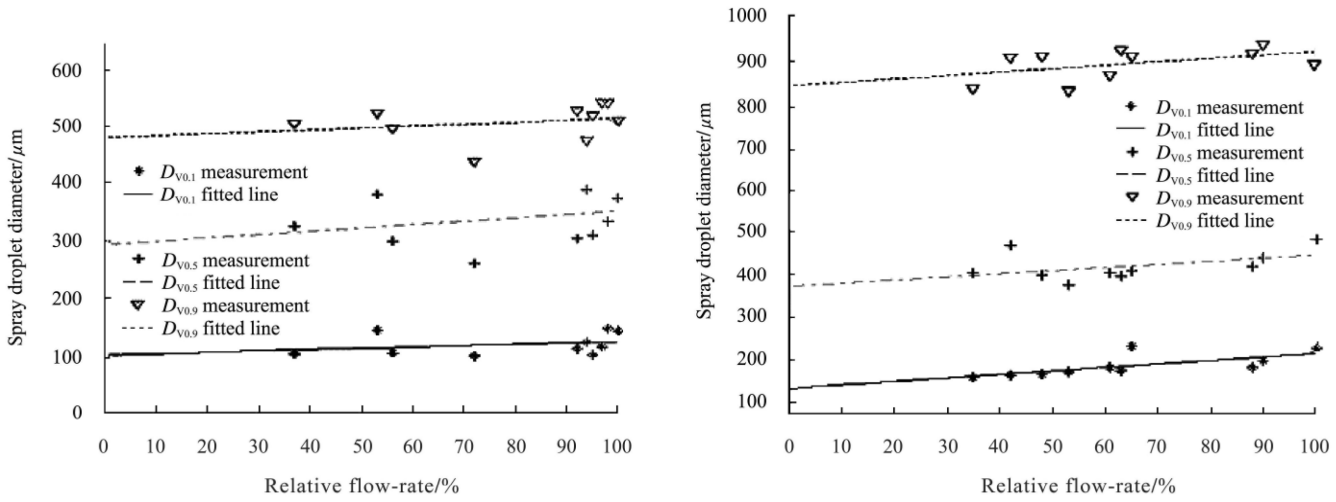
The observed droplet size data and statistical results for solid-cone nozzle appear in Table 9 and Figure 9b, respectively. The same variation trend as the former nozzles was observed. The sensitivities of $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ to the flow control were 0.232, 0.584, and 0.343 μm/%. Over the continuous flow control range of 100% to 40%, the decrease in $D_{V0.1}$ was 49.5(0.825×60) μm, representing 21.8% of estimated full flow $D_{V0.1}$ of 227.1 μm; in $D_{V0.5}$ was 45.24(0.754×60) μm, representing 9.9% of estimated full flow $D_{V0.5}$ of 454.9 μm; in $D_{V0.9}$ was 48.9(0.816×60) μm, representing 5.2% of estimated full flow $D_{V0.9}$ of 938.8 μm.

Table 8 Estimates and sensitivities of droplet size to flow-rate for hollow-cone nozzle

Parameter	Measurement of a /μm	Evaluated value of a /μm	Evaluated of b /μm • $\%^{-1}$
$D_{V0.1}$	151.1	136.5	0.232
$D_{V0.5}$	375.0	358.6	0.584
$D_{V0.9}$	496.8	504.7	0.343

Table 9 Estimates and sensitivities of droplet size to flow-rate for solid-cone nozzle

Parameter	Measurement of a /μm	Evaluated value of a /μm	Evaluated of b /μm • $\%^{-1}$
$D_{V0.1}$	238..5	227.1	0.825
$D_{V0.5}$	481.6	454.9	0.754
$D_{V0.9}$	924.4	938.8	0.816



a. Hollow-cone nozzle b. Solid-cone nozzle

Figure 9 Droplet size vs. relative flow-rate for hollow-cone and solid-cone nozzles

4 Discussion

Reduction of nozzle flow-rates by means of PWM continuously variable flow control method resulted in spray distribution patterns with significantly more spray deposit concentrating directly underneath the nozzles. Corresponding to the increased deposits in the centre regions were reductions in deposit in the outer regions of the pattern, and even no deposition at all in some boundary areas. Figure 3 and Figure 4 show that the distortion was relatively minor for flat-fan nozzle while it was relatively severe for hollow-cone nozzle and solid-cone nozzles. Spray distribution patterns distorted seriously and had some skewing as flow rate was reduced to 40% below.

Reduction of nozzle flow-rates by means of PWM continuously variable flow control method resulted in overall significant decrease in spray angles produced by the three nozzle types. The sensitivities of the spray angles produced by flat-fan, hollow-cone, and solid-cone nozzles to the variable flow were 0.83, 0.67, and 0.58 (^{o})/% respectively. Considering the reason for the great change of the spray angles with variable flow, was probably due to the opening adjustment of the electromagnetic proportional regulating valve which was closely connected to the nozzle tip. The change of the inner structure of the nozzle probably had a great effect on spray angles.

Reduction of nozzle flow-rates by means of PWM continuously variable flow control method resulted in a slight decrease in the size of spray droplets produced by the three nozzle types tested. The sensitivities of the spray droplet size spectra described with $D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$ to the variable flow were 0.063, 0.349, and 0.529 (μm) /% for flat-fan nozzle; 0.232, 0.584, and 0.343 (μm) /% for hollow-cone nozzle; 0.825, 0.754, and 0.816 (μm) /% for solid-cone nozzle respectively. Over a continuous flow control range of 80% to 20%, the decrease in $D_{v0.5}$ for flan-fan, hollow-cone, solid-cone nozzles were, respectively, 5.4%, 9.8%, and 9.9 % of estimated full flow $D_{v0.5}$. Compared with other flow control method, for example, pressure-based flow control method and PWM-based intermittent flow control method[15, 16], the spray droplet size from the three types of nozzle diminished slightly as the flow-rate decreased and was probably negligible. Considering the reason that the spray droplet size decreased as the flow decreased, hypothesis was that the narrowed valve opening caused the subtle decrement. The valve was connected closely to the nozzle, so to some extent the narrowed valve opening was equal to reducing the nozzle tip size which would cause the spray droplet size decrease because the smaller the spray nozzle tip size, the smaller the spray droplet size. The effect of PWM continuous flow control on spray droplet size spectra was valuable in improving the spray deposition because not only the flow-rate was controlled but also the spray droplet size decreased.

5 Conclusions

PWM continuously variable spray via an electromagnetic proportional regulating solenoid actuated by an electrical PWM signal was investigated as a flow rate control strategy. Flow control effects on spray distribution patterns, spray droplet size spectra and spray angles were quantified for flat-fan, hollow-cone and solid-cone nozzles. The following conclusions are drawn.

1) The flow regulating ranges for flat-fan, hollow-cone, and solid-cone nozzles under standard operating pressure were 7.14:1, 3.57:1, and 3.70:1 respectively.

2) Spray distribution patterns and spray angles from all nozzles tested are significantly affected by flow control. As the flow-rate was reduced, the spray divergence and the spray angles decrease greatly, and spray deposition was concentrated in the region underneath the nozzle and reduced in the outer regions of the pattern. More and more areas have no deposition with the decrease of flow-rate.

3) The effects of spray flow-rate control on droplet size spectra of spray produced by the three kinds of nozzles are all slight. The spray droplet size decreased slightly with the decrease of flow-rate. For flat-fan, hollow-cone and solid-cone nozzles, the sensitivities of the volume median diameter to flow-rate were 0.35, 0.58, and 0.75 (μm/%), respectively.

[References]

[1] Schueller J K. A review and integrating analysis of spatially-variable control of crop production. Fertilizer Research, 1992; 33: 1－34.

[2] Zhang Naiqian, Maohua Wang, Ning Wang. Precision agriculture——a worldwide overview. Computers and Electronics in Agriculture, 2002; 36: 113－132.

[3] Paice M E R., P C H Miller, W Day. Control requirements for spatially selective herbicide sprayers. Computers &

Electronics in Agriculture, 1996; 14(2/3): 163－177.

[4] Rockwell A D, Ayers P D. A variable rate, direct nozzle injection field sprayer. Applied Engineering in Agriculture, 1996; 12(5): 531－538.

[5] Koo Y M, Sumner H R. Total flow control for a direct injection sprayer. Applied Engineering in Agriculture, 1998; 14(4): 363－367.

[6] Ghate S R, Perry C D. Ground speed control of pesticide application rates in a compressed air direction injection sprayer. Transactions of the ASAE, 1994; 37(1): 33－38.

[7] Unavut J K, Schueller J K, Mason P A C. Continuous control of a sprayer pinch valve. Trans of the ASAE, 2000; 43(4): 829－837.

[8] Giles D K, J A Comino. 1989. Variable flow control for pressure atomization nozzles. Society of automotive Engineers Technical Paper No 89-1836, SAE, Warrendale, PA.

[9] Giles D K, J A Comino. Droplet size and spray pattern characteristics of an electronic flow controller for spray nozzles. J Agric Engng Res, 1990; 47: 249－267.

[10] Giles D K, E. Ben-Salem. Spray droplet velocity and energy in intermittent flow from hydraulic nozzles. J Agric Engng Res, 1992; 51: 101－112.

[11] Deng Wei, Ding Weimin. Variable-rate continuous spray equipment based on PWM technology and its spray characteristics. Transactions of the CSAM, 2008; 39(6): 77－80.

[12] Wang Zhao-an, Huang Jun. Power Electronic Technology. Beijing: China Machine Press, 2000.

[13] Product specification: PWM Solenoid/Valve Driver, DRV101. Texas Instruments Incorporated, 2003.

[14] Deng Wei, Ding Weimin. A method of processing the atomization image and detecting the spray angle. Journal of Northwest Science-Technology University of Agriculture and Forestry, 2006; 34(7): 155－159.

[15] Fan Ming-hao, Zhou Hua, Yang Hua-yang. Research on atomization characteristics of high-pressure water mist atomizer for fire suppression. Chinese Journal of Mechanical Engineering, 2002; 38(9): 17－21.

[16] Ahmad S I; Bode L E; Butler B J. A variable-rate pesticide spraying system. Transactions of the ASAE, 1981; 24(3): 584－598.