Spatial distribution visualization of PWM continuous variable-rate spray

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Abstract: Pesticide application is a dynamic spatial distribution process, in which spray liquid should be able to cover the targets with desired thickness and uniformity. Therefore, it is important to study the 2-D and 3-D (dimensional) spray distribution to evaluate spraying quality. The curve-surface generation methods in Excel were used to establish 1-D, 2-D, and 3-D graphics of variable-rate spray distribution in order to characterize the space distribution of the variable-rate spray. The 1-D, 2-D, and 3-D distribution graphs of pulse width modulation (PWM)-based continuous variable-rate spray were developed to provide a tool to analyze the distribution characteristics of the spray. The 1-D graph showed that the spray distribution concentrated toward the center of the spray field with the decreased flow-rate. The 2-D graph showed that the spray distribution always spread as the shape of Normal Probability Distribution with the change of the flow-rate. The 3-D graph showed that the spray distribution tended to be uniform when the sprayer travelled forward at the appropriate speed. This study indicated that the visualization method could be directly used for analysis and comparison of different variable-rate spray distributions from different experimental conditions and measuring methods.

Keywords: spray distribution, pulse width modulation (PWM), variable-rate spray, distribution visualization
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1 Introduction

In order to solve prominent problems of pesticide waste and environmental pollution caused by obsolete techniques and equipments used in chemical application, plant protection machinery has been included in the product directory of China Compulsory Certification (CCC) in China’s WTO (World Trader Organization) commitments[1]. Diseases, pests and weeds are unevenly distributed in agricultural fields due to the complexity and variability from field to field[2-4]. Compared with the traditional large-scale uniform spraying, variable-rate spraying technology can improve pesticide utilization, reduce operating costs, and alleviate environment pollution[5-8]. Variable-rate spraying techniques are increasingly being focused on engineering research and development for agricultural operations[9].

Characterization of spray distribution is one of the important parameters for evaluating spraying quality, which directly affects the possibility and accuracy of the sprayed pesticide reaching the targets, and is significant for improving the utilization rate of pesticide application

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as well. There are many measurement methods available for evaluating spray distribution[10,11]. Practical experience has proved that traditional methods of measuring the features of spray distribution impose certain limitations upon the test comparison and make it difficult to evaluate and compare spray distributions measured using different methods and under different experimental conditions[12]. In order to ensure the accuracy of the test, various experimental designs and test methods should be consistent and standardized so as to eliminate the deviation due to the inconsistency of experimental conditions and human operation.

In a previous study, the authors designed and developed a pulse-width modulation (PWM) continuous variable-rate spray device and evaluated its spray characteristics in terms of flow-rate regulation range, spray distribution pattern, spray angle, droplet size, droplet velocity, spray specific energy, and spray kinetic energy median diameter[13]. Under the same experimental conditions, the spray characteristics of PWM-based intermittent variable-rate spray and pressure-based variable-rate spray were studied and compared[14-16]. The results of one-dimensional (1-D) spray distribution and spray angle tests showed that the divergence of PWM-based continuous variable-rate spray was reduced with the decreased flow rate. However, chemical application is typically a dynamic process of spatial distribution, during which a certain thickness of sprayed liquid covers the target surface with a certain homogeneous degree of spraying liquid. Therefore, a 1-D spray distribution pattern is still far from clearly describing the actual spray distribution of spray processes and the study needs to go further.

The objectives of this study were to develop 2-D and 3-D models of spatial spray distribution patterns for PWM-based continuous variable-rate spray, by using the methods of creating 2-D and 3-D curved surfaces in Excel in order to analyze the dynamic spatial spray distribution, and depositing features covering the target surfaces under different conditions, including fixed-point spraying and spraying in the traveling process with variable flow rate. This study could provide an improved method for evaluating PWM-based continuous variable-rate spray equipment in chemical application.

2 Materials and methods

2.1 PWM continuous variable-rate spray

2.1.1 Definition of PWM

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 ton is adjusted is called PWM, where t_{on} is the turn-on time of the output voltage, t_{off} is the turn-off time of the output voltage, $\phi= t_{on}/T$ is the conduction duty cycle, or duty cycle for short[17].

2.1.2 Principle of PWM

Flow control principle schematic of PWM-based continuous variable spray is shown in Figure 1, and the waveform figures for indicating the control principle are shown in Figure 2.

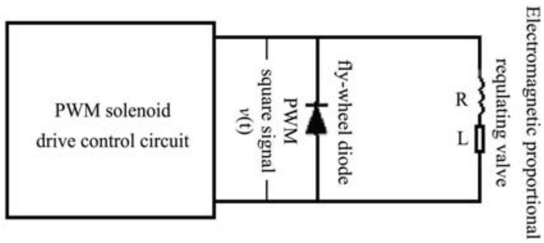


Figure 1 Schematic of control principle for pulse-width modulation (PWM) continuous variable-rate spray

Square signal $v(t)$ is the output of PWM control circuit, and electromagnetic proportional regulating valve (EPRV) is the load of control circuit, an inductive load. Square signal with three segments of differing duty cycles is shown in Figure 2. When the square signal is at high level (t_{on}), control circuit supplies power to load, then load current rises gradually with charging process of the inductive load. When square signal is at low level (t_{off} segment), no power is supplied to the load. Then the inductive load will back discharge via the diode which is reversely connected in parallel to the load. The charging and discharging process makes load current continuous. If the inductance in inductive load is large enough, namely the inductance value is considerably larger than the impedance value (wL >> R), the load current $i_o(t)$ will reach and even become constant current flow, shown as the I_o in (d). By adjusting the duty cycle of PWM square signal, all of the charge and discharge time of inductance and output current I_o will change. By enlarging the duty cycle, valve opening becomes wider and flow-rate larger accordingly. In this way, output power of control circuit and the opening of EPRV are controlled, and spray flow-rate is regulated.

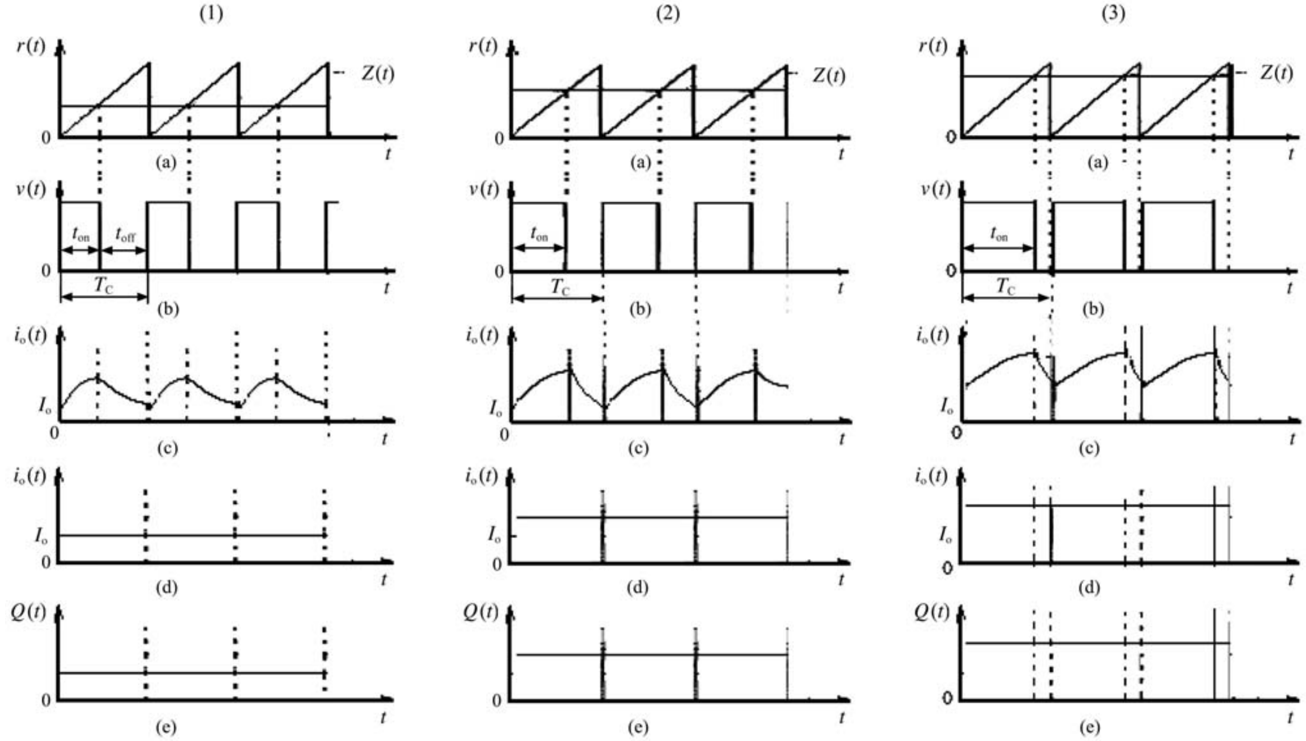


Figure 2 Wave figures of control principle for pulse-width modulation (PWM) continuous variable-rate spray. For duty cycles: (1)<(2)<(3).

2.1.3 Spray unit

The PWM continuous variable-rate spray unit[13] is composed of an electromagnetic proportional regulation valve (EPRV) (model No. 6023, produced by Burdert Company in Germany) and a PWM control circuit (The key part of the control circuit is a chipset, Model DRV101) which was designed and set up for controlling the valve. In the spray unit, the EPRV is driven by a PWM control signal which is produced by the circuit. The control signal is a square wave signal with a constant 24 kHz frequency and continuously adjustable duty cycle within 10% - 100%. The unit could work in stepless and continuous adjustment of the valve opening and realize the stepless regulating control of the spray flow-rate within the flow-rate regulating range.

2.1.4 Flow regulating range

By adjusting the duty cycle of control signal, different test conditions was obtained, in which the spray flow-rate (L/min) was an average of the volume of two times spraying separately within one minute. The relative flow-rate (%) is equal to the quotient when the flow-rate of each tested spray condition is divided by the full flow-rate when the valve opens completely. In all the tests, liquid pressure is set at 0.3 Mbar. Test conditions and the corresponding relative flow-rate are shown in Table 1 for PWM-based continuous variable spray.

Table 1 Flow regulating rate of PWM continuous variable-rate spray

Duty cycle/%	Relative flow-rate/%	Duty cycle/%	Relative flow-rate/%
100	100	60	52
90	89	55	42
80	85	50	27
75	83	45	16
70	81	40	14
65	68		Max/Min = 100/14 = 7.14

Although the duty cycle of PWM square signal can be adjusted from 100% to 10%, in the tests the EPRV nearly shut when duty cycle was tuned down to 35% below due to the driving power becoming too weak. Consequently, the practical tunable range of duty cycle was set as 100% - 40%, as shown in Table 1. Flow-rate adjusting range was obtained through dividing maximum flow-rate by minimum flow-rate. The flow-rate regulating range, namely the ratio of maximum flow-rate to minimum flow-rate, was up to 7.14:1, with the ratio equal to the maximum flow-rate divided by the minimum flow-rate within the flow-rate regulating range.

2.2 Experimental platform

The experimental platform is shown in Figure 3. Spray samples were collected on a patternator, a device used to measure the uniformity of spray distribution of a nozzle. The patternator was configured on a nozzle integrative performance test-bed (manufactured by Harbin Boehner Technology Co., LTD., Harbin, Heilongjiang province, China) in the Testing Laboratory for Agro-chemical Application in the Scientific Observation and Experimental Field Station for Precision Agriculture Research in Beijing, China. The patternator is a V-shaped structure with a width up to 50 mm and depth up to 40 mm (Figure 4). The V-shaped structure of the patternator has higher measurement accuracy due to its ability to prevent spray droplets from splashing and spilling out. All the measuring cups were glass with 5-cm diameter, and each measuring cup was placed just below the outlet of each V-shaped slot so that all the sprayed liquid flowing from the V-shaped slot could be

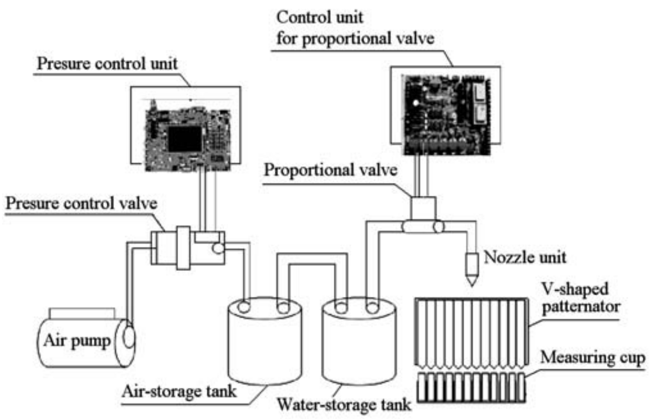


Figure 3 Experimental platform of PWM-based variable-rate spray

collected entirely. The distance from nozzle to the surface of the patternator was 50 cm. The ST110 flat-fan nozzle (Lechler GmbH, Metzingen Stuttgart, Baden-Württemberg, Germany) was selected in the test because flat-fan nozzle is generally used in agriculture. The spray angle of the nozzle is 110^o.

2.3 Experimental conditions

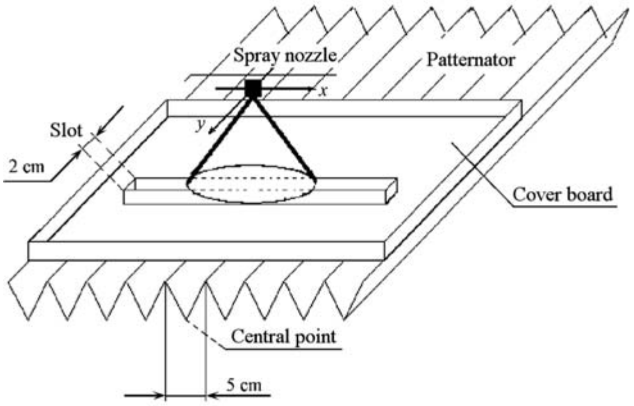
All the test data were measured using the experimental platform described above on Oct. 25-28, 2010. Various parameters describing spray characteristics could be automatically measured on the platform, such as the nozzle spray pressure, flow rate, nozzle height, and spray angle. After measurement, data were transferred and visualized using the software (Harbin Boehner Technology Co., LTD., Harbin, Heilongjiang province, China) designed for the nozzle integrative performance test-bed system by the manufacturer. During the test, the spray pressure in the test system was kept stable.

2.4 Experimental methodss

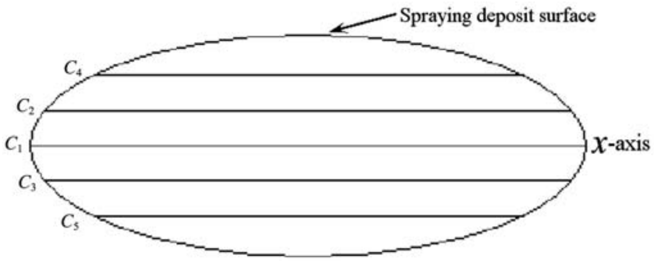
2.4.1 Data collection

The data collection method of 1-D spray volume distribution has been described in detail in the previous studies[13-16], and the measurements were conducted without any covering plate on the patternator. The nozzle axis was perpendicular to the horizontal plane and passed through the central point of the patternator. The nozzle was placed 50 cm height above the patternator, and graduated glasses were used to collect the spray liquid. The spray volume in each graduated glass was accurately measured using an ultrasonic ranging device, so that the spray volume distribution of spray 1-D deposit along the X-axis (spray deposit section) could be obtained.

The schematic diagram of the experimental platform for collecting data of 2-D spatial spray volume distribution is shown in Figure 4a, and the practical sampling sites and methods of collecting data of spray deposit volume is shown in Figure 4b. A stainless-steel cover board, in the middle of which was a 2-cm-wide slot, was covered on the patternator, which was used to collect and quantify the amount of spray emitted from a sprayer. Around the slot welded with a circle of 2-cm-high dam-board in case the spray droplets outside the measurement range flew into the gap. The position of the nozzle was fixed while the cover board was moved along the Y-axis (the moving direction of the cover board), so as to keep the gap on the cover board always parallel with the axis of the spray deposit section (X-axis). When the gap on the cover board was moved to the positions of line C1, C2, C3, C4, and C5 on the spray deposit section, the spray volumes were measured at corresponding positions, and the data were recorded using the method of measuring the 1-D spray deposit volume distribution described in the first paragraph in Section 2.4.1.



a. Schematic diagram of experimental setup for collecting data



b. Schematic diagram of sampling sites

X-axis: spray deposit section; Y-axis: moving direct of the cover board

Figure 4 Schematic diagrams of the method for collecting data of 2-D spatial spray deposit volume

2.4.2 Data processing and modeling

(1) 1-D spray distribution

The data of the liquid volume in all graduated glasses was added up after the 1-D spray distribution measurement was completed. Then each liquid volume datum measured in each graduated glass was divided by the summation of liquid volume in all graduated glasses. Thus, we calculated the percentage of each liquid volume datum measured by using graduated glasses at different position in the total sprayed liquid volume. The percentage was defined as the normalized spray volume and regarded as the spray volume distribution at the corresponding position for statistical analysis. In order to establish the statistical 1-D spray volume distribution, the normalized spray volume was taken as the vertical axis, and the distance from each collecting position of spray volume to the midpoint of the patternator as the horizontal axis.

(2) 2-D spatial spray distribution

At each cross section (shown as lines C1, C2, C3, C4, and C5 in Figure 5) along the direction of the X-axis in parallel to the spray deposit area, the spray volume datum at each sampling point was measured, as displayed in Figure 5. By using the 2-D surface creating method in Microsoft (MS) Excel spreadsheets, the data of spray volume measured at each collecting point were superimposed so as to establish a 2-D spray distribution model.

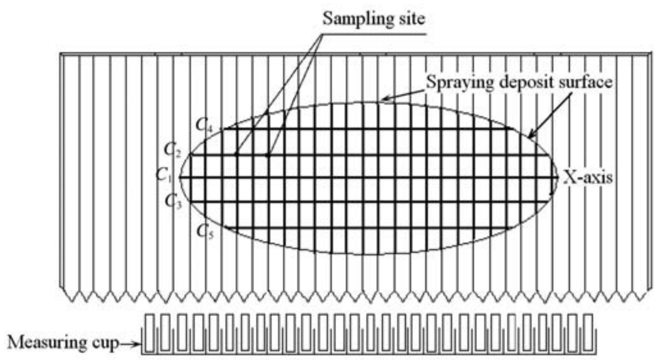


Figure 5 Schematic diagram for modeling 2-D spray distribution

(3) 3-D space-time spray distribution

Different working conditions could be obtained by changing the duty cycle of the PWM square wave signal (i.e. changing the flow-rate). Under different working conditions, the 2-D static spatial models of spray volume distribution at different flow-rates were established in accordance with the methods of collecting data and modeling for analyzing the 2-D spatial spray distribution introduced above in Figure 5. Figure 6 is a schematic diagram of the superimposing method used for modeling the 3-D space-time spray distribution. It demonstrates that 2-D static spatial spray volume distributions at different flow-rates were randomly superimposed at a certain regular interval so as to establish the 3-D space-time model of dynamic spray distribution. It is shown in Figure 6 that the X-axis direction is the axis of spray deposit surface on the patternator, the Y-axis is the forward direction during machinery operation (i.e. superimposing direction), and the Z-axis direction characterizes the thickness of the deposit volume in the spray distribution model.

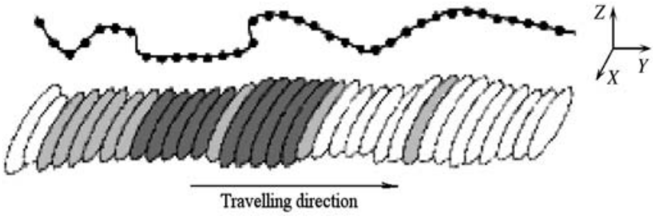


Figure 6 Superimposing method for modeling 3-D space-time spray distribution pattern

3 Results and discussion

3.1 1-D spray distribution

After measuring the data concerning the spray distribution of the flat-fan nozzle, the data were statistically analyzed. The result is visually displayed with the line chart in Figure 7. From Figure 7 it is clearly shown that spray volume distribution concentrates towards the center of the patternator with decreasing flow-rates.

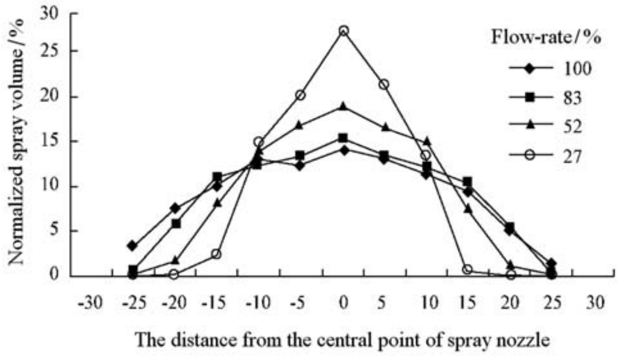


Figure 7 1-D spray distribution pattern

3.2 2-D spatial spray distribution

The 2-D spatial model of spray-volume distribution was set up through superimposing the data of spray deposit volume collected at different collecting positions by using the surface creating method in the MS Excel spreadsheets. Using the 2-D spatial model, the features of spatial distribution of spray volume and deposit condition were analyzed and studied for variable-rate spray. Figure 8 demonstrates the 2-D static model of the spray deposit volume distribution for PWM continuous variable-rate spray with duty cycles of 50%, 60%, 70%, and 80%. Figure 8 shows that the 2-D spray deposit volume distribution appears to be a normal distribution. It also shows that the proportion of spray volume deposited at the central area increases with the increasing flow rate which is due to the increase of the duty cycle.

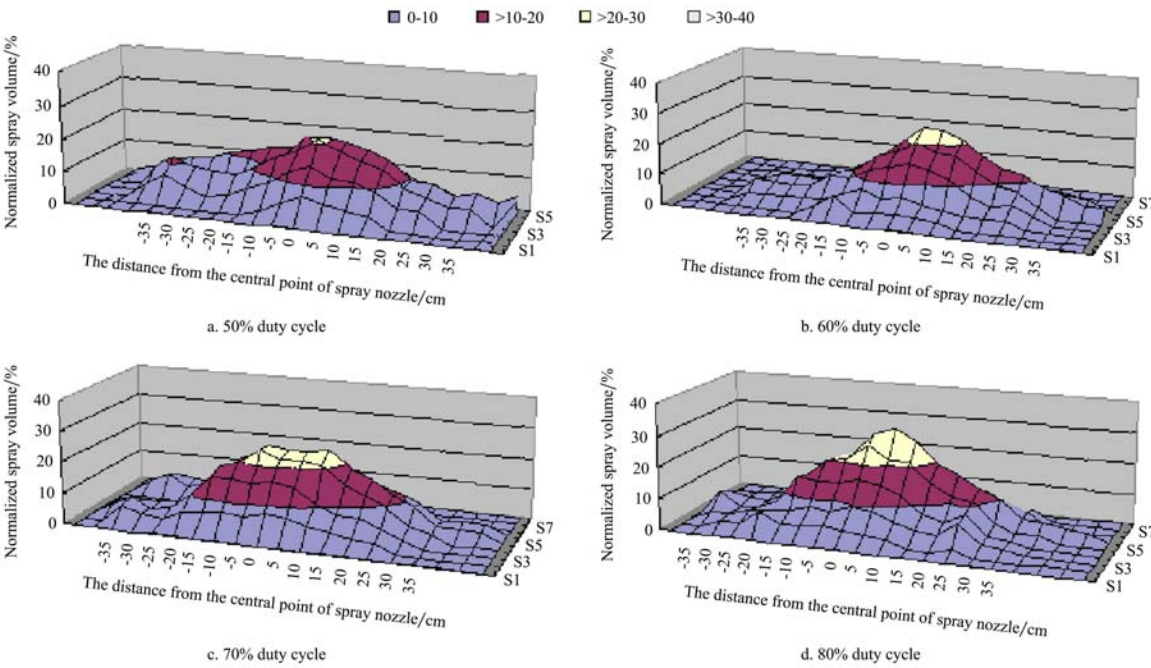
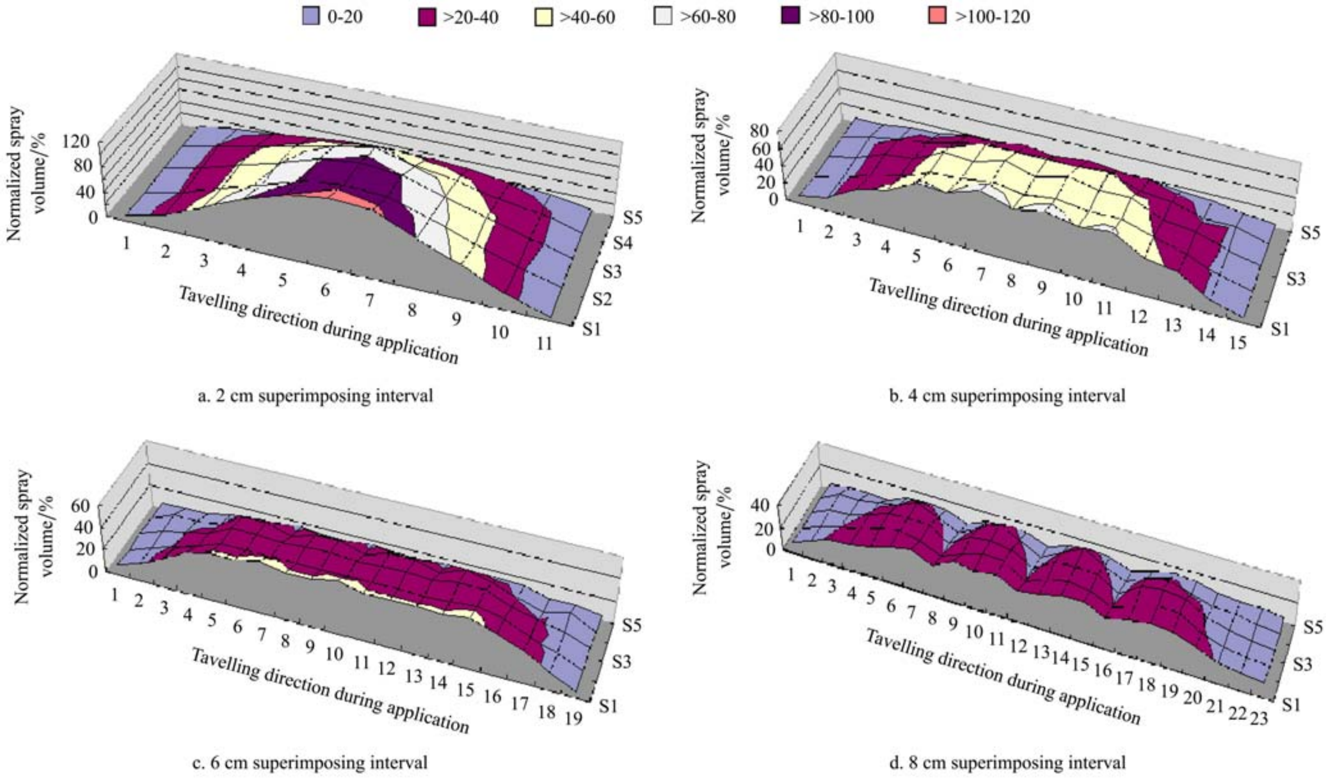


Figure 8 2-D spatial spray distribution pattern. S1, S2, ... , S7, mean the span of deposit surface.

3.3 3-D spatial-temporal spray distribution

Based on the approach introduced in Section 2.4.2, with the changing duty cycle of PWM square-wave signal (i.e. changing flow-rate), the 2-D models of spray volume distribution were established under different working conditions. According to the superimposing method shown in Figure 6, a 3-D model was built by superimposing the 2-D models of spray volume distribution in the traveling direction of agricultural operation at a certain interval. For example, in the case of the spraying working condition with duty cycle of 80%, the 2-D models of spray volume distribution was superimposed at the interval of 2, 4, 6 and 8 cm. The cross-sectional view of the 3-D spatial-temporal model of spray deposit volume distribution for a single nozzle is shown in Figure 9. Figure 9 shows that the spray deposit distribution with the superimposing interval of 6 cm is more uniform than the other superimposing intervals. This indicates that the appropriate traveling speed during pesticide application in fields should be carefully chosen so as to produce more uniform spray distribution.



Note: S1, S2, ..., mean the span of deposit surface

Figure 9 3-D spatial-temporal spray distribution pattern

4 Conclusions

(1) After visually modeling the measured data of spray volume distribution from the PWM-based continuous variable-rate spray, the results indicated that the 1-D model shows that the spray volume distribution concentrated toward the center with the decreasing flow-rate. The 2-D model demonstrated that the 2-D spatial distribution was consistently normally-distributed as the flow-rate was changing, and the proportion of spray volume in the central of the spray depositing region increased with increasing flow-rate. The 3-D spatial-temporal model showed that the spray volume depositing distribution tended to be more uniform when the suitable traveling speed of the sprayer was chosen.

(2) This study indicated that a graphic method could be used to make a spatial analysis of spray distributions more informative for the PWM-based continuous variable-rate spray and other types of variable-rate spray as well. With the development of computer technologies and simulation algorithms, this method

could be widely used as an effective tool for estimation and analysis of spray spatial distribution characteristics.

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