COMPARISON AND EVALUATION OF SPRAY CHARACTERISTICS OF THREE TYPES OF VRIABLE-RATE SPRAY

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ABSTRACT

For the present developing direction of "low-input sustainable agriculture", variable-rate technology is increasingly concerned in agricultural engineering field. The technology of variable-rate precision chemical application is the typical of variable-rate technology. In China, agro-chemical production technology has reached the international advanced level, but the chemical application technology is still relatively backward, which has caused serious problems such as excessive utilization of agro-chemical, environmental pollution, food security, and so on. The current situation showed that continued deep research on variable spray technology and its spray characteristics is necessary and significant. In this research, three variable-rate spray equipments, PWM-based (namely, based on Pulse Width Modulation (PWM) technology) intermittent variable spray, PWM-based continuous variable spray, and pressure-based variable spray, were set up and their spray characteristics were studied in terms of flow-rate regulating range, spray distribution pattern, spray angle, spray droplet size, spray droplet velocity, spray specific energy and spray kinetic energy median diameter. The spray characteristics of the three kinds of variable spray methods were compared. Besides, a set of evaluation methodology for studying variable spray characteristics was put forward to provide a reference method of systematic study on variable spray characteristics. The results show that the influence of PWM-based intermittent variable spray on spray characteristics is the slightest. The flow regulating range of PWM-based continuous variable spray is the widest, which can reach 7:1 for flat-fan nozzle. The flow regulating range of pressure-based variable spray is the narrowest, which is just about 2:1. And the influence of pressure-based variable spray on its characteristics is the most serious. For the variable spray on fixed-width linear row crops, PWM-based intermittent variable spray should be the first choice. Yet, when the transverse width needs to be considered in spatially variable application, PWM-based continuous variable spray can be an alternative method.

Keywords: Variable-rate spray, Spray characteristics, Pulse-Width Modulation, flow-rate control

INTRODUCTION

Plant diseases, insect pests and weeds distribute unevenly in the fields (Chen et al, 2003; Thornton et al, 1990; Wilson & Brain, 1991). Chemicals need to be applied accurately according to actual situations in fields. In such a system, features of spray targets should be inspected continuously, and be used as the foundation to optimize application operation and adjust spray volume and spray characteristics, so as to improve the effectiveness and accuracy of chemical application. Therefore, various kinds of variable spray equipment need be developed to meet the need of complicated field conditions. Consequently the negative impact of chemical over-usage can be diminished to the smallest extent so as to keep the continuous growth of agriculture (Chen & Zheng, 2005). Accurate spraying relies on reliability and perfection of variable volume control. After a type of variable spray equipment is designed and set up, its spray characteristics must be studied. Giles et al. has studied on PWM-based intermittent variable spray extensively (Giles &Comino, 1989, 1990; Giles & Ben-Salem, 1992). As a kind of traditional spray method, although pressure-based variable spray has some disadvantages, for example it changes spray droplet size dramatically, it remains in use in many commercial spray systems.

In this paper, a type of variable spray, namely PWM-based continuous variable spray, was developed and studied by the authors. The purpose of this paper is to compare spray characteristics of PWM-based continuous, PWM-based intermittent, and pressure-based variable spray under the same experimental condition, in terms of flow-rate regulating range, spray distribution pattern, spray angle, spray droplet size, spray velocity, spray specific energy (SE), and spray kinetic energy median diameter (KEMD).
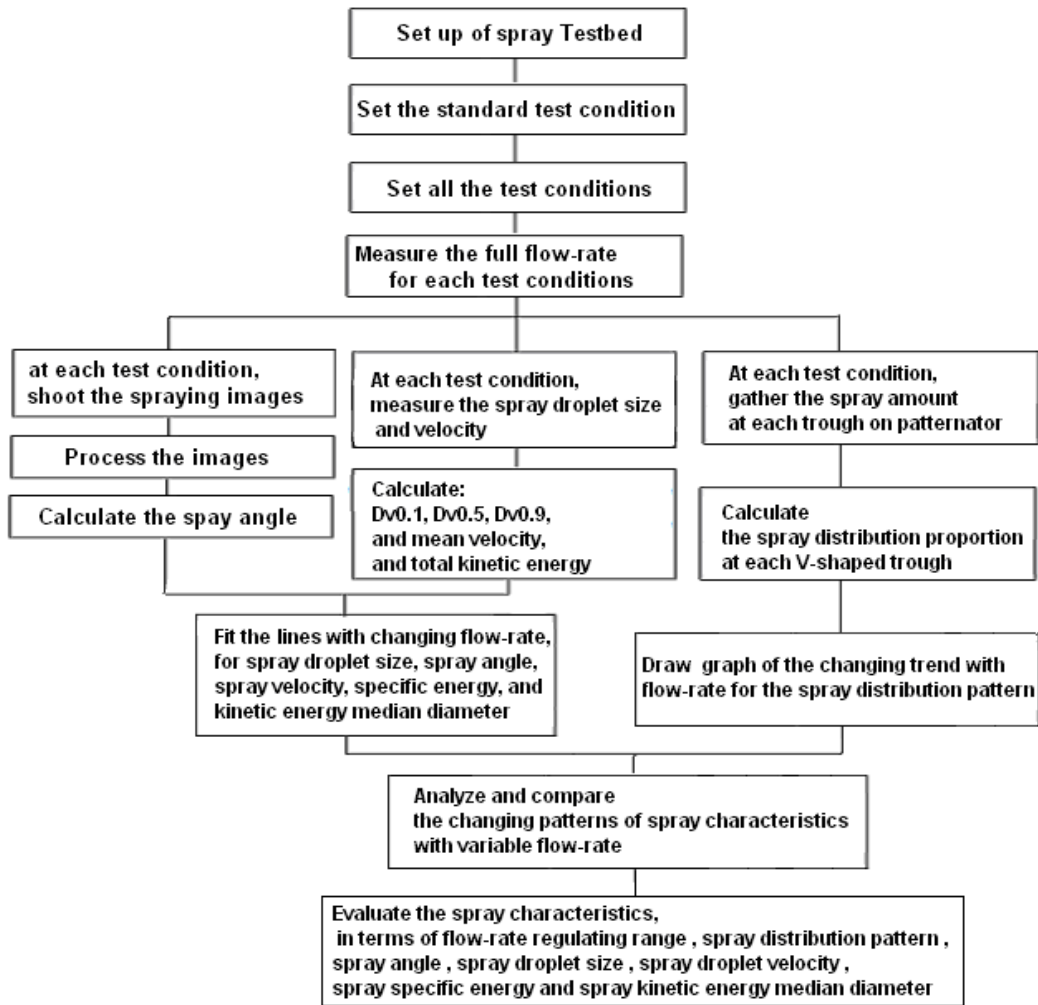
2 Materials and methods

2.1 Evaluation methodology for studying variable spray characteristics

Parameters for describing spray characteristics are as follow: (1)Spray distribution pattern: to describe the spray distribution pattern on targets. (2) Spray angle: To describe the spray divergence degree. (3)Spray droplet size $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$: $D_{V0.5}$ is also called Volume Median Diameter (VMD), 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; The definitions of $D_{V0.1}$ and $D_{V0.9}$ are all similar with $D_{V0.5}$. (3) Spray dynamic characteristics: Spray droplet velocity, Specific energy (SE), Kinetic energy median diameter (KEMD). Spray SE is the amount of energy per unit of flow mass. The definition of KEMD is similar to VMD.

Through reading in the literatures and summarizing from the study and test, the authors put forward a set of evaluation methodology for studying variable spray characteristics so as to provide a reference method of systematic study on

variable spray characteristics. Flowchart of the study method is shown as follow.

Set up of spray Testbed

Set the standard test condition

Set all the test conditions

Measure the full flow-rate for each test conditions

| at each test condition, shoot the spraying images | At each test condition, measure the spray droplet size and velocity | At each test condition, gather the spray amount at each trough on patternator |

Process the images

Calculate the spay angle

Calculate: Dv0.1, Dv0.5, Dv0.9, and mean velocity, and total kinetic energy

Calculate the spray distribution proportion at each V-shaped trough

Fit the lines with changing flow-rate, for spray droplet size, spray angle, spray velocity, specific energy, and kinetic energy median diameter

Draw graph of the changing trend with flow-rate for the spray distribution pattern

Analyze and compare the changing patterns of spray characteristics with variable flow-rate

Evaluate the spray characteristics, in terms of flow-rate regulating range , spray distribution pattern , spray angle , spray droplet size , spray droplet velocity , spray specific energy and spray kinetic energy median diameter

Fig.1 Flowchart of study method

2.1　Measuring set–up

A frame diagram of test-bed for spray flow-rate control is shown in Figure 1. The liquid supply system is composed of liquid container, electrical motor and pump, overflow mechanism, fluid delivery tube, flow-rate meter, and pressure meter.　Two sets of flow-rate control equipment were set up in the study, namely, PWM-based intermittent spray equipment and PWM-based continuous spray equipment.　No. N11012 flat-fan nozzle of N110 series which is commonly applied in agriculture was used in the study.
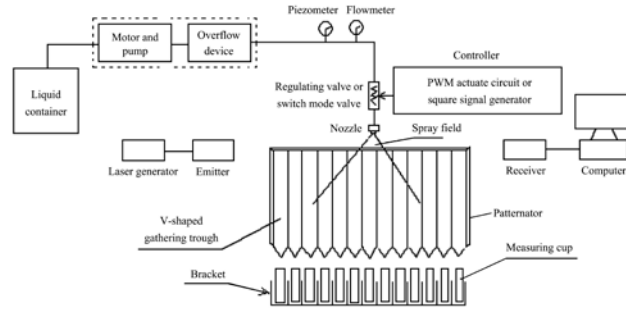
Fig. 1 Diagram of nozzle spray flow-rate control test-bed

2.1.1 Measuring and statistic methods of spray droplet size and velocity

Phase-Doppler Particle Dynamic Analyzer (PDA) manufactured by Dantec Dynamics Company was used to measure spray droplet size and velocity. PDA consists of a laser generator, a laser shot set, an optical receiving set, and a computer. The advantages of this device are high precision, undisturbed measurement, no need for temperature correction and pressure correction (Zhang et al, 2002; Li & Yan, 2003). 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 synchronously.

The descriptive parameters of spray droplet size spectrum were calculated from measured droplet size data. The descriptive parameters are: (1) $D_{V0.5}$; (2) $D_{V0.1}$; (3) $D_{V0.9}$. $D_{V0.5}$ is also called Volume Median Diameter (VMD), 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. Definitions of $D_{V0.1}$ and $D_{V0.9}$ are all similar with $D_{V0.5}$. The independent variable was the normalized (0-100%) flow-rate and the response variables were $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$. The relationship between droplet size parameters and flow-rate was quantified by least squares fitting with first-order to the observed data. The form of the model (Giles & Comino, 1990) is:

$$Y = \alpha + \beta * (X - 100) \qquad (1)$$

where, Y is droplet size statistic data, namely, $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$, whose unit is μm. X is relative flow-rate (%). Parameter α has the physical meaning of droplet size statistic value at full flow-rate (100%), whose unit is μm. β is sensitivity of droplet size statistics to nozzle flow-rate, namely slope coefficient of fitted line, whose unit is μm/%. Applying the measured data (relative flow-rate and corresponding droplet size statistics) to formula (1), the relationship curve between spray droplet diameter and relative flow-rate can be obtained through fitting $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ values to different flow-rates using first-order linear least-squares fitting.

Three descriptive terms, spray droplet velocity, spray specific energy (SE) and kinetic energy median diameter (KEMD), are used to describe spray dynamic

characteristics (Giles & Ben-Salem, 1992). Spray SE is the amount of energy per unit of flow mass. It is a concept of intensity equal to the total kinetic energy divided by the flow quantity from the nozzle per unit time. Total kinetic energy is the sum of kinetic energy of each droplet. The definition of KEMD is similar to VMD. KEMD indicates energy distribution among spray droplets. The utility of SE and KEMD parameters can best be illustrated by an example (Giles & Ben-Salem, 1992).

For each test condition, KEMD and SE were computed using droplet size and velocity. Linear least squares fittings produce trend lines which indicate changes of KEMD and SE with flow-rate.

2.1.2 Set-up and measurement of spray distribution

A patternator for measuring spray distribution pattern was made according to the universal test methods of plant protection in machinery industrial standards (JB/T 9782-1999) coming into effect in China since 2000. Each gathering trough is a V-shaped configuration with 50 mm in width and 40 mm in depth, as shown in Figure 1.

Timed by using a stopwatch, spray distribution was sampled for each test. Spray volume collected in all sample cups was summed. The volume in each sample cup was divided by the collected total flow volume. The resulting fraction was just the spray distribution proportion at each V-shaped trough and was used as the response variable in all statistical analysis.

2.1.3 Spray angle measurement

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 test condition was shot by a camera. The spray angle was worked out using the method in the document (Deng et al, 2006). The relationship between spray angle and flow-rate was quantified by least squares fitting with first-order. All the least squares fittings in the paper were done in MATLAB.

2.2 Testing techniques

2.2.1 Principles of Pulse Width Modulation (PWM) spray equipment

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 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, $\varphi = t_{on}/T$ is the conduction duty cycle, or duty cycle for short (Wang & Huang, 2000).

2) Principle of PWM-based continuous variable spray

Flow control principle schematic of PWM-based continuous variable spray is shown in Figure 2(a), and the waveform figures for indicating the control principle are shown in Figure 2(b).
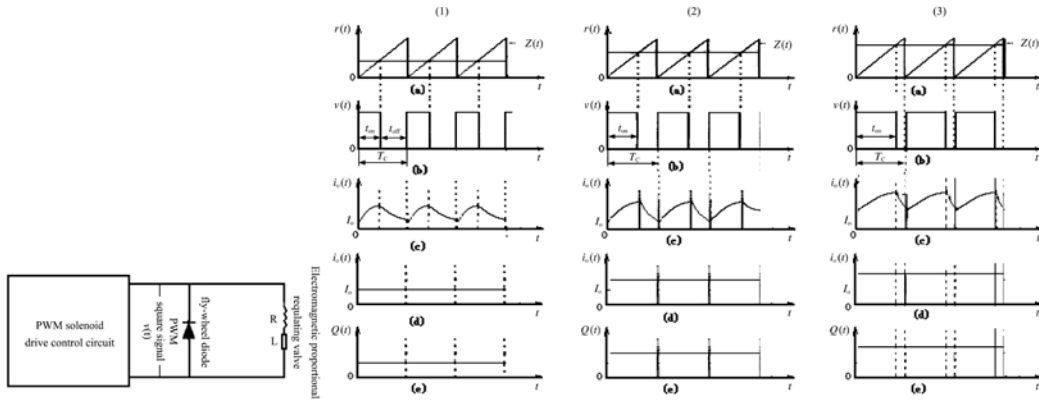
(a) Schematic   (b) Wave figures, for duty cycles: (1)<(2)<(3)

Fig. 2　control principle for PWM-based continuous variable 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 3. 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 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, the charge and discharge time of inductance and output current I_o all 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.

　　3) Principle of PWM-based intermittent variable spray

　　The principle of PWM-based intermittent spray flow-rate control is shown in Figure 3. $R(t)$ is control signal with certain frequency produced by microcomputer. Compare $R(t)$ and modulated signal $Z(t)$. If $R(t)<Z(t)$, then control circuit outputs high level and valve is open. Otherwise, if $R(t)>Z(t)$, circuit outputs low level and valve is close. A serial of pulse control signals $V(t)$ is shown in Figure 3. Within one cycle T_C, with the valve open, flow-rate is Q in t_{on} period; with the valve closed, no flow through the valve in t_{off} period. The flow-rate can be adjusted through adjusting the duty cycle.

**2.2.2　Equipment of PWM-based continuous variable spray**

　　1) *Electromagnetic proportional regulating valve* (EPRV)

　　An electromagnetic proportional regulating valve (model No. 6023) produced by Burdert Company in Germany was chosen. It is a direct-acting, two-way,

normally-closed solenoid valve. The EPRV shuts off when electric power is cut off; when power is supplied, valve opening is adjusted continuously according to the different duty cycles of the 24 kHz PWM electrical signal. This kind of EPRV must be controlled with PWM control signal.

2) *Control circuit of PWM EPRV*

The control circuit of PWM continuous variable spray is shown in Figure 4. The key part of the control circuit is a chipset with Model DRV101. It can output a PWM square control signal with 24 kHz frequency. The duty cycle of PWM output signal can be adjusted between 10%-100% by tuning the resistor RPWM (DRV101 Specification, 2003). By adjusting the duty cycle, the opening of EPRV is controlled and spray volume adjusted. For an inductive load, a fly-wheel diode must be connected to the load in reverse parallel for external inverse discharging.
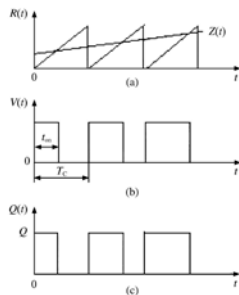
Fig. 3 Wave figure of control principle for PWM-based intermittent spray
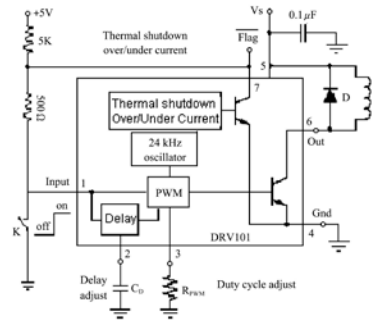
Fig. 4 Control circuit of PWM EPRV

2.2.3 Equipment of PWM-based intermittent variable spray

A low-flow, direct-acting, normal close, switch-mode solenoid valve was used in PWM-based intermittent spray equipment. The valve is open with electrified solenoid coil, and closed with un-electrified coil. The switch-mode solenoid valve was actuated using a square signal with tunable frequency within 20 Hz and tunable duty cycle within 10%-100%.

2.2.4 Equipment of pressure-based variable spray

The system pressure was adjusted by overflow mechanism.

2.3 Test conditions

For PWM-based continuous spray, the actuating signal of EPRV is a square signal with 24 kHz frequency and duty cycle adjustable continuously between 10%-100%. Test conditions were obtained by adjusting the duty cycle of control signal. For all the test conditions, the spray flow-rate (L/min) was an average of the volume of two times spraying separately within 1 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. For PWM-based intermittent spray, test conditions were obtained by changing frequency and duty cycle of driving signal. In the two types of variable spray

above, liquid pressure is set at 0.3 Mbar.   For pressure-based spray, flow-rate is adjusted through changing liquid pressure.   We assumed a standard test condition as the spray condition with 0.3 Mbar pressure and without any auxiliary flow-rate control device. The relative flow-rate is equal to the ratio of flow-rate at each test condition to flow-rate at standard test condition.

The data for showing test conditions and the corresponding relative flow-rate for PWM-based continuous variable spray, PWM-based intermittent spray, and pressure-based spray are omitted here because of the page limitation.

3   Results and discussion

3.1   Flow regulating range

For PWM-based continuous spray, 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 which is 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 by dividing maximum flow-rate by minimum flow-rate.   The flow-rate regulating range was 7.14:1.

For PWM-based intermittent spray, at 5, 8, and 10 Hz frequency, the spray flow-rate was measured when duty cycle was adjusted from upper limit to lower limit, as shown in Table 4.   The flow-rate regulating range was 4.17:1 (=100%/24%).

From Table 3, flow-rate regulating range for pressure-based spray was 1.88 (=124/66) when liquid pressure changed from 0.5 MPa to 0.15 MPa.

Table 4   Relative flow-rate at upper and lower limits of duty cycle at 5.0, 8.0, 10.0Hz

| Frequency /Hz	Lower limit of duty cycle/%	Relative flow-rate/%	Upper limit of duty cycle/%	Relative flow-rate/%
5.0	10	24	100	100
8.0	10	29	100	100
10.0	10	32	100	100

3.2   Spray distribution

For PWM-based continuous spray, example pattern data are shown graphically in Figure 5(a) in histogram form.   The spray pattern is proportionally illustrated to make spray distribution patterns at various flow-rates shown in a unified coordinate system in order to compare spray patterns at different flow-rates.   It indicates that the spray distribution pattern is influenced significantly by PWM-based continuous variable spray.   With flow-rate decreasing, distribution pattern greatly concentrated toward the center below the nozzle, namely, spray divergence and transverse span reduce.   But the spray

shape presents basically a symmetrical distribution.

Similarly, spray distribution patterns with changing flow-rate for PWM-based intermittent and pressure-based variable spray were shown in Figure 5(b) and 5(c). They indicate that flow-rate changing under PWM-based intermittent spray mode has less effect on its spray distribution pattern, whereas for pressure-based variable spray, its spray distribution becomes more dispersed and distribution span becomes broader with increasing pressure and flow-rate. And such changes are significantly notable.

Spray distribution patterns become wider with increasing flow-rates for all the three types of variable flow control.　This effect is the greatest for pressure-based variable spray, but the smallest for PWM-based intermittent spray, which nearly can be neglected.
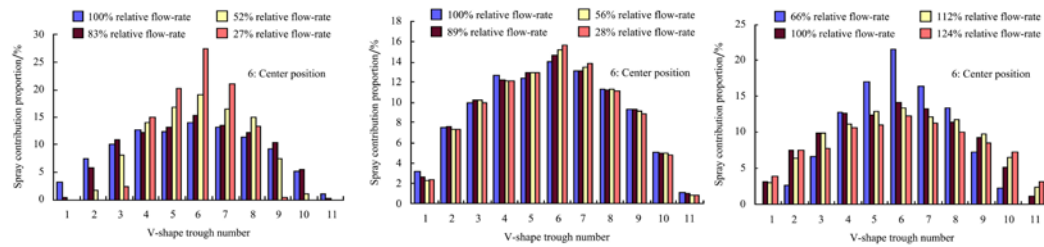
a. PWM-based continuous variable spray　　b. PWM-based intermittent　c. Pressure-based

Fig. 5　Spray distribution pattern for three types of variable spray

3.3　Spray angle

The relationships between spray angle and flow-rate for the three types of variable spray are shown in Figure 6.　It can be seen that the spray angle reduces for PWM-based continuous variable spray with a decreasing flow-rate.　The slope of the fitted line, namely, the sensitivity of spray angle to flow-rate change is $0.83°/\%$ (where, $°/\%$ is the angle decrement for each per cent of flow-rate decrease).　When flow-rate decreases from 100% to 40%, the spray angle decreases by $49.8°$ (which is equal to $(100\%-40\%)\times0.83\ °/\%$).　This value is equal to 45.27 percent of $110°$.　$110°$ is the spray angle at full spray flow-rate. This indicates that spray angle for PWM-based continuous variable spray is sensitive to flow-rate control.

For PWM-based intermittent spray, the change rate of spray angle is $0.04°/\%$, namely, the spray angle decreases by $0.04°$ when the flow-rate decreases one percent.　This indicates that spray angle decreases slightly with decreasing flow-rate, and flow-rate control has less effect on spray angle.　For pressure-based spray, the changing rate of spray angle to flow-rate is about $1.08°/\%$, namely, the spray angle increases by $1.08°$ when the flow-rate increases by one percent.

Spray angles for the three types of variable spray become bigger with

increasing flow-rates.   The sensitivities of spray angle to flow-rate changing are 1.08°/% for pressure-based variable spray, 0.04°/% for PWM-based intermittent spray, and 0.83°/% for PWM-based continuous spray.   It illustrates that the effect of pressure-based spray flow-rate control on spray distribution pattern, spray angle, and space spread degree is the most significant among the three types of variable spray.   Space spread degree directly affects the kinetic characteristics of spray droplets (Sidahmed, 1997, 1999; Tuo et al, 2006).
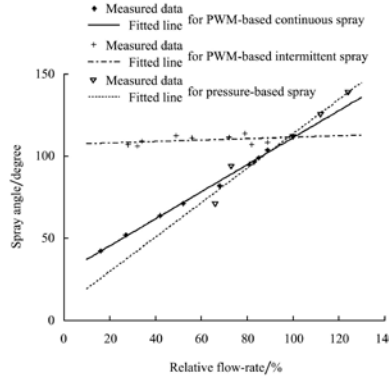
Fig. 6   Spray angles vs. flow-rate, for three types of variable   spray

3.4   Spray droplet size

The droplet size statistic data obtained at full flow-rate were compared with estimated α. Model parameter estimates and observed droplet size statistics appear in Table 5 for PWM-based continuous variable spray.   The change rates of $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ to flow-rate change are 0.063, 0.349, and 0.529 μm/%, respectively.   Over a flow-rate changing range of 100% to 40%, the diminishment in $D_{V0.1}$ is 3.78(=0.063×60) μm, which represents 1.7% of estimated $D_{V0.1}$ of 228.9 μm at full flow-rate; the diminishment in $D_{V0.5}$ is 20.94(=0.349×60) μm, which represents 5.4% of estimated $D_{V0.5}$ of 385.4 μm at full flow-rate; the diminishment in $D_{V0.9}$ is 31.74(=0.529×60) μm, which represents 3.6% of estimated $D_{V0.9}$ of 878.4 μm at full flow-rate.

Table 5   Parameter estimates and sensitivities of droplet size to PWM-based continuous spray flow control

Parameters	Measurements of α /μm	Estimates of α /μm	Estimates of β / (μm/%)
$D_{V0.1}$	233.4	228.9	0.063
$D_{V0.5}$	413.3	385.3	0.349
$D_{V0.9}$	896.8	878.4	0.529

Model parameter estimates, statistical value of measurements of spray droplet diameter are shown in Table 6 and Table 7, respectively for PWM-based

intermittent and pressure-based variable spray.　For PWM-based intermittent spray, the spray droplet size decreases with an increasing flow-rate. $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ respectively increase for about 0.237, 0.616, and 1.982 μm, when the flow-rate decreases by one percent.　When the relative flow-rate decreases from 80% to 20%, $D_{V0.5}$ increases by 36.96(=0.616×60) μm.　This increment is equal to 8.7% of estimated full flow $D_{V0.5}$ of 423.4 μm.　It indicates that the effect of intermittent flow control on $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ is minor. For pressure-based spray, the change rates of $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ to the changing flow-rate are 1.023, 1.562, and 3.609 μm/%, respectively.　Spray droplet diameters decrease significantly with increasing pressure.

Table 6　Parameter data and sensitivity of droplet size to intermittent flow-rate control

Parameters	Measurements of α /μm	Estimates of α /μm	Estimates of β/ (μm/%)
$D_{V0.1}$	233.4	241.3	-0.237
$D_{V0.5}$	413.3	423.4	-0.616
$D_{V0.9}$	896.8	957.8	-1.982

**Table 7　Measurements and sensitivities of droplet size to flow-rate for pressure-based variable spray**

Feature diameters /μm	Flow-rate/%					Sensitivities of droplet size to flow-rate/μm·%$^{-1}$
	66	73	100	112	124	
$D_{V0.1}$	263.1	249.7	233.4	207.9	203.6	-1.023
$D_{V0.5}$	482.3	456.3	413.3	402.5	387.5	-1.562
$D_{V0.9}$	1006.3	959.6	896.8	832.8	785.1	-3.609

　　The fitted lines for showing the relationships between spray droplet diameter and relative flow-rate for the three types of variable spray are shown in Figure 7 using VMD, which is the representative parameter to describe the spray droplet size.　The observed and predicted values are in close agreement.　It can be seen that droplet size decreases with decreasing flow-rate for PWM-based continuous variable spray and increases with the decreasing flow-rate for PWM-based intermittent and pressure-based variable spray.　The change rates are 0.349, -0.616, and -1.562, respectively.　The effect degree of pressure-based variable spray on droplet size is the greatest.　The droplet size spectrum obviously moves toward the smaller side when the supplied pressure increases.　For PWM-based intermittent and PWM-based continuous variable spray, although flow-rate control has some influence on droplet size, it hardly makes the spray droplet size spectrum move toward the smaller or the larger side.　Therefore, the change

nearly can be neglected.

3.5 Spray droplet velocity

For PWM-based continuous variable spray, at 100%, 75%, 65% and 50% duty cycles, the droplet size and velocity were measured with PDA. Each block of results was grouped into sub-blocks of 30 μm intervals. The mean velocity and the mean diameter of each sub-block were calculated. Treating the droplet velocity as a function of the droplet size, we fitted the measured data by using the least-squares equation for each duty cycle. The fitting order was 3. The resulting relation lines are shown in Figure 8. It can be seen that the velocity decreases with the reducing flow-rate. Especially when the duty cycle is below 75%, the relationship between droplet velocity and diameter changes significantly, and the droplet velocity falls greatly with the decreasing flow-rate.
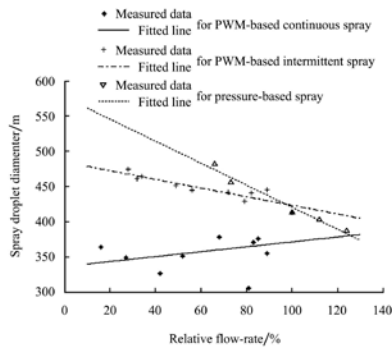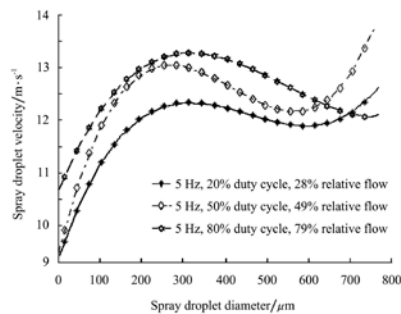

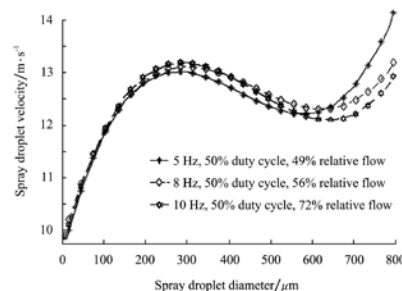**Fig. 7 Droplet size VMD vs. relative flow-rate for three types of variable spray**
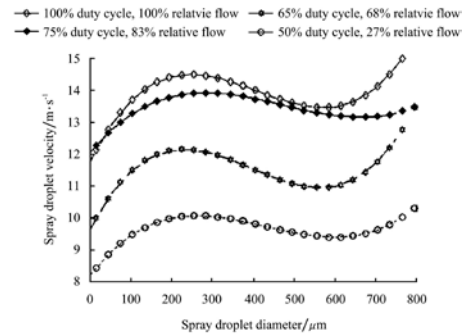
Fig. 8 Droplet velocity vs. diameter for PWM-based continuous variable spray

For PWM-based intermittent spray, (a) with 5 Hz frequency at 20%, 50%, and 80% duty cycle respectively (corresponding to 28%, 49%, and 79% relative flow-rate), (b) with 50% duty cycle at 5, 8, and 10 Hz respectively (corresponding to 49%, 56%, and 72% relative flow-rate), the droplet velocity and diameter data were measured and processed. Their relationship curves between droplet velocity and diameter are shown in Figure 9 and 10. A small change in droplet velocity with a changing flow-rate was observed.

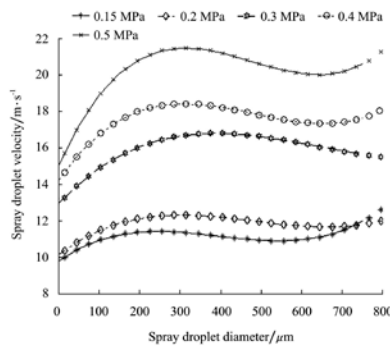**Fig. 9 Droplet velocity vs. diameter,   for intermittent spray at 5 Hz with**

20%, 50%, and 80% duty cycle   diameter, for intermittent spray at
Fig. 10   Droplet velocity vs.   50% duty cycle in 5, 8, and 10 Hz

For pressure-based variable spray, relationship curves between droplet velocity and diameter at different pressure are shown in Figure 11.   It is observed that the droplet velocity increases obviously and conformably with increasing pressure.

With a decreasing flow-rate, the spray droplet velocity decreases for pressure-based and PWM-based continuous variable spray, whereas the velocity for PWM-based intermittent variable spray changes little.   An obvious rise is observed for larger droplets, which may be due to insufficient precision of the measuring technique which treats some random sample noises as large droplets.


Fig. 11   Droplet velocity vs. diameter, for pressure-based variable spray

3.6   Specific energy (SE) and kinetic energy median diameter (KEMD)

The fitted lines of SE and KEMD to flow-rate change for the three types of variable spray are shown in Figure 12 and 13.   It is shown in Figure 12 that SE of the three types of variable spray all increases with an increasing flow-rate. The change rates of SE for PWM-based continuous, PWM-based intermittent and pressure-based variable spray are respectively 0.1472, 0.2451, and 0.2287 (J/kg)/%.   All the spray SE change rates are relatively small and similar.   Only for pressure-based spray, the SE growth is raised by increasing system pressure and energy.   So it is inferred that the capacity usage ratio is the lowest for pressure-based variable spray.

The changing trends of KEMD are shown in Figure 13.   For PWM-based continuous variable spray, KEMD slightly decreases with a reducing flow-rate, but the trend is not statistically significant.   Change rates are 0.35 μm/% for VMD and 0.34 μm/% for KEMD.   For PWM-based intermittent spray, KEMD and VMD increase slightly with a decreasing flow-rate. Change rates are -0.63 μm/% for KEMD and -0.62 μm/% for VMD.   For pressure-based spray, KEMD decreases with an increasing flow-rate.   Change trends of KEMD and VMD are all the same for the three types of variable spray, which indicates that KEMD is related with the droplet size.
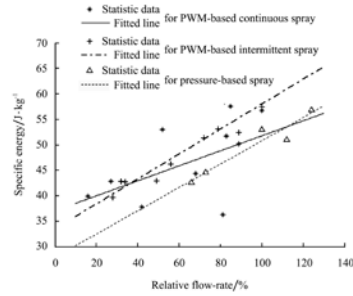
Fig. 12　SE vs. relative flow-rate for three types of variable spray
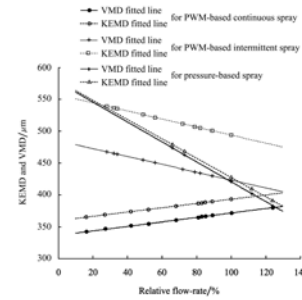
Fig. 13　KEMD and VMD vs. relative flow-rate for three types of variable spray

4　Conclusions

1) For pressure-based variable spray, the flow-rate regulating range is the narrowest, namely about 2:1. However, the effect on spray characteristics is the most significant.　When pressure is raised to increase the spray flow-rate, the spray distribution pattern distorts seriously, and the spray angle remarkably enlarges.　The spray size spectrum obviously moved toward a smaller droplet size.　The energy utility ratio is relatively low.

2) For PWM-based intermittent variable spray, the effect of flow-rate control on spray characteristics is the lightest.　Compared with pressure-based variable spray, the effect of PWM-based pulse spray on spray distribution pattern, spray angle, and spray droplet size spectrum can be basically neglected.　Consequently, PWM-based intermittent variable spray should be preferred for variable spray on lines with fixed width.　One shortcoming for PWM-based intermittent spray is the short lifetime of its solenoid valve due to frequent turning-on/off for valve spool.　However, this problem can be solved if a high-speed acting electromagnetic valve is chosen.

3) For PWM-based continuous variable spray, the flow-rate regulating range is the widest, which is about 7:1.　Although this kind of flow control has a certain influence on spray distribution pattern and spray angle, its effect on droplet size spectrum is negligible.　The spray distribution becomes wider with an increasing flow-rate, but the change degree is less than that of pressure-based spray.　When a request for transverse width changing spray is considered, variable spray should be implemented according to the transverse spatial change of spraying targets. PWM-based continuous variable spray should be an alternative choice.

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