EQUIPMENT AND EXPERIMENT OF GREENHOUSE HIGH-PRESSURE ATOMIZATION SPRAYING BASED ON PLC
/
基于 PLC 的温室高压雾化喷药设备及试验

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ABSTRACT
Aiming at the problems of the low efficiency of manual pesticide application in the greenhouse, the narrow operating space of plant protection machinery, and the possibility of poisoning the pesticide applicators due to the closed space, a high-pressure atomization spraying equipment for the greenhouse was designed. The spraying equipment adopts two-way communication between PLC and HMI to realize the adjustment of atomization pressure and atomization flow, and the control equipment completes automatic spraying. To determine the best working parameters of the spraying equipment, orthogonal tests were conducted with atomization pressure and atomization nozzle aperture as the test factors and the coefficient of variation of the fog volume distribution as the evaluation index. The optimum combination after parameter optimization was determined to be as follows: atomization pressure of 4 MPa, atomization nozzle aperture of 0.4 mm. The test results under the optimal parameters showed that the spray distribution coefficient of variation was 10.5%, and the uniformity of fog volume distribution was good to meet the requirements of spraying in greenhouses.

摘要
针对温室手动施药效率低、植保机械作业空间狭窄、空间封闭容易造成施药人员中毒等问题，设计了一种温室高压雾化喷药设备。该喷药设备采用 PLC 和 HMI 之间的双向通信实现对雾化压力和雾化流量的调整，控制设备完成自动喷药。为确定喷药设备的最佳工作参数，以雾化压力和雾化喷头孔径为试验因素，以雾量分布变异系数为评价指标，进行了正交试验。获取最优参数组合为雾化压力为 4MPa、雾化喷头孔径为 0.4mm。最优参数下的试验结果表明，雾量分布变异系数为 10.5%，雾量分布均匀性较好，满足在温室大棚内的喷药要求。

INTRODUCTION
The greenhouse is to create a growth environment suitable for crop development under relatively controlled environmental conditions to achieve uninterrupted production of vegetables in all seasons, but the warm, humid greenhouse environment is very likely to cause disease and pest outbreaks, seriously affecting crop growth, yield, and quality (*He, 2020; He, 2018*). The current greenhouse application equipment is mainly semi-automatic rough machinery, spraying process droplet particle size, settling fast, easy to lose from the crop target, resulting in pesticide waste, soil pollution, while the closed, high-temperature greenhouse environment is easy to cause pesticide poisoning of application personnel (*Wang et al., 2021; Guo et al., 2022).*

Therefore, developing spray medicine equipment suitable for greenhouse growing patterns is an urgent need to achieve efficient production, and scholars at home and abroad have conducted a lot of research on spray medicine equipment for greenhouse environments. Some scholars used GPRS communication and control technology to achieve remote control and operation of the fogging machine in the greenhouse cluster (*Qi et al., 2016*). Some scholars used PLC as the controller, the developed greenhouse track application robot travels on the paved track, which initially realizes the automatic control of application in the greenhouse (*Li et al., 2016*). Some scholars have installed the spray nozzles on fixed brackets inside the greenhouse and used relays to automatically control the application time to achieve unmanned automatic applications (*Rowe et al., 2000*).

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Some scholars have designed a greenhouse automatic sprayer that advances and retreats along a rail laid between greenhouse crops (*Alireza Rafiq et al., 2014*). At present, some scholars have designed small spraying robots for greenhouse spraying that use sensors to detect plants and spray them (*Hossein Mosalanejad et al., 2021*).

This paper uses PLC controller as the core. The high-pressure atomization control system is used to control the spraying pressure and spraying time of the equipment. In order to spray automatically and isolate people from drugs in the spraying process, various sensors are adopted to real-time monitor the running status of the equipment, and the water consumption and the alarm of the equipment are recorded after each spraying.

MATERIALS AND METHODS

System design

The greenhouse high-pressure atomization spraying equipment mainly consists of four parts: control system, actuator, sensor module, and auxiliary components. The control system includes PLC controller and HMI touch screen. The actuator includes the inverter, high-pressure atomization pump, electric ball valve, high-pressure atomization nozzle, etc. The sensor modules include pressure sensors, flow sensors, and level sensors. The auxiliary components include medicine tank, water tank, high-pressure fogging pipeline etc.

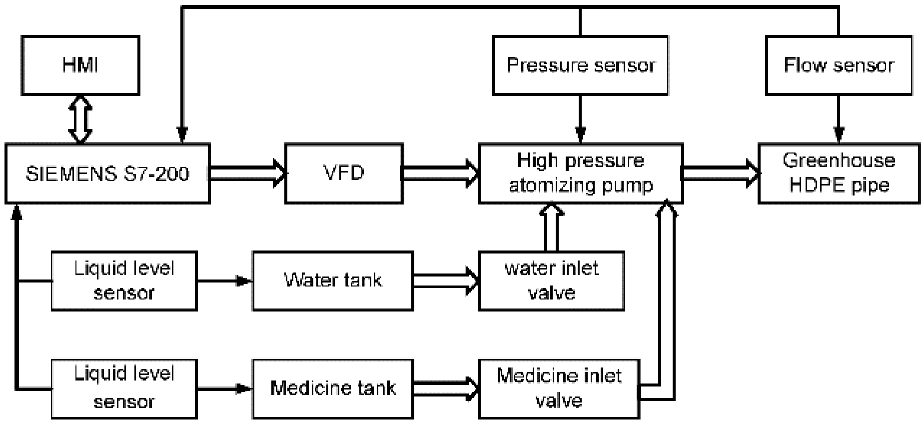

Fig. 1 - Block diagram of high-pressure atomization spraying system

The high-pressure fogging pipeline is arranged over the greenhouse, the pipeline selects 9.52 mm HDPE pipe, and the connection of the pipeline selects quick-connect 180° straight double spray joint, the spacing is 1.5 m, and the connection is made in straight series. High-pressure atomization spraying equipment is equipped with a standard interface for quick docking, and the high-pressure atomization pipeline is equipped with a corresponding docking interface for quick docking with the equipment. Each greenhouse requires only one set of high-pressure fogging pipes to be installed, and one unit can be used for multiple greenhouses, improving the utilization of equipment and reducing purchase costs.

Hardware design

The control system controller is an S7-200 SMART PLC, including a 4-way analogue input/2-way analogue output module, EM AM06. The working performance is more stable and can meet the requirements of the greenhouse site. The touch screen is PI8102-R of WECON, using PIStudio configuration software to write a greenhouse spray control system program, for parameter setting and real-time monitoring, communicating with PLC via RS-485 bus.

The actuator uses the BZ-986-45 high-pressure atomization pump with a power of 5.5KW. It has the advantage of high volumetric efficiency, good uniformity of liquid flow, and can meet high-pressure work. The working principle is: after the power is turned on, the liquid at low water level first enters from the inlet of the pump, generating a vacuum, and then discharges after being pressurized by the pump, and the discharged fluid is conveyed along the line into the spray tube, sprayed from each nozzle on the spray tube under high pressure. Depending on the spray pressure and nozzle type, fog with different droplet diameters is produced.

The performance of the nozzle directly affects the effect of atomized spraying. Select the high-pressure atomization nozzle with excellent atomization effect, stable spraying, and anti-drip. Commonly used nozzles are divided into 9 models from 0 to 8. After experimental testing, the No.4 high-pressure nozzle meets the greenhouse spraying requirements. Through the regulation of pressure, its spraying effect can meet the needs of greenhouse spraying pesticides and foliar fertilizers.

Table 1

Flow rates of different nozzle aperture at different pressures

Nozzle model		Flow rate（L/min）		
Model number	**Nozzle aperture**	**4MPa**	**5MPa**	**6MPa**
No. 2	0.2mm	0.07	0.08	0.09
No. 3	0.3mm	0.09	0.10	0.11
No. 4	0.4mm	0.22	0.25	0.28
No. 5	0.5mm	0.23	0.26	0.30
No. 6	0.6mm	0.27	0.32	0.38

As the detection part of the whole control system, the sensor element plays a crucial role and is the basis for the decision of the control system, the data acquired by the sensors directly affects the execution of the system actions (*Zhang et al., 2017*). The sensor module of this system mainly includes pressure sensor, flow sensor, and liquid level sensor. The selection is shown in Table 2.

Table 2

Sensor Model

Name of sensor	Model Specification
Pressure sensor	Measuring range: 0~20MPa, Accuracy: 0.5%, Two-wire system, Output: 4~20mA
Flow sensor	WL-LWGB-30 flowmeter, Two-wire system, Output: 4~20mA
Liquid level sensor	Measuring range: 0~1000mm, Accuracy: 0.2%, Two-wire system, Output: 4~20mA

Software design of high-pressure fogging spraying equipment for greenhouse

PLC control program design

The control programming is mainly written in the ladder language under the Siemens programming software STEP 7-Micro/WIN SMART environment. The system workflow is shown in Figure 2.

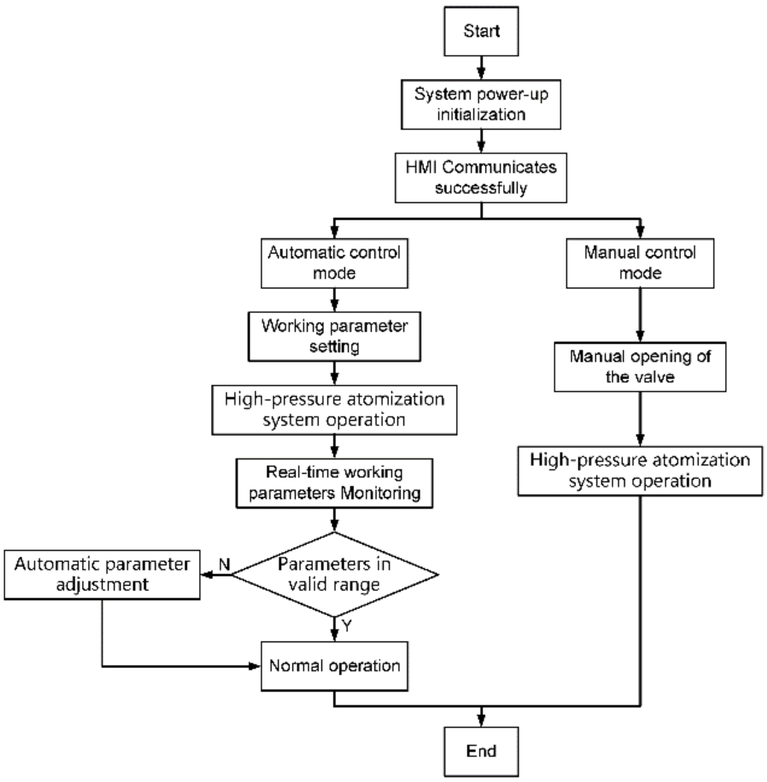

Fig. 2 - Control system workflow

After the greenhouse spraying equipment is started, there are two working modes to choose from, automatic and manual. In the automatic mode, the greenhouse spraying equipment enters the autonomous spraying state. After initialization, the system first reads the liquid level of the medicine tank and water tank and issues an alarm if it is lower than the minimum liquid level.

Set the working pressure, and working time, on the touch screen, the liquid level sensor detects that the liquid level has reached a predetermined value and turns on the spraying, medicine tank, water tank solenoid valve which open at the same time, after mixing water and medicine through the high-pressure pump to reach the nozzle to start the spraying work. The pressure sensor detects whether the pressure is within the set value in real-time, flow sensors measure the total spray volume, and the solenoid valve closes when the set time is reached. After reaching the set time, the solenoid valve closes and the spraying work stops automatically. In manual mode, spraying works by human control. The operator can freely set the equipment spraying pressure, spraying time, solenoid valve flow, and other various parameters to achieve a more accurate spraying effect.

HMI design

The Human Machine Interface (HMI) allows users to observe the operation status of spraying equipment at all times to achieve the purpose of real-time monitoring. Design the equipment operating status interface through the WECON PIStudio configuration software programming environment.

The default state of the system is the interface for setting the operating parameters of the device, as shown in Figure 3. Manual and automatic working modes can be selected in the parameter setting interface. In manual mode set the high-pressure pump pressure, click the spray pump, water valve, and drug valve switch button in turn, and you can carry out spraying work. In automatic mode set high-pressure pump pressure, and atomization time can be automatic spraying.

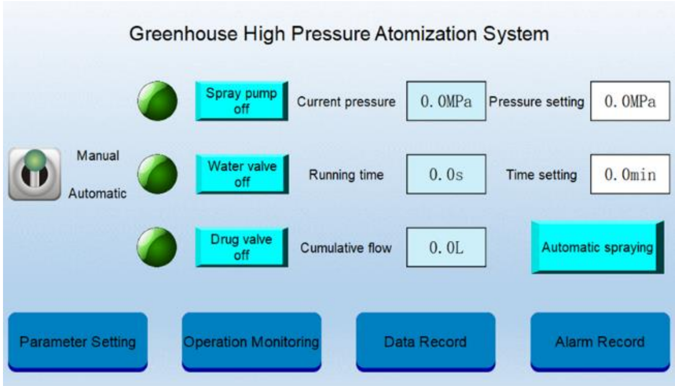

Fig. 3 - Working parameter setting interface

In the system operation monitoring interface, as shown in Figure 4, users can observe the current working pressure of the high-pressure pump, the working status of the solenoid valve of the medicine tank and water tank, as well as the liquid level of the medicine tank and water tank. In the data logging screen, users can view the equipment's past work history. In the alarm logging interface, users can view the contents of the alarms during the operation of the device.

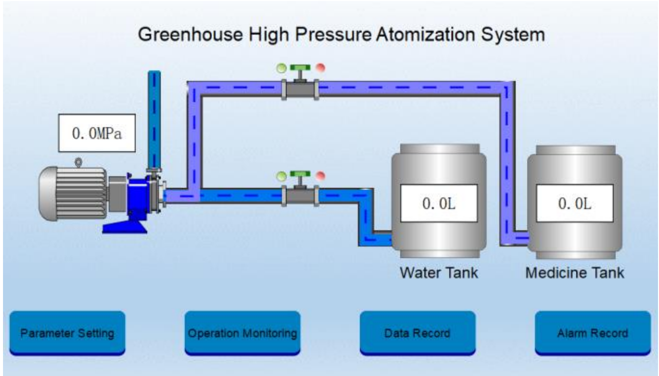

Fig. 4 - Work status monitoring interface

Experimental design

The high-pressure atomization spraying test is conducted according to the relevant national standard JB/T 9782-2014 "Equipment for crop Protection-General test methods". The experiment was conducted in June 2022 in Dongying City, Shandong Province. The greenhouse spans 10 m in the east-west direction and 70 m in the north-south direction, and a green pepper crop with a plant height of 150 cm and a spacing of 40 cm was used as the test object.

Randomly select 6 rows of green peppers in the greenhouse and fix the Water Sensitive Paper on the leaf with a paper clip, adjust the working parameters of the equipment for spraying operations, and collect the Water Sensitive Paper after completion. Fog drop coverage of Water Sensitive Paper was obtained by image processing using DepositScan software. The coefficient of variation of the fog volume distribution is used as an indicator, and the data obtained are analysed to determine the optimal value of each influencing factor.

The coefficient of variation of the fog volume (CV) distribution is an indicator that reflects the uniformity of the fog volume distribution along the axial direction of the fog flow of the nozzle. The smaller the coefficient of variation, the more uniform the distribution of spraying.

The calculation formula is as follows:

$$CV = \frac{S}{\overline{X}} \times 100\% \tag{1}$$

Where:

CV- is the spray distribution coefficient of variation;

S- is the standard deviation of the sample data;

$\overline{X}$- is the mean of the sample data.

RESULTS AND ANALYSIS

Single factor test

The range of the three factors that significantly affect the uniformity of atomization distribution is determined by single-factor tests, and the basis for orthogonal tests to determine the optimal test parameters is laid. The main factors affecting the uniformity of atomization distribution are high-pressure atomization pressure, high-pressure atomization nozzle aperture, and high-pressure atomization time.

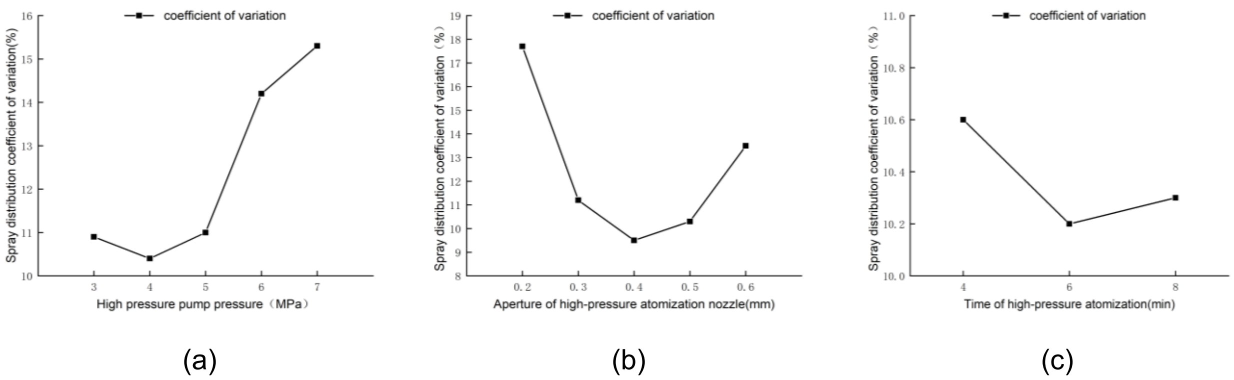

Fig. 5 - Influence of different factors on the effect of greenhouse fogging spraying

Before the experiment, run the high-pressure atomization pump to empty the air in the HDPE pipe and wait for the system to run stably. High-pressure atomization nozzle aperture selection of 0.4 mm is made, nozzle spacing is 100 cm, high-pressure atomization time is set to 5 min, and high-pressure atomization pressure is set to 3, 4, 5, 6, and 7 MPa respectively. It can be seen from Figure 5-a that with the increase of the atomization pressure, the coefficient of variation of the fog volume distribution increases and decreases. When the fogging pressure is in the range of 3 MPa to 5 MPa, the coefficient of variation is less than 11%, indicating that the fogging spraying effect is better.

High-pressure atomization pressure is set to 4 MPa, nozzle spacing is 100 cm, high-pressure atomization time is set to 5 min, high-pressure atomization nozzle aperture selection of 0.2, 0.3, 0.4, 0.5, 0.6 mm respectively is made. It can be seen from Figure 5-b that with the increase of atomization pressure, the coefficient of variation of fog volume distribution decreases and increases. The coefficient of variation was less than 11% when the nozzle aperture diameter was in the range of 0.3 mm to 0.5 mm, indicating a better fogging application effect.

High-pressure atomization pressure is set to 4MPa, high-pressure atomization nozzle aperture selection of 0.4 mm is made and nozzle spacing is 100 cm. High-pressure atomization time is set to 4, 6, and 8 min respectively. It can be seen from Figure 5-c that the coefficient of variation of the fog volume distribution does not change significantly with the extension of the fogging time. The coefficients of variation of the distributions were all below 11%, indicating that there was no significant correlation between the coefficients of variation and the fogging time.

Orthogonal experiment

Through the single-factor test, the coefficient of variation of the fog volume distribution did not change significantly with the extension of the atomization time, and the high-pressure atomization pressure and the aperture diameter of the atomization nozzle had a significant effect. The orthogonal test was designed according to the range obtained from the Single factor test, and the levels of each factor were determined as shown in Table 3.

Table 3

Experimental factors and levels

levels	Factors	
	High-pressure atomization pressure (MPa) A	Aperture diameter of the atomization nozzle (mm) B
1	5	0.5
2	4	0.4
3	3	0.3

According to the test scheme, 9 groups of tests were performed, and each group of tests was repeated three times. Take the average value as the test results. And the test results are shown in Table 4.

Table 4

The experiment results

Test number	A (MPa)	B (mm)	Average droplet coverage (%)	Coefficient of variation (%)
1	1	1	45.1	12.1
2	1	2	28.0	11.6
3	1	3	14.7	12.5
4	2	1	38.5	11.4
5	2	2	21.2	10.7
6	2	3	12.4	11.9
7	3	1	24.6	13.2
8	3	2	16.7	12.6
9	3	3	9.9	13.9
Y	k1	36.2	36.7	
	k2	34.0	34.9	
	k3	39.7	38.3	
	R	5.7	3.4	
	better level	A_2	B_2	
	Major and minor factors	A_2B_2		

Analysis of variance was performed using Design Export 12.0 and the results are shown in Table 5.

Table 5

Variance analysis results

Source	SS	DF	MS	F Value	P Value
Model	7.46	5	1.49	156.45	0.0008
A	2.04	1	2.04	214.08	0.0007
B	0.43	1	0.43	44.74	0.0068
AB	0.022	1	0.022	2.36	0.2221
A^2	3.47	1	3.47	363.55	0.0003
B^2	1.50	1	1.50	157.51	0.0011
Residual	0.029	3	9.537×10-3		
Cor Total	7.49	8			

Note: SS is the sum of squares of deviations; DF is the degrees of freedom; MS is the average of the sum of squares of deviations; $P < 0.01$ (extremely significant); $0.01 < P < 0.05$ (significant); $P > 0.05$ (not significant).

It can be seen from Table 5 that A, B, A^2, and B^2 have extremely significant effects on the damage rate (P<0.01). Other factors had no significant effect on the damage rate (P>0.1).

After removing insignificant terms, the fitted regression equation is:

$$Y = 10.76 - 0.58A - 0.27B + 1.32A^2 + 0.87B^2 \tag{2}$$

Comprehensive range and variance analysis show that the optimal level combination of the uniformity of the distribution of spraying mist in the greenhouse is A_2B_2, and the order of influence on the uniformity of fog volume distribution is A>B. To obtain the optimal operating parameters of the greenhouse fogging spraying equipment, the optimization module in Design-Export 12.0 was used to solve for the optimal parameters with the coefficient of variation of the fog volume distribution as the optimization objective. It can be obtained in the test range, when the high-pressure atomization pressure is 4 MPa, atomization nozzle aperture diameter is 0.4 mm. The test results may obtain the minimum spray distribution coefficient of 10.6%.

With the optimal combination of test parameters, when other parameters remain unchanged, high-pressure fogging pressure is 4 MPa, fogging nozzle aperture is 0.4 mm for greenhouse fogging spray test, the results of the three tests are averaged. The spray distribution coefficient of variation is 10.5%, which is similar to the predicted 10.6%. The results from the experimental analysis are consistent with the actual working results.

CONCLUSIONS

In this study a greenhouse high-pressure fogging spraying equipment based on PLC controller and HMI touch screen was designed. The equipment can complete the manual or automatic spraying work in the greenhouse.

To determine the optimal operating parameters of the equipment, orthogonal tests were conducted with atomization pressure and atomization nozzle aperture as the test factors and the spray distribution coefficient of variation as the evaluation index. Through the range and variance analysis of the spray distribution coefficient of variation, the influence of the factors on the response index is obtained.

Taking the spray distribution coefficient of variation as the optimization goal, the best working parameters are obtained. The best working parameters are: high-pressure atomization pressure 4 MPa, atomization nozzle aperture 0.4 mm, to obtain the spray distribution coefficient of variation 10.5%. The results of the validation tests show that the results from the test analysis are consistent with the actual working results.

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