Design of a fixed-pipe cold aerosol spraying system for chemical application in greenhouse

Shilin Wang[1,2†], Daipeng Lu[1†], Xue Li[1*], Xiaohui Lei[1], Yuxin Tang[1], Xiaolan Lyu[1,2]

(1. *Institute of Agricultural Facilities and Equipment, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China*;
2. *Key Laboratory of Agricultural Engineering in the Middle and Lower Reaches of Yangtze River, Nanjing 210014, China*)

Abstract: Since the high temperature and humidity in a closed environment, pests and diseases are infecting and spreading seriously in greenhouses. However, the prevention and control of pests and diseases in greenhouses are still dominated by knapsack sprayers. For those reasons, based on twin-fluid atomization, droplet dispersion, and constant pressure transportation technique, a fixed-pipe cold aerosol spraying system composed of the control unit and the fixed-pipe spraying unit comes into being. The indoor pipeline execution unit of the spraying system could be interfaced with the liquid-supply or gas-supply equipment such as the liquid pump, air compressor, and tank of the outdoor master control unit through a quick coupling, which could realize the separation of operator and sprayer in hermetic greenhouses. The atomization of twin-fluid nozzle and the droplet deposition and distribution of the spraying system in the greenhouse were tested. Results showed that about 70% of the particle size of the twin-fluid flow nozzle concentrated in the range of 32-65 μm under the spraying air pressure ranged from 0.2 MPa to 0.4 MPa. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the wind speed at the nozzle outlet reached supersonic speed, as the corresponding VMD of droplets were 45.6 μm, 43.2 μm, and 36.8 μm, respectively. The higher the air pressure is, the more uniform the spray deposition is in the greenhouse. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the CVs of the liquid deposition in the greenhouse were 109.1%, 62.6%, and 35.4%, respectively. The droplets produced by the spraying system will rapidly disperse into the whole greenhouse. The average deposition was 2.99 μL/cm^2 in the front area of the nozzle, the deposition was 1.24 μL/cm^2 in the area between two nozzles, and the deposition was 0.58 μL/cm^2 in the area behind the nozzles. The spraying system is characterized by the distribution of spraying liquid throughout the entire greenhouse.

Keywords: greenhouse, twin-fluid nozzle, spraying system, droplet spectra, distribution, deposition
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1 Introduction

With China's fast booming economy, more and more four-season vegetables have been put on the table, as people's growing demand for the yield and quality of vegetables. Therefore, protected agriculture has become an important vegetable planting model. After years of development, China's protected horticulture technology has made a comprehensive breakthrough and a better agricultural production system has been gradually established, providing important technical support for agricultural modernization[1]. At present, China's facility vegetable planting area is as high as 3.86 million hm^2, ranking first in the world[2,3].

Since the high temperature and humidity in a closed environment, the pests and diseases are infecting and spreading seriously in greenhouse, hence making it more difficult the prevention and control pests and diseases[4,5]. At the same time, it is difficult for droplets to penetrate into the vegetation canopy in greenhouses due to the dense crop canopies and the mutual shielding of leaves[6]. In addition, the hermetic environment and the diversity of planting patterns in greenhouses increase the difficulty of mechanical access in greenhouses. In this case, the prevention and control of pests and diseases in greenhouses are still dominated by manual spray guns, spray lances, and knapsack sprayers[7-9].

As early as the 1980s, researchers were committed to the innovation and development of new plant protection machinery and pesticide application technology for cultivation in accordance with the specific agronomic requirements and management procedures of protected agriculture. Nuyttens et al.[10,11] designed a vertical spraying boom in greenhouse that can reduce labor costs, and operator exposure and improve the uniformity of pesticide distribution to a certain extent. Liop et al.[12] found that air-assisted spraying is a key factor in improving the effectiveness of pesticide application for canopy-intensive crops in greenhouse. Similarly, Derksen et al.[13] found that air-assisted spraying can increase pesticide deposition in the bottom of the pepper canopy. In the past few years, many advanced spraying types of equipment used for plant protection products (PPPs) in greenhouse have been developed or modified, such as automation equipment based on automatic navigation systems, and ultrasonic or machine

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Biographies: Shilin Wang, PhD, Assistant Professor, research interest: crop protection machinery and pesticide application techniques, Email: shilinag@163.com; **Daipeng Lu**, Master, Assistant Professor, research interest: facility vegetable mechanization planting equipment, Email: ldp@jaas.ac.cn; **Xiaohui Lei**, Master, Assistant Professor, research interest: agricultural mechanization, Email: leixiaohui.2008@163.com; **Yuxin Tang**, Associate Professor, research interest: agricultural facilities and equipment, Email: tang@jaas.ac.cn; **Xiaolan Lyu**, PhD, Professor, research interest: crop protection machinery and pesticide application technique, Email: lxlanny@126.com.

†These authors contribute equally to this research.

***Corresponding author: Xue Li**, PhD, Associate Professor, research interest: crop protection machinery and pesticide application techniques. Institute of Agricultural Facilities and Equipment, Jiangsu Academy of Agricultural Sciences, No.50 Zhongling Street, Nanjing 210014, China. Tel: +86-15951638328, Email: lixue@jaas.ac.cn.

vision[14,15]. Gonzalez et al.[16] adopted both deliberative and pseudo-reactive techniques to realize autonomous navigation of agricultural robots in greenhouse, so that the use of mobile robots can avoid many dangers and hazardous agricultural tasks such as pesticide application in greenhouse. Considering the geological complexity of the ground inside the greenhouse, Lee et al.[17] designed an accurate navigation driving algorithm for automatic greenhouse sprayers. The sprayer was based on a body frame with an optimal size for the narrow aisle in greenhouse, and the driving algorithm was carried by an automatic turning algorithm under the no-rail circumstance, maximizing the using space in greenhouse. In addition, a variety of mist sprayers and the remote-control-based automatic spraying system were designed for pesticide application in greenhouse[18-21]. These advanced sprayers effectively improved the spray distribution and reduced labor strength and operator exposure. However, the promotion and application of these technologies are greatly limited by the high cost of the equipment, complex maintenance, and the limitation of cultivation methods and greenhouse layouts.

Therefore, under the premise that the use of PPPs is still the main method for pest and disease control, a new kind of sprayer or technique that can adapt to different greenhouse structures and growing patterns are on an urgent basis. For those reasons, a fixed-pipe cold aerosol spraying system was developed. In this research, the atomization of the spraying system, droplet deposition, and distribution in greenhouse were tested. The purpose of this paper was to provide a new method and technical reference for safe, quick operating, and efficient pesticide application in hermetic greenhouse.

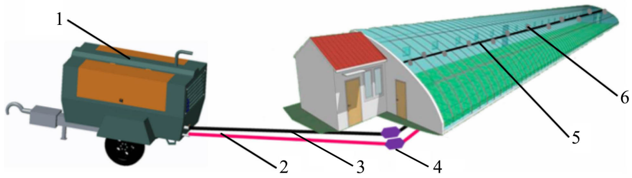
2 Materials and methods

2.1 Design of fixed-pipe cold aerosol spraying system

The fixed-pipe spraying system mainly consists of the outdoor master control unit and the indoor pipeline execution unit (Figure 1). The outdoor master control unit includes power unit, pipe of gas fluid, pipe of liquid fluid, and control unit. The indoor pipeline execution unit includes gas pipeline, liquid pipeline, twin-liquid nozzle, and constant pressure dropper. The indoor pipeline execution unit of the spraying system could be interfaced with liquid-supply and gas-supply equipment such as liquid pump, air compressor, and tank of outdoor master control unit through a quick coupling.

This fixed-pipe spraying system is specially designed for use in protected agriculture. Through the quick coupling between outdoor master control unit and indoor pipeline execution unit, it can be quickly transformed into different greenhouses, saving the input costs of facility construction and improving the efficiency of pesticide application operations. Meanwhile, the spraying system can isolate people and pesticides, making it possible for operators to work without entering the greenhouse, which is better to reduce labor intensity and guarantee people's physical security.

It should be noted that it is necessary to use agricultural tractors or other power devices to pull the outdoor master control unit near the operating greenhouse before the operation of the spraying system and connect the gas and liquid pipelines with that indoor pipeline execution unit through a quick coupling. The doors and vents of the greenhouse should be closed before the pesticide operation. The spraying volume should be determined in terms of the size and crop features in greenhouse, and the outdoor master control unit should set the operating parameters such as air pressure, liquid pressure, and spraying duration. When the spraying operation is completed, the quick coupling of the gas and liquid pipes should be disconnected, then the outdoor master control unit should be towed by the tractor to the next ready-to-work greenhouse and connected to its indoor execution unit. The greenhouse should be kept closed for more than 2 h after pesticide application so that droplets could be fully diffused and deposited on crops.



1. Control unit 2. Pipe of liquid fluid 3. Pipe of gas fluid 4. Quick connector coupling 5. Pipeline in greenhouse 6. Twin-fluid nozzle

Figure 1 Schematic diagram of the designed fixed-pipe cold aerosol spraying system

2.2 Design of the twin-fluid nozzle

Xiahou et al.[22] found that gravity has a significant effect on droplet settling character, in general, the larger the droplet size is, the faster the droplet settles. For these facts, the aerosol droplet is better than coarse droplet for dispersion or adhesion on solid surfaces in greenhouse. In this paper, a kind of twin-fluid nozzle was designed based on the Venturi effect. The Venturi effect can increase the airflow at the nozzle outlet, creating a negative pressure at the throat to absorb liquid. In order to realize a faster and more evenly droplets distribution over the entire cross section of the throat, a radial inward water supply method[23] was adopted to increase the speed difference between air phase and liquid phase, reducing the flow rate of liquid. In this case, the spray liquid was atomized into mist and transported meters away.

2.2.1 Atomizing analysis of twin-fluid nozzle

For the twin-fluid nozzle, the complex atomization process can be analyzed from hydrodynamics aspect. It could be considered that R_e and W_e are two important factors in droplets splitting and breaking process. R_e and W_e are described as,

$$R_e = \frac{v_0 \cdot d_0 \cdot \rho_1}{\mu} \tag{1}$$

$$W_e = \frac{\rho_z \cdot d_0 \cdot v_0^2}{\mu} \tag{2}$$

where, v_0 is the flow speed in liquid outlet, m/s; d_0 is the nozzle outlet diameter, m; ρ_1 is the liquid density, kg/m^3; ρ_z is the air density, kg/m^3; μ is the dynamic viscosity coefficient of the fluid, N·s/m^2.

When the atomized medium and the nozzle outlet are fixed values, it can be inferred from Equations (1) and (2) that the values of R_e and W_e will increase with the increase of the liquid flow rate, indicating that the increase of the flow speed in liquid outlet (v_0) is good to droplets splitting and breaking process and doing a positive effect on improving the atomization performance of the nozzle. The droplet size of the twin-fluid nozzle can be calculated by Equation (3).

$$d_s = \frac{585}{v} \times \frac{\sqrt{\sigma_L}}{\sqrt{\rho_L}} + 597 \times \left[\frac{\mu_L}{\sqrt{\sigma_L \times \rho_L}}\right]^{0.45} \times \left(1000 \times \frac{Q_L}{Q_g}\right)^{1.5} \tag{3}$$

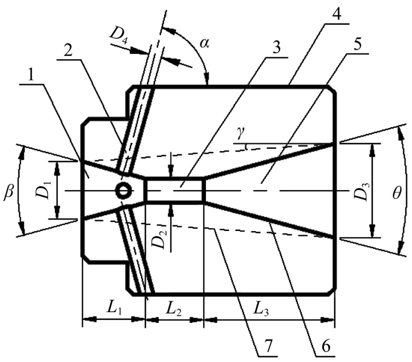
where, v is the relative flow speed of gas and liquid; ρ_L is the liquid density, g/cm^3; σ_L is the liquid surface tension, dyn/cm; μ_L is the liquid viscosity, dyn·s/cm^2; Q_L is the liquid flow rate, cm^3/s; Q_g is the gas flow rate, cm^3/s; d_s is the droplet diameter, μm.

As can be seen from Equation (3), when the gas phase and the liquid phase are fixed values, the droplet size will decrease with the increase of the velocity difference between the gas phase and the liquid phase. The atomization processing in the air field outside the nozzle depends mainly on the increase of air flow speed to increase the velocity difference between liquid phase and gas phase.

By analyzing the atomization principle of the nozzle above-mentioned, it is obvious that the velocity difference between the gas phase and the liquid phase is an important factor affecting the atomization performance of the nozzle. Considering that ultra-low volume spraying is a kind of spraying technology that is widely used in the plant protection industry when increasing the speed at the nozzle outlet, it is also necessary to reduce the liquid amount and the liquid-supply pressure, and better follow the principle of water absorption in negative pressure, which can not only reduce the liquid-supply amount but also reduce the abrasion on the nozzle.

2.2.2 Structure of twin-fluid nozzle

In order to improve the atomization performance of the nozzle, the Venturi effect was used to change the geometry structure of the valve core in the twin-fluid nozzle to improve the velocity difference between gas phase and liquid phase by replacing the conical structure with a Venturi structure. As shown in the dotted line of Figure 2, the air inlet of the valve core in the twin-fluid nozzle is of a conical structure, with a contraction cone angle γ of 15°. When the outlet size and the total length of the valve core are fixed, the diameter of the outlet is 2.2 mm (D_1), the diameter of the air inlet is 3.6 mm (D_3), and the total length of the valve core is 9.5 mm (L).



1. Outlet of valve core 2. Liquid inlet 3. Hollow throat 4. Structure of valve core 5. Air inlet 6. Venturi structure 7. Conical structure

Figure 2 Valve core structure inside the twin-fluid nozzle

In order to reduce the friction and the airflow loss in expansion section, the central angle of expansion section should not be too small. In this study, the center angle θ in the expansion section is 24°, the center angle β in the contraction section is 13°, the diameter of the valve core is 2.2 mm (D_1), the diameter of liquid inlet is 3.6 mm (D_3), L is 9.5 mm. The Venturi structure is described as:

$$L_1 + L_2 + L_3 \tag{4}$$

$$\frac{D_1 - D_2}{L_1} = 2\tan\frac{\beta}{2} \tag{5}$$

$$\frac{D_3 - D_2}{L_3} = 2\tan\frac{\theta}{2} \tag{6}$$

$$L_2 = D_2 \tag{7}$$

Based on Equations (4)-(7), the geometries of the improved valve core structure are listed in Table 1.

Table 1 Key parameters of the valve core

Parameter	Value
Outlet diameter D_1/mm	2.2
Hollow throat diameter D_2/mm	1.5
Air inlet diameter D_3/mm	3.6
Liquid-inlet diameter D_4/mm	0.5
Length in the contraction section L_1/mm	3.0
Length of hollow throat L_2/mm	1.5
Length in the expansion section L_3/mm	5.0
Total length L/mm	9.5
Inclination angle of the liquid-inlet α/(°)	75°
Central angle in the contraction section β/(°)	13°
Central angle in the expansion section θ/(°)	24°
Number of liquid inlet	4

The nozzle with the improved valve core structure is defined as the twin-fluid Venturi nozzle, which is made of SUS304 with a cone spray angle of 60°. Figure 3 shows the structure diagram of the twin-fluid Venturi nozzle, it mainly consists of the nozzle tip, the ultrasonic head, the valve core structure, the liquid inlet, the air inlet, and the air channel. The ultrasonic head is a cylinder. The nozzle tip, on which a concentric blind hole is settled, is connected with the head through the steel wire. The liquid channel is a sleeve gap constituted by the air channel and the rear cover. The ultrasonic head is screwed to the air channel and the valve core structure is fixed inside the sleeve. The low-pressure airflow in the air channel of the nozzle forms a high-speed airflow passing through the throat of the valve core, then the high-speed air and the low-pressure liquid sucked in the sleeve gap are fully mixed and collided in a narrow vacuum region, finally ejected in the form of a high-speed aerosol flow. The aerosol flow was again atomized into mist by the nozzle tip through the secondary crash.

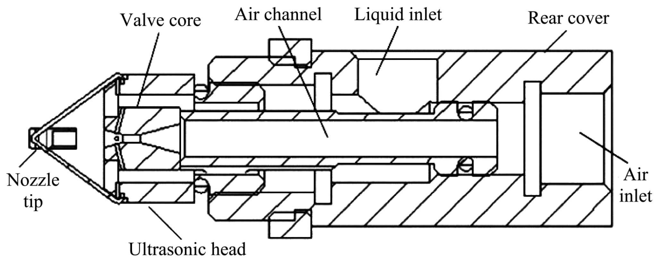


Figure 3 Structure diagram of the designed twin-fluid nozzle based on Venturi effect

a. Control unit of spraying system b. Quick connector coupling c. Twin-fluid nozzle in greenhouse

Figure 4 Photograph showing key components of the spraying system

2.3 Integration of the spraying system

To ensure the flow uniformity of the twin-fluid nozzles at different places in greenhouse, it is necessary to connect the liquid inlet of the twin-fluid nozzle and the liquid pipeline via a constant pressure dropper. In this case, the constant pressure dropper can make the elastic part of the flow channel of the nozzle deform by the liquid-phase pressure, making the cross-section of the flowing liquid-phase variable and the flow rate stable. In this spraying system, the constant pressure dropper consists mainly of a quick coupling, a PE tube, and an 1822-type dripper (Shanghai Irrist Co., Ltd.). The outdoor master control unit can control the size of droplets, spray volume, and range by controlling the liquid-supply and gas-supply equipment such as the liquid pump, air compressor, and tank.

When using this spraying system, the connector coupling of master control unit and the indoor pipeline unit should be connected quickly, the gas-phase and the liquid-phase pipelines should be arranged along the middle axis in greenhouse, and the nozzles need to be fixed with metal clamps under the pipeline. Considering the structural characteristics of the greenhouse and the requirements of agricultural operations, the pipelines and nozzles were installed at a height of 2.0 m. The distance between nozzles was determined through numerical simulation with ANSYS CFX solver. The simulation was a gas-liquid two-phase unsteady numerical simulation, regarding the air as a continuous medium and droplets as a discrete phase[24]. The turbulence model in the computational domain was the standard k-ε model. The boundary conditions of the droplets were calculated and set according to the Rosin-Rammler distribution model based on the droplet spectrum. The simulation results showed that the distance between nozzles is 3.0 m, and the spraying direction should be horizontal when the adjacent nozzles are installed in the opposite direction.

Based on the twin-fluid atomization technique, droplet dispersion, and constant pressure transportation, the fine mist droplets produced by this spraying system could be dispersed rapidly in the whole greenhouse under the disturbance of airflow. Even when reducing the dosage of pesticides, vegetable canopies could also be surrounded by pesticides, and the same effect can reach insect and disease prevention. The relevant technical parameters of the spraying system are listed in Table 2.

Table 2 Technical parameters of the fixed-pipe cold aerosol spraying system

Component	Parameter	Value
Control unit outside greenhouse	Working air pressure/MPa	0.3-0.6
	Working liquid pressure/MPa	0.05-0.10
	Boundary dimension/mm×mm×mm	2500×1450×1500
The fixed-pipe spraying unit inside greenhouse	Air flow/L·min^{-1}	115
	Liquid flow/L·h^{-1}	4.0-6.0
	volume medium diameter/μm	30-60
	Spraying range/m	4-5
	Nozzle height/m	2.0
	Nozzle spacing/m	3.0

2.4 Atomization and deposition test of the spraying system

2.4.1 Droplet spectra and air-flow of the nozzle outlet

Droplet spectra of the twin-fluid nozzle at different air pressure were measured with a laser particle size analyzer Winner 318B (Weina Technology Co., Ltd., China) by scanning the cross-sectional area of the spray at a distance of 160 cm ahead of the nozzle. Three replicate measurements were performed for each spray condition. In the test, the air inlet of the nozzle was connected to the air pump (Aotus Co., Ltd., China) via a pressure regulating valve (Airtac Co. Ltd, AR2000, China), and the liquid inlet was connected to the liquid pump (Ningbo Leicheng Pump Co. Ltd., LS-0416) via the other pressure regulating valve. When the liquid pressure is constant at 0.05 MPa, the droplet spectra of the nozzle at the air pressure of 0.2 MPa, 0.3 MPa, and 0.4 MPa were tested. The data were analyzed to determine the spraying volume median diameter (VMD) and the proportion of the droplets in different particle sizes.

Airflow buffer stabilizer and thermal anemometer (Benitech Co., Ltd., GM8903, China) were used to test the airflow velocity of nozzle at the air outlet central area. When the nozzle is working under the pressure to be measured, the airflow inlet buffer stabilizer is connected to the nozzle outlet, and the airflow velocity at the outlet of the buffer stabilizer is measured with the anemometer. Repeat three times in each test as the wind speed stabilizes. The air velocity of the nozzle outlet (V_n) is calculated by Equations (8) and (9).

$$V_t \times A_t = A_n \times V_n \tag{8}$$

$$V_n = V_t \times \left(\frac{D_t}{D_n}\right)^2 \tag{9}$$

where, V_t is the velocity of the buffer stabilizer air outlet, m/s; A_t is the area of the buffer stabilizer air outlet, mm^2; A_n is the area of the nozzle outlet, mm^2; D_n is the diameter of the nozzle outlet with 2.2 mm; D_t is the diameter of the buffer stabilizer air outlet with 20 mm; V_n is the velocity of the nozzle outlet, m/s.

2.4.2 Droplet distribution in greenhouse

In order to evaluate the field performance of the spraying system, pesticide application experiments were carried out both in the bare greenhouse and the greenhouse where pepper was planted. The single-body width, length, and height of the greenhouse are 8.0 m, 50.0 m, and 3.4 m, respectively. The spraying volume was 10.0 L in each test, and Brilliant sulfoflavine (BSF) with a mass fraction of 0.1% was added into the spray liquid as a tracer to quantify the droplets deposition. When the droplets were fully deposited after spraying, collected all the samples into labeled ziplock bags and brought back to the laboratory for testing. A quantitative volume of deionized water was added into the bags in the laboratory and ultrasonicated for 2 min, and the absorbance of the eluate was measured at a wavelength of 501 nm by LS55 fluorometer (Perkin Elmer, USA).

In this study, the effect of air pressure on spraying droplet distribution was conducted in a bare greenhouse. When the liquid pressure was 0.05 MPa, test the droplets' deposition and uniformity in different areas of the greenhouse with the gas pressure 0.2 MPa, 0.3 MPa, and 0.4 MPa respectively. In the greenhouse, two adjacent twin-fluid nozzles were divided into a group, and then test the distribution of droplet deposition in different areas of a nozzle group was. As shown in Figure 5, four rows of petri dishes (d = 15 cm) were placed in the horizontal direction on the ground, with a row-spacing of 1 m and 9 petri dishes per row. Three nozzle groups were selected as repeats under each test condition. After the test, the deposition of the spraying liquid in each petri dish was tested by LS55 fluorometer, and the uniformity of the droplet distribution is calculated.

The deposition effect of this spraying system on greenhouse peppers was tested when the liquid pressure is 0.05 MPa and the gas phase pressure is 0.3 MPa. Peppers in greenhouse were cultivated in double rows with large ridges, and the two sides near the edge of the greenhouse are planted in a single row (10-row in total). The intervals of the ridges and the rows were 120 cm and 40 cm, respectively. The average height of the pepper plants was about 60 cm. For the symmetrical structure of the greenhouse, test the droplets deposition of five rows of peppers in front of nozzle, behind of nozzle, and in the middle area of the nozzle group. Each sampling row was labeled 1-5 from the central axis position to the edge of the greenhouse. Placing Mylar sheets (5 cm×10 cm) on the top, middle, and bottom layers of the peppers in sampling area to collect deposited droplets. After pesticide application and the droplets are sufficiently settled, it is necessary to take the dried Mylar sheets back to the laboratory for elution with deionized water, measure the fluorescence value of the eluate solution, and then calculate the amount of liquid deposition.

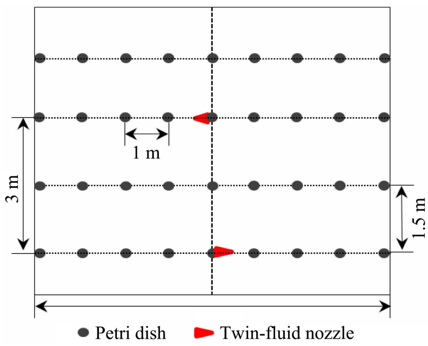


Figure 5 Petri dish distribution in a nozzle group

3 Results and discussion

3.1 Droplet spectra and outlet air-flow results

Table 3 lists the proportion of the droplets in the different particle size distributions of the nozzles under different air pressure. The results showed that most of the droplets were concentrated in the range of 32-65 μm. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the corresponding droplet proportion was 73.1%, 75.7%, and 69.7% respectively. In terms of larger droplets, when the air pressure is 0.2 MPa and 0.3 MPa, the droplets larger than 80 μm is 3.6% and 1.3% respectively, and all the droplet sizes are less than 80μm at the air pressure of 0.4 MPa.

In scientific research, researchers typically use the VMD to represent the size of the droplets. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the corresponding VMD of droplets was 45.6 μm, 43.2 μm, and 36.8 μm, respectively. According to the classification of droplet in ISO 25358[25], the droplet is classified as an extremely fine droplet at the pressure of 0.2-0.4 MPa. On the whole, the droplet size of the twin-fluid nozzle decreases with the increase of air pressure, and the VMD of the droplet is less than 50 μm, which is classified as fog or fine mist droplet[26], as increasing the suspension time of droplets in the air. In this case, the nozzle can be used for diffusing spray in greenhouse.

During the operation of the spraying system, the pressure energy can be converted into kinetic energy as the compressed air in the flow channel, and the maximum velocity can be reached in the hollow throat of the nozzle[27]. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the corresponding air flow speed at the nozzle outlet was 401 m/s, 463 m/s, and 482 m/s, which reached supersonic speed, and the airflow velocity in the nozzle outlet increases with the increase of the air fluid pressure. The air velocity with subsonic or supersonic velocity in the central area of the nozzle outlet has a great transport effect on droplets, which is favorable for further distribution and uniform deposition of droplets in greenhouse.

Table 3 Droplets distribution of twin-fluid nozzle at different air pressure

Air pressure /MPa	Droplet ratio of different particle size/%					
	0-3 μm	3-32 μm	32-65 μm	65-80 μm	≥80 μm	VMD
0.2	0.0	13.2	73.1	10.1	3.6	45.6
0.3	0.0	16.3	75.7	6.7	1.3	43.2
0.4	0.3	29.6	69.1	1.0	0.0	36.8

3.2 Droplet distribution in bare greenhouse

Figure 6 shows the distribution and deposition of the droplets at different air pressure in bare greenhouse. The results showed that the droplets were mainly concentrated at about 1 m straight ahead of the nozzle spraying direction. When the distance in front of the nozzle was more than 1 m, the liquid deposition decreases with the increase of nozzle distance, and the amount of droplets deposition in the middle area between two nozzles was lower than that in the front area of the nozzle. The lower the air pressure is, the shorter the spraying range of droplets is, and the lower droplets deposit on the boundary of the greenhouse, so that more droplets gather near the front area of the nozzles. In the previous greenhouse sprayer research[28-30], it was found that the distance can significantly affect the droplet distribution of the cold fogger sprayer, thermal fogger sprayer, and knapsack mist sprayer, which decreased sharply with increasing distance from the targets. Compared with those traditional sprayers, the droplet deposition of the fixed-pipe spraying system diminished the influence of distance on the droplet distribution performance.

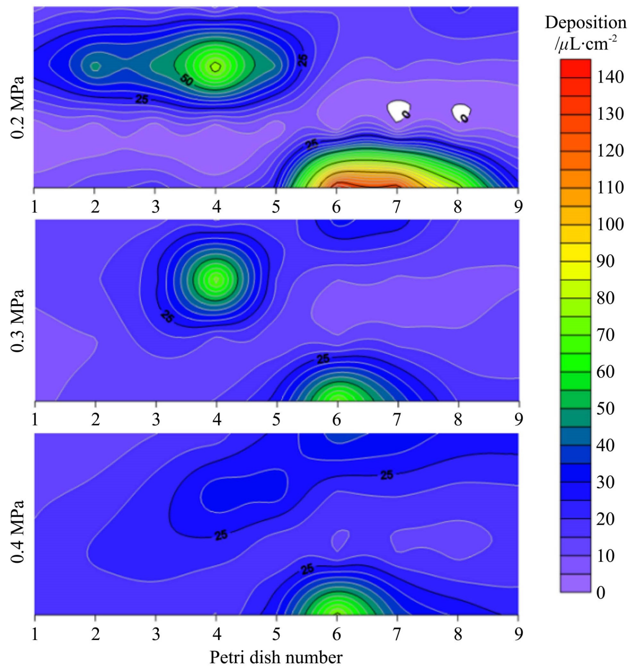


Figure 6 Droplet distribution of a nozzle group in bare greenhouse at different air pressure

For a more specific comparison of liquid distribution at the different air pressure, the representative values of deposition at different air pressure are listed in Table 4. When the air pressure was 0.2 MPa, the maximum deposition was 137.6 $\mu L/cm^2$ in front of the nozzle, while the minimum deposition was only 0.6 $\mu L/cm^2$ in the middle of nozzles. When the air pressure was 0.3 MPa, the maximum deposition was 74.1 $\mu L/cm^2$ in front of the nozzle, and the minimum deposition amount was 8.5 $\mu L/cm^2$. Similarly, when the air pressure was 0.4 MPa, the maximum deposition was 77.8 $\mu L/cm^2$ in front of the nozzle, and the minimum deposition was 10.4 $\mu L/cm^2$. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the average liquid depositions in the whole greenhouse were 22.8 μL/cm^2, 18.4 μL/cm^2, and 22.9 μL/cm^2, respectively. Overall, the average liquid deposition amount at 0.2 MPa and 0.4 MPa is higher than that at 0.3 MPa.

Meanwhile, the uniformity of droplet distribution is more important than the deposition amount in some situations[28,31]. The coefficient of variation (CV) was used to evaluate the uniformity of spraying liquid deposition. The smaller the CV is, the better the uniformity of the spray deposition is[32]. When the gas pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the CVs of the liquid deposition in greenhouse were 109.1%, 62.6%, and 35.4% respectively. As can be seen, the higher the air pressure is, the stronger the droplet movement performance is, and the more uniform the deposition of droplets is in the greenhouse.

Table 4 Distribution of spraying liquid and CV at different air pressure

Air pressure /MPa	Minimum /μL·cm^{-2}	Maximum /μL·cm^{-2}	Median /μL·cm^{-2}	Average /μL·cm^{-2}	CV/%
0.2	0.6	137.6	15.1	22.8	109.1
0.3	8.5	74.1	12.9	18.4	62.6
0.4	10.4	77.8	20.3	22.9	35.4

3.3 Spray deposition in pepper canopy

Table 5 lists the results of average deposition in different heights of crop canopy and different areas of greenhouse. Considering the spatial distribution of droplets in the canopy and the leaf inclination, the liquid deposition, and CV values were lower than those in bare greenhouse. The results showed that the liquid deposition in the area in front of the nozzle was higher than that behind the nozzle and in the middle area between the two nozzles, and its average liquid deposition amount is 2.99 μL/cm^2. Then the average deposition amount in the middle area between the two nozzles is 1.24 μL/cm^2, and the lowest is 0.58 μL/cm^2 in the area directly behind the nozzles. When the liquid sprayed out from the nozzle, a large number of droplets dispersed rapidly in the straight ahead area of the nozzle, and some coarse droplets deposited on crop canopies in the front area of the nozzle, therefore, the highest liquid deposition area was in front of the nozzles. In addition, a small number of coarse droplets may spread and deposit on crop canopies in the middle area. Other, those fine droplets dispersed rapidly throughout the greenhouse and were forced by air flow to float around the greenhouse, where they eventually deposited on crop canopies in different areas. The liquid deposition of crop canopy in the area behind nozzles was mainly from those dispersed fine droplets, as a result, the behind area with the lowest average deposition.

On different rows of peppers in the front area of the nozzle, the closer the peppers were to the nozzle, the higher amount of the liquid deposition was. In the middle area of the nozzle group, the liquid deposition increased first and then decreased. Because the movement of coarse droplets was very limited in the atomization processing, the main droplet concentration area was near the nozzle. While the spraying droplets cannot spread to the crops near the nozzle position but to the middle area on account of the limitation of the spraying angle. In addition, the droplet movement performance decreases with the distance increasing from the area behind the nozzle, as a result, the liquid deposition in the behind area of the nozzle decreased with the distance away from the nozzle.

For the uniformity of droplets distribution in greenhouse, the CV values in the front, middle, and behind the area of the nozzle were 97.2%, 129.8%, and 62.0%, respectively. The liquid deposition behind the nozzle was the lowest, while its distribution uniformity was the best. This was also because the deposited droplets came from the dispersed droplets in the greenhouse, and the dispersion of these droplets in greenhouse was relatively uniform, therefore, the distribution uniformity at the behind area of the nozzle was better than that of other areas.

Wang et al.[30] compared the droplet deposition of spray gun, thermal fogger sprayer, knapsack mist sprayer, and electric knapsack sprayer in tomato canopy and found that all the CVs obtained from sprayers were greater than 70%. Sanchez-Hermosilla et al.[33] compared the deposition uniformity of spray gun, trolley sprayer, and different nozzles on the tomato canopy, finding that all treatments had large CVs. Compared with previous studies, the fixed-pipe spraying system has not significantly improved the uniformity of droplet distribution in crop canopy, and the uniformity of droplet distribution in greenhouse application is still a problem.

In general, it can be concluded that the fixed-pipe cold aerosol spraying system caused a deposition over the whole greenhouse, while its spraying parameters should be further optimized to improve the distribution uniformity of liquid deposition. It is worth mentioning that this whole greenhouse application method may cause ground loss in zones without vegetation.

Table 5 Average deposition of spraying liquid and CV on pepper canopy

Sampling area	Layer	Number of pepper plant					Average	CV/%
		1	2	3	4	5		
Front of nozzle	Top	8.22±6.06	4.99±2.81	2.69±1.07	1.68±0.98	1.66±1.00	2.99	97.2
	Middle	7.21±2.69	3.76±2.14	1.98±0.69	1.60±0.58	0.99±0.77		
	bottom	2.44±1.40	3.19±0.96	1.80±0.72	0.91±0.71	0.92±0.89		
Behind the nozzle	Top	0.76±0.47	0.60±0.53	0.42±0.29	0.36±0.17	0.44±0.26	0.58	62.0
	Middle	0.67±0.35	0.55±0.35	0.51±0.18	0.47±0.23	0.45±0.17		
	bottom	0.83±0.40	0.68±0.59	0.76±0.60	0.54±0.28	0.57±0.29		
Middle of nozzle	Top	0.79±0.56	2.03±1.51	0.95±1.11	0.49±0.26	0.43±0.20	1.24	129.8
	Middle	1.25±0.86	3.21±2.86	0.78±0.37	0.80±0.63	0.82±0.56		
	bottom	0.92±0.67	3.77±2.67	0.92±0.61	0.78±0.68	0.63±0.21		

Note: Average deposition±standard deviations, μL/cm^2.

4 Conclusions

A fixed-pipe cold aerosol spraying system was developed based on two-phase flow atomization technique, dispersion of droplet, and constant pressure transportation, which could realize the separation of operator and sprayer in the hermetic greenhouses. In this study, the atomization of the spraying system and droplet deposition and distribution in greenhouse were tested. The conclusions are as follows:

1) About 70% of the droplets of the twin-fluid nozzle

concentrates in the range of 32-65 μm at the air pressure range of 0.2 MPa to 0.4 MPa. When the air pressure is 0.2 MPa, 0.3 MPa, and 0.4 MPa, the wind speed at the nozzle outlet reached supersonic speed, as the corresponding VMDs of droplet were 45.6 μm, 43.2 μm, and 36.8 μm, respectively.

2) The droplets were mainly concentrated at about 1 m straight ahead of the nozzle spraying direction. When the distance in front of the nozzle was more than 1 m, the liquid deposition decreases with the increase of nozzle distance, and the amount of droplets deposition in the middle area between two nozzles was lower than that in the front area of the nozzle. The higher the air pressure is, the more uniform the spray deposition is in the greenhouse. When the air pressure was 0.2 MPa, 0.3 MPa, and 0.4 MPa, the CVs of the liquid deposition in greenhouse were 109.1%, 62.6%, and 35.4%, respectively.

3) The droplets produced by the spraying system will rapidly disperse into the whole greenhouse. The average deposition was 2.99 $\mu L/cm^2$ in the front area of the nozzle, the deposition was 1.24 $\mu L/cm^2$ in the area between two nozzles, and the deposition was 0.58 $\mu L/cm^2$ in the area behind the nozzles. The spraying system is characterized by the distribution of spraying liquid throughout the entire greenhouse.

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