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SIMULATION AND ANALYSIS OF SPRAY DISTRIBUTION AND DROPLET SIZE OF LARGE SPRINKLER MACHINES LOADED WITH ATOMIZING MICRO-SPRINKLERS

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Abstract. *Current agricultural spraying faces issues such as excessive application, pesticide waste, and environmental pollution. This paper analyzes the hydraulic performance of several atomizing micro-sprayers (hollow cone, solid cone, and fan-shaped) used in large-scale irrigation machines, providing a theoretical basis for selecting spraying nozzles. Three types of micro-sprayers were tested at pressures of 0.2MPa, 0.3MPa, and 0.5MPa, and ground heights of 0.5m, 0.8m, 1.2m, and 1.5m. Each test was repeated three times. The results show that: (1) The hollow cone sprayer has a bimodal water distribution, the solid cone is unimodal, and the fan-shaped sprayer is long-strip shaped. As pressure increases, water distribution increases, while height increases reduce water distribution. (2) The droplet size distribution follows a normal distribution. Higher pressure increases the number of larger droplets, while lower pressure increases smaller droplets. Larger aperture sprayers generate more droplets, with the fan-shaped sprayer producing the most. (3) The particle size of the hollow cone sprayer ranges from 0.312mm to 1.187mm, with speeds below 1.4m/s; the solid cone sprayer ranges from 0.312mm to 6.5mm, with speeds below 2.4m/s; and the fan-shaped sprayer ranges from 0.312mm to 2.75mm, with speeds below 2.5m/s. The experimental results provide a theoretical basis for selecting and using atomizing micro-sprayers in large-scale irrigation, offering guidance for reducing pesticide use and improving agricultural efficiency.*

Key words: *Pesticide application, Large-scale irrigation machine, Atomizing micro-sprayer, Particle size, Velocity*

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1. INTRODUCTION

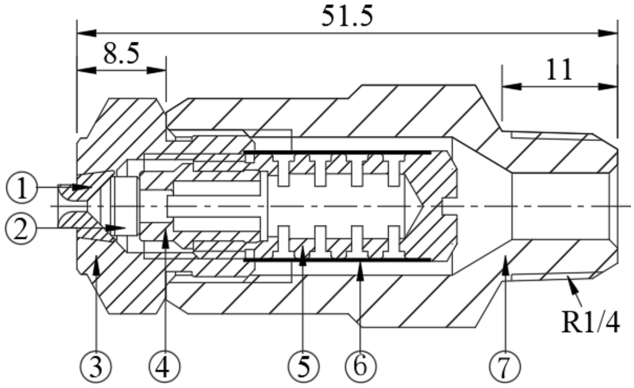
Under the backdrop of global climate change, the situation of pests and diseases is becoming increasingly severe [1-4]. There is an urgent need to establish a technical system for rapidly and effectively eliminating pests and diseases over large areas [5-6], to accelerate the fundamental transformation of pest and disease control models, and to achieve intelligent plant protection and green ecology. The growth of crops is inseparable from efficient and safe plant protection machinery and pesticide application techniques [7-9]. Currently, pesticides can be applied through four methods: manual spraying, ground mechanical spraying, unmanned aerial vehicle (UAV) spraying, or through irrigation systems. Manual spraying makes it difficult to grasp the timing and precision of pesticide application, which not only leads to environmental pollution but also poses a significant risk to the health of farmers due to the close contact with pesticides [10-12]. Ground mechanical spraying is costly and has a low effective utilization rate of pesticides, and the movement of machinery can cause mechanical damage to crops and soil compaction near the wheels [13]. UAV spraying is a viable alternative, but compared with ground mechanical spraying, the phenomenon of droplet drift during UAV application is more severe [14-17], which can cause environmental pollution due to pesticide drift [18-20]. In actual UAV operations, if the wind field is too strong, crops on both sides of the flight path may lodge, and the plant damage caused by lodging essentially provides favorable conditions for the spread of diseases [21]. Large sprinkler machines (including linear and center-pivot sprinkler machines) equipped with atomizing micro-sprinklers can be used for chemical irrigation, effectively avoiding mechanical crushing of crops during pesticide application, and reducing the drift loss of chemicals [22-25].

To reduce the drift loss of pesticide droplets, scholars worldwide have conducted numerous studies and experiments on droplet drift. Sushilendra et al. [26]investigated the impact of different nozzle types, forward speeds, and spray heights on droplet size of UAV sprayers, and the results showed that nozzle type had a significant effect on droplet size, while forward speed and spray height had a smaller impact. Fattahi et al. [27] developed various artificial neural network methods to study the factors affecting the drift of pesticide sprays. Sensitivity analysis of the neural network model indicated that the impacts of independent variables, including wind speed, spraying pressure, boom height, and nozzle type, were 42%, 27%, 16%, and 15%, respectively. Singh et al. [28] explored the impact of Pulse Width Modulation (PWM) systems at different frequencies on spray coverage and droplet size uniformity. Park et al. [29] utilized computational fluid dynamics (CFD) simulations to explore the effects of droplet size and wind speed on collection performance.

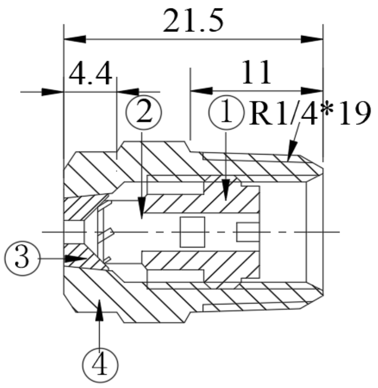
Large sprinkler machines equipped with atomizing micro-sprinklers for pesticide application offer the advantage of more precise control over pesticide use, reducing pesticide waste and environmental pollution, while enhancing crop protection effectiveness. However, current research primarily focuses on traditional spraying technologies, and further investigation is needed on the spray distribution, droplet size, and movement characteristics of this new type of equipment. Therefore, this paper aims to simulate and analyze the spray distribution and droplet size of large sprinkler machines equipped with atomizing micro-sprinklers, filling the research gap and providing new theoretical foundations and practical directions for water resource conservation and pesticide reduction in agriculture.

2. Experimental Design and Methods

The experiment selected three types of micro-sprinklers, namely solid cone, hollow cone, and fan-shaped. The solid cone nozzle models are: M4 and M8, totaling two models. The hollow cone nozzle models are: LNN3W and LNN4W, also totaling two models. One model of the fan-shaped nozzle was chosen for the experiment. The experiment selected three pressures: 0.2 MPa, 0.3 MPa, and 0.5 MPa, and the micro-sprinkler heights above the ground were chosen as 0.5 m, 0.8 m, 1.2 m, and 1.5 m. A rain gauge was used to measure the water distribution of each sprinkler over a period of 1 hour. The size of droplets and the uniformity of droplet deposition have a significant impact on the efficacy of pesticides. A Parsivel2 laser raindrop spectrometer was used to measure the droplet size, particle velocity, and deposition distribution of the atomization micro-sprinklers. The structure and dimensions of the LNN series and M series atomization micro-sprinklers, as well as the fan-shaped atomization micro-sprinkler, are shown in Fig. 1.



a) Schematic diagram of the LNN series atomization micro-sprinkler structure: 1 - insert, 2 - swirl core, 3 - prinkler body, 4- swirl core seat, 5 - filter frame, 6 - L-shaped filter mesh, 7 - base



b) Schematic diagram of the M series atomization spray head structure: 1 - swirl core seat, 2 - swirl core, 3 - insert standard angle, 4 - main body	c) Dimensional diagram of the fan-shaped atomization spray head

Fig. 1 Schematic and dimensional diagrams of different types of atomization spray heads

The basic parameters of the spray nozzles are given in Table 1.

Table 1 Basic parameters of spray nozzles

Micro-sprinkler number	Type of micro-sprinkler	Rated Orifice Diameter (mm)	Total Length (mm)	Base (Hexagonal) (mm)
1	LNN3W	0.99	47.5	20.6
2	LNN4W	1.5	47.5	20.6
3	M4	1.1	21.5	14.2
4	M8	1.5	21.5	14.2
5	Fan-shaped nozzle	0.91	23	14
Micro-sprinkler number	Sprinkler (Hexagonal)	Pressure (MPa)	Flow Rate (L/h)	Spraying Angle (degrees)
1	17.4	0.2	9.7	157
2	17.4	0.2	16.1	155
3	-	0.2	12.9	72
4	-	0.2	26	85
5	-	0.2	30	110

The experiment was conducted in the Quality Inspection and Testing Hall of the Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences, China. The experimental setup is shown in Fig. 2.

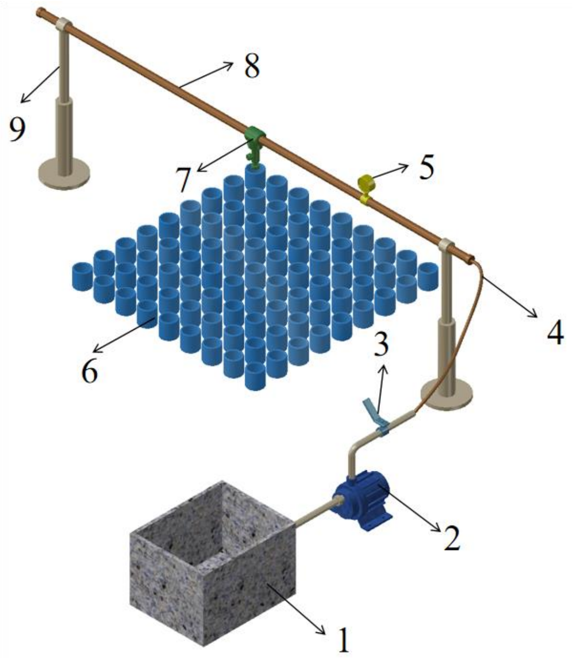


Fig. 2 Nozzle spray test setup diagram: 1 - Reservoir; 2 - Water pump; 3 - Control valve; 4 - Plastic PE hose; 5 - Pressure gauge; 6 - Rain gauge; 7 - Atomization micro-sprinkler; 8 - Water pipe; 9 - Height adjustment stand

The Parsivel2 laser raindrop spectrometer uses laser remote sensing technology to derive droplet size distribution, precipitation kinetic energy, particle concentration, and radar reflectivity from the diameter and velocity of precipitation. The measurement area is 54 m^2. The size range is 0.062 to 54.5 mm, and the velocity range is 0.05 to 20.8 m/s, both with a resolution of 32 levels, and the measurement accuracy is ±1 level. In this experiment, the Parsivel2 laser raindrop spectrometer is used to measure the droplet size and particle velocity of various types and pressure conditions of atomization micro-sprinklers. During the measurement, the distance between each atomization micro-sprinkler and the Parsivel2 laser raindrop spectrometer is 0.5 m. The Parsivel2 laser raindrop spectrometer measures the range of droplet sizes and the range of particle velocities as shown in the following Table 2.

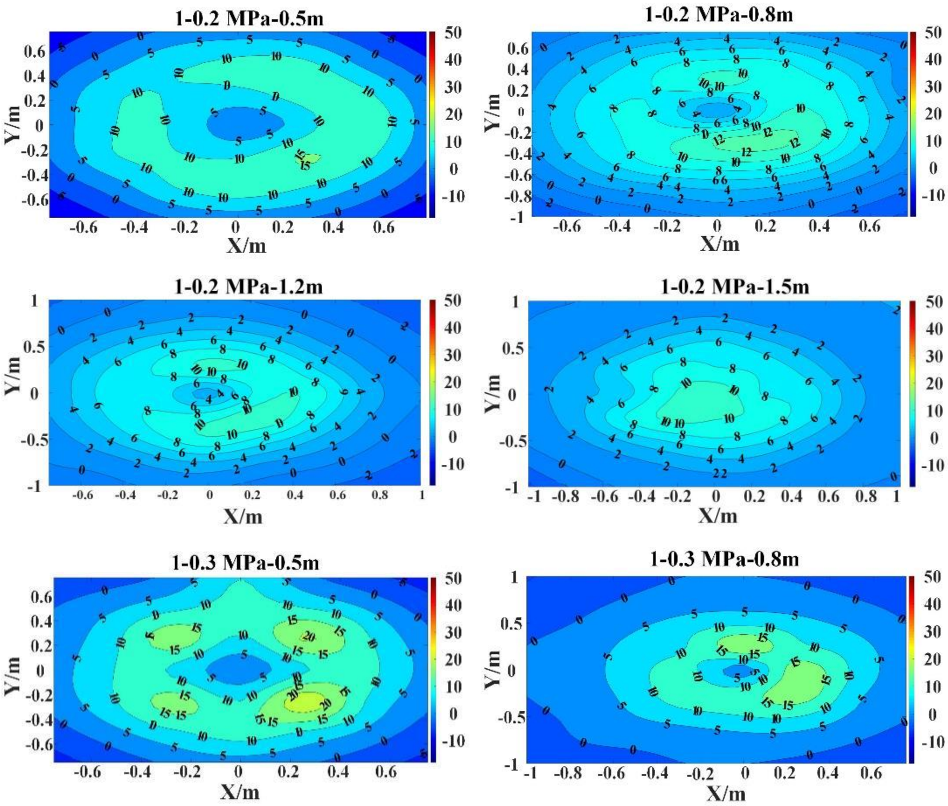
Table 2 Correspondence table of particle groups with size and velocity relationships

Group number	Average Diameter (mm)	Average Velocity (m/s)
1	0.062	0.05
2	0.187	0.15
3	0.312	0.25
4	0.437	0.35
5	0.562	0.45
6	0.687	0.55
7	0.812	0.65
8	0.937	0.75
9	1.062	0.85
10	1.187	0.95
11	1.375	1.1
12	1.625	1.3
13	1.875	1.5
14	2.125	1.7
15	2.375	1.9
16	2.750	2.2
17	3.250	2.6
18	3.750	3
19	4.250	3.4
20	4.750	3.8
21	5.500	4.4
22	6.500	5.2
23	7.500	6
24	8.500	6.8
25	9.500	7.6
26	11.000	8.8
27	13.000	10.4
28	15.000	12
29	17.000	13.6
30	19.000	15.2
31	21.500	17.6
32	24.500	20.8

3. Experimental Results and Analysis

3.1 Comparative Analysis of Water Distribution Isolines for Atomization Microsprinklers

The water distribution of No. 1 atomization micro-sprinkler under different pressures and heights above the ground is plotted as an isoline map, the X-axis represents the lateral spraying range, and the Y-axis represents the longitudinal spraying range, as shown in Fig. 3. For the No. 1 atomization micro-sprinkler, the experiment selected three pressures and four heights above the ground, adopting a complete test design, resulting in a total of 12 test groups. It can be seen from the figure that the water distribution of the No. 1 atomization micro-sprinkler tends to increase with the increase of pressure, indicating that agricultural spraying can increase the amount of pesticide applied by increasing the pressure of the spraying nozzle, thereby improving the spraying effect. As the height of the No. 1 atomization micro-sprinkler above the ground increases, the water distribution generally tends to decrease, indicating that the height of the spraying nozzle from the crop pest position is a key factor affecting the effectiveness of the medication. With the increase of the height of the atomization micro-sprinkler from the ground, the water distribution tends to decrease, indicating that to improve the effectiveness of the medication, the spraying nozzle needs to be as close as possible to the crop foliage.



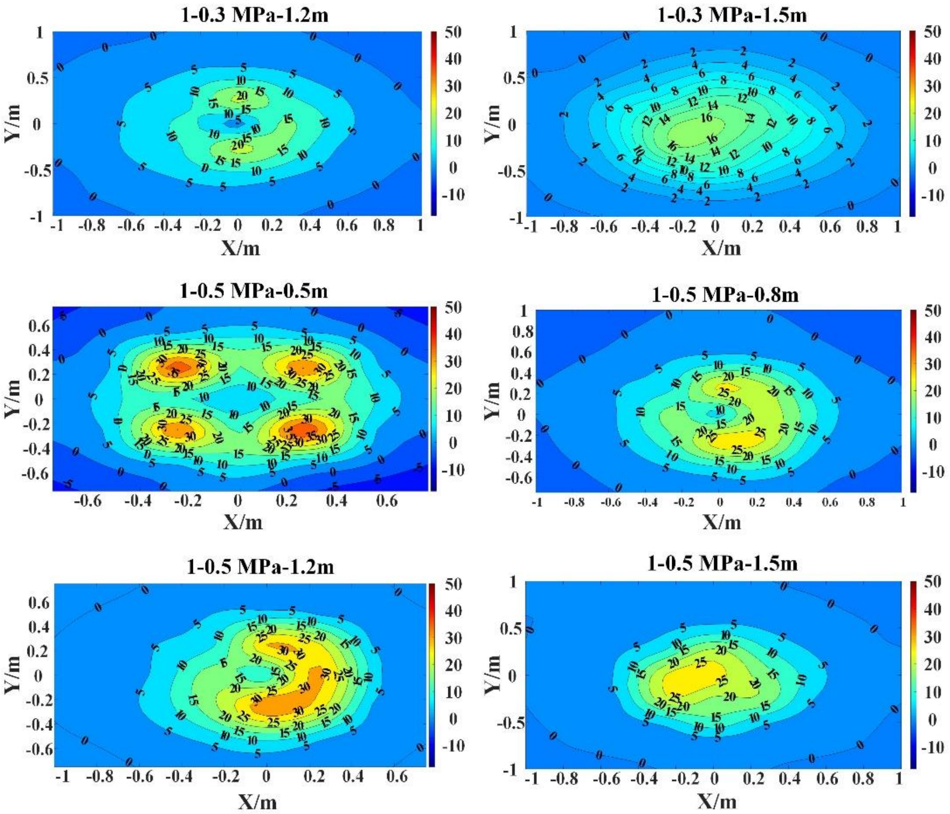
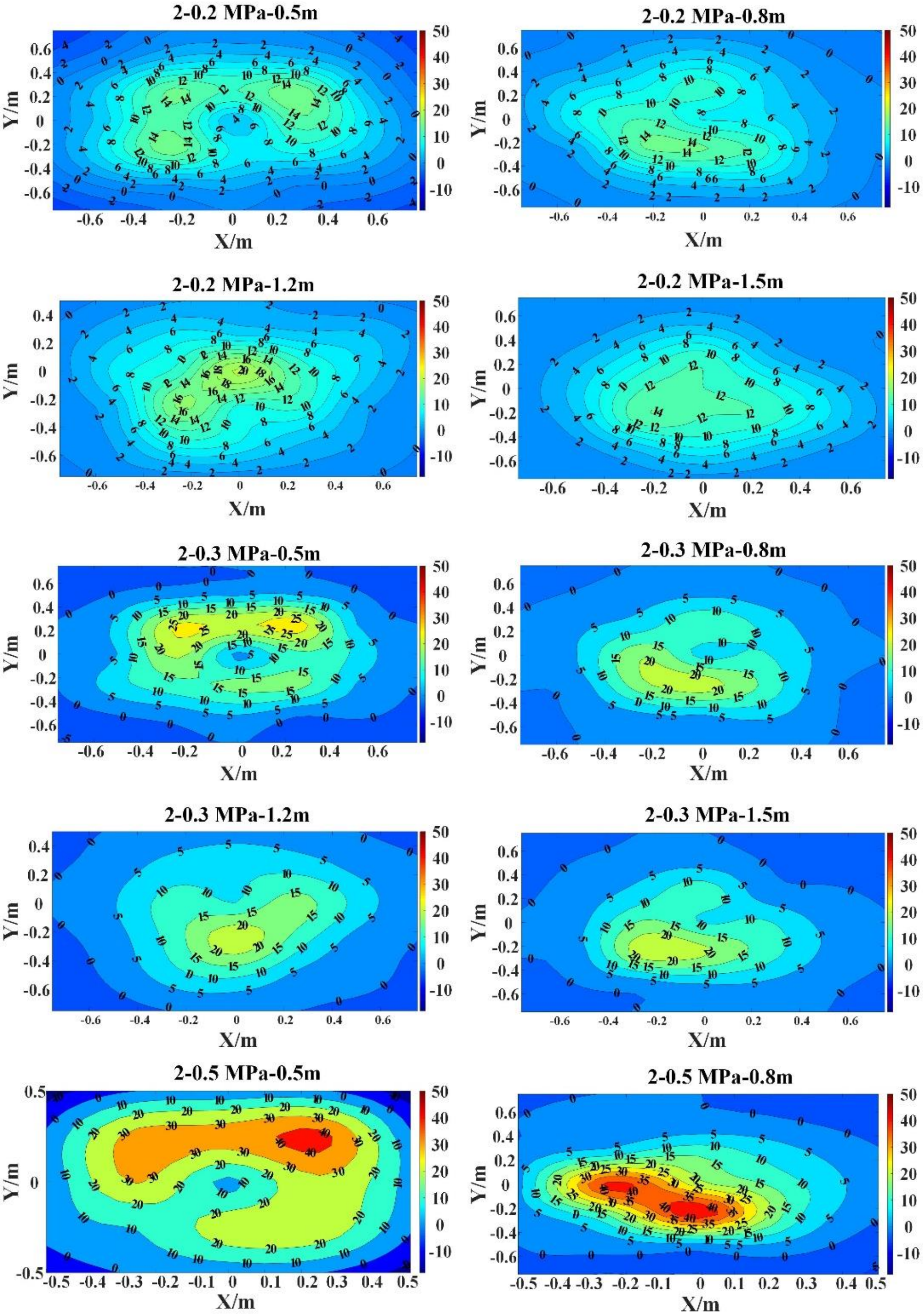


Fig. 3 Isolines of water distribution under different test conditions for No. 1 atomization micro-sprinkler

The water distribution of No. 2 atomization micro-sprinkler under different pressures and heights above the ground is plotted as an isoline map, as shown in Fig. 4. It can be seen from the figure that under the same conditions, the spraying water volume of No. 2 atomization micro-sprinkler tends to increase with the increase of pressure, and the water distribution shows a bimodal pattern. The reason is that No. 2 nozzle is a hollow cone atomization micro-sprinkler, hence there is a smaller water spraying volume at the center and a larger water spraying volume around the periphery. When the nozzle height above the ground is 0.5 m, 0.8 m, and 1.2 m, the bimodal pattern is more pronounced, and when the nozzle height above the ground is 1.5 m, the spraying water volume basically shows a unimodal pattern. The reason is that when the distance from the ground is higher, the water spraying volume is more affected by gravity and air resistance in the air, and the water spraying state of the hollow cone atomization nozzle approaches that of the solid cone atomization nozzle.


2-0.2 MPa-0.5m
2-0.2 MPa-0.8m
2-0.2 MPa-1.2m
2-0.2 MPa-1.5m
2-0.3 MPa-0.5m
2-0.3 MPa-0.8m
2-0.3 MPa-1.2m
2-0.3 MPa-1.5m
2-0.5 MPa-0.5m
2-0.5 MPa-0.8m
X/m
Y/m

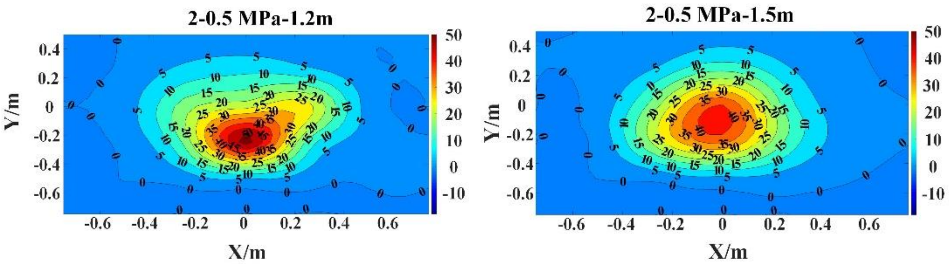
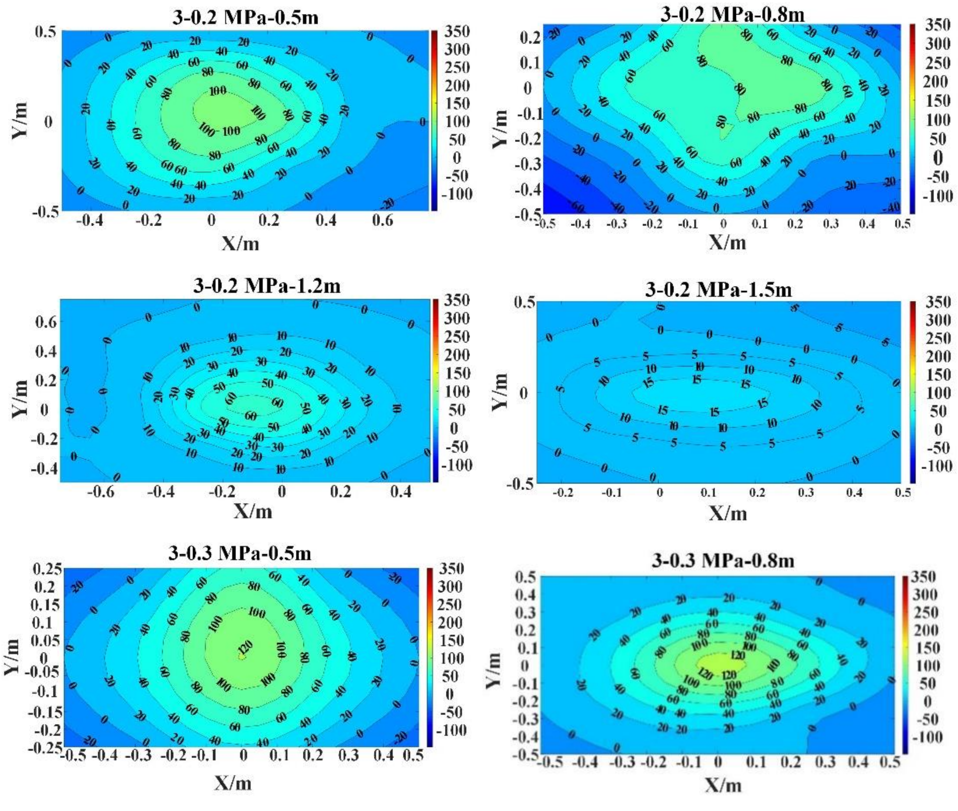


Fig. 4 Isolines of water distribution under different test conditions for No. 2 atomization micro-sprinkler

The isolines of water distribution for the No. 3 atomization micro-sprinkler under different test conditions are shown in the following Fig. 5. It can be observed from the figure that as the pressure increases, the water volume of the atomization micro-sprinkler tends to increase; as the height above the ground increases, the water distribution of the atomization micro-sprinkler tends to decrease. Since the No. 3 atomization micro-sprinkler is a solid cone atomization micro-sprinkler, it can be seen from the figure that the water distribution at each point shows a unimodal pattern, that is, the center point is the largest, and the surrounding areas are smaller.



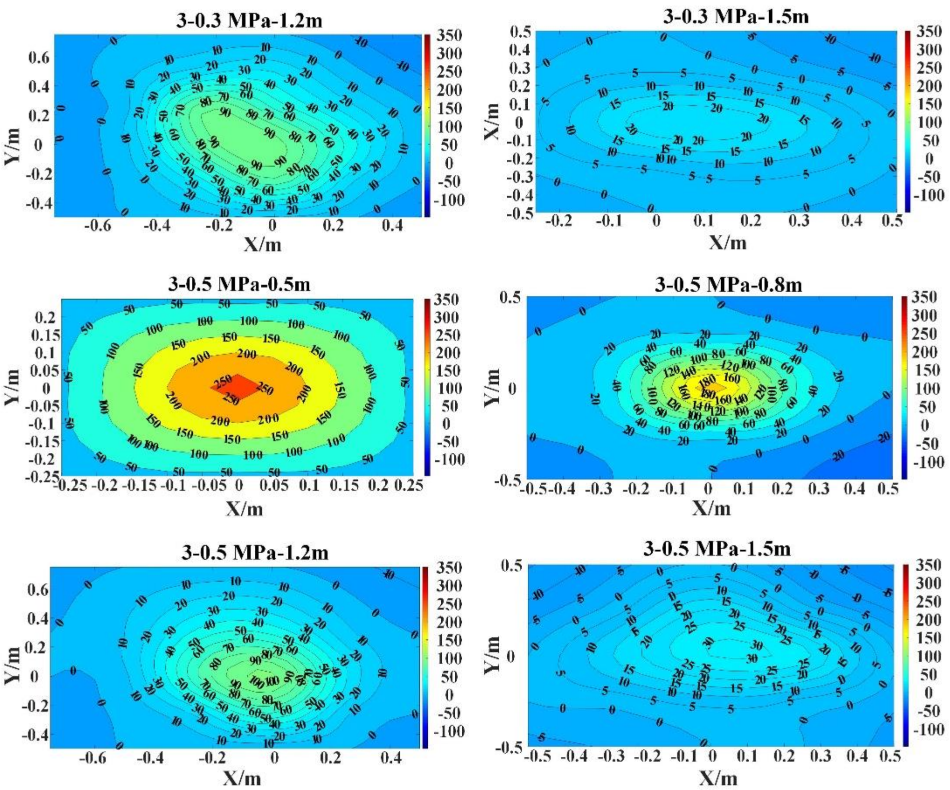
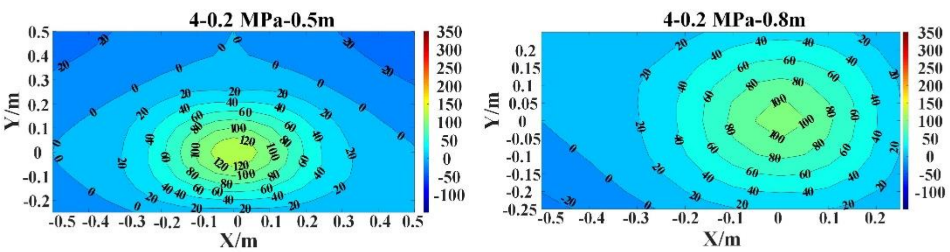


Fig. 5 Isolines of water distribution under different test conditions for No. 3 atomization micro-sprinkler

It can be seen from Fig. 6 that as the pressure increases, the No. 4 atomization micro-sprinkler shows an increasing trend in water spraying volume, and as the height above the ground increases, the water spraying volume shows a decreasing trend.



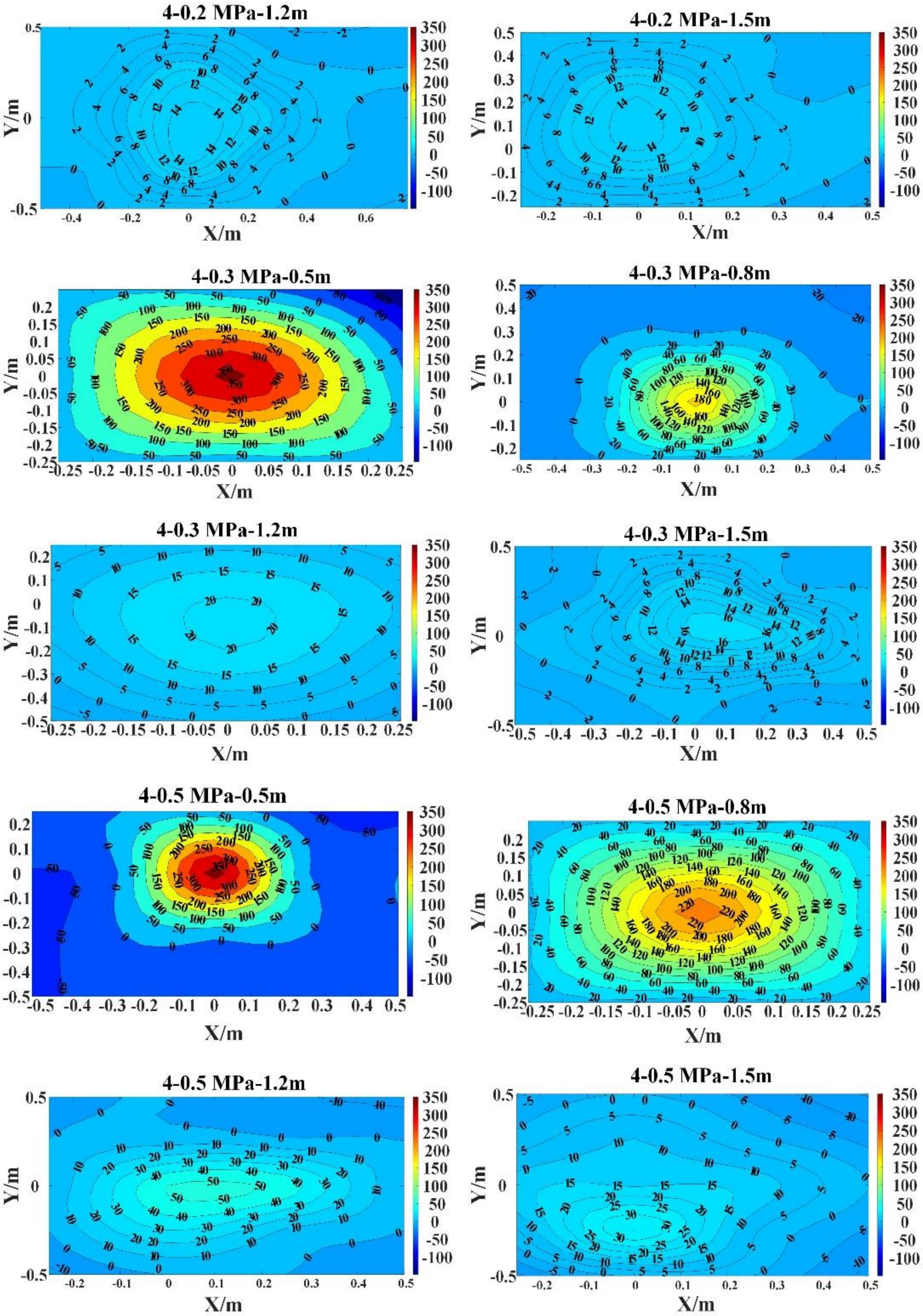
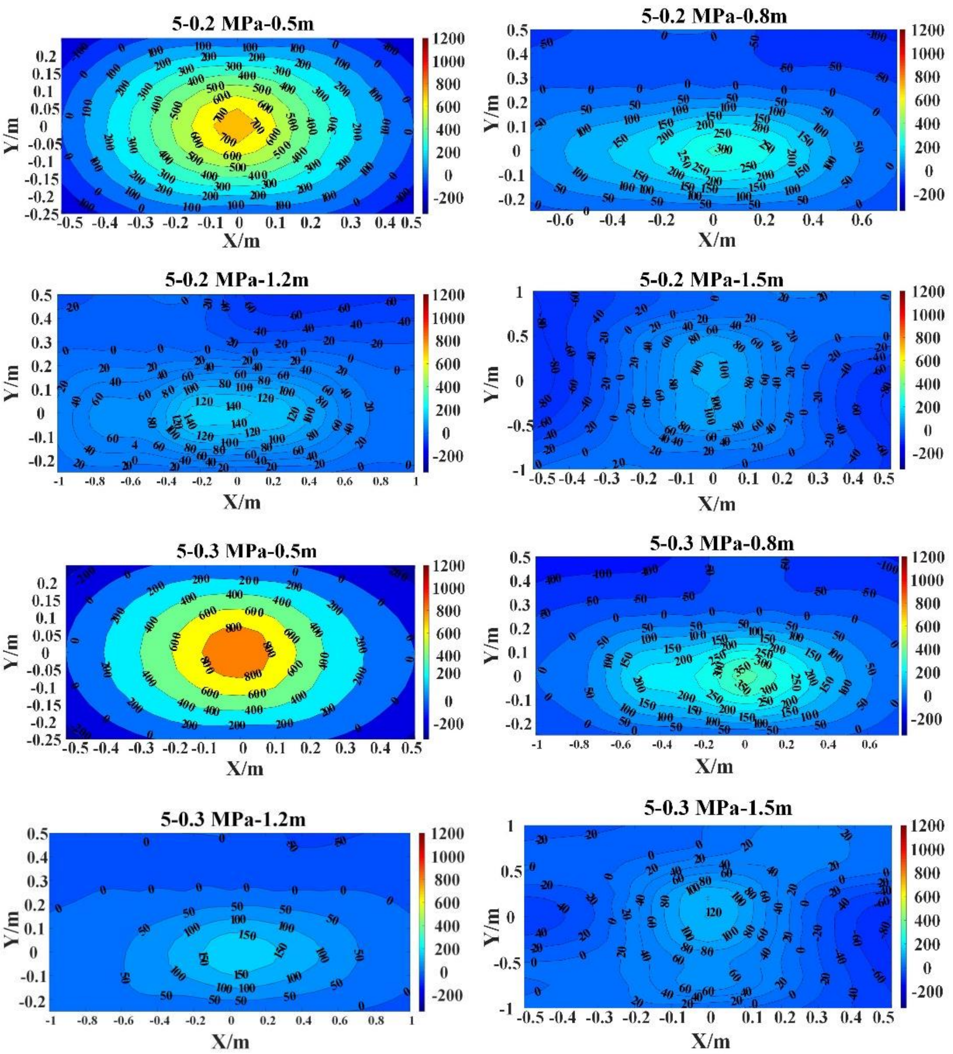


Fig. 6 Isolines of water distribution under different test conditions for No. 4 atomization micro-sprinkler

It can be observed from Fig. 7 that the No. 5 fan-shaped atomization micro-sprinkler exhibits an increasing trend in water spraying volume with the increase of pressure, and a decreasing trend in water spraying volume with the increase of height above the ground. The spraying pattern of the No. 5 fan-shaped atomization micro-sprinkler is approximately elongated, with higher water volume at the center and lower water volume around the periphery.



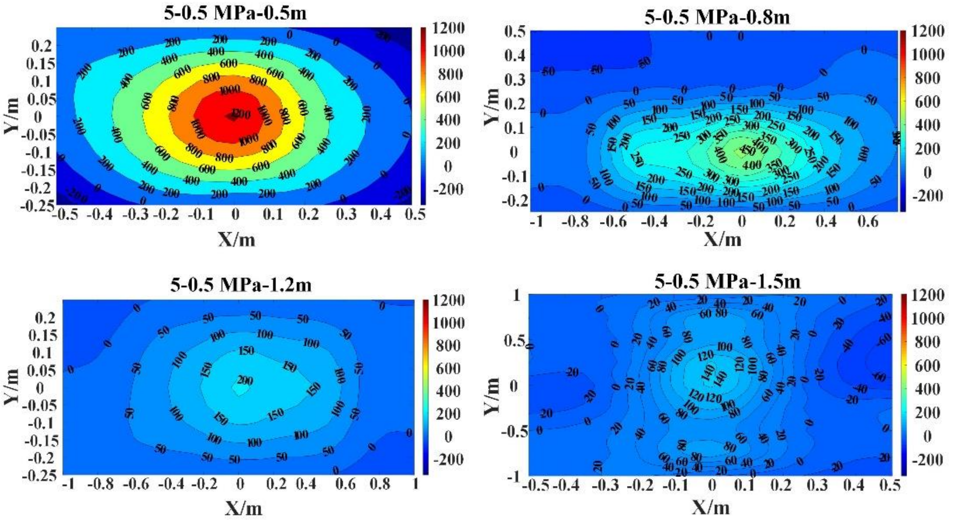


Fig. 7 Isolines of water distribution under different test conditions for No. 5 atomization micro-sprinkler

3.2 Droplet Size Distribution under Different Test Conditions for Different Types of Atomization Microsprinklers

The degree of pesticide atomization refers to the size dispersion of the droplet group produced during the spraying process, that is, the number of droplets formed after a certain volume of liquid is dispersed through a certain atomization method. The more droplets that can be formed from the same volume of liquid, the finer the droplets are indicated to be, and vice versa, they are coarser. The finer the droplets, the greater the surface area of the target object that can be deposited and covered, which means that the control effect will be improved, and the amount of pesticide used will be reduced. However, fine spraying is not necessary in every situation. For example, in the use of herbicides, fine spraying is more likely to cause droplet drift, which can cause damage to neighboring crops or environmental pollution. The experiment adopts three different pressure conditions of 0.2 MPa, 0.3 MPa, and 0.5 MPa, and uses the Parsivel2 laser raindrop spectrometer to test the number of droplets under different spraying droplet size conditions at different pressures, and draw a curve chart as shown in Fig. 8.

For the LNN series atomizing nozzles (Nozzle No. 1 and Nozzle No. 2), Fig. 8(a) indicates that the number of particle sizes is roughly normally distributed with respect to droplet sizes. As the pressure increases, the peak value of the droplet size quantity shifts to larger droplet sizes, meaning that higher pressure results in more droplets with larger sizes, while lower pressure results in more droplets with smaller sizes. Under the same pressure conditions, Nozzle No. 2 (LNN4W) produces more droplets than Nozzle No. 1 (LNN3W), and the nozzle diameter of Nozzle No. 2 is 34% larger than that of Nozzle No. 1. This suggests that under the same experimental conditions, an atomizing micro-sprinkler nozzle with a larger orifice can generate a greater number of droplets.

For the M series atomizing micro-sprinklers (Nozzle No. 3 and Nozzle No. 4), Fig. 8(b) shows that at higher pressures, there are more droplets distributed in the larger size ranges. Taking Nozzle No. 4 (M8) as an example, when the pressures are 0.2 MPa, 0.3 MPa, and 0.5 MPa, the proportion of droplets with sizes greater than 1.375 mm in the total number of droplets for Nozzle No. 4 are 0.58%, 8.58%, and 12.64%, respectively, with a ratio of 1:14.74:21.72. When the pressures are 0.2 MPa, 0.3 MPa, and 0.5 MPa, the proportion of droplets with sizes less than 1.375 mm in the total number of droplets for Nozzle No. 4 are 99.42%, 91.42%, and 87.36%, respectively, with a ratio of 1.14:1.05:1.

For the fan-shaped series of atomizing micro-sprinklers (Nozzle No. 5), Fig. 8(c) indicates that the particle size range of the fan-shaped atomizing micro-sprinkler is

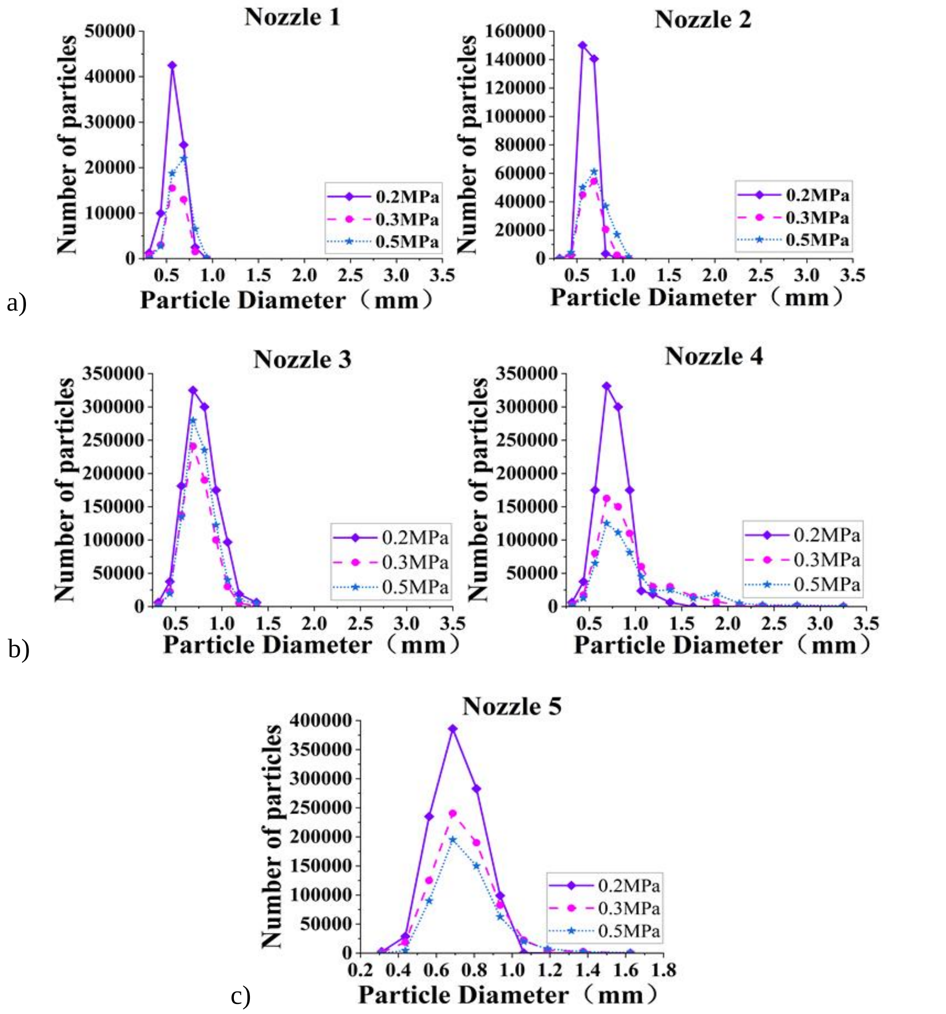


Fig. 8 Particle size distribution under different pressure conditions for different series of micro-sprinklers: a) LNN series, b) M series, c) fan-shaped micro-sprinkler

primarily distributed between 0.473 mm and 1.062 mm, accounting for more than 90% of the total proportion. When the pressures are 0.2 MPa, 0.3 MPa, and 0.5 MPa, the proportion of droplets with sizes distributed between 0.473 mm and 1.062 mm to the total number of droplets for the fan-shaped atomizing micro-sprinkler are 99.75%, 98.73%, and 97.89%, respectively. Compared to the conical atomizing micro-sprinklers of the LNN series and M series, the fan-shaped atomizing micro-sprinkler has the highest total number of droplets for several reasons: on one hand, the nozzles of fan-shaped spray heads are typically designed to cover a larger area, so they may have a larger orifice area, which allows more water flow to pass through in a unit of time. On the other hand, the water flow distribution pattern produced by the fan-shaped spray head is within a fan-shaped area, rather than being distributed within a conical space like the conical spray heads. This design enables the fan-shaped spray head to produce more droplets over a broader area. At the same working pressure, the fan-shaped spray head may convert pressure into kinetic energy more effectively due to its internal structure design, resulting in the production of more droplets. The spraying angle of the fan-shaped spray head is usually larger, which means it can distribute droplets over a wider fan-shaped area.

3.3 Distribution Charts of Droplet Size vs. Operating Speed for Atomization Micro-sprinklers

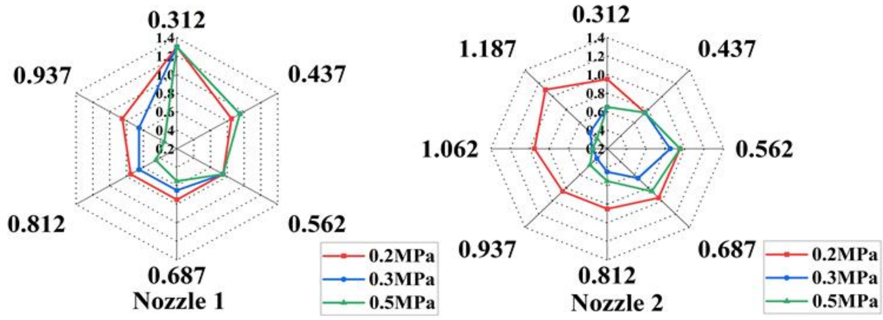
The radar charts in Fig. 9 below illustrate the relationship between particle size and velocity under different pressure conditions for different models of atomizing micro-sprinklers. From Fig. 9(a), it can be seen that for the hollow cone atomizing micro-sprinklers of the LNN series, the particle size range is mainly distributed between 0.312 mm and 1.187 mm, and the velocity range is primarily within 1.4 m/s. The characteristic is that the range of droplet sizes is relatively small, all distributed in the range of smaller sizes, and the droplet travel speed is also low.

From Fig. 9(b), it can be observed that for the solid cone atomizing micro-sprinklers of the M series, the particle size range is primarily distributed between 0.312 mm and 6.5 mm, and the velocity range is mainly within 2.4 m/s. The characteristic is that the droplet size range is relatively large, predominantly distributed in the larger size range, and the operating speed is also comparatively higher.

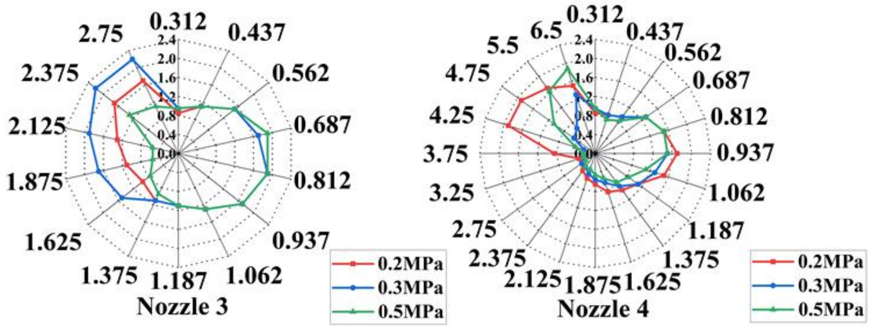
From Fig. 9(c), it can be seen that for the fan-shaped atomizing micro-sprinklers, the particle size range is mainly distributed between 0.312 mm and 2.75 mm, and the velocity range is primarily within 2.5 m/s. The characteristic is that the particle size range is also relatively large, mainly distributed in the medium size range, and the operating speed is relatively high.

The distribution of droplet size and velocity under different pressure conditions for different series of atomization micro-sprinklers is shown in the following Fig. 10. It can be observed from Fig. 10 that under the same pressure conditions, the LNN series has a narrower droplet size distribution range, all of which are distributed within a smaller range, while the M series has a larger droplet size distribution range, and the droplet sizes are larger than those of the LNN series. For micro-sprinklers of the same series, the larger the nozzle orifice, the more the sprayed droplet size distribution tends towards the larger droplet size range. For instance, compared to the No. 3 atomization micro-sprinkler, the No. 4 atomization micro-sprinkler produces larger droplet sizes.

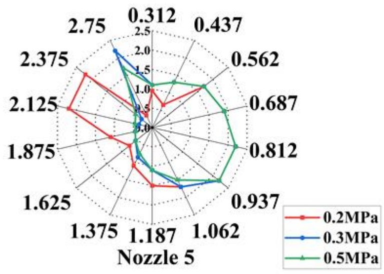
For the same type of atomization micro-sprinkler, under the same pressure conditions, the larger the orifice diameter, the larger the sprayed droplet size, but the droplet velocity decreases. For the same atomization micro-sprinkler, the greater the pressure, the larger the size of the sprayed droplets, but the droplet velocity is lower.



a)

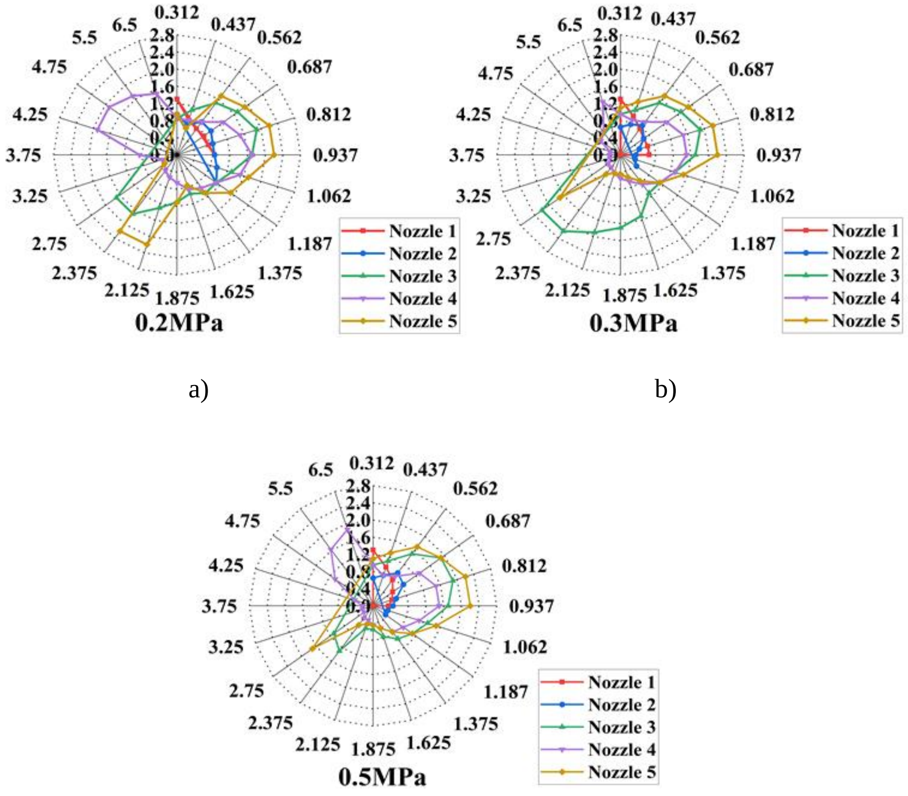


b)



c)

Fig. 9 Radar chart of droplet size vs. velocity of atomizing micro-sprinklers from different series under various pressure conditions a) LNN series, b) M series, c) fan-shaped micro-sprinkler



a) b)

c)

Fig. 10 Size-velocity distribution under different pressure conditions for different series of atomization micro-sprinklers: a) at 0.2 MPa, b) at 0.3 MPa, c) at 0.5 MPa

4. Conclusion

This study experimentally investigated the water distribution, droplet size characteristics, and spraying effects of different types of atomizing micro-sprinklers under varying pressure and height conditions. The results indicate that the spraying performance of atomizing micro-sprinklers is significantly affected by pressure, sprinkler type, and spraying height.

The main findings are as follows:

- Water Distribution: The water distribution of atomizing micro-sprinklers increases with increasing pressure, while the water distribution generally decreases as the height of the sprinkler above the ground increases.
  - Hollow Cone Sprinkler Water Distribution: The water distribution of the hollow cone atomizing sprinkler exhibits a bimodal pattern, with smaller water volume at the center and larger water volume around the edges. As the height from

the ground increases, the water distribution is more influenced by gravity and air resistance, and it approaches the behavior of a solid cone atomizing sprinkler.

- Solid Cone Sprinkler Water Distribution: The water distribution of the solid cone atomizing sprinkler follows a unimodal pattern, with the highest water volume at the center and smaller volumes around the edges.
- Fan-Shaped Sprinkler Water Distribution: The water distribution of the fan-shaped atomizing sprinkler is elongated in shape, making it suitable for spraying over a larger area.

- Droplet Size Distribution and Pressure Relationship: The droplet size distribution of LNN and M series atomizing micro-sprinklers follows a normal distribution. As pressure increases, the number of larger droplets increases. Conversely, when pressure decreases, the number of smaller droplets increases.
- Nozzle Aperture and Droplet Size Relationship: Under the same experimental conditions, nozzles with larger apertures generate more droplets. Additionally, as the nozzle aperture increases, the droplet size also increases, but the droplet's velocity decreases.
- Droplet Size Characteristics of Different Sprinklers: The LNN series hollow cone atomizing micro-sprinkler has a smaller droplet size range and lower droplet velocity. The M series solid cone atomizing micro-sprinkler has a larger droplet size range and higher droplet velocity. The fan-shaped atomizing sprinkler has a relatively large droplet size range and also higher droplet velocity.
- Effect of Pressure on Droplet Size and Velocity: For the same type of atomizing micro-sprinkler, as the pressure increases, the sprayed droplet size increases, but the droplet velocity decreases.

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