RESEARCH ARTICLE

Investigation on the Mechanism of Nebulized Droplet Particle Size Impact in Precision Plant Protection

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Abstract

Precision plant protection, a crucial facet of precision agriculture, assumes a paramount role throughout diverse stages of agricultural pesticide utilization. It not only furnishes indispensable reference parameters for agricultural production but also minimizes the employment of pesticides and their environmental footprint. This investigation employs a laser particle size analyzer to gauge the particle size information of the atomization field under assorted conditions, commencing with ground plant protection. The findings reveal that particle size escalates with the ascent of spray pressure and spray angle while diminishing with their augmentation. It proposes that pressure adjustments can optimize atomization outcomes when the deposited atomized droplet size is suboptimal. This study provides a data foundation for pesticide atomization in ground plant protection procedures and presents corrective actions for inadequate sedimentation effects, thereby mitigating the environmental harm associated with agricultural endeavors.

Keywords: atomization parameters, optimized particle size, particle size, precision plant protection, weight.

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1 Introduction

Precision agriculture has been evolving at a rapid pace, yet this advancement brings to light substantial environmental concerns, especially in the realm of precision plant protection within agricultural ecology. The Ministry of Agriculture of China has promulgated the "National Action Plan for 'Grain Capture by Inspections' to Ensure a bumper Harvest in 2021". This document discloses that major grain pests and diseases are becoming more widespread, impacting an area of 2.1 billion mu across the nation. In an effort to curb the proliferation of these pests and diseases, the frequency and volume of pesticide spraying are escalating on an annual basis. Despite this chemical control approach, the damage inflicted by pests remains acute and poses a considerable threat to the environment [1].

However, the utilization of pesticides in China is relatively limited. Statistics indicate that the quantity of pesticides employed per hectare in China is fivefold the global average, and the utilization rate amounts to merely 20% [2]. This inefficient usage leads to 200,000 tons of pesticides in China each year and 26 million tons of pesticide policies globally per annum. Distinct atomization parameters give rise to a spectrum of droplet sizes, ranging from tens to hundreds of micrometers. Smaller droplets possess a larger specific surface area and enhanced sedimentation efficiency. Nevertheless, this increased

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surface area can induce the evaporation and drift of the pesticide solution, resulting in wastage of pesticides and escalated application costs. Uneven sizes of atomized droplets can also give rise to pesticide waste. The crucial matter that demands attention is how to optimally set spray parameters to maintain the atomized droplet size within an appropriate range.

Generally, a pesticide becomes highly volatile when its particle size is smaller than 10um. If the droplet size is less than 100um, environmental factors can readily exert an influence on it, causing drift. In contrast, larger droplets are less prone to interference, but their small specific surface area and low adsorption capacity hinder the even distribution of pesticides on the target. Hence, controlling the particle size of atomized droplets is of utmost importance. In recent years, there has been a remarkable innovation in the technology for monitoring atomized droplet particle size. At present, the main methods for observing particle size include CFD simulation methods and image-based techniques.

As early as 1950, Dombrowski and his colleagues [3–7] conducted research on fan-shaped nozzles. Linear stability analysis was mainly used to explore the rupture of fan-shaped spray, understand the process of liquid film from the rupture zone to droplets, and establish the Dombrowski model. Post et al. [8] used dimension analysis to simplify the Dombrowski model, which predicts the volumetric average diameter of a fan-shaped nozzle in terms of spray pressure and internal structure. Liao et al. [9] studied the effect of spray parameters such as spray pressure, wind speed, and equivalent aperture on droplet characteristics. Musiu et al. [10] used a Lagrangian method to track droplets in a fluid dynamics (CFD) model. The results found that compared with the experiment, tIt can be seen from the above that the numerical simulation method is mainly applied to complex processes that are difficult to directly test, which can reduce the influence of environmental factors on the experimental results, but requires high computing power. The actual experimental observation method can more intuitively show the dynamic change process of droplets, and the accuracy mainly depends on the accuracy of equipment and methods. This study focuses on exploring the influence of spray parameters on the particle size of atomized droplets, and the actual experimental method can obtain the information of fog field particle size more intuitively and quickly.e model has good reliability in predicting droplet size, with an average variance of 8.29 µm.

The equipment utilized in the image method primarily encompasses the phase Doppler particle analyzer (PDPA) [11, 12] and the laser particle size analyzer (PIV) [13]. The measurement accuracy of the image method predominantly relies on the number of samples. Generally, the number of samples varies from several hundred to several thousand [14, 15]. Different quantities of samples will result in varying measurement accuracies of droplet size. When the number of droplets approximates 10,000, the measurement accuracy is approximately 1%. When the number of droplets is around 1000, the measurement accuracy is 3% [16]. Azzopardi et al. [17] discovered through experimental design that when the number of droplet samples was 5500, the measurement accuracy of droplet size was 5%. Yuan Jiangtao et al. [18] altered the number of droplet samples; when the number of droplet samples was 4000, the measurement accuracy was 4.84% . To minimize the number of tests and enhance the testing efficiency, Tate proposed that the number of droplets should be controlled at approximately 3000 to 4000 [19]. Kooij et al. [20] employed a Malvern particle size meter to acquire the spray diffraction pattern and combined it with high-speed photography to confirm that the broken droplets were spherical and determine the droplet size distribution. Urbán et al. [21] leveraged phase Doppler technology to investigate the atomization characteristics of a jet atomizer, thereby characterizing the droplet size distribution. Xia et al. [22] utilized high-speed photography in conjunction with this technique to measure droplet size and velocity, and the outcomes demonstrated an axisymmetric planar distribution of droplet size, with smaller droplets situated at the center of the spray. Employing this technique, Wang et al. [23] discovered through experimental research that pressure can modify the droplet size, and the atomization field proximal to the nozzle is more stable than the atomization field distant from the nozzle. Wang et al. [9] employed a PDPA-based laser measurement apparatus to assess the droplet size of a centrifugal nozzle, furnishing fundamental information for quantifying the impact of droplet size on the spray drift potential of unmanned aerial vehicles (UAVs) . Park et al. [24] conducted point-by-point measurements of the atomization field to observe the droplet size, average diameter, and droplet velocity of the atomized droplets at varying test pressures emanating from the nozzle. The results indicate that the average diameter of the droplets diminishes with escalating pressure. Bracho et al. [25] assessed spray droplet size at three distinct injection pressures using PDPA and high-speed microscopy imaging (HSMI) with water. Zhao et al. [26] gauged the spray utilizing a charge-coupled camera and PDPA and demonstrated that the droplet diameter augments in the direction away from the spray center. Poozesh et al. [27] examined the nebulizer atomized droplet velocity applying the PIV technique, considering spray angle, droplet breakup length, droplet size, and velocity distribution characteristics. Kang et al. [28] employed the device to measure the velocity of the axial droplets in the atomization field of a fan nozzle and constructed a droplet velocity prediction model with a high degree of accuracy. Simultaneously, the study also revealed that the average droplet size of the axial cross-sections at different heights did not undergo significant alterations in the atomization field. This method is employed to measure a broad spectrum of complex flow fields, encompassing cyclonic and turbulent flows. Miranda et al. [29] utilized PIV to measure the droplet size of a pneumatic nebulizer and discovered that alterations in nozzle diameter notably modified the droplet size. Katzman et al. [30] further probed the effect of additives on the droplet size of nozzle atomization. Liao et al. [9] employed PIV to observe droplet size in the atomization field of a fan nozzle at varying pressures and concluded that the droplet diameter reduction rate declined with the increment of spray pressure. Musiu et al. [10] Utilized the Lagrangian method to track the droplets in the computational fluid dynamics (CFD) model based on the equipment and discovered that the distance from the nozzle and the nozzle flow rate influenced the droplet size distribution. In contrast to the image method, the laser diffraction technology is more conducive to the measurement of particles with a small particle size. Generally, when the particle size is less than 25 μm, the accuracy is higher, and the method necessitates calculating the complex refractive index of the reagent [31]. The majority of laser diffraction utilizes a He-Ne laser source with a wavelength of 632.8 nm. This method boasts a short measurement time and good repeatability. This method couples a series of linear equations into the instrument algorithm and deduces it based on Fraunhofer diffraction [32].

It can be seen from the above that the numerical simulation method is mainly applied to complex processes that are difficult to directly test, which can reduce the influence of environmental factors on the experimental results, but requires high computing power. The actual experimental observation method can more intuitively show the dynamic change process of droplets, and the accuracy mainly depends on the accuracy of equipment and methods. This study focuses on exploring the influence of spray parameters on the particle size of atomized droplets, and the actual experimental method can obtain the information of fog field particle size more intuitively and quickly.So, this study plans to use a Marvin particle size analyzer to measure droplet size in the atomization field. We will analyze the weight proportion of the influence that spraying parameters have on droplet size. Our findings will provide a theoretical foundation for optimizing the particle size necessary for spraying.

2 Materials and Methods

2.1 Nozzle Selection

In this study, the commonly used fan-shaped nozzle is employed as the research object, and the Lechler brand, which is widely used worldwide, is adopted for the fan-shaped nozzle. The droplet size in the spray field can be regulated by altering the spray parameters. The parameters primarily encompass: spray angle, pressure, and flow rate. The spray angle and flow rate are determined by the internal parameters of the nozzle. Once the nozzle model is established, the above two parameters will remain unchanged. The internal parameters of the fan-shaped nozzle are depicted in Figure 1.

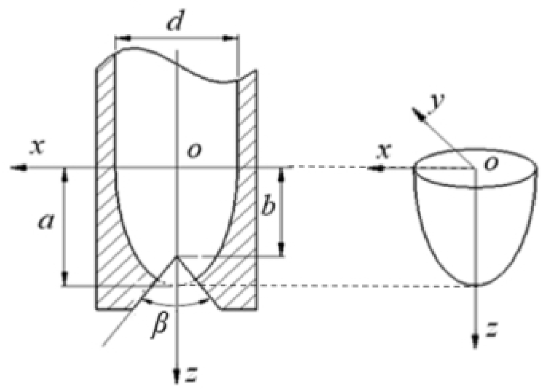

Figure 1. Internal structural parameters of fan nozzle.

It can be observed from Figure 1 that the inner cavity of the nozzle assumes an ellipsoidal shape, which is defined by a (the length of the semi-major axis of the ellipse) and b (the distance from the center of the ellipse to the bottom of the "V"-shaped groove). The outlet takes the form of a "V"-shaped groove, and the groove angle is β, which predominantly influences the spray angle of the nozzle [33]. Moreover, the nozzle flow is primarily determined by the diameter d of the nozzle incident section. Commonly utilized fan-shaped cleaning nozzles available in the market are selected, and the parameters of these nozzles are presented in Table 1 below.

Table 1. The selection of nozzle parameters.

Spray angle (°)	Nozzle type	A(r) (mm)	Flow code
20	633.361.30.CC	1.00	AL
	633.441.30.CC	1.35	BL
	633.511.30.CC	1.65	CL
	633.601.30.CC	2.20	DL
	633.671.30.CC	2.70	EL
30	633.362.30.CC	1.00	AL
	633.442.30.CC	1.35	BL
	633.512.30.CC	1.65	CL
	633.602.30.CC	2.20	DL
	633.672.30.CC	2.70	EL
45	633.363.30.CC	1.10	AF
	633.443.30.CC	1.30	BF
	633.513.30.CC	1.40	CF
	633.603.30.CC	1.60	DF
	633.673.30.CC	1.80	EF

3 Theoretical Basis

The volume median diameter (VMD) is generally utilized to analyze droplet size [34], as depicted in Equation (1):

$$D_v = \left(\frac{\int_{D_{\min}}^{D_{\max}} D^3 \mathrm{d}N}{\int_{D_{\min}}^{D_{\max}} \mathrm{d}N} \right)^{1/3} \tag{1}$$

where D_v is the median diameter of the atomization droplet, m; D refers to the droplet diameter at any position in the atomization field, m; and N is the number of droplets with diameter D.

The process by which the liquid film breaks into droplets is associated with the Reynolds number (RE). When the Reynolds number is low, the jet will fracture into spherical droplets with nearly the same diameter; as the Reynolds number continues to rise, the resistance from the ambient gas will gradually increase, subsequently augmenting the oscillation of the circular jet, and ultimately leading to the complete fragmentation of the jet into stable and large-scale droplets. When the Reynolds number is substantial, the circular jet will undergo complete disintegration into extremely minute droplets at the nozzle outlet [35]. Through the in-depth investigations of subsequent scholars, it was discovered that the breaking of the liquid film was correlated to the surface wave of the jet. The amplitude variations of the surface wave in the temporal and spatial modes are as follows:

$$\varepsilon = \varepsilon_0 \exp(\omega t + ikx + in\theta) \tag{2}$$

where, ε_0 represents the initial surface amplitude, which is determined by the geometry of the nozzle; $\omega = \omega_r + i\omega_i$, $k = k_r + ik_i$, if it is a time mode, ω_r represents the growth rate of the surface wave, and k_r represents the surface wave number; if is the spatial mode, k_r represents the surface wave growth rate, k_i represents the surface wave growth rate in the corresponding time mode; ω_r represents the surface wave number, and ω_i represents the surface wave number in the corresponding time mode. n represents the order of the surface wave, and θ represents the phase difference between the surface waves on the upper and lower gas-liquid interface.

York [36] believed that the surface wave was the main factor causing the breakup of the liquid film, and believed that the initial disturbance wave of the jet liquid film had the following form:

$$\varepsilon = \varepsilon_0 \exp(\beta t) \tag{3}$$

where, β is the disturbance growth factor, and t is the time.

The liquid film breakup time is obtained based on the expression of the initial disturbance wave:

$$t = \beta^{-1} \ln \frac{h_0}{2\varepsilon_0} \tag{4}$$

where, h_0 is the initial thickness of the liquid film. From the formula (4), it can be known that there is a logarithmic relationship between the liquid film thickness and the breaking time, and the breaking time increases with the increase of the liquid film thickness.

Based on the same supposition, Squire [37] postulated that only the initial disturbance wave with a wavelength exceeding a certain value would undergo expansion and growth under the influence of surface tension, while the disturbance wave shorter than the critical wavelength would decay. When the Weber number We is significantly greater than 1, the analysis takes into account that the critical wavelength is:

$$\lambda = \frac{2\pi\sigma}{\rho_g v^2} \tag{5}$$

where σ is the surface tension coefficient, ρ_g is the air density, and v is the velocity of the liquid.

The wavelength of the disturbance wave with the largest growth rate and its growth factor are:

$$\lambda_{\max} = 2\lambda,\ \beta = \frac{\rho_g v^2}{\sigma(\rho_l \varepsilon_0)^{1/2}} \tag{6}$$

It can be deduced from the aforementioned formula that the wavelength of the disturbance wave with the fastest growth rate is directly proportional to the surface tension of the liquid. In other words, the higher the surface tension of the liquid, the larger the wavelength of the critical disturbance wave, resulting in larger droplet sizes formed by the breakup. The effects of gas density and gas-liquid relative velocity on the critical wave of droplet disturbance are contrary to that of surface tension.

3.1 Design of the Test Method

3.1.1 Test System Construction

In this experiment, the Malvern laser particle size analyzer was utilized to measure the droplets within the atomization field. This device can quickly and accurately measure the particle size information of the droplets along a line. The nozzle is fixed on the motor control platform, and the height and position of the nozzle are adjusted via the platform. The laser particle size analyzer emits a laser beam to measure the droplet size passing through it. The particle size information passing through the laser beam is transmitted to the computer control system, where data processing is performed to calculate the average particle size of the axial section of the atomization field and analyze the particle size distribution. The liquid medicine pressure stabilization system is mainly achieved through the pressure stabilizing pump. By adjusting the value of the pressure stabilizing pump, the test pressure is stabilized within a certain range to ensure the stable progress of the test. The liquid medicine reflux system is used to collect the atomized liquid medicine, and the collected liquid medicine is recirculated back to the pressure stabilizing pump to complete the recycling of the liquid medicine. The test system was configured as shown in Figure 2. Additionally, some critical equipment parameters are provided in Table 2.

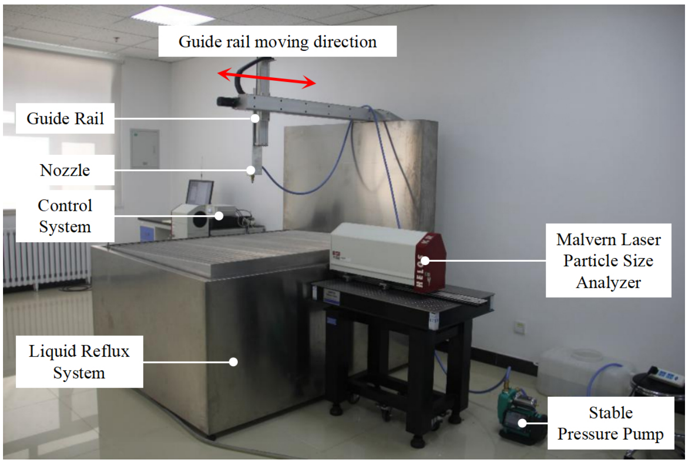

Figure 2. The construction of the atomization experiment system.

3.1.2 Experimental Scheme

The experiment was carried out in a closed environment. To simulate the actual operating circumstances, the temperature for this experiment was kept between 20°C∼22°C, and the humidity ranged from 50%∼70%. Temperature and humidity sensors were utilized for real-time monitoring of the indoor environment. The nozzle was installed vertically downwards with a test distance of 0.5 m. We adjusted the laser position to guarantee that both ends of the laser were at the same height, enabling full reception of the laser beam. The nozzle was fixed at the end of the guide rail, with the movement direction of the guide rail perpendicular to the direction of the laser beam. As the guide rail moved, the laser beam swept across the spray axis section to determine the droplet size on the spray field axis section, as depicted in Figure 2. The preset pressure range was set from 0.1∼0.3 MPa in increments of 0.1 MPa. The experiment did not take into account factors such as the surface tension of the spraying liquid. To reduce testing risks and costs, water was employed in the spray test. To ensure the measurement accuracy of the laser particle size analyzer, we shielded the external light source for this experiment. Prior to the initiation of the test, we adjusted the pressure stabilizer pump based on the pressure gauge and conducted the test once the pressure reached the predetermined value and stabilized.

Table 2. Primary test equipment and parameters.

Equipment	Type	Company
Laser particle size analyzer	HELOS-VARIO	Sympatec GmbH Co
stabilized pressure pump	1WZB-25Z	PRODN Intelligent Electronic Technology Co

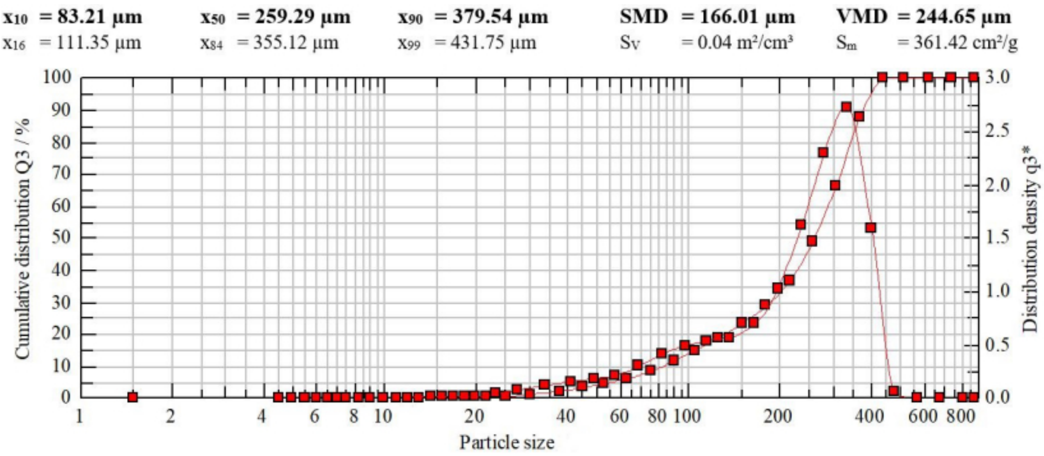

Figure 3. Particle size information of atomization field axial section.

4 Results and Discussion

4.1 Influence Mechanism of Spray Parameters on Atomized Particle Size

We measured the droplet size in the atomization field of nozzles with different parameters under different pressures. We analyzed the weight ratio of the influence of these parameters on the droplet size, and finally selected the spray parameters suitable for UAV cleaning. By measuring the droplet particle size of the spray section under different parameters, we obtained the overall particle size distribution information of the atomized droplets. Figure 3 shows the droplet size information on the axial section 50 cm away from the 63236430 nozzle under a pressure of 2 bar.

As shown in Figure 3, under the given parameters, the droplet size is mainly concentrated around 300 µm, and the droplet size in the range of 200–400 µm accounts for more than 60% of the liquid volume. The average particle size (volume median diameter VMD) of the droplet in the axial section of the entire atomization field is 244.65 µm. Through this method, atomization tests were carried out on all fan-shaped nozzles, and the particle size information of all axial sections was measured. Figure 4 shows the droplet size information in the atomization field under different parameters.

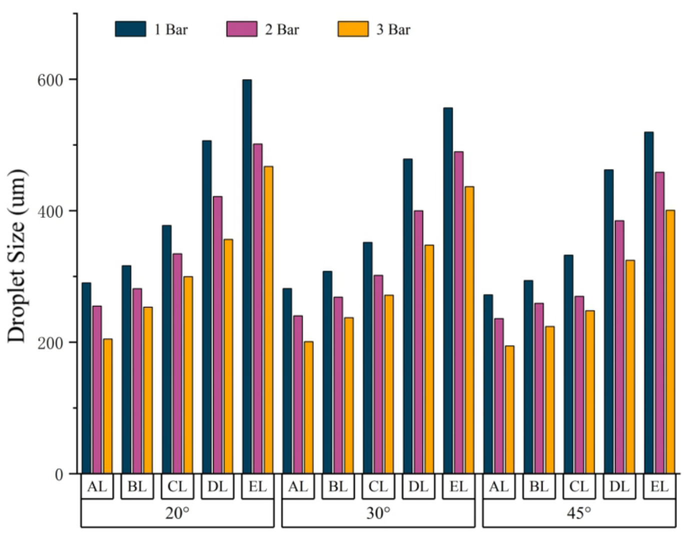

Figure 4. particle size information of atomization field axial section under different pressures and flows.

As shown in Figure 4, under the same spray angle and flow rate, the droplet diameter in the axial section of the atomization field reduces as the pressure increases. The chemical liquid adheres to the law of energy conservation. When the pressure of the spray system is high, the atomized liquid droplets generate a high velocity, thereby increasing the resistance of the liquid droplets. Under the influence of air resistance, the liquid droplets initially change from a spherical to a thin disk shape, with the middle of the thin disk gradually thinning to form a liquid ring. Due to the action of surface tension and liquid viscous force, the liquid contracts into a sphere. As the droplet moves at high speed, the tangential resistance of air balances the internal viscous force of the droplet. When the droplet is large, the air resistance exceeds the droplet's internal viscous force, leading to droplet fragmentation. The particle size of the fragmented droplet is small, and its air resistance is low. When the air resistance equates to the droplet's internal viscous force, the droplet attains a stable state. Therefore, a higher pressure leads to a larger droplet velocity and increased air resistance. To reduce air resistance, the droplet fragments into smaller particles.

Simultaneously, as seen in Figure 5, under the same spray angle and pressure, the droplet diameter increases as the flow rate increases. With a fixed spray

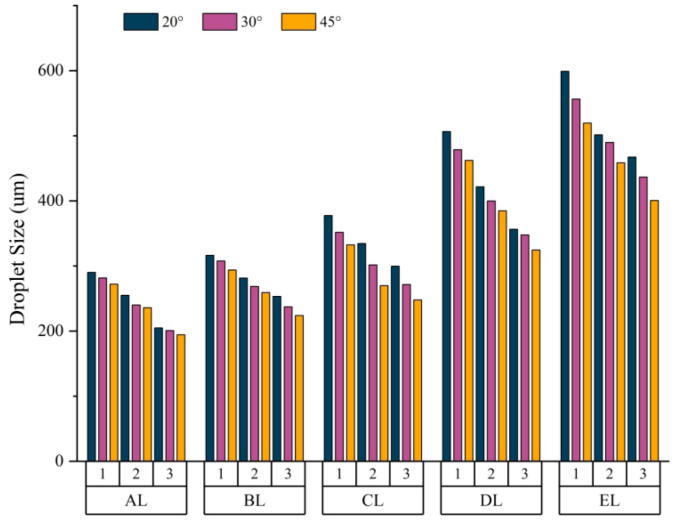

Figure 5. Particle size information of atomization field axial section at different spray angles.

angle, an increase in the flow rate thickens the liquid film in the atomization field. The thicker liquid film causes uneven final fragmentation, fewer fragmented droplets, and a longer overall fragmentation distance, resulting in an uneven droplet size distribution in the atomization field. Droplets with a larger particle size have a significant impact on the average particle size of the droplets in the atomization field. These droplets dominate the atomization field and are less affected by turbulence, enabling them to maintain their original motion state. Therefore, when the spray angle and pressure remain unchanged, increasing the nozzle flow will enlarge the overall particle size of the droplets in the atomization field. We used the same method to compare the particle size of the atomization field under the same flow and pressure. For this study, we selected three types of spray angle nozzles commonly used for drone cleaning. Each nozzle underwent atomization experiments in a specific application environment. Figure 5 shows the observed particle size data.

As depicted in Figure 5, under the same flow and pressure, the droplet size in the atomization field diminishes as the spray angle enlarges. When the flow rate and pressure remain unchanged, the energy of the jet droplet remains constant as well, and the liquid film coverage in the atomization field with a larger spray angle is more extensive. Considering that the liquid volume stays constant, the liquid film thickness in this scenario is decreased. Consequently, the droplets generated by the breakup of the liquid film are smaller and more uniform in size.

4.2 Spray Parameter Influence Weight Analysis

The size of droplets in the atomization field is affected by numerous factors. Section 3.1 of this paper discusses the impact mechanisms of spray angle, flow rate, and pressure on the size of atomized droplets. Each of these factors affects the droplet size to varying degrees. When the size of atomized droplets cannot meet the cleaning requirements or the cleaning effect of the atomized droplets is not optimal, the atomization effect needs to be adjusted promptly. Therefore, how to quickly adjust the droplet size to achieve a better cleaning effect requires further exploration.

In this study, we use SPSS software to analyze the weight of atomization parameters. We perform a multivariate statistical analysis between the atomization parameters and the particle size data obtained from the experiment to determine the influence weight proportion of different parameters on the atomization particle size. Figure 6 shows the resulting influence weight proportions.

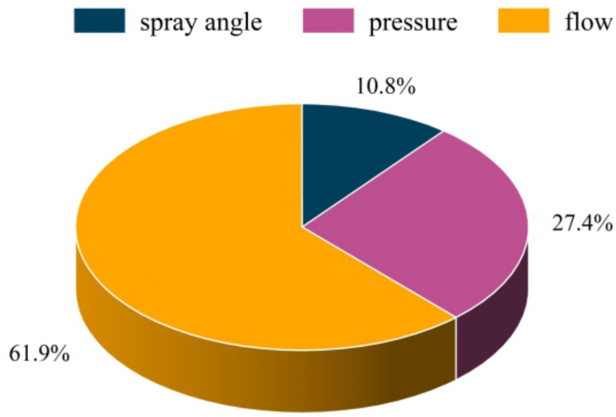

Figure 6. influence weight ratio of different parameters on atomized particle size.

As depicted in Figure 6, within the parameter scope of this experimental investigation, the spray flow rate exerts the most significant influence on droplet uniformity, whereas the spray angle has the least. The influence weight of the spray flow rate on droplet size surpasses 60%, and the combined influence weight of spray pressure and flow rate is nearly 90%. Consequently, if it is necessary to precisely regulate the droplet size in the atomization field, adjusting the spray pressure can directly enhance the atomization effect. If the desired atomization particle size cannot be attained by modifying the pressure, the nozzle should be replaced, and the nozzle's flow rate altered. Naturally, the range of atomized particle size must be established based on the cleaning environment. In environments characterized by strong wind and high temperatures, the atomized particle size can be appropriately augmented. As it is inconvenient to frequently change the nozzle during cleaning, the atomization pressure should be the primary adjustment when modifying the atomized particle size.

5 Conclusions

This paper explores the factors affecting the particle size of atomized detergent. In the experimental setup, a Laser Particle Sizer is employed to measure the droplet size in the axial section of nozzles operating under different flow rates, spray angles, and pressures. We analyze the effect of these parameters on droplet size and the weight proportion of each parameter on particle size. The main conclusions are as follows:

1. The droplet size grows as the nozzle flow increases and shrinks as the spray pressure escalates. The spray angle, within the range investigated in this experiment, has a negligible impact on particle size.
2. Within the range of nozzles selected for this experiment, the influence weight of atomization droplet size is ranked as nozzle flow, pressure, and spray angle. The respective influence weight of each parameter on atomization particle size is 61.9%, 27.4%, and 10.8%.
3. If the particle size of atomized droplets is not suitable for deposition, it is recommended to modify the particle size of the droplets by adjusting the atomization pressure.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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