Influences of nozzle parameters and low-pressure on jet breakup and droplet characteristics

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Abstract: Experiments were carried out to investigate the influences of nozzle geometric parameters and injection pressure on jet breakup characteristics using a high-speed photography (HSP) technique. The flow rates and spraying ranges of sprinkler with different nozzles were measured. In this research, HSP technique was also used to photograph the drops emitted by sprinkler with different nozzles at different pressures, photographs were taken at different horizontal distances from the sprinkler and the equivalent circle diameter was used to represent the particle sizes. Based on HSP technology, the effects of flow velocity and nozzle geometric parameters on jet breakup length were studied, and the droplet diameters with different nozzle types were obtained. The result showed that for the sprinkler with different nozzles, the breakup length decreased with the increases of pressures. At the nearby (3-9 m) region and distant (12-18 m) region of sprinkler, the droplet diameters of sprinkler with type B nozzle were the largest, which meant the sprinkler with type B nozzle was the optimal choice by synthesizing the droplet diameter distribution. The fitting relationship of jet breakup length with Reynolds number and Weber number (*Re* and *We*), and the regression equation of the end droplet diameters were deduced with errors of less than 5% and 4% respectively.

Keywords: nozzle, high-speed camera, jet breakup length, droplet diameter, fitting formula

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1 Introduction

With the development of irrigation techniques, better spraying range and atomization performances of jet flows is highly required. The atomization effect which is justified by the size of droplet diameter and the spraying range both represent the external characteristics of jet. Therefore, the breakup process and droplet diameter of round jet have been studied by a lot of scholars[1-4].

Early in 1879, the axisymmetric deformation and the breakup process of round jet were researched under low *Re* number, which revealed that the breakup of jet was caused by the surface tension without the effect of viscosity and gravity[5,6]. Considering the effect of viscosity and density, the result showed that viscosity had a stable effect on jet[7]. The variation in breakup length of a liquid jet subjected to different physical parameters was investigated experimentally[8]. The phenomenon of surface stripping in round jet was tested and analyzed using the high speed camera[9]. The influence of *Re* number on jet breakup length of nozzle liquid membrane was studied by the image method[10]. Considering the effect of nozzle parameter, the influence of nozzle structure and pressure on nozzle atomization characteristics was discussed on the basis of experiments[11].

For the studies of droplet diameter, the measuring

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methods of spraying droplet diameter are wheat flour method, stain method, optical method and photographic method, however, there is a big difference of the scope, measuring cost, and testing accuracy for different methods. The flour method was used to measure the droplet size distributions of sprinklers with three nozzles, and the effects of rotating speed, nozzle diameter and operating pressure on the droplet size were analyzed[12]. The droplet diameter of ZY sprinkler head under different work pressures was measured using flour method[13]. Bai[14] established a modified calibration equation considering two factors of droplet size and impact angle using flour method. For the studies of stain method, Xu et al.[15] obtained the formulation with the factors of height and stain diameter by dealing data firstly. For the studies of optical method, laser precipitation monitor (LPM) provided a relatively easy means to obtain reliable estimates of sprinkler kinetic energy per unit volume of applied water[16]. A statistical treatment of the passing time measured by an optical disdrometer can eliminate a large number of erroneous measurements[17]. Bautista-Capetillo et al.[18] proposed an optical particle tracking velocimetry (PTV) technique to determine drop velocity, diameter and angle. For the studies of photographic method, a new technique based on low-speed photography was presented and validated to directly measure drop diameter, velocity and angle[19,20].

An alternative, simple method is needed for evaluating the breakup and droplet characteristics of low-pressure jet, which would be able to provide information of at least the jet breakup length and the droplet diameter. A photographic method which could be used to obtain adequate data sets for detail analysis of sprinkler irrigation problems was used in recent developments in digital photography. The existing researches have discussed the jet breakup with a nozzle of small aperture and high pressure, for the purpose of obtaining a better effect of atomization. However, the nozzle used in agriculture irrigation has a larger aperture and a longer spraying range.

Thus, this paper reported the application of a high-speed photography (HSP) technique to the characterization of jet breakup and the droplet diameter by changing the structure parameter of nozzle. The specific objectives of the study were: (1) to characterize spraying range, jet breakup length and droplet diameter with different structure parameters of nozzle; and (2) to test the adequacy of HSP technique method to obtain correlations between pressure and breakup length.

2 Materials and methods

2.1 HSP experimental system

This experiment was carried out in the laboratory of the Research Center of Fluid Machinery Engineering and Technology, Jiangsu University in China. The experimental setup is schematically presented in Figure 1, the experimental system is composed of the jet system and the HSP system. The jet system was composed of: (1) a water pump with a power of 5.5 kW; (2) an electromagnetic flowmeter and a piezometer; (3) a valve and a sprinkler. The HSP system was composed of: (1) a CCD camera and sensor manufactured by IDT Co.; (2) a white LED light with a power of 120 W; (3) a data acquisition computer; (4) a dark screen and a tape. Figure 2 represents the observation points of droplets.

The water is firstly pumped out from the reservoir by the water pump, then it flows to the sprinkler through a long pipe and finally sprayed out. A $PY_1$15 type sprinkler was adopted as prototype, the installation height is 0.85 m from the ground and the spraying angle is 23°. The flow and pressure of jet could be read out by the flow meter and pressure gauge. A black curtain was placed at the back of the jet region, and the jet flow was irradiated by an illuminant, horizontally at the capture zone. Once the beam light was in the capture zone, the jet flow was amplified using optical lenses to obtain a larger sheet than the area covered by the camera lens. The distance between the CCD device lens and the laser sheet was 0.5 m in all cases. The CCD camera and the trigger were computer-operated in a procedural time sequence. The capable maximum frame rate of CCD camera is 150 000 frames per second (fps), and it was set to 10 000 fps with each frame time of 0.1 ms in this test. The exposure time was set to 5 μs to ensure the clarity of droplets. The experiment of HSP was done at night to prevent the disturbance of day light.

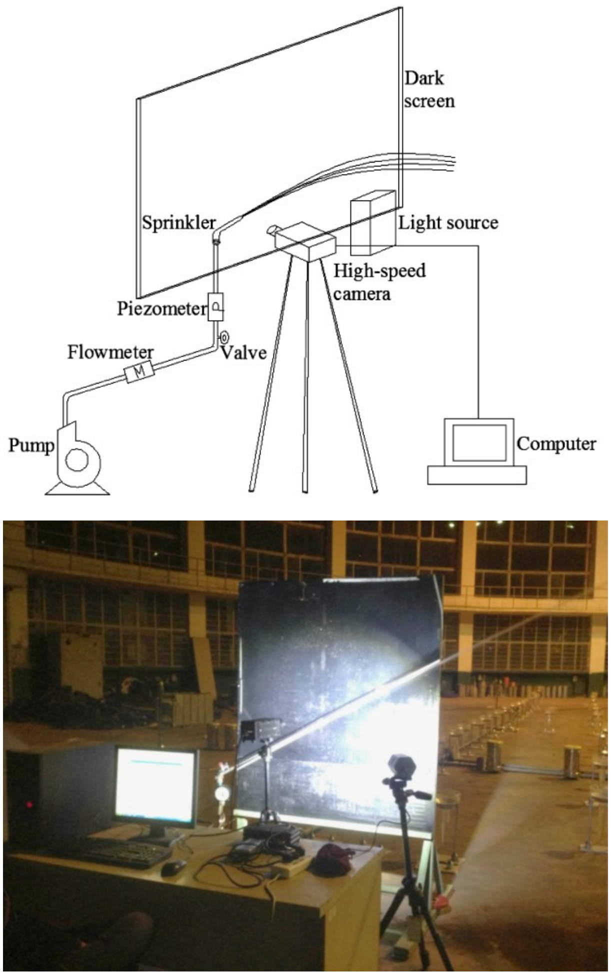


Figure 1 Experimental setup for breakup and drop characterization

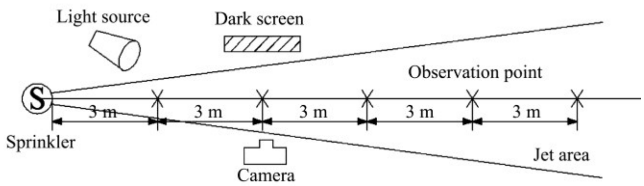


Figure 2 Location of observation points for the measurement of droplet

The values of jet parameters used in the experimental system are presented in Table 1. The environmental pressure was 100 kPa and the injection pressure was 200-400 kPa. The spraying ranges, end raindrop diameters and the pictures of jet broken were obtained through the experiments under different injection pressures and different geometric structures of nozzle. The optimal combination of geometric parameters of the nozzle could be determined by analyzing the spraying ranges and droplet diameters of jet quantitatively. Besides, the effect of nozzle parameters on jet broken could be judged by observing the way of jet broken from the photos of high speed photography qualitatively.

Table 1 Jet parameters used in the experiment

Parameters	Value
Experimental temperature/ºC	20
Water density/kg·m^{-3}	998
Water viscosity/kg·(m·s)$^{-1}$	1.01×10^{-3}
Air density/kg·m^{-3}	1.293
Air viscosity/kg·(m·s)$^{-1}$	1.79×10^{-5}
Water surface tension/N·m^{-1}	0.072
Air velocity/m·s^{-1}	0.1-0.5

2.2 LPM experimental system

The laser precipitation monitor (LPM, ThiesClima, German) used in this research for the measurement of the droplet diameters is composed of two subsystems: (1) an imaging system composed of photodiode detector, laser transmitter, storage circuit and et al, as shown in Figure 3; (2) an analysis display system composed of LNM View software which is used to display data generated by the LPM.

LPM can accumulate the measured droplet volumes and calculate the rainfall intensity, and the droplet spectra of LPM can be drawn, containing the drop size range, droplet speed range and corresponding particle numbers. The data collected per minute could be output to an EXCEL file. The test area is 46 cm^2 (23.0 cm×2.0 cm); the measurement range of particle diameter is 0.16-8.00 mm; the velocity range of particle is 0.2-20.0 m/s; the measurement range of rainfall intensity is 0.005-250.000 mm/h[21].

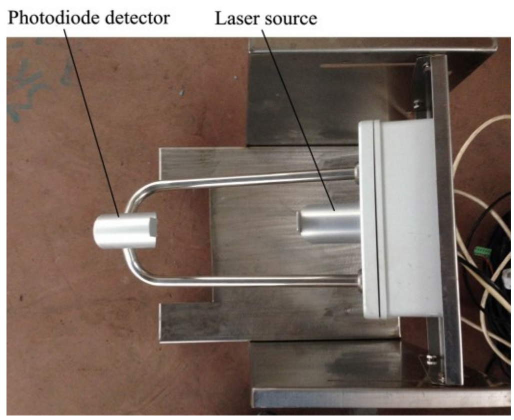


Figure 3 Structure of LPM

2.3 Structure and application of the jet nozzle

In order to investigate the influence of nozzle geometric parameters on jet breakup characteristics, different geometric parameters of nozzle such as shrinking entrance diameters, angles and outlet diameters were applied respectively in the experiment, as presented in Figure 4. In which, D_1 is the outlet diameter of jet; D_2 is the shrinking entrance diameter of jet; θ is the angle of nozzle. Five nozzle models with different structures were self-designed and self-made, then compared on their calculations, as presented in Table 2.

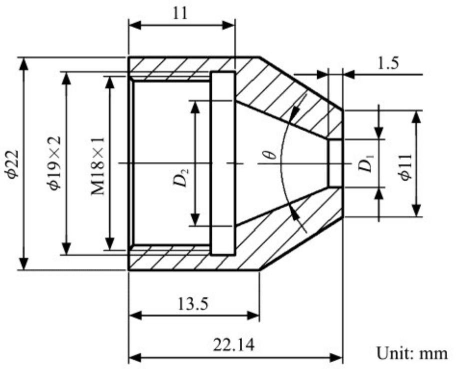


Figure 4 Structure of the nozzle

Table 2 Parameters of five nozzles

Nozzle type	D_1/mm	θ/(°)	D_2/mm
A	4	45	12
B	5	45	13
C	6	45	14
D	5	35	10.5
E	5	55	15

2.4 Calculation method of droplet average diameter

Jet flow spraying from the nozzle will be broken up by the air entrainment, forming numerous different diameter droplets and then drops within the scope of spray. The average droplet diameter represents the drop size at different positions due to the changing of droplet diameter in a comparatively larger range. At present, the methods used to calculate the average droplet diameter include the Number Average Method, Weighted Average Method and Middle Cumulative Frequency Diameter Method. And in this research, the realistic Weighted Average Method was adopted.

Weighted Average Method is the ratio of corresponding weight of droplet diameters by different standard sieve meshes to the total weight of droplets at the sample location, using the following equations:

$$\bar{d} = \sum_{i=1}^{n} W_i d_i \Big/ \sum_{i=1}^{n} W_i \tag{1}$$

$$W_i = m_i \frac{\pi}{6} d_i^3 \gamma_w \tag{2}$$

where, $\bar{d}$ is the average size of droplets at sampling locations, mm; d_i is drop diameter, mm; W_i refers to the weight of water for droplet with diameter d_i; γ_w is the bulk density of water, N/m^3; m_i is the number of droplet with diameter d_i and n corresponds to the types of droplet diameters.

2.5 Image processing of drop size

The Image J software was used to process the images, the droplet field with different lengths from the nozzle was the research object, and the particle properties on a millimeter range scale were analyzed. Following image processing, a statistic analysis was performed on the drop shape to obtain droplet parameters, as presented in Figure 5. The method of equivalent circle diameter was used to represent the particle sizes, which physically stands for the diameter of circles on the projection area. In this experiment, area was selected as the projection parameter, the projected area diameter could be estimated by Equation (3)[22]:

$$d_a = \sqrt{4A/\pi} \tag{3}$$

where, d_a is a single projected area diameter, mm; A is the projected area, mm^3.

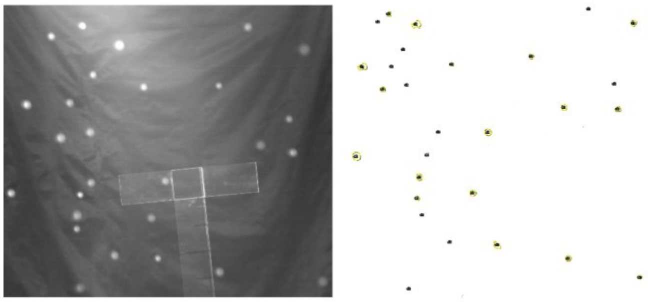


Figure 5 Contour extraction of droplets

3 Results and discussion

3.1 Measurement of flow rate and range

The flow rate and range of above five nozzles with different structural parameters were measured; the working pressures of sprinkler were set as 200 kPa, 250 kPa, 300 kPa, 350 kPa and 400 kPa. Measurement under each pressure was repeated three times, and the average value was calculated.

Table 3 presents the flows and ranges of PY_115 sprinkler under different pressures. As expected, the flows and ranges of the five nozzles increased with the increase of pressure. Under the same pressure and nozzle angle, the flow and range of sprinkler increased with the increase of jet outlet diameter; When the jet outlet diameter kept unchanged, the flow of sprinkler decreased and the range increased firstly and then drops with the angle of nozzle rose from 35° to 55°, which agreed well with the relationships between angle of nozzle and range presented by Zhao et al.[11] The sprinkler with type C nozzle had the biggest flow and range, which meant that the mass flow nozzle should be selected to ensure a long range for sprinkler.

Table 3 Flow and range of the $PY_1$15 sprinkler under different pressures

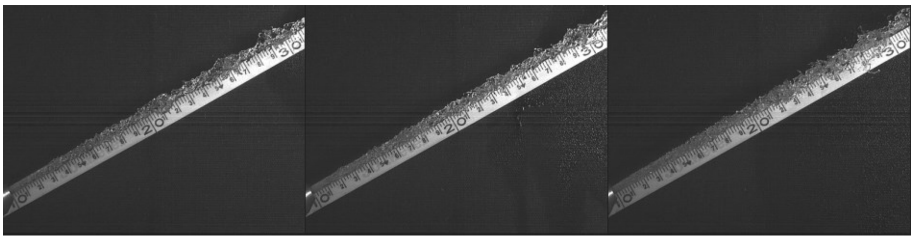
Nozzle type	Flow/$m^3 \cdot h^{-1}$					Range/m				
	200 kPa	250 kPa	300 kPa	350 kPa	400 kPa	200 kPa	250 kPa	300 kPa	350 kPa	400 kPa
A	0.804	0.898	0.984	1.068	1.148	14.9	16.1	16.9	17.5	17.6
B	1.192	1.350	1.507	1.618	1.732	16.1	17.2	18.0	18.5	19.7
C	1.792	1.971	2.201	2.383	2.554	16.8	18.3	19.9	20.8	21.5
D	1.290	1.430	1.572	1.724	1.847	15.9	17.0	17.9	18.5	19.0
E	1.140	1.301	1.415	1.529	1.635	14.1	16.8	17.6	18.2	18.8

3.2 Jet breakup characterization with different pressures and nozzle types

With the entrainment of air into the jets, the amount of liquid drops increase as the jet moves continuously, and as the jet boundary extends to the sides, flow friction increases. Due to the principle of mixture of jet and static flow, the jet starts to fracture and break up. In this research, the length from nozzle outlet to where the jet flow breakup the first time was defined as the jet breakup length.

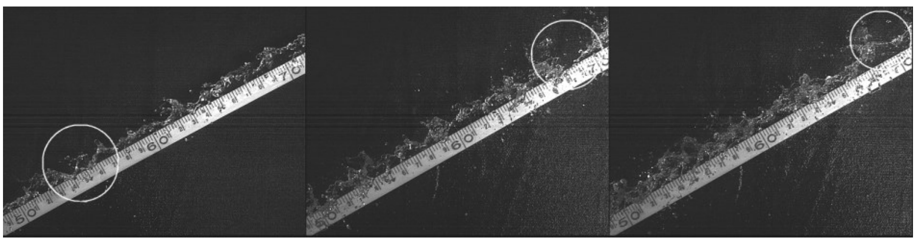
Different photographs were captured for this analysis. Figure 6 presents the breakup process of jet under different pressures with type B nozzle. In these figures, the jet direction is from left to right and the start measuring position of tape is 10 cm. The jet breakup sections were marked with white circles. With the increase of pressures, the jet breakup lengths increased. Analyzing from the aspect of force, the surface of jet became rough at the jet's initial section, where the surface waved frequency quickens but no droplet stripped from jet appeared. This is a result that the jet with its aerodynamic force is inadequate to overcome surface tension yet. When the jet flow comes to the breakup section, the air surface force to jet is bigger than surface tension to make the jet broken, and the droplets were observed.

Figure 7 presents the breakup process of jet under different nozzle parameters. Comparing the five different nozzles at the same pressure 300 kPa, the jet breakup length of sprinkler with type C nozzle was the largest and the length scope was 720-730 mm, while it was the shortest for type A nozzle, which conformed to the trend of ranges. Comparing the type B, type D and type E nozzles, the breakup length decreased with the increasing nozzle angle at the same pressure.



200 kPa 300 kPa 400 kPa

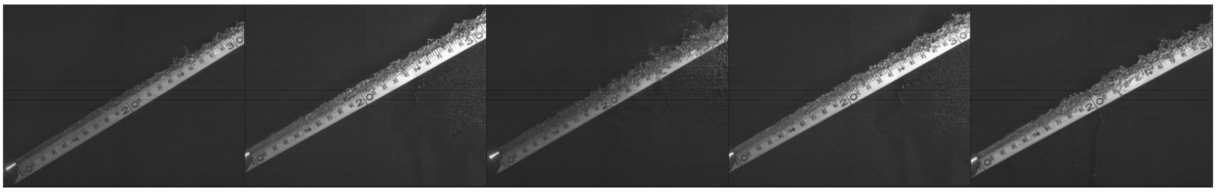
a. Jet initiation sections



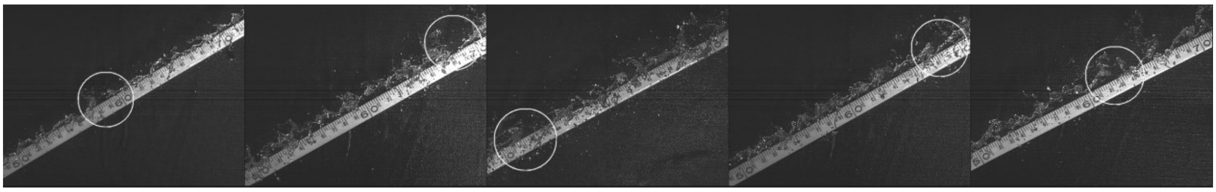
200 kPa 300 kPa 400 kPa

b. Jet breakup sections

Figure 6 Photographs of jet under different pressures with type B nozzle



a. Jet initiation sections



b. Jet breakup sections

Figure 7 Photographs of jet under different nozzle parameters under 300 kPa

3.3 Effect of *Re* and *We* on jet breakup length

Researches show that the factors which influence the jet breakup length are viscosity force, surface tension, gravity and inertia force[23]. The relative value of the factors can be characterized by non-dimensional numbers such as *Re* and *We*, using the following equations:

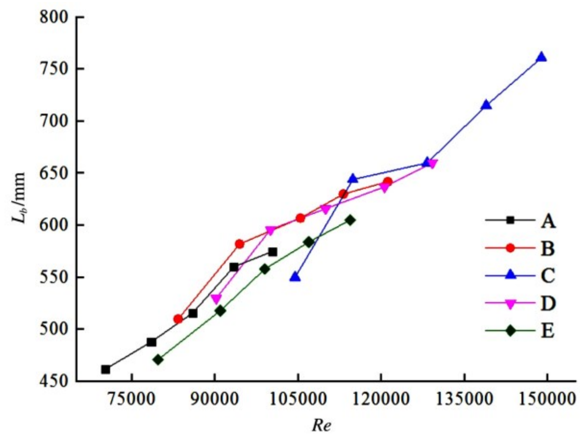
$$Re = \frac{\rho_l u_0 d_0}{\mu_l} \tag{4}$$

$$We = \frac{\rho_l u_0^2 d_0}{\sigma} \tag{5}$$

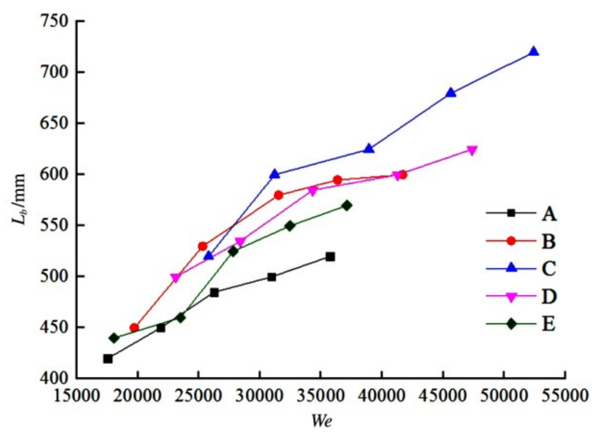
where, ρ_l is the liquid phase density, kg/m^3; u_0 is the liquid velocity, m/s; d_0 is the jet orifice diameter, m; μ_l is the viscosity of liquid, N·s/m^2; σ is the surface tension of liquid, N/m.

Because the gas-liquid density ratio remained unchanged, *Re* and *We* were considered only in the research of jet breakup.

Relationships between *Re*, *We* and jet breakup length are depicted in Figure 8, the jet breakup length is expressed as L_b. In order to measure the accurate lengths, at least 3 measurements were taken and took an average. The jet breakup lengths increase with the increase of *Re* and *We*. Analyzing from the aspect of *Re*, the flow is in the state of turbulence for a while with the increase of velocity, the jet breakup lengths increase due to the restraining of the propagation velocity of interference wave. Analyzing from the aspect of *We*, *We* represents the relationships between inertia force and surface tension of jet. Within the discussed working pressure range, the increase of *We* reflects the less overcome effect of inertia force on the surface tension of jet, and the jet breakup lengths increase. When the surface tension of jet keeps unchanged, L_b increases with the increase of flow velocity because the aerodynamic force is not able to overcome surface tension at a low flow velocity.



a. Variation of jet breakup length with *Re*



b. Variation of jet breakup length with *We*

Figure 8 Variation of jet breakup length with *Re* and *We*

The jet breakup length L_b of sprinkler is the longest with type C nozzle, and the shortest for type A nozzle. Comparing the sprinklers with type A, B and C nozzle with the same angle, L_b increases with the increase of outlet diameter. Comparing the sprinklers with type B, D and E nozzle with the same outlet diameter, L_b of sprinkler with type D nozzle is the longest, and the shortest for type E. Combined with Table 2, the L_b of sprinkler with type B nozzle is shorter and the atomization effect is the best, although the range of sprinkler with type B nozzle is the longest. Considering the range of synthesizes and the atomization effect, the sprinkler with type B nozzle would be an optimal choice.

3.4 Discussion on empirical formulas of jet breakup length

Considering the influence of *Re* and *We* to jet breakup from the aspect of stress in this research, the index equation of jet breakup length can be expressed as:

$$\frac{L_b}{D_1} = aRe^b We^c \tag{6}$$

where, a is a coefficient; b and c are indexes. The experimental parameter a, b and c varies with the changes of D_1, *Re* and *We*, and the values are shown in Table 4.

Table 4 Fitting parameters of sprinklers with different nozzles

Nozzle type	a	b	c
A	0.3947	0.4196	0.0926
B	0.2729	0.3119	0.2324
C	0.2073	0.2597	0.3008
D	0.4255	0.4473	0.1023
E	0.2669	0.3064	0.2372

Comparing the results with experimental data, the changing trend of jet breakup length could be reflected well by the fitted formulas with an accuracy error of less than 5%, as shown in Figure 9.

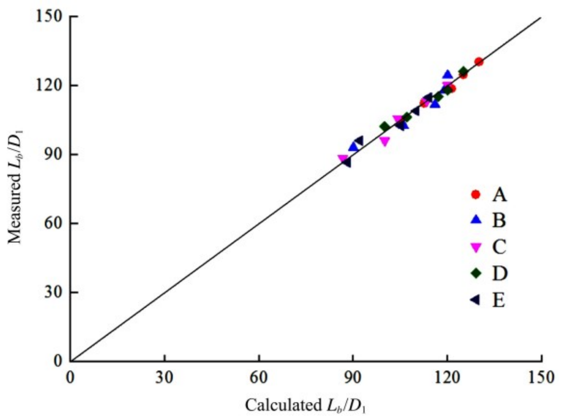


Figure 9 Comparison of measured L_b/D_1 to predicted results

From the formulas, we can find that viscous force and inertial force have a stronger effect on jet while the constant value in formulas reached 10^3 orders of magnitude, which means there are other parameters that have a great influence on jet, and this needs further research.

3.5 Validation of droplet diameter along the range

The droplet diameter is an important index parameter for the hydraulic performance of sprinklers[24]. The droplet diameter sizes of different nozzles and different distances from the sprinkler were measured by two methods: "P. M" (Photographic method) and "L. M" (Laser method), and the results of statistical analysis are presented in Tables 5 and 6.

As is shown in Table 5, the droplet diameters show a tendency of increasing along the range under the same pressure, and the droplet diameters increase with an increase in pressure at the same distance. The reason is that the breakup degree of jet is more intense with increasing distance from the sprinkler, and the droplets will generate from the surface to the core of jet, and becomes larger when it is closer to the core of jet. The measurement results of droplet diameter with laser method are larger than those with photographic method. That is because the droplets will overlap in the process of measuring with laser method, and the measured droplet diameters which are trapped by laser are larger. In the process of measuring with photographic method, the droplets will be targeted screened and the measured droplet diameters are smaller, with the relative errors of less than 10%.

As shown in Table 6, the sizes of droplet diameters in different range vary with different nozzles under the same pressure. In the vicinity of sprinkler (3-9 m), the droplet diameters of sprinkler with type B nozzle are larger; in a slightly distant area (12-18 m) from sprinkler, the droplet diameters of sprinkler with type A nozzle and type B nozzle are larger. This shows that the sprinkler with type B nozzle has a better droplet diameter distribution comparing with different types nozzle, which further reveals that the sprinkler with type B nozzle is the optimal choice.

Table 5 Droplet diameters of sprinklers with type B nozzle under different pressures Unit: mm

Distance/m	Pressure/kPa									
	200		250		300		350		400	
	P. M	L. M	P. M	L. M	P. M	L. M	P. M	L. M	P. M	L. M
3	0.41	0.43	0.39	0.42	0.35	0.41	0.32	0.41	0.30	0.34
6	0.89	0.94	0.80	0.91	0.75	0.78	0.72	0.74	0.60	0.63
9	1.79	1.82	1.65	1.73	1.45	1.50	1.41	1.49	1.18	1.24
12	3.65	3.69	3.27	3.35	2.21	2.39	1.95	2.03	1.64	1.64
15	3.97	4.01	3.88	3.97	3.42	3.51	2.75	2.93	2.01	2.19
18					4.02	4.15	3.91	3.99	3.15	3.33

Note: P. M: Photographic method, L. M: Laser method. The same below.

Table 6 Droplet diameters of sprinklers with different types nozzle under 300 kPa pressure Unit: mm

Distance/m	Nozzle type									
	A		B		C		D		E	
	P. M	L. M	P. M	L. M	P. M	L. M	P. M	L. M	P. M	L. M
3	0.33	0.39	0.35	0.41	0.33	0.38	0.30	0.40	0.26	0.35
6	0.71	0.79	0.75	0.78	0.58	0.69	0.60	0.66	0.48	0.59
9	1.23	1.43	1.45	1.50	1.17	1.25	1.17	1.25	1.11	1.17
12	2.16	2.35	2.21	2.39	2.76	2.98	1.83	1.92	1.92	2.03
15	3.41	3.50	3.42	3.51	3.55	3.62	2.86	2.94	3.01	3.07
18			4.02	4.15	3.81	3.90				

Note: The ranges of sprinklers with type A, type D and type E nozzle were less than 18 m, there was no droplet at that point.

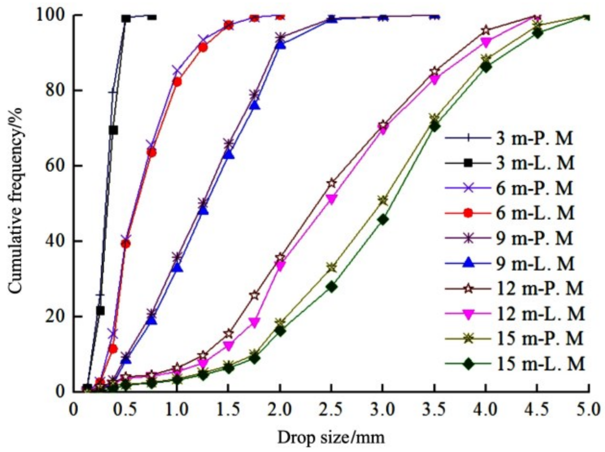
3.6 Weighted cumulative frequency of droplet diameter along the range

The weighted cumulative frequency means the cumulative value of specific gravity between the weighted which is less than one droplet diameter and the total weighted of spray. Figure 10 presents the weighted cumulative frequency of droplet diameters with different types of nozzle under the pressure of 300 kPa. As shown below, the weighted cumulative frequency of droplet diameters with different types of nozzle are different by different measuring methods. With an increase in distance, the weighted cumulative frequency which is less than one droplet diameter will decrease, and the slope of weighted cumulative frequency decreases with the increase of range distance. Meanwhile, the slopes of weighted cumulative frequency measured by the photographic method are smaller than the measurement slopes with laser method, which also indicates that the measurement results of droplet diameter with photographic method are smaller than those with laser method. At the same time, it is seen that the slope of weighted cumulative frequency of droplet diameters with type B nozzle and type C nozzle are much larger far from the sprinkler, which indicates the droplet diameters are much larger far from the sprinkler with the same conclusion as shown Table 5.

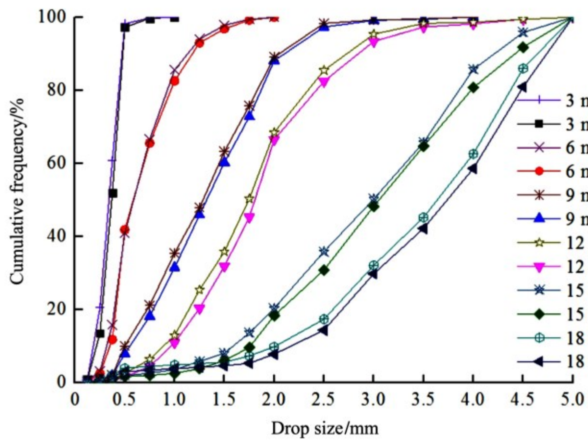
3.7 Measurement of end droplet diameters and regression analysis

The droplet diameter increases along the range of radial direction when the sprinkler is working, and the water drops with maximum diameter at the terminal position.

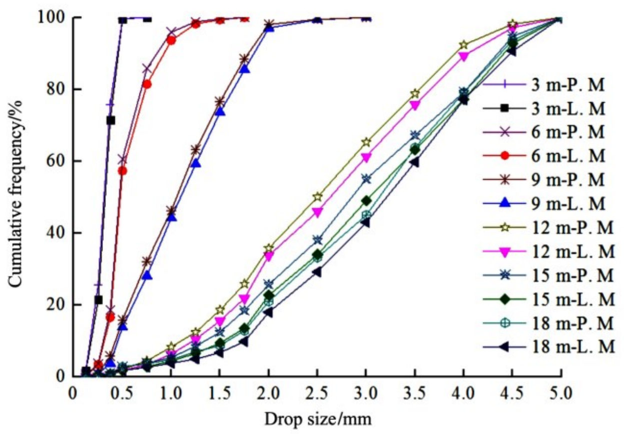
End droplet diameters for the $PY_1$15 sprinkler under different pressures are presented in Table 7. With an increase in pressure, the end droplet diameter of five nozzles decreases, which proves that the atomization effect of jet would be better when the pressure increases. When comparing different measuring methods, the measured end droplet diameters with photographic method are smaller than those with laser method, with the maximum error of less than 7% and comparing the five types of nozzle, when the pressure and angle of nozzle keep unchanged, the end droplet diameter increases with an increase of outlet diameter. When the outlet diameter of nozzle keeps unchanged, the end droplet diameter increases firstly and then drops with the increase of angle of nozzle, which shows that the change of outlet diameter and angle of nozzles have an impact on the end droplet diameter of sprinklers, and the atomization effect of jet is best with the type A nozzle, which is consistent with the trend of core length and breakup length.



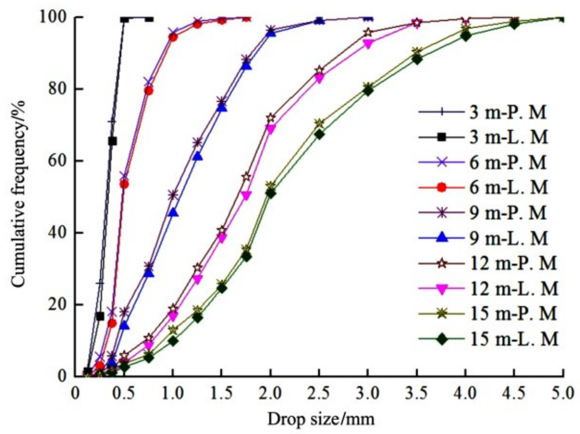
a. Type A nozzle



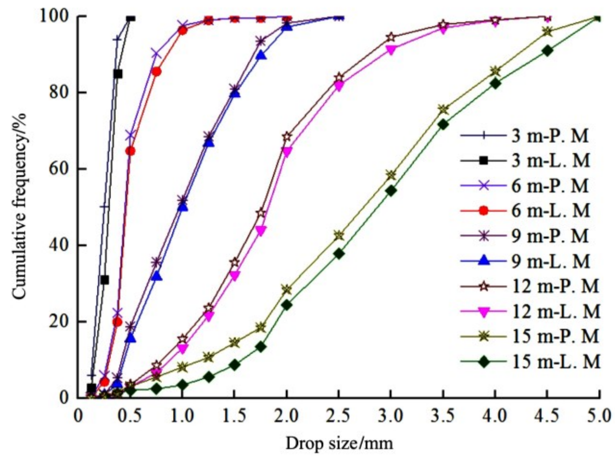
b. Type B nozzle



c. Type C nozzle



d. Type D nozzle



e. Type E nozzle

Figure 10 Cumulative frequency of droplet diameter with different types of nozzles under different methods

Table 7 End droplet diameters of the sprinkler under different pressures Unit: mm

Nozzle type	Nozzle type									
	200		250		300		350		400	
	P. M	L. M	P. M	L. M	P. M	L. M	P. M	L. M	P. M	L. M
A	4.01	4.18	3.99	4.11	3.87	4.05	3.72	3.99	3.64	3.84
B	4.11	4.21	4.08	4.19	4.03	4.15	3.98	4.09	3.89	3.99
C	4.19	4.25	4.15	4.19	4.09	4.13	3.99	4.09	3.91	4.01
D	4.05	4.15	4.01	4.12	3.98	4.08	3.88	4.01	3.75	3.92
E	4.08	4.20	4.05	4.16	4.01	4.11	3.95	4.07	3.83	3.97

Research on the variation trend of droplet diameter was carried out by using the linear theory, and the experimental correlation of droplet diameters was concluded as Equation (7). Comparing the results with experimental data, the accuracy error was less than 4% and the analysis of droplet diameters was accurate. According to this equation, the shrinking entrance diameter of nozzle and working pressure have influences on end droplet diameter of sprinklers, and the changing trend is presented as a nonlinear equation.

$$d = 3.8791 D_2^{0.2395} p^{-0.1028} \tag{7}$$

where, d is the drop diameter, mm; D_2 is the shrinking entrance diameter of nozzle, mm; p refers to working pressure, kPa.

4 Conclusions

The jet breakup length was defined and the influences of nozzle geometric parameters and injection pressure on jet breakup characteristics were analyzed in this research. Besides, the sizes of droplet diameter with different nozzles and different working pressures along the range were measured. The conclusions include:

(1) Comparing five nozzles with different parameters, the flow and range of five nozzles increased with an increasing pressure. The range of sprinkler increases with the increasing jet outlet diameter when the angle of nozzle remains unchanged.

(2) Sprinkler type B was the optimal choice. With the increase of *Re* and *We*, the jet breakup length increased for all types of nozzles. For the sprinklers with the same angle, the jet breakup length increased with the increase of outlet diameter. For the sprinklers with the same outlet diameter, the jet breakup length decreased with the increase of angle. Also the equivalent circle diameter proved that the type B nozzle had a better droplet diameter distribution.

(3) With the increase of distance, the weighted cumulative frequency which is less than one droplet diameter decreased, the slope of weighted cumulative frequency increased with the increase of range distance and had a maximum value with type B nozzle and type C nozzle far from the sprinkler. Meanwhile, the slopes of weighted cumulative frequency measured by the photographic method were smaller than the measured slopes with laser method.

(4) The fitting relationship of jet breakup lengths with *Re* and *We* and the regression equation of the end droplet diameters were obtained. Comparing results with experimental data, the changing trends were accurately similar, and the accuracy errors were less than 5% and 4%, respectively.

Additional works are arranged to compare the high-speed photography (HSP) technique with numerical simulation method to investigate the jet core length and changes of jet velocity in three dimensional flow fields.

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