

Comparison of droplet distributions from fluidic and impact sprinklers

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Abstract To adapt to the trend toward low-energy precision irrigation, the droplet distributions for two new prototype sprinklers, outside signal sprinkler (OS) and fluidic sprinkler (FS), were compared with impact sprinkler (IS). A laser precipitation monitor was used to measure the droplet distributions. Droplet size and velocity distributions were tested under four operating pressures for nozzles 1.5 m above the ground. For the operating pressures tested, the mean OS, FS and IS droplet diameters ranged from 0 to 3.4, 0 to 3.5, 0 to 4.0 mm, respectively. The mean OS and FS droplet velocities ranged from 0 to $6.3 \text{ m} \cdot \text{s}^{-1}$, whereas IS ranged from 0 to $6.3 \text{ m} \cdot \text{s}^{-1}$. Being gas-liquid fluidic sprinklers, droplet distributions of the OS and FS were similar, although not identical. IS mostly produced a 0.5 mm larger droplet diameter and a $0.5 \text{ m} \cdot \text{s}^{-1}$ greater velocity than OS and FS. A new empirical equation is proposed for determination of droplet size for OS and FS, which is sufficiently accurate and simple to use. Basic statistics for droplet size and velocity were performed on data obtained by the photographic methods. The mean droplet diameter (arithmetic, volumetric and median) decreased and the mean velocity increased in operating pressure for the three types of sprinkler.

Keywords outside signal sprinkler, fluidic sprinkler, impact sprinkler, sprinkler irrigation, droplet size, droplet velocity

1 Introduction

Sprinkler irrigation can be defined as any irrigation system which distributes water as discrete droplets through the air. A water droplet may be considered as symmetric with

respect to its axis of motions. In the absence of the wind, a droplet has a vertical trajectory. Two forces act upon a droplet in the air: (1) resistance, which opposes the relative movement of the droplet in the air and (2) gravity, which is in the vertical direction^[1,2]. The effect of resistance is to reduce the absolute magnitude of both velocity components. The effect of gravity is to increase the absolute magnitude of the vertical component when the droplet has a downward component and to decrease it when the drop has an upward component. Hence it follows that acceleration of a droplet is impossible as long as it has an upward velocity component. Acceleration of a droplet can never be followed by deceleration. Additionally, smaller droplets concentrate in the vicinity of the sprinkler and larger droplets always appear at the edge of the wetted radius. Accurate knowledge of droplet distribution for sprinklers is important. First, smaller droplets are subject to wind drift, distorting the application pattern. Second, larger droplets possess greater kinetic energy which is transferred to the soil surface causing particle dislodgement and ponding that may result in surface crusting and run-off^[3–6]. Thus, such information can be of practical importance in the design of sprinkler irrigation systems. Several articles have been published describing the droplet size distributions of specific types of sprinklers^[7–10]. Several models of sprinkler droplet flight trajectory have been developed in recent decades^[11–17] to investigate and predict sprinkler operating droplet characteristics. As reported by Hills and Gu, the effect of pressure on droplet diameter was more evident at large distances from the sprinkler^[18]. The process of jet break-up into droplets is quite complex. At least two phases can be distinguished. In the first (no more than 1 or 2 m), the jet is quite compact, and in the second, the jet has nearly completely disintegrated, with a corresponding transitional phase^[19].

Sprinkler irrigation systems operated at lower pressure have received attention in recent years because the energy loss increases. Today, the impact sprinkler is widely

Received February 3, 2015; accepted March 21, 2015

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used around the world^[20]. Two new prototype sprinklers, which were being adopted in the move toward low energy precision irrigation, may soon replace impact sprinkler^[21–24]. Dwomoh et al. have experimentally determined the droplet size distribution characteristics of one new type of sprinkler, complete fluidic sprinkler^[25]. Zhu et al. compared the mean droplet diameter of different types of fluidic sprinkler^[26]. However, information comparing droplet size and velocity distributions is still limited, and there have been only a few published reports. Three types of sprinkler, namely outside signal sprinkler (OS), fluidic sprinkler (FS) and impact sprinkler (IS), were compared in this study at different operating pressures. The aims of this study were to: (1) compare the three sprinkler types for droplet size and velocity distributions, and (2) develop a simple mathematical model to represent droplet distributions for OS and FS.

2 Materials and methods

2.1 Sprinklers

Three types of sprinkler head were specially fabricated for this study. OS and FS head designs were developed by the Research Center of Fluid Machinery Engineering and Technology (Jiangsu University, Zhenjiang, China). OS heads were specifically manufactured by mechanical machining as an experimental sample. FS heads were manufactured by Shanghai Watex Water-economizer Technology Co, Ltd., China. IS heads were from the Nelson Irrigation Co. Walla Walla, Washington, USA. The main differences among OS, FS, and IS were the nozzles: OS were equipped with 4.57 mm ellipse type nozzles (equivalent diameter), FS with 4.58 mm waist type nozzles, and IS with 4 mm circular nozzles. Additionally, the sprinkler jet formed 27°, 22°, 23° angles (with respect to the horizon) for OS, FS and IS, respectively. The OS and FS are gas-liquid fluidic sprinklers, whose driving moment is achieved by the flow reaction^[21–24].

2.2 Experimental design and procedure

The sprinklers were mounted on 1.5 m risers at 90° to the horizon. Four operating pressures were tested: 200, 250, 300 and 350 kPa, all within the manufacturer's recommendations. Droplet sizes and velocities from the sprinklers were measured using a Thies Clima laser precipitation monitor (LPM) (Adolf Thies GmbH & Co. KG, Goettingen, Germany). The schematic diagram of experimental apparatus is shown in Fig. 1. Figure 2 shows the nominal measuring area of the laser beam. The wavelength of the laser diode was 785 nm and the droplet size and velocity measurement ranged from 0.16 to 8.00 mm and 0.20 to 20.00 m·s⁻¹, respectively. The sprinkler

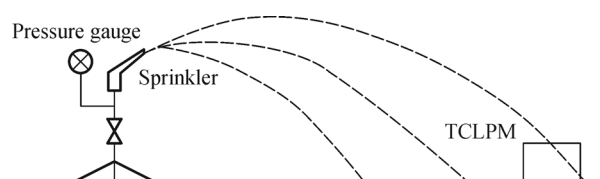


Fig. 1 Schematic diagram of experimental apparatus

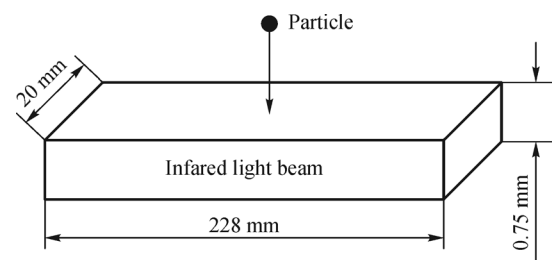


Fig. 2 Nominal measuring area of the laser beam

was allowed to rotate over the LPM at least five times to ensure a sufficient number of droplets passed through the measuring area. When a water droplet falls through the measuring area, the transmitted signal is reduced. The diameter of the droplet is calculated from the amplitude of the signal's reduction, and velocity from its duration. In this study, droplet velocity measurements were collected at the edge of a wetted radius. The LPM was angled to allow the droplet to pass through the laser beam approximately normal to its face. The following standards were adopted in the design of the experimental setup and in the experiment itself: ASAE S.330.1 (1985), ASAE S.398.1 (1985) and ISO 7749-2 (1990), MOD GB/T 19795.2 (2005)^[27–29]. A minimum of three replications assessments were made for each pressure and data were averaged for use as the final experimental data.

2.3 Droplet characterization experiments

Different experimental methods for evaluating droplet characteristics have been reported in the literature^[30–32]. The experiment was designed to characterize droplets from distances at the end of a wetted radius of the sprinklers at the four experimental pressures. At the observation point, droplets were characterized using the photographic method^[33]. Specific details of the experimental methods were as described by King et al.^[34]. The main problem with the laser method is that multiple drops, simultaneously moving through the laser beam, produce overlapped images which appear as a larger drops, causing overestimation of droplet sizes^[35]. However, this problem was greatly reduced by the computer estimation of droplet velocity and subsequent rejection of droplets whose

velocities were not consistent with the size class^[36], thus reducing the probability of overlapped droplet images.

2.4 Basic droplet statistics: centrality and dispersion

Managing the large data sets obtained from the photographic detection required a statistical approach. While it is convenient to represent the sets by a reduced number of parameters, some traits of the droplet populations can be obscured by the choice of statistical parameters. The parameters for droplet diameter used in this work included the arithmetic mean diameter (\bar{d} , mm), the volumetric mean diameter (d_V , mm)^[37], the median diameter (d_{50} , mm), the standard deviation (SD_D , mm) and the coefficient of variation (CV_D , %). They were determined by the equations:

$$\bar{d} = \frac{\sum_{i=1}^n m_i d_i}{\sum_{i=1}^n m_i} \quad (1)$$

$$d_V = \frac{\sum_{i=1}^n d_i^4}{\sum_{i=1}^n d_i^3} \quad (2)$$

$$SD_D = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (d_i - \bar{d})^2} \quad (3)$$

$$CV_D = \left(\frac{SD_D}{\bar{d}} \right) \times 100\% \quad (4)$$

where d_i is the diameter of each droplet in the set (mm), m_i is the droplet numbers of diameter d_i , and i is the number of droplets in the set (an ordinal number from 1 to n). Parameter \bar{d} corresponds to the arithmetic mean droplet

diameter. Parameter d_V corresponds to the volume-weighted average droplet diameter. Parameter d_{50} can be obtained by sorting all droplets in the set by diameter and selecting the droplet diameter that represents 50% of the cumulative droplet frequency.

The arithmetic mean, standard deviation, and coefficient of variation were also used for droplet velocity (\bar{V} and SD_V , $\text{m} \cdot \text{s}^{-1}$; CV_V , %).

3 Results and discussion

Regarding the results of this study it should be noted that operating conditions were controlled but differed slightly between each measurement (in particular, operating pressures varied slightly) and the number of droplets measured on each occasion was different.

3.1 Droplet size distributions

In this study, results using the photographic method were obtained at the edge of the wetted radius. The cumulative droplet diameter frequencies as a function of droplet diameter for the three sprinklers are shown in Fig. 3. Recently, King et al. and Salvador et al. presented cumulative frequency charts and histograms based on photographic methods^[33,34]. These frequency charts describe the distribution of droplet diameters at each observation point. Both authors reported a large variability in droplet diameters, with trajectories similar to those reported in this article.

As seen in Fig. 3, droplets had a wide range of diameters. The observation that very small droplets were found at the edge of a wetted radius supports the idea that not all droplets are formed at the nozzle. The mean OS droplet diameters varied from 0 to 3.4 mm. As a consequence, droplets under 1 mm had cumulative frequencies of 87%, 79%, 75% and 70%, under 2 mm of 94%, 93%, 95% and 96%, under 3 mm of 100%, 99%, 99%, and 100% at pressures of 200, 250, 300 and 350 kPa, respectively.

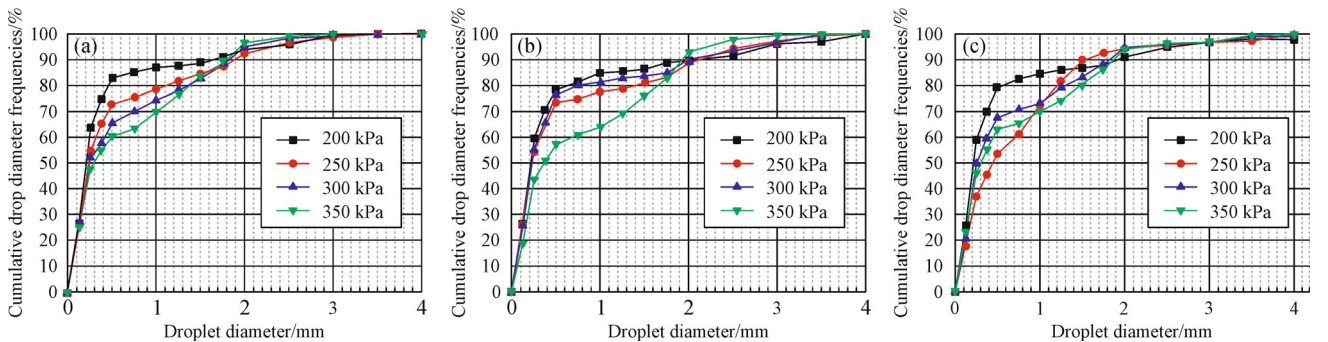


Fig. 3 Measured droplet size distributions for each operating pressure. (a) OS (outside signal sprinkler); (b) FS (fluidic sprinkler); (c) IS (impact sprinkler).

The mean FS droplet diameters varied from 0 to 3.5 mm. As a consequence, droplets under 1 mm had cumulative frequencies of 85%, 78%, 81% and 64%, under 2 mm of 90%, 89%, 90% and 93%, under 3 mm of 96%, 97%, 97% and 99% at pressures of 200, 250, 300 and 350 kPa, respectively. The mean IS droplet diameters varied from 0 to 4.0 mm. As a consequence, droplets under 1 mm had cumulative frequencies of 84%, 72%, 73% and 70%, under 2 mm of 91%, 94%, 94% and 94%, under 3 mm of 97%, 97%, 96% and 97% for a pressure of 200, 250, 300 and 350 kPa, respectively.

A summary of droplet sizes for 10%, 25%, 50%, 75% and 90% of the three sprinklers are given in Table 1.

The comparison of droplet size distribution from the three types of sprinkler shows that OS and FS were similar to each other, as was expected given both are the gas-liquid fluidic sprinklers. Of the three sprinklers, OS had the narrowest droplet size range and the smallest maximum droplet diameter (about 3.4 mm), and IS had the widest droplet size range with a maximum value of about 4.0 mm. IS also had an approximately 0.5 mm larger droplet diameter than OS and FS. A new empirical droplet size equation for OS and FS was developed:

$$CF = 15.7 \ln(d_i) + 75.3 \quad (5)$$

where CF is cumulative droplet diameter frequency, d_i is droplet diameter.

Overall, the expected values generated by this equation showed little deviation from the observed values overall. The average square of the correlation coefficient were 94% and 95% for OS and FS, respectively. The proposed equation is considered to be sufficiently accurate and simple for practical use for OS and FS.

3.2 Droplet velocity distributions

The relationship between velocity and distance was previously analyzed by Salvador et al. using the photo-

graphic method^[33]. These authors reported velocities of 4 to 6 m·s⁻¹ for distances exceeding 10 m. Figure 4 shows the frequency distribution of droplet velocities for the three sprinklers at operating pressures of 200, 250, 300 and 350 kPa.

It is apparent that for various operating pressures, the mean OS droplet velocities ranged from 0 to 6.3 m·s⁻¹. As a consequence, droplets under 1 m·s⁻¹ had a frequency of 27%, 23%, 20% and 18%, under 3 m·s⁻¹ of 4%, 6%, 8% and 9%, under 5 m·s⁻¹ of 4%, 2%, 3% and 6% for a pressure of 200, 250, 300 and 350 kPa, respectively. The mean FS droplet velocities ranged from 0 to 6.3 m·s⁻¹. Droplets under 1 m·s⁻¹ had a frequency of 24%, 22%, 21% and 16%, under 3 m·s⁻¹ of 5%, 6%, 5% and 8%, under 5 m·s⁻¹ of 4%, 3%, 4% and 5% for a pressure of 200, 250, 300 and 350 kPa, respectively. The mean IS droplet velocities ranged from 0 to 6.8 m·s⁻¹. Droplets under 1 m·s⁻¹ had a frequency of 23%, 17%, 17% and 21%, under 3 m·s⁻¹ of 5%, 6%, 6% and 5%, under 5 m·s⁻¹ of 3%, 3%, 2% and 3% for a pressure of 200, 250, 300 and 350 kPa, respectively.

This comparison shows that the maximum frequency value was obtained at velocities of 1 m·s⁻¹ for each combination. Velocities for OS and FS droplets were similar but not identical. Overall, IS tends to give greater velocities than OS or FS.

3.3 Droplet characterization: basic statistics

Table 2 show a number of statistical parameters for droplet diameter and velocity obtained for the three sprinklers at four operating pressures. Parameters include the arithmetic mean, standard deviation, coefficient of variation (for diameter, and velocity), the volumetric mean diameter, and the median diameter.

The mean droplet diameter (arithmetic, volumetric, and median) decreased and the mean velocity increased with an increase in operating pressure for all these three sprinklers.

Table 1 Droplet sizes (mm) for 10, 25, 50, 75 and 90% (d_{10} , d_{25} , d_{50} , d_{75} , and d_{90} , respectively) of three types of sprinkler

Sprinkler type	Operating pressure/kPa	d_{10}	d_{25}	d_{50}	d_{75}	d_{90}
OS	200	0.04	0.11	0.24	0.37	1.69
	250	0.04	0.12	0.23	0.69	1.88
	300	0.05	0.13	0.23	1.02	1.82
	350	0.05	0.14	0.21	1.18	1.78
FS	200	0.04	0.12	0.37	0.44	2.05
	250	0.05	0.13	0.24	0.77	2.10
	300	0.05	0.13	0.23	0.48	2.02
	350	0.07	0.16	0.22	1.47	1.93
IS	200	0.05	0.12	0.44	0.44	1.92
	250	0.07	0.17	0.31	1.07	1.53
	300	0.06	0.14	0.25	1.07	1.82
	350	0.06	0.13	0.23	1.28	1.84

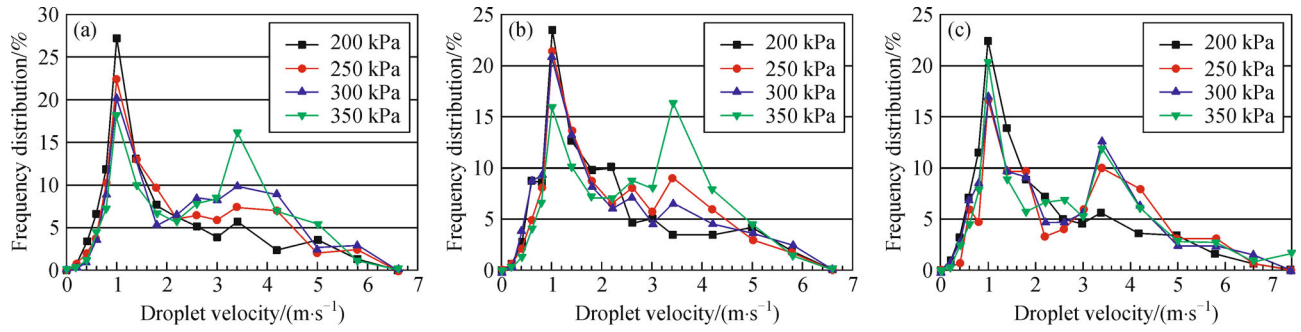


Fig. 4 Droplet velocity frequency distribution for each operating pressure. (a) OS (outside signal sprinkler); (b) FS (fluidic sprinkler); (c) IS (impact sprinkler).

Table 2 Statistical parameters for droplet diameter, and velocity obtained for different operating pressures

Sprinkler		OS (outside signal sprinkler)				FS (fluidic sprinkler)				IS (impact sprinkler)			
Operation pressure/kPa		200	250	300	350	200	250	300	350	200	250	300	350
Diameter/mm	\bar{d}	0.84	0.75	0.67	0.56	0.89	0.76	0.70	0.68	0.78	0.76	0.73	0.64
	d_V	2.70	2.24	2.21	2.18	2.78	2.74	2.16	1.48	2.99	2.39	2.21	1.92
	d_{50}	0.24	0.23	0.23	0.21	0.37	0.24	0.23	0.22	0.44	0.31	0.25	0.23
	SD_D	0.87	0.67	0.75	0.81	1.01	0.99	0.94	0.85	0.92	0.63	0.77	0.77
	CV_D	104	89	112	145	113	130	134	125	118	83	105	120
Velocity/(m·s ⁻¹)	\bar{v}	1.79	2.00	2.21	2.31	1.87	1.92	2.01	2.35	1.83	2.34	2.50	2.64
	SD_V	1.41	1.34	1.36	1.36	1.47	1.29	1.43	1.33	1.35	1.31	2.10	2.25
	CV_V	78	67	62	59	79	67	71	57	74	56	84	85

For OS, the standard deviation of droplet diameter ranged from 0.67 to 0.87, with a mean of 0.78; the coefficients of diameter variation ranged from 89 to 145, with a mean of 112; the standard deviation of velocity ranged from 1.36 to 1.41, with a mean of 1.37; the coefficients of velocity variation ranged from 59 to 78, with a mean of 66. For FS, the standard deviation of droplet diameter ranged from 0.85 to 1.01, with a mean of 0.95; the coefficients of diameter variation ranged from 113 to 134, with a mean of 126; the standard deviation of velocity ranged from 1.29 to 1.47, with a mean of 1.38; the coefficients of velocity variation ranged from 57 to 79, with a mean of 68. For IS, the standard deviation of droplet diameter ranged from 0.63 to 0.92, with a mean of 0.77; the coefficients of diameter variation ranged from 83 to 120, with a mean of 107; the standard deviation of velocity ranged from 1.31 to 2.25, with a mean of 1.75; the coefficients of velocity variation ranged from 56 to 85, with a mean of 75.

4 Conclusions

The comparison of the droplet distributions for three types of sprinklers lead to the following important conclusions and outcomes:

(1) OS and FS droplet sizes and velocities were similar but not identical, because both are gas-liquid fluidic sprinklers. IS tends to give a 0.5 mm larger droplet diameter and 0.5 m·s⁻¹ greater velocities than OS and FS.

(2) The mean droplet diameter (arithmetic, volumetric, and median) decreased and the mean velocity increased in operating pressure for all three sprinklers.

(3) An new empirical equation (Eq. 5) for droplet size of the OS and the FS has been proposed. This equation provides sufficient accuracy and simplicity for routine application for OS and FS.

Acknowledgements This work was supported by grants from the Program for National Hi-Tech Research and Development of China (2011AA100506), the National Natural Science Foundation of China (51309117), and the Six Talent Peaks Project in Jiangsu Province (ZBZZ-018).

Compliance with ethics guidelines Xingye Zhu, Shouqi Yuan, Junping Liu and Xingfa Liu declare that they have no conflict of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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