

IMPROVING THE WATER DISTRIBUTION UNIFORMITY BY INVESTIGATING THE HYDRAULIC PERFORMANCE OF BIG GUN SPRINKLER

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ABSTRACT

The hydraulic performance of sprinkler equipment largely determines the quality of the irrigation. Big gun sprinklers are one of the most useful rotating sprinklers, and the most widely used globally. The large areas covered by big gun sprinklers result in fewer sprinklers and less pipes required per unit area. Relevant factors of big gun sprinkler affecting the irrigation performance are the nozzle diameter, operating pressure, layout form, and overlapping distance which were studied under no wind condition. The discharge coefficient ranged from 0.96 to 0.99. A mathematical model of radius of throw was also regressed and the coefficient of determination was found as 0.9765. The application rate was lower near the sprinkler, and a peak value occurred under the radius of throw from 4 to 6 m for each water distribution pattern. The average application rate decreased with increase of operating pressure. The average application rate increased with the increase of nozzle diameter. The increase or decrease in magnitude of average application rate under small nozzle diameter was larger than large nozzle diameter sprinklers within the same range of variation in operating pressure. The maximum Christiansen's uniformity (CU) values increased with the increase in operating pressure under different nozzle diameter or different layout. Equilateral triangle layout achieved higher uniformity compared with square layout. The optimal CU values and spacing coefficients of the big gun sprinkler with different layout forms, operating pressure and nozzle diameter were proposed.

Keywords: Sprinkler irrigation, Hydraulic performance, Water distribution uniformity, layout.

1. INTRODUCTION

Sprinkler irrigation system has been widely employed due to the operational simplicity that this irrigation method offers. Additionally, it provides good water distribution uniformity, precise control of application depth, high application efficiency and adaptable to different soils and topography (Louie & Selker, 2000; Zhu et al., 2012).

One of the key components of a sprinkler irrigation system is the sprinkler. Its purpose is to distribute water over an area so that the appropriate amount of water is applied at all locations. It is therefore important to know and understand the expectation from any irrigation sprinkler and what the designer's plan of use. Some general characteristics that should be understood include sprinkler discharge, radius of throw, water distribution pattern and application rate. For combination application, positioning sprinkler is one of the important decisions to design an irrigation system. A poor design will likely result in uneven water distribution with more water in some places than others. There are two basic choices in positioning sprinkler, triangular and square spacing. Water application uniformity is influenced by several factors which may be controlled or uncontrolled by the operator. The factors that can be controlled by the operator include: i) geometric shape of radial leg, which depends on

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the kind of sprinkler, nozzle diameter, operating pressure and trajectory angle; ii) sprinkler layout forms (rectangular and triangular); and iii) overlapping distance) (Keller & Bliesner, 1990). However, wind (speed and direction) cannot be controlled by the operator (Seginer et al., 1992; Montero et al., 2001).

Furthermore, water distribution uniformity is an important performance characteristic and the most relevant parameter of the sprinkler irrigation system. Undeniably, the parameter affects on important aspects such as water use efficiency, leaching of fertilizers and crop yield (Seginer et al., 1991). Non-uniform water distribution does not only leave parts of the crop field deficiency of water, also could result to over irrigation which causes ponding, plant damage, soil salinization and leaching of nutrients from the soil (Silva, 2006; Mateos, 2006). Increasing water application uniformity can improve irrigation efficiency by preventing deep percolation and surface runoff due to over irrigation (Faci et al., 2001).

A great deal of research has been conducted on the effects of operating pressure, nozzle diameter and layout form on hydraulic performance and water uniformity for small or medium size sprinkler (Mateos, 1998; Liu et al., 2013; Burillo et al., 2013). Canessa et al. (1994) described that a correct over-lap is the result of a correct combination of sprinkler spacing, pressure and nozzle diameter. Burt et al. (1997) indicated that the most influential factors of heterogeneity in water distribution are operating pressure variation at the hydrant, sprinkler design and sprinkler layout. Low values of CU are usually indicators of a faulty combination of nozzle diameter, operating pressure and sprinkler spacing (Tarjuelo et al., 1999; Zhang et al., 2013). Salmeron et al. (2012) illustrated that low values of CU indicate poor combination of nozzle size, operating pressure, and other design factors.

Sprinkler irrigation with big gun sprinkler is widely used in the world as it allows for the efficient watering of middle-scale fields at relatively low cost (Pascal et al., 2006; Osman et al., 2014). The large throw diameters of big gun sprinkler result in fewer sprinklers and less pipe per field. The big gun sprinkler is also used around the world for open area fire protection systems, such as fire protection for private estates, forest areas, archaeological sites, industrial sites, and recreational areas. But, few people have studied the hydraulic performance and optimal layout of big gun sprinkler. So, based on the previous studies, the objectives of this paper are: (1) to characterize flow rate and radius of throw on different operating pressures and nozzle diameters on big gun sprinkler and to propose predictive equations to estimate flow rate and radius of throw using multiple regression; (2) to analyze the water distribution pattern and average application rate; (3) to analyze the effect of operating pressure, nozzle diameter, layout form and overlapping distance on water uniformity; (4) to give some optimal values for sprinkler layout to help on design and manage in sprinkle irrigation system with big gun sprinkler.

2. MATERIALS AND METHODS

2.1 Sprinkler

The big gun sprinkler was selected for this study and it was from the Nelson Irrigation Co., Walla Walla, Washington, USA. Figure 1 presents the photograph of the big gun sprinkler. The inlet diameter of sprinkler is 38 mm, and the sprinkler jet forms a 24° angle with respect to the horizontal. The operating pressure range is from 300 kPa to 800 kPa. Circular nozzle with four different nozzle diameters (12.5, 15.1, 19 and 22.5 mm) was selected in this study.



Figure 1. Photographs of big gun sprinkler.

2.2 Experiment Set-Up

Performing experiments in an indoor facility ensures water distribution and avoids wind drift losses (Sourell et al., 2003; Dukes, 2006; Liu et al., 2016). In this work, an indoor experiment apparatus was set up in the experimental hall of the Research Centre of Fluid Machinery Engineering and Technology at Jiangsu University, China. A schematic of the sprinkler set-up is shown in Figure 2. A centrifugal pump supplied water to the irrigation system from a constant level reservoir. Discharge was measured by an electromagnetic flow meter with an accuracy tolerance of 0.5 %. Pressure was measured at the base of the sprinkler head using a pressure gauge with an accuracy tolerance of 0.4 %. The catch cans used in the study for testing radial water application were cylindrical in shape with a height of 0.6 m and an inside diameter of 0.2 m. Catch cans, which were used to collect water, were spaced at 1.0 m intervals from the sprinkler in one single collector lines. The water collected in each can was measured using a graduated cylinder. The application rate was calculated based on the diameter of the catch cans and the duration of each test. The radial application rate distributions for the sprinklers were obtained in the laboratory.

The big gun sprinkler was installed on a 1.5 m riser at a 90° angle to the horizontal and was placed approximately 0.9 m above the top of the catch cans. The following six operating pressures were tested for the big gun sprinkler: 300, 400, 500, 600, 700 and 800 kPa, respectively. The sprinkler was run for 20 minutes before performing the experiments in order to standardize environmental conditions. The following standards were adopted in the design of the experimental set-up and in the experiment itself: ASAE S.330.1 (1985), ASAE S.398.1 (1985) and MOD GB/T 19795.2 (2005). Three repetitions were made for every operating pressure. The volume of water in each catch can was determined as the average of catch cans and for three repetitions.

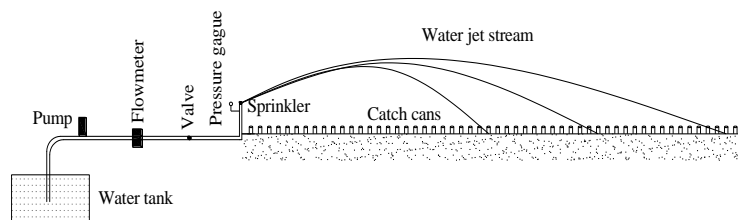


Figure 2. Schematic diagram of the experimental conditions in the laboratory.

2.3 Sprinkler Flow Rate

A relationship which is necessary for designing sprinkler irrigation system have been described between discharge and pressure for an orifice nozzle by y Li& Kawano (1998) as follows:

$$Q=cA(2gH)^x \quad (1)$$

Where: Q is nozzle discharge rate in $m^3 \cdot s^{-1}$; A is orifice cross-sectional area in m^2 ; g is gravitational acceleration in $m \cdot s^{-2}$ ($9.8m \cdot s^{-2}$); H is sprinkler pressure head in m ; c is discharge coefficient and x is the discharge exponent.

2.4 Christiansen's Uniformity Coefficient

Sprinkler irrigation uniformity coefficient mainly reflect the distribution of the water volume in the irrigation area of homogeneous degree, it has a decisive influence on the growth of crops, is one of the important indexes to measure quality of sprinkler irrigation. Christiansen's uniformity coefficient was defined to evaluate sprinkler irrigation systems and has the strongest historical precedent in the sprinkler irrigation industry (CHRISTIANSEN, 1942). Christiansen's equation is defined as:

$$CU = 100 \left[1.0 - \frac{\sum |x_i - x_m|}{\sum x_i} \right] \quad (3)$$

Where: CU is Christiansen's uniformity coefficient, %. x_i is measured depth (volume or mass) of water in equally spaced catch cans on a grid; x_m is mean depth (volume or mass) of water of the catch in all cans.

Matrix laboratory (MATLAB) was used as the computational program to calculate the combined CU values according to the radial application rate of water distribution. In this work, two common different layout forms were adopt to analysis the effects of different layout form and overlapping distance on CU values. Figure 3 presents the two different layout forms, one is square layout and the other is equilateral triangle layout. Spacing coefficient was defined as a parameter to describe the overlapping distance of two sprinklers for two different layout forms, and spacing coefficient was equal to the times of radius of throw. As can be seen from Fig. 3a, the relationship between overlapping distance and radius of throw can be presented as follow:

$$L = S_d \cdot R \quad (4)$$

Where, L is overlapping distance of two sprinklers in m , S_d is spacing coefficient, R is radius of throw in m . The maximum S_d can be achieved for square layout from Fig. 3a and the value was 1.41. In the same way, the maximum S_d can be achieved for equilateral triangle layout from Fig. 3b and the value was 1.73. When the spacing coefficient exceeded 1.41 with square or 1.73 with equilateral triangle layout respectively, some area could not be irrigated with the sprinkler. Therefore, five different spacing coefficients were selected for square layout, 1.0, 1.1, 1.2, 1.3 and 1.4. Eight different spacing coefficients (1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 and 1.7) were selected for equilateral triangle layout.

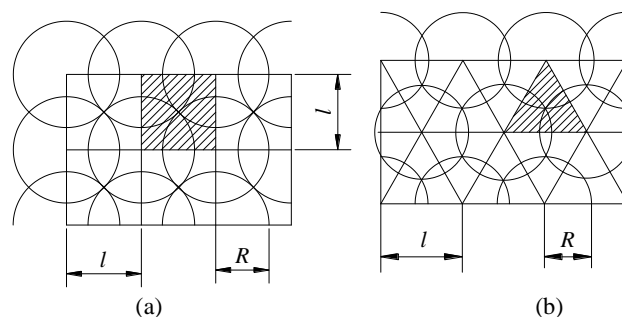


Figure 3. Two different layout forms of big gun sprinkler. (a) Square layout, (b) Equilateral triangle layout.

3. RESULTS AND DISCUSSION

3.1 Sprinkler Flow Rate

Figure 4 shows the results of flow rate under different operating pressures and nozzle diameters. The flow rate of the evaluated big gun sprinkler increased with operating pressure and nozzle diameter.

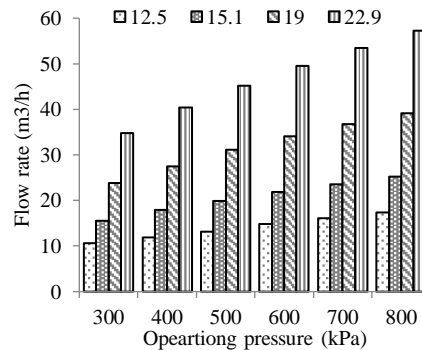


Figure 4. Flow rate of big gun sprinkler under different operating pressures and nozzle diameters.

With regard to the discharge equation (Eq. (1)), several studies applied to irrigation sprinklers interpreted that discharge exponent is essentially independent of operating pressure for a given nozzle diameter and that discharge exponent is constant and equal to 0.5 (Li, 1996; Li & Kawano, 1998; Tarjuelo et al., 1999). We also assumed discharge exponent to be equal to 0.5.

Table 1 shows a summary of the calculated results of the discharge coefficient under different operating pressures and nozzle diameters. The discharge coefficient ranged from 0.96 to 0.99, and it remained basically unchanged for the entire range of operating pressures with each nozzle diameter. Small differences were due to experimental error. This indicated that the discharge coefficient was independent of the operating pressure. The discharge coefficients that were showed in Table 1 and Eq. (1) allowed us to calculate flow rate for every operating pressure and nozzle diameter.

Table 1. Discharge coefficient under different operating pressures and nozzle diameters

Operating pressure (kPa)	Nozzle diameter (mm)			
	12.5	15.1	19	22.9
300	0.99	0.99	0.97	0.97
400	0.96	0.99	0.96	0.97
500	0.95	0.99	0.98	0.97
600	0.97	0.99	0.98	0.97
700	0.98	0.99	0.98	0.97
800	0.99	0.99	0.97	0.97

3.2 Radius of Throw

The relationship between radius of throw and operating pressures under different nozzle diameters is shown in figure 5. The results showed that there was a linear relationship between the radius of throw and operating pressures under the same nozzle diameter and the radius of throw increased with increase in operating pressure. Under the same operating pressure, the radius of throw increased with the increase of nozzle diameter. When the nozzle diameter was 12.5 mm, the radius of

throw was 27 m and 38 m at 300 kPa and 800 kPa, respectively, and the growth range was 11 mm. When the nozzle diameter was 22.9 mm, the radius of throw was 38 m and 52 m at 300 kPa and 800 kPa, respectively, and the growth range was 14 mm. This indicated that the growth range of radius of throw with larger nozzle diameter was bigger than smaller nozzle diameter when the same operating pressure was increased. A regress equation about the radius of throw and operating pressure and nozzle diameter was built by using the regression analysis, and the model was proposed as follow:

$$R=0.0164 \cdot p \cdot e^{0.0242d} + 15.534 \cdot \ln(d) - 18.861 \quad (5)$$

Where: R is radius of throw in m, p is operating pressure in kPa, d is nozzle diameter in mm, and the coefficient of determination is 0.9765.

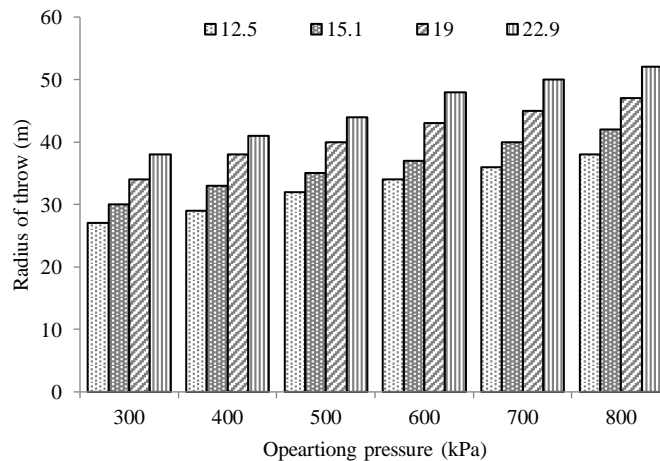


Figure 5. Radius of throw of big gun sprinkler under different operating pressures and nozzle diameters.

3.3 Sprinkler Water Distribution Pattern

Due to the shape of water distribution under different nozzle diameters versus the distance from sprinkler had the similar rule. Therefore, the water distribution patterns under the nozzle diameter were 12.5 mm were selected to analyze the effect of different operating pressure on water distribution pattern. A graphic representation of single-radius sprinkler water distribution patterns with the nozzle diameter was 12.5 mm obtained in tests is shown in figure 6. Comparing the six water distribution patterns, curves with triangular shape can be observed at the end of radius of throw. Also, it can be observed that the application rate was lower near the sprinkler (1–3 m) and a peak value of application rate occurred under the radius of throw from 4 to 6 m for each water distribution pattern. When the operating pressures (300, 400 and 500 kPa) were relatively lower, the application rates at the end of radius of throw declined dramatically. However, when the operation pressures (600, 700 and 800 kPa) were relatively higher, the application rates at the end of radius of throw declined gradually. Further, when the operating pressure exceeded 500 kPa, the application rate at the middle radius of throw had a good consistency and water distribution uniformity.

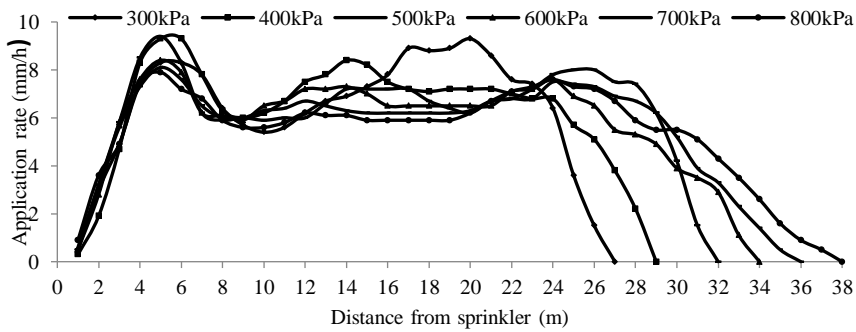


Figure 6. Water distribution patterns of the big gun sprinkler with the nozzle diameter 12.5 mm under different operation pressures (300, 400, 500, 600, 700 and 800 kPa).

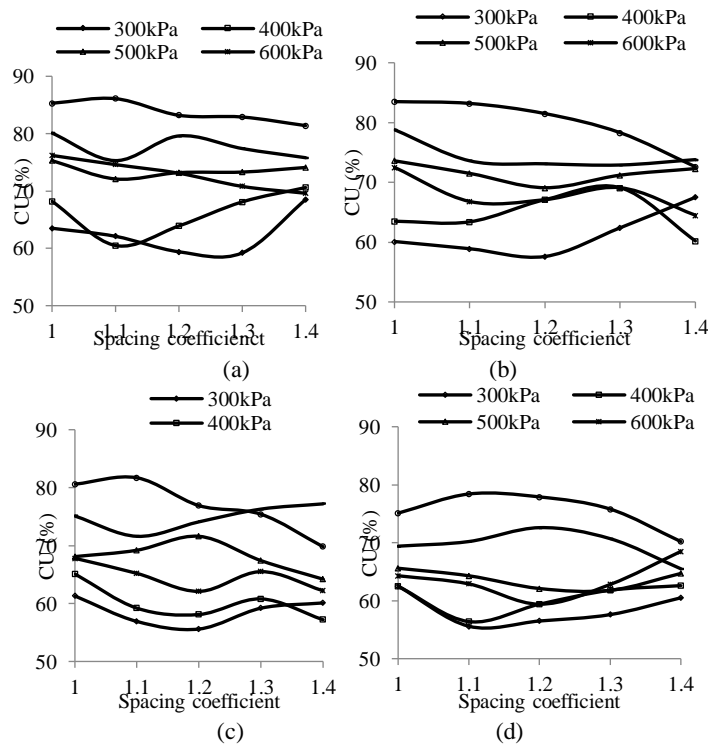


Figure 7. The CU values under different nozzle diameters (12.5, 15.1, 19 and 22.5 mm), operating pressure (300, 400, 500, 600, 700 and 800 kPa) and spacing coefficient (1.0, 1.1, 1.2, 1.3 and 1.4) for square layout. (a) Nozzle diameter is 12.5 mm, (b) Nozzle diameter is 15.1 mm, (c) Nozzle diameter is 19 mm, (d) Nozzle diameter is 22.5 mm.

3.4 Uniformity Coefficient Analysis for Square Layout

The CU values under different operating pressures (300, 400, 500, 600, 700 and 800kPa), nozzle diameters (12.5, 15.1, 19 and 22.9 mm) and spacing coefficients (1.0, 1.1, 1.2, 1.3 and 1.4) for square layout in no wind conditions are shown in Figure 7. As can be seen in Figure 7a, at 300 kPa, the maximum CU was 68.5% with spacing coefficient of 1.4, and the minimum CU was 59.2% with spacing coefficient of 1.3. When the operating pressure increased to 800 kPa, the CU value changed slightly to 82% with the increase of spacing coefficient. When the nozzle diameter increased from 12.5 to 22.9 mm, the maximum CU decreased from 86.1% to 78.4%.

It can be concluded from the results that CU values increased with the increase in operating pressure and decreased with the nozzle diameter. Also, the optimum spacing coefficients under different operating pressure were not same. This agrees with Tarjuelo et al. (1999), who said that CU can be improved through increasing operating pressure or decreasing nozzle diameter.

3.5 Uniformity Coefficient Analysis for Equilateral Triangle Layout

The CU values under different operating pressures (300, 400, 500, 600, 700 and 800kPa), nozzle diameters (12.5, 15.1, 19 and 22.9 mm) and spacing coefficients (1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 and 1.7) for equilateral triangle layout in no wind conditions were shown in Figure 8. It shows that the maximum CU decreased from 86.2 with the nozzle diameter of 12.5 mm and spacing coefficient of 1.1 to 79.5 with the nozzle diameter of 22.5 mm and spacing coefficient of 1.3 under the operating pressure of 800 kPa. The comparison analysis results of CU values with square layout and CU values with equilateral triangle layout illustrated that equilateral triangle layout can achieve higher uniformities compared with square layout.

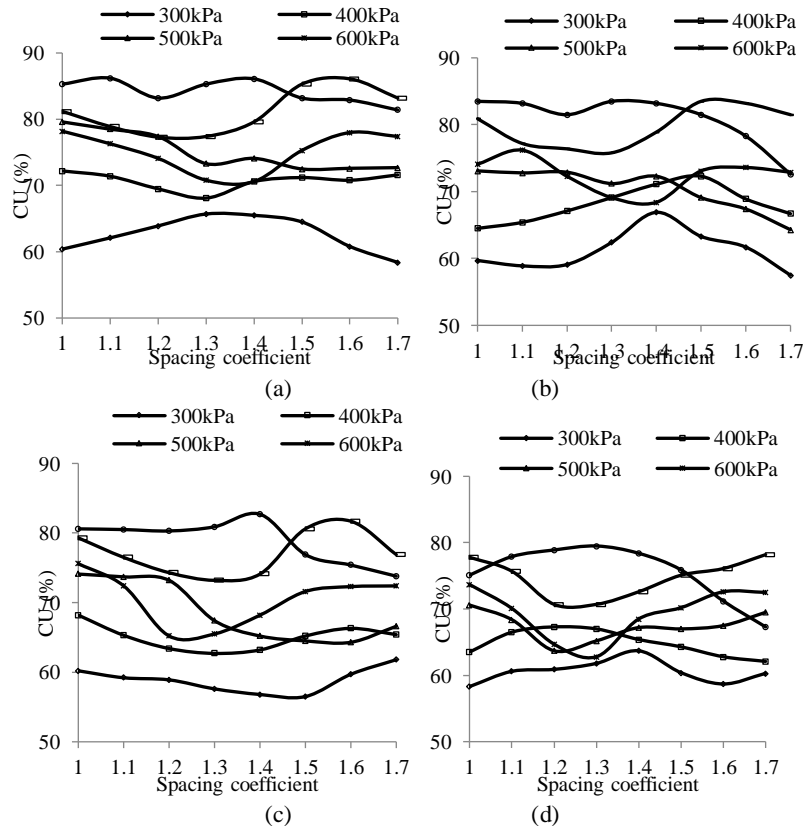


Figure 8. The CU values under different nozzle diameters (12.5, 15.1, 19 and 22.5 mm), operating pressure (300, 400, 500, 600, 700 and 800 kPa) and spacing coefficient (1.0, 1.1, 1.2, 1.3 and 1.4) for equilateral triangle layout. (a) Nozzle diameter is 12.5 mm, (b) Nozzle diameter is 15.1 mm, (c) Nozzle diameter is 19 mm, (d) Nozzle diameter is 22.5 mm.

4. CONCLUSIONS

For sprinkler discharge, the discharge coefficient ranged from 0.96 to 0.99. A mathematical model of radius of throw was also regressed and the coefficient of determination was 0.9765.

The application rate was lower near the sprinkler, and the peak value had occurred under the radius of throw from 4 to 6 m for each water distribution pattern. The average application rate decreased with increase in operating pressure. The average application rate increased with the increase of nozzle diameter. The increase or decrease of average application rate under small nozzle diameter was larger than large nozzle diameter within the same range of variation of operating pressure.

The maximum CU values increased with the increase of operating pressure under different nozzle diameter or different layout forms. Equilateral triangle layout achieved higher uniformities compared with square layout.

5. ACKNOWLEDGEMENTS

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