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Original research paper

DROPLET CHARACTERIZATION AND WATER DISTRIBUTION OF FIXED SPRAY PLATE SPRINKLER USED IN LINEARLY MOVED IRRIGATION SYSTEM

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Abstract: The irrigation uniformity of sprinkler irrigation system depends on many design factors such as nozzle diameter, operating pressure and riser height. An experimental study was conducted to investigate the effect of combination factors of operating pressure and riser height on water distribution and droplet diameter. To study the droplet characteristics of the fixed spray plate sprinkler (FSPS), droplet diameter and velocity were measured using a Thies Clima laser precipitation monitor. Statistical analysis was conducted on the drop size distribution using volume-weighted method. The volumetric cumulative frequency of drop diameters permitted to reconstruct water application along the sprinkler radius in term of the frequency of drops of different diameters with respect to elevation and working pressure. Wetted diameters and average application rates increased with the increase in pressure and nozzle elevation within a distance of less than 2m from the sprinkler. The results showed that various combinations of the sprinkler could greatly change droplet and water distribution characteristics. Empirical equations for the water distribution from FSPS were also developed with coefficients of determination ranging from 95.0% to 99.6%. The study concluded that the uniformity of a sprinkler irrigation system is more affected by the combination of distance from sprinkler, riser height and operating pressure.

Keywords: application rate, droplet diameter, hydraulic performance, sprinkler irrigation, water distribution.

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INTRODUCTION

Irrigation is a basic determinant of agriculture because its inadequacies are the most powerful constraints on the increase of agricultural production. Sprinkler irrigation remains one of the successful methods used by farmers to apply water to their crops. It is a planned system in which all necessary components have been installed for efficient application of irrigation water by means of sprayheads operated under pressure. The purpose of a sprinkler system is to efficiently and uniformly apply irrigation water to the crops or soil without causing erosion, excessive water loss, or reduction in water quality. It is necessary to evaluate the quality and efficiency of sprinkler irrigation system, including droplet size distribution and their influence on soil and crop growth. Designing and optimizing sprinkler irrigation systems is essentially based on achieving adequate hydraulic performance, which is significantly related to the droplet size and water distribution patterns [8], [16], [17], [23]. The characterization of drops resulting from fixed spray-plate sprinkler primarily implies the determination of their diameter as they approach the soil surface. Fine droplets of water travelling through the air have more evaporation losses rather than coarse droplets with respect to wind speed [9], [24]. Size distribution of the drops discharged by the water jet of an agricultural sprinkler has major influence on evaporation losses, modifying the infiltration capacity of the soil, and distortion of water distribution pattern applied by sprinkler [13], [15], [19], [25]. It is therefore of paramount interest to investigate drop size distribution over an irrigated area as its implication could affect the whole irrigation process.

Currently, linearly moved irrigation systems and center-pivot models are based on the overlapping of experimental sprinkler application pattern [20], [11]. According to [20], spray sprinklers which use low pressures are now been employed in linearly moved irrigation systems and centre pivots. The jet produced at the sprayhead immediately undergoes an inelastic shock as it frontally hits a plate. However, it appears that the drop formation begins at the surface of the jet and continues towards the centre [19], [27]. The upper limit lognormal distribution model was used to fit droplet size data which correlated with nozzle parameters and also ballistic models have been used to estimate the initial droplet size produced by a sprinkler. [13], [19], [28]. A third-order polynomial was used to describe the radial distribution [18] and [11] developed a model to simulate the application of water in a centre pivot irrigated field. From the above discussion it is evident that limited work has been done to compare the hydraulic parameters of FSPS on linearly moved irrigation system.

Hence the objective of this paper is to compare the effects of FSPS using different pressure regulator sprinklers at different height positions using a linearly moved irrigation system (LMIS) designed by the Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, China. This study focuses on comparing the hydraulic performance of the pressure regulator sprinklers introducing empirical equations for the water distribution and droplet diameter with respect to operating height and pressure.

MATERIALS AND METHODS

The experiments were performed in an indoor laboratory of the Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, China. The experiment layout of the system is as shown in Fig. 1. The FSPS studied in this research was the Nelson D3000 sprayhead, with 36-grooved blue plate with a medium angle from the horizontal plane. Ouazaa et al. [21], reported that the water distribution of grooved deflector plates was similar to donut shaped patterns and can result in discrete streams with different throw distance. A 5.5mm nozzle diameter of the FSPS was utilized during the experiment. The FSPS used was manufactured by Nelson Irrigation Corporation in Walla, Washington, USA (Fig. 2).

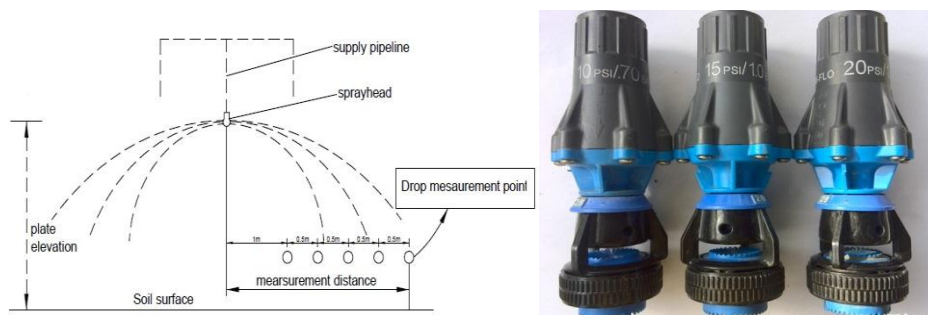


Figure 1. Experimental layout of the system



Figure 2. Fixed spray pressure heads used

The sprayheads were mounted on two different heights; h_1 -100cm and h_2 -150cm above the surface dependent on the experiment done for that occurrence and operated at working pressures of P1-10 psi, P2-15 psi and P3- 20 psi at different times during the experiment. A centrifugal pump was used to supply water to the irrigation system from a constant-level reservoir near the research laboratory. Thies Clima laser precipitation monitor (TCLPM) manufactured by Adolf Thies GmbH & Co. KG, Goettingen, Germany was used to measure the sizes and velocities of the droplets emitted from the FSPS types selected for the experiments. The testing location for the TCLPM was set at 1m from the FSPS for the initial reading followed by 0.5m increment for successive readings. In the design of the experimental system, the following standards were taken into consideration to meet international standards: ASAE S.330.1. [1], ASAE S.398.1. [2], ISO7749-2. [12], and MOD GB/T 19795.2 (2005). The TCLPM is made up of with an imaging system composed of photodiode detector, laser transmitter and a storage circuit as shown in Figure 3. It is also connected to an analysis display system which assists in displaying data generated by the TCLPM. The TCLPM can accumulate the measured droplet diameter, calculate the application rate and hence the droplet spectra which contain the drop size range, the droplet velocity and corresponding particle number can be input in an excel file for further analysis.

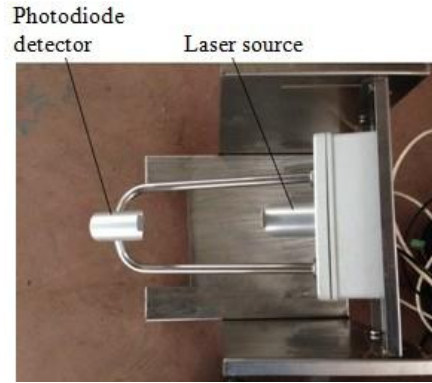


Figure 3. Structure of TCLPM

King et al. [15], described the test area of the TCLPM to be 23.0cm × 2.0cm with the measurement range of particle diameter from 0.16mm to 8.00mm. Bautista-Capetillo et al. [3], further postulated that TCLPM measured drop sizes 0.2mm to 8.0mm. When using TCLPM, measurement errors caused by coincidence errors and edge effects cannot be eliminated. The edge effect errors occur when only a fraction of a droplet passes through the laser beam. When this phenomenon occurs, the laser detects a droplet that is smaller than its actual size. The average droplet diameter was represented to the drop size at different positions due to the changing droplet diameter in a comparatively large range. Currently, the methods used in calculating the average droplet diameter include the number average method, weighted average method and middle cumulative frequency diameter method. This article makes use of the realistic weighted average method to calculate the average size of droplets. Weighted average method means 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 equation:

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

$$W_i = m_i \frac{\pi}{6} d_i^3 \gamma_w \quad (2)$$

where \bar{d} is the average size of droplets at sampling locations; d_i is drop diameter; W_i refers to weight of water for droplet with diameter d_i ; γ_w is the bulk density of water; m_i is the number of droplet with diameter d_i and n corresponds to the types of droplet diameters. Data interpolation and representation of drop diameter, total volume and regression analysis were done using Microsoft Excel Program (2010).

EXPERIMENTAL RESULTS AND DISCUSSION

Water distribution pattern of FSPS

For any combination of sprinkler nozzle elevation and working pressure, the water pattern distribution pattern was different for each experiment carried out. As an illustrative example of the individual water distribution pattern, Figure 4 presents the relationship between the application rate and distance from the sprinkler to LPM at h_1 and h_2 respectively for P1, P2 and P3.

Very large variability occurred in the radial direction. As a consequence, narrow wetted area resulted in large average precipitation and water droplets, which may lead to soil runoff losses and soil erosion [10] and [22, 23].

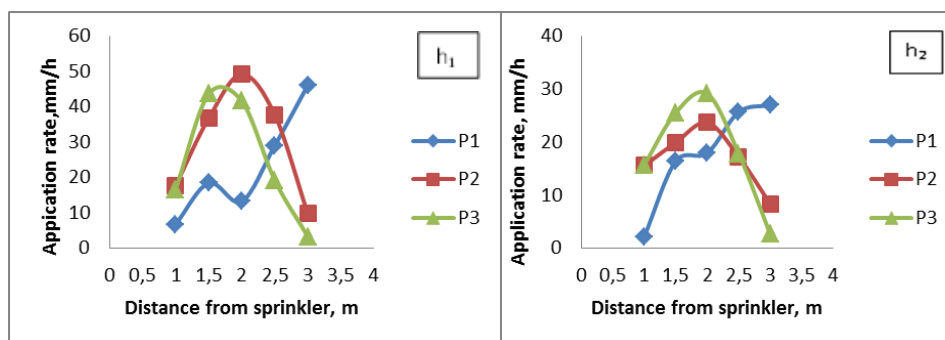


Figure 4. Water distribution pattern for FSPS at h_1 and h_2

Application rate found by the radial test as related to distance revealed that water distribution pattern curve under P1 for both height situations recorded water concentrated around and a distance away from the sprinklers due to probably unsatisfactory pressure. This is unlike that of the curves for P2 and P3 which showed that water from the FSPS settled around sprinkler due to fine drops caused by increased pressure. At P2 and P3 for the two different elevations used, the application patterns were evenly distributed along both sides of the sprinkler. With reference to h_1 , water distribution from P1 showed that the application rate was dropped from 19mm/h to 11mm/h at 2m throw radius and rose to about 45mm/h at 3m throw radius. This pattern was different to that of h_2 however, at a throw distance of 2.5m; the increase in application rate was marginal. Curves by P2 and P3 took a bell shape. Comparing the water distributions of P2 and P3 from the different elevations under the same condition, h_1 produced a higher average application rate ranging from 0.5mm/h to 50.0mm/h than at h_2 which also ranged from 0.4mm/h to 30mm/h. This indicates that the variations in the water application rate are quite significant and P3 appears to have more uniformity in application rate than at P2 and P1. Although the operating conditions were controlled, they differed slightly between each measurement and the droplets measured on each occasion were different.

The working and hydraulic parameters of the different types of pressure regulators used at their specific elevations are as shown in Table 1.

Table 1. Working and hydraulic parameters of the FSPS.

<i>Operating pressure level</i>	<i>Nozzle diameter</i> <i>mm</i>	<i>Flow rate m³/h</i>
<i>P₁</i>	5.5	1.61
<i>P₂</i>	5.5	1.79
<i>P₃</i>	5.5	1.82

Comparing the water distributions at the three operating pressure levels, P1 produced a lower application rate than at P2 and P3 for distance less than 2m away from the sprinkler. Raising pressure from 10psi to 20psi generally increased the application rate at h2 at a distance less than 2.5m away from the sprinkler. At h1 application rates at the different pressure level; P1, P2 and P3 were quite higher than at the elevation of h2. The differences can be attributed to the flow rate factor. Higher pressures increase flow along any pipe. As the flow increases, water velocity increases as well and as the water is rushing through the pipe, the interior walls of the pipe create friction against it which causes pressure loss thereby reducing the application rate. Hence it is important for irrigation system engineers to regulate the pressure at optimal levels to reduce such losses.

Drop diameter values versus distance from FSPS

Drop diameter distribution curves are presented in Figure 5 for all distances to the sprinkler. As the distance to sprinkler increases, the frequency of large drops increases. The smooth transition observed for distances up to 2.0m becomes abrupt between distances of 2.0 and 3.0 m especially at h1. These differences could be attributed to the fact that drops landing at distances less than 2.0m from the sprinkler can either be emitted from the nozzle or separate from the jet along its trajectory. This fact could explain the presence of drops with diameters less than 0.8mm, which completely disappear at a distance of 2.0m. From 2.0m onwards, all drops seem to result from the disintegration of the jet, and the modal diameters are in the interval 2–7mm. This proposition was presented by [26] who reported similar results when analyzing drop diameter measurements of FSPS using a low speed digital photography method.

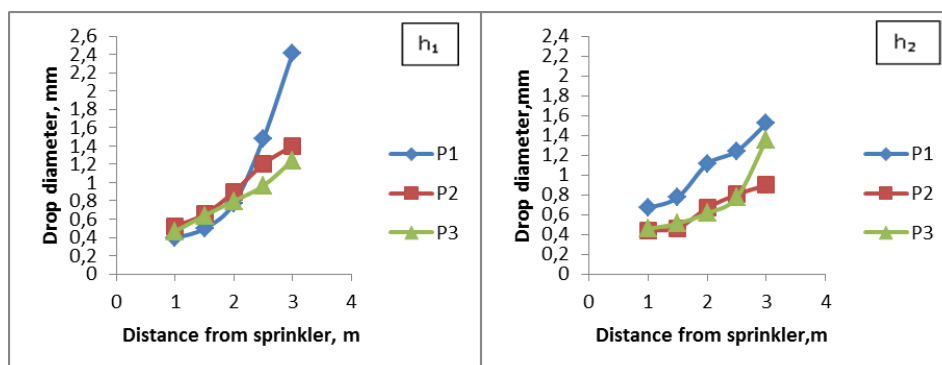


Figure 5. Drop diameter values versus distance from FSPS

The qualms associated with disdrometer measurements, evidenced by Burguete et al. (2007) raised some concern about the quantitative importance of these small drops. Photographic data confirmed the relevance of small drops at large distances from the sprinkler and pose further concerns about the adequacy of the sprinkler irrigation ballistic theory, specifically about the hypothesis stating that all drops are created at the nozzle.

Total volume and weighted cumulative frequency of droplet diameter along the range

Total volume of water applied for each pressure at given distances from the FSPS is presented in Figure 6 for different operating conditions. Three pressure regulators at h_1 and h_2 were employed in the experiments. As shown in Figure 6, generally, the total volume of the drops increased with increasing the distances from the sprinkler for both h_1 and h_2 . This was however different in the case of operating pressure especially for P2 and P3 as the total volume of drops began to decrease at a distance of 2m from the sprinkler position. This can be attributed to the differences in the frequency of the large drops. Total volume of drops at P1 kept increasing with increase in distance from the sprinkler for both h_1 and h_2 . This indicates that although the number of large drops is low, their contribution with respect to volume is quite significant. The total volume distribution graphs indicate that the gradients of the total volume are greater when the droplets were near the sprinkler and their size was small. The results varied for higher distances from the sprinkler particularly at an elevation of h_2 .

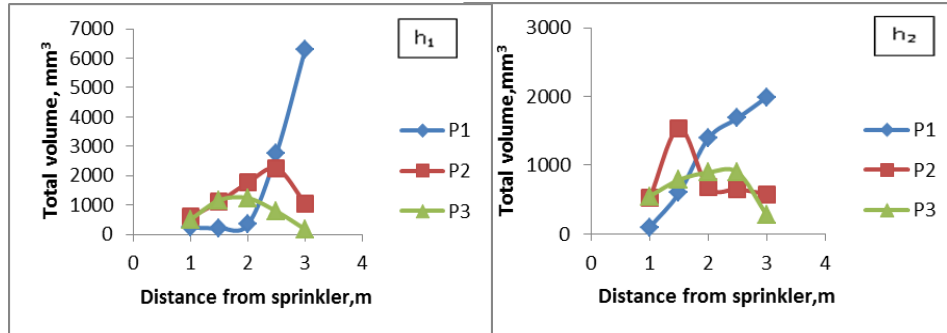


Figure 6. Total volume of water applied by each pressure as a function of distance to the sprinkler at h_1 and h_2

These outcomes are in concurrence with those reported by other researchers [19], [25]. In this work, it may not be essential to operate at pressure level of P1 and at a riser height of h_1 because using a combination of P1 h_1 results in increasing the total volume of applied water which will in the long run have an implication on cost and energy. Hence a combination of P3 h_1 and P3 h_2 will be considered more optimum when related with a normal distribution curve.

The weighted cumulative frequency means the cumulative value of specific gravity between the weighted which is less than one droplet diameter and the total weight of the spray. Figure 7 presents the weighted cumulative frequency of droplet diameters with different pressure regulators at two different height positions above the ground surface. As shown below, the weighted cumulative frequency of droplet diameters with different pressure regulators are different. 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 increases with the increase in the range distance. These results are in conformity with those reported by other researchers [25] and [19].

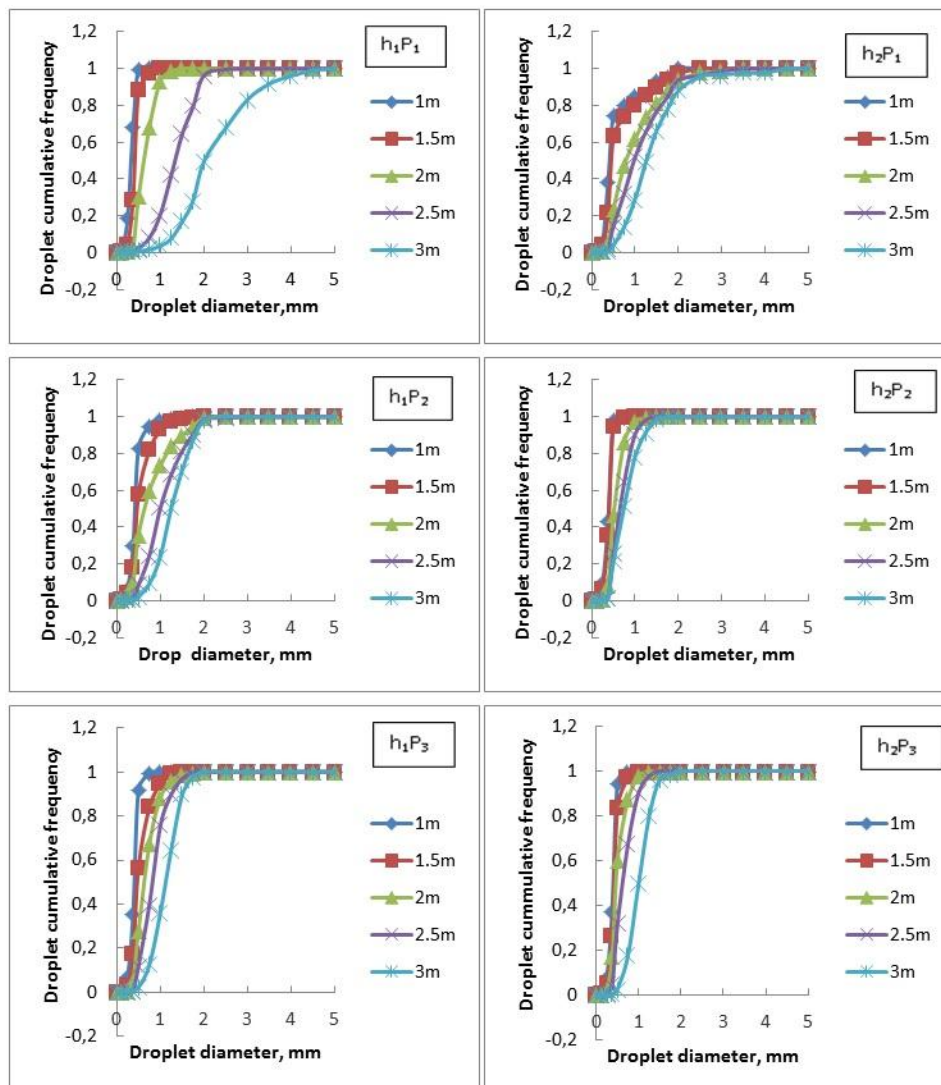


Figure 7. Curves of cumulative frequency of droplet diameter using different pressure regulators at different elevations.

Besides increasing drop size with increasing operating pressure, an increase in the range of drop diameters can be seen in Figure 7 above. The drops deposited at each observed distance were not of the same diameter but varied. This phenomenon may have two major causes. First, the minimum values of the droplet diameter are almost the same for all evaluated conditions but their maximum values differ in accordance with sprinkler working conditions. This entails that, at any rate of the sprinkler working conditions, some fine droplets fall at distances near to the sprinkler where the amount of applied water is very low.

Establishment of a mathematical Model for FSPS

Special attention was given to the development of empirical equations for the water distribution model regarding the distance traveled from the FSPSs. A third –order polynomial regression line to describe the radial presented in Table 2 was drawn to the distance from the sprinkler and the application rate data to estimate the water distribution where y is the application rate and x is the distance from the sprinkler. The coefficient for determination of FSPS ranged from 95.0% to 99.6%, with an average of 97.6%. The range is in agreement with the findings of [17] who postulated the coefficient of determination for PXH sprinkler as ranging from 95.1% to 98.8%.

Table 2 Regression analysis with third-order polynomial.

Operating pressure level	Riser height level	Third-order polynomial	Coefficient of determination (%)
P_1	h_1	$y = 12.137x^3 - 637x^2 + 116.72x - 57.35$	95.0
	h_2	$y = 4.16x^3 - 30.377x^2 + 80.412x - 51.498$	96.3
P_2	h_1	$y = 6.6007x^3 - 5.8857x^2 + 58.259x - 40.254$	99.1
	h_2	$y = -1.1767x^3 - 3.4271x^2 + 25.406x - 5.5418$	96.7
P_3	h_1	$y = 23.617x^3 - 172.05x^2 + 374.52x - 209.79$	99.6
	h_2	$y = 1.5833x^3 - 28.045x^2 + 85.071x - 43.219$	98.6

Research on the variation trend of the droplet diameter was carried out using the linear theory and the experimental correlation of droplet diameters is concluded in Equations 3 and 4. Comparing the results with experimental data, the accuracy error was less than 4% and the analysis of droplet diameters was accurate. According to these equations, the distances from the sprinkler and the working pressure have influences on the end droplet diameter of the sprinkler at the two elevations used in this research and changing the trend as a nonlinear equation.

$$h_1: d = 1.707L^{1.549}p^{-0.6539} \quad (3)$$

$$h_2: d = 2.226L^{0.8918}p^{-0.6101} \quad (4)$$

where d is the drop diameter, mm; L is distance from sprinkler, m and p is working pressure, psi.

CONCLUSION

The size distribution of the droplets discharged by the water jet of a sprinkler is very important as this can explain several processes related to water distribution. Individual water distribution pattern and discharge-pressure relation of D3000 sprayhead at the designed working pressures and nozzle elevations were of importance in designing the LMIS and to evaluate the quality of water distribution. An indoor experiment was conducted to obtain droplet size distribution and radial application patterns of D3000 sprayhead sprinkler fitted at different and working pressures.

The volumetric cumulative frequency of drop diameters permitted to reconstruct water application along the sprinkler radius in term of the frequency of drops of different diameters with respect to elevation and working pressure. As a result, wetted diameters and average application rates increased with the increase in pressure and nozzle elevation within a distance of less than 2m from the sprinkler. The results showed that various arrangements of the sprinkler could greatly change droplet and water distribution characteristics. Empirical equations for the water distribution from FSPS were also developed with coefficients of determination ranging from 95.0% to 99.6%. These relationships could enable designers to properly analyze the water distribution patterns produced by an FSPS. The study concluded that the irrigation uniformity of a sprinkler irrigation system is more affected by the combination of distance from sprinkler, riser height and operating pressure.

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KARAKTERIZACIJA KAPLJICA I DISTRIBUCIJE VODE FIKSNOG RASPRSKIVAČA KOJI SE KORISTI U SISTEMU NAVODNJAVANJA LINEARNOG TIPRA

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Abstract: Ujednačenost sistema navodnjavanja sa rasprskivačima zavisi od mnogih faktora projektovanja, kao što su: prečnik mlaznice, radni pritisak i visina postolja. Sprovedena je eksperimentalna studija kako bi se ispitaio uticaj kombinacije faktora radnog pritiska i visine postolja na raspodelu vode po površini i prečnik kapljice. Da bi se proučile karakteristike kapljice fiksnog rasprskivača tipa FSPS, prečnik i brzina kapljica su mereni pomoću laserskog monitora tipa Thies Clima.

Statistička analiza je urađena za raspodelu veličine kapi korišćenjem ponderisanog modela, metoda odnos zapremina-težina. Kumulativna zapremina učestalosti prečnika pada kapljica urađena je u odnosu na radijus rasprskivača u smislu učestalosti kapljica različitih prečnika u odnosu na visinu postolja i radni pritisak. Prečnici vlažene površine i prosečne brzine kapljica su registrovane kod povećanja pritiska i mlaznice na udaljenosti manjoj od 2m od rasprskivača.

Rezultati su pokazali da promene kombinacije rasprskivača mogu značajno promeniti karakteristike kapljice i raspodelu vode. Empirijske jednačine za distribuciju vode iz programa FSPS su razvijene sa koeficijentima određivanja u rang od 95,0% do 99,6%.

Studija ima zaključak da je ujednačenost sistema navodnjavanja sa rasprskivačima najviše zavisi od kombinacije udaljenosti rasprskivača, visine postolja i radnog pritiska vode u sistemu .

Ključne reči: norma navodnjavanja, prečnik kapljice, hidraulične performanse, navodnjavanje rasprskivačem, distribucija vode.

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