The effect of changing the spray angle of the irrigation device on the spray diameter

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Abstract. The paper is devoted to the research in the field of the effective application of the main working elements of sprinkler machines showing the influence of their basic capabilities on each other. The aim of the study was to develop and improve the performance of irrigation systems for the possibility of irrigation process optimization. As a result, it was found that the ratio between the spray angle and its maximum height at different pressures is equivalent to the second-order parabola equation. The inferred expected dependencies between the radius and the spray angle can be used to determine the degree of spray due to the inclination of the spray tube, which leads to a change in the spray angle when it rotates around its axis and, thus, the degree of spray and the shape of the irrigated area.

1. Introduction
The optimal operation and investment into sprinkler irrigation systems is of concern to manufacturers and investors, as they require precise technical knowledge of the elements of their work. Particular attention is paid to studies of the functionality of spray devices, which are their main working bodies. It is known that the spray angle of such devices is expressed by the angle of inclination of the water stream flowing from the spray nozzle with respect to the soil horizon [1]. Specialized scientific sources and most manufacturers often provide very different information on the values of spray angles, ranging from a few angles to 320 ones. Sprinklers are classified according to the spray angle: for sprinklers with a low spray angle, the range is from 60 to 70 and they are used for irrigation under the branches of fruit trees, for spraying wastewater it is about 120, and for the ones used for spraying over the vegetative part of the plant, the range of spray angles is from 230 to 320 [2-4].

The purpose of using low spray angles, in the case of wastewater spraying, is the absence of water droplets reaching high heights, which at large distances make them vulnerable to strong gusts of wind, which is unacceptable to human health [5]. Since the distribution of water droplets occurs under a vegetative slice at relatively high altitudes in the case of garden irrigation, trees become more susceptible to fungal diseases [6]. This means that the height reached by the flow of water in both cases is the starting point for research to determine the optimal spray angle. Figure 1 shows some types of sprinklers: with normal (230) and low (120) spray angles [7-9].

Specialized literary sources indicate the need for caution when designing sprinkler irrigation networks near power lines [10]. There are certain requirements for the distribution of water flow relative to power lines and electrical poles, which must be strictly observed, as illustrated in figure 2.
The most important factor that controls the determination of a suitable spray angle is the spray radius, that is, the level to which droplets of water dispersed from the nozzle of the sprayer reach. Therefore, in these studies, a search is made for the spray angle, which will give its greatest radius. The results of the experiments show that the largest spray range that was obtained for the spray angle is from 230 to 320. An increase in the spray radius increases the distance between the sprayers and reduces the spray density, which is desirable for the investor and manufacturer [11].

The purpose of the study

The purpose of the study is to develop and improve the performance of irrigation systems to optimize the irrigation process by examining: the effect of the spray angle on its radius and the influence of the spray angle on the maximum height of the water jet emanating from the spray nozzle, as well as the effect of the slope of the pipe lift on the change in the spray angle.

The ratio between the spray radius $R \, (m)$, the pressure in the spray nozzle $H \, (m)$ and the nozzle diameter $d \, (mm)$ is [5]:

- for a spray angle in the range of $28^\circ$ and $32^\circ$ and the nozzle diameter between 4 and 7 mm:
  \[ R = (2d - 0.5) + 0.18 \, H \]  
  \[ (1) \]

- for spray nozzle diameter from 8 mm to 10 mm:
  \[ R = 1.4d + 0.3 \, d \, H \]  
  \[ (2) \]
• for spray angles below the declared values, the spray radius can be calculated using the Hawaii ratio, which takes into account \( \alpha \) spray angle.

The inclination of the soil horizon also affects the spray angle, as it leads to a change in its radius, area and shape of the irrigated area with one sprayer. This effect is expressed by a decrease in the spraying radius in the direction of the earth’s surface and its increase when the jet is directed downward, and with respect to the angle of inclination to the soil horizon, it changes the shape of the irrigated area formed by one sprinkler, i.e., it takes an elliptical shape on inclined soil. Thus, if you change the spray radius, then the shape of the irrigated area will also change by the angle of the soil horizon (\( \alpha \)).

3. Materials and research methods
The sprayer used is a plastic sprinkler of the John Deere S5000 type with four main nozzles, which can have different colors and diameters (2.0; 2.6; 3.4; 4; 4.4 and 5 mm), as shown in figure 3.

In addition, Pedrollo Pump 2CPm16/160n electric pump was used, and the height of the spray nozzle was 70 cm.

The following equipment was used for the experiments: a Bourdon pressure gauge with a scale from zero to 6 kg/cm\(^2\) and an accuracy of 0.20 kg/cm\(^2\), a metal tape 25 m long, a set of equipment for measuring the volume of water flowing from the sprinkler, and a chronometer for measuring time.

The measurements were carried out using a sprinkler with a main nozzle with a diameter of 3.4 mm and a sprinkler with two main and secondary nozzles having diameters of 3.4 and 2.6 mm, respectively. The flow measurement was carried out at different pressures, radii and the highest spray height, as well as from the peak point to the spray point for different spray angles with respect to the horizon - from 90 - 390, at various operating pressures in the range from 2 to 5.8 kg/cm\(^2\). Figure 4 shows the analog form of the experiment. Due to the rotation of the spray head around its axis, the spray radius decreased. In the case where there was no rotation, the spray radius was 92% of the radius with the rotating head. The number of circular movements of the sprinkler head in one session was 127, for each movement it took 0.63 seconds, which means that each revolution of the sprinkler head around its axis takes 80 seconds.

![Figure 3. Sprinkler John Deere S5000 brand.](image)

![Figure 4. Analog form of the experiment.](image)
4. Results and discussion

The spray nozzle flow coefficient $\mu$ is one of the criteria that expresses the quality of the sprayers and is the efficiency of the narrowing coefficient of the water flow section when leaving a nozzle, according to $f_1$ speed coefficient, and the flow coefficient is calculated by the ratio of the actual flow from the spray nozzle to the theoretical flow rate according to the Thorschl ratio:

$$\mu = \frac{q_{act}}{q_{th}}$$

Actual flow rate was measured using a sprinkler with one main nozzle with a diameter of 3.4 mm, as well as a sprinkler with two nozzles with a diameter of 3.4 and 2.6 mm, respectively, with a pressure range: 2.0; 2.5; 3; 3.5 and 4 bar. The flow coefficient $\mu$ was calculated for a spray with one main nozzle, the average value of which was 0.917, for a spray with two nozzles the average value for the main nozzle was 0.929, and for the secondary - 0.514, and by comparing the actual flow of the spray with the flow according to the rating data, it turned out to be equivalent to 88.078% of the measured flow rate. For the main nozzle and the measured flow rate from it and the secondary nozzle in total, it is equivalent to the flow rate from them according to the catalog of the company.

To determine the spray angle giving the largest radius, it was measured at various spray angles ($9^\circ, 11^\circ, 13^\circ, 15^\circ, 17^\circ, 19^\circ, 21.9^\circ, 23^\circ, 25^\circ, 26.9^\circ, 29^\circ, 30.5^\circ, 32^\circ, 34^\circ, 39^\circ$) without rotation of the spray head per specific pressure. Then, the spray angle, giving its greatest radius, was determined from the curve of the dependence of the spray radius on the spray angle. The test was repeated at a pressure range of 2-5.8 kg/cm$^2$ with a sequential increment of 0.2 kg/cm$^2$, and the ratio of the spray radii was determined when the sprinkler head was rotated around its axis to its radius without head rotation. It was found that it turned out equal to 0.92. The test results showed that the spray radius increased with an increase in its angle until it reached a value after which, with its further increase, it decreased. This angle was the determined angle. It turned out that the spray angle giving the largest spray radius at operating pressures of 2.0, 2.4, 2.6, 2.8, 3.0, 3.2 kg / cm$^2$ was 320, and the corresponding spray radius was within 15, 15.80, 16, 16.35, 16.60, 16.85 m. Figure (5a) shows a curve illustrating this.

![Figure 5](image-url)  
**Figure 5.** Relationship between radius and spray angle to horizon at operating pressure: a) 2.0 kg/cm$^2$, b) 3.4 kg/cm$^2$, c) 3.6 kg/cm$^2$, d) 4.0 kg/cm$^2$. 
It turned out that the spray angle, giving the largest radius at an operating pressure of 3.4 kg/cm\(^2\), was 310, while the corresponding spray radius turned out to be 17.12 m, as shown in figure (5 b).

It turned out that the spray angle of 30.50 led to its largest radius, which was 17.4 m at an operating pressure of 3.6 kg/cm\(^2\), as shown in figure (5c).

It turned out that the spray angle 300 gave the largest spray radius at operating pressures (3.8, 4.0, 4.2, 4.4 kg/cm\(^2\)), and the corresponding spray radius was respectively: 17.45, 17.55, 17.60 and 17.77 m, as illustrated in figure (5 d).

It was found that the spray angle 29\(^0\) gave the largest spray radius at a spray pressure of 4.6 kg/cm\(^2\), while the corresponding spray radius was 17.85 m, as shown in figure (6a). It turned out that the spray angle 28\(^0\) gave the largest spray radius at an operating pressure of 4.8 kg/cm\(^2\), while the corresponding spray radius was 17.92 m, as shown in figure (6 b), and the spray angle 26\(^0\) gave the largest radius at operating pressures the sprinklers 5.0, 5.2 and 5.4 kg/cm\(^2\), while the corresponding spray radii were 18.1, 18.3 and 18.3 m, respectively, as shown in figure (6 c).

**Figure 6.** Relationship between radius and spray angle with respect to the soil horizon at operating pressure: a) 4.6 kg/cm\(^2\), b) 4.8 kg/cm\(^2\), c) 5.0 kg/cm\(^2\).

Table 1 shows the relationship between the radius (\(R_a\)) and the spray angle, for the curves derived above at various operating pressures.

**Table 1.** Functions for plotting dependencies between (\(R_a\)) radius and (\(\alpha^\circ\)) spray angle at various pressures.

| \(R^2\)   | \(R_a = f(\alpha)\)                                                                 | \(P(\text{kg/cm}^2)\) |
|---------|-----------------------------------------------------------------------------------|------------------------|
| 0.9717  | \(R_a = -0.0003\alpha^3 + 0.0141\alpha^2 + 0.0123\alpha + 9.9037\)                | 2.0                    |
| 0.9816  | \(R_a = -0.0002\alpha^3 + 0.0083\alpha^2 + 0.1770\alpha + 9.6497\)                | 2.4                    |
Table 2 shows the values of the spray angles giving the largest spray radius at various pressures, which clearly showed that the spray angle, with its largest radius, is in the range between 26° and 32°.

**Table 2.** Spray angles giving the largest spray radius at various pressures.

| Ra (m) | P (kg/cm²) | α (deg.) |
|--------|------------|----------|
| 15.15  | 2.0        | 32       |
| 15.8   | 2.4        | 32       |
| 16.2   | 2.6        | 32       |
| 16.52  | 2.8        | 32       |
| 16.6   | 3.0        | 32       |
| 16.85  | 3.2        | 32       |
| 17.12  | 3.4        | 31       |
| 17.40  | 3.6        | 30.5     |
| 17.45  | 3.8        | 30       |
| 17.55  | 4.0        | 30       |
| 17.60  | 4.2        | 30       |
| 17.77  | 4.4        | 30       |
| 17.85  | 4.6        | 29       |
| 17.92  | 4.8        | 28       |
| 18.1   | 5.0        | 26       |
| 18.3   | 5.2        | 26       |
| 18.3   | 5.4        | 26       |
Based on the study of the relationship between the height and the spray angle, it was found that the maximum height of the water flow (i.e. the height of the tube $h_r$ plus the maximum height of the water flow $h_{\text{max}}$) increases with increasing spray angle. Figures (7 a, b, c) show models of the curves of the relationships between the maximum height and spray angle at various pressures.

![Figure 7. Relationship between radius and spray angle with respect to the soil horizon at operating pressure: a) 4.0 kg/cm$^2$, b) 3.4 kg/cm$^2$, c) 3.0 kg/cm$^2$.](image)

Table 3 shows the equations of the curves of the dependences of the maximum height on the spraying angle at various pressure values. Using these ratios, it is possible to determine the largest spray angle under the vegetative cut of trees at a maximum spraying height less than the height of the plant crown above the soil horizon.

| R$^2$ | $h_{\text{max}} + h_r = f(\alpha)$ | P(kg/cm$^2$) |
|------|---------------------------------|-------------|
| 0.967 | $h_{\text{max}} + h_r = 0,002\alpha^2 + 0,02\alpha + 0,965$ | 2.0 |
| 0.978 | $h_{\text{max}} + h_r = 0,002\alpha^2 + 0,030\alpha + 0,9650$ | 2.4 |
| 0.985 | $h_{\text{max}} + h_r = 0,002\alpha^2 + 0,018\alpha + 1,021$ | 2.6 |
| 0.982 | $h_{\text{max}} + h_r = 0,003\alpha^2 + 0,007\alpha + 1,185$ | 2.8 |
| 0.982 | $h_{\text{max}} + h_r = 0,003\alpha^2 + 0,007\alpha + 1,233$ | 3.0 |
| 0.971 | $h_{\text{max}} + h_r = 0,003\alpha^2 + 0,001\alpha + 1,357$ | 3.2 |
| 0.949 | $h_{\text{max}} + h_r = 0,004\alpha^2 + 0,025\alpha + 1,595$ | 3.4 |
The inclination of the spray tube, caused by its deviation from the vertical according to its design, has a significant effect on the distribution of moisture on the irrigated surface, due to the angle of inclination of the soil horizon and a change in the spray angle. Further research in this area may be of scientific interest.

The spray angle corresponding to the largest spray radius at low working pressures in the range 2.0 - 3.2 kg/cm² of the test sprayer was 32°.

Spray angles corresponding to their largest radii, with an average working pressure (3.4, 4.4 kg/cm²) of the studied sprayer, were as follows 30°, 30.5°, 31°, respectively.

The ratio between the spray angle and the maximum spray height at different pressures is equivalent to the second-order parabola equation.

The obtained estimated dependency curves between the radius and spray angle can be used to determine the degree of spraying depending on the inclination of the spray tube, which leads to a change in the spray angle when it rotates around its axis and, thus, the degree of spraying and the shape of the irrigated area.

The inclination of the spray tube, caused by its deviation from the vertical according to its design, has a significant effect on the distribution of moisture on the irrigated surface, due to the angle of inclination of the soil horizon and a change in the spray angle. Further research in this area may be of scientific interest.

| α   | h_max + h_r = 0.003α² + 0.002α + 1.420 | 3.6 |
|-----|-------------------------------------|-----|
| 0.953 | h_max + h_r = 0.003α² + 0.003α + 1.388 | 3.8 |
| 0.961 | h_max + h_r = 0.003α² + 0.012α + 1.377 | 4.0 |
| 0.970 | h_max + h_r = 0.002α² + 0.029α + 1.252 | 4.2 |
| 0.962 | h_max + h_r = 0.002α² + 0.045α + 1.150 | 4.4 |
| 0.959 | h_max + h_r = 0.002α² + 0.045α + 1.176 | 4.6 |
| 0.961 | h_max + h_r = 0.002α² + 0.049α + 1.160 | 4.8 |
| 0.962 | h_max + h_r = 0.002α² + 0.043α + 1.152 | 5.0 |
| 0.965 | h_max + h_r = 0.002α² + 0.043α + 1.247 | 5.2 |
| 0.964 | h_max + h_r = 0.002α² + 0.042α + 1.286 | 5.4 |

Analyzing the results obtained, it should be noted that the maximum spray height increases with increasing its angle and that the ratio between the angle and the maximum spray height at a certain working pressure is equivalent to parabolic equations of the second degree, as can be seen from the ratios of table 3.

It can also be noted that the maximum spray height decreased with increasing spray angle, and the angle itself is not a decisive factor for determining the range of peaks in the water flow.

5. Conclusion

Designing and investing irrigation systems in an appropriate manner is very important to obtain the best results when applying this type of modern technology, however, this requires knowledge of the issues of investment, production and design. One of these problems is the spray angle.

The spray angle, which gives the largest spray radius, ranged from 26° to 32° depending on the operating pressure. The values of the spray angles, which give its greatest radius with respect to the range of the operating pressure of the sprayer used, ranged from 30° to 32°. The derived equations for the curves giving the maximum radius depending on the spray angle, represent the set of limitations of the fourth degree at high operating pressures of the sprayer and the third degree at low and medium pressures. The minimum values of spray angles (26°, 28°, 29°), giving the largest spray radius, were obtained at a relatively high pressure (4.6, 5.4 kg/cm²).

The spray angle corresponding to the largest spray radius at low working pressures in the range 2.0 - 3.2 kg/cm² of the test sprayer was 32°.
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