Heterogeneity Analysis of the Irrigation in Fields with Medium Size Sprinklers

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ABSTRACT

In order to determine the main factors that affect the water application at field level using solid set systems (experimental plots and actual irrigation installations), more than 300 tests have been carried out with different types of sprinkler-nozzle-pressure. Radial leg tests have been previously performed to find the water distribution pattern. Afterwards both outdoor single-sprinkler and block irrigation tests have been also performed to know the water distribution pattern distorted by wind action.

Results show that the main factors to be controlled are: the radial application rate distribution pattern, the sprinkler spacing, the time of irrigation and the riser height. For a certain sprinkler the radial pattern is determined by working pressure, nozzle and use or not use of the jet-straightening vane (VP) within the main nozzle. The main factor not controlled is wind speed (W). Results also show that higher Coefficients of Uniformity (CU) are attained with two nozzles than with a single nozzle under low wind speeds. VP must be incorporated for wind speed higher than 2 m/s with the aim of reducing the depletion of uniformity. A single nozzle must be used when the secondary nozzle has an incorrect design and then producing a big proportion of small-size drops.

Keywords: Irrigation, Coefficient of Uniformity, Sprinklers, Irrigation Uniformity, Solid Set Systems, Wind.

INTRODUCTION

Most sprinkle irrigation systems require a minimum value of water distribution uniformity (Christiansen's Coefficient of Uniformity (CU) ≥ 80 %) (Keller and Bliesner, 1990). Low values of CU are usually indicators of a faulty combination of the number and size of nozzles, working pressure and spacing of sprinklers.

The process of water application in solid set systems mainly depends on the sprinkler distribution model (determined by the sprinkler design itself, the number and type of nozzles and the working pressure), the sprinkler layout and the wind. Together with these factors, there are others less relevant in the distribution of water, such as: the length of irrigation, the use of VP inside the main nozzle, riser height of the sprinkler, discharge angle, etc (Tarjuelo *et al.*, 1992). A larger duration of irrigation favours uniformity, as this partly compensates wind distortions since the wind varies along the time. The VP equally decreases wind distortion making the jet compact and getting a longer distance. It has been already shown that when using the VP for a W>2 m/s, CU values obtained are better (Tarjuelo, 1999; Montero, 1999).

To determine Christiansen's Coefficient of Uniformity (CU) (Christiansen, 1942) and other parameters characterizing surface water distribution, we need to know the application rate caught in a grid of cans within the wetted area. The procedures to determine sprinkler water distribution can be grouped into three types:

a) To apply the catch can grid to the existing irrigation system: evaluation of the system (Merriam and Keller, 1978; Merriam *et al*., 1980).
b) To place a catch can grid around a single sprinkler head in no-wind conditions and establish the corresponding overlapping for any sprinkler spacing (Solomon, 1979).
c) To reduce the catch cans grid to a single-leg in a radial pattern, in no-wind and with high relative humidity conditions. The application rate can be calculated by rotating the radial pattern around the sprinkler (Vories and von Bernuth, 1986).

The first procedure allows us to know the working conditions of an existing irrigation system. The second one has the advantage of knowing the entire water distribution pattern of the sprinkler, as well as uniformity parameters under any irrigation spacing. Nevertheless, the problem of changing environmental conditions during the test is highlighted (e.g. wind direction and speed, evaporation, etc.). To this must be added changing evaporation in the catch cans, depending on their location at the center or on the edges of the wetted pattern. The third one has the advantage of controlling all factors in the process, especially sprinkler water distribution, thus allowing us to establish comparisons between different sprinklers.

OBJECTIVES

The present study tries to estimate and quantify the effect of the main factors that affect the water distribution over the plot in solid set systems, as well as deduce several recommendations for helping about design and management of sprinkle irrigation.

MATERIALS AND METHODS

Two types of sprinklers (Agros 35® and Rain Bird-46® (1)) and two riser pipe heights (0.6 and 2 m) were tested with several nozzle combinations (double nozzle 4.4+2.4 mm, and single nozzle 4.8 mm), operating at different working pressures (300, 350 and 400 kPa). The effect of a jet-straightening vane in the main nozzle on irrigation uniformity was also studied. The discharge angle was 27º in nozzles fitted with the Agros 35 sprinkler and 23º with the Rain Bird 46 sprinkler.

To enhance uniformity, some variations concerning nozzles were tested. A new plastic, main nozzle with built-in jet-straightening vane (VI) was tested in the case of the Rain Bird 46 sprinkler. The main irrigation spacing to be studied was square 18 x 18 m. Results obtained from radial tests also permitted us to calculate the uniformity parameters under any spacing.

To determine the sprinkler water distribution radial profile in no-wind and high relative humidity conditions, the following standards were adopted: ASAE.S.330.1 (1985), ASAE.S.398.1 (1985), ISO 7749-2 (1990) and UNE 68-072-86 (1986). Automated apparatus, similar to that used by Seginer *et al*. (1992) and Fischer and Wallender (1988), was constructed to perform tests.

Two types of outdoor tests were conducted: single sprinkler and block irrigation tests. Tests were conducted adopting the methodology stated by Merriam *et al*. (1980)

(1) Agros 35 is a trademark registered by COMETAL, S.L. Rain Bird 46 is a trademark registered by RAIN BIRD Corp. Makes are given only for informative purposes.

and Merriam and Keller (1978), as well as UNE-68-072-86 (1986), ISO 7749-2 (1990), and ASAE S330.1 (1985) standards.

From outdoor single sprinkler tests the water distribution pattern was obtained in a square grid of catch cans under the effect of any wind speed and direction. In addition, water application uniformity can be computed for any irrigation spacing.

The sprinkler was arranged in the center of a two-meter square grid of catch cans, at an equal distance from the four catch cans that surrounded it. A continuous grid of 22 columns by 22 rows of collectors is used. The catch cans were 16 cm in diameter and 15 cm in height. Risers allowed the sprinkler nozzle to be placed either 0.6 m or 2 m above the catch can opening.

Environmental conditions were registered at 1-min frequency with an automatic weather station, located 40 meters away from the test site (e.g. air temperature (HMP35AC model, with 0.2º C of accuracy and range –20 to 55º C), air relative humidity (HMP35AC model, with 2% of accuracy and range 0 to 100%), wind speed (A100R model, with 0.1 m/s of accuracy and range 0.25 to 75 m/s) and wind direction (W200P model, with 2º of accuracy and range 0 to 360º) at three heights (1, 2, and 4 m)).

Water temperature in the feed tank was measured with a thermometer. Tests had a one–hour duration, although 45 minutes may be sufficient with this catch can size (Fischer and Wallender, 1988).

Block irrigation tests were conducted with an installation made up of four laterals of aluminum pipeline (76 mm in diameter), with four sprinklers per lateral, placed at an 18- x 18-m spacing. A two-meter square grid of catch cans was located between the four central sprinklers.

Field evaluations were conducted adopting the methodology of Merriam and Keller (1978) and Merriam *et al*. (1980).

From data registered during irrigation tests and evaluations, a set of efficiency and uniformity parameters were calculated for several spacing between sprinklers. The parameters used in the analysis were:

- *Distribution Uniformity (DU)*

$$DU = \frac{\text{mean depth caught on the fourth of the field receiving the least amount}}{\text{mean depth caught on the entire field}} \text{x}100$$

- *Christiansen's Coefficient of Uniformity (CU)* (Christiansen, 1942)

$$CU = \left[1 - \frac{\sum_{i=1}^{n} \left| x_i - \overline{x} \right|}{n \cdot \overline{x}}\right] \text{x}\, 100$$

where: x_i = water depth collected by a catch can *i*; $\overline{x}$ = mean water depth collected in all catch cans; n = number of catch cans.

- *Discharge Efficiency (E_d)*

It shows the relationship between water collected by catch cans and water discharged by sprinklers. The difference between them is intended to be evaporation and drift losses during the irrigation event, mainly due to environmental conditions (air temperature and humidity, wind, etc.). Methodology errors must also be assumed within these differences:

$$E_d = \frac{\text{mean water depth observed}}{\text{mean water depth discharged}} \times 100$$

RESULTS

1. Radial Test Results

Table 1 lists the results obtained from radial leg tests. With no wind, better uniformity of water distribution is achieved in those combinations with two nozzles, compared to those that use one nozzle. This is due to two nozzles producing a 'triangular' in shape radial pattern, while a single nozzle draws 'rectangular' or 'donut' shape. Under strong wind conditions, this behaviour seems to be different for the 18 m x 18 m spacing.

It can be seen that combinations of nozzles with VP have a greater length (up to 1 m or more) and, usually, faster rotation speed than those without them. A significant influence is not observed between the utilisation or not of jet straightening vane (VP) in relation to the uniformity kept in conditions without wind action; in some cases CU improves incorporating VP.

When the sprinkler is located at 2 m, the wetted radius is bigger (about 1 m), in relation to the riser height of 0.6 m.

Figure 1 illustrates the CU values achieved for the irrigation spacing of 18 x 18 m (square) for all combinations.

Figure 1. Results of CU in radial tests at several working pressures.

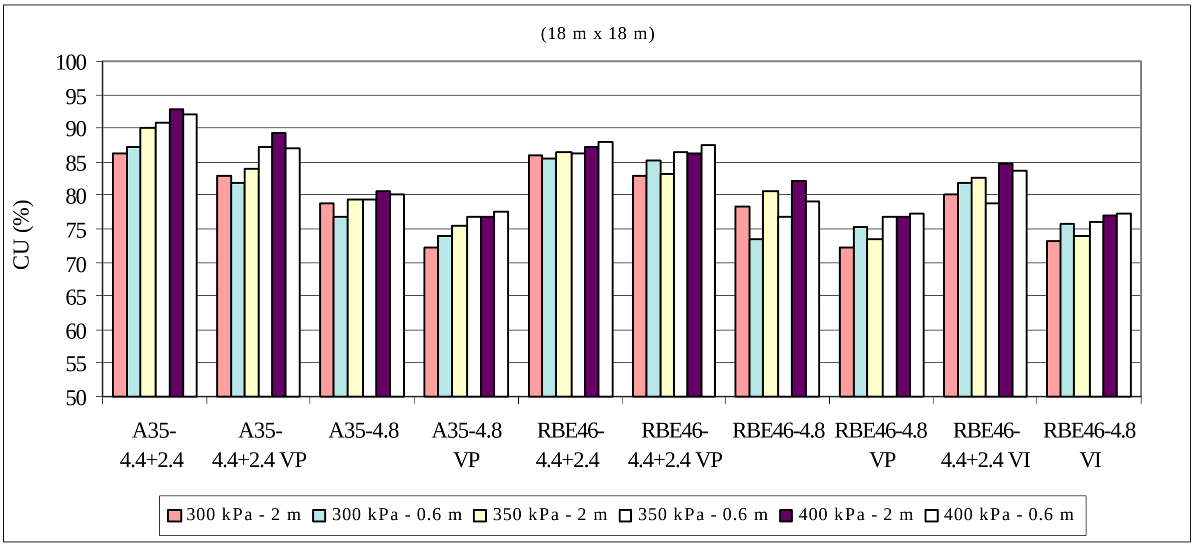

Table 1. Radial test performed with different sprinkler-nozzle-riser pipe height combinations.

Sprinkler	Nozzles	Working Pressure	Throw 0.6 m	Throw 2.0 m	CU (%) - Spacing (m*m) 0.6 m				CU (%) - Spacing (m*m) 2 m				DU (%) - Spacing (m*m) 0.6 m				DU (%) - Spacing (m*m) 2.0 m			
		(kPa)	(m)	(m)	12*12	12*18	18*18	18*15 T	12*12	12*18	18*18	18*15 T	12*12	12*18	18*18	18*15 T	12*12	12*18	18*18	18*15 T
Agros 35	4.4+2.4	300	14.7	15.2	89.7	82.4	87.3	85.6	87.0	83.7	86.1	87.8	86.0	75.9	83.5	77.9	82.0	76.0	80.9	80.7
	4.4+2.4 VP	300	15.4	15.8	80.2	79.8	81.8	88.5	81.3	82.5	83.0	89.9	70.5	67.5	74.2	81.0	71.4	70.0	75.2	84.7
	4.8	300	15.3	15.8	90.6	75.0	76.8	75.1	90.0	77.6	78.9	79.1	89.6	60.5	58.5	58.3	86.5	62.8	63.1	63.2
	4.8 VP	300	16.0	16.7	83.7	72.0	74.0	80.7	81.8	76.5	72.1	89.5	76.0	52.1	64.0	67.4	69.8	57.1	69.0	79.4
Rain Bird 46	4.4+2.4	300	13.9	14.6	88.7	86.0	85.5	80.4	93.6	86.3	86.0	80.0	81.6	80.0	74.4	65.3	89.5	81.3	73.5	66.0
	4.4+2.4 VP	300	15.2	15.5	90.6	81.6	85.1	80.6	87.0	82.5	82.8	84.9	88.6	75.1	74.9	69.0	82.6	70.1	76.3	73.4
	4.8	300	14.1	15.1	88.6	78.2	73.4	70.9	91.2	76.9	78.4	73.8	84.8	74.8	54.7	49.2	89.7	66.0	59.3	55.8
	4.8 VP	300	15.2	16.1	87.1	71.0	75.3	74.2	81.6	75.3	72.1	84.8	83.7	53.6	57.2	57.8	71.5	56.2	66.6	72.0
	4.4+2.4 VI	300	14.6	15.2	86.3	79.0	82.0	81.8	85.4	83.9	80.1	82.9	80.5	70.7	76.3	69.6	78.8	73.8	70.2	73.9
	4.8 VI	300	15.2	16.0	87.1	71.0	75.8	74.5	82.6	74.9	73.1	83.3	84.3	54.3	58.5	59.7	73.8	56.2	67.1	70.3
Agros 35	4.4+2.4	350	14.7	15.7	93.4	88.4	90.7	88.1	90.3	89.1	90.0	91.5	92.2	84.1	87.8	82.1	85.6	83.1	85.3	86.0
	4.4+2.4 VP	350	15.8	16.5	86.1	86.1	87.2	91.8	83.4	87.5	84.0	93.4	78.6	77.7	82.0	86.9	72.4	77.3	75.8	90.4
	4.8	350	15.9	16.5	93.2	80.4	79.3	78.8	90.4	80.4	79.3	84.2	92.5	68.6	64.2	63.4	85.2	66.5	68.5	71.4
	4.8 VP	350	16.5	17.2	87.4	78.0	76.8	84.9	86.1	80.0	75.4	90.4	81.0	61.1	68.0	73.3	76.4	63.7	71.3	82.8
Rain Bird 46	4.4+2.4	350	14.0	15.0	90.0	89.0	86.2	82.0	94.2	88.2	86.5	81.5	84.6	83.7	77.4	67.6	92.4	83.4	74.6	67.7
	4.4+2.4 VP	350	15.4	16.2	90.9	85.1	86.6	85.2	88.4	86.2	83.2	89.9	88.5	77.4	78.0	74.3	82.9	75.0	79.7	80.4
	4.8	350	14.6	15.6	92.3	79.4	76.7	73.3	91.4	79.5	80.6	78.4	89.1	73.4	57.6	53.3	89.5	67.4	63.3	61.7
	4.8 VP	350	16.0	16.8	87.3	75.9	76.7	81.1	84.1	78.4	73.5	89.1	81.8	58.8	64.4	66.8	73.2	60.6	69.9	78.7
	4.4+2.4(VI)	350	15.3	15.9	87.4	81.6	78.7	83.2	85.5	87.0	82.7	88.5	82.6	72.7	67.2	71.4	77.6	77.3	73.9	81.5
	4.8(VI)	350	16.2	16.9	86.1	75.9	76.1	83.1	84.1	78.6	73.9	90.2	79.7	58.1	66.1	70.3	73.4	61.1	70.6	81.1
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	4.4+2.4 VP	400	16.0	16.6	85.1	86.1	87.1	93.3	87.3	89.3	89.2	95.8	76.8	76.3	81.7	88.7	79.8	81.1	83.9	93.3
	4.8	400	16.0	16.3	95.3	82.4	80.0	78.7	95.2	83.0	80.7	80.4	94.3	72.3	65.0	63.5	93.5	72.7	65.9	65.8
	4.8 VP	400	16.7	17.4	89.9	79.4	77.5	83.5	88.9	81.2	76.7	87.6	84.6	63.7	66.5	71.7	82.4	66.7	69.8	79.1
Rain Bird 46	4.4+2.4	400	14.2	14.7	90.9	89.2	88.0	82.9	92.9	90.1	87.3	81.8	84.4	83.4	79.3	70.1	87.9	84.7	76.8	67.7
	4.4+2.4 VP	400	15.5	16.0	92.0	86.2	87.6	85.6	91.5	87.1	86.2	88.2	89.4	78.5	78.7	74.3	87.2	77.8	80.6	77.9
	4.8	400	14.7	15.3	93.6	80.5	79.2	74.9	93.2	82.4	82.2	78.5	90.7	73.8	61.6	57.0	91.7	73.0	66.7	62.3
	4.8 VP	400	16.1	16.6	87.7	77.1	77.4	82.3	87.1	80.2	76.7	87.4	82.3	60.5	66.1	68.3	79.2	64.7	69.8	76.0
	4.4+2.4 VI	400	15.4	16.1	87.3	86.6	83.6	86.4	87.8	89.1	84.8	89.9	81.6	79.5	76.3	77.3	80.8	81.8	76.5	83.3
	4.8 VI	400	16.0	16.8	89.1	77.2	77.4	80.4	88.6	80.6	77.1	87.0	85.7	61.4	64.7	66.5	81.3	65.8	69.3	76.3

2. Results Obtained from Outdoor Single Sprinkler Tests (FIGURES 2A – 2B):

Thirteen sprinkler-nozzle-riser height combinations were tested, totaling 94 tests. For every combination, at least four tests were conducted with different wind speeds, ranging from 0.55 to 8.07 m/s. The average value was 3.27 m/s. Discharge efficiency (E_d), ranged from 55.3 to 99.5% (average E_d= 80.0%). The value of efficiency, together with climatic data, are currently being using to develop a mathematical model for predicting evaporation and drift losses.

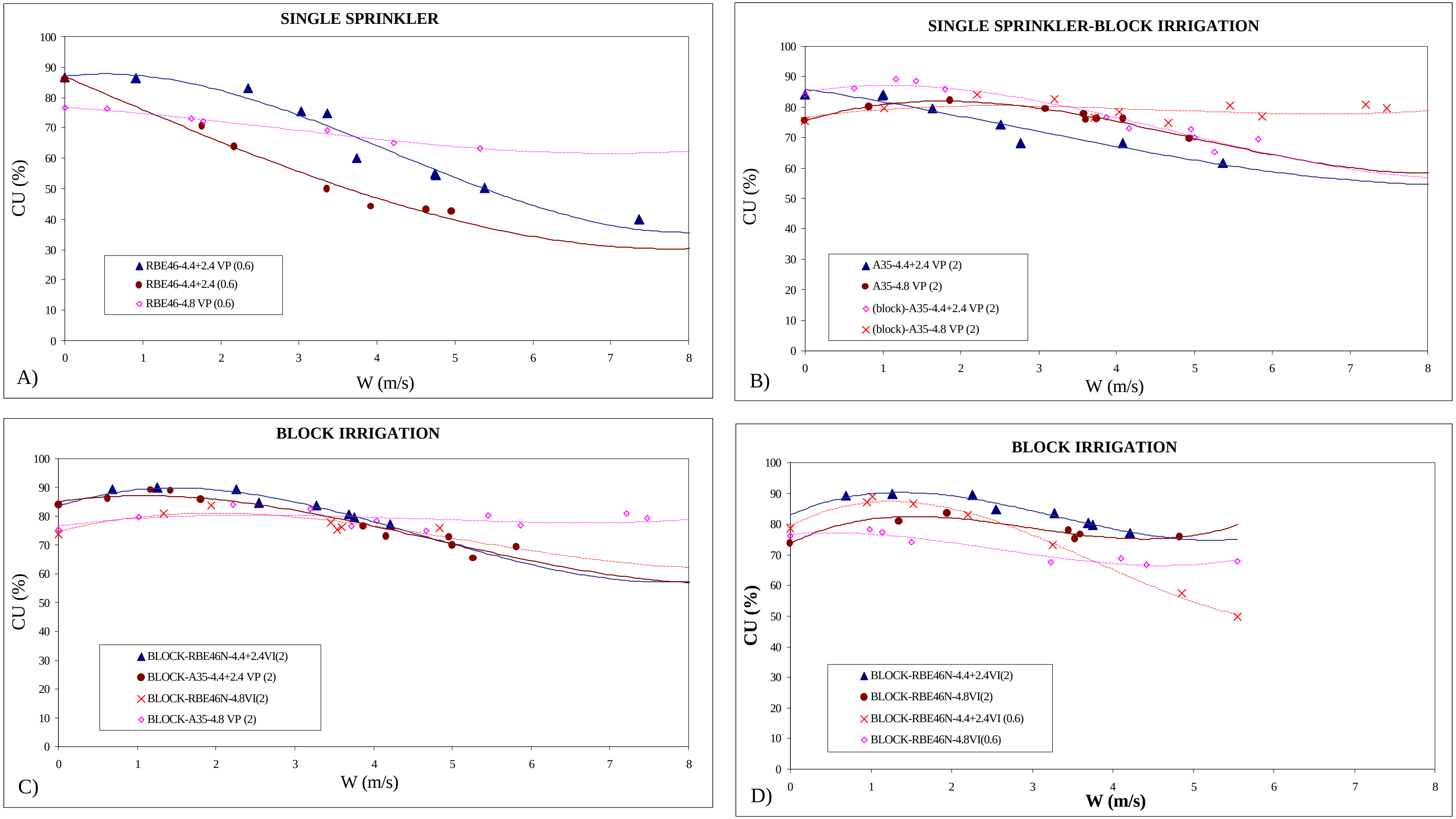
- The first consequence deduced from all nozzle-sprinkler combinations tested under different wind conditions is that wind action on the water distribution pattern is fundamental. The higher the wind speed, the smaller the CU values, the larger the distortion in the distribution pattern, and the smaller the wetted area.
- CU and wind speed (CU-W) data fit acceptably in almost combinations. The best determination coefficients (R^2) are obtained with 3-degree polynomial equations.
- Under low wind speeds, uniformity is higher with two nozzles and VP than with single nozzle, although higher uniformity is attained with one nozzle under high wind speeds and it decreases more slowly than with two nozzles under high wind speed conditions.
- When the sprinkler works with two nozzles, uniformity is higher when incorporating the jet straightening vane (VP). Uniformity is similar incorporating the vane when using a single nozzle.
- In relation with the single sprinkler water distribution, and depending on the combination nozzles-sprinkler, we can affirm that the leeward wetted radius increases between 0.6 and 1.3 m for every increment of 1 m/s of wind speed. The similar proportion of water distribution gravity centre is displaced in the direction of the wind (0.9 to 1.40 m). The reduction of the windward wetted radius is 1.3 to 2.6 every 1 m/s wind speed increases. In the same way, the wetted radii are reduced 0.8 to 1.9 m every 1 m/s in perpendicular directions to wind. These data may be important in order to characterise bidimensionally the influence of wind speed on the sprinkler water distribution.

3. Results Obtained in Block Irrigation Tests (FIGURES 2C Y 2D):

Nine combinations were tested with the Agros 35 and Rain Bird 46 sprinklers fitted with several nozzles, operating at 350 kPa for the 0.6- and 2-m riser heights under an 18- x 18-m spacing. Eighty-two tests were conducted where wind speed ranged from 0.63 to 9.14 m/s (mean wind speed= 3.26 m/s). Discharge efficiency ranged from 99.2% and 69.5% (mean E_d= 85.2%). Note that the mean E_d achieved in these tests was higher than that of single sprinkler tests.

- Higher uniformity is attained in block irrigation tests than in single sprinkler tests. This effect may be reasonable, since when some sprinklers are simultaneously irrigating, both wind speed and direction may compensate water distribution in different areas. In addition, possible errors due to different evaporation of water collected in the catch cans will be smaller in block irrigation, since the number of catch cans is minor (less time for measuring), and a favourable microclimate is achieved in the test area too, reducing evaporation and drift losses.
- Uniformity keeps a constant relation with wind in block irrigation tests with single-nozzle sprinklers.

Figure 2. Influence of sprinkler-nozzle-riser height on irrigation uniformity for the 18 m x 18 m spacing operating at 350 kPa



- Comparing the use of single nozzle or two nozzles in block irrigation, uniformity is higher by using two nozzles with low wind speed, whilst uniformity is higher with one nozzle under high wind speed (> 4.5 m/s).
- When the sprinkler is located at 2 m above the ground uniformity is always higher when using two nozzles than with one nozzle. However the same behaviour is noticed at 0.6 m under low wind speeds, but not under high wind speeds.
- There are no significant differences according to uniformity among the AGROS 35 and RBE 46 sprinklers.

4. Field Test Results

During the spring of 1996, 33 permanent solid set catch can tests were conducted in an area of 700-ha of collective irrigation in Albacete (Spain). The Rain Bird 46 sprinkler was used in almost all farms fitted with 4.4- + 2.4-mm nozzles and jet-straightening vane (VP). The irrigation spacing was square in shape. The distance between sprinklers ranged from 15.4 to 17.5 m. Only in three tests the spacing was 13.3 m x 17.0 m. The sprinkler was located 2.3 m above the ground.

Discharge efficiency ranged from 75% to 98%, with wind speed ranging form 0.2 m/s to 4.6 m/s, temperature ranging from 18 ºC to 34 ºC and relative humidity ranging from 38% to 57%.

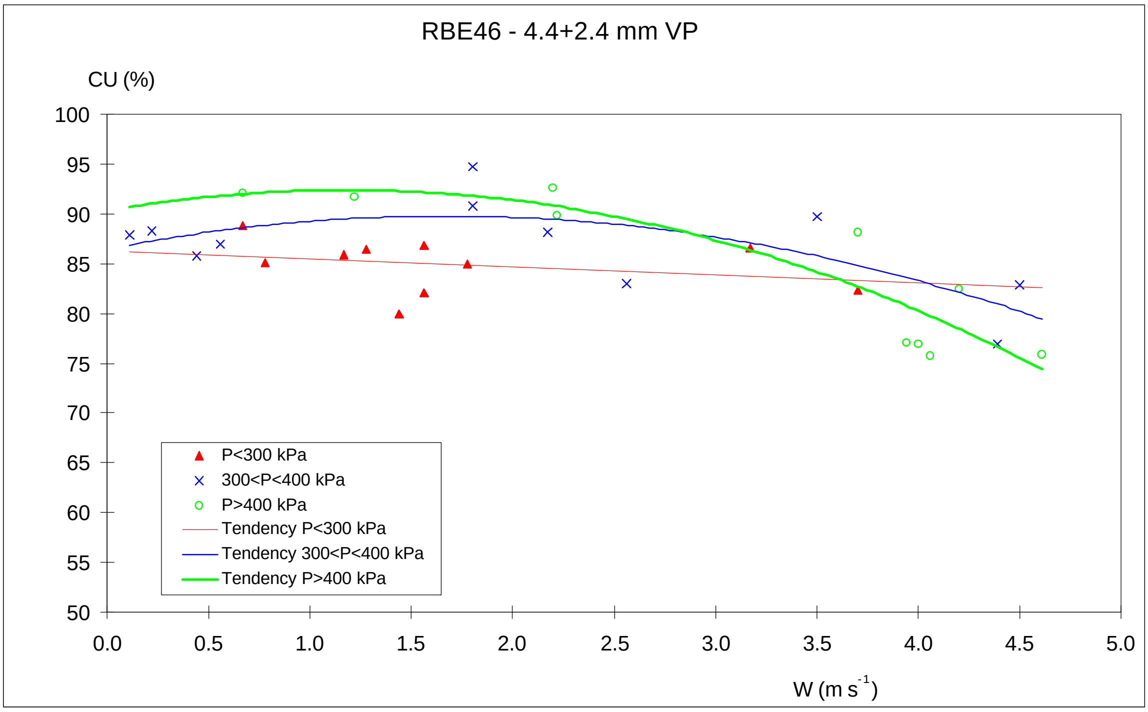
The mean CU achieved from the entire set of tests was 84.6% with a mean DU of 75.4%. A value of CU ≥ 80% was attained in 79% of tests. When winds were lower than 2 m/s, the mean CU value was 87.4%. For wind speeds ranging 2 to 4 m/s, the average CU value was 85.3%; and for wind speed higher than 4 m/s, the average CU value was 77.2%.

Ten evaluations with variable winds were available. Five of them had CU values higher than 90%, in three others CU values were over 87%, and the other two had CU values higher than 75%, but with wind speeds higher than 4.3 m/s. This shows the positive effect of wind variations (either in speed or direction) on uniformity.

Ten evaluations were carried out with a sprinkler average working pressure lower than 300 kPa, 12 with a working pressure between 300 and 400 kPa, and 11 with an excessive working pressure (>400 kPa). Figure 3 shows the relationship between CU values and wind speed as a function of working pressure. High pressures resulted in a greater CU dispersion. Under these conditions, the CU values became more affected by other factors (e.g. wind speed, irrigation layout, variable winds, etc). However, CU seems to be more stable with low pressures. Uniformity only increased as a function of pressure with low winds.

Existing pressures in different places of the evaluated plot were controlled in measuring and locating lowest and highest pressures around the sub-unit. It is normally accepted that the limit of discharge variation in the different points of the sub-unit is about 10% of average discharge in order to obtain an acceptable uniformity. For this to happen, the pressure difference limit must not exceed 20% of mean working pressure. With excessive pressure variations there will be areas receiving more water than others will. This problem may occur when the hydraulic design of the installation is not correct, i.e., when pipe diameters are small in relation to the flow to be delivered. In 59.3% of evaluations pressure variation exceeded 20% of average working pressure.

Figure 3.- CU vs. W in an actual irrigation set operating at several working pressures (mean spacing: 17 m x 17 m)



CONCLUSIONS

We can highlight the following conclusions:

- In radial indoor tests, higher irrigation uniformity was achieved when the sprinkler works with double nozzle than when it does with a single nozzle. When the sprinkler fitted a VP or was located at two meters, farther throw was attained. With VP, CU values decrease whereas at two meters uniformity was similar or slightly higher.
- Wind action on the water distribution pattern is fundamental. The faster the wind speed, the smaller the CU values (above some minimum value). Greater distortion in the distribution pattern resulted in a wetted area of smaller size.
- Higher irrigation uniformity is achieved when the sprinkler incorporates VP within the main nozzle, especially with two nozzles.
- Uniformity is higher when using two nozzles under low wind speeds (W<3 m/s), whereas it is higher with a single nozzle under high wind speeds.
- Uniformity increases by locating the sprinkler at 2 m above the ground as opposed to 0.6 m, especially under high wind speeds.
- Uniformity is slightly higher in block irrigation than in single sprinkler irrigation, especially with high wind speeds.
- The shape of the radial leg pattern influences irrigation uniformity achieved in the open field under wind action.
- With low pressures (<300 kPa):
  - The irrigation uniformity is less affected by wind speed than by high pressures (>350 kPa).
  - Smaller uniformity for middle or low wind speeds (<4 m/s) is obtained comparing with medium and high pressure, though this uniformity is maintained, thus attaining CU values from 80 to 90 %.

- Higher uniformity value dispersion is observed when irrigating under high pressures that means that uniformity is affected by additional factors such as distance between sprinklers, wind, etc. CU values are a little lower but more stable under low pressures.

RECOMMENDATIONS

- Higher Christiansen's Coefficient of Uniformity (CU) is normally attained using two nozzles (under low wind), adding a jet-straightening vane (VP) when wind speed is higher than 2 m/s. In that case it is very important the correct design of the secondary nozzle to achieve the water distribution radial pattern of the sprinkler to be triangular in shape, when there is no wind. An excess of rainfall (not more than 6-8 mm/h) close to the sprinkler must be avoided. This fact would imply an excessive proportion of small-size droplets which are easily dragged by wind. This increases evaporation losses and makes strongly decrease irrigation uniformity when the wind speed is higher. If the secondary nozzle does not comply these standards with, may result desirable to utilise a single nozzle, since higher irrigation uniformity is achieved under higher wind speeds, although a lower irrigation uniformity is achieved under low wind speeds (< 3 m/s),
- Working pressures higher than 400 kPa must be avoided, since these pressures imply a higher economic cost, but also produce small-size drops, generating the consequences indicated in the previous point.
- It is convenient to design solid set systems with low application rate (from 5 to 7 mm/h), so that the irrigation time will be greater and likely runoff problems will decrease. A greater irrigation time usually supposes higher irrigation uniformity, as the wind is not usually constant both in intensity and direction.
- When using two-nozzle sprinklers, higher CU values are attained with square-shaped spacing (15 m x 15 m and 18 m x 18 m) than when using equivalent rectangular-shaped spacing (12 m x 18 m and 16 m x 12 m). This happens whatever the wind speed is. This fact also happens when using a single-nozzle sprinkler without a jet-straightening vane, but the opposite effect is attained when incorporating the jet-straightening vane (VP).
- In rectangular spacing, such as the 12 m x 18 m one, the shortest spacing may be located parallel to the wind direction, if single-nozzle sprinklers are used. However, in the case of two-nozzle sprinklers, is desirable to locate the largest spacing parallel to the wind direction. Then the effect of wind direction is reduced, especially if the main nozzle incorporates jet-straightening vane.
- In solid set systems, significant differences have not been found in the variation of uniformity with wind speed for different riser height (0.6 and 2 m). Higher uniformity may be attained with 2 m riser height when the water distribution radial pattern has not a clear triangular shape.
- The minimum spacing recommended in the case of extensive herbaceous crops is 12 m x 12 m and the maximum is 18 m x 18 m. The optimal operating pressure must range from 250 kPa to 350 kPa.
- With hand-move laterals the recommended spacing are 12 m x 15 m or 12 m x 18 m to reduce carriage of pipes, using two-nozzle sprinklers (4 + 2.4 mm) and operating at 300 kPa. Nevertheless higher CU values are attained with a single nozzle (4.8 mm) in the 12 m x 18 m spacing.
- In solid set systems the spacings recommended are 12 m x 15 m both rectangular and triangular in shape, and the triangular-shaped 18 m x 15 m, always with two-nozzle

sprinklers (4 + 2.4 mm or 4.4 + 2.4 mm) operating at 300 and 350 kPa respectively. One another interesting spacing is 15 m x 15 m with 4 + 2.4 mm and working pressure of 300-350 kPa.

- In buried solid set systems (the most interesting system if the plot is continuously irrigated) the suitable spacings are 18 m x 15 m (triangular in shape) and 15 m x 15 m or 18 m x 18 m (square in shape). However, the actual spacing depends on available sowing and harvesting machinery. The most suitable nozzles are 4 + 2.4 mm, 4.4 + 2.4 mm and 4.8 + 2.4 mm, with working pressure of 300-350 kPa, depending on the spacing size, with the aim of achieving an application of 6.5 mm/h.

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REFERENCES

- ASAE Standard: ASAE.S 330.1. 1985. Procedure for sprinkler distribution testing for research purposes. In: ASAE Standards. ASAE, St. Joseph, MI.
- ASAE Standard: ASAE.S 398.1. 1985. Procedure for sprinkler testing and performance reporting. In: ASAE Standards. ASAE, St. Joseph, MI.
- Christiansen, J.E. 1942. Irrigation by sprinkling. California Eg. Exp. Sta. Bull. 670.
- Fischer, G. and W. Wallender. 1988. Collector size and test duration effects on sprinkler water distribution measurement. Trans. ASAE. 31(2): 538-542.
- ISO 7749-2. 1990. Matériel d'irrigation - Asperseurs rotatifs - Parte 2. Uniformité de la distribution et méthodes d'essai.
- Keller, J. and R.D. Bliesner. 1990. Sprinkle and Trickle Irrigation. AVI Book. Van Nostrand Reinhold. New York.
- Merriam, J.L. and J. Keller. 1978. Farm irrigation system evaluation: a guide for management. Utah State University, Logan, Utah.
- Merriam, J.L., M.N. Shearer. and C.M Burt. 1980. Evaluating irrigation systems and practices. In: Design and Operation of Farm Irrigation Systems (ed. M.E. Jensen) ASAE monograph no. 3 pp. 721-760.
- Montero, J. 1999. Análisis de la distribución de agua en sistemas de riego por aspersión estacionario. Desarrollo del Modelo de Simulación de Riego por Aspersión (SIRIAS). Tesis Doctoral. ETSIA-Universidad de Castilla-La Mancha.
- Seginer, I., D. Kantz, D. Nir and R.D von Bernuth. 1992. Indoor measurement of single-radius sprinkler patterns. Trans. ASAE. 35(2): 523-533.
- Solomon, K. 1979. Variability of sprinkler coefficient of uniformity-test results. Trans. ASAE. 22(5): 1078-1086.
- Tarjuelo, J.M. 1999. El Riego por Aspersión y su Tecnología. Mundi-Prensa S.A., Madrid, Spain.
- Tarjuelo, J.M., M. Valiente and J. Lozoya. 1992. Working conditions of a sprinkler to optimize the application of water. J. Irrig. Drain. Eng. 118(6): 895-913.
- UNE 68-072-86. 1986. Aspersores rotativos. Requisitos generales y métodos de ensayo. AENOR, Spain.
- Vories, E. and R.D. von Bernuth. 1986. Single nozzle sprinkler performance in wind. Trans. ASAE. 29(5): 1325-1330.