# Sprinkler rotation and water application rate for the newly-designed complete fluidic sprinkler and impact sprinkler

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**Abstract:** One important indicator of the good performance of rotating sprinklers is the uniformity of rotation. The objective of this experimental study was to investigate the rotation uniformity and water application rate of the newly designed complete fluidic sprinkler in comparison to the widely used impact sprinkler, with the goal to offer recommendations to improve the fluidic sprinkler's operation performance. Single-sprinkler water application experiments were conducted in accordance with the American Society of Agricultural and Biological Engineers standard. Sprinkler completion time through the four quadrants of rotation and water delivery in catch cans were measured at different operating pressures for each sprinkler-nozzle size configuration. The capabilities of Matrix Laboratory were employed to simulate the overlap of adjacent quadrants and to visualize the effect of sprinkler rotation speed variation on water application rate. Quadrant completion time variations were small for both impact and fluidic sprinklers. However, variations in completion time through the quadrants were higher for the fluidic sprinkler compared to the impact sprinkler. Relatively higher variations in water application rates were also observed for the fluidic sprinkler. The optimization of the design features of the fluidic component is necessary to improve rotation stability and to minimize variability in water application rate of the fluidic sprinkler. The study significantly highlighted some performance qualities of the complete fluidic sprinkler in comparison to that of the impact sprinkler. The findings of this research will help to improve the efficiency of the new type complete fluidic sprinkler.

**Keywords:** sprinkler rotation, variation, water application rate, complete fluidic sprinkler, impact sprinkler, rotation uniformity
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## 1 Introduction

The sprinkler head is regarded as a key component of any sprinkler irrigation system. Several factors affect sprinkler irrigation uniformity. Over the years a lot of research have been done on sprinklers, focusing on factors such as sprinkler nozzle characteristics, operating pressure, flow rate, riser characteristics, sprinkler spacing, pattern of sprinkler grid and environmental factors[1-8].

The effects of variation in rotation speed are lightly considered. One characteristic of good performance of a

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rotating member is the uniformity of rotation rate[9,10]. However, few researches have acknowledged sprinkler rotation speed variation as a factor that can influence overall uniformity of water application. Uniformity and rotation speed of sprinklers are important for a number of reasons. A rotation rate that is too high would cause the jet stream to bend. This causes gaps in the pattern which, due to frictional characteristics, are often repeated at the same area[11]. A speed that is too slow would cause an increase in intensity of application for the time the jet stream remains in one area. This intensity when repeated will cause sealing of the soil which may lead to run off and sheet erosion[11].

Sprinkler irrigation uniformity is an important measure of the performance characteristic in sprinkler irrigation. The uniformity is based on measured water application depth in catch cans[1,12,13]. Solomon[14] indicated that the most significant cause of variation in uniformity of application is the fact that not all the important factors are measured or reported. Li Jiusheng [2] related uniformity of application with sprinkler riser tilt and maximum rotation time deviation as specified by the Chinese National Standard GB[15]. The sprinkler riser tilt was a significant contributor to non-uniformity of sprinkler rotation and that the value of the maximum relative deviation increased as the riser tilt angle increased. This results in decreasing uniformity, slightly. Zhu Xingye[16], in discussing how rotation speed relates to operating pressure, stated that the rotation speed for a given inner contraction angle of the fluidic sprinkler varied in a quite small range among the geometrical parameters. However, studies on differences in water application depth with angular rotation demand further research for the fluidic sprinkler.

The main objective of this research was to investigate the rotation uniformity and water application rate of the newly designed complete fluidic sprinkler in comparison to the well-known and widely used impact sprinkler, with the goal to offer recommendations to improve the fluidic sprinkler's operation performance. The capabilities of Matlab were employed to simulate overlaps and to visualize the effect of rotational speed variation on water application.

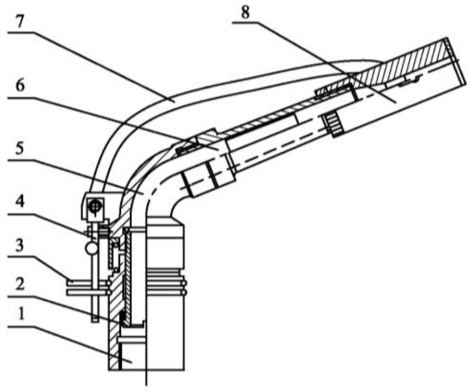
## 2 Materials and methods

Two types of sprinklers namely the complete Fluidic (PXH) and the Impact (PY) with different nozzle size combinations were employed for this study (Figure 1 and Table 1). The basis for using these two sprinkler types was for comparison of the relatively new PXH sprinkler with the popular and highly utilized impact sprinkler to ascertain the performance quality of the PXH sprinkler. The fluidic sprinkler was invented by Jiangsu University in China and manufactured by Shanghai Watex Water-economizer Technology Co, Ltd., China[17]. It is schematically and pictorially shown in Figure 1.

**Table 1 Sprinkler-nozzle and operating pressure configurations**

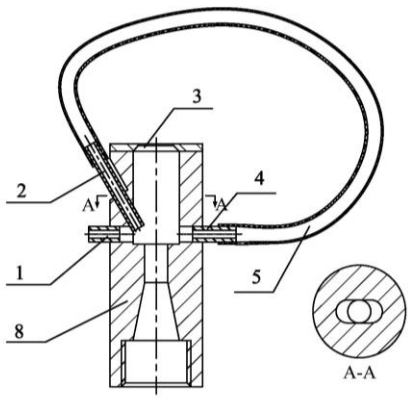
| Sprinkler type | Nozzle /mm | Wetted radius/m | Pressure /kPa | Measured discharge/$m^3 \cdot h^{-1}$ |
|---|---|---|---|---|
| PXH10 | 4 | 10 | 200 | 0.87 |
| | 4 | 10 | 250 | 0.95 |
| | 4 | 10 | 300 | 1.04 |
| PXH20 | 8 | 20 | 250 | 3.80 |
| | 8 | 20 | 300 | 3.90 |
| | 8 | 20 | 350 | 4.20 |
| PY20 | 7 | 20 | 250 | 3.07 |
| | 7 | 20 | 300 | 3.15 |
| | 7 | 20 | 350 | 3.40 |
| PY20 | 8 | 20 | 200 | 3.50 |
| | 8 | 20 | 250 | 3.90 |
| | 8 | 20 | 350 | 4.25 |

The fluidic sprinkler operates by the principle of the Coanda effect to perform the function of rotation[16,18]. The main distinguishing feature of the fluidic sprinkler is the fluidic component (Figure 1b). A brief description of the working principle of the fluidic sprinkler is as follows: as water is ejected from the nozzle of the main tube into the fluidic component, a region of low pressure forms on both sides at the entry into the main jet flow. Fluid flow from the reversing plastic tubing (left) into the right side, forces the jet to deflect towards the right boundary of the fluidic component where it eventually attaches. Subsequently the jet flow bends to the right boundary such that the signal nozzle 1 (Figure 1b) cannot receive any flow and later becomes straight as it exits the fluidic component. Alternate air movement from the signal nozzles and the plate cover account for the stepwise rotation of the fluidic sprinkler automatically[16,17,19] .



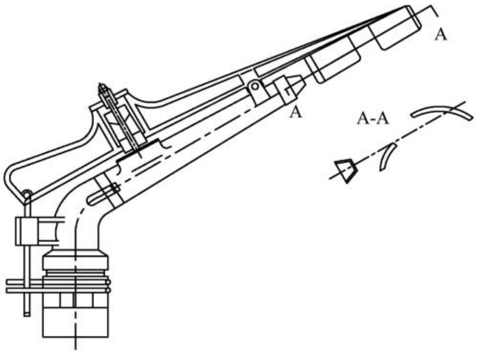

1. Swivel connection 2. Connecting sleeve 3. Limiting mechanism 4. Reversing mechanism 5. Body sprayer 6. Pipe sprayer 7. Plastic tube 8. Fluidic component

a. Schematic view




1. Signal nozzle 1 2. Signal nozzle 2 3. Main flow jet 4. Signal nozzle 3 5. Signal tube 8. Body of fluidic element

b. Fluidic component




c. Schematic view of impact sprinkler

d. Sprinkler used in experiments

Figure 1 Schematic and pictorial views of fluidic and impact sprinklers used in the experiment

Twelve sprinkler-nozzle and operating pressure configurations were tested under indoor conditions (Table 1). All nozzle sizes and operating pressures were within the manufacturer's recommendations. The experiments were conducted in the indoor sprinkler laboratory of Jiangsu University. The laboratory is circular in shape with a diameter of 44 m (Figure 2). Performing the experiment in an indoor facility could ensure uninterrupted radial water application and avoid wind resistance to rotation[20]. The sprinkler heads were mounted on a 1.5 m riser at 90° to the horizontal. Catch cans used in the study were cylindrical in shape, 20 cm in diameter and 60 cm in height. They were arranged in an orthogonal pattern (eight radial lines) around the sprinkler as shown in Figure 2. Each radial line had 10 catch cans placed 2 m apart constituting 80 catch cans in total around the sprinkler. The circular path (area) of rotation of the sprinkler was categorized into four quadrants for purposes of accessing the rotation uniformity from quadrant to quadrant. Each quadrant consisted of three radial lines. Quadrants Q1, Q2, Q3 and Q4 comprised of radial lines 0, 45, 90; 90, 135, 180; 180, 225, 270 and 270, 315, 0, respectively (Figure 2).

The water application depth measurements were performed in accordance with the ASABE S398.1-1985[21]. For each sprinkler-nozzle-pressure setting, the experiment was operated for one hour and then the water application depths in the catch cans were measured with a graduated measuring cylinder. Each one hour application test was repeated three times. Operating pressure at the base of the sprinkler head was regulated and maintained by a valve with the aid of a pressure gauge with an accuracy of ±1%. Discharge was recorded every 15 minutes by means of an electromagnetic flow meter with an accuracy of ±0.5%. To investigate the sprinkler rotation speed uniformity, a stopwatch was used to record the time taken by the sprinkler to move from one quadrant to the other, in the course of the one hour duration. Three replications of completion time through the quadrants were recorded for each sprinkler-nozzle-pressure configuration. Water application depths in the catch cans and sprinkler completion time through each quadrant for a complete rotation of the sprinkler head constituted the main input parameters. These were used for analyzing the extent of rotation variation and the effect on water application rate as well as on uniformity of water application.

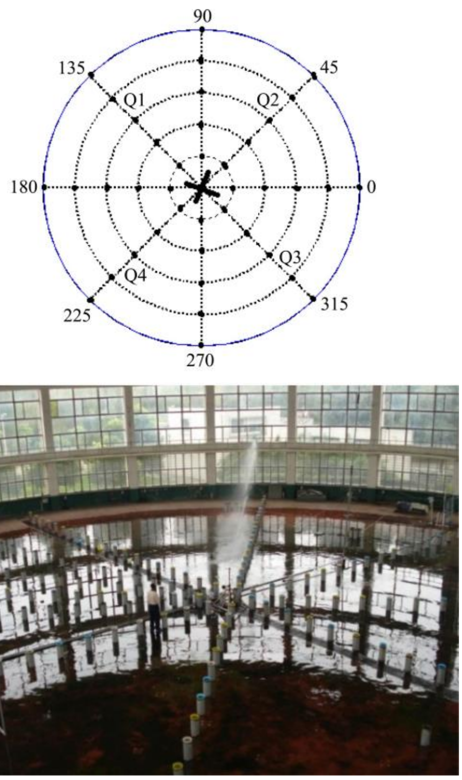



Figure 2 Schematic and pictorial views of layout of cans around sprinkler in the indoor laboratory

## 2.1 Sprinkler performance parameters

In order to assess the performance of the sprinklers with regards water application, Christiansen's Coefficients of Uniformity, Standard Deviation of application rate and quadrant completion time were calculated from the test data for all configurations. Christiansen's Coefficient of Uniformity (CU) is given at Equation (1):

$$CU = \left[1 - \frac{\sum_{i=1}^{n}(X_i - \bar{X})}{n\bar{X}}\right] \times 100\% \qquad (1)$$

where, $X_i$ is the water depth collected from the $i^{th}$ catch can (mm/h); $\bar{X}$ is the mean water depth collected in all catch cans within the area (mm/h); $n$ the total number of catch cans in the area under consideration.

The mean application rates at each catch can location were taken into consideration when evaluating the standard deviations. Standard deviations were calculated from the repeated experiments for each sprinkler nozzle configuration using Equation (2).

$$\text{Standard deviation}=\sqrt{1/(n-1)\sum_{i=1}^{n}(t_i - \bar{t})^2} \qquad (2)$$

where, $t_i$ is the mean quadrant completion time through the $i^{th}$ quadrant in a complete rotation (360°); $n$ is the number of replications and $\bar{t}$ is the mean of completion time through the four quadrants.

## 2.2 Visualization and overlap distribution

A computer program was written in Matlab to visualize the water application pattern around the sprinkler and to also overlap adjacent quadrants of the same single sprinkler experiment. The goal was to investigate the dampening effect that overlapped distribution may have on non-uniform water application rate. The quadrants were overlapped in both horizontal and vertical directions (Figure 3) by employing the transformation and superimposition features in Matlab. Cubic spline interpolation was used to interpolate between the patterns of can measurements.

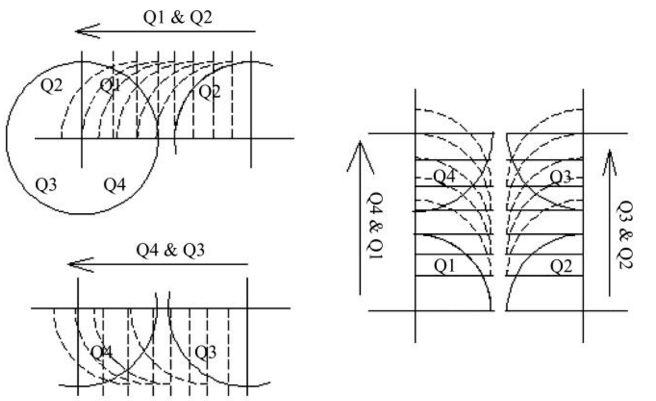



Figure 3 Schematic view of overlap of quadrants for a complete single sprinkler coverage area

For horizontal overlap of quadrants, modified matrixes were added as follows:

$$F=[C_{il}\ \ O_{ij}\ \ O_{ik}]+[O_{il}\ \ b_{ij}\ \ O_{ik}]+\ldots.. \qquad (3)$$

For vertical overlap of quadrants, the resultant pattern is as follows:

$$G=\begin{bmatrix} C_{il} \\ O_{ij} \\ O_{ik} \end{bmatrix}+\begin{bmatrix} O_{il} \\ b_{ij} \\ O_{ik} \end{bmatrix}+\ldots.. \qquad (4)$$

where, $b_{ij}$ and $C_{il}$ are matrices, with catch can readings in the quadrants as elements; $O_{ik}$ and $O_{ij}$ are null matrices inserted for purposes of mathematical correctness. The null matrices technically indicate areas where no water was applied. The number of shifts necessary for overlap was determined by:

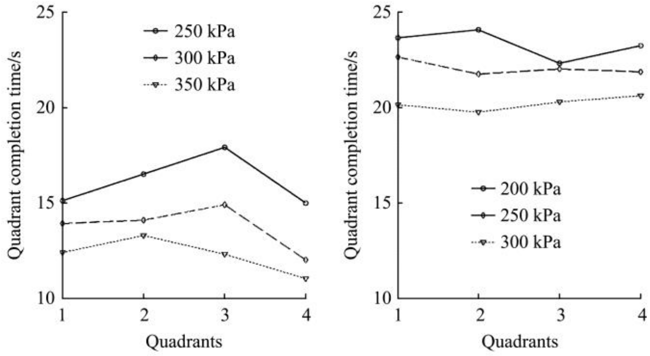
$$sh = r / s\left(\frac{x}{100}\right) \quad (5)$$

where, $x$ = percentage of overlap (%); $r$ = radius of throw (m); $sh$ = number of shifts of elements; $s$ = spacing of each cans (m).

The model calculates the number of shifts required (Equation (5)) and then shifts the modified input matrix forward from right to left or upward from bottom as the case may be and sums the corresponding elements for overlaps (Equations (3) and (4)). CU values were calculated for the resultant patterns using Equation (1).

## 3 Results and discussion

The quadrants completion times at constant operating pressure are shown in Figure 4 for the PXH20 and PY20 sprinklers. In general, the PXH20 sprinkler rotates faster than the PY20 sprinkler. This can be attributed to the stepwise rotation of the PXH20 sprinkler accounted for by the quite fast wall attachment phenomenon that takes place in the fluidic component[23]. The wall attachment phenomenon is caused by the pressure variations created by alignment of signal nozzles and fluid flow through the signal pipes in the fluidic component[17]. This observation is in quite agreement with the observation of Zhu Xingye[16]. It is obvious then that further studies are necessary to optimize the alignment and size of the signal nozzles. Variations in completion time through the quadrants are higher for the PXH20 sprinkler (Figure 4). For the PXH20 sprinkler, and operating pressures of 250 kPa, 300 kPa and 350 kPa, measured ranges of quadrant completion time were 2.9 s, 2.87 s and 2.28 s, respectively. In the case of the PY20_8 mm sprinkler, measured ranges of quadrant completion time of 1.77 s, 0.88 s and 0.86 s were recorded at operating pressures of 200, 250 and 300 kPa, respectively. Variations in quadrant completion time indicate instability in sprinkler rotation.




a. PXH20 b. PY20

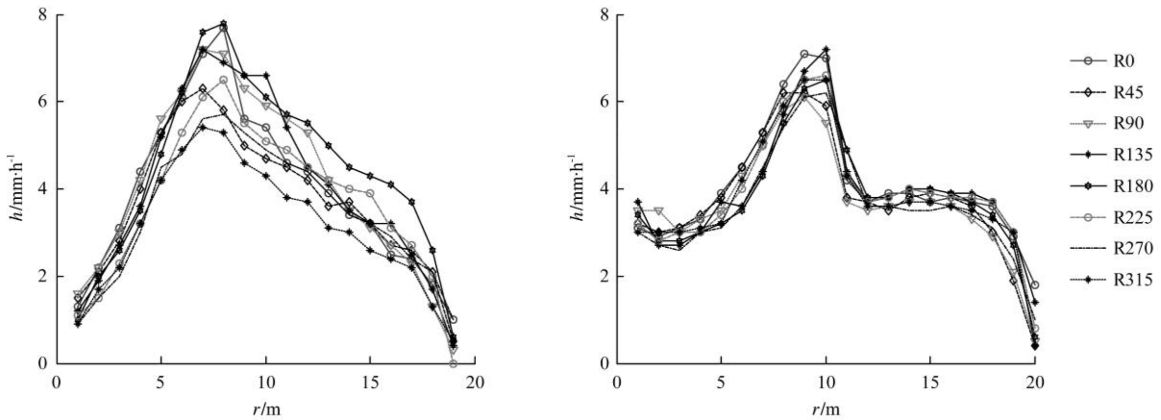
Figure 4 Quadrants completion time through the four quadrants of rotation at varying operating pressures with nozzle size (8 mm)

### 3.1 Variations in water application intensity

Figure 5 shows plots of water application rate for eight radial lines, within the cycle of rotation, for the PXH20 and PY20 sprinklers, respectively. At any distance from the sprinkler, the variation in water application rate across radial lines is easily noticed, especially for the PXH20 sprinkler, between 5 m to17 m from the sprinkler. This quite agrees with the findings of Liu Jumping[23], in the study on comparative research on hydraulic performance of sprinkler heads in sprinkler irrigation. Relating quadrant completion time (Figure 4) to average water application rate in their corresponding quadrants (Figure 6), quadrants which recorded high completion times also registered high average water application rate for most portions along the radial lines and vice versa (Figure 6). The trend was not different for the PY20 sprinkler at 7 mm nozzle size and that of the PXH10 sprinkler at 4 mm nozzle size (not shown), which also showed positive correlation between quadrant completion times and application rate in most cases.

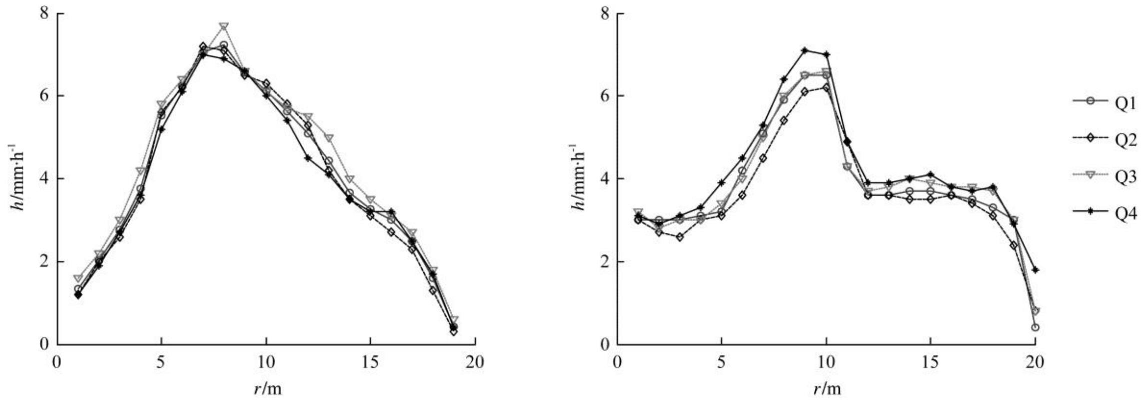
### 3.2 Plots of water application patterns

Color and contour plots of water application patterns for the sprinklers are shown in Figure 7. As seen in the color and contour maps, some portions around the sprinkler had different water application rates. Rings that are the same continuous color and intensity, obviously, indicate uniformity of water application, while different colors in a ring indicate non-uniformity in water application by the sprinkler across quadrants. From the color plots, it is easy to notice quite higher non-uniformities with regards the PXH20 sprinkler.



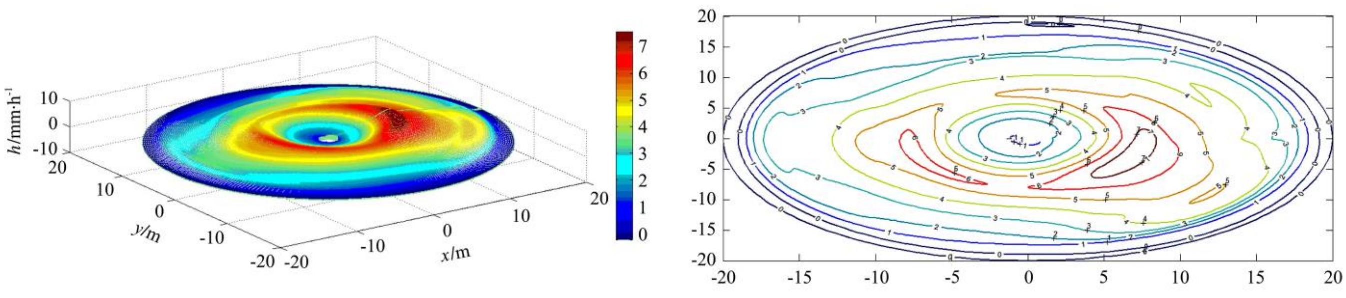

a. PXH20 b. PY20

Figure 5 Radial leg data along eight radial lines for the PXH20 and PY20 sprinklers with nozzle size of 8 mm at 300 kPa

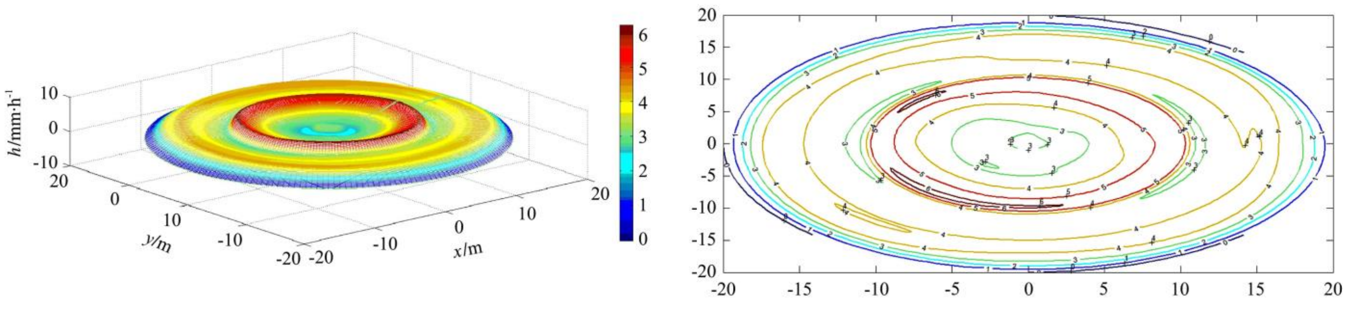



a. PXH20 b. PY20

Figure 6 Average water application patterns in the quadrants for the PXH20 and PY20 sprinklers with nozzle size of 8 mm at 300 kPa




a. PXH20



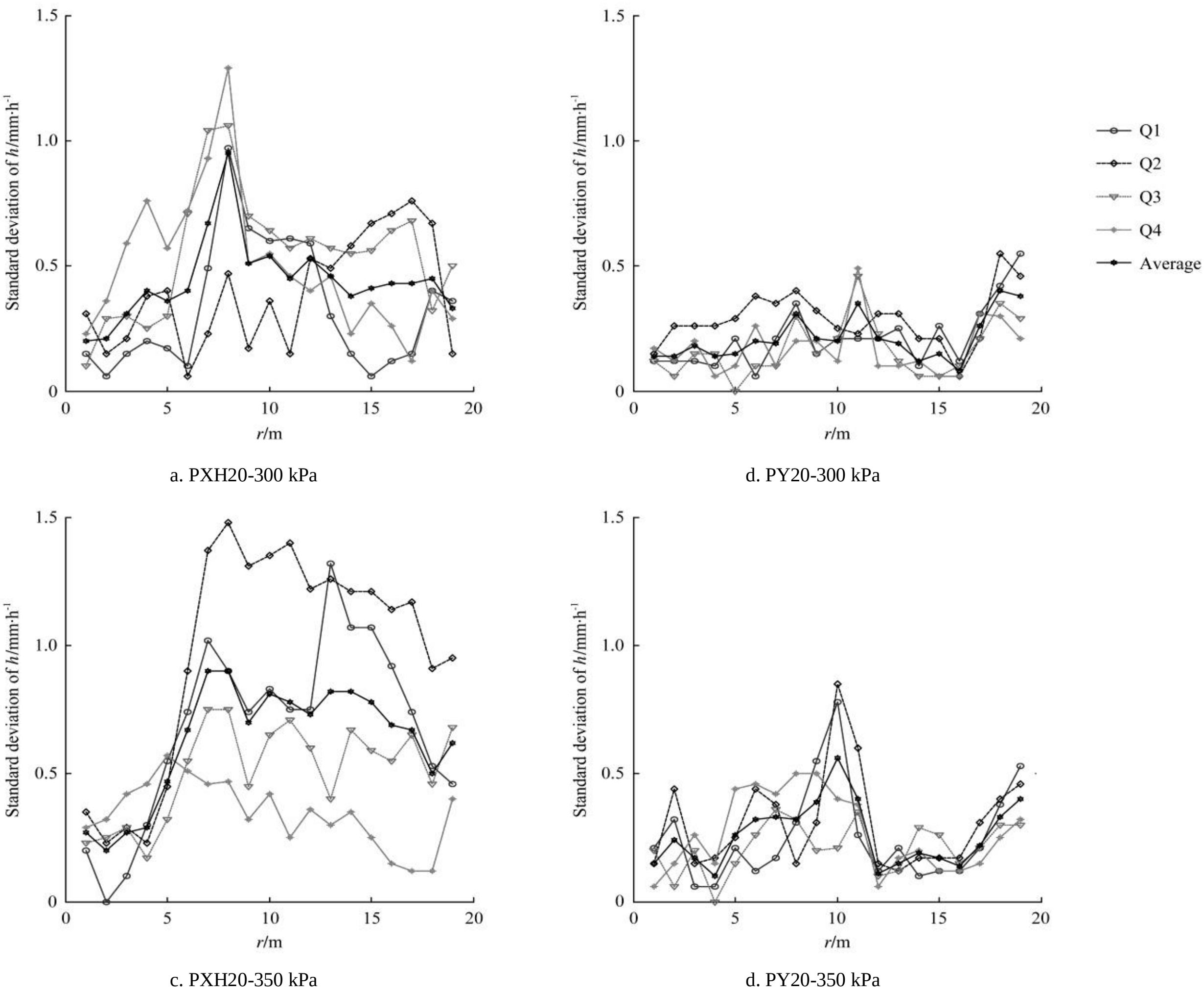

b. PY20

Figure 7 Sample water application pattern for the PXH20 and PY20 sprinklers with nozzle size of 8 mm at 300 kPa. The color bars indicate the water application rate

### 3.3 Deviation in water application intensity

The standard deviations of water application rate along individual radii within the four quadrants of rotation are shown in Figure 8. The variations in standard deviation were quite high. Again, the form of the plotted data for individual quadrants looks similar for almost all quadrants for the same sprinkler configurations. This can be attributed to the fact that variations in water application rate were quite consistent at the same distances along the radial lines, and for that matter, their respective quadrants.

For the PY20 sprinkler at 300 kPa and radial distances of 8, 10 and 16 m, ranges of standard deviation were 0.31-0.40, 0.12-0.25 and 0.26-0.55 mm/h, respectively. In the case of PXH20 at 300 kPa, ranges of standard deviation were 0.47-1.29, 0.36-0.64 and 0.12-0.71 mm/h at radial distances of 8 m, 10 m and 16 m, respectively. They indicate that variations in water application rate are quite significant and the PXH sprinkler appears to have more variability in application rate (0-1.5 mm/h) than the PY sprinkler (0-0.8 mm/h). This can possibly be traced to the design features of the fluidic component of the fluidic sprinkler. This is because the fluidic component is the main feature responsible for the stepwise rotation of the fluidic sprinkler. The impact sprinkler on the other hand, rotates by the impact of a swinging arm which repeatedly strikes the body of the sprinkler. Further optimization of the design features of the fluidic component will therefore be necessary to minimize variability in water application rate by improving the rotation stability of the fluidic sprinkler.




a. PXH20-300 kPa

d. PY20-300 kPa

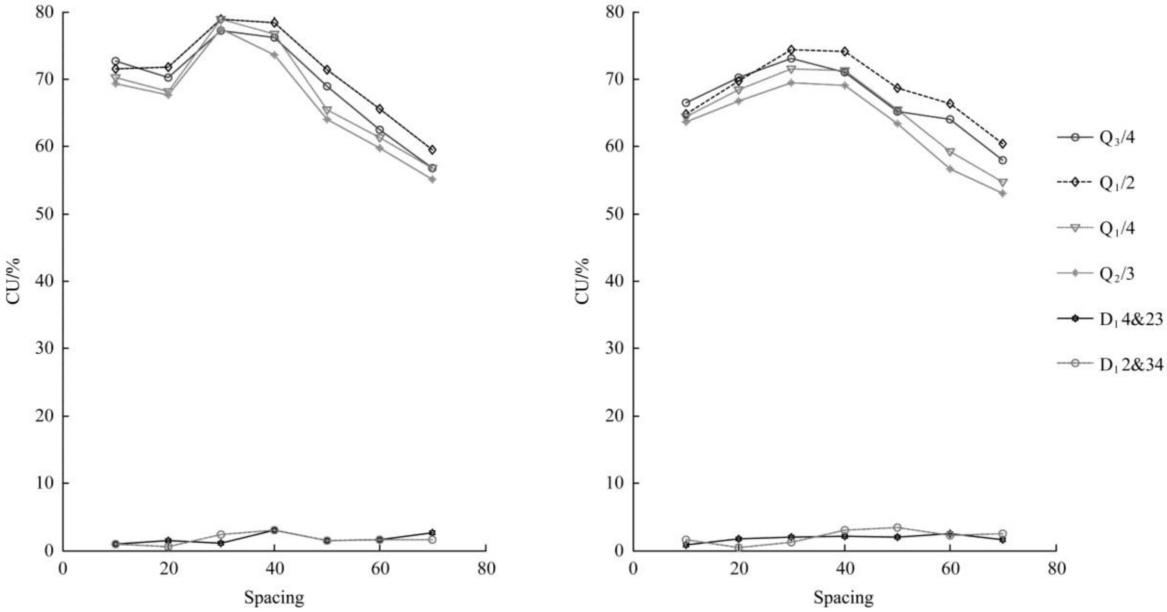
c. PXH20-350 kPa

d. PY20-350 kPa

Figure 8 Standard deviation of water application rate against distance from sprinkler within quadrants

### 3.4 Overlap distribution analysis

Differences in CU values between overlapped quadrants for the same configuration of sprinkler distribution were very small and quite negligible (Figure 9). The obvious explanation could be that positions of higher water application depths overlapped with positions of lower application depth from the other quadrant, producing overall uniform distribution. The converse is also true, leading to lower CU [22]. For instance, for PXH20 sprinkler, the largest difference in CU values for the overlapped quadrants was 3.04% for $Q_1/2$ and $Q_3/4$ at 40% spacing and the lowest was 0.44% for $Q_1/2$ and $Q_3/4$ at 20% spacing. Overlap of quadrants for the PY sprinklers gave similar results (Figure 9). The negligible differences in CU for overlapped quadrants indicate the importance of sprinkler spacing in dampening the effect of non-uniform water application.




a. PXH20 b. PY20

Figure 9 CU values of overlapped quadrants against spacing for the PY20 and PXH20 sprinklers with nozzle size of 8mm at 300 kPa. Horizontal overlaps (x-direction) are: 1st & 2nd quadrants represented as $Q_1/2$; 3rd & 4th quadrants represented as $Q_3/4$. Vertical overlaps (y-direction): 1st & 4th quadrants represented as $Q_1/4$; 2nd & 3rd quadrants represented as $Q_2/3$. $D_1$2 & 34 and $D_1$4 & 23 are the differences in the CU values of the respective overlaps.

## 4 Conclusions

This study has significantly highlighted some performance qualities of the complete fluidic sprinkler in comparison to that of the impact sprinkler. The findings of this research will help to improve the efficiency of the new type complete fluidic sprinkler. Completion time variations through the quadrants were higher for the fluidic sprinkler compared to the impact sprinkler. Quite significant deviation and variations in water application intensity across the quadrants were observed for both sprinklers. Relatively higher standard deviations in water application rate were also observed for the fluidic sprinkler. Optimization of the design features of the fluidic component is necessary to improve the rotation stability and to minimize variability in water application rate of the fluidic sprinkler. Differences between CU values of overlapped adjacent quadrants were quite negligible for the same configuration of the sprinkler, indicating the importance of proper sprinkler spacing to minimize the effect of water application rate variability. Improving upon the design features as highlighted in the study will maximize the fluidic sprinklers efficiency.

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