Romanian Journal of Civil Engineering, Volume 17 (2026), Number 3

Contributions to the resolution of issues relating to the performance of fire extinguishing sprinkler systems (2)

Contribuții la rezolvarea unor problematici privind performanța sprinklerelor utilizate în stingerea incendiilor (2)

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DOI: 10.37789/rjce.2026.17.3.3

Abstract. *This paper presents an in-depth experimental and analytical study focused on evaluating the performance of sprinkler systems used in fire suppression. The research explores the interaction between droplet distribution, droplet velocity, kinetic energy, and their role in effective fire control. Various measurement and evaluation methods were applied, including Laser Precipitation Monitors (LPM), image processing techniques, and multiple coefficients for distribution uniformity. The study also details a flexible and mobile experimental stand developed to test different types of sprinklers under controlled conditions. Conclusions are drawn based on data gathered from both field and laboratory conditions, offering practical recommendations for system configuration, operation, and optimization.*

Key words: *Fire suppression, sprinkler systems, droplet size, CFD simulations, performance evaluation*

1. Introduction

Designing and executing fire suppression systems that use sprinklers involves several complex challenges, such as extrapolating droplet behavior beyond the standardized test height, accounting for airflow disturbances, evaluating drop distribution in irregular geometries, and managing variable heat release rates. Due to the limitations of traditional full-scale fire testing, computational and instrument-based measurements now provide critical insights for improving sprinkler performance.

The article was received on 27.04.2025, accepted on 11.09.2026 and published on 22.09.2026
The first part of this article was published in Romanian Journal of Civil Engineering, Volume 17 (2026), Number 2

2. Experimental setup and methodologies

2.1. Description of the mobile experimental sprinkler stand

General dimensions:

- **Stand height:** 2000 mm (2 meters)
- **Stand width:** 2000 mm (2 meters)
- **Stand length:** 3000 mm (3 meters)
- **Base height:** 1000 mm (1 meter)
- **Total stand height:** 3000 mm (3 meters)
    - Note: Sprinkler head manufacturers provide spray cone diagrams for a height of 3 meters measured from the sprinkler nozzle.

Main structure:

- The stand is constructed from 2-inch zinc pipes, forming the main frame.
- Pipes are arranged vertically and horizontally to create a robust support for mounting sprinklers.
- It is a mobile structure with 4 wheels at the base.

Connections and fittings:

- The stand is equipped with threaded plugs of 1/2 inch and 3/4 inch, alternately placed for mounting sprinklers:
    - **1/2 inch threaded plugs:** 8 pieces
    - **3/4 inch threaded plugs**: 8 pieces
    - **2-inch connection for pumps** with parameters Q= mc/h and H = mH2O

Sprinkler configuration:

- Sprinklers are mounted on the threaded connections, evenly distributed across the stand.
- Two types of sprinklers are used on the top bar of the stand:
    - **Bronze sprinkler head down 1/2"; 68°C, K 80, STANDARD**
    - **Bronze sprinkler head down 3/4"; 68°C, K115, STANDARD**

Sprinkler distribution:

- Sprinklers are placed so that each connection supports one of the two types of sprinklers, ensuring uniform and alternating distribution:
    - 1/2" threaded plug -> Bronze sprinkler head down 1/2"
    - 3/4" threaded plug -> Bronze sprinkler head down 3/4"

Stand sections:

- The stand is divided into sections of 1000 mm in width and 3000 mm in length, creating a network of supports for the mounted sprinklers.

Experimental use:

1. **Water distribution measurement:**
    - The stand allows simultaneous mounting and testing of multiple sprinklers to evaluate water distribution and performance under controlled conditions.
    - Data can be collected on flow rate, operating pressure, and spray uniformity.

2. **Flexible configuration:**
   - Due to the alternating 1/2-inch and 3/4-inch connections, the stand offers flexibility in changing and reconfiguring the types of sprinklers used.
3. **Precise measurements:**
   - Collection containers (e.g., trays, precipitation cylinders) can be placed under each sprinkler to measure the volume and distribution of applied water.
4. **Monitoring and analysis:**
   - The stand allows the installation of additional equipment, such as distrometers, to measure the size and number of droplets in the spray cone.

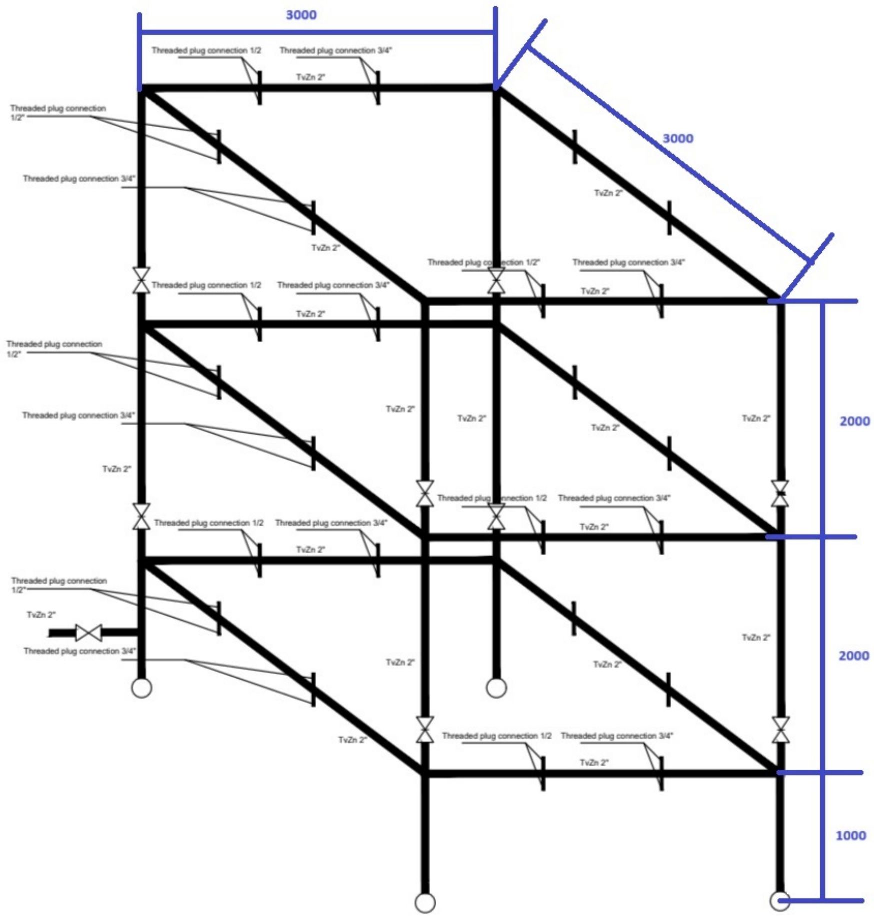

Fig. 1. Design of the experimental and research stand

Equipping the stand with sprinklers

For:

Bronze Sprinkler Head Down 1/2"; 68°C, K 80, STANDARD

General characteristics:

- Model: Pendent sprinkler, bronze.
- Connection Diameter: 1/2 inch.

- Operating Temperature: 68°C.
- K-Factor: 80 (metric units).

Flow characteristics:

- K-Factor: 80.
- Flow relationship: $Q=KP$

Where:

- Q is the water flow rate (l/min),
- K is the sprinkler coefficient (l/min·bar 0.5),
- P is the pressure at the sprinkler head (bar).

Example calculation:

- At 1 bar: Q=80 l/min.
- At 2 bars: Q=113 l/min.
- At 3 bars: Q=139 l/min.

Operating pressure:

- Typical operating pressure: between 1 and 3 bars (depending on manufacturer specifications).

Spray cone dimensions:

- Installation height (H): Depends on installation specifications and ceiling mounting height.
- Minimum spray cone section: Approximately 2-3 meters (standard height).
- Maximum spray cone section: Up to 4-5 meters (depends on operating pressure and system configuration).

Bronze Sprinkler Head Down 3/4", 68°C, K115, STANDARD

General Characteristics:

- Model: Pendent sprinkler, bronze.
- Connection diameter: 3/4 inch.
- Operating temperature: 68°C.
- K-Factor: 115 (metric units).

Flow characteristics:

- K-Factor: 115.
- Flow relationship: $Q=KP$

Where:

- Q is the water flow rate (l/min),
- K is the sprinkler coefficient (l/min·bar0.50.5),
- P is the pressure at the sprinkler head (bar).

Example calculation:

- At 1 bar: Q=115 l/min.
- At 2 bars: Q=163 l/min.
- At 3 bars: Q=199 l/min.

Operating pressure:

- Typical operating pressure: between 1 and 3 bars (depending on manufacturer specifications).

Spray cone dimensions:

- Installation Height (H): Depends on installation specifications and ceiling mounting height.
- Minimum spray cone section: Approximately 2-3 meters (standard height).
- Maximum spray cone section: Up to 4-5 meters (depends on operating pressure and system configuration).

These specifications often include performance graphs, spray distribution diagrams, and installation instructions, providing precise information about flow rate, pressure, and spray cone dimensions.

2.2. METHOD 1 Applied to the structure and design of the experimental stand

A detailed methodology is proposed to use the Christiansen Uniformity Coefficient (CUC) to evaluate the uniformity of water distribution in a trigger area Ad, specifically in the context of the stand.

Types of water collection containers:

- **Precipitation cylinders:**
    - Graduated plastic or glass cylinders used to measure the amount of water collected at a specific point.
- **Collection trays:**
    - Flat trays of various sizes used to collect and measure water distributed by sprinklers. These are typically made of waterproof materials and positioned in the field to capture sprayed water.
- **Collection cups:**
    - Small cylindrical containers placed at various measurement points to collect sprayed water.
- **Collection containers:**
    - Any type of container (e.g., plastic cups, jars) that can be used to collect and measure sprayed water.

Proper use of collection containers:

- **Positioning containers:**
    - Containers are placed in a dense matrix under the sprinkler spray area to capture variations in water distribution.
- **Measuring water:**
    - After collecting water, the volume of water in each container is measured to calculate the water depth (hi).

- **Data analysis:**
  - With the collected data, the average water depth is calculated, and absolute deviations and the uniformity coefficient are determined.

Detailed methodology:

1. **Experiment setup**

Experimental stand:

- The 8 sprinkler heads are placed at the top of the stand according to the design.
- Sprinklers are positioned at established distances on the stand and mounted with heads down in the two types of 1/2 and 3/4 inch fittings on the top bar of the stand. All other fittings in the structure are sealed with plugs.
- The stand is connected to the pumping group to ensure minimum and maximum flow parameters Q and pumping height H, and to the water source to provide the water volume for at least 30 minutes at maximum flow and maximum operating pressure, considering linear, local losses, and geodetic height. A flow meter can be placed between the pumping group and the stand connection. A pressure gauge is mounted on one of the stand's top bars in a 1/2 inch fitting.

Measurement area:

- The measurement area under the experimental stand is established, considering that this is the area to be protected, covering the entire spray area of the 8 (4) sprinklers.
- Collection containers (e.g., collection boxes) are arranged in a dense matrix in this area, with a total surface area equal to the calculated spray area of the sprinklers' capacity, to capture droplets and variations in spray intensity from the overlapping spray cones of the sprinklers.
- Σ Base surface of boxes + Σ Spray surface of sprinklers in the cone sections corresponding to the protected area.

2. **Measuring water distribution**

Measuring water volume:

- The pumping group is started after verifying that the water source ensures the pumping flow. The system is filled and vented through an automatic vent or vent vessel placed at the top of the stand.
- All 8 (4) sprinkler heads are operated simultaneously, and water is collected in containers for a determined period (e.g., 30 minutes).
- The volume of water collected in each container/collection box is measured, and the water depth (hi) is calculated at each measurement point.

3. Calculating average water depth

Average water depth:

- The average water depth (hm) is calculated using the formula:

$$h_m = \frac{1}{n} \sum_{i=1}^{n} (hi) \ (1)$$

Where:

- n is the number of collection containers.

4. Calculating absolute deviations

Absolute deviations:

- Absolute deviations from the average water depth:

$$/ h_m - h_i /) \ (2)$$

are calculated for each measurement point.

5. Calculating Christiansen Uniformity Coefficient

Sum of absolute deviations:

- The sum of absolute deviations is calculated:

$$\sum_{i=1}^{n} \mid hm - hi \mid \ (3)$$

Christiansen Uniformity Coefficient (CUC):

- The uniformity coefficient CUC is obtained using the relationship:

$$CUC = [1 - \left(\sum_{i=1}^{n} \mid hm - hi \mid \right) x \frac{1}{n \ x \ hm}] = \times 100\% \qquad (4)$$

6. Additional considerations

Operating pressure and flow:

- The operating pressure for each type of sprinkler is checked and adjusted to ensure they function within specified parameters.

Data analysis:

- The uniformity of water distribution is analyzed to identify possible variations in the performance of different types of sprinklers.
- Based on the results, the experimental configuration is adjusted to improve performance if necessary.

Results analysis:

- All observations and obtained results are recorded, including calculated CUC values and any adjustments made.

2.3. METHOD 2 Applied to the structure and design of the experimental stand

In specialized literature, there are several methods like the Christiansen Uniformity Coefficient (CUC) for evaluating the uniformity of water distribution in sprinkler systems. One of the most common alternative methods is:

1. **Heermann and Hein Uniformity Coefficient (CUH)**

$$CUH = [1 - (\sum_{i=1}^{n} \mid hi - hm \mid) / \sum_{i=1}^{n} hi\ ] = \times 100\% \quad (5)$$

Where:

- hi is the depth of water collected at point i,
- hm is the average depth of water collected,
- n is the number of measurement points.

2. **Distribution Uniformity Coefficient (DU)**

The Distribution Uniformity Coefficient (DU) is used to evaluate the efficiency of distribution, specifically the intensity of spraying. The calculation formula for DU is:

$$DU = \frac{hmin}{hm}\ x\ 100\% \quad (6)$$

Where:

- $hmin$ is the average depth of water from the 25% of points with the lowest values,
- hm is the average depth of water collected.

3. **Application Uniformity (UA)**

Application Uniformity (UA) is like CUC and is used to evaluate the uniformity of water distribution over a sprayed area. The formula for UA is:

$$UA = [1- (\sum_{i=1}^{n} \mid hi - hm \mid)/ \sum_{i=1}^{n} hm \ ] = \times 100\% \ (7)$$

4. Coefficient of Variability (CV)

The Coefficient of Variability (CV) is used to measure the variability of the applied water depth. The formula for CV is:

$$CV = \frac{\sigma}{hm} \ x \ 100\% \ (8)$$

Where:

- σ is the standard deviation of the collected water depth,
- hm is the average depth of water collected.

5. System Performance Index (SPI)

The System Performance Index (SPI) is a complex measure that considers both the uniformity of water distribution and the efficiency of water application. SPI is defined as:

$$SPI = \frac{DU \ x \ Ea}{100} \ (9)$$

Where:

- DU is the Distribution Uniformity Coefficient,
- Ea is the efficiency of water application.

Calculating the efficiency of water application (Ea) in sprinkler systems for fire suppression is essential for evaluating system performance. By collecting and analyzing data on the volume of water applied and effectively used, the system's efficiency can be determined, and opportunities for performance improvement and risk reduction associated with fires can be identified.

3. Calculation methodology for application efficiency (Ea) in fire sprinkler systems

1. Defining Water Volumes:

- Applied Water Volume (V_applied): The total volume of water discharged by the sprinkler system during an operational cycle. This can be measured using water meters installed on the sprinkler supply system.
- Effectively Used Water Volume (V_utilized): The volume of water that actively contributes to extinguishing the fire or protecting surfaces from excessive heat. This can be determined through direct measurements and post-fire analyses.

2. Data Collection:

- Applied Water Volume (V_applied):
  - The test stand is equipped with a water meter or flowmeter to record the total volume of water used by the sprinkler system.
  - Alternatively, the total volume can be calculated based on the nominal flow rate of each sprinkler head and the operating time.
- Effectively Used Water Volume (V_utilized):
  - After the fire is extinguished or after the predefined experimental time, the affected areas are assessed to determine the efficiency of water use. This may include measuring residual water, or the amount collected in control zones.
  - In a real fire scenario, post-fire analysis and visual inspection help estimate the proportion of water that effectively contributed to controlling and extinguishing the fire.

3. Application Efficiency (Ea) calculation:

The application efficiency is calculated using the formula:

$$Ea(\%) = (V_{utilizat}/V_{aplicat})\times 100 \quad (10)$$

Example calculation:

- Suppose that during one operational cycle, the sprinkler system discharged a total of 10.000 liters of water (V_applied).
- Post-event evaluation determined that 7,500 liters were effectively used for fire suppression and surface protection (V_utilized).

Thus, the application efficiency would be: Ea (%)= 75%

This means that 75% of the applied water was effectively used to control and extinguish the fire.

4. Factors influencing Application Efficiency (Ea):

1. **Distribution uniformity:** Non-uniform water distribution can result in over-irrigated and under-irrigated areas. Ensuring even water coverage significantly improves application efficiency.
2. **Pressure and flow rate:** Proper pressure and appropriate flow rate are essential for optimal sprinkler performance. Regular inspection and maintenance of these parameters can greatly impact efficiency.
3. **Interference and obstacles:** Furniture, equipment, or other physical barriers may obstruct or deflect water spray, reducing effectiveness. Proper space planning and arrangement can mitigate these issues.

4. **Sprinkler type and nozzle characteristics:** Selecting the appropriate sprinkler type and nozzle design for the specific application maximizes coverage and optimizes water use efficiency.

4. Methodology for using a disdrometer to evaluate sprinkler performance for fire suppression applications

Test stand:

- **Stand Dimensions:** Height: 2000 mm, Width: 2000 mm, Length: 3000 mm.
- **Types of sprinklers used:**
  - 4 units of Standard Bronze Pendent Sprinklers, 1/2", 68°C, K80.
  - 4 units of Standard Bronze Pendent Sprinklers, 3/4", 68°C, K115.
- **Sprinkler arrangement:** Sprinklers were alternately mounted on 1/2-inch and 3/4-inch threaded pipe fittings to ensure a uniform distribution of each type across the stand.

Disdrometer:

- Model Used: Optical disdrometer for droplet size and velocity measurement.

Methodological steps

1. **Setting up the experimental stand:**
   - Install the eight sprinkler heads on the stand according to the specified layout and design.
   - Ensure that each sprinkler is correctly connected to the water supply system and operates at the specified pressure.
2. **Mounting the disdrometer:**
   - Position the disdrometer so it can measure the droplet size and velocity within a cross-section of the spray cone.
   - Align the device carefully to accurately capture the necessary data.
3. **Configuring and calibrating the disdrometer:**
   - Set up the disdrometer according to the manufacturer's instructions.
   - Calibrate the device to guarantee precise measurements of droplet size and velocity.
4. **Data collection:**
   - Operate the sprinklers at the specified pressure and flow rates.
   - Measure droplet size and velocity at different heights and positions within the spray cone using the disdrometer.
   - Record data on droplet size, number, and distribution in each cross-section.
5. **Measurements at 1-meter intervals:**
   - Perform droplet size and velocity measurements at 1-meter intervals from the sprinkler heads.

  - Document the disdrometer's angle and position at each measurement location.

6. **Data filtering and analysis:**
   - Filter the collected data to eliminate errors caused by droplet coincidence and edge effects.
   - Group droplet size measurements in 0.1 mm increments, ranging from 0.25 mm to 7.95 mm.
   - Exclude droplets smaller than 0.2 mm in diameter.
   - Eliminate droplets with velocities exceeding ±2 standard deviations from the mean velocity measured for a given droplet size at a specific radial location.
7. **Kinetic energy calculation:**
   - Calculate the kinetic energy of each droplet measured at each radial measurement location.
   - The kinetic energy per unit volume of water applied (J/L) is obtained by dividing the cumulative kinetic energy of measured droplets by the total measured water volume.
8. **Evaluation of droplet size distribution and kinetic energy:**
   - Compare the measured droplet size distributions with those obtained through alternative measurement methods.
   - Calculate the average droplet size distributions and kinetic energy for each sprinkler type.
9. **Fire Suppression applicability:**
   - Assess the uniformity of water distribution and the efficiency of spray coverage based on the kinetic energy transferred to the ground or protected surfaces.
   - Determine whether the sprinkler type and setup provide adequate and uniform coverage for effective fire suppression.
10. **Documentation and reporting:**
   - Record all observations, measurements, and calculated results.
   - Prepare a comprehensive report including conclusions regarding the sprinkler system's performance and recommendations for improvements.

This detailed methodology leverages a disdrometer to evaluate the performance of sprinklers used for fire suppression purposes. It provides accurate data regarding droplet size and velocity, enabling precise calculation of the kinetic energy transfer—an essential factor in ensuring efficient and uniform coverage during firefighting operations.

5. Methodology for using imaging systems to evaluate sprinkler performance for fire suppression applications

Test Stand:

- **Stand dimensions:** Height: 2000 mm, Width: 2000 mm, Length: 3000 mm.

- **Types of sprinklers used:**
  - 4 units of Standard Bronze Pendent Sprinklers, 1/2", 68°C, K80.
  - 4 units of Standard Bronze Pendent Sprinklers, 3/4", 68°C, K115.
- **Sprinkler arrangement:** Sprinklers were alternately mounted on threaded pipe fittings of 1/2 inch and 3/4 inch, ensuring an even distribution of each sprinkler type across the stand.

Imaging systems:

- High-speed cameras for capturing images of water droplets within the sprinkler spray cone.
- Specialized image analysis software for measuring droplet size and distribution based on the captured images.

Methodological steps

1. **Setting up the experimental stand:**
   - Install the eight sprinkler heads on the test stand according to the design and specifications provided.
   - Ensure that each sprinkler is properly connected to the water supply and operates at the designated pressure.
2. **Installing and configuring the imaging system:**
   - Position the high-speed cameras to capture clear images of the droplets within the spray cone of each sprinkler.
   - Align the cameras correctly to cover different cross-sections of the spray pattern.
   - Adjust camera settings (e.g., recording speed, resolution) to obtain high-quality images of the droplets.
3. **Data collection:**
   - Operate the sprinklers at the specified pressure and flow rates.
   - Capture images of the droplets at different heights and positions within the spray cone.
   - Ensure that images cover multiple sections to provide a comprehensive view of droplet distribution.
4. **Measurements at 1-meter intervals:**
   - Capture images at intervals of 1 meter from the sprinkler heads.
   - Document the camera position and angle at each measurement location.
5. **Image analysis:**
   - Analyze the captured images using image processing software to measure droplet size and distribution.
   - Filter the data to remove artifacts and measurement errors.
   - Group the droplet size measurements into 0.1 mm increments for detailed analysis.
6. **Kinetic energy calculation:**
   - Calculate the kinetic energy of each measured droplet based on its size and estimated velocity.

- Compute the kinetic energy per unit volume of water applied (J/L) by dividing the total kinetic energy by the measured water volume.

7. **Evaluation of droplet size distribution and kinetic energy:**
   - Compare the measured droplet size distributions with those obtained from other measurement methods.
   - Calculate the mean droplet size distributions and kinetic energy for each sprinkler type.

8. **Fire suppression applicability:**
   - Evaluate the uniformity of water distribution and the effectiveness of spray coverage based on the kinetic energy transferred to the ground or protected surfaces.
   - Determine if the sprinkler configuration and type provide adequate and uniform coverage for effective fire suppression.

9. **Documentation and reporting:**
   - Record all observations, measurements, and calculated results.
   - Prepare a comprehensive report including conclusions on sprinkler system performance and recommendations for improvements.

Specific details for using imaging systems

Principle of imaging systems:
- High-speed cameras capture moving droplets within the sprinkler spray cone.
- Images are processed using specialized software to measure droplet size and distribution.
- The data provide an accurate characterization of droplet size and dispersion patterns.

Recommended equipment:
- High-Speed Cameras: For capturing sharp images of moving droplets.
- Image Analysis Software: For precise measurement of droplet size and distribution.

Following the analysis and measurements, the results confirmed that the droplet distribution complies with the specifications outlined in Table 1.

The calculations were carried out in tabular form based on the measurements taken from Sprinkler Head 1 at an operating pressure of P = 1 bar, recorded every 5 minutes up to 30 minutes. The results are presented in Table 1.

The absolute deviations range between 0.5 mm and 3.25 mm, which are relatively small compared to the average depth, suggesting that the water distribution in the four trays is very uniform. This uniformity is essential for fire suppression systems, as a homogeneous water distribution across the entire protected area helps reduce temperatures and prevent the spread of fire. The largest deviations occur at t6

(30 minutes), when the total water volume is at its maximum. Even under these conditions, the distribution remains uniform, indicating reliable system performance in scenarios with higher water flow rates.

Table 1.

Calculating the Christiansen Uniformity Coefficient (CUC)

Measurement Time	Water Depth in Tray 1-h1 [mm]	Water Depth in Tray 2-h2 [mm]	Water Depth in Tray 3-h3 [mm]	Water Depth in Tray 4-h4 [mm]	Average Water Depth - hm [mm]	Calculation of Absolute Deviations from the Average Water Depth				Sum of Absolute Deviations	Christiansen Uniformity Coefficient (CUC) [%]
						Tray Deviation 1 [mm]	Tray Deviation 2 [mm]	Tray Deviation 3 [mm]	Tray Deviation 4 [mm]		
t_0 =0 min	0	0	0	0	0	0	0	0	0	0	100
t_1 = 5 min	44	42	45	43	43,5	0,5	1,5	1,5	0,5	4,0	97,70
t_2 = 10min	89	85	87	90	87,75	1,25	2,75	0,75	2,25	7,0	98,00
t3 = 15 min	133	131	130	135	132,25	0,75	1,25	2,25	2,75	7,0	98,68
t4 = 20 min	178	179	175	173	176,25	1,75	2,75	1,25	3,25	9,0	98,72
t5 = 25 min	222	220	223	225	222,5	0,5	2,5	0,5	2,5	6,0	99,33
t_6 =30 min	267	261	264	263	263,75	3,25	2,75	0,25	0,75	7,0	99,34

The CUC values, ranging from 97.70% to 99.34%, demonstrate a good uniformity of water distribution, which is essential for an effective fire suppression system. A high CUC suggests that water is evenly dispersed in all directions, reducing the risk of leaving certain areas uncovered. This very good uniformity indicates that at a pressure of 1 bar, the sprinkler effectively covers the protected area, ensuring that the entire surface receives an adequate amount of water to control or extinguish a fire.

6. Conclusions

This methodology employs advanced imaging systems to evaluate the performance of sprinklers specifically designed for fire suppression applications. By utilizing high-speed cameras and image analysis software, the method enables the precise measurement of droplet size and distribution within the sprinkler spray cone.
Accurate data regarding droplet size and distribution are critical for ensuring efficient and uniform water coverage during fire suppression operations. Uniform distribution improves the sprinkler's ability to suppress fires effectively, minimizing unprotected zones and optimizing the use of water resources. Furthermore, by analyzing droplet characteristics, it becomes possible to better understand the dynamics of water dispersion, which directly influences the kinetic energy transferred to the protected surfaces — a key factor in fire control efficiency.

Through detailed image-based evaluation, this approach provides valuable insights for selecting, configuring, and improving sprinkler systems to enhance their real-world performance. Ultimately, the use of imaging systems supports the design of safer, more reliable fire suppression strategies by ensuring that sprinklers deliver water where it is most needed, with the appropriate energy and coverage.

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