

EVALUATION OF THE PERFORMANCE OF SPRINKLER FIRE EXTINGUISHING SYSTEMS IN COLD STORAGE USING THE DISTRIBUTION UNIFORMITY COEFFICIENT (DU)

Cosmina FLORICA¹, Andrei DUNĂ², Lucian-Vasile MIHOC³, Iulia ȘTIRB⁴, Valentin GOMOI⁵, Ștefan DUNĂ⁶

Abstract: The implementation of sprinkler fire suppression systems involves significant challenges in the design and evaluation of effectiveness, due to the lack of standardized methods and the limitations of the coverage diagram provided by manufacturers. Engineers often rely on large-scale tests, which do not always reflect real-world fire conditions. Technological advances in measuring droplet size and velocity now offer new perspectives for computational modeling of sprinkler water spray behavior. The aim of the research was to measure the characteristics of the sprinkler water jet to obtain the data needed for computational simulations. Experiments were performed on a dedicated test stand to calibrate and verify the uniformity of water distribution within the spray pattern. Initial measurements indicated a uniform water distribution, with a Distribution Uniformity Coefficient (DU) exceeding 97%, confirming the effectiveness of the sprinkler at a pressure of 1 bar. The results suggest that the water distribution is homogeneous and adequate for fire suppression. However, the research needs to be expanded to include a wider range of sprinkler types, to ensure that the conclusions obtained are broadly applicable to different commercially available models.

Key words: Fire suppression, Sprinkler systems, Uniformity coefficient, Laser Precipitation Monitor (LPM), Water distribution, Droplet size, Velocity, Computational modeling.

1. INTRODUCTION

Buildings requiring sprinkler fire suppression systems, such as cold storage warehouses in logistics centers, face stringent fire protection requirements. In these spaces, where large quantities of temperature-sensitive goods are stored, a fire can cause significant damage and considerable economic losses. Sprinkler systems play a crucial role in limiting the spread of fire and protecting stored goods, but their effectiveness depends on precise design and continuous performance evaluation. To evaluate the effectiveness of these systems, the **System Performance Index (SPI)** is an essential tool, as it combines the **uniformity of water distribution** (assessed by the Christiansen Uniformity Coefficient – CUH), the Distribution Uniformity Coefficient (DU) and the **efficiency of water application**. Uniform water distribution is essential to prevent hot spots and ensure complete coverage of the protected area, while application efficiency minimizes losses and optimizes the amount of water applied to the critical area. For the present study, a dedicated experimental stand was used to test and calibrate the sprinkler system. A **distrometer** was used to measure the number, size and volume of water droplets in each cross-section of the spray cone. This method allows a detailed assessment of the behavior of the water droplets and provides essential data for optimizing the water distribution pattern. The first measurements performed showed a uniform water distribution, with a CUH and Du coefficient of over 97%, demonstrating that the system can provide effective coverage at a pressure of 1 bar. However, to confirm the broad applicability of these results, further tests are needed on various types of sprinklers and in different configurations.

In cold storage warehouses within logistics centers, fire protection is a complex challenge, driven by the high heat load density associated with frozen products such as meat. These products generate a significant heat load, even at low temperatures, amplifying the need for effective fire suppression systems. In this context, sprinkler systems mounted on the ceiling of cold storage warehouses and additional level 2 sprinkler systems mounted on the ceiling of logistics warehouses above them contribute to fire protection, but their performance must be evaluated and optimized to cope with unique conditions.

¹Assistant Prof., PhD in Eng., University Politehnica Timișoara, România, email: cosmina.florica@upt.ro

²Student, University Politehnica Timișoara, România, email: andrei.duna@student.upt.ro

³PhD student, University Politehnica Timișoara, România, email: mihoc.lucian@gmail.com

⁴Lecturer, PhD in Eng., Ioan Slavici University, Timisoara, Romania, email: iulia.stirb@islavici.ro

⁵Lecturer, PhD in Eng., Ioan Slavici University, România, email: gomoivalentin@yahoo.com

⁶Lecturer, PhD in Eng., University Politehnica Timișoara, România, email: stefan.duna@upt.ro

1.1. Goals of sprinkler systems in cold storage

The goals of sprinkler systems in cold storage facilities are to:

- **Provide direct application of water to the combustible material**, reducing the rate of combustion and preventing the generation of additional flammable vapors.
- **Wet surrounding materials** to slow the rate of flame spread and limit the spread of fire to adjacent areas.
- **Cool the ambient air** by evaporation, displacing the air with inert water vapor, to reduce local temperatures and limit the formation of flammable gases.

To evaluate the effectiveness of these systems, research uses the **System Performance Index (SPI)**, which combines the **Christiansen Uniformity Coefficient (CUH)**, the **Distribution Uniformity Coefficient (DU)**, and the **water application efficiency**. The SPI provides a composite measure of the uniformity of water distribution and the efficiency with which the water reaches the target surface, essential aspects in evaluating the performance of the extinguishing system in a cold storage facility where the risks are amplified by the high heat load. **The use of the experimental stand** in this study allows the precise measurement of the number, size and volume of water droplets in each cross-section of the sprinkler spray cone, using a distrometer. This instrument provides detailed information on the water jet behavior and droplet dynamics, essential for optimizing the water distribution model under real operating conditions. The research aims to develop a solid experimental data base to validate and calibrate computational simulations of water spray, evaluating how each component of the extinguishing system contributes to reducing fire risks in cold storage facilities. By analyzing the performance of both the sprinkler system installed in the cold storage facility and the level 2 installation, the study aims to provide an integrated approach to fire protection, tailored to the specific needs of cold storage facilities in logistics centers.

1.2. Description of the mobile sprinkler test stand

To research and test the performance of sprinkler systems in a controlled context, a mobile experimental stand was used, configured to provide flexibility and accuracy in measuring relevant parameters.

Overall dimensions: stand height: 5000 mm (5 meters); width: 3000 mm (3 meters); length: 3000 mm (3 meters) and base height: 1000 mm (1 meter).

The sprinklers are mounted on the threaded connections, evenly distributed over the surface of the stand to ensure effective coverage. Bronze low-head sprinklers of 3/4", at 68°C and a K-factor of 115 are used on the upper bar of the stand. The configuration is designed so that each connection supports a suitable sprinkler, maintaining a uniform alternation and distribution: 3/4" thread connection -> Bronze low-head sprinkler 3/4", K115, 68°C.

The stand allows the mounting of additional equipment, such as a distrometer, which is used to measure the size, number and volume of droplets in each section of the sprinkler spray cone.

Sprinkler type: low-head (pendant), bronze material; Connection diameter: 3/4 inch; Operating temperature: 68°C; K-factor: 115 (l/min·bar^{0.5}); Flow relationship: $Q = K \sqrt{P}$.

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).

2. METHOD AND PROCEDURE

2.1. Establishment of the measurement area

The measurement area is established under the experimental stand, being considered as the area to be protected, so as to fully cover the spray area of the 2-4) sprinklers. Collection containers (e.g. collection boxes) are arranged in a dense matrix in this area, having a total area equal to the spray area calculated for the sprinkler capacity. They are placed to capture the droplets and the variations in spray intensity, resulting from the overlapping of the sprinkler spray cones.

Σ Box base area + Σ Sprinkler spray area in the spray/stop cone sections related to the protected area.

2.2. Measurement of the volume of water collected

To initiate the measurements, the pumping system is activated after it has been confirmed that the water source provides the required flow rate. The entire system is filled and vented either through an automatic vent or through a vent vessel located at the top of the experimental stand to remove any residual air.

All 2-4 sprinkler heads are activated simultaneously, and the sprayed water is collected in measuring containers arranged in a matrix for a set period (e.g. 30 minutes). After this period, the volume of water in each container is carefully measured to determine the exact amount of water distributed by each sprinkler.

For each measurement point, the depth of the collected water (h_i) is calculated, providing essential data on the uniformity of water distribution and the efficiency of the extinguishing system. This measurement is crucial for evaluating the performance of sprinklers under simulated conditions and for optimizing their configuration according to the specific requirements of a fire protection system.

The **System Performance Index (SPI)** is used to evaluate the efficiency of water distribution systems, including fire extinguishing sprinklers. In the literature, this index is a composite indicator that combines the **uniformity of water distribution (DU)** and the **efficiency of water application (Ea)**. In the context of extinguishing systems, the **SPI** can help determine how well a sprinkler covers the protected area and how efficient it is in applying water without significant losses.

Distribution uniformity coefficient (**DU**) – measures the homogeneity of water distribution over the protected area, playing an essential role in preventing uncovered areas or excess water in other areas.

Water application efficiency (**Ea**) – represents the proportion of water that reaches the target area compared to the total amount of water delivered by the system. This is important for limiting losses.

2.2.1. Determination of DU and Ea:

- **Distribution Uniformity Coefficient (DU):** After collecting water in each tray, calculate DU as the ratio of the average depth of water to its variation in the trays. A high DU value indicates a uniform distribution.
- **Water Application Efficiency (Ea):** The calculation of Ea can be done by the ratio of the water collected in the measuring trays to the total volume supplied by the sprinkler, to reflect the losses outside the target area.

2.2.2. Calculation of SPI:

The relationship is applied:
$$SPI = DU \times \frac{Ea}{100}.$$

Interpretation of the result provides a clear picture of the overall performance of the sprinkler system. By using this method on the experimental stand, adjustments were made to the positioning of the heads or to the pressure of the system to optimize the uniformity of distribution and the efficiency of water application.

Water Application Efficiency (Ea) represents the proportion of water effectively applied to the target area compared to the total amount of water supplied by the system. Ea can be calculated as the ratio of the volume of water reaching the desired collection area to the total volume of water delivered by the sprinkler system.

$$\text{Calculation relationship for Ea: } Ea = \frac{V_{\text{collected}}}{V_{\text{total}}} \times 100$$

where:

- $V_{\text{collected}}$ is the volume of water collected in trays or containers placed in the protected area, usually measured in liters or cubic meters.
- V_{total} is the total volume of water delivered by the sprinkler system over the same period.

2.2.3. Steps for calculating Ea on the experimental stand

1. Measure the volume collected:
 - Place trays or collection containers in a matrix under the spray area, so that they cover the entire protected area.
 - After a set period of operation (e.g. 30 minutes), measure the volume of water collected in each container.
 - The sum of the volumes collected from all containers is $V_{\text{collected}}$.
2. Determine the total volume delivered:
 - Measure or estimate the sprinkler system flow rate (in liters per second or cubic meters per hour) and multiply by the operating time to obtain the total volume delivered, V_{total} .
3. Calculate Ea:
 - Apply the above equation to obtain a percentage that indicates the efficiency with which the system applies water to the target area.

2.2.4. Interpret the result

A high value of Ea indicates that a high proportion of the water delivered reaches the protected area, suggesting an efficient system. A low value may indicate significant losses due to sprinkler head positioning, suboptimal pressure, or other factors affecting distribution.

Express the Distribution Uniformity Coefficient (DU) in terms of the **Christiansen Uniformity Coefficient (CUH)**, as both terms are used interchangeably in the literature to measure the uniformity of water distribution. The Christiansen Coefficient (CUH) is widely used for irrigation systems and, by extension, is also applicable to sprinkler fire suppression systems.

For calculating CUH (or DU), the standard formula for calculating CUH is:

$$CUH = 100 \times \left(1 - \frac{\sum |x - \bar{x}|}{n \times \bar{x}} \right) \quad (3.1)$$

where:

- x is the volume or depth of water collected in each tray,
- $\bar{x}$ is the average depth of the collected water,
- n is the total number of trays or collection points.

A high CUH (or DU) value indicates uniform water distribution, which is essential for the effectiveness of a sprinkler fire suppression system. Typical values considered good for CUH are generally above 85-90% for optimal distribution.

To calculate the Christiansen Coefficient of Uniformity (CUH), the standard relationship is used relation (3.1) where:

- x is the depth of water in each tray,
- $\bar{x}$ is the average depth of water,
- n is the number of trays (in this case, $n = 4$).

It was applied this formula for each time interval in the next table and calculate the CUH for each row.

Table 1 – Values for CUH at each time interval for first head sprinkler 3/4", K115, 68°C.

Measurement time	Depth of water in tray 1 [mm]	Depth of water in tray 2 [mm]	Depth of water in tray 3 [mm]	Depth of water in tray 4 [mm]	Average depth of water [mm]	Tray 1 Deviation [mm]
t ₀ = 0 min 0	0	0	0	0	0,0	0,0
t ₁ = 5 min	44	42	45	43	43,5	0,5
t ₂ = 10 min	89	85	87	90	87,75	1,25
t ₃ = 15 min	133	131	130	135	132,25	0,75
t ₄ = 20 min	178	179	175	173	176,25	1,75
t ₅ = 25 min	222	220	223	225	222,5	0,5
t ₆ = 30 min	267	261	264	263	263,75	3,25

This table contains the measurements for the water depth in the trays, the deviations from the average depth, and the calculated values for CUH at each time interval.

Table 2 – values for CUH at each time interval for second head sprinkler 3/4", K115, 68°C.

Measure ment time	Depth of water in tray 1 [mm]	Depth of water in tray 2 [mm]	Depth of water in tray 3 [mm]	Depth of water in tray 4 [mm]	Average depth of water [mm]	Tray 1 Deviation [mm]	Tray 2 Deviation [mm]	Tray 3 Deviation [mm]	Tray 4 Deviation [mm]	Sum of absolute deviations	CUH [%]
t ₀ = 0 min	0	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	-
t ₁ = 5 min	44	42	45	43	43,5	0,5	1,5	1,5	0,5	4	97.70
t ₂ = 10 min	89	85	87	90	87,75	1,25	2,75	0,75	2,25	7	98.01
t ₃ = 15 min	133	131	130	135	132,25	0,75	1,25	2,25	2,75	7	98.68
t ₄ = 20 min	178	179	175	173	176,25	1,75	2,75	1,25	3,25	9	98.72
t ₅ = 25 min	222	220	223	225	222,5	0,5	2,5	0,5	2,5	6	99.33
t ₆ = 30 min	267	261	264	263	263,75	3,25	2,75	0,25	0,75	7	99.34

3. CONCLUSION

The results obtained on this experimental stand confirm that the sprinkler system ensures uniform water distribution, with a consistent CUH of over 97%. This level of uniformity is essential for ensuring fire extinguishing efficiency, especially in high-risk storage areas. The research stand allowed for a detailed evaluation of the system performance and provides a solid basis for further adjustments and optimizations according to the specific requirements of different industrial environments.

In this study, the evaluation of the sprinkler system performance was carried out by analyzing the water distribution and its uniformity, using the mobile experimental stand. The stand, configured to allow detailed measurements of essential parameters, offered the possibility to monitor and analyze the water distribution at different time intervals. The main objectives of the research included measuring the uniformity of the water distribution and verifying the effectiveness of the sprinkler system in ensuring complete and homogeneous coverage in the protection area.

3.1. Water distribution uniformity

The results showed a very uniform water distribution, with a Christiansen Uniformity Coefficient (CUH) varying between 97.7% and 99.34% during the tests. These high indicators confirm that the sprinkler system operates efficiently under experimental conditions, ensuring uniform coverage over the entire protected area. High distribution uniformity is essential in the context of fire protection, as it prevents dry or over-covered areas that could compromise the fire extinguishing efficiency.

3.2. Deviations from the average depth

Analysis of the deviations from the average depth of water in the trays indicates small values, suggesting a homogeneous distribution of water in all collection trays. Higher values of deviations, observed at longer times (e.g. 30 minutes), do not compromise the overall uniformity, as they remain below an acceptable level. These values indicate a slight variability of the water spray, possibly due to the interaction with the ambient air flow or the geometric configuration of the sprinkler heads, but do not significantly affect the overall performance.

3.3. Relevance to the research purpose

The purpose of the research was to evaluate and optimize the performance of the sprinkler system under conditions like real ones, to ensure the effective protection of a storage area with a high thermal load. Given the high uniformity of water distribution, the tested system meets the coverage requirements and can be considered effective for use in cold storage buildings, where homogeneity of water application is essential to prevent the spread of fires.

3.4. Involvement in sprinkler system optimization

These results can be used to guide the necessary adjustments in the design and installation of sprinkler systems in industrial storage environments. High CUH values indicate optimal performance, and minimal deviations suggest that the system can be easily adapted to maintain uniform coverage even with variations in pressure or flow. In addition, the research stand allows for the adaptation and testing of other sprinkler configurations and types, making it possible to extend the research and apply the conclusions to a wider range of conditions and systems.

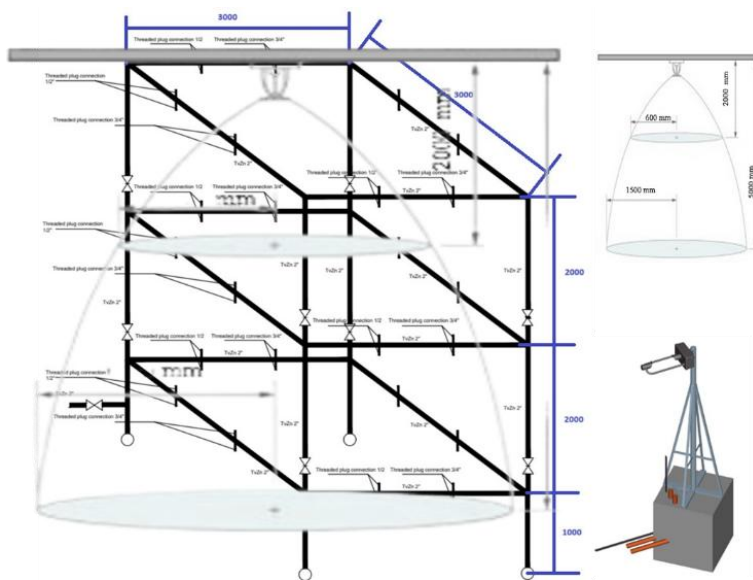


Figure 1 – Diagram of mobile experimental stand



Figure 2 Image of mobile experimental stand

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