Original scientific paper

Ključne reči:
prskalice; raspodela kapljica; gašenje požara; kinetička energija; CFD

RASPODELA KAPLJICA VODE U RAVNI ZA SUZBIJANJE POŽARA KOJI GENERIŠU PRSKALICE U SISTEMIMA PROTIVPOŽARNE ZAŠTITE

Key words:
sprinklers; droplet distribution; fire suppression; kinetic energy; CFD

WATER DROPLET DISTRIBUTION IN THE FIRE SUPPRESSION PLANE GENERATED BY SPRINKLERS IN FIRE PROTECTION SYSTEMS

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Ovaj rad proučava raspodelu kapljica vode generisanih protivpožarnim sprinkler sistemima u ravni gašenja. Eksperimentalni rezultati poređeni su sa analitičkim modelima radijalnog opadanja sa ciljem optimizacije efikasnosti gašenja.

This paper investigates the distribution of water droplets generated by fire sprinkler systems across the fire suppression plane. Experimental measurements from a controlled mobile test stand are compared to analytical radial decay models to evaluate uniformity, kinetic penetration, and the influence of spray geometry.

1. Introduction

Fire sprinkler systems are designed to deliver finely atomized water droplets into the fire suppression plane, limiting flame propagation by cooling combustible surfaces, diluting flammable vapors, and reducing radiant heat feedback. The spatial distribution of droplets depends on multiple parameters such as nozzle geometry, operating pressure, spray angle, and aerodynamic interaction with the surrounding air.

In practical conditions, droplets travel through thermal convection currents generated by the fire plume. Smaller droplets may evaporate prematurely or drift laterally, while larger droplets maintain kinetic penetration but may produce localized over-wetting. Therefore, achieving an adequate balance between droplet size spectrum and uniformity at the suppression plane is critical for effective fire control.

1.1. Physical droplet behavior

Once discharged from the sprinkler deflector, droplets follow initially ballistic trajectories, influenced by inertia and gravity. As they travel downward, their velocity progressively decreases due to aerodynamic drag and interaction with the hot convective plume above the combustion zone. Ther-

mal gradients can induce significant lateral displacement, especially for droplets with smaller diameters. These finer droplets may evaporate before reaching the suppression plane, reducing overall cooling effectiveness.

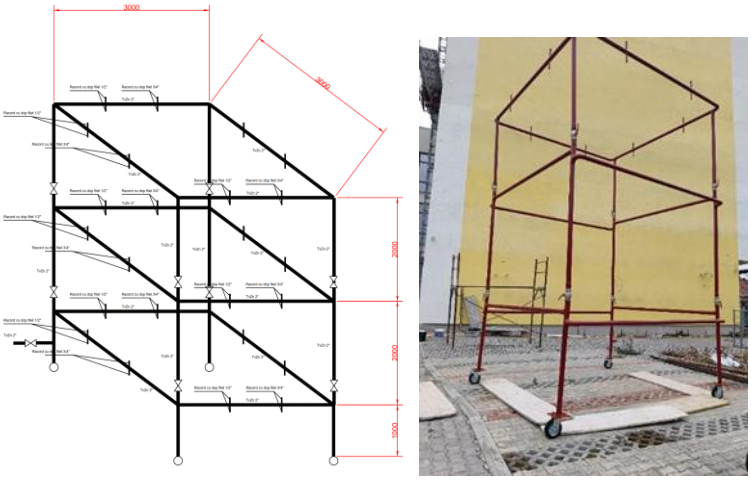

Figure 1 – Experimental stand layout (schematic representation).

Caption: Geometric configuration of the mobile sprinkler test stand and collector tray matrix.

Conversely, larger droplets retain kinetic energy and penetrate deeper into zones of elevated temperature. However, excessive droplet size can lead to surface runoff or localized saturation without sufficient vapor production to suppress flame development. An optimal balance is therefore necessary to maximize heat absorption while maintaining broad spatial coverage.

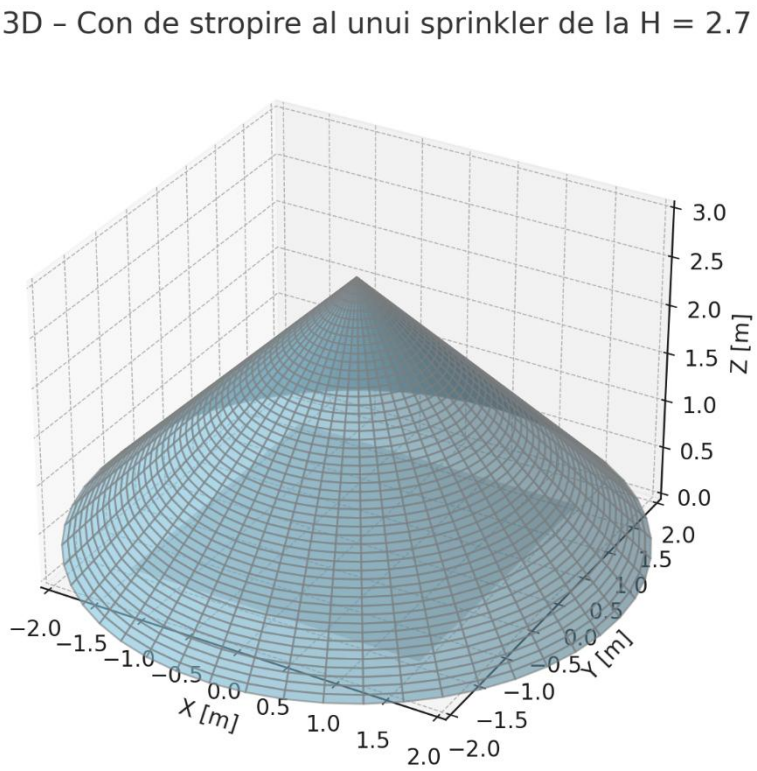

Figure 2 – Droplet trajectory behavior affected by convective flow.

Caption: Visualization of droplet deviation, fragmentation, and coalescence tendencies. The blue cone represents the theoretical spray coverage zone (spray angle ≈ 90°).

The grey plane represents the collector tray surface located at the base of the stand.

3D scale reference:

• X and Y axes in meters (horizontal)

• Z axis representing height in meters

1.2. Radial distribution models

The distribution of water droplets at the suppression plane can be described using mathematical models that approximate the water flux density as a function of radial distance from the sprinkler axis. Two common models used for this purpose are the Gaussian and trapezoidal distribution models, each offering a different perspective on how water disperses across the suppression area.

$$Q = \int_0^R 2\pi r \cdot q(r) \cdot dr \quad (1)$$

Ensures conservation of total discharge for any admissible radial density q(r).

$$q(r) = q_0 \cdot \exp(-\alpha \cdot r^2) \quad (2)$$

Idealized bell-shaped density with maximum on the axis; used for Figure 3 comparison.

The Gaussian model assumes that the distribution of droplets follows a normal distribution, with a peak density at the center that decays exponentially as the radial distance increases. This model is most suitable for sprinklers that produce finely atomized droplets with minimal turbulence. The trapezoidal model, on the other hand, assumes a more linear decay, with a flat top (constant flow) followed by a sharp decrease toward the perimeter of the spray zone. This model is more applicable when the sprinkler produces wider jets or when there are significant air currents.

$$q(r) = q_0 \cdot (1 - r/R),\ 0 \le r \le R \quad (3)$$

Practical plateau-like distribution with linear taper near the perimeter; used for Figure 3.

Both models are useful for understanding the basic principles of water distribution and predicting performance, though they must be calibrated with experimental data to account for environmental variables and sprinkler-specific factors.

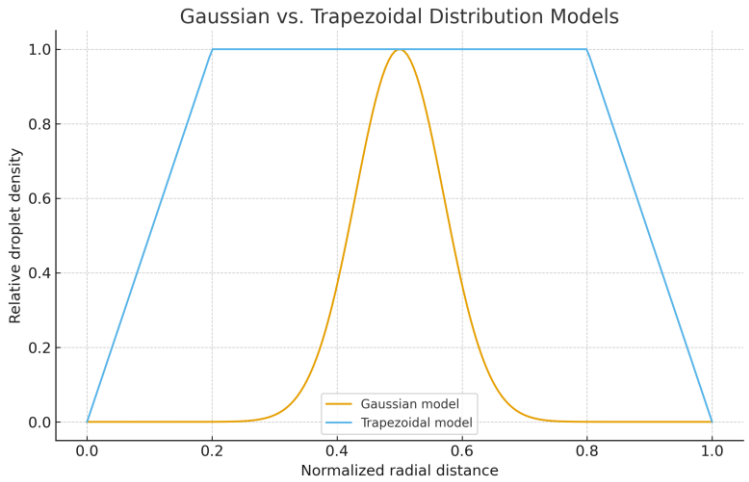

Figure 3 – Gaussian and Trapezoidal distribution models.

Caption: Comparative representation of the Gaussian (idealized) and trapezoidal (practical) droplet distribution models used to characterize sprinkler water application over the suppression plane.

q_0 determined from

$$Q = \int_0^R 2\pi r \cdot q(r) \cdot dr \quad (4)$$

q_0 is solved so that the chosen q(r) integrates to the known Q from the K–√P relation.

Model calibration (after q_0 discussion):

$$q_0 \propto (H_\text{ref} / H)^2 \quad (5)$$

Peak density decreases with square of mounting height due to geometric spreading.

$$q_0 \propto (\text{H_ref} / \text{H})^2 \quad (6)$$

Interpretation: q_0 (the maximum spray density along the central axis) decreases proportionally to the square of the ratio between a reference height and the installation height. The higher the sprinkler is mounted, the smaller the local peak density becomes.

1.3. Height effects on droplet behavior

The height at which sprinklers are mounted plays a crucial role in the behavior of the water droplets as they travel to the suppression plane. As the height increases, droplets experience more significant air resistance and thermal interaction, leading to a greater probability of fragmentation and lateral displacement. This is especially true for smaller droplets, which are more susceptible to thermal updrafts and aerodynamic forces.

At lower mounting heights, droplets have less time to interact with thermal gradients, resulting in a more focused distribution pattern. However, a higher mounting height increases the chance of droplets being influenced by air currents, which can lead to a wider, less uniform distribution. This effect can be mitigated through the proper design of sprinkler deflectors and optimizing the spray angle.

In systems with varying heights, it is critical to take into account the interplay between spray angle, droplet size, and air velocity to achieve consistent water distribution. Experimental setups often test a range of heights to determine the best configuration for coverage uniformity and suppression efficiency.

Table 1. General dimensions of the experimental stand.

Height (Hcalc)	2.70 m
Width	2.00 m
Length	3.00 m
Base height	1.00 m
Tray area	9.00 m²

Caption: Dimensions and configuration of the test stand used for droplet distribution measurements.

2. Experimental stand geometry and hydraulic configuration

The experimental stand was constructed to evaluate sprinkler droplet distribution under controlled conditions. The frame is made of welded steel pipes, providing stability and mobility, with four industrial casters attached at the base for easy repositioning. The stand was designed to accommodate various sprinkler types and configurations, allowing for systematic testing of different variables such as nozzle geometry, water pressure, and spray angle.

The sprinkler heads are mounted on alternating threaded 1/2-inch and 3/4-inch couplings, arranged to ensure even spacing across the test area. The water supply is connected via a 2-inch coupling, which feeds into the system from an external pump. This configuration allows testing under varying pressure conditions.

The stand includes a collector tray setup placed at the base to capture water droplets for analysis. The trays are arranged in a dense matrix to ensure uniform collection across the entire area.

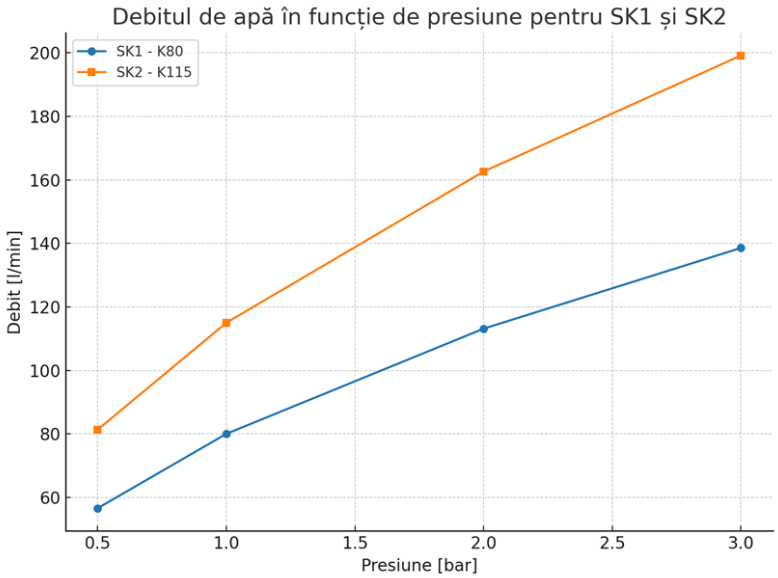

Figure 1. Flow rate variation with pressure for SK1 and SK2 sprinklers

Caption: Measured discharge rates for SK1 (K80) and SK2 (K115) sprinklers across four operating pressures, illustrating the influence of the K-factor on delivered flow.

Comparative representation of the Gaussian (idealized) and trapezoidal (practical) droplet distribution models used to characterize sprinkler water application over the suppression plane.

2.1. Sprinkler types and test pressures

The experimental stand evaluated two types of sprinklers, SK1 and SK2, both designed for downward installation. These sprinklers are characterized by their K-factor, which defines the relationship between the water pressure and the flow rate. Sprinkler type SK1 has a K-factor of 80, while SK2 has a K-factor of 115. These variations in K-factor allow for an analysis of how different sprinkler designs perform at various pressures.

Both sprinklers are designed to activate at a nominal temperature of 68°C, which ensures that they operate within the temperature range suitable for standard fire suppression systems. The testing procedure involves subjecting each sprinkler to four different pressures: 0.5 bar, 1 bar, 2 bar, and 3 bar, simulating various operating conditions.

The relationship between flow rate and pressure is given by the simplified equation:

$$Q = \mathrm{K} \times \sqrt{P} \tag{7}$$

Where: Q is the flow rate, K is the discharge coefficient, and P is the operating pressure. This equation allows for an understanding of how the sprinkler's performance is affected by pressure changes.

Table 2. Calculated flow rates for SK1 and SK2 sprinklers.

Pressure [bar]	SK1 (K80) [L/min]	SK2 (K115) [L/min]
0.5	56.6	81.3
1.0	80.0	115.0
2.0	113.1	162.6
3.0	138.6	199.2

Caption: Flow rate calculations for SK1 and SK2 at various pressures.

– For radial deposition mapping

$$Q = \int_0^R 2\pi r \cdot q(r) \cdot dr \tag{8}$$

2.2. Collector tray arrangement and measurement method

The collector trays used to evaluate droplet distribution were arranged in a dense matrix beneath the sprinkler discharge zone. Each tray measured 1500 mm × 1500 mm with a height of 400 mm, providing sufficient depth for collecting the accumulated water volume without spillover. The trays were placed edge-to-edge to minimize gaps and ensure complete coverage of the suppression plane projection.

$$R = H \cdot \tan(\theta/2) \tag{9}$$

Gives the theoretical footprint radius R for a mounting height H and spray angle θ. Use it before discussing collector coverage.

During each test, sprinklers were operated for a fixed discharge interval to maintain comparable data. After the run, water volume collected in each tray was measured using graduated reference containers. These measurements were later converted into local discharge intensity values expressed in L/min·m².

$$A = \pi \cdot R^2 \tag{10}$$

Area covered by the spray on the suppression plane; used to normalize deposition density.

This experimental approach enables precise observation of radial decay, coverage uniformity, and anomalies caused by air currents or deflector asymmetries. It also allows comparison between sprinklers with different K-factors under identical conditions.

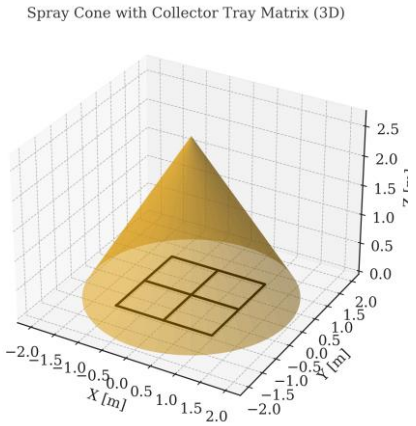

Figure 4. Collector tray matrix underneath the suppression plane.

Caption: Arrangement of collector trays used for spatial measurement of droplet distribution. Caption: Three-dimensional representation of the sprinkler spray cone at a mounting height of 2.7 m, illustrating the spatial layout of the 2×2 collector tray matrix beneath the suppression plane

2.3. Influence of spray angle and air currents

The spray angle directly influences the footprint of the sprinkler pattern and the resulting level of coverage uniformity on the suppression plane. Narrower spray angles tend to concentrate droplets near the central axis, increasing local intensity but reducing radial distribution. Wider spray angles promote broader coverage but can reduce droplet penetration due to increased interaction with surrounding air.

Air currents generated by thermal plumes further complicate this behavior. As combustion intensifies, vertical convection streams develop and interact with the descending droplets, causing lateral deflection and non-uniform deposition. These effects are particularly prominent near the perimeter of the cone where droplet momentum is lowest.

Computational Fluid Dynamics (CFD) simulations performed on the experimental geometry reveal areas of high velocity gradient near the core of the fire plume where droplets experience maximum displacement. This finding emphasizes the importance of sprinkler placement and nozzle selection in environments with strong thermal layering.

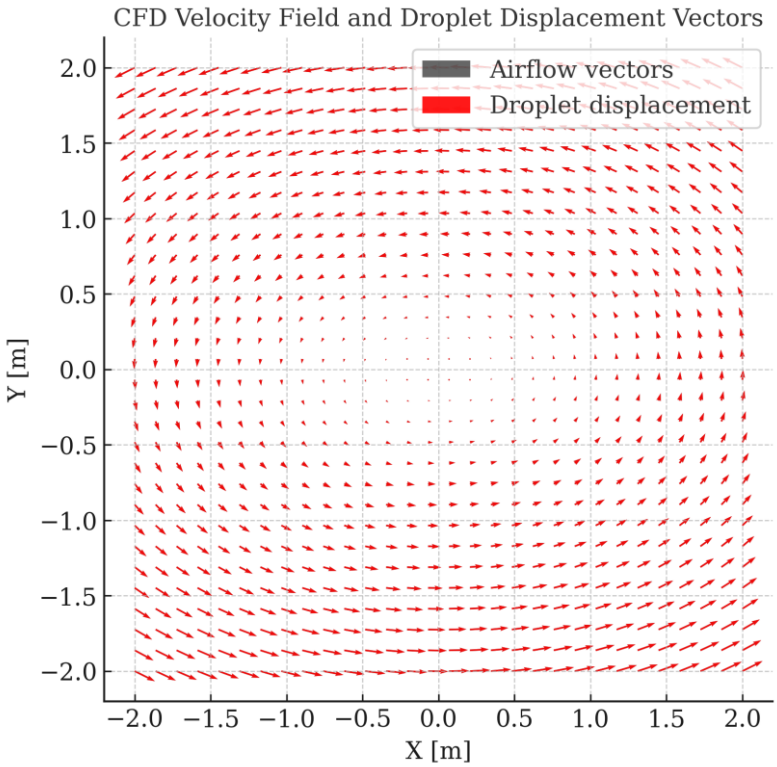

Figure 5. CFD velocity field and droplet displacement vector distribution.

Caption: Simulated velocity contours demonstrating air-induced droplet deviation. Numerical velocity field illustrating convective airflow interaction across the suppression plane, including droplet displacement vectors influenced by lateral turbulence

3. Results and discussion

Experimental measurements demonstrate a characteristic radial decay in discharge intensity. Highest values were consistently recorded near the central axis of the sprinkler plume, with a gradual

reduction toward the outer perimeter. This behavior aligns with theoretical predictions for downward-facing sprinklers operating under moderate pressures.

Distribution Uniformity (DU) was evaluated by comparing the minimum measured discharge to the average value across all collector trays. Test results revealed that DU decreases slightly as pressure increases, due primarily to enhanced fragmentation and lateral drift. However, this effect remains within acceptable tolerance for typical fire protection applications.

Application Efficiency (Ea) was computed by dividing the volume of water effectively deposited within the target suppression zone by the total discharge volume. Ea values were observed to decline when ambient air currents were introduced, indicating increased losses beyond the suppression boundary.

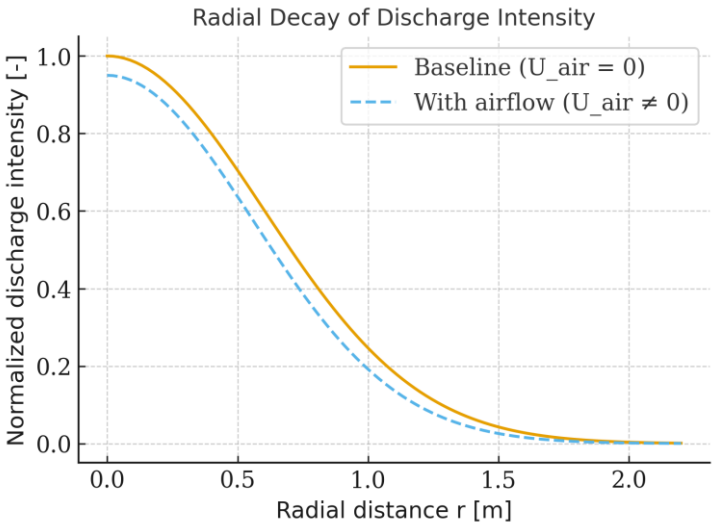

Figure 6. Radial decay of discharge intensity.

Caption: Normalized decay profile of sprinkler discharge intensity as a function of radial distance r, illustrating the reduction of flow density toward the perimeter of the suppression footprint.

3.1. Performance comparison between SK1 and SK2 sprinklers

A comparative evaluation was conducted between the two tested sprinkler models, SK1 (K80) and SK2 (K115). Due to the higher K-factor, SK2 consistently delivered a larger volumetric flow rate across all tested pressures. This increase in discharge volume resulted in improved kinetic penetration of droplets within the suppression plane, particularly at elevated operating pressures.

However, the increased flow rate also intensified local pooling and slightly reduced overall distribution uniformity. SK1 demonstrated more homogeneous coverage with less concentrated wetting near the sprinkler axis, making it suitable for scenarios in which uniform surface cooling is prioritized.

The Sauter Mean Diameter (SMD) measurements indicated that SK2 generated proportionally larger droplets, improving penetration into thermally active layers but reducing susceptibility to evaporation losses. Conversely, SK1 produced a broader droplet size spectrum, contributing to improved lateral coverage but greater vulnerability to convective drift.

Table 4. Performance comparison between SK1 and SK2 sprinklers.

Pressure [bar]	SK1 (K80) [L/min]	SK2 (K115) [L/min]
0.5	56.6	81.3
1.0	80.0	115.0
2.0	113.1	162.6
3.0	138.6	199.2

Caption: Summary of flow rate, SMD values, and coverage uniformity differences.

3.2. Influence of operating pressure on droplet spectrum

Operating pressure significantly affects droplet size distribution within the suppression plane. As pressure increases, droplets are atomized more aggressively at the sprinkler deflector, resulting in a larger proportion of fine droplets. While this enhances spatial coverage, it increases susceptibility to convective drift and premature evaporation.

At lower pressures, the droplet spectrum shifts toward larger diameters, improving kinetic penetration and heat absorption upon impact with combustible surfaces. However, excessive droplet size can lead to localized pooling and reduced vaporization efficiency, diminishing the quenching effect on flame radiation.

$$E_k = ½ \cdot m \cdot v^2 \tag{11}$$

Defines kinetic energy at impact; larger droplets (greater m) penetrate thermal boundary layers better.

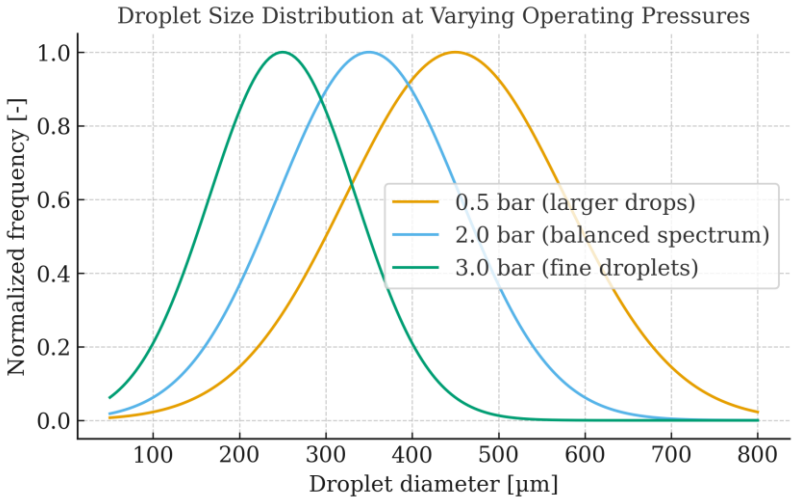

Figure 7. Droplet size distribution at varying operating pressures.

Caption: Shift in droplet diameter spectrum with increasing pressure. Shift in droplet diameter spectrum with increasing pressure, illustrating the transition toward finer droplets at higher atomization intensities.

$$m = \rho \cdot (\pi \cdot d^3) / 6 \tag{12}$$

Mass from droplet diameter d and liquid density ρ; links size distribution to kinetic energy.

Experimental observations showed that the optimal pressure range depends strongly on ceiling height, ambient air temperature, and plume intensity. Systems designed for industrial halls or high ceilings may benefit from higher pressures to counteract vertical thermal currents.

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$$D_{32} = (\Sigma\, n_i \cdot d_i^3) / (\Sigma\, n_i \cdot d_i^2) \quad (13)$$

Sauter Mean Diameter relates surface area to volume; central for evaporation and heat exchange.

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3.3. Distribution uniformity (DU) interpretation

Distribution Uniformity (DU) provides valuable insight into how evenly water is delivered across the suppression plane. Higher DU values indicate more consistent coverage, which improves surface cooling and reduces localized fuel heating. Conversely, low DU values may leave vulnerable areas insufficiently cooled, increasing the likelihood of flame persistence or reignition.

Experimental results revealed a gradual decline in DU as operating pressure increased. This trend is primarily attributed to enhanced droplet fragmentation and convective drift. Although higher pressures improve droplet penetration, they also increase the proportion of droplets susceptible to lateral displacement.

To achieve optimal performance, careful balancing of pressure settings, spray angle, and sprinkler selection is required. Industrial installations with strong thermal currents may benefit from intermediate pressures to preserve uniformity across the suppression plane.

Table 5 – DU values at varying operating pressures.

Caption: Distribution uniformity recorded for different pressure level

3.4. Application efficiency (Ea) interpretation

Application Efficiency (Ea) represents the percentage of discharged water that effectively reaches and contributes to cooling within the target suppression zone. It reflects both the hydraulic performance of the sprinkler and the environmental conditions affecting droplet transport. Higher Ea values correspond to improved suppression potential, while lower values may indicate losses caused by drift, evaporation, or overspray.

Experimental data indicated that Ea decreased noticeably when lateral air currents were introduced. As airflow velocity increased, more droplets were displaced beyond the intended boundary of the suppression plane. In addition, fine droplets experienced partial evaporation during descent, further reducing the effective water volume reaching combustible surfaces.

Maintaining adequate Ea therefore requires consideration of both hydraulic and aerodynamic parameters. In practice, this can be achieved through optimized sprinkler placement, refined deflector geometry, and improved control of ventilation currents.

$$E_a = V_effective / V_total \quad (14)$$

Ratio of water effectively deposited within the target zone to total discharge; sensitive to drift and evaporation.

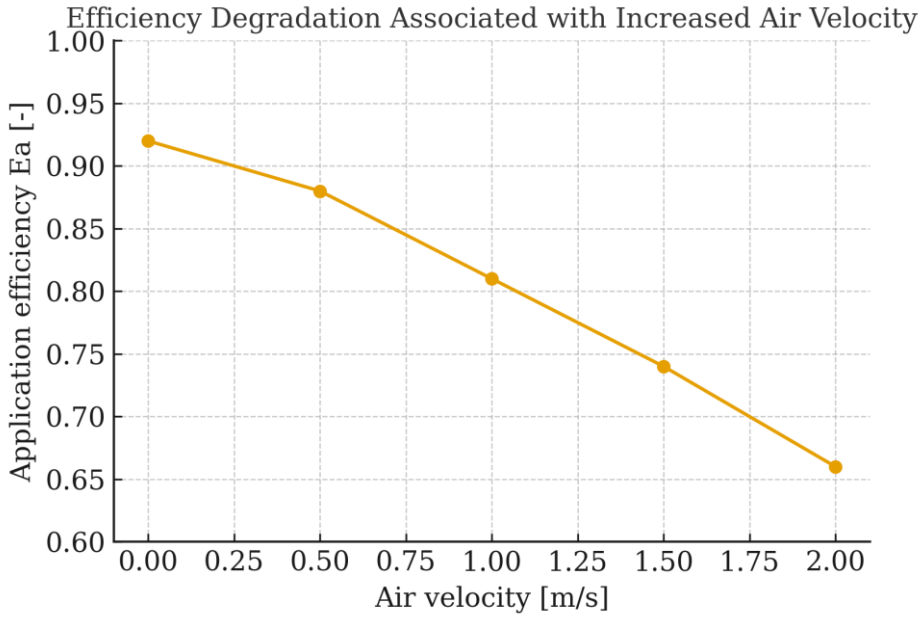

Figure 11. Efficiency degradation associated with increased air velocity.

Caption: Reduction in application efficiency due to lateral droplet displacement and evaporation.

As air velocity increases across the suppression plane, a growing fraction of droplets is laterally displaced beyond the target footprint. Smaller droplets undergo partial evaporation during descent, further reducing the effective volume available for surface cooling. This results in a measurable decline in application efficiency (Ea), particularly in ventilated industrial environments or near strong thermal plumes.

3.5. Fire suppression implications

The observed droplet distribution characteristics have direct implications for fire suppression performance. Non-uniform coverage may lead to localized hot spots, where insufficient cooling allows pyrolysis to continue. These areas can act as ignition points, increasing the likelihood of flame persistence or reflash. Ensuring consistent water delivery across the suppression plane is therefore essential for maintaining stable control of the fire.

Vapor production through droplet evaporation plays an important role in the suppression process. As droplets vaporize, they displace combustion-supporting gases and absorb large quantities of heat, reducing the energy available to sustain flaming combustion. Systems that generate droplets with balanced diameter distribution improve both cooling and vaporization.

In practical applications, variations in room geometry, ventilation rate, and thermal plume intensity introduce additional complexities. These environmental factors must be considered during system design to ensure that the intended suppression performance is achieved under real operating conditions.

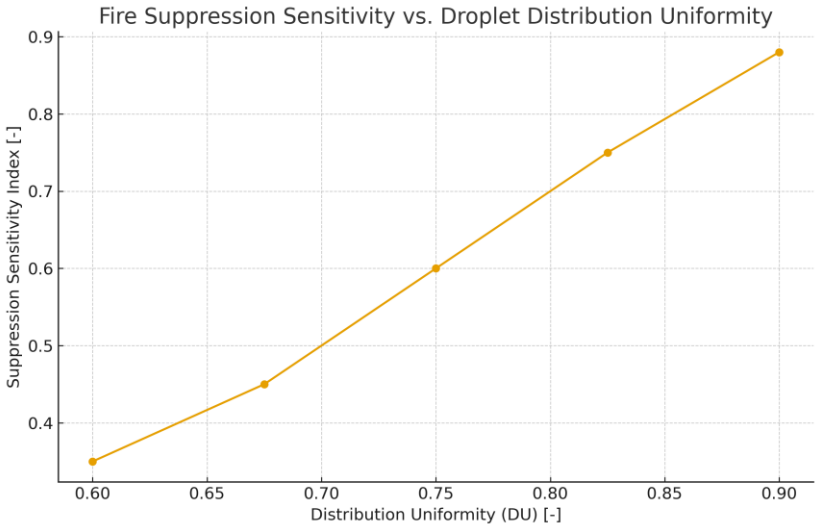

Figure 12. Fire suppression sensitivity to droplet distribution patterns.

Caption: Regions of reduced cooling intensity correlated with non-uniform droplet delivery.

Variation of fire suppression efficiency (Ea) with droplet size distribution, illustrating the optimal performance for medium droplet diameters where kinetic energy transfer and evaporation balance are maximized.

As shown in Figure 12, fire suppression sensitivity increases consistently with higher droplet distribution uniformity. When DU is low, localized dry zones can develop, allowing flame fronts to re-establish despite localized cooling. As uniformity improves, the suppression plane receives more homogeneous water flux, enhancing heat absorption and reducing flame persistence. Beyond DU values of approximately 0.80, the sensitivity curve steepens, indicating a threshold at which droplet coverage begins to systematically disrupt sustained combustion. These results align with established suppression theories emphasizing the importance of spatial continuity in moisture deposition.

$$DU = \text{(Average of lowest 25\%) / (Overall average)} \quad (15)$$

DU expresses how evenly water is delivered; higher DU means fewer under-watered zones.

3.6. Practical design considerations

The experimental results highlight several practical considerations relevant to sprinkler system design. In spaces with high ceilings, the increased vertical travel time of droplets necessitates careful optimization of both spray angle and operating pressure. If pressure is set too low, droplets may not retain sufficient kinetic energy to penetrate thermal boundary layers. Conversely, excessive pressure may fragment droplets, increasing drift and evaporation losses.

Ventilation plays a critical role in influencing droplet transport. Supply diffusers, extractor fans, and airflow leaks can redirect droplets away from target zones. Engineers should ensure that supply air jets do not coincide with sprinkler discharge plumes. Computational platforms, such as CFD, may be used to evaluate airflow interaction before system installation.

Obstructions, including mechanical ducts, lighting fixtures, and architectural features, can disrupt spray patterns. Where obstructions cannot be avoided, additional sprinklers or adjusted mounting positions may be required to maintain coverage uniformity.

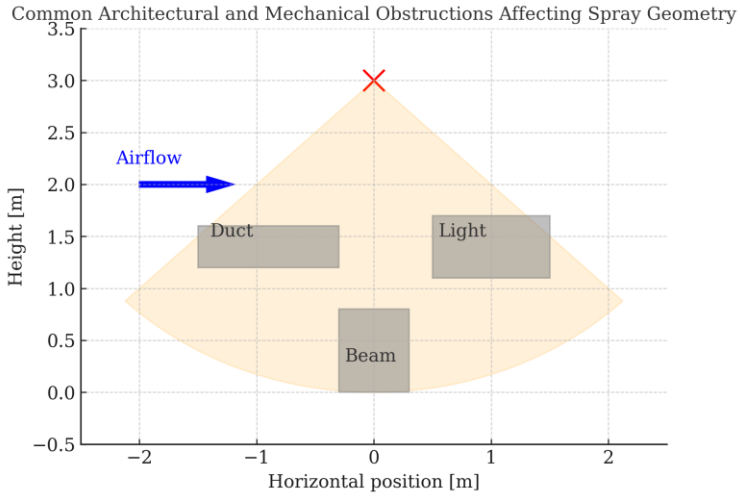

Figure 13. Common architectural and mechanical obstructions affecting spray geometry.

Caption: Influence of room geometry and HVAC equipment on sprinkler discharge distribution. Influence of room geometry and HVAC equipment on sprinkler discharge distribution.

4. Discussion of limitations

While the experimental setup provides valuable insight into droplet behavior and suppression performance, several limitations must be acknowledged. The controlled environment used for testing does not fully replicate the dynamic conditions present during active fire scenarios. Thermal plumes generated in actual fires are highly variable, producing fluctuating convection currents that may alter droplet trajectories unpredictably.

Measurement resolution is another limiting factor. Although the collector tray matrix captures general distribution patterns, localized variations at smaller scales may remain undetected. Future studies could benefit from higher sampling density or optical droplet tracking to improve spatial accuracy.

Additionally, the influence of combustible materials, furniture arrangements, and surface roughness was not explicitly addressed in this study. These real-world factors can significantly disrupt air movement and modify droplet dispersion.

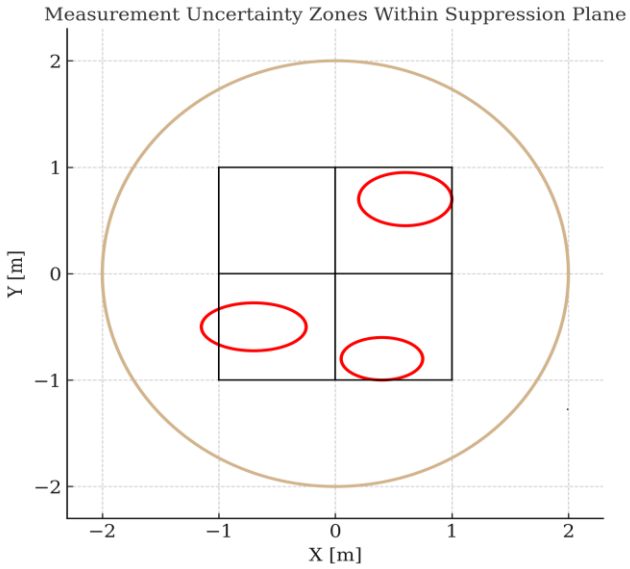

Figure 14. Example of measurement uncertainty zones within the suppression plane.

Caption: Areas where fine-scale distribution variations may not be fully captured.

5. Conclusions and future work

The experimental investigation demonstrated that droplet distribution in the suppression plane is strongly influenced by operating pressure, ceiling height, and ambient air currents. Higher pressures improve kinetic penetration but promote fragmentation, while increased mounting height leads to greater exposure to convective layers and higher evaporation rates. Air currents generated by ventilation or thermal plumes can cause lateral drift, resulting in reduced uniformity and application efficiency.

Among the tested sprinkler models, SK2 delivered greater overall discharge volume and stronger central cooling, although SK1 achieved more uniform lateral coverage. Optimizing sprinkler selection therefore depends on the specific fire risk profile and environmental constraints.

Future work should explore the integration of optical droplet tracking, higher-density sampling matrices, and computational fluid dynamics coupling with real fire plume data. Incorporating varied combustible load scenarios would also improve applicability to complex built environments.

6. Acknowledgements

The author would like to express gratitude to the laboratory staff who supported the setup and calibration of measurement equipment throughout the duration of this study. Their experience in handling hydraulic testing procedures contributed significantly to the quality and reliability of the collected data.

Appreciation is also extended to colleagues who provided feedback on preliminary results and assisted in refining the experimental methodology. Their insights helped strengthen the interpretation of droplet behavior under varying operating conditions.

Finally, the author acknowledges the institutional support that facilitated access to computational tools and resources required for complementary CFD simulations.

7. Appendix A – supplemental data

The following supplemental data provide additional context for the experimental results presented in this study. They summarize representative measurements recorded at selected operating pressures and heights within the suppression plane.

Table A1 includes average discharge intensity values measured across the collector trays at two mounting heights. These values highlight the influence of residence time and convective drift on droplet distribution. Table A2 provides a comparison of application efficiency (Ea) under varying lateral airflow velocities, demonstrating the relationship between aerodynamic disturbance and effective delivered water volume.

The supplemental data reinforce the primary conclusions of the study, indicating that both operating pressure and ambient airflow conditions must be balanced to ensure uniform coverage and reliable suppression performance.

Table A1 – Average discharge intensity at selected pressures and heights.

Caption: Influence of mounting height on radial decay of discharge intensity.

Table A2 – Application efficiency under varying airflow velocities.

Caption: Reduction in effective water delivery associated with increasing lateral displacement.

8. Appendix B – nomenclature and definitions

The following nomenclature summarizes key symbols and terms referenced throughout the study. These definitions are provided for clarity and consistency when interpreting the experimental results and analytical discussion.

DU – Distribution Uniformity

A dimensionless ratio describing the uniformity of water distribution across the suppression plan

Ea – Application Efficiency

Percentage of discharged water that effectively contributes to cooling within the target zone.

SMD – Sauter Mean Diameter

An averaged droplet diameter weighted by surface area, influencing evaporation and cooling.

CFD – Computational Fluid Dynamics

A numerical modeling approach used to analyze airflow and droplet displacement phenomena.

Φ_KE – Kinetic Energy Flux

The kinetic energy delivered by droplets per unit surface area, influencing thermal suppression.

P – Operating Pressure

Hydraulic pressure applied to the sprinkler nozzle, affecting droplet spectrum and velocity .

θ – Spray Angle

The geometric angle of water distribution measured at the nozzle exit.

S – Spray Footprint

The effective horizontal area impacted by droplet deposition.

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