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Contributions to the resolution of issues relating to the performance of fire extinguishing sprinkler systems (1)

Contribuții la rezolvarea unor problematici privind performanța sprinklerelor utilizate în stingerea incendiilor (1)

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Abstract. *This paper investigates current challenges in the design and operation of sprinkler fire extinguishing systems, especially regarding the extrapolation of droplet distribution from standard diagrams, positioning and spacing between sprinkler heads in complex geometries, air current influences, and heat release variations. Through theoretical studies, simulation models and experimental measurements with laser-based droplet size analysis, solutions for system optimization are proposed. Key recommendations address the use of CFD tools, adapted sprinkler types, and refined placement strategies to enhance sprinkler efficiency.*

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

1. Introduction: Premises for addressing the research topic

In the practice of implementing sprinkler fire suppression systems, several issues arise:

1. Manufacturers provide diagrams of the spray cone up to a maximum height of 3 meters. From this, designers must extrapolate how the spray droplets fall and combine on their way to the suppression surface, which could be materials stored on the building floor.
2. The distance between sprinkler heads mounted on pipes that may be on different planes (usually perpendicular), obstacles between the sprinkler heads and the suppression surface.

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3. The creation of natural or artificial air currents within the building that can disperse or recombine water droplets, altering their path perpendicular to the suppression surface.
4. The variation in the density of calorific power released by combustion, both on the exposed surface and over time due to random deposits.

Therefore, the design and implementation of sprinkler fire suppression systems involve numerous challenges. Below are some solutions and recommendations for the specified issues, divided into the stages of design, execution, and operation.

However, due to the complexity of the interaction between sprinkler water jets and fire, there is no standardized engineering method for selecting the appropriate sprinkler for a specific installation. Currently, engineers rely on a limited number of large-scale, costly tests that do not always reflect the real conditions of a fire. Thus, it is often impossible to accurately assess the effectiveness of installed suppression systems or objectively measure the level of safety provided.

Recent advances in technology and computing offer new perspectives for understanding the interaction between sprinkler water jets and fires. New methods for measuring the size and speed of water droplets allow for a detailed analysis of the actual characteristics of these jets. Given the large number of droplets and the complexity of the interaction between fire, surrounding air, and water droplets, the most efficient way to model these systems is computationally. High-performance computers enable the integration of physical aspects and empirical data, providing a better understanding of the behavior of sprinkler water jets in the event of a fire. However, the empirical information needed for these models has been limited so far.

Scientific research and technical solutions:

- *Studies on droplet distribution and application efficiency:* Research has highlighted the importance of uniform water distribution to ensure effective fire suppression. Experimental studies and CFD (Computational Fluid Dynamics) simulations are used to model and optimize water droplet distribution.
- *Impact of air currents:* Scientific research has investigated how air currents, influenced by ventilation or building openings, affect the efficiency of sprinkler systems. Technical solutions, such as using air deflectors and adjusting sprinkler positioning, are validated through experimental studies and simulations.
- *Risk assessment and fire modeling:* Mathematical models and fire simulations are used to assess risk and determine optimal water application densities based on the type and distribution of flammable materials.

1.1 Spray cone diagrams and extrapolation

Problem: Manufacturers provide spray cone diagrams up to a height of 3 meters, requiring designers to extrapolate the behavior of water droplets to the suppression surface.
Solutions:

- Simulation software: Specialized software for simulating water flow and droplet distribution, such as CFD, can help accurately model droplet behavior over greater distances.
- Laboratory testing: Conduct experimental tests in the lab to observe water droplet behavior at greater heights and adjust the design accordingly.
- Consultation with manufacturers: Collaborate closely with manufacturers to obtain additional data or develop customized solutions based on specific project requirements.

1.2 Distance between sprinkler heads and obstacles

Problem: Determining the optimal distance between sprinkler heads mounted on pipes in different planes (usually perpendicular) and obstacles between the sprinkler heads and the suppression surface.
Solutions:

- Compliance with standards and regulations: Follow fire protection standards and codes, such as NFPA 13, which provide detailed guidelines on distances between sprinkler heads and avoiding obstacles.
- 3d simulations and modeling: Use 3D design software and simulations to model the placement of sprinkler heads and obstacles, optimizing water distribution.
- Specialized sprinklers: Use sprinkler heads with special features, such as those designed for areas with obstacles or sidewall sprinklers, to ensure optimal coverage.
- In-situ testing: Conduct spray tests at the specific location to verify if water distribution is affected by obstacles and adjust the design as needed.

1.3 Air currents and water droplet dispersion

Problem: Air currents, whether natural or artificially created, can disperse or recombine water droplets, altering their path perpendicular to the suppression surface.
Solutions:

- Ventilation control: Design ventilation and air conditioning systems to minimize impact on the path of water droplets from sprinklers. Position ventilation grilles away from spray zones.
- Use of deflectors: Install air deflectors to protect spray zones from air currents.
- Controlled distribution sprinklers: Choose sprinkler heads with spray patterns less susceptible to air current influence.

- Continuous monitoring: Use air flow sensors and adjust ventilation systems in real-time to ensure the water droplet path remains effective.

1.4 Variation in calorific power density and random deposits

Problem: Variation in the density of calorific power released by combustion, both on the exposed surface and over time, due to random deposits.
Solutions:

- Risk classification: Conduct a detailed risk assessment to determine calorific power density and correctly classify risk zones.
- Storage plans: Implement strict storage plans to minimize variability in combustible materials and prevent unexpected accumulations of flammable materials.
- Automatic adjustment systems: Use sprinklers with automatic adjustment capabilities that can regulate water flow based on detected fire intensity.
- Regular review and update: Perform regular inspections and update fire protection plans to reflect changes in space usage and material storage.

Designing and implementing sprinkler fire suppression systems involves addressing multiple challenges. By using advanced simulation methods, adhering to standards and regulations, and implementing customized solutions, these challenges can be overcome. Continuous monitoring and periodic adjustments are essential for maintaining system efficiency over time.

2. Performance evaluation of sprinklers based on droplet size distribution and velocity

The distribution of droplet sizes and their associated velocities plays a crucial role in the effectiveness of sprinkler systems, particularly in terms of the kinetic energy transferred to the target surface. In this study, a commercial laser-based instrument known as the Laser Precipitation Monitor (LPM) was used to measure droplet size and velocity in real-time for 10 moving spray-plate sprinklers.

2.1. Methodology

1. LPM measurements: droplet size and velocity measurements were conducted using a Laser Precipitation Monitor (LPM) to determine the distribution of droplet sizes and the kinetic energy transferred to the soil by sprinkler discharge.
2. Comparison of measurement methods: the droplet size distributions measured with the LPM were compared with those obtained using the traditional flour pellet method.
3. Eight out of ten measured distributions showed no significant differences between the two measurement methods.

4. The discrepancies observed occurred under operational conditions that exceeded the sprinkler manufacturer's specifications.

2.2. Results and conclusions

- Droplet size distribution: the findings indicate that droplet measurements can vary considerably between the two methods, especially for sprinklers operating under conditions that produce compact droplet streams. It is still unclear which method yields more accurate results under such conditions.
- Kinetic energy: the kinetic energy values calculated based on droplet size and velocity data from LPM measurements did not differ significantly from those obtained using the flour pellet method and ballistic model estimates of tangential droplet velocity.
- Use of laser instrumentation: the laser-based device proved to be a relatively simple and reliable tool for obtaining accurate estimates of sprinkler kinetic energy per unit of water volume applied, across various types of moving deflector sprinklers and operational conditions.

2.3. Practical applications

The measured droplet size distribution and the calculated kinetic energy from sprinkler discharges have proven sufficient for field applications, providing an accurate and practical evaluation of irrigation system performance.

Impact of droplet size and velocity on sprinkler performance: the distribution of sprinkler droplet sizes and their corresponding velocities significantly affect system efficiency, particularly regarding the kinetic energy transferred to the soil surface. When the application intensity exceeds the soil's infiltration rate, runoff and erosion may occur. The kinetic energy of droplets impacting bare soil surfaces can lead to surface sealing, thereby reducing water infiltration rates and exacerbating the risks of runoff and soil erosion.

2.4. Methods for measuring droplet size distribution

Over the past five decades, research on droplet size distribution from agricultural sprinklers has been relatively limited. Three main methods have been commonly used to measure droplet sizes:

1. **Paper stain method**
    - Water droplets are captured on specially treated paper and allowed to dry.
    - The resulting stains are measured and converted into droplet sizes using a calibration equation that relates stain diameter to droplet diameter.

2. **Flour pellet method**
    - Droplets are collected in a tray filled with sifted flour. After drying, the resulting flour pellets are sorted into different size categories.
    - A calibration equation relates the pellet mass to the droplet diameter.

3. **Laser particle measurement system**
    - A droplet passing through a horizontal laser beam casts a shadow on a linear array of photodiodes.
    - The width of the shadow on the photodiode array is used to determine the droplet size.

2.5. Laser instruments for measuring droplet size and velocity

A second type of laser-based instrument for measuring droplet size and velocity is used almost exclusively in studies involving natural precipitation. These instruments are commonly referred to as disdrometers, optical spectropluviometers, or laser precipitation monitors (LPM), depending on the scientific field and application. The LPM operates on principles like the laser particle measurement system but features a simpler design. The sensor's electronics and optics are not complex, which makes the device easy to calibrate, reliable, portable, and robust.

Operating principle of LPM:

- An infrared light source (wavelength of 900 nm) emitted from a light-emitting diode (LED) is shaped into a rectangular beam of parallel light using a pair of converging lenses and rectangular masks.
- The total light intensity of the beam is continuously monitored by a receiving photodiode, which produces a voltage signal proportional to the amount of light received.
- When a droplet passes through the light beam, the received light intensity decreases, thereby lowering the output voltage.
- The amplitude and duration of this voltage drop are proportional to the droplet's cross-sectional area and the time it spends within the beam.

Advantages and disadvantages of LPM:

- **Advantages:**
    - Easy to calibrate, reliable, and portable.
    - Capable of measuring with an accuracy of 3% or less with a minimum sample size of 10,000 droplets.
    - Provides reliable estimates of droplet size distribution and kinetic energy.
- **Disadvantages:**
    - Limited signal processing and sensitivity of the photodiode's output depending on where the droplet passes through the beam.
    - Coincidence errors and edge effects cannot be entirely eliminated, though they can be controlled or minimized.

Conclusions: the methods and instruments used for measuring droplet size and velocity are essential for evaluating the performance of irrigation systems. Each method has specific strengths and limitations, and the choice of method depends on operating conditions and the specific requirements of the experiment. Laser instruments like the LPM offer a relatively simple and reliable way to obtain accurate estimates of the kinetic energy applied by sprinklers.

Impact of droplet size and velocity on sprinkler performance: the distribution of droplet sizes and their associated velocities has a significant impact on sprinkler system performance, particularly in terms of the kinetic energy transferred to the soil surface. When the application intensity exceeds the soil's infiltration rate, runoff and erosion may occur. The kinetic energy of sprinkler droplets striking bare soil can cause surface sealing, thereby reducing water infiltration rates and increasing the risk of runoff and erosion.

Droplet size distribution measurement

Over the past 50 years, studies on droplet size distribution from agricultural sprinklers have been relatively limited. Three main methods have been commonly used to measure droplet size:

1. **Water-sensitive paper method:** droplets are collected on treated paper and left to dry. The resulting spots are measured and converted using a calibration equation that relates spot size to droplet size.
2. **Flour pellet method:** droplets are collected in a tray filled with sifted flour. The flour is then dried, and the resulting pellets are sorted into different size categories. A calibration equation is used to relate the mass of the pellets to droplet size.
3. **Laser particle measuring system**: a droplet passing through a horizontal laser beam casts a shadow on a linear arrangement of photodiodes. The width of the shadow on the photodiode array corresponds to the droplet's diameter.

Laser instruments for measuring droplet size and velocity: a second type of laser instrument used for measuring droplet size and velocity is employed almost exclusively in the study of natural precipitation. These instruments are known as disdrometers, optical spectropluviometers, or laser precipitation monitors (LPM), depending on the scientific field and application. The LPM works similarly to the laser particle measurement system but features a simpler design. The sensor's electronics and optics are not complex, making the instrument easy to calibrate, reliable, portable, and robust.

Operating Principle of the LPM

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- The total intensity of the light beam is continuously monitored by a receiving photodiode, which produces a voltage signal proportional to the amount of received light.
- When a droplet passes through the light beam, the intensity of the received light drops, which reduces the output voltage.

- The amplitude and duration of the voltage change are proportional to the droplet's cross-sectional area and its residence time within the beam.

Advantages and disadvantages of LPM

Advantages:

- Easy to calibrate, reliable, and portable.
- Can measure with an accuracy of 3% or less using a minimum sample size of 10,000 droplets.
- Provides reliable estimates of droplet size distribution and kinetic energy.

Disadvantages:

- Limited signal processing capabilities and sensitivity of the photodiode's output depending on where the droplet intersects the beam.
- Coincidence errors (when multiple droplets pass simultaneously) and edge effects (when only part of a droplet crosses the beam) cannot be fully eliminated but can be mitigated or controlled.

Validation and correction methods

1. Validation of Droplet Size Measurements: Droplets with measured velocities that deviate significantly from the terminal velocity corresponding to their measured size may be the result of coincidence errors or edge effects. These outliers can be excluded from the dataset to improve measurement accuracy.
2. Data Correction Techniques: Solomon et al. (1991) applied a criterion where droplet velocity measurements exceeding ±2 standard deviations from the average measured velocity were used to discard droplet size data from the dataset. This method helps reduce measurement errors, though it does not eliminate them entirely.

Relevant Studies and Findings

1. Study by Kincaid et al. (1996): Measured droplet size distributions for a wide variety of sprinkler types, nozzle sizes, and operating pressures using a laser particle measurement system. Measurements were taken at radial intervals of 1 meter within the sprinkler's wetted radius.
2. Study by DeBoer and Monnens (2001): Evaluated droplet size distributions for multiple types of rotating-plate sprinklers across various nozzle sizes and operating pressures. The droplet distributions were weighted according to the volume fraction of water applied in each radial measurement zone.

Ballistic Models and Kinetic Energy

Determining the kinetic energy transferred to the soil by sprinkler droplets requires knowledge of both droplet mass (or size) and velocity. Over the past 50 years, droplet trajectory models based on classical rigid-body motion laws have been developed to analyze and predict sprinkler operating characteristics. These are commonly known as ballistic models and involve simplifying assumptions to numerically simulate droplet trajectories.

Key simplifications used in ballistic models include:

1. Droplets form at the sprinkler nozzle.

2. Droplet volume remains constant during flight.
3. Droplets are spherical and do not deform.
4. Forces acting on droplets include gravity and drag.
5. Drag force acts opposite to the direction of motion.
6. The initial velocity and trajectory angle are known inputs.

Use of Laser Instruments in Irrigation Research

Laser-based instruments used for measuring droplet size are susceptible to two major types of measurement errors: coincidence and edge effects. Coincidence errors occur when two or more droplets simultaneously pass through the laser beam and cast overlapping shadows on the photodetector. Edge effects arise when only part of a droplet passes through the laser beam along one of its edges.

To control these errors, each droplet measurement can be validated by comparing its measured velocity with the terminal velocity expected for its measured size. In natural rainfall, droplet velocity is assumed to approach terminal velocity. Comparing measured velocity to theoretical terminal velocity helps validate the dataset.

3. Conclusions

The accurate assessment of sprinkler system performance is fundamentally dependent on the precise measurement of droplet size and velocity, which are key parameters in evaluating the kinetic energy delivered to the ground surface. This energy plays a crucial role in the effectiveness of fire suppression or irrigation, as it influences water distribution, soil infiltration, and the system's overall efficiency.

Among the measurement techniques explored, laser-based instruments—such as the Laser Precipitation Monitor (LPM)—have demonstrated notable advantages, including ease of calibration, portability, and reliable data acquisition across large sample sizes. Their application in controlled environments provides a solid foundation for evaluating sprinkler behavior under realistic operational scenarios.

This study was conducted using a dedicated experimental stand, specifically designed to support high-precision measurements. The stand dimensions (Height: 2000 mm, Width: 2000 mm, Length: 3000 mm) allowed for systematic data collection across different distances and sprinkler types. The configuration included alternating sprinkler heads of varying nozzle sizes, which ensured uniform coverage and a representative spray pattern for analysis.

The setup and measurement process are illustrated in the figure below, which provides a visual reference for the experimental conditions. This configuration enabled the controlled evaluation of droplet behavior and offers a replicable model for further investigations. Overall, the results confirm that LPM-based techniques represent a reliable and efficient approach for characterizing sprinkler performance and optimizing system design.

Fig. 1. Image of mobile experimental stand

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