Protection of Storage Under Sloped Ceilings – Phase 2 – Measurement of Sprinkler Spray Patterns and Impingement Near Sloped Ceilings

FINAL REPORT BY:

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There is limited prior research related to protection of storage under ceilings with slopes steeper than 2/12. Previous studies exist from FM Global, University of Maryland/Custom Spray Solutions, the Fire Protection Research Foundation, and National Fire Sprinkler Association (NFSA), but there are still many open questions related to the protection criteria for storage under sloped ceilings. The questions include, but are not limited to, sprinkler activation pattern relative to fire source location, and optimal sprinkler installation orientation.

There are many different parameters related to this design challenge. Some of the key parameters include the slope of the ceiling, the commodity being stored, types of sprinklers (including ESFRs), sprinkler orientation, and sprinkler spacing. Some possible protection design solutions to sloped ceiling facilities are to use higher densities or larger calculation areas than for storage under flat ceilings.

The Fire Protection Research Foundation initiated this project to undertake modeling analysis in order to understand the potential protection challenges related to sloped ceilings, and to determine the range of scenarios that should be studied further through testing in order to help inform requirements and guidance related to sloped ceilings over storage in NFPA 13, *Standard for the Installation of Sprinkler Systems*. This report presents laboratory experiments conducted as part of Phase 2 to gain insight into the effect of the sloped ceiling configuration on the spray.

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Keywords: storage protection, sloped ceilings, NFPA 13, automatic sprinklers, warehouse protection, modeling, test matrix

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Protection of Storage Under Sloped Ceilings – Phase 2: Measurement of Sprinkler Spray Patterns and Impingement Near Sloped Ceilings

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1. Executive Summary

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) “Protection of Storage Under Sloped Ceilings” project seeks to address knowledge gaps related to the impact of sloped ceilings on storage protection. There is currently a lack of clear guidance on how to design fire sprinkler systems for storage protection under these conditions. The overall goal of the project is to develop the technical basis for new sprinkler protection guidance.

The findings from Phase I and II of the project were reviewed to support the development of a test plan for large-scale fire suppression experiments. Phase I studied the relevant parameters associated with storage protection under sloped ceilings through an industry survey and numerical simulations of sprinkler activation and water spray patterns under smooth sloped ceilings. Phase II extended the numerical work performed in Phase I by considering obstructed ceiling construction, ridges, and additional sprinkler types also focusing on sprinkler activation time and water delivery performance. Laboratory experiments were also conducted in Phase II to gain insight into the effect of the sloped ceiling configuration on the spray.

The potential for the spray to be blocked and/or redirected is of particular concern in the sloped ceiling configuration, especially when the sprinkler is oriented with the deflector parallel to the floor. These impingement effects may compromise the suppression performance, modifying the spray from that of the original design. Complex impingement interactions, which may include spray shadowing, filming, and even splattering are unpredictable and should be avoided.

Impingement interactions depend on the sprinkler spray pattern and installation details. Three storage sprinklers were used in this study; an ESFR Pendent K240 (K16.8 gpm/psi$^{0.5}$), an ESFR Pendent K200 (K14.0 gpm/psi$^{0.5}$), and an ELO Upright K160 (K11.2 gpm/psi$^{0.5}$). These measurements were conducted using the Spatially-resolved Spray Scanning System (4S) to completely characterize the initial spray and average spray field for the three different storage sprinklers. In order to assess these impingement effects, the sprinkler discharge characteristics were first measured to quantify the differences in the initial spray produced by each sprinkler. Fractional impingement experiments were conducted to estimate the partial impingement to the ceiling for these sprinklers for a variety of installation configurations (i.e. ceiling slopes and standoff distances). Finally, flux redistribution experiments were conducted to evaluate how the sprinkler spray may be redirected by sprinkler impingement, potentially changing the spray pattern from that expected in a standard flat ceiling configuration. The laboratory spray distribution tests were performed at approximately 1.7 bar (25 psi). The details of the spray pattern are modified by operating pressure and the quantitative results will vary based on operating pressures. Nevertheless, the sprinkler spray data obtained in the laboratory experiments are valuable for numerical modeling, numerical validation, and establishing trends for the impact of ceiling slope.

The initial spray measurements obtained with the 4S provide extremely detailed spray information (included in the Appendix) highlighting the different discharge characteristics for the sprinklers. This information is useful for input into numerical simulations for fire suppression analysis. These measurements compare favorably with volume flux measurements previous published in FM Global datasets for the K200 (K14.0 gpm/psi$^{0.5}$) and ELO Upright K160 (K11.2 gpm/psi$^{0.5}$) sprinklers and established drop size correlations. While the unique
spray pattern from each sprinkler affected the extent of impingement, all impingement fractions were estimated to be less than 5% for slopes less than 18.4° (4:12) or less even for standoff distances as small as 0.075 m (3 in.). This small fraction of water impinging on the ceiling is redirected, largely down the slope. In fact, measurable redirection of flux is only observed in the sprinklers with the largest slope (18.4°) and smallest standoff distance tested (0.075 m, 3 in.). This data is especially useful to evaluate numerical impingement models because of the available detailed measurements of the initial spray, ceiling impingement flux distribution, and target flux distribution (1 m below the sprinkler deflector) under a variety of conditions.
2. Introduction

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) “Protection of Storage Under Sloped Ceilings” project seeks to address knowledge gaps related to the impact of sloped ceilings on storage protection. There is currently a lack of clear guidance on how to design fire sprinkler systems under these conditions [1-5]. Large-scale suppression tests with sloped ceilings are not readily available [6], and only a few small- and intermediate-scale suppression studies have been conducted [7,8]. The empirical evidence needed to develop suppression system design guidance does not exist.

Phase 1 [9, 10] of this project included a review of current storage configurations and numerical modeling of the effects of ceiling slope on suppression performance using the computational fluid dynamics (CFD) code FireFOAM [11, 12]. The Phase 1 numerical modeling [10] investigated sprinkler activation and sprinkler spray patterns resulting from a fire on a 3-tier high rack storage array of Cartoned Unexpanded Plastic (CUP) commodity under ceilings of various slopes, ranging from a flat ceiling to a ceiling with a slope of 33.7° (8 in 12). Ceiling clearances (between the top of the storage and the ceiling) of 3.05 and 6.1 m (10 and 20 ft) were examined. During the sprinkler spray portion of the numerical modeling, the sprinkler spray from a pendant, K14.0/0.0 gpm/psi (K200 lpm/bar) sprinkler at 50 psi (3.4 bar) was studied, with the deflector oriented in parallel-to-ceiling and parallel-to-floor configurations.

Phase II of the project consisted of laboratory characterization of sprinkler sprays and numerical modeling using FireFOAM [11, 12] that extended the work performed in Phase I. The ultimate goal of this sloped ceiling protection project is to develop guidance for storage protection under sloped ceilings. Numerical simulations evaluated sprinkler activation times and patterns from large-scale growing fires involving a 3-tier high rack storage commodity in the presence of obstructed ceiling construction, ridges and over a range of slopes up to a ceiling inclination of 18.4° (4 in 12). These results were used to specify a series of large-scale tests to further support the development of design guidance for storage protection under sloped ceilings. Simulations were also used to study the water-flux distributions and the effect of deflector orientation on additional sprinklers not considered in Phase I, including upright and pendent sprinklers. Referenced simulation results can be found in a separate report [13].

The current report provides the laboratory sprinkler spray pattern analysis of upright and pendent sprinklers (beyond those considered in Phase I) and their interactions with sloped ceilings under a variety of installation configurations. The effect of sprinkler type, ceiling slope, and standoff distance was explored using measurements in the Spatially-resolved Spray Scanning System (4S) [14]. These laboratory experiments provide valuable insight into the differences in the sprinkler spray patterns (and their respective impingement behavior with sloped ceilings) used in the Phase II study, data for use in numerical simulations, and unique, rare data for validating spray impingement models on surfaces.
3. Discharge Characteristics

Discharge characteristics for K160 (K11.2 gpm/psi^{0.5}), K200 (K14.0 gpm/psi^{0.5}), and K240 (K16.8 gpm/psi^{0.5}) storage sprinklers operating at 1.7 bar (25 psi) were determined for this study.

3.1 Characterization Methodology

The sprinkler discharge characteristics were determined from very detailed initial spray measurements using the Spatially-resolved Spray Scanning System (4S). The 4S was developed to capture the complete spatio-stochastic nature of the spray at its point of origin for documentation and analysis. The 4S synthesizes spray measurements, transport analysis, and statistical representation frameworks providing high-fidelity spray characteristics suitable for evaluation of component-level performance (e.g. sprinkler spray pattern uniformity) or system-level performance (e.g. fire suppression system simulations). Each sprinkler’s unique spray pattern is captured through optical and mechanical probing of the spray over a measurement (or initialization) surface close to the sprinkler head (0.4 - 0.8 m) and analyzing local drop characteristics (e.g. drop size, velocity, and volume flux) [14].

The 4S measurement approach facilitates data collection, reduction, and analysis through innovative experimental facilities and analytical approaches. The 4S measurement system is arranged into four main subsystems enumerated in Figure 1 and supported by automation, instrumentation, and data acquisition processes. Data reduction and analytical approaches are applied to the data to provide a complete, spatially-resolved characterization of the sprinkler. Sprinklers were installed into the 4S measurement device and operated at 1.7 bar (25 psi). Mechanical measurements were captured over an initialization sphere with radius of 405 mm while the optical measurements were captured at a radius of 550 mm. As previously described, the applied process results in the ability to completely reproduce the spray generated from these measurements. The captured spray characterizations for the sprinklers of interest are sufficient for use in any presently available mathematical or numerical simulation framework and are used in this work to examine the interaction of the sprinkler with the sloped ceiling [14, 15, 16].

3.2 Detailed Spray Characterizations

The three storage sprinklers demonstrate markedly different discharge characteristics especially when comparing the ELO sprinkler with the ESFR sprinkler as shown in Figure 2. The upright ELO sprinkler (K160) produces very little flux near the equator until polar angles of around 115° compared to approximately 105° in the pendent ESFR sprinklers (K200 and K240). It can also be seen in the detailed volume flux measurements included in the Appendix that very little flux is directed straight down (~ 0 mm/min) as expected for an upright sprinkler while extremely high fluxes are observed at similar locations for the ESFR sprinklers (> 8,000 mm/min). It should be noted that the installation method of the upright sprinkler was such that it prevented water from being delivered at the location directly below the sprinkler, an observation consistent with the installation practices of upright sprinklers. Showing from branch-line installations were not considered. Volume flux measurements taken demonstrate the spatial variations associated with the slot and tine formations of the deflector. Asymmetries in the measured volume flux are especially pronounced at the frame arm features of the sprinkler which occur at the 90° and 270° azimuthal locations.
The characteristic drop size, quantified by the volume median diameter, for each of the sprinklers was about 1.5 mm and showed only weak spatial variation. The drop size distribution parameter, a measure of the spray uniformity, was generally measured between 2.5 and 3.0. This value also showed weak spatial variation. This relatively narrow drop size distribution (higher distribution parameters) may be attributed to the low operating pressure for this test. A detailed presentation of all of the 4S measurements is included in the Appendix.

Figure 1: Spatially-resolved Spray Scanning System (4S) measurement processes and subsystem elements (dashed regions); (1) flow control and conditioning; (2) mechanical sphere patternation; (3) integral line patternation; (4) optical sphere patternation [14].
Figure 2: Initial spray volume flux distribution at a radius of 0.4 m with $REF_{MAP} = 250$ mm/min for (a) K160 ($K_{11.2}$ gpm/psi$^{0.5}$); (b) K200 ($K_{14.0}$ gpm/psi$^{0.5}$); and (c) K240 ($K_{16.8}$ gpm/psi$^{0.5}$) sprinklers operating at approximately 1.7 bar (25 psi).
4. Ceiling Impingement Effects

4.1 Impingement Measurement Methodology

The 4S facility was used to obtain average spray-fields below each of the three storage sprinklers tested in this study (in addition to the detailed initial sprinkler spray measurements described in Sec. 3). Integral line patternation measurements typically associated with a 4S spray characterization are taken at 1 m below the sprinkler. The initial fields captured in this analysis were obtained from line patternator flux measurements taken at elevations between 0.0 m and 1.0 m below each sprinkler in increments of 0.2 m as demonstrated in Figure 3. Measurements taken at 0.0 m below the sprinkler were captured in the same horizontal plane as the sprinkler deflector to account for any spray thrown above the equator on the initialization sphere. Each sprinkler was rotated slowly, 0.1 rpm, during these line patternator measurements to produce average radial flux distributions at each elevation. The rotation time used for these measurements was identified as the maximum measurement time that limited collection cylinder overfill. The measured average fluxes were integrated from the sprinkler centerline radially outward to provide flow patterns for each sprinkler. In addition to the initial field measurements, tests were conducted with the integral line patternation device positioned at 1 m below the sprinkler and a ceiling structure positioned above the line patternation device. The ceiling was adjusted between slopes of 9.5 and 18.4 degrees with standoff distances of the sprinkler at 3”, 6”, and 13”.

![Figure 3: Integral line patternation measurement configuration and sample filling.](image)

4.2 Spray Impingement Results

The spray flow patterns are described in terms of iso-contours of total sprinkler flow between 0 and 100% of the measured flow (increasing from the south pole, 180° to the equator, 90°). The spray patterns for K160 (K11.2 gpm/psi^{0.5}), K200 (K14.0 gpm/psi^{0.5}), and K240 (K16.8 gpm/psi^{0.5})...
gpm/psi$^{0.5}$) storage sprinklers operating at 1.7 bar (25 psi) are provided in Figure 4 and are shown from an axisymmetric reference frame. While interesting in themselves, these flow patterns are ultimately used to evaluate ceiling impingement effects for a variety of ceiling slopes and sprinkler standoff configurations.

![Spray Pattern Flow Iso-Contours](image)

**Figure 4:** Spray pattern flow iso-contours (axisymmetric) from 0 to 100% for sprinklers operating at 1.7 bar (a) K160 (K11.2 gpm/psi$^{0.5}$) Upright ELO; (b) K200 (K14.0 gpm/psi$^{0.5}$) Pendent ESFR; (c) K240 (K16.8 gpm/psi$^{0.5}$) Pendent ESFR.

Distinct differences are observed in Figure 4 when comparing the sprinkler flow patterns. The K160 ELO upright sprinkler produces a compact spray with iso-contours between 10% and 90% spanning radial locations from 0.2 m to 1.2 m (at an elevation 0.5 m below the sprinkler). The K200 and K240 sprinklers have an extended reach at the same elevation and iso-contours within the spray spanning from 0.2 m to 1.6 m for the K200 Pendent and from 0.2 m to 1.5 m for the K240 Pendent. While not evident from the spray patterns it is worth noting that approximately 10% of the flow is concentrated in radial locations less than 0.2 m (at an elevation of 0.5 m below the sprinkler) despite the large differences measured in downwardly directed flux; 0 mm/min for the K160 Upright ELO, 8300 mm/min for the K200 Pendent ESFR, and 12100 mm/min for the K240 Pendent ESFR. While these comparisons are interesting, it should also be noted that the spray patterns generated by these sprinklers may change significantly with operating pressure.

### 4.3 Fractional Impingement Analysis

The fraction of the sprinkler flow that impinges on the ceiling is evaluated to quantify the extent of ceiling impingement effects on the sprinkler spray pattern. The spray patterns described in the previous section are interrogated at the ceiling for a variety of ceiling slopes and sprinkler
standoff configurations to determine theoretical ceiling impingement fluxes and ultimately the fractional flow impingement should a ceiling be placed at that location. The presented results represent a first order approach as the effect of the ceiling on air entrainment and spray pattern formation are not directly assessed.

The spray patterns for the three storage sprinklers are displayed in Figure 5 with sprinkler standoff distances of 3, 6, and 13 inches and ceiling slopes of 9.5° and 18.4°. It is necessary to reiterate that the average spray patterns in Figure 5 should be viewed from an axisymmetric frame of reference. In contrast, the ceiling boundaries (often intersecting the axisymmetric spray pattern) should be viewed as 2D planar, extending infinitely in the third dimension (i.e. into and out of the page). It is clear from Figure 5 that ceiling impingement will occur in a number of configurations and the extent of this impingement will change with sprinkler spray pattern. For example, all sprinklers with 3” and 18.4 deg. show non-negligible intersection between the ceiling boundary and sprinkler spray pattern as measured without the ceiling interaction. It should also be noted that the crossing indicated in Figure 5 displays the maximum ceiling interference with average spray patterns and this interference will reduce along the infinite extent of the ceiling with corresponding extended radial distance from the sprinkler centerline.

The fractional impingement of total sprinkler flow is quantified in Figure 6 for each storage sprinkler as a function of ceiling slope and standoff distance. As expected, the fractional impingement is a strong function of standoff distance dropping off steeply with increasing standoff distance for all sprinklers and slopes. Even for a very small standoff distance (3” or 0.08 m), the estimated fractional impingement flow from this approach is less than 4% for all sprinklers and slopes suggesting that impingement effects should be small for the range of standoff distances and slopes proposed for storage configurations. While interesting, caution should be exercised when making qualitative comparisons between spray pattern interference presented in Figure 5 with calculations reported in Figure 6. Consideration should be given to the fact that the axisymmetric geometry of the average spray pattern in contrast with the planar geometry. Figure 5 is presented as a two-dimensional slice of a three-dimensional impingement problem while Figure 6 considers the third dimension.
Previous results by FM Global also reported low values of fractional impingement based on their simulations [17]. For example, FM Global predicted a 4.4% fractional impingement for the K14.0 sprinkler with an 18.4° slope operating at 3.4 bar and installed with a 13” standoff distance from the ceiling. While this value is small, the current study estimates approximately negligible fractional impingement in this configuration (operating at 1.7 bar). The fractional impingement differences between estimates from this study and FM Global FireFOAM predictions may be due to numerical approximations in simulations, measurement analysis, or different sprinkler operating pressures between the experiments and the simulations.
Figure 6: Impingement fractions for various configurations including (0, 0.08, 0.15, and 0.33 m) standoff distances and 9.5° (red) and 18.4° (blue) ceiling slopes; (a) K160 Upright ELO; (b) K200 Pendent ESFR; (c) K240 Pendent ESFR.

4.4 Flux Redistribution

Impingement interactions with the ceiling can be complex resulting in spray shadowing effects, filming, and even splattering. Few measurements are available in open literature quantifying these spray-surface interactions. While the details of these processes are beyond the scope of this study, measurements have been performed to shed light on ceiling impingement redistribution of the sprinkler spray. These measurements include detailed initial spray measurements and near field flux distributions with and without the ceiling. Ultimately, accurate modeling of these interactions is important in order to predict this impingement flow redistribution. The detailed spray data obtained in this study can also be used for model development and validation focused studies.

The predictions of Figure 6 and the measurements of Figure 7 provide information on the location and amount of spray impacting the ceiling while quantifying some of the details of spray redirection after impact (i.e. redistribution). Figure 6 shows the highly localized ceiling impingement and its dependence on ceiling slope and sprinkler type. The higher impingement fluxes from larger sprinklers are not surprising in the 18.4° configuration; however, spray pattern effects are also observed when comparing flux distributions at a ceiling slope of 9.5°. While small, impingement is only predicted for the K200 Pendent ESFR sprinkler at this ceiling slope, with no foreseeable impingement for the K160 Upright ELO or K240 Pendent ESFR sprinklers at the same operating pressure.

The redistribution effects appear complex from the measurements captured with and without a ceiling configuration. For all cases presented in Figure 7, very little difference in the flux distribution, measured 1 m below the sprinkler, is observed between the 0.08 m (small circles) and 0.15 m (larger circles) standoff distances. In contrast, the flux distribution can change dramatically when the ceiling slope is changed from 9.5° (red) to 18.4° (blue). For the K160 sprinkler shown in Figure 7a, the flux distribution profile under the 9.5° ceiling slope
configuration (red circles) is basically unchanged from the flat ceiling configuration (dashed lines). For the K200 sprinkler shown in Figure 7b, the flux distribution profile under the 9.5° ceiling slope configuration (red) is nearly unchanged from the flat ceiling configuration (dashed lines) until remote radial locations where the flux is increased (from that of the flat ceiling configuration) delivering the impingement flow far away from the point of spray impingement or identifying. This increase in flux is also observed at remote radial locations in the 18.4° ceiling configuration albeit slightly closer to the centerline. For the K240 sprinkler shown in Figure 7c, a slight increase in flux is observed at remote radial locations for the 9.5° and 18.4° ceiling configurations. It should be noted that flux increases due to ceiling impingement reflected in Figure 7 may occur as a result of the air entrainment physics which were not considered as part of this experimental study.

![Graph](image_url)

Figure 7: Flux distributions 1 m below the sprinkler; without ceiling (dashed line); with ceiling and 3” (small circle) and 6” (large circle) standoff distances and 9.5° (red) and 18.4° (blue) ceiling slopes; (a) K11.2 Upright ELO; (b) K14.0 Pendent ESFR; (c) K16.8 Pendent ESFR.
4.5 Trajectory Analysis

An alternative approach for the analysis of spray impingement on the ceiling was conducted based on the highly resolved spray measurements captured with the 4S. From these measurements, detailed information on the average flux profile as a function of elevation angle was determined for each sprinkler. Using the average flux profile, the fraction of spray blocked by the ceiling was conservatively estimated for different sprinkler standoff distances, ceiling slopes, and sprinkler types. With the quality of detailed data provided in 4S measurements, this analysis could be expanded in future work to evaluate the effect of frame arm alignment on the spray impingement on the ceiling.

For a planar ceiling obstruction, positioned tangent to a 0° reference datum, the effective distance a droplet needs to travel in order to impact the ceiling will trend toward infinite as the azimuthal angle approaches ±90°. As the azimuthal position on the sprinkler is varied and the effective distance to the ceiling increases, a proportionally smaller region of the initial spray will be obstructed by the ceiling. Using simplified projectile analysis, the minimum spray angle (closest to the equator) was calculated for each azimuthal angle at which an ejected particle’s trajectory will not intersect with the ceiling. The particle trajectory used in this analysis was calculated based on an unobstructed flow. From the established average flux profiles, the volume of water measured above the calculated minimum spray angle was accumulated and compared to the total sprinkler flowrate. The affected areas of the sphere for a ceiling slope of 18.4° and various standoff distances are shown in Figure 8 as the red region of the sphere.

![Figure 8: Regions of initialization spheres effected by 18.4° ceiling placement at different standoff distances; (a) 0.08 m standoff; (b) 0.15 m standoff; (c) 0.33 m standoff.](image)

At the 9.5° ceiling slope, the obstructed flow was estimated at nominally 1% or less of the total sprinkler flowrate for all three sprinklers at the 0.08 m standoff distance. The remainder of ceiling standoff distances evaluated resulted in negligible volumes of water obstructed by the 9.5° ceiling. With the 18.4° ceiling installation, the maximum obstructed volume percentage of water was predicted for the K200 ESFR sprinkler at 9.7% with a standoff distance of 0.08 m. This value was determined to reduce to 6.5% with an increased standoff distance of 0.15 m and 2.4% at 0.33 m. The values calculated with this trajectory analysis methodology are presented in Table 1 and are expected to be conservative based on the fact that the sphere measurements are taken without a ceiling and the trajectory model applied is simplistic and does not account for the effect of the ceiling on the flow field.
Table 1: Estimated percentage of flow blocked for K160 / K200 / K240 sprinklers.

<table>
<thead>
<tr>
<th>Standoff</th>
<th>9.5° Slope</th>
<th>18.4° Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08 m</td>
<td>0.3% / 1.2% / 1.0%</td>
<td>1.2% / 9.7% / 3.7%</td>
</tr>
<tr>
<td>0.15 m</td>
<td>0.1% / 0.3% / 0.5%</td>
<td>0.7% / 6.5% / 2.6%</td>
</tr>
<tr>
<td>0.33 m</td>
<td>0.0% / 0.1% / 0.2%</td>
<td>0.4% / 2.4% / 1.3%</td>
</tr>
</tbody>
</table>
5. Summary

Using the Spatially-resolved Spray Scanning System (4S), detailed measurements were performed on storage sprinklers sprays to determine their initial spray characteristics and to evaluate their spray impingement interactions with sloped ceilings. From an engineering perspective, these measurements are useful to determine the relative impact of various sprinkler system installation details (e.g. ceiling slope, standoff distance, or sprinkler type) on spray dispersion performance in sloped ceiling storage protection applications. These measurements are also useful in the application and development of spray dispersion and impingement models used in fire suppression simulations. Upright ELO K160, Pendent K200, and Pendent K240 sprinklers all operating at 1.7 bar and each producing a unique spray pattern were used in this study. The relatively low experimental operating pressure resulted from flow capacity limitations in the laboratory; a new facility is being fabricated at FRA capable of flows up to 950 LPM (250 GPM) and pressures up to 10.3 bar (150 psi) and will be used for future measurements. Higher operating pressures will certainly affect the measured initial spray, spray patterns, and ceiling impingement behavior and additional pressures are needed to provide a more complete view of the sprinkler dispersion behavior. Nevertheless, these measurements provide a first look at sprinkler spray impingement details and valuable data to support simulations.

As expected, the initial spray measurements show downward directed fluxes (directly below the sprinkler) greater than 40 times the average flux for the Pendent ESFR sprinklers. In contrast, the Upright ELO sprinkler produced no flux directly below the sprinkler as expected based on the obstruction provided by the sprinkler piping. In the case of Upright ELO and Pendent ESFR sprinklers, steep flux gradients in elevation angles naturally result in addition to the azimuthal variations associated with the frame arms, and tine-slot structure of the sprinkler. The spray measurements and impingement predictions show that a small fraction of the spray (< 6.5%) impinges on the ceiling for standoff distances greater than 0.08 m and slopes up to 18.4°. Flux measurements below the sprinkler (~ 1 m) demonstrate that when the ceiling interferes with the spray, the flow is redistributed (from that measured with a flat ceiling) providing local increases in flux not close to the point of impingement.

The combined detailed measurements of the initial spray patterns, impingement fractions, and flux redistributions provide a rich, comprehensive self-consistent data set for further exploration and model validation. Impingement fractions calculated from the detailed distribution data compare favorably to those calculated from trajectory analysis and detailed initialization sphere data. Further, the spray impingement values presented are consistent with previous modeling results in that a higher pressure, as used in the modeling, is expected to result in a larger fraction of water obstructed by the ceiling. Characterization of additional sprinkler types and operating conditions are planned for the future to provide a more complete view of spray dispersion in storage sprinklers and to expand support for numerical simulations in this important fire protection application.
References


Appendix A

Spray patterns from the three sprinklers were measured on an initialization sphere following the natural coordinate system for the sprinkler spray with droplets traveling radially outward from a central point, ostensibly at the origin of the sprinkler deflector. The sphere patternation measurements were performed using the Spatially-resolved Spray Scanning System (4S) as described previously in Section 3. Measurements of volume flux, characteristic drop size ($d_{v50}$), drop size distribution parameter (gamma), and velocity were performed. These measurements are reported as sphere maps detailing the parameters over the surface of the initialization sphere for each sprinkler characterized. An isometric view followed by a bottom view are provided for each of the sphere maps. The white dashed line in the figures represent the measurement datum, referenced as 0°, while the gray dashed line represents the locations of the frame structure of the sprinkler, positioned at 90° and 270°, which can result in visible spray abnormalities. A more detailed numerical breakdown of the spray characteristics for each sprinkler are provided in sphere profiles distributed over 360 azimuthal degrees for every 10° change in elevation angle in the following sections of the appendices. These sphere profiles demonstrate the effect of sprinkler deflector geometry on the resulting spray characteristics, specifically noticeable in the flux distributions around the pendent style sprinklers. The non-uniformities in the spray characteristics around the frame arm assembly should also be noted.
01/18/17 [K160]

$K = 11.2 \text{ GPM/PSI}^{0.5}$, $P = 25.0 \text{ PSI}$, $\dot{V} = 56.0 \text{ GPM}$

$[ R_{\text{MEAS}} = 0.4 \text{ m}, \delta\phi_{\text{MEAS}} = 5^\circ, \delta\theta_{\text{MEAS}} = 10^\circ, \delta\phi_{\text{SPH}} = 5^\circ ]$

Volume Flux (mm/min)

$\dot{V}_{\text{AVG}} = 172.1 \quad \dot{V}_{\text{MAX}} = 3239 \quad \text{REF}_{\text{MAP}} = 250.0$

Drop Size (mm)

$d v_{\text{50}} = 1.5 \quad d v_{\text{50}}_{\text{MAX}} = 2.0 \quad \text{REF}_{\text{MAP}} = 2.0$

Drop Size Distribution Parameter ()

$\Gamma = 2.7 \quad \Gamma_{\text{MAX}} = 4.0 \quad \text{REF}_{\text{MAP}} = 4.0$

Velocity (m/s)

$U_{\text{AVG}} = 10.9 \quad U_{\text{MAX}} = 15.0 \quad \text{REF}_{\text{MAP}} = 15.0$

$[0.0 \ 0.1 \ 0.2 \ 0.3 \ 0.4 \ 0.5 \ 0.6 \ 0.7 \ 0.8 \ 0.9 \ 1.0 \times \text{REF}_{\text{MAP}}]$
01/18/17 [ K160 ]

\[ K = 11.2 \text{ GPM/PSI}^{0.5}, \ P = 25.0 \text{ PSI}, \ \dot{V} = 56.0 \text{ GPM} \]

[ \ R_{\text{MEAS}} = 0.4 \text{ m}, \ \delta \phi_{\text{MEAS}} = 5^\circ, \ \delta \theta_{\text{MEAS}} = 10^\circ, \ \delta_{\text{SPH}} = 5^\circ ]
01/18/17 [ K160]

$K = 11.2 \text{ GPM/PSI}^{0.5}$, $P = 25.0 \text{ PSI}$, $\dot{V} = 56.0 \text{ GPM}$

*Volume Flux, $\dot{V}_{AVG} = 172.1 \text{ mm/min}$ [ $R_{MEAS} = 0.4 \text{ m}$, $\phi_{MEAS} = 5^\circ$, $\delta_{MEAS} = 10^\circ$ ]*
01/18/17 [ K160]

K = 11.2 GPM/PSI^{0.5}, P = 25.0 PSI, \dot{V} = 56.0 GPM

Drop Size, dv50 = 1.5 mm [ \theta_{MEAS} = 0.4 \text{ m}, \delta\theta_{MEAS} = 5^\circ, \delta\theta_{MEAS} = 10^\circ ]

\begin{align*}
\text{dv50 = 1.1 mm} \\
\text{dv50 = 0.97 mm} \\
\text{dv50 = 1.0 mm} \\
\text{dv50 = 1.3 mm} \\
\text{dv50 = 1.5 mm} \\
\text{dv50 = 1.6 mm} \\
\text{dv50 = 1.7 mm} \\
\text{dv50 = 1.4 mm} \\
\text{dv50 = Indeterminate mm}
\end{align*}
01/18/17 [K160]

K = 11.2 GPM/PSI^{0.5}, P = 25.0 PSI, \dot{V} = 56.0 GPM

Drop Size Distribution Parameter, \Gamma = 2.7 [R_{MEAS} = 0.4 m, \delta \phi_{MEAS} = 5^\circ, \delta \theta_{MEAS} = 10^\circ]
01/18/17 [ K160]

K = 11.2 GPM/PSI^{0.5}, P = 25.0 PSI, \dot{V} = 56.0 GPM

Velocity, \( U_{AVG} = 10.9 \text{ m/s} \) [ \( R_{MEAS} = 0.4 \text{ m}, \delta \phi_{MEAS} = 5^\circ, \delta \theta_{MEAS} = 10^\circ \) ]

- \( U_{AVG} = 6.6 \text{ m/s} \)
- \( U_{AVG} = 6.4 \text{ m/s} \)
- \( U_{AVG} = 7.1 \text{ m/s} \)
- \( U_{AVG} = 9.0 \text{ m/s} \)
- \( U_{AVG} = 11.1 \text{ m/s} \)
- \( U_{AVG} = 11.1 \text{ m/s} \)
- \( U_{AVG} = 11.1 \text{ m/s} \)
- \( U_{AVG} = 11.1 \text{ m/s} \)
- \( U_{AVG} = 12.0 \text{ m/s} \)
- \( U_{AVG} = 9.9 \text{ m/s} \)
- \( U_{AVG} = 5.3 \text{ m/s} \)
A.2 K200

01/10/17 [ K200]

\[ K = 14.0 \text{ GPM/PSI}^{0.5}, \ P = 25.0 \text{ PSI}, \ \dot{V} = 70.0 \text{ GPM} \]

[ \[ R_{\text{MEAS}} = 0.4 \text{ m}, \ \delta \phi_{\text{MEAS}} = 5^\circ, \ \delta \theta_{\text{MEAS}} = 10^\circ, \ \delta_{\text{SPH}} = 5^\circ \] ]

Volume Flux (mm/min)

\[ \dot{V}_{\text{AVG}} = 219.0, \ \dot{V}_{\text{MAX}} = 9967, \ \text{REF}_{\text{MAP}} = 250.0 \]

Drop Size (mm)

\[ d_{50} = 1.4, \ \text{d}_{50_{\text{MAX}}} = 2.0, \ \text{REF}_{\text{MAP}} = 2.0 \]

Drop Size Distribution Parameter ()

\[ \Gamma = 3.0, \ \Gamma_{\text{MAX}} = 4.0, \ \text{REF}_{\text{MAP}} = 4.0 \]

Velocity (m/s)

\[ U_{\text{AVG}} = 11.6, \ U_{\text{MAX}} = 15.0, \ \text{REF}_{\text{MAP}} = 15.0 \]

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 \times \text{REF}_{\text{MAP}}
01/10/17 [K200]

$K = 14.0 \text{ GPM/PSI}^{0.5}, P = 25.0 \text{ PSI}, \dot{V} = 70.0 \text{ GPM}$

[$R_{MEAS} = 0.4 \text{ m}, \phi_{MEAS} = 5^\circ, \theta_{MEAS} = 10^\circ, \phi_{SPH} = 5^\circ$]
01/10/17 [ K200 ]

\[ K = 14.0 \text{ GPM/PSI}^{0.5}, \ P = 25.0 \text{ PSI}, \ \dot{V} = 70.0 \text{ GPM} \]

Volume Flux, \( \dot{V}_{\text{AVG}} = 219.0 \text{ mm/min} \) [ \( R_{\text{MEAS}} = 0.4 \text{ m}, \ \delta\phi_{\text{MEAS}} = 5^\circ, \ \delta\theta_{\text{MEAS}} = 10^\circ \)]
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01/10/17 [K200]

K = 14.0 GPM/PSI^{0.5}, P = 25.0 PSI, \dot{V} = 70.0 GPM

Drop Size, dv50 = 1.4 mm [R_{MEAS} = 0.4 m, \delta\phi_{MEAS} = 5^\circ, \delta\theta_{MEAS} = 10^\circ]

\begin{align*}
\theta &\quad 0^\circ & 60^\circ & 120^\circ & 180^\circ & 240^\circ & 300^\circ & 360^\circ \\
\text{dv50} &\quad 1.3 \text{ mm} \\
\text{dv50} &\quad 1.1 \text{ mm} \\
\text{dv50} &\quad 1.6 \text{ mm} \\
\text{dv50} &\quad 1.1 \text{ mm} \\
\text{dv50} &\quad 1.1 \text{ mm} \\
\text{dv50} &\quad 1.2 \text{ mm} \\
\text{dv50} &\quad 1.3 \text{ mm} \\
\text{dv50} &\quad 1.4 \text{ mm} \\
\text{dv50} &\quad 1.5 \text{ mm} \\
\end{align*}
01/10/17 [ K200]
K = 14.0 GPM/PSI^{0.5}, P = 25.0 PSI, \dot{V} = 70.0 GPM

Drop Size Distribution Parameter, \gamma = 3.0 [ R_{MEAS} = 0.4 m, \delta\theta_{MEAS} = 5^\circ, \delta\phi_{MEAS} = 10^\circ ]
01/10/17 [ K200 ]

$K = 14.0 \text{ GPM/PSI}^{0.5}$, $P = 25.0 \text{ PSI}$, $\dot{V} = 70.0 \text{ GPM}$

Velocity, $U_{AVG} = 11.6 \text{ m/s}$ [ $R_{HEAS} = 0.4 \text{ m}$, $\delta_{MEAS} = 5^\circ$, $\delta_{MEAS} = 10^\circ$ ]

$U_{AVG} = 12.0 \text{ m/s}$

$U_{AVG} = 8.3 \text{ m/s}$

$U_{AVG} = 10.5 \text{ m/s}$

$U_{AVG} = 11.0 \text{ m/s}$

$U_{AVG} = 11.0 \text{ m/s}$

$U_{AVG} = 11.0 \text{ m/s}$

$U_{AVG} = 12.0 \text{ m/s}$

$U_{AVG} = 12.0 \text{ m/s}$

$U_{AVG} = 13.0 \text{ m/s}$

$U_{AVG} = 13.0 \text{ m/s}$

$U_{AVG} = 13.0 \text{ m/s}$

$U_{AVG} = 15.0 \text{ m/s}$

$U_{AVG} = 15.0 \text{ m/s}$

$U_{AVG} = 15.0 \text{ m/s}$
A.3 K240

01/13/17 [K240]

\[ K = 16.8 \text{ GPM/PSI}^{0.5}, \ P = 24.0 \text{ PSI}, \ \dot{V} = 82.3 \text{ GPM} \]

\[ R_{\text{MEAS}} = 0.4 \text{ m}, \ \delta_{\text{MEAS}} = 5^\circ, \ \delta_{\text{SPH}} = 10^\circ, \ \delta_{\text{SPH}} = 5^\circ \]

Volume Flux (mm/min)

\[ \dot{V}_{\text{AVG}} = 262.8 \dot{V}_{\text{MAX}} = 1210 \text{ REF}_{\text{MAP}} = 250.0 \]

Drop Size (mm)

\[ dv_{50} = 1.4 \quad dv_{50,\text{MAX}} = 2.0 \quad \text{REF}_{\text{MAP}} = 2.0 \]

Drop Size Distribution Parameter ()

\[ \Gamma = 3.0 \quad m_{\text{MAX}} = 4.0 \quad \text{REF}_{\text{MAP}} = 4.0 \]

Velocity (m/s)

\[ U_{\text{AVG}} = 11.4 \quad U_{\text{MAX}} = 15.0 \quad \text{REF}_{\text{MAP}} = 15.0 \]

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 X REF_{\text{MAP}}
01/13/17 [K240]

$K = 16.8 \text{ GPM/PSI}^{0.5}$, $P = 24.0 \text{ PSI}$, $\dot{V} = 82.3 \text{ GPM}$

[$R_{\text{MEAS}} = 0.4 \text{ m}$, $\delta_{\phi\text{MEAS}} = 5^\circ$, $\delta_{\theta\text{MEAS}} = 10^\circ$, $\delta_{\text{SPH}} = 5^\circ$]

Volume Flux (mm/min)

$\dot{V}_{\text{MAX}} = 12100$, $REF_{\text{MAP}} = 250.0$

$\dot{V}_{\text{AVG}} = 262.8$

Drop Size (mm)

$dv_{50\text{MAX}} = 0.2$, $REF_{\text{MAP}} = 2.0$

$dv_{50} = 1.4$

Drop Size Distribution Parameter ($\gamma$)

$\gamma_{\text{MAX}} = 4$, $REF_{\text{MAP}} = 4.0$

$\gamma = 3.0$

Velocity (m/s)

$U_{\text{MAX}} = 15$, $REF_{\text{MAP}} = 15.0$

$U_{\text{AVG}} = 11.4$

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 X REF_{\text{MAP}}
01/13/17 [ K240]

K = 16.8 GPM/PSI^{0.5}, P = 24.0 PSI, \dot{V} = 82.3 GPM

Volume Flux, \dot{V}_{AVG} = 262.8 \text{ mm/min} \quad [R_{MEAS} = 0.4 \text{ m}, \delta\phi_{MEAS} = 5^\circ, \delta\theta_{MEAS} = 10^\circ]
01/13/17 [K240]

\[ K = 16.8 \text{ GPM/PSI}^{0.5}, \ P = 24.0 \ \text{PSI}, \ \dot{V} = 82.3 \ \text{GPM} \]

Drop Size, \( d_{50} \approx 1.4 \text{ mm} \) \[ R_{\text{MEAS}} = 0.4 \ \text{m}, \ \delta_{\phi_{\text{MEAS}}} = 5^\circ, \ \delta_{\theta_{\text{MEAS}}} = 10^\circ \]
01/13/17 [ K240 ]

\[ K = 16.8 \text{ GPM/PSI}^{0.5}, \ P = 24.0 \text{ PSI}, \ \dot{V} = 82.3 \text{ GPM} \]

Drop Size Distribution Parameter, \( \Gamma = 3.0 \) [ \( R_{\text{MEAS}} = 0.4 \text{ m} \), \( \delta \phi_{\text{MEAS}} = 5^\circ \), \( \delta \theta_{\text{MEAS}} = 10^\circ \) ]
01/13/17 [ K240]

\[ K = 16.8 \text{ GPM/PSI}^{0.5}, \ P = 24.0 \text{ PSI}, \ \dot{V} = 82.3 \text{ GPM} \]

**Velocity,** $U_{AVG} = 11.4 \text{ m/s}$\ [R$_{HEAS} = 0.4 \text{ m}$, $\delta \phi_{HEAS} = 5^\circ$, $\delta \theta_{HEAS} = 10^\circ$]