Optimized Sprinkler Development through Spray Field Engineering Analysis: Initial Spray Characterization and Reduced Order Modeling

Stephen J. Jordan, Noah L. Ryder
Fire & Risk Alliance, LLC., Rockville, MD, U.S.A.

Robert J. Ballard
Victaulic, Easton, PA, U.S.A.

Andre W. Marshall
Custom Spray Solutions, Inc., Silver Spring, MD, USA

Abstract

Today's fire protection challenges for storage classifications push the boundaries of what the ESFR sprinkler may be capable of protecting. With every new sprinkler listing there exists potentially a hundred designs deemed unsuitable to meet the protection challenge asserted as determined through spray distribution testing, actual delivered density testing, or full-scale fire tests. In this work a new screening approach is introduced based on measurements of the initial spray characteristics as governed by sprinkler deflector geometry. By taking sprinkler measurements back to their origin, the deflector, sprinkler dispersion is simulated and interrogated in comparison of resulting spray characteristics from two candidate ESFR deflector designs. Observations of the spray based on spray measurements and simulated sprinkler wetting are compared to actual full scale fire test results presenting a new tool in the deflector design methodology.

Keywords: suppression, fire sprinkler, spray measurement, 4S, ESFR

Introduction

Sprinkler design innovation historically struggles to maintain pace with the developing fire protection scenarios. Demands for protection of increased commodity storage height long go unanswered due to the cost of the extensive testing required to develop these new products. Further, small alterations to the shape of the deflector amplified over the trajectory of the droplet propagate highly sensitive designs that compromise the efficacy of the suppression system. As a result, traditional methods of sprinkler design may not be sufficient to efficiently innovate for the modern day challenges addressing fire protection system component design.

With every new protection challenge, a web of candidate sprinklers is conceived as deflectors slowly evolve through the design process. With a series of increasingly elaborate tests, the field of candidate designs is focused until a select few are put through the paces of full scale fire testing. Each phase of the design process is intended to assess the efficacy of the candidate designs in the most fiscally responsible and timely manner. Having passed all internal assessments, if a candidate deflector design can pass the gauntlet of tests posed by the listing agency a new sprinkler design arrives to market.

Since the advent of the ESFR sprinkler, the industry has continuously pushed the bounds of fire protection in storage classifications [1]. It was at this time that the actual delivered density (ADD) of water compared to an experimentally determined required delivered density (RDD) was identified as a critical design parameter for effectively suppressing a fire in a storage configuration. The device developed to measure the ADD of a sprinkler under a simulated fire scenario has since served as a predictive tool for use in developing new sprinklers for the protection of high storage facilities [2-4].

The ADD measurement device, designed to provide simulated fire characteristics without the expense of a full scale fire testing, has remained unaltered for over a decade yet its empirical nature makes the approach inherently expensive [5]. Although ADD measurements indicate the far field consequences of the spray interaction with a fire source and resulting buoyancy driven plume, the results of the measurement are secondary to the spatio-stochastic spray initially defined by the deflector geometry.

To examine the effects of sprinkler geometry directly, the two candidate ESFR sprinkler deflector designs used in this study were characterized with the Spatially-resolved Spray Scanning System (4S) providing a complete, 3-D map of the spray characteristics and leaving nothing to guess about the initial spray formed [6]. The spray characterizations captured with the 4S are sufficiently detailed for use with any analytical framework developed. The results of the 4S measurement approach have been utilized throughout the fire protection industry, from fundamental research [7-9] to the development of recommendations for the codes and standards that govern fire protection practice [10]. The detailed spray measurements, consisting of flux, drop size and velocity distributions across the surface of a spherical measurement surface, can be applied to the development process of new sprinkler deflectors. The current study presents a comparative analysis of the sprays formed by two candidate sprinkler deflector designs as they relate to the component performance in large scale fire testing.

Approach

Spray patterns from two candidate ESFR sprinklers were evaluated with the 4S measurement device over a spherical surface, following the natural coordinate system for the sprinkler spray. The 4S synthesizes optical and mechanical spray measurements, transport analysis, and statistical representation frameworks providing high-fidelity spray characteristics suitable for evaluating both fire sprinkler and fire protection system performance. Through integration of automation, flow control, data acquisition and data analysis systems, the characterizations of the 4S provide insight into the sprinkler spray patterns and their connection with deflector geometry, dispersion modeling, research and development.

From the measured spray characteristics, a thorough comparison of the two candidate ESFR deflector designs was initiated. Volume flux measurements of the two sprays are compared at the holistic level as well as over discrete regions of the initialization sphere. The influence of sprinkler geometry on the resulting spray characteristics is examined based on volume flux and drop size distributions. Further, measured spray characteristics are applied through SprayVIZ, a reduced order spray simulation tool, to model the spray distribution for both candidate designs in a quiescent environment. The simulated wetting performance of each sprinkler is compared over measurement planes at two different elevations below the sprinkler.

Full-scale fire testing previously conducted with each of the candidate sprinkler designs identified critical differences in the structure of the spray. For one of the candidate designs, candidate ‘a’, following activation of the sprinkler system the fire was quickly knocked down and successfully controlled. For the other candidate design, candidate ‘b’, the buoyant smoke plume penetrated a spray region lacking sufficient momentum, overwhelming the spray, and resulting in a fire scenario that was not successfully controlled. Observations of the spray structure in both the near-field measurements and far-field predictions are discussed in comparison to full-scale fire testing results and observations in order to identify the critical spray characteristics that resulted in the failed full-scale testing.

Results

The spray characterization measurements captured for the two candidate deflector designs are reported as spherical profiles with the volume flux distribution highlighted in Fig. 1. It can be observed that volume flux is highly distributed for both sprinklers with high fluxes occurring near the frame arms as identified in the figure by the gray datum.

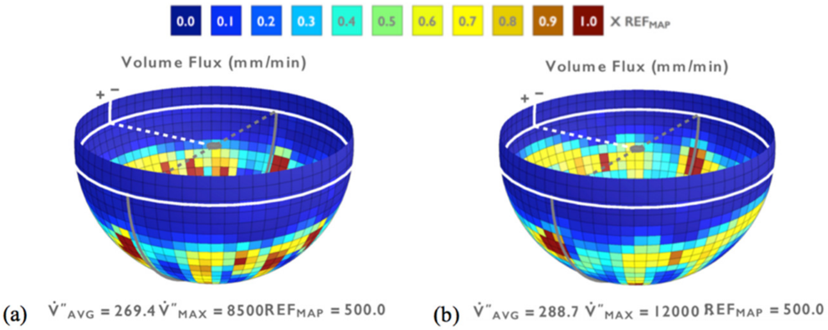

Fig. 1. Measured volume flux for two candidate deflector designs.

It is also clear from this volume flux distribution that the water is concentrated near the south pole of the sphere, as expected for ESFR style sprinklers, with candidate ‘b’ having a much larger concentration near the core but lacking the flux displayed by candidate ‘a’ in the region of $\theta = 120°$. Details of the measured volume fluxes at four distinct elevation angles for the two candidate designs are detailed in Fig. 2. Candidate deflector ‘b’ is observed to have a significant flux measured at the outer edge of the spray, nominally 100° in elevation angle, resulting in a wider spray pattern compared to the flux of candidate ‘a’ which exhibits a negligible flux at the same measurement location. The sprays produced by both candidate designs exhibit strong azimuthal variation toward the middle of the spray as demonstrated in the 120° elevation angle detail of Fig. 2; however, the flux from candidate ‘a’ is nearly double that of candidate ‘b’ indicating a weaker spray region.

Differences in deflector geometry were identified to have an impact on the shadowing effects of the frame arm assembly as seen in the 170° elevation angle detail of Fig. 2. The geometry associated with the candidate ‘a’ deflector results in the concentration of the spray near the frame arms in direct contrast to the geometry of the candidate ‘b’ deflector which results in spray dissection near the frame arms and an ensuing shadow effect. The two designs present a similar average flux at the 170° elevation angle yet at the core of the spray, deflector ‘b’ produces a volume flux approximately 150 % that of deflector ‘a’.

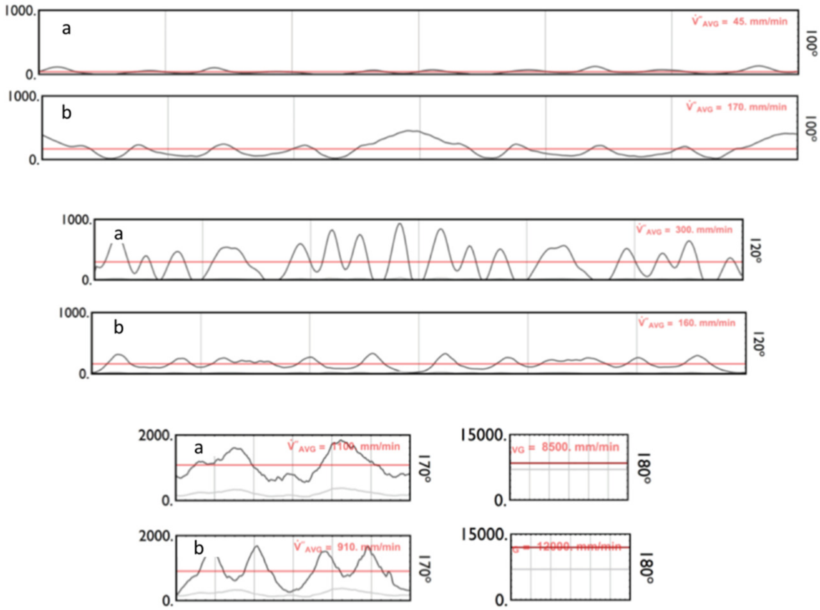

Fig. 2. Spatially-resolved flux measurement details at four elevation angles.

Informed by the 4S initial spray measurements, the quiescent dispersion of the spray is examined by simulating the flux delivered to planes parallel to the deflector plate offset at 4.6 m (15 ft) and 9.1 m (30 ft) below the sprinkler for each candidate design using SprayVIZ, a reduced order spray trajectory model. The simulated spray patterns clearly show the non-uniformity of the sprinkler spray, translating the observation made on the sphere to the floor using detailed information on drop size, drop size distribution and drop velocity.

In both designs evaluated, high volume fluxes are delivered in the central core of the spray; however, it is clear from these simulated spray patterns that candidate ‘a’ has a more uniform, tighter distribution than the candidate ‘b’ sprinkler, specifically at radial locations within the first few meters of the sprinkler. Candidate ‘b’ shows a more open star pattern than the candidate ‘a’ design; a difference especially evident at 9.1 m (30 ft) where the star spray pattern is nearly filled for candidate ‘a’ while an 8-point star pattern persists for candidate ‘b’ as evident in Fig. 3.

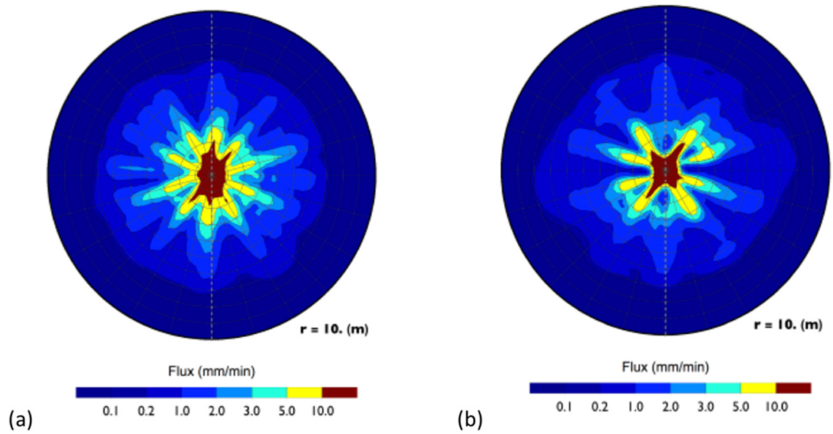

Fig. 3. Dispersion simulations for candidate sprinklers at 9.1 m (30 ft)

Average azimuthal profiles calculated from these predictions provide a one-dimensional summary of the density profile with radial distance from the centerline for the sprinkler. The 1-D summaries for a ceiling height of 9.1 m (30 ft) are shown in Fig. 4 for both deflector designs. For each candidate design, the bold line represents an azimuthally averaged volume flux around the sprinkler while the shaded region spans from the minimum flux to the maximum flux observed at a given radial location; the thin rectangular region at the bottom of the plot denotes the overall average flux and the maximum throw of the spray.

The two azimuthally averaged profiles present similar trends with the high flux core region of the spray tapering off to average flux values below 10 mm/min at radial positions above nominally 1 m. When comparing the profiles representative of the range of fluxes observed for each deflector, the supremacy of deflector ‘a’ is evident. As observed in Fig. 4, the spray produced by deflector ‘a’ establishes a flux greater than the overall average flux across all azimuthal positions out to a radius of 2 m. In comparison, the spray produced by deflector ‘b’ results in a flux to the measurement plane that drops below an overall average flux as close as radial positions 1 m away from the sprinkler.

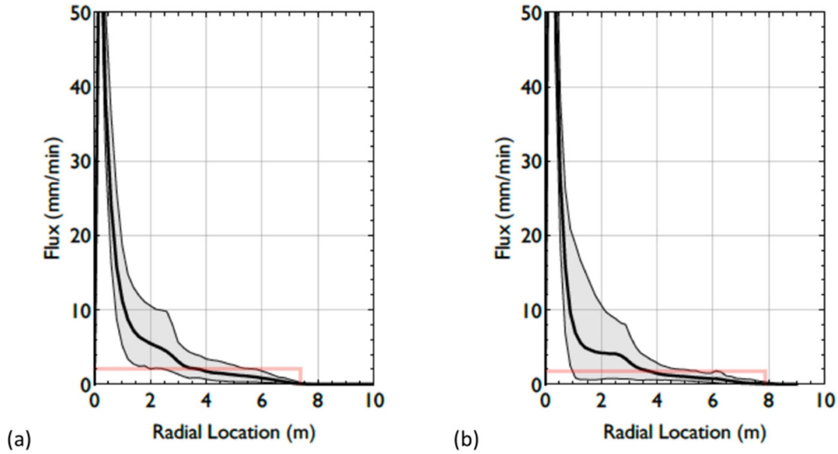

Fig. 4. Average radial flux profile with maximum and minimum flux limits.

Having completed full scale fire testing on both of the candidate designs, the analysis conducted based on the sprinkler spray measurements is revisited. The qualitative observations made during full scale fire testing are related to quantitative trends identified from the dispersion analysis. The hollow interior region of the spray noted in dispersion simulations of candidate 'b' as a 'break' in the spray pattern was also observed in the full-scale fire tests conducted. Video of this fire test shows this 'break' in the spray pattern allowed for plume penetration resulting in the failed test of the candidate 'b' design. Candidate 'a' demonstrated superior spray performance, with a more concentrated spray starting at lower elevation angles, it maintained higher fluxes in the middle of the spray and passed the fire test.

References

[1] Yao, C., "*The development of the ESFR sprinkler system*," Fire Safety Journal, 14(1-2), pp. 65–73, 1988.

[2] Bill, R. G., Jr., Kung, H.-C., Vincent, B. G., Brown, W. R., and Edward E Hill, J. R., "*Predicting the Suppression Capability of Quick Response Sprinklers in a Light Hazard Scenario*," Journal of Fire Protection Engineering, 3(3), pp. 95–107, 1991.

[3] Schwille, J. A., KUNG, H. C., Hjohlman, M., Laverick, G. E., and Gardell, G. W., "*Actual Delivered Density Fire Test Apparatus For Sprinklers Protecting High Commodity Storage*," Fire Safety Science, 8, pp. 823–833, 2005.

[4] Yao, C., "*Overview Of Sprinkler Technology Research*," Fire Safety Science, 5, pp. 93–110, 1997.

[5] Friedman, R., "*Fire Protection Engineering — Science or Art?*," Journal of Fire Protection Engineering, 2(1), pp. 25–32, 1991.

[6] Jordan, S. J., "T*OWARDS DEVELOPMENT OF A SPATIALLY-RESOLVED SPRAY SCANNING SYSTEM*", 2017.

[7] Myers, T. M., and Marshall, A. W., "*A description of the initial fire sprinkler spray*," Fire Safety Journal, 84, pp. 1–7, 2016.

[8] Ren, N., and Marshall, A. W., "*ScienceDirect.com - International Journal of Multiphase Flow - Characterizing the initial spray from large Weber number impinging jets*," International Journal of Multiphase Flow, 2012.

[9] Link, E. D., Jordan, S. J., Myers, T. M., Sunderland, P. B., and Marshall, A. W., "*Spray dispersion measurements of a sprinkler array,*" Proceedings of the Combustion Institute, 2016.

[10] Isman, K. E., Jordan, S. J., Marshall, A. W., and Ryder, N. L., *Protection of Storage Under Sloped Ceilings – Phase 1: Final Report*, Custom Spray Solutions, Inc., Silver Spring, Maryland, 2015.