KNOWING THE FIRE SPRINKLER SPRAY

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ABSTRACT

Sprinklers generate complex large scale sprays using an elegant and efficient design concept. These devices establish thin sheets via jet impact onto a deflector. These inherently unstable sheets fragment readily breaking up to form drops (~ 0.1 x jet diameter). Despite their conceptual simplicity, sprinklers produce highly three dimensional stochastic sprays whose characteristics are poorly understood. Only the most basic connections have been made between sprinkler design details and their resulting sprays. In fact, the understanding of sprinkler spray formation has not progressed beyond the conceptual stage despite over 100 years of operational experience with these devices in concert with relentless testing and measurement of the sprays that they produce. Sprinkler design innovation is slow, in part, because spray characterization has focused primarily on delivery (i.e. readily measured farfield performance) with very little attention given to generation (i.e. intractable nearfield details). Advanced measurement concepts and techniques are currently being applied to the previously intractable nearfield providing the insight (into sprinkler discharge characteristics) required to improve not only sprinkler design but also engineering practices. A number of modern measurement techniques and modeling tools are presented to illuminate the path toward development of next generation water-based fire suppression systems.

INTRODUCTION

Despite diversity in size, shape, and design details, most modern fire sprinklers use the same fundamental method of spray generation. Water is initially forced through an orifice to produce a continuous water jet. This jet then impinges onto a deflector to form a thin sheet of water. The sheet subsequently disintegrates into ring-like ligaments and ultimately into drops. Having this picture in mind, the sprinkler atomization process can be divided into stages for focused measurements and analysis. Several fundamental atomization studies have developed theories to describe physical processes relevant to fire sprinkler spray generation. There is also a separate body of more applied research focused on quantifying discharge characteristics (i.e. drop size and velocity) and dispersion behavior from fire sprinklers.

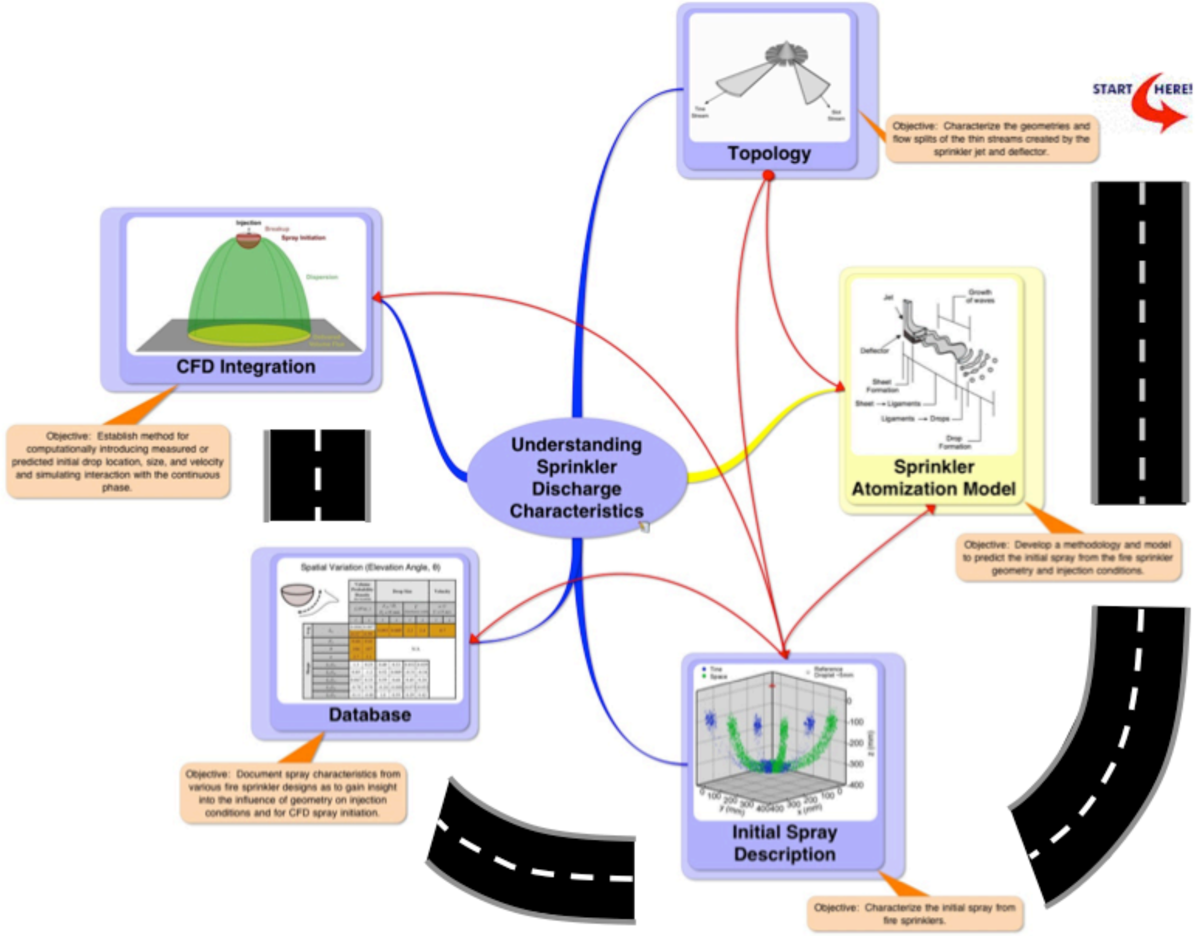
Numerous fundamental studies have been conducted to examine the atomization process responsible for transforming continuous liquid streams into discrete drops. These studies considered the fundamental physical processes leading to atomization and their dependence on injection and environmental conditions. Dombrowski and Hooper developed mathematical equations to describe sinuous break-up and dilatational break-up modes ultimately leading to a prediction of characteristic drop size [1]. On the other hand, Huang utilized a high-speed motion photographic technique to study the break-up mechanisms of liquid sheets formed by the impingement of two co-axial jets [2]. He reported three break-up regimes and their trends by plotting the ratios of break-up radii over nozzle radius against the jet Weber number, *We*. More recently, Clanet and Villermaux conducted a series of experiments to study the formation and disintegration of smooth and flapping liquid sheets, generated by impinging a jet onto a flat deflector [3,4]. They found break-up distance trends similar to those reported by Huang despite differences in their experimental configuration.

A number of experiments have been conducted over the past four decades to measure the discharge characteristics of sprinkler sprays. These experiments utilized a wide range of experimental methods and diagnostics, including simple short time exposure photography and more advanced diagnostic techniques such as Phase Doppler Interferometer (PDI) and Particle Image Velocimetry (PIV). Dundas evaluated scaling laws proposed by Heskestad, $d_{v50} / D_o = NWe^{-1/3}$ where d_{v50} is the volumetric median diameter, D_o is the nozzle diameter, and N is a constant ranging from 1.74 to 3.21 [5]. More than a decade later, Yu employed a laser-based imaging technique to measure drop size from three upright sprinklers [6]. The measured overall characteristic drop size followed a $We^{-1/3}$ scaling law consistent with Dundas's sprinkler measurements. The PDI technique was first validated and utilized by Widmann to measure the spray from four real sprinklers with orifice diameters [7,8]. Soon after Widmann, Sheppard made his contribution to the database of sprinkler spray measurements through a comprehensive set of experiments on sixteen commercially available pendant and upright sprinklers [9,10]. Employing PDI techniques, Sheppard obtained local measurements of drop size at various azimuthal and elevation angles. Sheppard also applied the PIV technique to measure drop velocity. The velocity magnitude data, presented in spherical coordinates with the sprinkler head at the center, showed significant variation with elevation angle. Most recently, sprinkler measurements were conducted at the University of Maryland by Blum [11], Ren [12,13], and Do [14]. They explored sprinkler geometry effects by using different nozzle configurations. In the simplest configuration (referred to as the Basis Nozzle), a jet was orthogonally injected onto a flat circular deflector disk, while a commercially available Tyco D3 spray nozzle (referred to as the Standard Nozzle) was used to represent a more complex nozzle similar to that of an actual fire sprinkler. High-speed flash photography and Planar Laser Induced Fluorescence (PLIF) techniques were employed to measure sheet topologies and sheet break-up distances. They found that two distinct streams are formed from flow deflected along the tines and flow passing through the slots. They found that the break-up distances produced by the Basis and Standard Nozzles follow a $We^{-1/3}$ scaling law. Shadowgraphy was also used to measure local and overall drop size distributions. These distributions also followed scaling laws, $We^{-1/3}$ for the Standard Nozzles and a much weaker We dependence for the Basis Nozzles.

Traditionally, sprinkler performance has been evaluated through testing (as described previously). However, with the advent of the Fire Dynamics Simulator (FDS) first released in 2000 [15], modeling of fire phenomena with computational fluid dynamics (CFD) tools is becoming increasingly popular. Some early computational studies [16-18] focused on studying the interaction between fire plumes and sprinkler sprays; however, without detailed knowledge of initial spray characteristics, dispersion predictions, typically quantified through analysis of volume flux to the floor, is not very satisfying.

Based on recent measurements and analysis, it is possible to imagine a pathway toward integration of reliable high fidelity sprinkler spray characteristics into CFD simulations for detailed fire suppression analysis. Figure 1 shows this pathway beginning with understanding the topology of the streams generated by the sprinkler deflector which informs the development of physics based atomization models along with the development of measurement approaches to support their development. Because of the complexity of the spray, these measurements will necessarily consist of literally millions of drop realizations, which will require a framework to extract useful discharge characteristics and a database to facilitate the understanding of sprinkler geometry and injection pressure effects on the discharge characteristics of the spray. Measurements that provide the foundation for this pathway are described in this paper.

In this study, detailed measurements have been conducted near the sprinkler discharge (i.e. the near-field) to characterize the initial sprinkler spray. A comprehensive framework for representing these detailed measurements in a compact format has been established for spray analysis and modeling. This framework provides the opportunity to establish a high-fidelity spray initiation database (at least for the most popular sprinkler models) useful for widespread and consistent sprinkler dispersion and fire suppression analysis.



Objective: Characterize the geometries and flow splits of the thin streams created by the sprinkler jet and deflector.

Objective: Establish method for computationally introducing measured or predicted initial drop location, size, and velocity and simulating interaction with the continuous phase.

Objective: Develop a methodology and model to predict the initial spray from the fire sprinkler geometry and injection conditions.

Objective: Document spray characteristics from various fire sprinkler designs as to gain insight into the influence of geometry on injection conditions and for CFD spray initiation.

Objective: Characterize the initial spray from fire sprinklers.

Fig 1. Pathway to understanding the fire sprinkler spray and CFD integration through advanced measurements and analysis.

MEASUREMENTS

Sheet Measurements

Flow visualization can reveal qualitative information about the atomization process including the basic process by which the continuous jet is transformed into discrete droplets (in the case of fire sprinklers by thin sheet formation and wave instabilities). Flow visualization performed by Blum revealed that pendent sprinkler sprays typically consist of two distinct streams, i.e., the horizontal streams formed along the tines and the vertical streams produced by forcing water through the void spaces between them [11]. Short time exposure photography and shadowgraphy techniques have both been successfully implemented to gain insight into the topology of these thin sheets. These sheets (or streams) are shown in Figure 2. Quantitative measurements of the sheet breakup distance were also determined from these images after spatial calibration. The sheet breakup distance is of great interest because it is one of the governing quantities that determine drop size and a key variable in physics based atomization models.

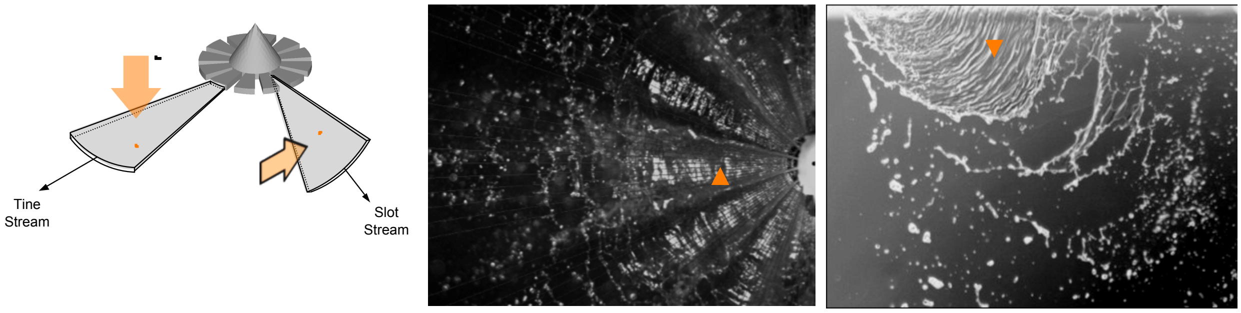
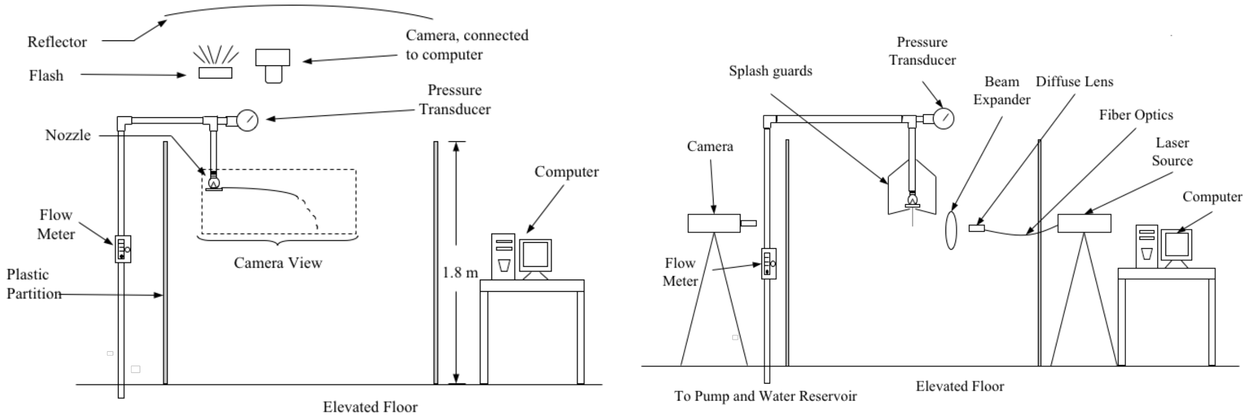


Fig 2. Tine and slot streams formed by typical pendent sprinklers captured by short exposure photography and shadowgraphy, respectively (Tyco D3, K = 81 lpm bar$^{-1/2}$).



(a) (b)

Fig 3. Experimental setup for sheet measurements: (a) short-time exposure photography setup; (b) shadowgraphy setup.

For the short exposure time photographs, a Canon EOS 40D 10.1 Megapixels digital camera fitted with a 50 mm Canon f1.4 lens was mounted approximately 1 m above the nozzle and focused on the horizontal sheet formed parallel to the deflector as shown in Figure 3. A Canon Speedlite 580EX II flash with discharge time of 7.8 μs was installed near the camera and bounced off a reflecting umbrella installed above the entire setup, to generate a diffuse light source for illuminating the liquid sheet. The image of the reflector on the sheet also helped to clearly distinguish the water streams from the black background below. Twenty images at each operating pressure were captured for each nozzle tested. In each image, break-up distances were determined at approximately 55 circumferential stations, created by a set of rays that span from -90° to 90° with the increment of 2° in the calibrated images.

Using a LaVision Sizing Master shadowgraphy system described in Figure 3, the vertical sheets formed from the space streams were carefully studied. The shadowgraphy measurements provided a means to measure sheet structure and sheet break-up distance in the vertical orientation, which was not feasible with the direct imaging approach. A Double Pulsed Yttrium-Aluminum-Garnet (YAG) Laser was used to generate pairs of 532 nm laser pulses at the frequency of 3 Hz. The laser pulses were directed by a 1-meter fiber optic into a diffuser whose screen lit up with each pulse. This screen was then expanded by a Fresnel lens to approximately 200 mm. The images were captured utilizing a 4-Megapixel Image Pro X Charge Coupled Device (CCD) Camera, fitted with a 50 mm Canon f1.4 lens. The imaging region of the camera consisted of a field of view of approximately 150 mm square with a depth of field of about 28 mm. The discharge rates of the laser source and capture rate of the camera were synchronized by a computer to obtain double images of the spray (useful for velocity measurements), although only one of the images in the pair was used for break-up analysis. A special set of splash guard partitions was fabricated for the sheet visualization and break-up distance measurements. These partitions allowed only one stream to enter the field of view of the shadowgraph camera. Twenty images were taken at each operating pressure for each nozzle tested. In each image, break-up distances were determined at 18 azimuthal stations sweeping a 90^{o} angle with the origin located at the beginning of the space slot.

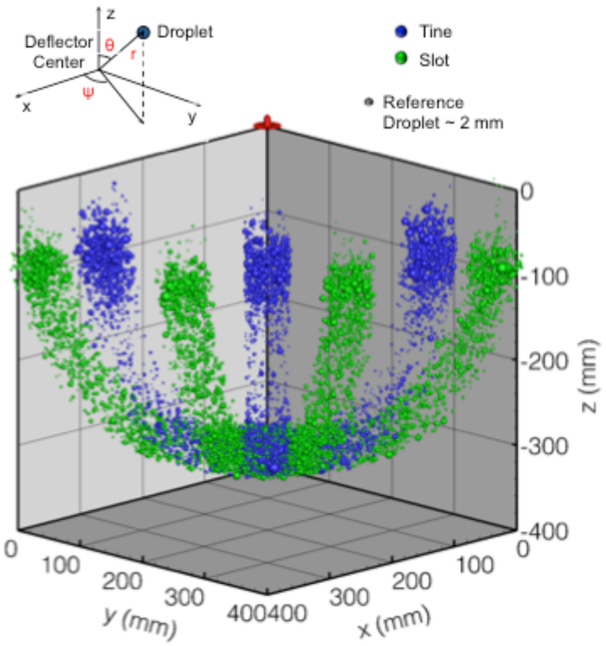
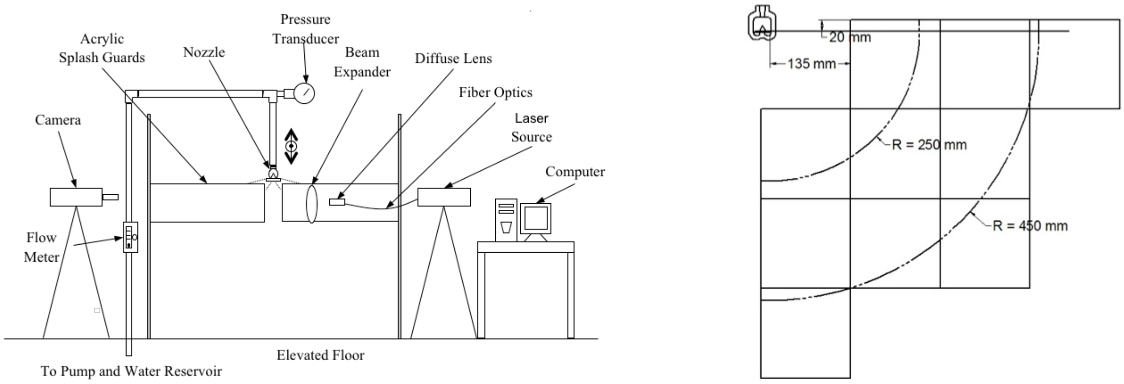


Fig 4. Drop size measurements of the initial spray (Tyco D3, K = 81 lpm bar$^{-1/2}$, P = 1.4 bar).

Drop Measurements

Detailed measurements of the initial spray are required for CFD suppression simulations. Because of the three dimensional geometry of the sprinkler deflectors which include the boss, frame arms, tines, and slots, the discharge characteristics of the spray will be highly three dimensional and of course inherently stochastic. Figure 4 shows a reconstructed 3-D spherical view of the sprinkler spray based on the shadowgraphy measurements after spray measurements were obtained in azimuthal planes aligned with the slots and tines. After individual images and imaging stations are combined, the shadowgraphy measurements produce almost one million drop measurements at each test condition, providing a sufficiently large sample for reliable statistics when evaluating basic discharge characteristics and specifying the initial spray in CFD simulations.

The shadowgraphy technique was also utilized to provide detailed simultaneous measurements of drop size and velocity shown in Fig. 4. The experimental setup for these measurements is provided in Fig. 5. The acrylic splash guard partitions allowed only the desired portion (30 mm thick) of the spray to enter the focal plane of the camera where the shadows of the droplets on the bright background were captured. For all nozzle configurations, drop size and drop velocity were measured simultaneously at several stations to cover the entire characteristic streams as shown in Figure 5. The locations in these measurements were obtained by traversing and rotating the nozzles with respect to the imaging station (i.e. 150 × 150 × 28 mm imaging region). At each measurement location, 200 pairs of images were taken, providing size and velocity of approximately 20,000 – 100,000 drops after being post-processed. Subsequently, data after the break-up region (between 400 mm to 450 mm from the basis deflector edge and between 250 mm and 450 mm from the standard deflector edge) was used for analysis purposes. After spatial calibration of the field of view at each imaging station, drop sizes were easily determined using an edge detection algorithm provided with the LaVision Sizing Master software. A Particle Tracking Velocimetry (PTV) algorithm also included in the software uses the shadowgraph image pairs separated by a short time increment, approximately 100 ms for the measurements in this study, to track the displacement between adjacent similarly sized particles. The displacement determined from the calibrated images along with the separation time provides velocity information for every drop.



(a) (b)

Fig 5. Drop size and velocity measurements: (a) short-time exposure photography setup; (b) shadowgraphy mapping of the initial spray region.

Data Consolidation Framework

The initial sprinkler spray can be completely characterized in terms of the following critical quantities; drop location (radius, elevation angle, azimuthal angle), drop velocity, drop diameter, and drop density available from stochastic analysis of the measurements. Although a formidable task, initialization tables for these quantities (drop by drop) could be generated for individual sprinklers at various operating conditions; however, a more compact representation of the initial spray provides the framework for generalized characterization over a range of operating conditions or even nozzle geometries [20].

The spray is completely described in terms of the volume probability density based on solid angle solid angle so that $\int_\theta \int_\psi \int_u \int_d f_V(\theta, \psi, u, d) d\theta \cdot d\psi \cdot du \cdot dd = 1$, where the integral represents the complete collection of unique drops accounting for the entire spray volume. A detailed analysis by Ren et al. [20] shows that the spatial variation in the conditional volume flux distribution, along with the local stochastic drop sizes and velocities can be estimated using a compact set of basis function coefficients determined from the experimental data. Transforming the complex stochastic spray into this compact physically accessible framework provides insight into the essential spray features and facilitates quantitative comparisons between sprinklers. In this compact representation, only a few physically coherent parameters are required, with experience potentially enabling approximation of spray details even when comprehensive measurements are not readily available.

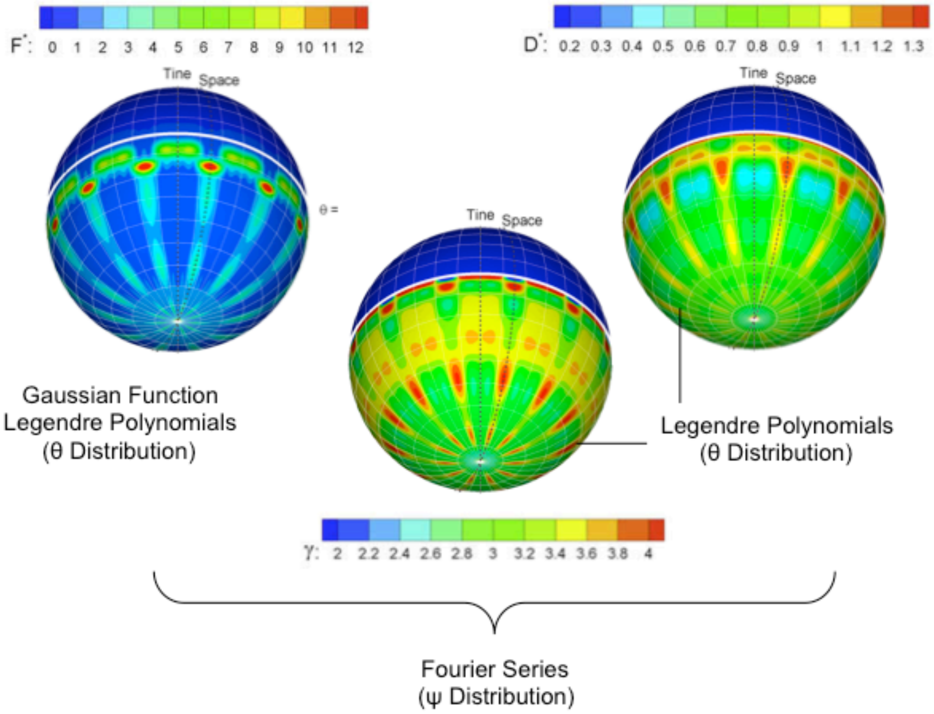


Fig 6. Dimensionless distributions of spray characteristics represented by basis functions on the initiation sphere ($r = 0.35$ m) of a Tyco D3 sprinkler at 2.8 bar. F^* describes the dimensionless volume flux (or drop density), normalized by the average flux on the sphere. D^* describes the dimensionless characteristic drop size, normalized by the characteristic drop size in the spray, and γ describes the Rosin-Rammler width parameter about the characteristic drop size.

For initiation of the spray in CFD simulations, the spray is generated by specifying a number of individual drops determined from stochastic distributions based on experimental measurements (or basis functions) of these quantities. Each initial drop is given four properties on a unit sphere, which include azimuthal angle ψ, elevation angle θ, dimensionless drop size, *d*, and dimensionless drop velocity, *u*. The droplets are generated on the surface of a sphere originating from the center of the deflector with radius equal to the initiation distance (typically about 0.35 m to complete spray formation). Analysis of the measurements reveals that drops move radially outward from this origin (i.e. velocity angle determined from position angle) so that only the velocity magnitude requires independent consideration. Figure 6 is provided to demonstrate the power of the measurements and the associated basis functions in treating the strong spatial distributions of the volume flux (used to locate droplets) and drop size characteristics. The distributions in Fig. 6 were generated from a compact set of coefficients and their corresponding basis functions, which include Gaussian functions, Legendre polynomials, and Log-Normal Rosin-Rammler distributions.

Volume Flux

The volume flux below the sprinkler is an important measurement to evaluate the wetting performance of the nozzle and to evaluate the ability of the CFD initiation and simulation approach to predict dispersion of the spray. A mechanical patternator is often used to measure the distribution of water flux, which consists of an array of containers placed at a specified height below the nozzle. Care must be taken to ensure that the container opening is large compared with the drop diameter (> 5*d*). Flux measurements 1 m below the nozzle are provided in Fig. 7 for Tyco D3, K = 81 lpm bar$^{-1/2}$, sprinkler operating at 2.8 bar. A convenient length scale, *R*, is introduced for normalization of the flux position data.

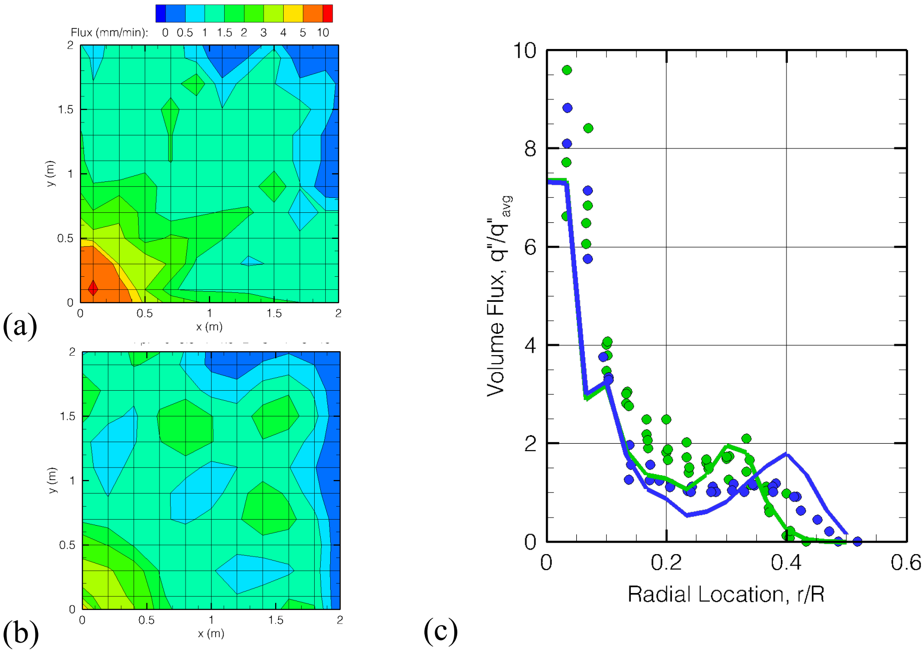


Fig 7. Volume flux measurements from a Tyco D3, K = 81 lpm bar$^{-1/2}$, P = 2.8 bar: (a) measurements; (b) predictions; (c) measurements of linear density of volume flux, (blue) tine stream, (green) slot stream.

The maximum inviscid reach is defined as $R = U(2h/g)^{1/2}$, where h is the measurement elevation below the nozzle, and g is the gravitational constant. This length scale was used to normalize the radial coordinate $r' = r/R$ [11]. The volume flux can also be expressed in terms of a linear density, $q' = (2q''r')/(Q/\pi R^2)$, where q'' is the area volume flux and Q is the nozzle flow rate. These measurements are provided in Fig. 7 showing dispersion measurements and predictions.

SUMMARY

The measurement approaches presented in this paper provide a suite of measurement and analysis tools to gain insight into the spray generation and dispersion performance of fire sprinkler sprays. These tools have been systematically applied to reveal the basic nature of sprinkler sprays while at the same time capturing the fine details of these sprays in all of their complexity. Application of these tools has demonstrated that it is possible to measure the spray very close to the sprinkler for insight into the basic sprinkler discharge characteristics (when sprinkler head features are of interest), for first order dispersion analysis (when overall wetting performance is of interest), or for detailed CFD simulations (when detailed fire suppression performance is of interest).

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