Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Spatially-resolved spray measurements and their implications

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ARTICLE INFO

Keywords:
Suppression
Sprinklers
Spray measurement

ABSTRACT

Fire sprinkler manufacturers have developed a great variety of application specific sprinkler designs. Advances in product development practices, performance based design, risk analysis, and fire suppression research have increased stakeholder interest in quantifying the spray produced by these devices. These sprinkler spray patterns consist of complex spatio-stochastic features originating near the sprinkler head. A Spatially-resolved Spray Scanning System (4S) has been 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). These high-fidelity 4S spray measurements consisting of terabyte scale data densities present remarkable challenges with regard to data management, test repeatability, and test timing. These challenges are addressed through integration of automation, flow control, data acquisition, and data analysis systems. Spatially-resolved sprinkler spray measurements are presented providing insight into the sprinkler spray patterns and their connection with deflector geometry. Comparisons between far-field spray dispersion measurements and simulations initialized with 4S measurements demonstrate unprecedented agreement further highlighting the value of spatially-resolved sprinkler measurements for modern suppression analysis.

1. Introduction

Water based, automatic fire protection systems are used throughout the world to protect people and reduce the cost and impact of fire. Each protection challenge, defined by application specific fire scenarios, relies on the effective dispersion and delivery of water to the fire source. Sprinklers are designed to create spray patterns for these specific applications. While each make of fire sprinkler is unique (defined by its geometry), most fire sprinklers share several primary structural components as enumerated in Fig. 1a. Following sprinkler activation, water ejected through an orifice (1); forms a jet that impinges on a conical boss structure (2); situated atop the deflector plate (3); and supported by a frame arm assembly. Note: the reference frame arm (4); has been identified as a datum for measurement alignment and data synchronization. After the water jet strikes the deflector, distinct streams are created as the water flows along tines (5); and travels through open slots (6). These streams quickly disintegrate due to aerodynamic instabilities forming ligaments followed by a complicated distribution of drops as observed in Fig. 1b.

It is clear from the body of work available on sprays that the drop size, velocity, and volume flux offer key insights into the spatio-stochastic nature of the spray. These characteristics have been the subject of extensive research [1]. Early measurement approaches for determining drop diameters for fire protection sprinklers included freezing droplets or capturing them with light oil [2]. These physical measurement techniques were phased out by the late 1980's with the introduction of optical measurement [3] and reverse spray modeling [4] approaches. Most notably, the complicated drop size distribution of a fire sprinkler was first measured with statistically sufficient detail by Yu [5] in 1986 using the FMRC Drop Size Measuring System. Yu confirmed the effect of pressure on drop size originally proposed by Heskestad in 1972 and the global effect of orifice size on drop size. This fundamental work established the combination log-normal Rosin-Rammler distribution still used presently to represent the drop size distributions observed for deflector based sprinklers. Despite the scientific advances in spray characterization near the turn of the century, numerical simulations of fire protection sprays by Bill [6] in 1993 and Nam [7] in 1996 were challenged to simultaneously imple-

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http://dx.doi.org/10.1016/j.firesaf.2017.03.007
Received 16 February 2017; Accepted 15 March 2017

Please cite this article as: Jordan, S., Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.03.007

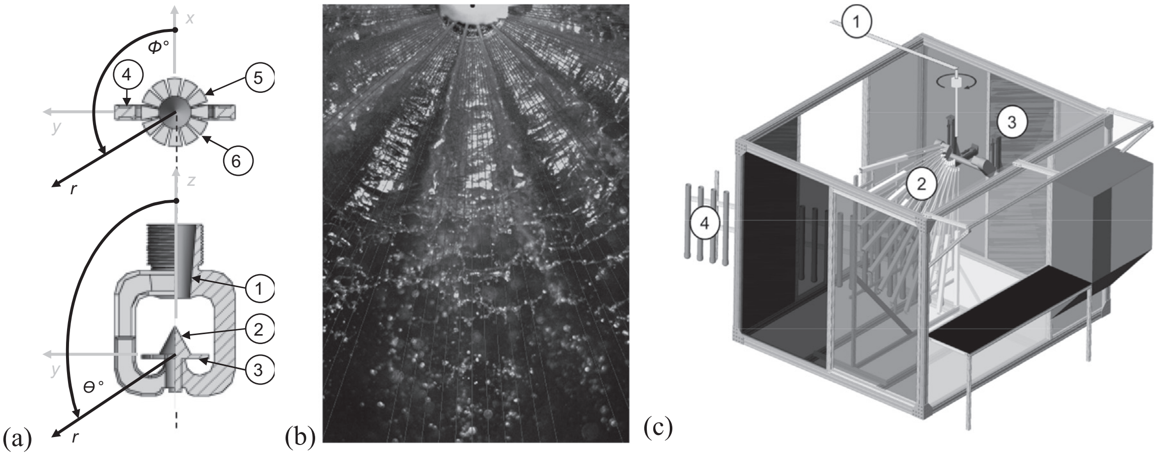

Fig. 1. Sprinkler, spray, and 4S measurement facility; (a) sprinkler with enumerated features; (b) spray formation; (c) Spatially-resolved Spray Measurement System (4S) with enumerated components.

ment a global drop size measurement and match experimental distribution data. These simulations lacked sufficient detail to fully describe the spatio-stochastic nature of sprinkler sprays.

In 2000, Sheppard [8] mapped experimental measurements to differential areas on the surface of a sphere surrounding the sprinkler in increments of 10 degrees. This work demonstrated the radial nature of drop velocity and the angular dependence of delivered density resulting from azimuthal variation in spray characteristics. Following the work by Sheppard, Walmsley and Yule [9] employed a photographic method to characterize the drop size distribution formed from the slot, tine, and frame arm features of the sprinkler identifying the potential for further improved spray modeling with more detailed measurements. More intricate local drop size measurements aligned with the slot and tine features were also conducted by Ren [10] in 2008 using a light diffraction technique for sizing and counting droplets. Volume flux measurements captured by Ren further demonstrated the distinctly different sprays formed by slot and tine streams. The measured overall flux-based drop size distribution was observed to agree well with the distribution originally proposed by Yu two decades prior.

Photographic measurement methods have evolved as the preferred approach for capturing spray characteristics due to the non-intrusive nature of the optical technique and the ability to simultaneously capture large quantities of multiple spray characteristics, reducing statistical error and increasing spray insight [2,11–14]. Applying a laser-based shadowgraphy imaging technique, Ren [15] captured nearly one million drop realizations to completely characterize the critical quantities of the spray in the form of probability distribution functions. Application of these measurements to spray initialization was further demonstrated to agree well with physical measurements of the spray [16]. Recent studies have employed a combined particle tracking velocimetry and shadowgraphy measurement approach to spatially characterize all critical spray characteristics. Data compression methods developed by Ren et al. [15,17] further developed the analytical framework required to digest the large quantities of data gathered.

Similar spray characterization methods were applied in 2011 by Zhou and Yu [18] to study the effects of sprinkler geometry on spray characteristics including spray angle and droplet size. Most recently, modern spray measurement approaches were applied by Zhou in characterizing upright and pendent type ESFR sprinklers [19,20]. These, and previous studies, demonstrate the feasibility of developing detailed spray characteristics through spatially resolved drop measurements and their utility.

Today's numerical simulations incorporating the detailed spatial dependence of the drop size and velocity distributions require extensive input parameters as identified by Myers [21]. Although modern measurement techniques are capable of gathering large quantities of data, as previous studies demonstrate, these measurement approaches are still prohibitively expensive and tedious. The need for easily accessible, detailed, spatially-resolved spray measurements has led to the development of the Spatially-resolved Spray Scanning System (4S) illustrated in Fig. 1c.

The present research fills a gap identified in previous measurement approaches applied to sprinkler spray characterization. Based on validated, proof of concept experimentation completed by Ren [10,15], the construction of a next generation spray measurement device was initiated. Previous spray measurement approaches applied within the fire protection industry relied heavily on the test operator's expert measurement experience. These proof of concept measurements lacked the user focus and automation features that can enhance test effectiveness and efficiency. Specialized measurements approaches of this sort can be prohibitively expensive outside of the academic or laboratory environment. Through the synchronization of modern automation and adaptive design features this research has produced a convenient, highly resolved sprinkler spray measurement technique suitable for widespread adoption.

2. Approach

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 Fig. 2 (also in Fig. 1c) and supported by automation, instrumentation, and data acquisition processes. Data reduction and analytical approaches are also applied to the data to provide a complete, spatially-resolved characterization of the sprinkler. A complete reproduction of the spray can be generated from these measurements, sufficient for use in presently available mathematical or numerical simulation frameworks [21]. The subsystems and process are summarized in the following discussion and detailed in Jordan [22].

2.1. *Flow control and rotation*

A vertical inline centrifugal pump provides water from the system supply tank to the testing facility through a closed loop system. The water is filtered and conditioned (to provide a clean fully developed turbulent flow) upstream of sprinkler discharge. After measurement, water is redirected (through the enclosure's foam spray dampening panels), and drained (through a grated, graded floor) back to the supply tank. A constant flow (within ± 2.5%) is maintained throughout the