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Measurements of spray-plume interactions for model validation

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ABSTRACT

Fire suppression using automatic fire sprinklers is tremendously successful in reducing loss of life and property in the event of a fire. With the increasing computing power available, as well as the spread of performance-based design methods, the ability to accurately model spray dispersion and suppression is desirable. In this study, experiments were conducted to quantify spray dispersion and spray-plume interactions for model validation. Numerical simulations of these spray interactions were performed using FireFOAM. These simulations were distinguished by the use of comprehensive highly-resolved initial spray measurements to generate the numerical spray. The experimental Sprinkler Array Facility (SAF) used in this study consisted of a centrally located, well-characterized, forced air jet (simulating the updraft from a real fire plume) providing a challenge to the spray. Reliable model boundary conditions were established from detailed measurements of the air jet injection velocities and detailed measurements of the initial spray using the Spatially-resolved Spray Scanning System (4 S). Measurements of volume flux as well as optical measurements of drop size and velocity were obtained at various locations within the air jet. Four flow conditions were investigated with the intent of providing model validation data; close and far sprinkler spacing, each with quiescent air and strong jet conditions. The strong jet was capable of overwhelming the smallest drops within the spray, reversing their direction, and reducing the volume flux at the floor. Computational simulations (informed by detailed initial spray measurements) demonstrated good agreement with the spray dispersion and plume penetration experiments.

1. Introduction

Fire sprinklers are a cost-effective water dispersion method for suppressing fire growth [1–3]. To achieve fire suppression, the sprinkler spray must penetrate the upward moving fire plume to reach the fire and deliver a sufficient volume of water to cool the burning fuel surface [2]. While fire sprinklers have been used successfully for many years, there is desire for a predictive modeling capability to support suppression system design and to spark technological innovation in the development of fire sprinklers. Accurate representation of the fire sprinkler spray, and the interaction of the spray with the fire induced flow, is necessary to predict suppression performance.

Accurate spray representation is made more difficult by the complexity of fire sprinkler sprays. A typical pendent sprinkler forms a spray by deflecting a water jet with a complex deflector plate, consisting of frame arms, a boss, tines, and slots. This spray formation method leads to a highly polydispersed spray, with large spatial variations in volume flux, drop size, and velocity. This polydispersity and spatial non-uniformity complicates predictions of spray dispersion, particularly when the effect of a fire plume must be considered.

Several previous studies have focused on the overall spray characteristics and spray dispersion of fire sprinklers. Far-field spray measurements have mostly focused on mechanical collection of water for volume flux measurements of delivered density, often in a quiescent case [4–7]. FM Global has been the leader in spray delivery measurements in the presence of real fire plume interactions with the use of their large-scale delivered density facility [5]. These previous measurements were all performed with relatively crude diagnostics–by physically collecting the water as it is delivered.

To provide deeper insight to spray physics, more advanced diagnostics have been used to measure spray characteristics. Much of the previous work using advanced diagnostics has focused on characterizing the initial near-field spray [7–13]. These measurements are vital in providing accurate initial conditions within computational models. The Spatially-resolved Spray Scanning System (4 S) is a comprehensive method for measuring the complex and non-uniform initial spray details of volume flux, drop size, and drop velocity [3,7,13].

There have been fewer applications of advanced diagnostic techniques in the far-field spray examining spray dispersion and the spray-plume interaction. Previous spray-plume interaction studies include

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work by Schwille [14], who implemented particle image velocimetry (PIV) measurements of a spray to measure the velocity field from large-angle spray nozzles. Additional measurements of the spray-plume interaction were taken using advanced infrared imaging to study the reaction of the plume structure to the momentum of the suppressing spray [15]. Zhou [16] performed PIV measurements on a small-scale buoyant plume interacting with water mist, identifying gas phase velocities, drop size evolution within the plume, and the location of the spray-plume interaction boundary.

Increasingly, computational fluid dynamics (CFD) models, such as FM Global's FireFOAM [17,18], are used to predict this multiphase behavior and capture spray complexity. With the more recent development of highly detailed initial spray measurements, as well as the ever-increasing computational power available, an increase in the fidelity of the initial spray conditions within the model has been possible. Early sprinkler models used relatively low fidelity transport models simulating only a few trajectories with uniform drop sizes [19–21]. More recently, higher fidelity models have been developed based on near-field initial spray characterization [11]; these models have been successfully used to simulate complex dispersion [22] and suppression [23] scenarios. The complexity of these simulation scenarios provides a realistic challenge for model capabilities, but limits insights into spray physics and utility for validation of the models.

The current experimental study implements advanced laser shadowgraph diagnostics to investigate the far-field spray-plume interaction in a canonical laboratory-scale Sprinkler Array Facility (SAF). The SAF uses a canonical gridded sprinkler array with full-scale fire sprinklers and a variable-speed vertical air jet to simulate the induced flow of a fire plume. The laser shadowgraph diagnostics within the facility provide detailed measurements of drop size, drop velocity, and spray volume flux throughout the dispersed spray. The SAF simulates full-scale spray behavior while maintaining the well-characterized boundary conditions necessary for CFD model validation. In the present study, experiments are conducted to explore the interaction of multiple sprinklers with an air jet to provide data for validation of computational models. Computational results from simulations with sprays generated based on the high-fidelity initial spray measurements are compared to the experimental spray-plume interaction data.

2. Approach

2.1. Configuration

Experiments were conducted in a modified Sprinkler Array Facility (SAF) previously used for spray dispersion measurements in quiescent conditions [7] as shown in Fig. 1. The SAF consists of a square array of Tyco D3 spray nozzles with k-factor 33.1 LPM/bar$^{1/2}$ operating at 1.38 bar. The Tyco D3 spray nozzle used for this study produces widely-dispersed sparse sprays consistent with standard pendant sprinklers. This particular nozzle has a horizontal deflector consisting of 12 rotationally symmetric slot/tine pairs with no geometric abstractions. The SAF was modified from the previous arrangement to include a centrally located plume generator to simulate the upward flow from a fire source while providing repeatable boundary conditions for CFD input. The plume generator provides a well-characterized jet of dry, ambient temperature airflow at uniform velocities with jet velocities v_p, up to 4 m/s. In this study, only two (#1 and #3) of the four SAF sprinklers located on opposite sides of the jet were used to avoid spray obstructions associated with positioning the laser-based optical diagnostics equipment. These diagnostics were implemented in the jet region indicated by the red shaded region in Fig. 1.

Air was delivered from a 1.1 kW electric centrifugal blower via a 0.2 m diameter round flexible duct to the jet exit through a 90° elbow with a 0.2 m×0.2 m square cross-section. To provide a uniform exit velocity profile, the airflow was conditioned by passing through six layers of 12 mm thick open-cell polyurethane foam with 20 pores per inch, supported by a perforated rigid aluminum plate (40% open area). An additional pressure drop is provided by a single stainless steel mesh layer (50×250 Mesh size) sandwiched between the foam. A wire screen cap prevented the foam from blowing out.

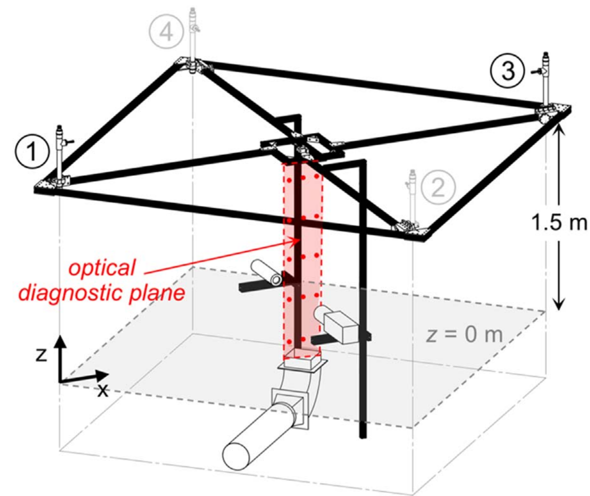

Fig. 1. Diagram of experimental configuration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Four spray conditions were measured for this study by combination of two sprinkler spacings and two air jet velocities. The sprinklers were positioned at one of two separation distances, Δr, measured from the sprinkler to the jet centerline—a close spacing case where Δr=0.65 m, and a far spacing case where Δr=1.87 m. For each spacing configuration, measurements were taken with a quiescent condition (v_p=0 m/s) and with a strong air jet (v_p=3.7 m/s).

Each of the four experimental conditions were modeled using CFD. An advanced large eddy simulation (LES) solver called FireFOAM was used for this study. FireFOAM is based on a general-purpose CFD solver called OpenFOAM [17], developed by FM Global [18,23]. FireFOAM uses an Eulerian–Lagrangian (EL) model for multiphase flow. In the EL approach, the gas phase is represented by an evolving Eulerian grid while the spray is modeled using Lagrangian particle tracking. In this model, the Lagrangian particles representing the sprinkler spray are injected into the modeled domain and particle motion is handled by solving the Lagrangian equations of motion. Particle interaction with the gas phase is handled through a variety of sub-models.

In the present study, the standard FireFOAM spray model was used with the addition of new scheme for the injection of the sprinkler spray. The new scheme, called *detailedSprinklerInjection2*, was developed based on work by Myers [3] to specify the full range of initial spray characteristics measured with the Spatially-Resolved Spray Scanning System (4S) at the University of Maryland [7,13]. In this new scheme, the complex spatio-stochastic characteristics of the initial sprinkler spray are represented by spatially varying near-field volume flux, drop size distribution, initial drop velocity, and initial drop formation radius. Lagrangian particles are injected stochastically across the spray, in accordance with the experimentally measured quantities, on a volume-weighted basis. Each simulated particle represents the same total volume, but carries a variable number of drops based on drop diameter and particle volume. After injection, particles move under the influence of gravity and spherical drag, calculated using a Reynolds dependent drag coefficient according to

$$C_D = \begin{cases} \frac{24}{Re}\left(1 + \frac{Re^{2/3}}{6}\right) & Re < 1000 \\ 0.424 & Re \geq 1000 \end{cases} \tag{1}$$

It should also be noted that further drop break-up, turbulent dispersion, and evaporation were neglected.