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A modeling basis for predicting the initial sprinkler spray

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Abstract

The performance of water-based fire suppression systems is governed by the dispersion of the water drops in the spray. Characterization of the spray is essential for predicting and evaluating the performance of these suppression systems. The dispersion of the spray is typically modeled using particle tracking methods. The accuracy of the spray characterization using this approach is quite sensitive to the initial spray specification. A physics-based atomization model has been developed for prediction of the initial spray. Inputs to this model include injector geometry, injection pressure, ambient environment, and suppressant fluid properties. This atomization model also accounts for the stochastic behavior of the physical processes governing spray formation and provides probability distributions of initial drop sizes and locations for the initial spray. This modeling approach can be integrated with drop dispersion models and CFD models to characterize spray dispersion in quiescent environments or evaluate suppression performance in fire environments. The drop size predictions using the proposed atomization model have demonstrated favorable agreement with actual sprinkler spray measurements over a range of operating conditions.

Keywords: Sprinklers; Atomization; Suppression; Sprays

1. Introduction

Characterization of the water spray is critically important in evaluating the performance of water-based suppression systems. A recent comprehensive overview of water-based fire suppression is provided in Grant et al. [1]. The performance of these suppression systems is primarily evaluated through full-scale spray dispersion tests and actual fire suppression tests. It is difficult to extrapolate the spray dispersion test performance to real fire scenarios because of the potentially strong coupling between the fire and the spray. Alternatively, actual full-scale suppression tests are expensive making it difficult to generate sufficient test statistics for proper evaluation of the test results. Predictive models are needed to evaluate spray characteristics or to couple with fire models to predict suppression performance. In fact, the atomization model is a critical missing link in the modeling of suppressed fires. Sophisticated gas phase models are in place for predicting the fire dynamics like Large Eddy Simulation (LES). Furthermore, drop dispersion models are well defined for tracking the drops after the atomization process is complete [2]. However, a general model has yet to be provided for predicting the initial spray properties for sprinklers. The atomization model developed in this study is a first step in addressing this deficiency.

Some simple correlations have been developed for estimating characteristic drop sizes based on a few experiments [3–5]. These correlations can be used as primitive predictive models; however, they have a limited range of validity and are insensitive to many effects that are known to influence the initial spray behavior. The data in these correlations are obtained under quiescent 'cool' conditions. However, the elevated velocities and temperatures in real fires are expected to influence the atomization process. A robust physics-based approach capable of handling this coupling has been used to develop the atomization model in this study. The present work provides the modeling basis to support the design of new

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suppression devices, characterization of spray details, or evaluation of the resulting suppression performance in the presence of a real fire.

Some experimental work has been conducted to characterize the details of the sprinkler spray. The results from these experimental investigations provide sprinkler design guidance and provide valuable information for the development of atomization and spray models. Dundas [4] provides drop size measurements for several sprinkler geometries along with a review of drop size data obtained in a variety of injectors. The data are correlated based on an expression first proposed by Heskestad [6], $d_{v50}/D_{orif} = C\,We^{-1/3}$, where d_{v50} is the volumetric median diameter, D_{orif} is the injection orifice diameter, and the Weber number, $We = \rho_l U^2 D_{orif}/\sigma$, is based on the liquid properties. The drop size data compiled by Dundas from various injectors demonstrates that the coefficient of proportionality, C, depends on the sprinkler geometry [4]. You's data reveal more insight into the dependency of the coefficient, C. His data clearly show that C increases with increasing injection orifice diameter for upright sprinklers [3]. Prahl and Wendt [7] measured flow patterns from an axisymmetric laboratory sprinkler and developed models to predict these flow patterns. Correlations along with assumed Rosin-Rammler distributions were used to estimate drop size. Initial drop locations were approximated based on wave instability concepts, and drop trajectories were determined from particle tracking. Adjustments were made to the modeling constants to match the predicted and measured flow patterns. More recently Widmann [8], Widmann et al. [9], Putorti et al. [10], and Sheppard [5] have characterized velocities and drop sizes from sprinklers using advanced diagnostics. Widmann used Phase Doppler Interferometry (PDI) to measure drop sizes and velocities from actual sprinklers having K-factors ranging from $7.2\times10^{-5}\,\mathrm{m^3\,s^{-1}\,kPa^{-1/2}}$ ($3.0\,\mathrm{gal\,min^{-1}\,psi^{-1/2}}$) to $1.35\times10^{-4}\,\mathrm{m^3\,s^{-1}\,kPa^{-1/2}}$ ($5.6\,\mathrm{gal\,min^{-1}\,psi^{-1/2}}$). This measurement technique provides detailed information at one point within the spray. Characterizing the overall spray with this technique is prohibitive because of the number of point measurements required to map out the spray distribution. Nevertheless, the drop size and velocity measurements were taken at a number of locations at a given plane to determine the mass flux distribution using the PDI technique. The mass flux obtained from these PDI measurements at specified locations compared favorably with mass flux measurements taken with collection tubes. Widmann also noted deviation from the $p^{-1/3}$ scaling law for drop size at low pressures (around 69 kPa), but obtained better agreement at higher pressures. Putorti measured drop size and velocity simultaneously using a two-color fluorescence technique in an axisymmetric sprinkler configuration. Putorti's measurements provide drop size/velocity correlations, drop size distributions, and drop trajectories. Sheppard measured velocities very close to the sprinkler (~0.2 m) to characterize the initial spray velocity using Particle Image Velocimetry (PIV). This technique allows for visualization of a cross-section of the spray. He presented these measurements in a spherical coordinate system having the origin located on the sprinkler centerline at a specified position between the orifice and the deflector plate. Sheppard showed the variation of radial velocity with polar angle (measured from the sprinkler centerline) at various azimuthal angles (measured from the sprinkler yoke arms). He compared his velocity measurements with PDI measurements noting discrepancies due to differences in experimental configuration and biasing issues related to the differing measurement approaches used in the respective diagnostic techniques.

Predicting spray characteristics has proven to be challenging because of the complexity and stochastic behavior of the breakup process. In fact, it is common to simply characterize the sprinkler spray using correlations, or curve fits, of available experimental data. These experimental data are often obtained at conditions well outside of the operating conditions of interest. However, Dombrowski and Johns [11] developed an actual atomization model based on wave dispersion theory to predict drop size. This atomization model was developed using fan type injectors. Dombrowski described the atomization process in terms of the growth of waves on an infinite unstable sheet. He simplified the wave dispersion equations and integrated them to quantify the sheet breakup characteristics and then related the sheet disintegration to initial drop characteristics. This wave dispersion model has been successfully used by Rizk for various types of fuel injection systems [12] and is applied to sprinklers in the current study. Marshall and di Marzo [13] have developed a complete atomization model for sprinklers by integrating a film formation sub-model proposed by Watson [14] with a sheet disintegration sub-model proposed by Dombrowski and Johns [11]. Furthermore, these models have been implemented with a modified stochastic formulation originally proposed by Rizk and Mongia [12]. The current study provides the details for this atomization modeling approach. Results from this atomization model are presented and comparisons are made with actual sprinkler measurements and correlations.

2. Model description

2.1. Atomization physics

A spray is formed by breaking up a volume of liquid into small drops. This process is referred to as atomization. Sprinklers use atomization to facilitate the dispersion of water over a large area to protect commodities not yet involved in the fire. The spray also delivers water to burning materials and decreases the burning rate by reducing heat feedback to the fuel surface. Moreover, atomization greatly increases the surface area of the injected volume of water. In the case of finely atomized water mist sprays, this increased surface area results in