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A description of the initial fire sprinkler spray

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ABSTRACT

Accurate representation of the fire sprinkler spray enables quantitative engineering analysis of fire suppression performance. Increasingly, fire sprinkler systems are analyzed with computational fluid dynamics (CFD) fire models where the sprinkler spray is simulated with Lagrangian particles dispersed throughout the fire induced flow. However, there is limited guidance for representing the complex, spatio-stochastic characteristics of the initial sprinkler sprays in terms of these Lagrangian particles. The present work establishes a descriptive analytical framework for the initial sprinkler spray that is rigorously grounded in statistical theory, related to local spray properties, and capable of translating high-fidelity measurements into CFD inputs. This framework describes the initial sprinkler spray as a unified probability distribution function, varying over an initialization surface, and statistically representing measurements of near field local spray properties (volume flux, drop size distribution, and drop size–velocity correlation). Lagrangian particles accurately representing the sprinkler spray may be initialized by a stochastic sampling of this probability distribution function. This novel representation enables high-fidelity initialization of the sprinkler spray in CFD fire models, improving their utility in quantitative engineering analysis.

1. Introduction

Fire sprinklers provide a simple and cost effective spray dispersion method to arrest fire growth [1]. A typical pendent sprinkler, as seen in Fig. 1, consists of a thermal activation element and flow controlling elements; specifically, the orifice, frame arms, boss, and deflector. Upon activation, a water jet (created by the orifice) strikes the frame arms, boss, and deflector, transforming the jet into a complex, cascading series of sheets, jets, and drops [2]. These sheets and jets move outward away from the sprinkler, interact with the surrounding air, and, because of aerodynamic instabilities, eventually break into drops. These drops form a dilute spray flying outward; dispersing through combustion products, plume, flame, and reactants; and interacting with surfaces.

The jet impingement atomization method produces a highly non-uniform spray, consistent with measurements by Sheppard [3,4]. Recent work by Ren [5] introduced a method characterizing measurements of the near-field fire sprinkler spray in support of numerical simulation of sprinkler spray dispersion. These measurements, as well as detailed measurements by Zhou [6], reveal large elevation and azimuthal variations in near-field volume flux, drop size, and velocity corresponding to geometric features of the fire sprinkler head. An example typifying these spatial variations is seen in Fig. 2, a measurement of the near-field volume flux for a typical, pendent-type sprinkler head, measured in the University of Maryland's spray lab with the Spatially resolved Spray Scanning System (4S) [7]. Any description of the fire sprinkler spray used for high fidelity fire protection analysis must capture these spatial variations.

Increasingly, computational fluid dynamics (CFD) fire models, like the Fire Dynamics Simulator (FDS) or FireFOAM, are trusted to inform fire protection decisions [8,9]. Both FDS and FireFOAM use an Eulerian–Lagrangian (EL) approach to describe multiphase flows. In the EL approach, the continuous phase (i.e. the gas phase, including the combustion products, plume, flame, and reactants) is represented as an evolving Eulerian field, while the dispersed phase (i.e. the sprinkler spray) is modeled using Lagrangian particle tracking [10]. In these models, Lagrangian particles, representing the sprinkler spray, are injected into the modeled domain. Particle motion is determined by solving the Lagrangian equations of motion and interaction with the Eulerian continuous phase is handled through a variety of sub-models (e.g. heat transfer, drop evaporation, turbulent dispersion, etc.).

There is limited guidance as to how the complex, spatio-stochastic characteristics of the initial fire sprinkler sprays can be represented in terms of these Lagrangian particles. Modeling is further complicated by the limited ability of current fire models to predict fire sprinkler atomization [6]. As a result, the initial fire sprinkler spray must be specified from measurements. Work by Ren [5] successfully identified the importance of measured local

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Nomenclature

$\vec{a}$	acceleration
d	drop diameter
D	rate of change of drop diameter
d_{v50}	median drop size
f^{*}	drop distribution function
f_N	drop number probability density function
f_V	volume flux probability density function
$f_{V,\Omega}$	angular volume flux probability density function
$f_{V,d}$	drop size volume flux probability density function
F_V	volume flux cumulative distribution function
$F_{V,\Omega}$	angular volume flux cumulative distribution function
$F_{V,d}$	drop size volume flux cumulative distribution function
G_V	inverse volume flux cumulative distribution function
N	drop number
N_p	Lagrangian particle number
$\dot{N}$	drop flow rate
$\dot{N}_p$	Lagrangian particle injection rate
$\hat{n}$	normal vector to a surface
p	probability space spanning 0 to 1
Q	rate of change of drop number
r	radius
r_0	initialization radius
r_{bu}	breakup radius
r_m	measurement radius
t	time
$\vec{u}$	velocity
u_0	initialization velocity
u_{bu}	breakup velocity
u_m	measured velocity
$\dot{V}$	volume flow
$\dot{V}''$	volume flux
W_p	particle weighting factor
$\vec{x}$	position

Greek symbols

Γ	drop size distribution width
θ	elevation angle
ψ	azimuthal angle
Ω	solid angle

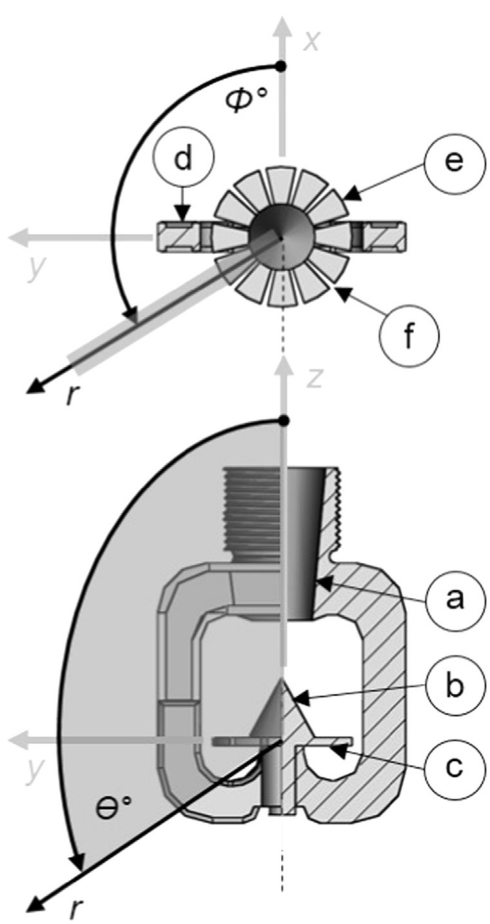

Fig. 1. Partial cross section of a pendent sprinkler illustrating components; (a) orifice, (b) boss, (c) deflector, (d) frame arm (ref), (e) tines, and (f) slots [7].

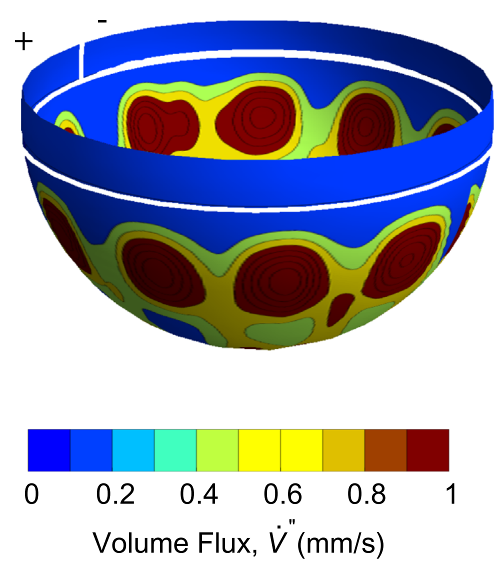

Fig. 2. Highly non-uniform volume flux for a typical pendent sprinkler head, measured at a radius of 0.4 m from the sprinkler head [7].

spray properties, but did not fully connect these filtered measurements to a robust statistical description of the flow or provide guidance to their implementation in high fidelity Lagrangian particle spray dispersion simulations.

The present work seeks to provide an initial spray description grounded in statistical theory, tied to near-field measurements, and suitable for translating these measurements into a Lagrangian spray modeling framework. First, the drop distribution function is introduced, providing a rigorous statistical description for any dilute spray. This drop distribution function is then applied and adapted, whereby the initial sprinkler spray is described by a multivariate probability density function varying across an initialization surface. This probability density function, and the corresponding cumulative distribution function are related to locally measured spray properties. The net result of the current study is an initial fire sprinkler spray description scheme, for use in measurement and modeling, presented with requisite theoretical basis, implementation framework, and CFD application guidance.