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Effect of initial conditions of modeled PDFs on droplet characteristics for coalescing and evaporating turbulent water spray used in fire suppression applications

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Abstract

Parametric studies were conducted for a coalescing and evaporating turbulent water spray using a stochastic separated flow technique that includes submodels for droplet dynamics, heat and mass transfer, and droplet–droplet binary collisions. While the initial droplet size distribution, in general, is not known due to the difficulty in the optical access to the nozzle exit region, the size distribution is modeled using the analytical PDFs (probability density functions) such as log-normal, Rosin–Rammler, Gaussian, and Nukiyama–Tanasawa distribution model. Standard deviation of the PDFs is varied and their effects on droplet size and speed distribution in the downstream are reported. The arithmetic mean droplet size at the nozzle exit, which is used as input for simulations, was extrapolated using the existing experimental data obtained at downstream locations.

Keywords: Turbulent spray; Droplet distribution; Initial condition; Rosin–Rammler; Log-normal; Gaussian

1. Introduction

Rapid fire suppression is a necessity for modern vehicle crew compartments and for enclosures containing critical equipment susceptible to fire damage. In a case where a fuel tank of a military or civilian vehicle is punctured by arsenal ammunition, liquid fuel is transported as atomized droplets as shown in Fig. 1(a) and, hence, forming a fuel-pool and flammable gas near the tank [1]. The spark from the incendiary in the flammable gas region initiates an ignition event which leads to a sustained pool fire. Another case in point is that of a moving vehicle collisions with flammable storage (i.e., gas station, liquid natural gas facilities, gas/oil pipeline), or a moving fuel-tank crashing against a building (i.e., the 9/11 terrorist attack) as shown in Fig. 1(b) of Ref. [2]. For these applications, high-momentum sprays are useful for quickly dispersing condensed-phase suppressants to the fire and the surrounding compartment to minimize the thermal insult to its occupants. Because of the high momentum of the water suppressant spray, water atomized droplets are expected to penetrate the flame and reach the fuel surface; hence, surface cooling would occur, which reduces the pyrolysis rate and so the rate of fuel supply to the flame zone. In addition, small water droplets with diameters of the order of tens of microns behave as a mist or cloud, which attenuates the radiant heat of the flame by absorbing and scattering the infrared wavelength characteristics of luminous flame. The high-speed water spray of great momentum, containing small droplets, is considered an ideal fire suppression spray.

The current paper focuses on the predictive modeling of a specific nozzle, typical of those that might be used to provide suppression in a compartment in a matter of seconds or less. Droplet size and velocity measurements are presented to help develop the appropriate initial conditions for this nozzle and to air in evaluating the model.

Understanding the size distribution of a spray at the liquid core region, where liquid becomes atomized, has always been an arcane subject in the atomization

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Nomenclature

B	spalding or mass transfer number
c_p	specific heat
C_D	drag coefficient
D	droplet or particle diameter
D_M	mass diffusivity
D_{10}	arithmetic mean diameter
D_{32}	Sauter mean diameter
$f(D)$	probability density function (PDF)
g	gravitational acceleration
h_v	heat of vaporization
k	thermal conductivity
Le	Lewis number
m	droplet or particle mass
Oh	Ohnesorge number
Pr	Prandtl number
q	Rosin–Rammler dispersion coefficient
Re	Reynolds number
Sc	Schmidt number
T	temperature
$\vec{u}$	velocity
We	Weber number
x	(or z) axial axis
X	characteristics mean diameter of the Rosin–Rammler PDF
y	(or r) radial axis
Y	mass fraction

Greek letters

θ	cone angle
μ	kinematic viscosity
ν	dynamic viscosity
ρ	density
σ	Gaussian deviation
$\sigma^*_{\ln}$	dimensionless log-normal deviation

Subscripts

$(\,)_c$	parcel property
$(\,)_f$	film property
$(\,)_g$	gas property
$(\,)_p$	droplet or particle property

community. The recent experiment by MacPhee et al. [3], and the computational work by Yoon [4], have shed light on this subject. (See Fig. 2(a) for the demonstration of the computational capability.) However, the photographic assessment by MacPhee et al. [3], which utilized the X-ray technique, has not yet revealed the complex shape of the liquid core, or the distribution shape of atomized droplets. The computational work of Yoon [4] and Park et al. [5], showed what was until now, the unknown shape of the liquid core and the distribution shape of the atomized

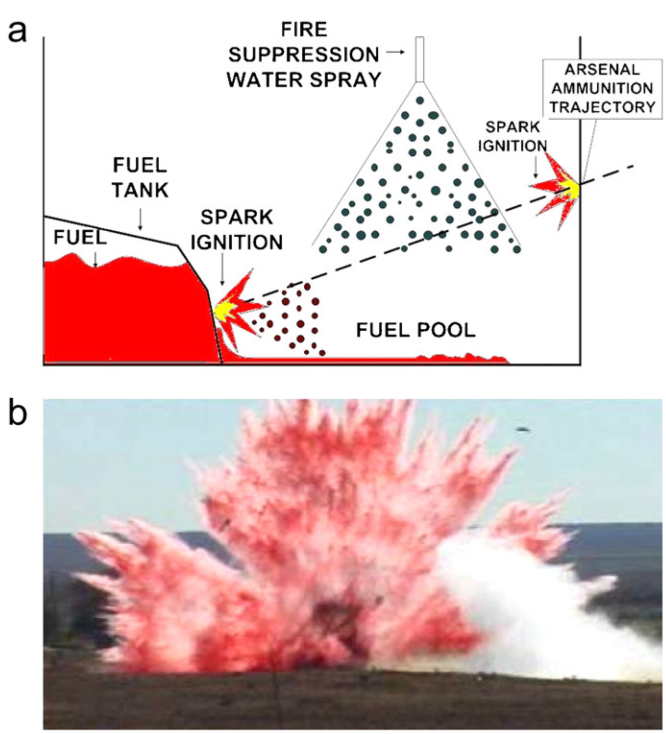

Fig. 1. (a) Live fire event illustrating liquid fuel spray ignition and sustained pool fire. (b) Atomized drop formation due to splashing upon the wall-impact of large scale fuel tank without ignition [2].

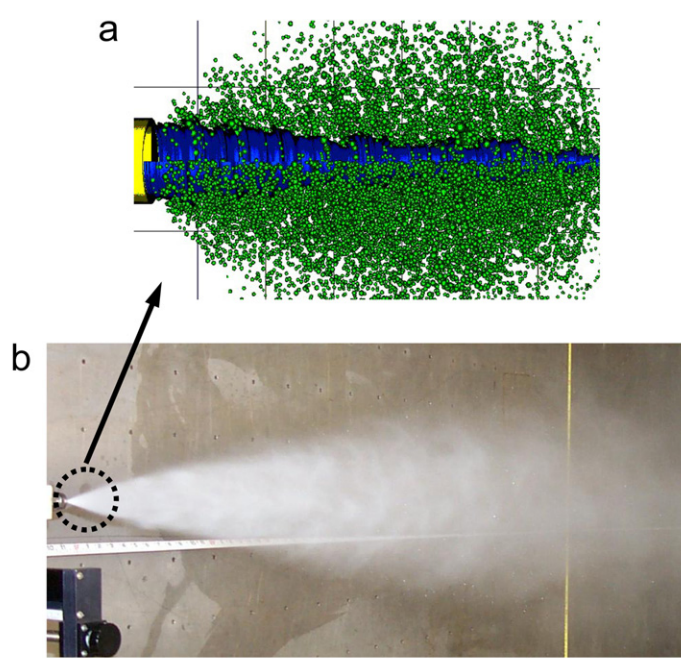

Fig. 2. (a) Near-field view of the high-pressure water spray at the liquid core region [4]. (b) Experimental image of near field view of the evaporating and coalescing turbulent water jet.