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Characterization of a simplex water mist nozzle and its performance in extinguishing liquid pool fire

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ABSTRACT

Pressure swirl nozzles are often employed in water mist fire suppression systems. In the present work, a single head full cone simplex nozzle with X-type swirl-insert and an orifice diameter of 1.2 mm is used to produce water mist. The objectives are to experimentally measure different characteristics of the spray and investigate extinction performance of diesel pool fires of size 0.1, 0.2, and 0.3 m. Discharge coefficient and spray cone angle are measured and correlations are presented as functions of Reynolds numbers (*Re*, based on orifice diameter). Mass flux density of the spray is measured with a patternator designed considering possible asymmetry in the spray. Droplet size and velocity distributions are measured using a particle droplet image analyser (*PDIA*) system for $28{,}850 \le Re \le 35{,}800$ and axial distances from the nozzle ($0.75 \le z \le 1.75$ m). Experimentally measured droplet number distributions are characterized by modified log-normal distribution. Rosin-Rammler and modified Rosin-Rammler model are presented to predict droplet volume distributions. Correlations are presented for calculating parameters of these models in order to describe droplet size distribution (*DSD*) for any combination of *Re* and *z*. Relative span factor (*RSF*), Sauter mean diameter (*SMD*), and average velocity of the spray are measured. Correlations for *SMD* and average velocity are presented as functions of experimental variables. The extinction performances are investigated through video recording for $28{,}850 \le Re \le 35{,}800$ and various vertical distances between the nozzle and the fuel surface (0.75–2 m). Extinction performance of the nozzle in the present work is compared with the other performances of different water mist systems reported in the literature.

1. Introduction

Liquid combustibles are primary fire hazards in industries. In engine rooms, machinery spaces of ships or liquid fuel storage rooms, fire may be an outcome of spillage of different types of fuels such as diesel, n-heptane, etc. and different ignition sources such as heated engine block, inadvertent electrical sparks, etc. Accidental fires may be simulated by pool fires since they replicate the type of combustion occurring on fuel spills. Halon 1301 and 1211 were the most effective chemical (chlorine- or bromine-based) fire suppressants. These were phased out inevitably under the terms of the amended Montreal protocol, being environmentally unacceptable. Shukhman et al. [1] have found out the adverse effects of Halon 1301 in the air on the performances of engines of motor vehicles used for extinguishing conflagration. They have also found out dramatic deterioration in efficiency of catalytic converter releasing more harmful substances. Complete flooding of confined spaces with personnel inside using chemical agents as extinguishers is prohibited. Hence, extensive efforts are being expended to arrive at alternative options. Water mist as a potential fire suppression agent is non-toxic and environment-friendly with no asphyxiation problems. Conventional sprinkler systems cannot typically be used for suppression of class B fires (flammable liquids, oils, etc.) as they may cause splashing, spillage and sputtering and help spread the fire instead of quenching it. Contrary to sprinklers, water mist systems produce droplets with lower momentum. As per *NFPA* 750 [2], water mist is defined as a water spray for which the $D_{v,0.99}$ (99% volume diameter) as measured at the coarsest part of the spray in a plane 1 m from the nozzle, at its minimum operating design pressure, is less than 1000 μm. Water usage by water mist systems is much lower than that by sprinkler systems, making the former more efficient. Also, damage to surfaces in a fire due to sudden quenching by high water flux from sprinkler systems is avoided in case of water mist systems.

Fundamental studies required for the design of water mist systems for fire suppression are discussed in detail [3–6]. Water mist systems have been applied or are being developed for the suppression of different classes of fire. Mawhinney [7] has listed the agencies all over the world and their research work on water mist fire suppression systems. Rasbash [8], Notarianni [9], Jones and Nolan [10], Liu and Kim [11]

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Nomenclature

A	area (m^2)
C_1	a constant
C_2	a constant
C_d	discharge coefficient
D	diameter (m or mm) or droplet diameter (μm)
$D_{v,y}$	diameter (μm) below which ($y \times 100$)% of the spray's volume resides, $0 \le y \le 1$
$\overline{D}_{ng}$	number geometric mean drop size (μm)
$f\,(D)$	droplet size distribution or probability density function (μm^{-1})
G	type of the thread
L	length (mm)
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of droplets between droplet sizes D and $D + \Delta D$
P	pressure (Pa)
Q	volume of droplets between droplet sizes D and $D + \Delta D$ (μm^3)
q	a distribution parameter
Re	Reynolds number based on orifice diameter
R^2	squared Pearson correlation coefficient or the coefficient of determination
S_g	geometric standard deviation (μm)
V	velocity (m s^{-1})
X	drop diameter such that 63.2% of the total liquid volume is in the drops of smaller diameter (μm)
z	axial distance from nozzle tip (m)

Greek letters

ρ	density of water (kg m^{-3})
μ	dynamic viscosity (Pa-s)
β	spray cone angle (°)
Δ	difference in quantity

Abbreviations

APV	adaptive phase Doppler velocimetry
BSPT	British standard pipe taper
DSLR	digital single lens reflex
DSD	droplet size distribution
HRR	heat release rate
LDV	laser Doppler velocimetry
MC	multicomponent
NFPA	national fire protection association
PDA	phase Doppler anemometry
PDIA	particle/droplet image analyzer
PIVS	particle image velocimetry and sizing
RSF	relative span factor
SMD	Sauter mean diameter
SS	stainless steel

Subscripts

act	actual
avg	average
i	size range
N	number
o	orifice
T	total
t	thread
th	theoretical
Q	volume

have reviewed numerous case studies of water mist fire suppression systems applied to different scenarios. Table 1 represents the review of the literature mainly concerned with class B fire in brief.

Extinction of different classes of fires by using water mist system is studied in the literature. Rasbash et al. [12] have attempted to provide a quantitative estimate of extinction time for few tests. Overall burning rate after application of the spray is experimentally investigated [14,15]. Instantaneous burning rate after application of water mist is measured using cone calorimeter [17,20]. Fire extinction limit is obtained from the critical pressure (minimum injection pressure required for extinction of fire for a given distance) [15,22]. Additives are added to water and their effect is seen on extinction performance [23,24]. Extinctions of fires of canola oil, soyabean oil and their mixture (class K fire) by application of the group of pressure swirl nozzles are experimentally investigated by Liu et al. [27–30]. Pressure swirl nozzles are chiefly used in the literature to produce water mist. The pressure-swirl atomizer is accepted as the most efficient method of producing a fine spray using pressurized liquid i.e. for a given flow rate, this method requires the minimal supply pressure to provide a given drop size [31]. Portable water mist systems are also used wherever fixed water mist systems cannot be deployed [24,29]. An effervescent atomizer is designed and characterized by Huang et al. [25]. The reliability of extinction by water mist is studied and the probability distribution of extinction time is given [26]. Thus, the extinction times for pool fires of different fuels, various sizes and shapes of the pan, different experimental parameters, and different designs of nozzles are extensively studied in the literature. However, there is a need to compare the extinction performance of different water mist fire suppression systems for the same scenario of the diesel pool fire.

A detailed characterization of the spray is essential for the preliminary design of the water mist system for the extinction of a given fire. It also helps in the standardization of the water mist system. An accurate knowledge of the droplet size distribution (*DSD*) as a function of the conditions of the system is a prerequisite for fundamental analysis of the transport of mass or heat or of the separation of phases in a dispersed system [32]. Several typical hydraulic atomizers, used in fire suppression, have been characterized by Tanner and Knasiak [33]. They also discussed the use of characteristics of the spray in computer modeling of fire protection systems. Kohnen et al. [34] have compared drop size distributions by two different methods: low-exposure-photography and laser diffraction. *LDV/APV* [17–20,22,23,26], laser diffraction-based instrument (Malvern) [14,15], *PDA* [24,25,33,35,36], *PIVS* [21,37] are the methods chiefly used for continuous-phase flow diagnostics. Comparison between *PIV* and *PDA* is reported [38]. Comparison between particle/droplet image analyzer (*PDIA*) and *PDA* technique is reported [39,40], former being better in the detection of the presence of predominantly non-spherical droplets of diameters larger than 100 μm. *PDIA* is designed employing *LED*-illumination and results are compared with laser-based illumination [41]. The distance of the nozzle (or spray height) is principle system variable for different applications of the nozzle spray. In the literature, the effect of axial distance from the nozzle on different characteristics of the spray is not studied except by Nasr et al. [31] and Santangelo [42] who have measured different characteristic diameters of the spray as functions of axial distance from the nozzle. However, knowledge of the *DSD* is important as an input for numerical investigation by different computational fluid dynamics packages. It is helpful to present the correlations for characterizing *DSD* in terms of a few principal system variables as stated by Grant et al. [6]. Thus, there is a need to study the variation in *DSD* of the spray with the increase in axial distance from the nozzle and also to present empirical equations of *DSD* as functions of different system variables. The value of the spray cone angle depends upon the