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Suppression effectiveness of water-mist sprays on accelerated wood-crib fires

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ABSTRACT

An experimental analysis was conducted to quantify the water-mist discharge characteristics required to suppress wood-crib fires. The overall aim of this research was to investigate the effectiveness of these innovative systems in a canonical fire scenario. To this end, an experimental suppression facility was constructed including commercially available water mist nozzles, thermocouples for measuring the thermal transient in and around the wood cribs and a load cell for measuring the mass loss rate and the final wood crib damage. $510 \times 510 \times 380$ mm wood cribs were used as the fuel source in all the experiments. The injection pressure and orifice diameter of the water-mist nozzles were varied in the experiments to modify the applied water flux and the initial spray momentum. These quantities were identified to be the governing parameters for suppression performance. They were characterized for all experiments along with the drop-size and velocity distributions. Critical values were determined for these quantities from first order kinematic and thermal analysis based on spray and fire source characteristics. The experimental results demonstrated critical suppression behavior consistent with this first order analysis.

1. Introduction

The extinguishment of solid-fueled fires by water sprays has received significant attention over the decades [1–4]. Studies aimed at elucidating the fundamental physical mechanisms responsible for suppression, as well as those yielding more empirical insights are well reported in the literature. More specifically, the burning of wood fires and their suppression by water sprays have been the focus of numerous research efforts. At the same time, interest in the use of water-mist sprays as a potential alternative to either traditional sprinklers or environmentally hazardous gaseous agents has been steadily increasing. Suppression mechanisms by water-mist systems can be different than those by traditional water sprays, as thoroughly described in the review by Santangelo and Tartarini [5]. These considerations constitute the motivation for the present work, where water-mist sprays are challenged by openly-packed wood-crib fires.

Success of water sprays against fire depends on a number of factors. For example, the presence of an enclosure may significantly alter the suppression dynamics, allowing potential oxygen displacement in addition to the other mechanisms typically present in fires suppressed by water sprays. Early enclosure-fire suppression research includes studies by Salzberg and Vodvarka [6] and Ball and Pietrzak [7]. Alternatively, early experiments by Kalelkar [8] focused on suppression behavior of open fuel-limited wood-crib fires. Kalelkar rigorously accounted for all the water applied to burning wood cribs and subsequently absorbed, evaporated, or drained off. An interesting observation from Kalelkar's research was that a lower rate of applied water resulted in a greater total quantity of water being needed for extinction than if a higher application rate was used. This outcome was also found by Unoki [9] and illustrated by Hirst [10]. Because Kalelkar's spray drop sizes were remarkably larger than the mist used in the current study, direct comparisons with the current experiments may have a merely qualitative extent. Tamanini [2,3] also studied open fuel-limited wood-crib fires with a focus on determining critical water flux requirements delivered to the burning wood crib and suppression time requirements. More recently, Heskestad [11,12] evaluated downward sprays on both methane-gas and heptane pool fires; he proposed a scaling analysis, resulting in

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Nomenclature

A	area (m^2)
c_p	specific heat capacity at constant pressure ($kJ\,g^{-1}\,K^{-1}$)
D_{ne}	effective nozzle diameter (m) [11]
FAR	Fuel-to-Air Ratio
h	stick height (m)
H	specific enthalpy ($kJ\,g^{-1}$)
H_C°	heat of combustion ($kJ\,g^{-1}$)
H_G°	heat of gasification ($kJ\,g^{-1}$)
HRR	Heat Release Rate (kW)
l	stick length (m)
m	mass (kg)
$\dot{m}$	mass rate ($g\,s^{-1}$)
$\dot{m}''$	mass flux ($g\,s^{-1}\,m^{-2}$)
M	momentum (N m)
N	total amount
$\dot{q}$	heat rate (kW)
T	temperature (°C)
v	velocity ($m\,s^{-1}$)
$\dot{V}''$	volume flux ($L\,m^{-2}\,min^{-1}$)
w	stick width (m)

Greek symbols

λ	laser-light wavelength (nm)
ρ	density ($g\,L^{-1}$)

Superscripts

*	dimensionless

Subscripts

0	initial
ave	average
b	burnt
Bernoulli	Bernoulli model
c,t	undergoing temperature change at time *t*
con	convective
crit	critical
del	delivered
eff	effective
es	total exposed surface of the crib
evap	evaporation
f	final
fire	fire
flame	flame
fuel	fuel
FB	Free Burn
i,h	internal horizontal surface
i,v	internal vertical surface
ig	ignition
L	layers per crib
max	maximum
rad	radiative
side	side of the crib
S	sticks per layer
top	top of the crib
v	vaporization
w	water

correlations between the required application rate of water to extinguish fires and parameters such as spray-cone angle, a momentum-based effective nozzle diameter, nozzle height and free-burn heat release rate. The capability of the spray to penetrate and overwhelm the plume was also investigated by Liu et. al. [13] through a momentum balance, which is ultimately related to heat release rate of the fire, spray momentum and drop size. Very recently, Yu [14] followed Heskestad's approach to experimentally understand the applicability of Froude-modeling-based scaling laws to water-mist suppression of wood-crib fires; the proposed model proved rather satisfactory, yet more sensitive to possible scaling distortion than in a typical liquid pool fire.

The primary objective of this study is to evaluate crib damage (i.e., suppression performance) as related to both fire source and mist characteristics in a canonical overhead spray configuration. A thermodynamic analysis of the potential cooling mechanisms provides physical insight into the experimental suppression results while spray-to-plume momentum interactions are discussed through the background provided by Heskestad [11,12] and Nyankina and Turan [15]. These latter present a comprehensive discussion of this phenomenon based on activation time and spray penetration. If drop-size distribution is kept the same between two tests, the one with a longer activation time is likely to have the downward droplets entering the upward plume overpowered, thus having a reduced residence time: not only do they hardly reach the fuel base, but they may not even cool down the gas phase reaction. The relationship between suppression effectiveness and activation time is also emphasized by Kalelkar [8], who suggests thermal inertia as the key to quantify this relation. The wood is initially at a relatively low temperature, as volatiles are released and combusted in the flame region, so thermal inertia is also low. Then, even though a certain amount of mass is lost, temperature increases. Therefore, the amount of water needed to cool very hot fuel is significantly larger than that necessary for an earlier suppression effort. Therefore, the results obtained in the present study should be considered as valid not only for the employed geometry and operating pressure, but also for the chosen timing.

Moreover, Pietrzak and Johanson [16] and Kung [17] relate drop-size distribution to the spray volume flux required for extinction; this feature was taken into account in this work as well, even though a parametric study based upon that falls outside the present scope. Notably, the source was characterized in terms of mass loss rate and surface temperatures. The mist spray was also characterized in terms of initial spray momentum, applied water flux and drop-size distribution following previous spray studies [18–21]. Ultimately, source and spray measurements provided the opportunity for quantitative connections between those parameters and suppression performance.

2. Experimental facility and procedure

2.1. Suppression and free-burn tests

The pine wood cribs used in this study had dimensions of $510 \times 510 \times 380$ mm (length × width × height). The individual members making up the cribs were 510 mm long with a 32×32 mm cross section. The members were arranged in twelve orthogonal layers of six members each and were "openly-packed"