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A simplified model for the shielding of fire thermal radiation by water mists

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ABSTRACT

A solution for the complete problem of attenuation of fire radiation by water mist is presented. This solution is based on simplified approaches for the spectral radiative properties of water droplets, the radiative transfer in the absorbing and scattering mist, and transient heat transfer taking into account partial evaporation of water mist. A computational study of the conventional model problem indicates the role of the main parameters and enables one to formulate some recommendations to optimize possible engineering solutions. The method developed is also applied to more realistic case study of a real fire. It is suggested to decrease the size of supplied water droplets with the distance from the irradiated surface of the mist layer. The advantage of this engineering solution is confirmed by numerical calculations. Potential possibility of microwave monitoring of water mist parameters is analyzed on the basis of Mie theory calculations.

1. Introduction

Since the ratification of the Montreal protocol in 1987, phasing out halon agents due to their negative environmental impacts, the use of water sprays and mists in fire protection has gained momentum. Water mist is defined according to the NFPA as sprays in which 99% of the volume is in droplets with diameters less than 1000 microns. Water spray/mist systems can be used for the dilution of toxic releases [1]. The scope of the present study is its fire application. There are two main strategies for using water sprays/mists in fire protection. In the first one, the intention is to extinguish or control the fire by applying the spray directly onto the fire source. Such applications have been well reviewed in [2] and considered also in [3]. In the second application strategy where there is no direct contact between the fire source and spray, the curtain of spray/mist is used as a radiation attenuation shield to protect potential targets which could be equipments or human beings [3]. The present study is concerned with such radiation shielding applications of water mist curtains. In the process industries, spray/mist curtains provide an effective mean to protect flammable targets (e.g. storage tanks) in the event of fires. They could also serve as protection against fire radiation for personnel during evacuation on-board carrier and chemical ships during maritime transport [4]. In some countries, fire engines used by firefighters to combat forest fires are fitted with water spray curtains as emergency personnel protection. Water spray curtains can also be employed as compartmentation to protect people in fire events [5].

Research on water spray/mist shielding has received considerable attention in the past two decades. Although the main mechanisms of radiation attenuation by a two-phase water spray have been identified as absorption and scattering by droplets and absorption by the gas phase (mainly water vapor), a rigorous model that account for the coupled radiation, heat and mass transfers in the spray is complex to develop and is too involved computationally. Such models are important to better design and optimize water sprays and mists for reliable and cost-effective solutions.

The bulk of the literature on water spray/mist curtain shielding has been devoted to radiation modeling by uncoupling it from other phenomena, in order to predict the transmittance and attenuation of the curtain. Obviously, the Beer–Lambert law used in [6] is inapplicable for the transmittance calculations in the problem under consideration. Therefore, the two-flux model was employed in more recent papers [7–10] for the transmittance calculations. These studies show that smaller droplets in high concentration provide better attenuation of the spray. However the important

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Nomenclature

a	radius of droplet
A	attenuation parameter introduced by Eq. (17)
c	specific heat capacity
C_D	drag coefficient
f_v	volume fraction of droplets
H	height of the mist curtain
k	thermal conductivity
L	latent heat of evaporation
m	complex index of refraction
n	index of refraction
q	radiative flux
Q	efficiency factor of absorption or scattering
R	reflectance
t	time
T	temperature
u	velocity
W	absorbed radiation power
x	diffraction parameter
y	horizontal coordinate
z	vertical coordinate

Greek symbols

α	absorption coefficient
ε	dielectric constant
η	dynamic viscosity of gas
κ	index of absorption
λ	wavelength
μ	cosine of an angle
ρ	density
σ	scattering coefficient or electrical conductivity
σ_0	Stefan–Boltzmann constant
ω	scattering albedo

Subscripts and superscripts

a	absorption
d	droplet
e	external
el	electrical
f	flame
g	gas
h	hemispherical
n-h	normal-hemispherical
rel	relaxation
s	scattering or static
t	transmitted
tot	total
tr	transport
w	water
λ	spectral

phenomena such as mass transfer and droplets evaporation were not considered in these papers.

More detailed description of radiative transfer based on the Discrete Ordinates Method (DOM), Finite Volume Method and even Monte Carlo simulation were also used in computational studies of water mists [11–17]. Some of these studies have coupled the radiation, heat, mass and momentum transfer in sprays using the combined Eulerian–Lagrangian approach for both dynamic and thermal non-equilibrium of droplets and ambient gas. However the complexity of this approach is an obstacle to their widespread use.

The current literature clearly shows the advances in modeling and improving the understanding of water spray/mist curtain in fire radiation mitigation. However these models are mainly employed by the research community and are rarely used in the water mist industry which is currently developing fast and needs such tools. The complexity and computing cost are clearly two major obstacles for the application of current methods. There is a need nowadays to develop engineering models for water mist curtain, which retains the physics of the problem and at the same time offers acceptable computing cost. The present study aims to achieve such a goal.

The objectives of the present paper are as follows: (1) to develop a simplified but complete model for the combined heat transfer processes in a semi-transparent layer of water droplets used as a shield for infrared radiation of fires, (2) to study computationally the role of the main parameters of water mist and to give preliminary recommendation on possible optimization of engineering solutions for fire protection, (3) to present a numerical solution for realistic case study, (4) to suggest possible principal approach to the microwave monitoring the mist parameters taking into account the effect of both the size and temperature of water droplets on absorption and scattering of the microwave radiation by the mist layer.

The methodology of the present paper is based on a combination of a set of approximate 1-D solutions for the radiative transfer problem and a simplified heat transfer model for heating and evaporation of water droplets. A relatively small absorption of radiation by water vapor, which is generated by partially evaporating water droplets, is neglected in a simplified model. The analysis of the analytical solution for radiative heat transfer through the mist layer makes it possible to suggest a decrease in the size of supplied water droplets with the distance from the irradiated surface of the mist layer. Subsequent numerical calculations for more realistic case study of fire protection confirm the advantages of the suggested engineering solution.

An analysis of possible microwave monitoring of water mist parameters is also given in the paper. The calculations based on the rigorous Mie solution for single water droplets showed that important information on average values of both the size and temperature of water droplets can be obtained using the measurements of directional-hemispherical reflectance of sub-millimeter radiation from the mist layer.

2. Spectral properties of water droplets

The spectral optical constants, n and κ, of pure water are well known [18,19]. For convenience of subsequent analysis, spectral dependences of these quantities in the most important part of the infrared range are presented in Fig. 1. The spectral characteristics of absorption and scattering of spherical water droplets can be calculated using the Mie theory [20–22]. Because of a simplified radiative transfer model used in the present paper, we will focus on two dimensionless far-field characteristics which can be obtained from the analytical Mie solution: the efficiency factor of absorption, Q_a, and the transport efficiency factor of scattering, Q_s^{tr}. According to Mie theory, the values of Q_a and Q_s^{tr} depend on both the complex index of refraction $m = n - i\kappa$ and the diffraction (size) parameter $x = 2\pi a/\lambda$, where a is the droplet radius. The exact Mie calculations are time-consuming especially for large droplets with $x >> 1$. Fortunately, one can use the following analytical