Infrared Physics & Technology 91 (2018) 55–62

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

An infrared scattering by evaporating droplets at the initial stage of a pool fire suppression by water sprays

Leonid A. Dombrovsky [a,b,*], Siaka Dembele [a], Jennifer X. Wen [c]

[a] Depart. of Mechanical & Automotive Engineering, Kingston University, London SW15 3DW, UK
[b] Tyumen State University, 6 Volodarsky St., Tyumen 625003, Russia
[c] School of Engineering, University of Warwick, Coventry CV4 7AL, UK

HIGHLIGHTS

- An initial stage of a pool fire suppression is considered.
- The motion, heating, and evaporation of water droplets are calculated.
- Focusing of evaporating water droplets in local regions is obtained.
- A strong infrared scattering by small water droplets is analyzed.
- The spectral region of a significant infrared scattering is determined.

ARTICLE INFO

Article history:
Received 30 January 2018
Revised 28 March 2018
Accepted 29 March 2018
Available online 30 March 2018

Keywords:
Suppression of pool fires
Evaporating water droplets
Thermal radiation
Strong infrared scattering

ABSTRACT

The computational analysis of downward motion and evaporation of water droplets used to suppress a typical transient pool fire shows local regions of a high volume fraction of relatively small droplets. These droplets are comparable in size with the infrared wavelength in the range of intense flame radiation. The estimated scattering of the radiation by these droplets is considerable throughout the entire spectrum except for a narrow region in the vicinity of the main absorption peak of water where the anomalous refraction takes place. The calculations of infrared radiation field in the model pool fire indicate the strong effect of scattering which can be observed experimentally to validate the fire computational model.

1. Introduction

The complex behaviour of water sprays used in suppression of pool fires is an important engineering problem [1–5]. Strictly speaking, one should take into account the effect of water sprays on flow field parameters. It is really important in the regular regime of fire suppression. Following [6], a preliminary probe stage of the fire suppression with a very small flow rate of water is considered. Obviously, the effect of a low flow rate water spray on the fire parameters at the probe stage is negligible. It means that one can consider the motion, heating, and evaporation of single water droplets in the flame without taking into account any feedback effects. It is also assumed that a relatively thin water spray moves down parallel to the flame axis. This approach is convenient to focus on the most important special features of the droplet behaviour at the probe stage. Of course, a simplified model for droplet motion and evaporation is insufficient to obtain accurate results for the interaction of a fast developing turbulent fire and water droplets. The latter is especially important when the characteristic times of the flow field changes and displacement of the droplets are comparable with each other.

In the limit of a relatively slow variation of the flow field, the evaporation of droplets accompanied by a decrease in their velocity may lead to a significant volume fraction of small droplets at several specific local areas. In the reality, both the position and parameters of these local areas in the developing flame are changed rather rapidly.

It is known that small water droplets are characterized by a strong scattering of light at the wavelength comparable with the droplet size [7]. This optical effect, which is commonly observed in the visible for the natural mists, has been recently considered as a promising way to improve shielding of fire radiation by multi-layered water sprays [8,9]. It is important that the gaseous

---

* Corresponding author at: Depart. of Mechanical & Automotive Engineering, Kingston University, London SW15 3DW, UK.
E-mail address: ldombr@yandex.ru (L.A. Dombrovsky).

https://doi.org/10.1016/j.infrared.2018.03.027
1350-4495/

Nomenclature

a	radius of droplet
c	specific heat capacity
D	radiation diffusion coefficient
C_D	drag coefficient
f_v	volume fraction of droplets
E	normalized coefficient
G	spectral irradiation
g	acceleration of gravity
I	radiation intensity
K	coefficient introduced by Eq. (6b)
k	thermal conductivity
L	latent heat of evaporation
m	complex index of refraction
n	index of refraction
Q	efficiency factor
r	radial coordinate
S	source function
u	velocity
W	generated radiation power
w	normalized radiation power
x	diffraction (size) parameter
z	axial coordinate

Greek symbols

α, β	absorption and extinction coefficients
γ	coefficient introduced by Eq. (6b)
ε	emissivity
η	dynamic viscosity
κ	index of absorption
λ	wavelength
ξ	coefficient in Eq. (11)
ρ	density
σ	scattering coefficient
ψ	coefficient introduced by Eq. (6b)
$\vec{\Omega}$	unit vector of direction

Subscripts

0	initial value
a	absorption
b	blackbody
d	droplet
g	gas
max	maximum
r	radiative
ref	referred
s	scattering
sat	saturation
t	total
tr	transport
w	water, wall

combustion products in the fire do not scatter the radiation. The radiation scattering by soot aggregates in the infrared range is also negligible (a considerable scattering by soot aggregates can be observed in the visible range only) [10–13]. As a result, one can observe local regions of small water droplets near the flame axis because of their infrared scattering. This may be a scattering of the flame self-emission, but one can also use an external irradiation.

The objective of this paper is twofold: (1) to study the behaviour of moving water droplets which can be collected in some local areas of the flame before their total evaporation and (2) to estimate the effect of scattering of the flame infrared radiation by these small droplets on the radiation source function, which is responsible for the observed flame emission.

It seems natural to consider first the typical trajectories and evaporation dynamics of water droplets to find the local regions where the volume fraction of highly scattering small droplets is expected to be significant.

2. Motion and evaporation of water droplets

The interaction of water sprays with fires has been modelled computationally in many papers especially during the last two decades [14–18]. However, there is no need to discuss here the state-of-the-art in this field because the present paper is focused on another particular problem. At the probe stage of the fire suppression, one can supply only the droplets falling down not far from the flame axis. For simplicity, the spherical water droplets are assumed to have the same radius at the initial cross section of the spray. It is sufficient to consider a few selected trajectories of droplets falling initially along the flame axis without any interactions between the droplets. According to [16,19], the following sets of equations are derived for the droplet motion:

$$\frac{dz_\mathrm{d}}{dt} = u_\mathrm{d} \qquad z_\mathrm{d}(0) = z_0 \tag{1a}$$

$$\frac{du_\mathrm{d}}{dt} = \frac{3C_\mathrm{D}}{8a}\frac{\rho}{\rho_\mathrm{w}}(u_\mathrm{g} - u_\mathrm{d})\,|u_\mathrm{g} - u_\mathrm{d}| - g \qquad u_\mathrm{d}(0) = -u_{\mathrm{d}0} \tag{1b}$$

$$C_\mathrm{D} = 24(1 + 0.15\mathrm{Re}_\mathrm{d}^{0.687})/\mathrm{Re}_\mathrm{d} \qquad \mathrm{Re}_\mathrm{d} = 2\rho|u - u_\mathrm{d}|a/\eta \tag{1c}$$

where the subscripts “g”, “d” and “w” refer to the gaseous medium, droplet and water, u is the velocity, a is the droplet radius, C_D is the drag coefficient, Re is the Reynolds number. It is assumed that water droplets are first heated up to the saturation temperature without evaporation (at $0 < t < t_\mathrm{sat}$):

$$\frac{dT_\mathrm{d}}{dt} = \frac{1.5\mathrm{Nu}k}{\rho_\mathrm{w}c_\mathrm{w}a^2}(T_\mathrm{g} - T_\mathrm{d}) \quad T_\mathrm{d}(0) = T_0 \quad t < t_\mathrm{sat} \tag{2a}$$

$$\mathrm{Nu} = 2 + 0.6\mathrm{Re}_\mathrm{d}^{1/2}Pr^{1/3} \qquad \mathrm{Pr} = \eta c/k \tag{2b}$$

(Nu and Pr are the Nusselt and Prandtl numbers) and then evaporated according to the following simple equation (at $t > t_\mathrm{sat}$):

$$\frac{da}{dt} = -\mathrm{Nu}\frac{k\,(T_\mathrm{g} - T_\mathrm{w,sat})}{2a\rho_\mathrm{w}L_\mathrm{w}} \qquad a\,(t_\mathrm{sat}) = a_0 \quad t > t_\mathrm{sat} \tag{3}$$

where L_w is the latent heat of evaporation of water. A similar model has been recently used in analysis of water mist curtains [8,9]. This simplified evaporation model is also sufficient for qualitative estimates of the present paper because of very fast heating of moving droplets and large molar fraction of water vapour in the flame. It is not necessary at the moment to consider sophisticated evaporation models like that developed in paper [20]. A transfer from the droplet heating to its evaporation is given by equation:

$$T_\mathrm{d}(t_\mathrm{sat}) = T_\mathrm{w,sat} \tag{4}$$

In contrast to recent papers [3,4,21], the effects of thermal radiation are neglected in the above model as compared with convective heat transfer from ambient hot gases. This assumption can be