SUPPRESSION OF POOL FIRES BY WATER SPRAYS: THE EFFECT OF LIGHT SCATTERING BY EVAPORATING DROPLETS

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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 strong scattering of visible and near-infrared radiation by partially evaporating small droplets. The positions of these local regions are very sensitive to flame parameters and this can be used to develop a new method of experimental optical observations at the probe stage of fire suppression by water sprays. Some of these optical measurements are expected to be useful for partial validation of transient CFD simulations of pool fire suppression by sprays.

INTRODUCTION

The complex behavior of water sprays used in suppression of pool fires is an important engineering problem. Strictly speaking, one should take into account the effect of water sprays on the flow field parameters of the flame, but it is necessary only in the regular regime of fire suppression. In this paper, a specific procedure of fire suppression is suggested. It includes a preliminary probe stage with a very small flow rate of water. It is expected that some observations at the probe stage will show us the depth of propagation of evaporating water droplets into the flame and this can be used to choose an appropriate parameters of effective fire suppression at the regular stage of fire suppression characterized by a large flow rate of water. Obviously, the effect of a water spray on the fire parameters at the short-time probe stage is negligible, and one can consider the motion, heating, and evaporation of single water droplets in the flame without taking into account any feedback effects. Obviously, the results of the “probe spray” study cannot be directly used in the analysis of the regular fire suppression.

A suggested short-time probe spraying looks as a relatively thin water spray moving down parallel to the flame axis. Evaporation of droplets accompanied by a decrease in their velocity makes impossible their propagation to the surface of a liquid fuel and leads to a significant volume fraction of relatively small droplets at several specific local positions. The latter may be interesting for validation of transient CFD simulations.

It is known that small water droplets are characterized by a strong scattering of light at the wavelength comparable with the droplet size [1]. This optical effect, which can be observed in natural mists, is considered as a promising way to improve shielding of fire radiation by multi-layered water sprays [2, 3]. It is important that the combustion products do not scatter the radiation and scattering by soot aggregates in the near infrared spectral range is usually negligible (a considerable scattering by soot aggregates can be observed in the visible range only) [4–7]. As a result, one can determine a quasisteady position of small water droplets at the flame axis because of their near-infrared scattering. This may be a scattering of the flame self-emission, but one can also use an external irradiation.

The objective of the paper is to present the particular finding related to the effects of evaporating droplets with different initial sizes in some local areas of the flame and the resulting strong infrared scattering by small water droplets.

Of course, one should calculate the motion, heating, and evaporation of water droplets in a model fire and also spectral optical properties of water droplets to estimate the effect under discussion.

MOTION AND EVAPORATION OF WATER DROPLETS IN THE FLAME

The interaction of water sprays with fires have been modeled computationally in many papers especially during the last two decades [8–12], but there is no need to discuss here the state-of-the-art in this field because we are focused on a very particular problem. For the probe stage of the fire suppression, it is sufficient to supply only the droplets falling down not far from the flame axis. It seems to be correct because the contribution of water droplets reaching the hot core of the flame is assumed to be the most important for the regular suppression procedure.

There is obviously a size distribution of water droplets at the initial cross section of the spray. However, it is convenient to obtain numerical solutions for monodisperse droplets with sizes corresponding to conventional boundaries of the distribution core. For simplicity, the selected trajectories of droplets along the flame axis are considered and possible interaction between the droplets is ignored. The following initial problems were considered for the droplet motion [11, 14]:

$$\frac{dz_\mathrm{d}}{dt} = u_\mathrm{d}, \; z_\mathrm{d}(0) = z_0 \qquad \frac{du_\mathrm{d}}{dt} = \frac{3C_\mathrm{D}}{8a}\frac{\rho}{\rho_\mathrm{w}}(u-u_\mathrm{d})|u-u_\mathrm{d}| - g, \; u_\mathrm{d}(0) = -u_\mathrm{d0} \tag{1a}$$

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

where the subscripts “d” and “w” refer to the droplet and to water, u is the velocity, a is the droplet radius, η is the dynamic viscosity, 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 (at $0 < t < t_\mathrm{sat}$):

$$\frac{dT_\mathrm{d}}{dt} = \frac{1.5\mathrm{Nu}\,k}{\rho_\mathrm{w} c_\mathrm{w} a^2}(T - T_\mathrm{d}), \; T_\mathrm{d}(0) = T_0 \qquad \mathrm{Nu} = 2 + 0.6\,\mathrm{Re}_\mathrm{d}^{1/2}\,\mathrm{Pr}^{1/3} \qquad \mathrm{Pr} = \eta c/k \tag{2}$$

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

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

where L_w is the latent heat of evaporation of water. This is a realistic assumption in the case of a large molar fraction of water vapor in the flame. A transfer from the droplet heating to its evaporation is given by equation $T_\mathrm{d}(t_\mathrm{sat}) = T_\mathrm{sat}$. In contrast to recent papers [2, 3, 14], the effects of thermal radiation are neglected in the above model as compared with convective heat transfer from ambient hot gases. The above suggested model is a little bit similar to a model of papers [15, 16]. Obviously, the local relative volume fraction of water droplets is calculated as follows:

$$\bar{f}_\mathrm{v} = f_\mathrm{v}/f_\mathrm{v0} = (u_\mathrm{d0}/u_\mathrm{d})(a/a_0)^3 \tag{4}$$

PARAMETERS OF THE CASE PROBLEM

Strictly speaking, one should take into account the effect of water sprays on the flow field parameters of the flame, but it is necessary only in the regular regime of fire suppression. In the present study, a specific procedure of fire suppression is suggested. It includes a preliminary probe stage with a very small flow rate of water. The observations at the probe stage will show us some important details of behavior of evaporating water droplets in the flame. Obviously, the effect of a water spray on the fire parameters at the short-time probe stage is negligible, and one can consider the motion, heating, and evaporation of single water droplets in the flame without taking into account any feedback effects.

The fire scenario considered in the study is based on a 28 cm diameter methane gas flame, burning in the open quiescent environment with a heat release rate of 53 kW. The LES (Large Eddy Simulation) CFD simulation of the flame was carried out using an in-house version of the code FireFOAM [17], compatible with OpenFOAM version 2.2.x. The combustion sub-model used in this code is based on the eddy dissipation concept (EDC) proposed by Magnussen et al. [18] for RANS applications and extended by Chen et al. [19] for LES. For soot modelling, Chen [20] extended the laminar smoke point soot to LES using the partially stirred reactor concept. The radiative transfer equation is solved with the finite volume method (FVM), which is open accessible. Gas radiation is treated with the box model approach based on the exponential wide band model to calculate the equivalent band absorption coefficient [21, 22]. The calculated transient flame is three-dimensional, but deviations of the main parameters from the axisymmetric case are not significant. Therefore, we consider similar axisymmetric fields obtained as averaged fields in a selected axial cross section of the real developing flame at $t = 1$ s (see Fig. 1).

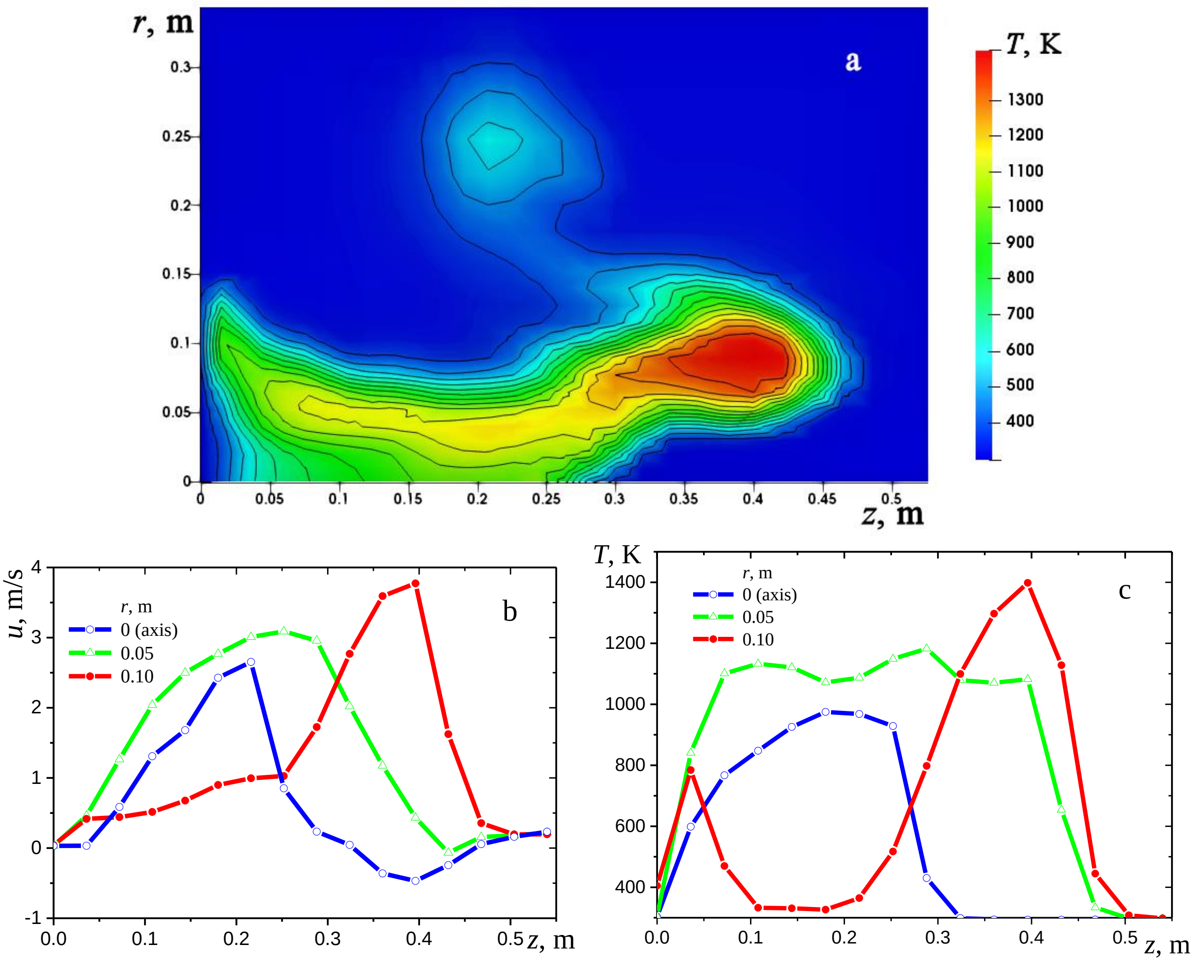

Figure 1. Parameters of the model flame: (a) – the gas temperature field; (b), (c) – the profiles of upward velocity and temperature.

The temperature field is strongly non-uniform and contains a hot circular region with radius about 8 cm in the forward part of the flame, at $z = 0.4$ m. This hot region moves upward with a speed of about 4 m/s (Fig. 1b). On the contrary, there is a region of a gas at the axis of the flame at $z > 0.3$ m. Moreover, a downward motion of a gas is observed in this central region. The above described specific structure of the flame was a motivation of subsequent attention to both the cold central region and the circular hot and high-velocity region of the flame.

COMPUTATIONAL RESULTS FOR MOTION AND EVAPORATION OF DROPLETS

The following parameters were taken for water droplets at the initial cross section of the spray for the case problem: $z_0 = 0.5$ m and $T_0 = 300$ K. As to the droplet size and their initial velocity, a set of various realistic values of these quantities was considered. The results of calculations for water droplets are presented in Fig. 2. The behaviour of water droplets moving along the parallel lines appeared to be quite different, but in both cases the evaporating droplets of different initial size are focused at small local regions. In the case of droplets moving along the axis, their initial velocity practically, makes no difference because of a relatively small relaxation time (Fig. 2a), and the final evaporation of these droplets is expected due to absorption of thermal radiation. On the contrary, the large droplets supplied near the hot region at $r_0 = 0.1$ m can penetrate to the hot region and totally evaporate during their backward motion at a small distance from this hot region.

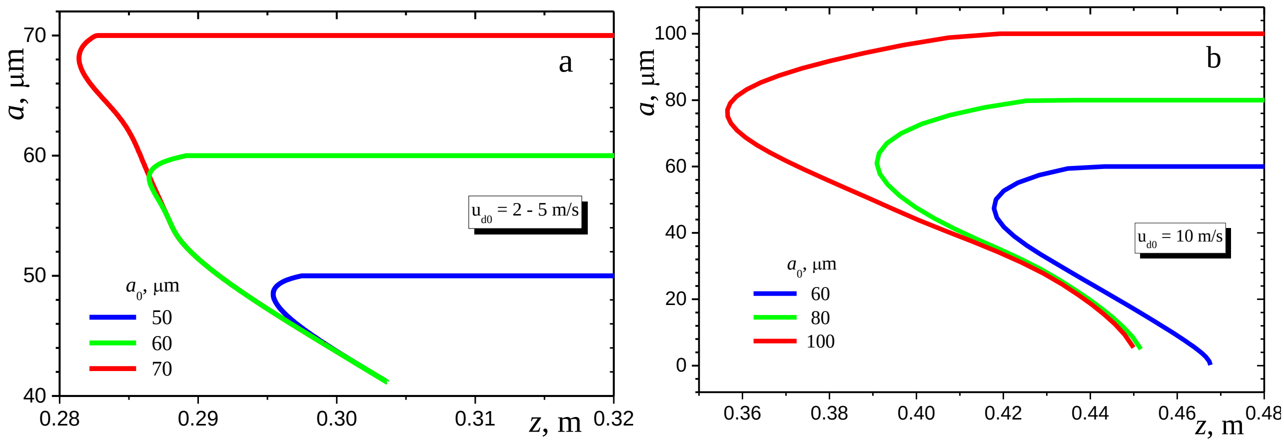

Figure 2. Variation of droplet radius along their trajectories at two initial positions of supplied droplets: (a) $r_0 = 0$ (along the axis) and (b) $r_0 = 0.1$ m (opposite to the hot region of the flame).

It is physically clear that volume fraction of water droplets increases dramatically in the local regions of their collections and total evaporation. Of course, the assumption of independently moving single droplets is incorrect in the vicinity of these regions, and it is a serious problem which does not have a simple solution at the moment.

ABSORPTION AND SCATTERING OF RADIATION BY WATER DROPLETS

The normalized coefficients of absorption and transport scattering (per unit volume fraction of water) for independently absorbing and scattering droplets with radius a can be determined as follows:

$$E_a = 0.75\, Q_a / a \qquad E_s^{tr} = 0.75\, Q_s^{tr} / a \tag{7}$$

The word "transport" means that we use the transport approximation of the scattering phase function which is presented as a sum of an isotropic part and a peak in the forward direction [23]. The multiple scattering in a semi-transparent optically thick medium is really favourable condition for the use of transport approximation because the details of angular distribution of light intensity in single scattering have a negligible effect on the light propagation [1].

According to the Mie theory [24, 25], the efficiency factor of absorption, Q_a, and transport efficiency factor of scattering, Q_s^tr depend on both the spectral complex index of refraction of water, $m = n - i\kappa$, and the diffraction (size) parameter $x = 2\pi a/\lambda$. The exact Mie calculations are time-consuming especially for large droplets. Therefore, as it was done in [2, 3], we use the following analytical relations [26]:

$$Q_\mathrm{a} = \frac{4n}{(n+1)^2}\left[1-\exp(-4\kappa x)\right] \qquad Q_\mathrm{s}^\mathrm{tr} = K\begin{cases} \psi/5 & \text{when } \psi \le 5 \\ (5/\psi)^\gamma & \text{when } \psi > 5 \end{cases} \tag{8a}$$

$$K = 1.5n(n-1)\exp(-15\kappa) \qquad \gamma = 1.4 - \exp(-80\kappa) \qquad \psi = 2x(n-1) \tag{8b}$$

Spectral optical constants of water, n and κ, are known from the literature [27, 28].

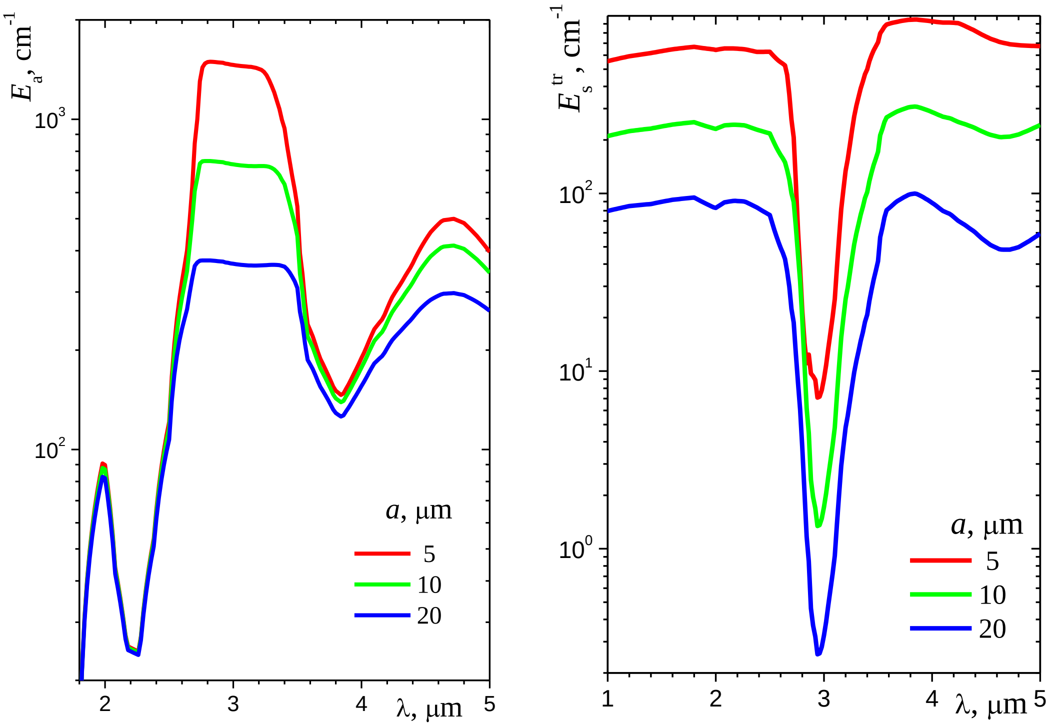

Figure 3. Normalized absorption and transport scattering coefficients of water droplets.

The calculated values of E_a and E_s^tr in the most important range of the problem parameters are presented in Fig. 3. These values should be multiplied by the volume fraction of water droplets to obtain the local values of both the spectral absorption coefficient and transport scattering coefficient of monodisperse droplets:

$$\alpha_\mathrm{d} = f_\mathrm{v} E_\mathrm{a} \qquad \sigma_\mathrm{tr} = f_\mathrm{v} E_\mathrm{s}^\mathrm{tr} \tag{9}$$

It is clear that the radiation absorption by water droplets may be significant in the near-infrared absorption bands of water, especially at the wavelength about 3 μm. This absorption contributes to water evaporation and flame suppression. On the contrary, the scattering of the flame radiation by water droplets is significant outside this absorption band, where this effect is expected to be observed. It is interesting that spectral behaviour of both the absorption and transport scattering coefficients of droplets is similar for droplets of different size, but the scattering is much greater for relatively small droplets. As to the sharp minimum of scattering at the absorption band, it is explained by the known effect of anomalous dispersion [29, 30].

The hypothesis of independent scattering does not work in the region of strong evaporation where the distance between the neighbouring droplets may be small as compared with both the droplet size and the radiation wavelength. According to [31–35], the dependent scattering may lead to significant changes in absorption and scattering characteristics of the turbulent gas flow with suspended clusters of closely spaced particles or droplets.

From Fig. 3, one can suggest one or another methodology for the scattering observation in the region of $z_1 < z < z_2$. Two kinds of these observations are possible. The simplest passive way is to record the infrared thermal radiation of the flame in the wavelength range of $3.6 < \lambda < 5\,\mu$m, when this radiation is strongly scattered by water droplets of radius $a < 10$ µm (see Fig. 3b). The other (active) method should use the external source of collimated infrared radiation in a wavelength range, where there are no strong absorption band of water and the scattering of the external collimated beam can be easily observed. The later measurements are expected to be more accurate and enable one to retrieve the scattering properties of the cloud of especially small droplets with radius less than 5 µm. Of course, one needs a selective sensor for the infrared measurements in both cases. The authors cannot go into details of any possible experimental studies which are beyond the scope of the present paper.

CONCLUSION

A computational study of a suggested preliminary probe spraying of water droplets before the regular suppression of a developing pool fire showed some interested features of behaviour of moving and evaporating droplets. In particular, the effect of focusing a lot of evaporating water droplets in the local regions of the pool fire was obtained for the first time. These local regions are characterized by a strong scattering of visible and near-infrared radiation (excluding the narrow range at the strong absorption bands of gases) by partially evaporated small droplets comparable in size with the wavelength. The scattering effect can be used to develop a new method of experimental optical observations at the probe stage of fire suppression by water sprays. The calculations showed that positions of these local highly-scattering regions are very sensitive to flame parameters. It is expected that the latter can be used in probe experiments for partial validation of transient CFD simulations.

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