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AN IMPROVED SOLUTION FOR SHIELDING OF THERMAL RADIATION OF FIRES USING MIST CURTAINS OF PURE WATER OR SEA WATER

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An improved theoretical model for the shielding of radiation from large-scale fires by the mists of pure water or sea water is presented. This is a continuation of a recent study by accounting for both the partial re-absorption of radiation in the absorption bands of gases and the variation of the incident radiative flux along the flame. As before, the solution to a combined problem of heat transfer consists of the spectral radiative transfer in a mist curtain, the kinetics of droplet evaporation, and convective heat transfer along the curtain. The previously suggested spectral models for optical properties of water droplets and salt particles formed by evaporation of sea water droplets are used in the calculations. Unlike in our previous study, the radiative heat losses to the nozzle head and the floor under the curtain and the decrease in the downward velocity near the floor are accounted for the first time using the 2-D radiative transfer calculations. It is shown that heat losses towards the floor and nozzle head are insignificant even for thick water curtains. Some recommendations on correct choice of parameters of two-layered mist curtains with relatively low total flow rate of supplied water are given. In particular, it is confirmed that the use of smaller droplets of water in the second layer of mist curtains reduces the required total flow rate of supplied water. It is also shown that the protection offered by sea-water curtain is almost the same as that of pure water. Moreover, the use of sea water is potentially preferable for better protection from the fire radiation in the lower part of the curtain. The latter statement is correct in the case of high protective mist curtains, when the droplets of pure water evaporate completely before reaching the floor, whereas the hollow particles of sea salt are there in the lower part of the sea-water mist curtain. The study confirms that sea-water curtains can be used in coastal areas, offshore platforms or maritime transportation ships for shielding fire thermal radiation.

KEY WORDS: *fire radiation, water mist, sea water, radiative heat transfer, double-layered mist curtain, computational model*

1. INTRODUCTION

Water mist curtains are widely used in safety engineering for the protection against fire radiation. In recent years, significant progress has been achieved in modelling heat transfer in water mist curtains. Nevertheless, the complexity of the proposed models and numerical approaches [Boulet et al. 2006; Hostikka and McGrattan 2006; Collin et al. 2007, 2008; Cheung 2009; Parent et al. 2016] is an obstacle to their extensive use in engineering calculations. The simplified approach developed by Dombrovsky et al. [2016a,b] is a promising alternative for practical applications. A computational study based on this approach enabled the authors to suggest the improved mist curtains with a variable size of supplied water droplets across the curtain. The model proposed in [Dombrovsky et al. 2016a] has been modified recently in [Dombrovsky et al. 2020a] as applied to large-scale fires by including a better approach for

evaporation of water droplets and extending the model for sea-water mist curtains. The latter is especially relevant for offshore platforms and maritime ships where sea water could be used as fire protection agent.

NOMENCLATURE			
a	radius of droplet	Greek symbols	
c	specific heat capacity	α	absorption coefficient
d	thickness of mist curtain	β	extinction coefficient
D	radiation diffusion coefficient	γ	coefficient in Eqs. (5b) and (14b,c)
F	function in Eqs. (6) and (7)	ε	emissivity
f_v	volume fraction of droplets or particles	η	dynamic viscosity
G	normalized irradiation	κ	index of absorption
H	height of the curtain	λ	wavelength
h	height of the non-equilibrium zone of the mist curtain	ξ	coefficient in Eq. (8)
I_b	Plank function for the intensity of blackbody radiation	ρ	density
L	latent heat of evaporation	σ	scattering coefficient
\dot{m}	mass flow rate of evaporation	Subscripts and superscripts	
n	index of refraction	a	absorption
q	radiative flux	air	air
Q	efficiency factor	b	blackbody
R	reflectance	f	flame
s	water salinity	fl	floor
St	Stokes number	inc	incident
t	time	max	maximum
T	temperature	nh	nozzle head
u	velocity	p	particle
W	absorbed radiation power	s	scattering
x	diffraction parameter	salt	salt
y	horizontal coordinate	tr	transport
z	vertical coordinate	w	water
		λ	spectral

The details of the combined heat transfer model for the mist curtains containing droplets of pure water or sea water including the kinetics of evaporation of droplets and the analysis of optical properties of water droplets and salt particles formed from the droplets of sea water can be found in [Dombrovsky et al. 2020a]. This material is not reproduced in the present paper. However, for convenience, a brief description of the general model is given below as well as the key differences with the present study. The present work is focused on the radiation problem and the relevant newly added modeling modifications, which make the problem statement closer to real engineering applications.

First of all, we consider two-layered mist curtains recommended by Dombrovsky et al. [2016a] (see Fig. 1) to decrease significantly the flow rate of supplied water with approximately the same radiation shielding effect as that in the case of a uniform curtain. **The vertical dashed line in Fig. 1 is not a real a boundary between noncontiguous layers. The real distance between these layers is not shown in this schematic figure.** It was shown that the use of smaller droplets in the back/shadow part of such “double-

layered” curtains can be recommended. This is explained by a different role of the absorption and scattering of incident radiation. Small droplets of size comparable with the radiation wavelength are characterized by strong wide-angle scattering as compared to large droplets with typical narrow-cone scattering near the forward direction [Bohren and Huffmann, 1983; Dombrovsky and Baillis, 2010]. However, the small droplets evaporate too rapidly to be placed near the irradiated (front) side of the mist curtain. Fortunately, the irradiation of water droplets decreases strongly with the distance from the directly irradiated side of the water mist curtain because of both absorption and scattering of radiation by the droplets. This enables one to decrease the size of supplied water droplets and their initial velocity with the distance from the front side of the curtain.

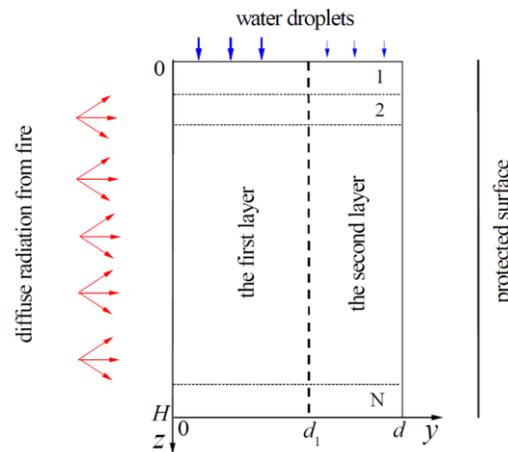


Figure 1. Scheme of irradiation of two-layered water mist curtain.

The use of small droplets in the back layer of the curtain appeared to be a good engineering choice. First of all, almost the same attenuation of the flame radiation can be reached by replacing the **back/shadow** part of the uniform curtain by a relatively thin second layer of the mist curtain containing slower moving small droplets. This is physically clear because of much stronger scattering of near-infrared radiation by relatively small droplets which are in the so-called Mie-scattering region characterized by moderate values of the diffraction parameter. As a result, the required total flowrate of supplied water decreases significantly. The second layer of the double-layered curtain should be placed at a distance from the **first/front** layer to minimize convective heat and mass transfer between the layers. This makes the design more flexible. In particular, the second nozzle head can be placed at a lower position than the first one. The latter is expected to be important to improve the shielding from the strong flame radiation in the lower part of the double-layered mist curtain.

A distance between two layers of the mist curtain makes no difference in propagation of thermal radiation through the double-layered curtain, and this distance is not a parameter of the radiative transfer problem to be solved. Therefore, the gap between the layers is not shown in Fig. 1. The exact distance between the flame of an unexpected fire and the nearest pre-installed nozzles to create a water mist curtain is difficult to estimate in advance simply because the exact location of a fire in practical

applications cannot be pre-determined. When designing the mist curtain, provided that the distance between the fire and the water curtain is much less than the height of the flame but sufficiently large to exclude the convective interaction between the fire and the mist curtain, the radiative heat transfer in the curtain will not depend on the distance from the fire. This distance is approximately 3 m for our radiation calculations. In this case, the radiative heat transfer in the curtain does not depend on the distance from the fire. It should be emphasized that the double-layered mist curtain is rather flexible engineering solution because of several additional parameters of the design. Of course, one cannot exclude possible use of the third layer of the mist curtain in some specific cases.

Another main difference between the present study and [Dombrovsky et al. 2020a] is the inclusion of realistic variations of the emitted power with the distance from the flame base. This variation normally depends on the nature and scale of fire and provides a more realistic incident radiation spectrum for the mist calculations. In the present paper, we limit our consideration to the case of large open hydrocarbon pool fires. These fires are also characterized by a strong re-absorption of radiation emitted in the internal region of the flame. The radiation is absorbed by relatively cooler molecular gases at the flame periphery and also by the surrounding air. In the case of large pool fires under consideration, a contribution of thermal radiation in spectral ranges outside the strong absorption bands to the total radiation power is significant to be attenuated by a mist curtain. Moreover, in the current work, the radiative heat losses to the spray nozzle head and to the floor under the curtain are estimated using 2-D radiative transfer calculations instead of a series of 1-D solutions across the mist curtain. Including these phenomena provides a more realistic representation of the real scenarios. The effect of a decrease in the downward velocity of air and suspended particles near the floor is also analyzed for the first time.

The above modifications of the problem statement affect the results of a comparison between the shielding properties of mist curtains composed of droplets of pure water and sea water. This comparison based on the improved computational model is the main objective of the present paper. It should be emphasized that a comparative computational analysis is used. As a result, a systematic/absolute error of a single calculation is not so important. Of course, the theoretical model should be physically sound for large-scale fires and water mist curtains to obtain the qualitatively correct results for the integral (over the spectrum) transmitted radiative flux.

It goes without saying that it would be good to minimize the systematic error of the model. This can be and should be done with the use of experimental studies of protective mist curtains for the large-scale open flames. To the best of our knowledge, there is no such data in the literature. Note that such an experimental work is beyond the scope of the present paper, but it would be really important to get the experimental data in a future work.

2. MATHEMATICAL FORMULATION OF THE COMBINED HEAT TRANSFER MODEL

The heat transfer model for water mist curtains is based on approach suggested recently by Dombrovsky et al. [2020a] and the main modifications of the model (aside of the two layers in the mist curtain) are in the radiative heat transfer problem. Therefore, the energy equation and the equations for evaporation of water droplets remain the same. As before, the isothermal droplets are considered by neglecting the relatively small effect of a nonuniform absorption of radiation in asymmetrically irradiated droplets (see [Dombrovsky 2004] for more details).

Assuming a constant downward velocity, u , of air with suspended evaporating water droplets, either the current time, t , or the vertical coordinate, z , measured from the upper initial cross section of the mist curtain (see Fig. 1) can be used as an independent variable in each of the equations (excluding those for the radiative transfer). In the case of pure water, the 1-D problem statement for the coupled equations and accompanying initial conditions can be written as follows:

$$(f_v \rho_w c_w + (1 - f_v) \rho_{\text{air}} c_{\text{air}}) u \frac{\partial T}{\partial z} = W - 3 f_v \dot{m} L / a \quad T(y, 0) = T_0 \quad (1)$$

$$\rho_w u \frac{\partial a}{\partial z} = -\dot{m} \quad a(y, 0) = a_0 \quad (2)$$

$$f_v = f_{v0} (a/a_0)^3 \quad (3)$$

A relatively small horizontal component of velocity of a gas and droplets in the mist curtain is neglected in the model. That is acceptable for large-scale curtains of the mist generated using many single nozzles. Note that there is no effect of horizontal widening of the mist curtain on radiative transfer across the curtain in the horizontal direction. **Our estimates have shown that the contribution of radiation absorption by water vapor between the droplets is insignificant compared to the absorption by numerous water droplets.** It is assumed also in Eq. (1) that water droplets and ambient air have the same velocity and temperature. This simplification follows the computational analysis reported by Dombrovsky et al. [2020a], where the motion and heating of single droplets in the upper part of the mist curtain was considered using the approach employed in [Hua et al. 2002, Dombrovsky et al. 2018a] (see also the book by Crowe et al. [2011]). It was shown that the relaxation time of water droplets is very small and both the dynamic and thermal non-equilibrium between the droplets and ambient air takes place only at small distances near the nozzle head. The height of the non-equilibrium zone of the curtain can be estimated as follows:

$$h = h_1 \frac{u_0}{u_{0,1}} \left(\frac{a_0}{a_{0,1}} \right)^2 \quad (4)$$

where $h_1 = 0.2\text{m}$, $u_{0,1} = 3\text{m/s}$, and $a_{0,1} = 100\mu\text{m}$. The physical sense of Eq. (4) is clear from the known expression for the Stokes number which is directly proportional to the relative velocity of a particle and to the squared particle size. Equation (4) gives $h = 0.4\text{m}$ even for $u_0 = 6\text{m/s}$ and $a_0 = a_{0,1}$. In the part of the mist curtain below the non-equilibrium height, one can use the same values of velocity and also temperature for the droplets and ambient air. Note that the equilibrium velocity used in the

calculations is much less than the initial velocity of water droplets. Obviously, the assumption of equilibrium between the droplets and ambient air is acceptable for large-scale fires only.

The first term on the right of Eq. (1) is the radiation power absorbed by the droplets and the second term is the heat consumption for droplet evaporation. The absorption of radiation by atmospheric gases in the mist curtain is relatively small as compared with the absorption by numerous water droplets or salt particles. Therefore, a contribution of gases to the absorption of the flame radiation in the mist curtain is neglected. The mass balance equation (2) describes a decrease in droplet radius with time due to evaporation of water. It is assumed that there is no fragmentation or coalescence of water droplets in the mist curtain, and the volume fraction of droplets is directly proportional to the volume of single droplets.

Almost all the quantities in Eqs. (1)–(3) depend not only on the vertical coordinate z measured from the conventional initial cross section of the mist curtain (near the nozzle exit, where the single spays cannot be distinguished) but also on the horizontal coordinate y measured from the front side of the curtain. However, the value of y is a parameter of the 1-D problem. The kinetic model of evaporation [Levashov and Kryukov, 2017; Levashov et al. 2018] is used to complete the problem statement, as it was done by Dombrovsky et al. [2020a,b,c]. A thin Knudsen layer on the droplet surface is taken into account in this model of evaporation.

As noted above, the velocity of droplet, u , is assumed to be constant along the mist curtain. It means that we focus on the central part of the mist curtain excluding the non-equilibrium flow in the upper part of the curtain and also in the lower part of the curtain (near the ground) where the flow pattern is relatively complex. The viscous boundary layers of the flow and the corresponding thermal boundary layers of the curtain are not considered as well. These assumptions lead to a systematic error of the calculations but do not affect the comparative study of mist curtains containing the droplets of pure water and sea water. The decrease in the downward velocity near the flow is taken into account in the last section of the paper.

In the case of sea water, the energy equation is similar to Eq. (1) up to the complete evaporation of water and formation of hollow salt particles. For salt particles, this equation is much simpler and there is no need in Eqs. (2) and (3) because there is no evaporation.

3. RADIATIVE HEAT TRANSFER MODEL

The propagation of a flame radiation through the mist curtain containing water droplets and salt particles which are formed after the total evaporation of sea water droplets is characterized by multiple interaction of radiation with single particles. As in many other cases, the complexity of the process does not mean that the computational procedure should be complicated and time-consuming. On the contrary, the physical degeneration of the problem can be used for considerable methodological simplifications based on multiple scattering. In our case, the details of single scattering are not important and one can use the

transport approximation when the scattering phase function is replaced by a sum of the isotropic part and the term responsible for the forward scattering [Dombrovsky 2012, 2019].

A significant optical density of mist curtains enables us to neglect the radiative heat transfer along the mist curtain (at least, in the regular calculations) and consider a set of 1-D problems for horizontal layers 1...N (see Fig. 1). This assumption will be examined in the last section of the paper. The other assumptions of the model are shown in Fig. 1. The mist curtain of constant thickness with the diffusely irradiated front side is considered. The latter makes the problem much simpler than the shielding of solar radiation by water mist [Dombrovsky et al. 2011] because there is no collimated radiation.

An accurate numerical solution to the radiative transfer equation (RTE) in scattering media is a very complicated task even in the case of transport approximation for single-scattering phase function. The main difficulty in solving the RTE is the angular dependence of the radiation intensity. Fortunately, this angular dependence is rather simple in many applied problems. This enables one to derive the so-called differential approximations. All the differential approximations are based on one or another analytical presentation of angular dependence of the radiation intensity. As a result, it is sufficient to consider a limited number of coordinate functions and turn to the coupled ordinary differential equations obtained by integration of RTE over the angle. It can be shown that the known two-flux approximation when the radiation intensity is presented in the form of two constant but different values in the forward and backward hemispheres is a good method for the problem to be solved. The boundary-value problem based on the two-flux approximation is as follows:

$$-\frac{d}{dy}\left(D_\lambda \frac{dG_\lambda}{dy}\right) + \alpha_\lambda G_\lambda = 0 \quad D_\lambda = 1/(4\beta_\lambda^{\text{tr}}) \quad (5a)$$

$$y = 0, \quad D_\lambda \frac{dG_\lambda}{dy} = \gamma_f (G_\lambda - 2)/2 \quad y = d, \quad D_\lambda \frac{dG_\lambda}{dy} = -G_\lambda/2 \quad (5b)$$

where $G_\lambda(y)$ is the normalized irradiation, D_λ is the radiation diffusion coefficient, and $\gamma_f = \varepsilon_f/(2 - \varepsilon_f)$. The problem (5a)–(5b) at arbitrary dependences of α_λ and $\beta_\lambda^{\text{tr}} = \alpha_\lambda + \sigma_\lambda^{\text{tr}}$ on coordinate y can be solved using the known numerical method. The integral radiative flux transmitted through the mist curtain, $q(d)$, and the profile of radiation power absorbed in the mist, $W(y)$, are respectively:

$$q(d) = 2\pi \int_0^\infty \bar{q}_\lambda F_\lambda d\lambda \quad \bar{q}_\lambda(d) = G_\lambda(d)/2 \quad (6)$$

$$W(y) = 2\pi \int_0^\infty \bar{w}_\lambda(y) F_\lambda d\lambda \quad \bar{w}_\lambda(y) = \alpha_\lambda(y) G_\lambda(y) \quad (7)$$

Note that the above radiative transfer problem is similar to that considered for a cloud of sublimated particles suggested to protect the solar probe from intense thermal radiation of the Sun [Dombrovsky et al. 2017]. However, the present problem is simpler because of negligible thermal radiation by water droplets.

It was assumed in [Dombrovsky et al. 2020a] that the spectrum of incident radiation is similar to that of the blackbody and the conventional temperature of the flame, T_f , is constant (independent of coordinate z). In this case, the spectral function F_λ is the Planck function at temperature T_f : $F_\lambda = I_b(T_f)$.

In the present paper, we consider both the realistic dependence of $T_f(z)$ and the re-absorption of the emitted thermal radiation in the main spectral bands of H_2O and CO_2 from large-scale hydrocarbon pool fires.

According to [Raj 2007a], the visible flame length of a large-scale buoyant diffusion hydrocarbon pool fire can be subdivided into three zones. In the first zone (persistent flame zone), near the fire base, the integral (over the spectrum) radiative flux from the flame is high and almost constant. In the second (intermittent) and third (plume) zones, the radiative flux decreases monotonically along the flame. The present study will focus on protection from intense thermal radiation coming from the first zone and the hot lower part of the second zone of a fire. The coordinate dependence of the incident radiative flux, $q_{inc}(z) = \pi \epsilon_f \int_0^\infty F_\lambda(z) d\lambda$, at the irradiated side of the mist curtain can be approximated as follows:

$$\bar{q}_{inc}(\bar{z}) = \begin{cases} 1, & \text{when } \bar{z} < 1 \\ \exp(-\xi(\bar{z} - 1)), & \text{when } 1 \leq \bar{z} < \bar{H} \end{cases}, \quad \bar{q}_{inc} = q_{inc}/q_{inc}^{(1)}, \quad \bar{z} = (H - z)/z_1, \quad \bar{H} = H/z_1 \quad (8)$$

where z_1 is the height of the first zone, $q_{inc}^{(1)}$ is the incident radiative flux in this zone, and H is the curtain height. The values of $\bar{H} = 10/3$ and $\xi = 0.3$ give sufficiently good approximation of the data reported in [Nédelka et al. 1989]. Note that the coordinate dependence (8) is reduced to the case of a uniform irradiation of the mist curtain in the case of $\xi = 0$. To analyze the effect of non-uniform irradiation of the mist curtain, it is natural to consider the same total irradiation:

$$\int_0^{\bar{H}} \bar{q}_{inc}(\bar{z}) d\bar{z} = \bar{q}_{inc}^{(0)} \bar{H} \quad \bar{q}_{inc}^{(0)} = q_{inc}^{(0)}/q_{inc}^{(1)} \quad (9)$$

where $q_{inc}^{(0)}$ is the constant integral radiative flux used in calculations of [Dombrovsky et al. 2020]. In our particular case of $\bar{H} = 1/\xi$, the following relation can be obtained from Eq. (9):

$$q_{inc}^{(1)} = q_{inc}^{(0)}/(1 + \xi - \exp(\xi - 1)) = 1.245 q_{inc}^{(0)} \quad (10)$$

The coordinate dependence of \bar{q}_{inc} used in the calculations is presented in Fig. 2.

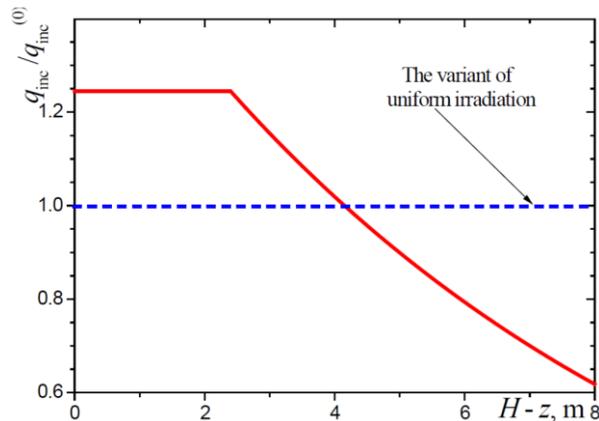


Figure 2. The coordinate dependence of incident radiative flux.

The experimental studies [Nédelka et al. 1989, Raj 2007b, Suo-Anttila et al. 2009, Erez et al. 2018, Parent et al. 2019] showed that thermal radiation of flames is far from being optically gray and the emission spectra are very different for small and large-scale flames. The re-absorption of thermal

radiation emitted in the internal part of a large flame is usually significant. This effect increases with the distance from the flame. However, the re-absorption is considerable even at distances about few meters from a conventional flame boundary. According to the data reported by Nédelka et al. [1989], the re-absorption of radiation is significant in two gas absorption bands: at the wavelengths about 2.7 μm and 4.3 μm . Therefore, we neglect thermal radiation in the ranges of $2.5 < \lambda < 2.9\mu\text{m}$ and $4.15 < \lambda < 4.45\mu\text{m}$ in subsequent spectral calculations to estimate the effect of infrared re-absorption of the flame radiation on shielding properties of water mist curtains for the spectral ranges outside these bands:

$$F_\lambda = \begin{cases} I_b(T_f), & \text{when } \lambda < 2.5 \mu\text{m}, 2.9 < \lambda < 4.15 \mu\text{m}, \text{ or } \lambda > 4.45 \mu\text{m} \\ 0, & \text{when } 2.5 < \lambda < 2.9 \mu\text{m} \text{ or } 4.15 < \lambda < 4.45 \mu\text{m} \end{cases} \quad (11)$$

To complete the radiative transfer model, one should consider the spectral radiative properties of mist curtains. Rigorously, the optical properties of the mist should be calculated taking into account the local size distribution of droplets or solid particles. Following [Dombrovsky et al. 2016a,b, 2020a], the monodisperse approximation when all the particles in a unit volume are assumed to have the same radius is used in the present study. In this case, the following equations are true for the absorption coefficient, α_λ , and transport scattering coefficient, $\sigma_\lambda^{\text{tr}}$:

$$\alpha_\lambda = 0.75f_v Q_a/a \quad \sigma_\lambda^{\text{tr}} = 0.75f_v Q_s^{\text{tr}}/a \quad (12)$$

where a is the particle radius, f_v is the local volume fraction of particles, Q_a and Q_s^{tr} are the dimensionless absorption efficiency factor and the transport efficiency factor of scattering to be calculated for single particles. Note that the present model is based on the hypothesis of independent scattering [Mishchenko 2014, 2018]. As to the monodisperse approximation considered instead of detailed calculations for one or another size distribution of droplets, it is known that this approach gives sufficiently accurate results for both absorption and scattering properties of the mist in the case when the so-called Sauter radius of droplets is used in the monodisperse calculations.

In the classical Mie theory for a homogeneous spherical particle, the complex index of refraction $m = n - i\kappa$, where n and κ are the spectral indices of refraction and absorption, is used to characterise optical properties of the particle substance. The other parameter of Mie theory (aside of spectral optical constants n and κ) is the diffraction parameter, $x = 2\pi a/\lambda$. The Mie theory is true for water droplets of arbitrary size but the spectral calculations for large water droplets are time-consuming. Therefore, the approximate expressions suggested by Dombrovsky [2002] for Q_a and Q_s^{tr} are used in subsequent calculations.

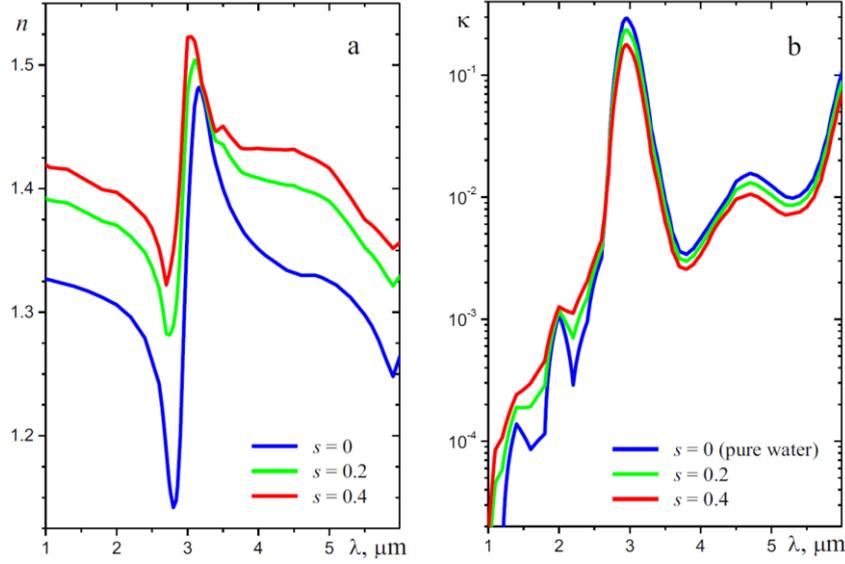


Figure 3. Indices of (a) refraction and (b) absorption of pure water and partially evaporated sea water.

The spectral optical constants of pure water reported by Hale and Querry [1973] and those suggested in [Dombrovsky et al. 2020a] for partially evaporated sea water are presented in Fig. 3. The value of n decreases with the salinity of water, s , defined as the relative mass of salt dissolved in water, whereas κ is almost the same for pure water and saline water. As a result, the droplets of pure water are characterized by a stronger scattering as compared to that of saline water, but the absorption is almost the same.

The current salinity of sea water droplets increases with water evaporation:

$$s(a) = s_0 \cdot (a_0/a)^3 \quad s_0 = s(a_0) \quad (13)$$

where s_0 is the initial salinity. It is assumed that the value of s cannot be greater than the salinity of a saturated solution of sea salt $s_{max}\%$ [Bharmoria et al. 2012]. The further process is accompanied by a relatively rapid formation of a hard salt crust on the surface of a liquid droplet [Cheng et al. 1988, Vehring et al. 2007, Fairhurst 2015]. Continued heating of salt water in the central part of the particle leads to an increase in steam pressure under the crust covering the particle. This pressure causes tensile stresses in the crust, which quickly leads to local destruction of the thin and fragile polycrystalline crust of sea salt. As soon as even a small hole appears in the crust, the steam pressure ejects the remaining salt solution from the particle. According to the model by Dombrovsky et al. [2020a], the fast process started from the salt crust formation on the droplet surface and finished by formation of a thin-walled hollow spherical particle of dry salt is not considered and the values of Q_a and Q_s^{tr} for hollow salt particles are be calculated using the generalized Mie theory for concentric core-mantle spherical particles. It was also shown that one can neglect the remaining salinity of water removed from the particle and subsequent formation of small particles of sea salt. The approximate spectral dependences of optical constants of sea salt presented in Fig. 4 are used in the calculations. Note that absorption and especially scattering of radiation by hollow salt particles contribute significantly to the attenuation of flame radiation.

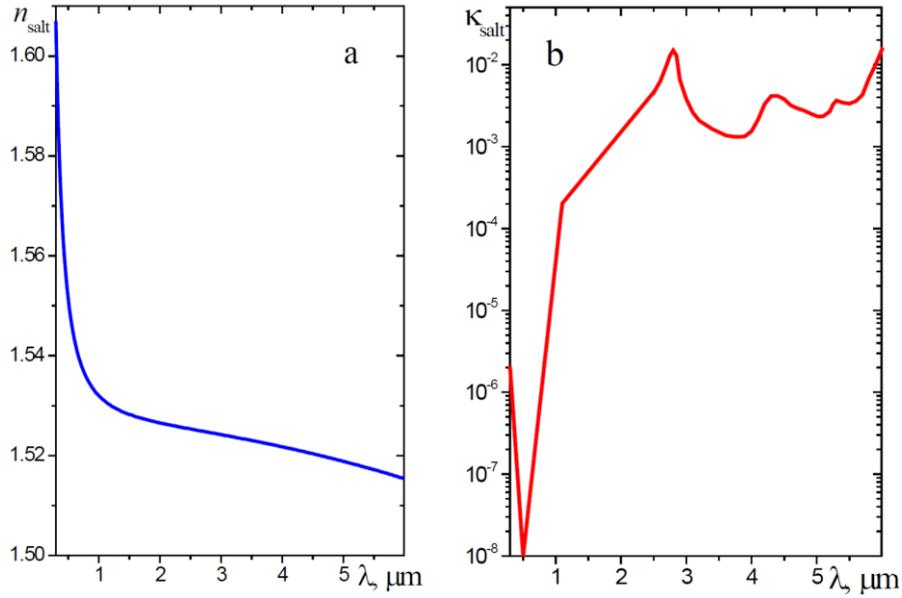


Figure 4. Indices of (a) refraction and (b) absorption of sea salt in the infrared.

4. NUMERICAL SOLUTION TO THE CASE PROBLEM

The case problem is concerned with a two-layer curtain. It may be better to call this “composite curtain” as a double-layered curtain because one should avoid direct contact between two parts of the curtain. The latter need is explained by the expected dynamic and thermal interaction of the neighboring flows with different sizes and velocities of water droplets. At the same time, the distance between two parts of the double-layered curtain makes no difference for the radiative transfer between them. Therefore, the radiative transfer problem can be considered as that for the conventional two-layered water mist curtain.

In the particular problem under consideration, the front part of the curtain of thickness $d_1 = 0.5\text{m}$ has the following initial parameters of water droplets: $a_0 = 100\mu\text{m}$, $u_0 = 2\text{m/s}$, $f_{v0} = 10^{-4}$. Both the initial size of water droplets and their initial velocity in the back layer of the curtain should be chosen less than the corresponding values in the front layer. The use of a relatively thin back layer containing slow moving droplets leads to the obvious economy in the flow rate of supplied water. To minimize the number of the problem parameters, it is assumed that the initial volume fraction of droplets, f_{v0} , is the same in both parts of the curtain, whereas the initial radius and velocity of droplets in the back layer of the curtain are taken equal to $a_{02} = 50\mu\text{m}$ and $u_{02} = 1\text{m/s}$. The role of the second layer thickness, d_2 , is considered in subsequent calculations. We use the constant value of the flame emissivity $\varepsilon_f = 0.9$, but the variable value of the local temperature, $T_f(z)$, of the flame. The coordinate variation of this temperature corresponds to the above discussed variation of the incident radiative flux (see Fig. 2). The re-absorption of radiation in the main infrared absorption bands of H_2O and CO_2 is also taken into account.

In all the variants, $N = 40$ horizontal layers were used in heat transfer calculations. The radiative heat transfer was calculated along the upper boundaries of every layer. The total amount of 80 intervals across

the curtain (along the horizontal layers) were used in radiative transfer calculations for the widest curtain, whereas 50 intervals were used for the thinnest mist curtain. The axial grid with the minimum of 200 intervals was used to solve the initial value problem in every of N layers along 81 vertical grid lines. It was numerically confirmed that such a discretization of the computational region is sufficient. The calculated fields of absorbed radiation power for two variants of thickness of the back layer of mist curtain containing pure water are presented in Fig. 5. The optical properties of the absorbing and scattering medium in the back layer of the curtain differ significantly from those of the medium in the first layer at the same height. Therefore, the dependence of the absorbed power on the horizontal coordinate is not continuous at the transition to the back layer. One can see that the back layer does not affect the maximum absorption of the external thermal radiation in the front layer of the curtain, but the additional attenuation of the incident radiation by the back layer is considerable. The latter is quite clear in Fig. 6a for the transmitted radiative flux. The relatively thin second layer of the curtain decreases strongly the transmitted radiative flux. It is reached at a small additional flow rate of supplied water. It is interesting that coordinate dependences of the transmitted radiative flux have a maximum at $z \approx 5.6\text{m}$, whereas the incident radiative flux is constant at $z > 5.6\text{m}$ (see Fig. 2). Note that the position of this maximum coincides with that of the maximum local absorption of radiation in the second layer (see the green region near the left boundary of the thin second layer in Fig. 5). The decrease in the transmitted radiative flux at $z > 5.6\text{m}$ is explained by the effect of radius of water droplets: small droplets scatter the radiation stronger than the large ones.

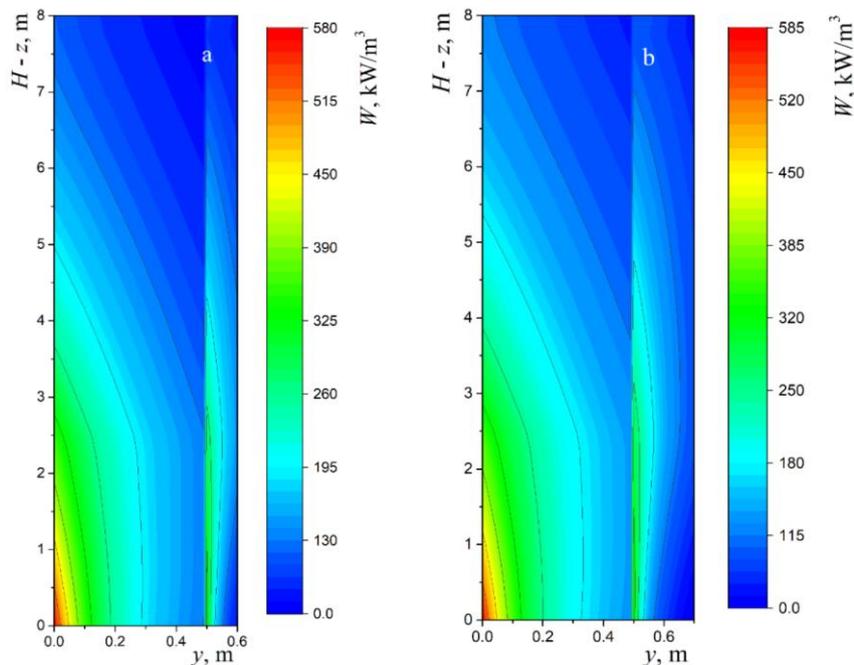


Figure 5. The radiation power absorbed in the mist curtain of pure water: a – $d_2 = 0.1\text{m}$, b – 0.2m . It is also important that the droplets of the second layer do not completely evaporate even near the boundary between two layers of the curtain (see curve A in Fig. 6b). This result does not depend on

thickness of this layer of the double-layered mist curtain. It means that both variants with $d_2 = 0.1\text{m}$ and $d_2 = 0.2\text{m}$ are acceptable for the attenuation of the flame radiation.

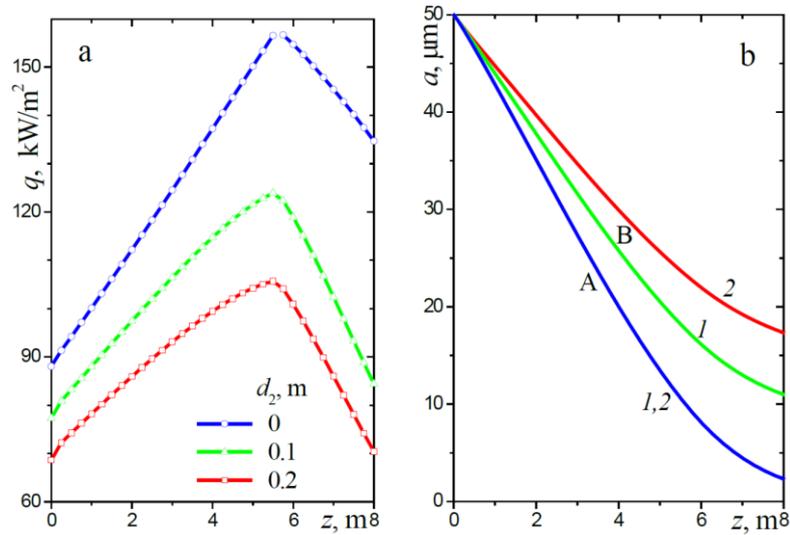


Figure 6. Numerical results for mist curtains of pure water: a – effect of the second layer on transmitted radiative flux, b – radius of water droplets in the second layer of the curtain (A – at the boundary between the layers, B – at the shadow side of the curtain; 1 – $d_2 = 0.1\text{m}$, 2 – 0.2m).

It is interesting to consider similar variants of a two-layered curtain for the mist containing salty sea water droplets. The typical fields of the absorbed radiation power are presented in Fig. 7.

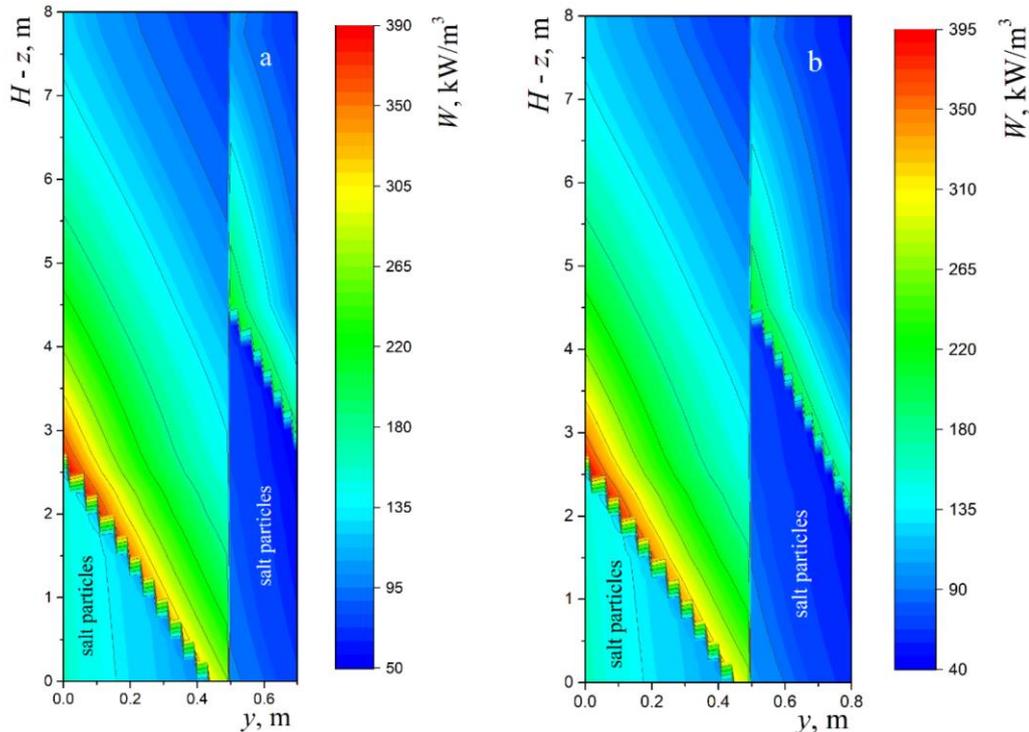


Figure 7. The radiation power absorbed in the mist curtain of sea water: a – $d_2 = 0.2\text{m}$, b – 0.3m .

As in the case of pure water, the back layer does not practically affect the absorption of radiation in the front layer of the curtain. The lines separating the zone of water evaporation from the lower part of the curtain containing only hollow particles of sea salt turned out to be zigzag due to an interpolation of the calculated node values of radiation power using standard software. In place of the zigzags there

should be smooth transition zones of a finite thickness, which is determined by the ejection time of a remaining salt water from a particle covered with a crust of sea salt. At the same time, the patterns in Fig. 7 are good illustrations of a lower part of a curtain formed by hollow particles of sea salt.

Figure 8 is more informative for the quantitative presentation of numerical data. The monotonic increasing the transmitted radiative flux in the downward direction is typical for sea-water mist curtains. This qualitative difference from the pure-water mist curtains is explained by the fact that the size of the formed hollow salt particles does not change over time. One can see in Fig. 8a that the thickening of the second layer increases significantly attenuation of the flame radiation by the curtain in its entire height. Fig. 8b plotted for the irradiated side of the curtain illustrates a transfer from the evaporation zone where the droplet radius decreases to the formation of solid crust on the particle surface. Note that this dependence of $a(z)$ does not depend of the second layer of the curtain. As one can expect, the thickness of a lower “dry” part of the curtain at the shadow surface decreases with the increase of the thickness of the second layer of the curtain (Fig. 8c). Note that constant minimum sizes of particles in Figs. 8b and 8c correspond to the formation of hollow salt particles.

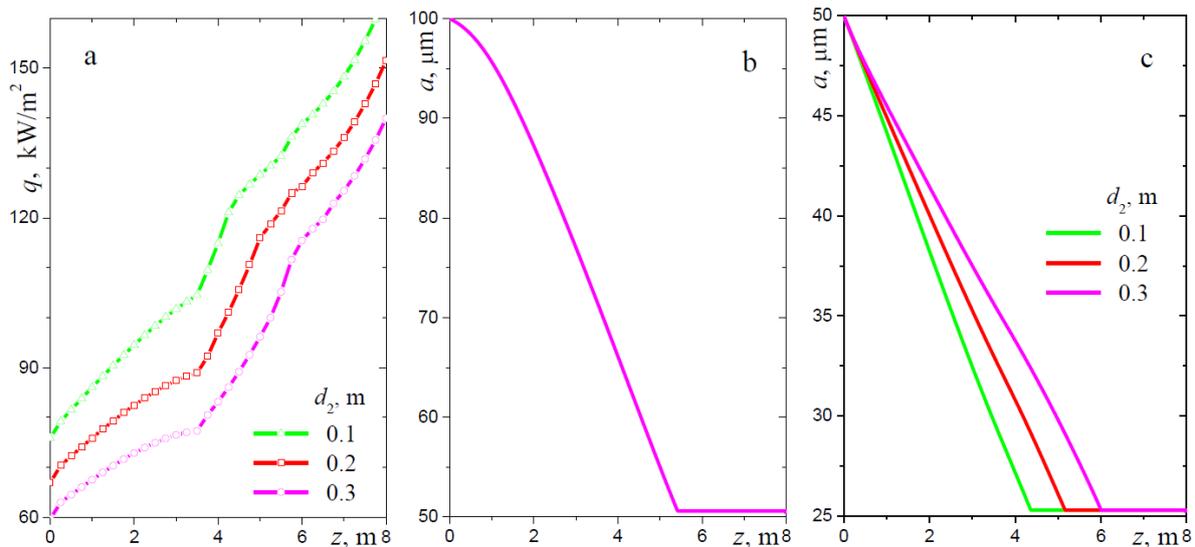


Figure 8. Numerical results for two-layered curtains of sea water: a – effect of the second layer on transmitted radiative flux, b, c – radius of particles at the irradiated surface (b) and at the shadow surface of the second layer (c).

In the case of a strong wind, it can be recommended to increase the flow rate of supplied sea water to minimize the thickness of the zone containing light-weight hollow salt particles. As a result, the sea water consumption required may turn out to be somewhat larger than the fresh water consumption.

5. ON THE APPLICABILITY OF LOCAL 1-D SOLUTIONS

All the above numerical results were obtained using the model based on a series of 1-D two-flux solutions for radiative transfer across the mist curtain. Strictly speaking, the two-flux approximation cannot be used to solve 2-D problems. However, one can consider the formulation of the P_1 boundary-value

problem for the normalized irradiation, $G_\lambda(y, z)$, with the radiation diffusion coefficient, D_λ , taken from the two-flux approximation [Dombrovsky and Baillis, 2010]:

$$\nabla \cdot (D_\lambda \nabla G_\lambda) - \alpha_\lambda G_\lambda = 0 \quad (14a)$$

$$y = 0, D_\lambda \frac{\partial G_\lambda}{\partial y} = \gamma_f \frac{G_\lambda - 2}{2} \quad y = d, D_\lambda \frac{\partial G_\lambda}{\partial y} = -\frac{G_\lambda}{2} \quad (14b)$$

$$z = 0, D_\lambda \frac{\partial G_\lambda}{\partial z} = \gamma_{nh} \frac{G_\lambda - 2}{2} \quad z = H, D_\lambda \frac{\partial G_\lambda}{\partial z} = -\gamma_{fl} \frac{G_\lambda - 2}{2} \quad (14c)$$

where $\gamma_{nh} = (1 - R_{nh})/(1 + R_{nh})$, $\gamma_{fl} = (1 - R_{fl})/(1 + R_{fl})$, and R_{fl} , R_{nh} are the values of reflectance of floor and nozzle head, respectively. The problem (14a-c) is reduced to the above considered 1-D problems in the case of negligible radiative transfer in z-direction (along the mist curtain). However, this simplification may lead to an overestimation of the transmitted radiative flux near the floor and the nozzle head because of the radiative heat losses at the lower and upper boundaries of the mist curtain. The maximum evaluation of this effect can be obtained for the case of a wide uniform curtain. Therefore, this variant for the mist curtain containing droplets of pure water is considered below. The calculations of [Dombrovsky et al. 2020a] are corrected by account for both the coordinate dependence of the flame radiation power and the re-absorption of radiation in spectral bands of gases.

Note that the error of diffusion-like approximations increases in 2-D problems near the corners of the computational region, but this error is not large in the case of an optically thick absorbing and scattering medium like that of the mist curtain. Therefore, our estimate is expected to be acceptable. The variational formulation and the finite element method were employed to solve numerically the 2-D radiative transfer problem. The details of the mathematical transformations and the computational procedure can be found in the book [Dombrovsky and Baillis, 2010]. A systematic error of numerical calculations is insignificant because of sufficiently detailed discretization of the computational region. In all cases, this error does not affect the comparison of solutions at different boundary conditions at two boundaries: $z = 0$ and $z = H$. The main difficulty of the general problem is the effect of absorbed radiation on the radius of evaporating droplets $a(y, z)$ and the resulting optical properties of the mist curtain. Fortunately, the estimates for the case problem showed that this feedback effect is insignificant and can be neglected. As a result, the computational procedure is similar to that used in the numerical study of thermal radiation in developing pool fires suppressed by a water spray [Dombrovsky et al. 2018b].

Some results of 2-D numerical solutions are presented in Fig. 9. In the radiative transfer calculations, the field of variable radius of water droplets and the corresponding spectral optical properties of the medium were used. The calculations were conducted for two variants: the reference calculation with “mirror” conditions at lower and upper boundaries of the curtain ($R_{nh} = R_{fl} = 1$) and the calculation for realistic case of $R_{nh} = 0.5$ and $R_{fl} = 0.2$. The reference variant neglects the radiative heat losses to the nozzle head (at $z = 0$) and also to the floor (at $z = H$).

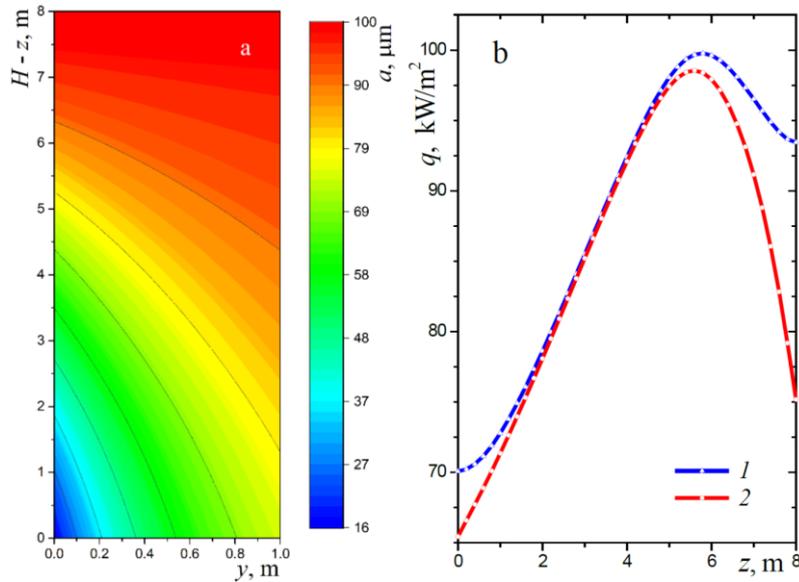


Figure 9. The field of radius of water droplets (a) and the transmitted radiative flux (b): $1 - R_{nh} = R_{fl} = 1$ (mirror conditions), $2 - R_{nh} = 0.5$ and $R_{fl} = 0.2$.

Fig. 9b shows that 2-D effects are considerable at distances of about 1m from the nozzle head and about 1.5 m from the floor. As one can expect, the radiative heat losses from the lower part of the curtain are more significant. However, the protective properties of mist curtains can be well predicted without account for these effects, and the upper estimate based on a set of 1-D solutions is quite correct even for the wide mist curtain considered in this example problem. The quality of the model based on 1-D solutions for radiative heat transfer across the curtain is better for the practically important case of a relatively thin double-layered curtain.

It should be recalled that the simple physical model under consideration has drawbacks not related to radiation transfer, but localized just in the upper and lower parts of the mist curtain. In particular, near the nozzle head there is no dynamic and thermal equilibrium between the water droplets and the surrounding air. However, the calculations by Dombrovsky et al. [2020a] showed that with the considered parameters of the problem, such an equilibrium is reached quite quickly: at distances of about 20 cm from the initial cross section of the mist curtain even for water droplets of radius 100 μm with initial velocity 3 m/s. A significantly larger mismatch between the actual gas flow with small droplets of water suspended in it and the theoretical model occurs in the lower part of the curtain. The fact is that the model used does not take into account the deceleration of gas flow near the floor under the curtain, as well as the associated increase in the role of natural convection. In general, more considerable methodological error in the calculations falls on the lower part of the mist curtain.

The mentioned error related with the deceleration of air flow can be calculated using the exact solution of the steady Navier–Stokes equations near the stagnation point. This solution is known as the two-dimensional Hiemenz stagnation flow [Batchelor 2000, Wang 2008]. In our case, it is not necessary to

consider thin viscous boundary layer at the floor surface [Schlichting and Gersten, 2017] and it is sufficient to account for the linear decrease of the downward velocity outside the boundary layer:

$$u = \frac{\pi}{4} \frac{H-z}{d} u_0 \quad z > z_* = H - 4d/\pi \quad (15)$$

As usually, the dynamic non-equilibrium between the particles and ambient air at $z > z_*$ can be characterized by the Stokes number defined as:

$$St = \frac{2}{9} \frac{\rho_p a^2}{\eta} \left| \frac{\partial u}{\partial z} \right|_{z=H} \quad (16)$$

where η is the dynamic viscosity of air and ρ_p is the volume-averaged density of the particle substance (the volume averaging is important for thin-walled particles of sea salt). It is known that only the particles with $St > St_* = 0.25$ deposit to the floor surface [Fuchs 1964, Soo 1989]. It is known that the viscous boundary layer increases the critical Stokes number, St_* . The estimates showed that water droplets of radius $a < 15\mu\text{m}$ and thin-walled salt particles in the lower part of the mist curtain satisfy the condition of $St < St_*$ and follow the gas flow even the case of a wide curtain with $d = 1\text{m}$. In other words, one can neglect the non-equilibrium of these particles and ambient air.

The results of calculations for the mist curtain containing droplets of pure water by account for the decrease of the downward velocity near the floor are presented in Fig. 10. As one can expect, the irradiation of slowly moving droplets results in their significant evaporation (compare Figs. 10a and 9a). This increases strongly the transparency of a lower part of the curtain (the curve B1 in Fig. 10b). However, there is a simultaneous increase in radiative heat losses to the floor (compare the curves A1 and B1). A comparison of curves B1 and B2 enables us to estimate the role of the radiation reflection from the nozzle head and from the flow. Of course, the variant B2 is more realistic one. As a result, the net effect of the flow deceleration near the obstacle is very small. In other words, neglecting both the flow deceleration and 2-D effects near the floor is acceptable for approximate calculations.

The mist curtain formed from sea water droplets is characterized by the quite different variation of the of the mist curtain transparency due to the flow deceleration. The hollow particles of sea salt do not evaporate but their volume fraction increases near the floor. As a result, the sea-water mist curtain is preferable as compared to pure-water curtain due to better protection from the fire radiation at small distances from the floor.

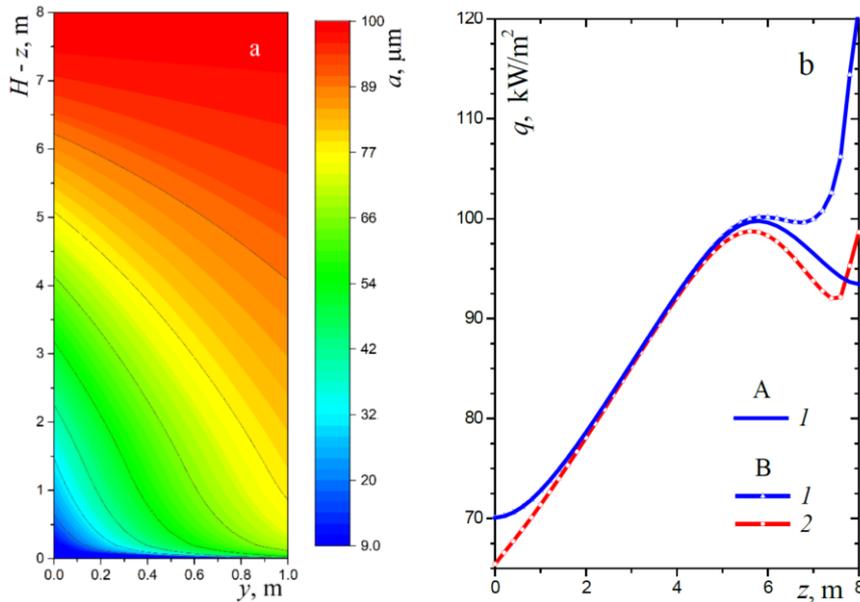


Figure 10. The field of radius of water droplets (a) and the transmitted radiative flux (b): 1 – $R_{nh} = R_{fl} = 1$ (mirror conditions), 2 – $R_{nh} = 0.5$ and $R_{fl} = 0.2$; A – calculations at constant velocity, B – calculations with account for the floor effect on decrease in the downward velocity.

6. CONCLUSIONS

An improved computational model suggested in the paper for the shielding of radiation from large-scale fires by the mists of pure water or sea water is developed for the case of double-layered mist curtains by account for the partial re-absorption of infrared radiation in the absorption bands of gases and the variation of the incident radiative flux along the flame. In addition, the radiative heat losses to the nozzle head and floor under the curtain are estimated for the first time using the 2-D calculations. The calculations for the pure-water curtain showed that the effect of decrease in the downward velocity near the floor on the transmitted radiative flux is compensated by the radiative heat losses to the floor.

The results obtained confirm that the use of smaller droplets of water in the second layer of a mist curtain reduces the total flow rate of supplied water at approximately the same attenuation of the flame radiation by the curtain. It was shown that one may need a little increase in consumption of water when sea water should be used instead of pure water and when there is a strong wind which can blow away the lower part of the curtain containing light-weight hollow particles of sea salt. However, the quality of sea-water curtain is almost the same as that of pure water. Moreover, the use of sea water is potentially preferable for better protection from the fire radiation in the lower part of the curtain. This can be treated as a confirmation that sea water can be used in coastal areas, offshore platforms or maritime transportation ships for the fire shielding curtains.

The quantitative analysis based on 2-D numerical solutions to the case problem of a large fire showed that radiative losses towards the floor and nozzle head are not significant even for thick water curtains and the developed computational model is sufficient to obtain a correct upper estimate of the transmitted radiative flux to the protected objects.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge The Leverhulme Trust (project VP2-2018-010) for the financial support of this work. The first author is grateful also for the financial support of the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. 075-1056-22-00).

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