SHIELDING OF FIRE RADIATION WITH THE USE OF MULTI-LAYERED WATER MIST CURTAINS: PRELIMINARY ESTIMATES

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ABSTRACT An approximate 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. An analysis of the example problem makes it possible to recommend a decrease in the size of supplied water droplets with the distance from the irradiated surface of the mist layer. This can be achieved with the use of multi-layered mist curtain. The advantage of this engineering solution is also confirmed by numerical calculations.

NOMENCLATURE

a	droplet radius	(μm)		*Greek symbols*	
d	thickness of the mist layer	(m)	α	absorption coefficient	(m^{-1})
D	radiation diffusion coefficient	(m)	β	extinction coefficient	(m^{-1})
c	heat capacity	(J kg^{-1}K^{-1})	γ, ξ	coefficients in Eq. (1a)	(-)
C	coefficient in Eq. (1a)	(-)	κ	index of absorption	(-)
f_v	volume fraction of droplets	(-)	ρ	density	(kg m^{-3})
F	droplet size distribution	(μm^{-1})	λ	wavelength	(μm)
H	height of the mist layer	(m)	σ	scattering coefficient	(m^{-1})
I	spectral radiation intensity	(W m^{-2} μm^{-1})		*Subscripts and superscripts*	
g	spectral irradiance	(W m^{-2} μm^{-1})	a	absorption	
m	complex index of refraction	(-)	b	blackbody	
n	index of refraction	(-)	g	gas	
q	spectral radiative flux	(Wm^{-2}μm^{-1})	rad	radiative	
Q	efficiency factor	(-)	s	scattering, saturation	
T	temperature	(K)	t	total (integral)	
x	diffraction parameter	(-)	tr	transport	
y, z	coordinates	(m)	w	water	

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INTRODUCTION

The radiation shielding applications using water mist curtains have received considerable attention of researchers working in the field of radiative and combined heat transfer. An overview of the earlier radiative transfer studies can be found in review paper by Sacadura (2005). Obviously, the oversimplified Beer–Lambert law used in (Ravigururajan and Beltran, 1989) is inapplicable for the transmittance calculations in the problem under consideration. Therefore, the two-flux model was employed in more recent papers (Copalle et al, 1993; Dembele et al, 2000; Buchlin, 2005; Tseng and Viskanta, 2007) for the transmittance calculations. These studies show that smaller droplets in high concentration provide better attenuation of the spray at the same volume fraction of water. However, the important 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, finite volume method and even Monte Carlo simulation were also used in computational models of water mists (Dembele et al, 1997; Berour et al, 2004; Collin et al, 2005, 2007, 2008, 2010; Boulet et al, 2006; Hostika and McGrattan, 2006). 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. The current literature clearly shows the advances in modelling and improving the understanding of water spray/mist curtain in fire radiation mitigation. However, the complexity of these models is a serious obstacle to the systematic analysis of various engineering solutions and the resulting practical recommendations. 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 objective of the present paper is two-fold: (1) to suggest a simplified but complete model for the combined heat transfer in a semi-transparent layer of water droplets used as a shield for radiation of fires and (2) to continue computational study of a recent work by the authors (Dombrovsky et al, 2016a) and outline some preliminary recommendations on possible use of multi-layered water mist curtains in engineering solutions for fire protection. The methodology of the presented study is based on a combination of a set of 1-D solutions for the radiative transfer problem and a simplified heat transfer model for heating and evaporation of water droplets. The theoretical analysis of the problem 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. The quality of the recommended multi-layered mist layer is estimated using a series of numerical calculations.

SPECTRAL PROPERTIES OF WATER DROPLETS

Both absorption and scattering of radiation by spherical water droplets can be calculated using the Mie theory (Bohren and Huffman, 1983; Hergert and Wriedt, 2012). Following (Dombrovsky et al, 2016a), only two dimensionless optical properties of particles are used: the efficiency factor of absorption, Q_{a}, and the transport efficiency factor of scattering, $Q_{\mathrm{s}}^{\mathrm{tr}}$. The values of Q_{a} and $Q_{\mathrm{s}}^{\mathrm{tr}}$ depend on both the complex index of refraction $m = n - \mathrm{i}\kappa$ and the diffraction (size) parameter $x = 2\pi a/\lambda$, where a is the droplet radius and λ is the radiation wavelength. Note that spectral indices of refraction and absorption, n and κ, of pure water are well known (Hale and Querry, 1973). The Mie calculations are time-consuming especially for large droplets with $x >> 1$. Therefore, according to (Dombrovsky et al, 2016a), the following analytical approximations suggested by Dombrovsky (2002) are used (see also monograph (Dombrovsky and Baillis, 2010):

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

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

These relations give sufficiently accurate results in the spectral range of a weak absorption (Dombrovsky et al, 2016a). An increasing error of Eq. (1a) for $Q_{\mathrm{s}}^{\mathrm{tr}}$ at the absorption band of water ($\lambda \approx 3\,\mu$m) is not important because $Q_{\mathrm{s}}^{\mathrm{tr}} << Q_{\mathrm{a}}$ in this spectral range.

The real mists contain water droplets of different sizes in every small volume of the mist. Therefore, the following relations for the spectral absorption coefficient and transport scattering coefficient of the mist (hereafter the subscript λ is omitted for brevity) are used:

$$\{\alpha, \sigma_{\mathrm{tr}}\} = 0.75\frac{f_{\mathrm{v}}}{a_{30}}\int_0^{\infty}\{Q_{\mathrm{a}}, Q_{\mathrm{s}}^{\mathrm{tr}}\}a^2 F(a)da \tag{2}$$

where f_{v} is the volume fraction of water droplets, $F(a)$ is the size distribution function, and

$$a_{\mathrm{ij}} = \int_0^{\infty} a^i F(a)da \Big/ \int_0^{\infty} a^j F(a)da \tag{3}$$

In the case of $i = j + 1$, the values of a_{ij} are the average radii of droplets. The integration according to Eq. (2) would strongly increase the computational time. Fortunately, the so-called monodisperse approximation when all the particles are assumed to have the same Sauter radius, a_{32}, is often applicable (Godoy and Des Jardin, 2007; Dombrovsky and Baillis, 2010):

$$\alpha = 0.75 f_{\mathrm{v}}\, Q_{\mathrm{a}} / a_{32} \qquad \sigma_{\mathrm{tr}} = 0.75 f_{\mathrm{v}}\, Q_{\mathrm{s}}^{\mathrm{tr}} / a_{32} \tag{4}$$

It should be noted that the above consideration is based on the widely used hypothesis of independent scattering (Mishchenko, 2014). It means that each droplet is assumed to absorb and scatter the radiation in exactly the same manner as if other droplets did not exist. In addition, there is no systematic phase relation between partial waves scattered by individual droplets during the observation time interval, so that the intensities of the partial waves can be added without regard to phase. In other words, each particle is in the far-field zones of all other particles, and scattering by individual particles is incoherent.

RADIATIVE TRANSFER MODEL

To choose relatively simple but physically sound radiative transfer model, consider the main characteristics of the real problem. First of all, the optical thickness of the mist layer should not be too small for a significant attenuation of the incident flame radiation. Therefore, the problem under consideration is characterized by multiple scattering at least in the range of water semi-transparency where the scattering cannot be neglected. In the case of multiple scattering, the details of scattering phase function are not important and one can use the transport approximation (Dombrovsky, 1996; Dombrovsky and Baillis, 2010; Dombrovsky and Lipiński, 2010; Dombrovsky, 2012).

It would be also good to use a set of local 1-D problems instead of much more complicated multi-dimensional radiative transfer problem. The use of 1-D solutions is not only the obvious way to simplify the mathematics. It is important that 1-D problems can be solved with sufficient accuracy using simple differential approximation without any additional computing overheads. Note that a similar approach based on a set of 1-D solutions in the case of relatively small 2-D effects has been recently used in (Dombrovsky et al, 2015, 2016b).

The schematic presentation of the problem in Fig. 1 makes clear some other assumptions of the computational model: (1) The mist of water droplets is generated by a set of nozzles at the top of the mist layer; (2) The flat mist layer of constant thickness is considered in the model; (3) One surface of the mist layer is diffusely irradiated by the flame which is also flat but a variation of radiative flux with the height is included in the model. We assume also that a protected wall is relatively cold and reflection of the radiation from the wall is negligible. An approximate radiative transfer model is used for several horizontal layers of the mist curtain. It is assumed that there is no radiative transfer between the neighboring layers. As a result, the radiation model is z-direction is similar to the Large-Cell Model suggested in (Dombrovsky, 2007) and employed in papers (Dombrovsky, 2009; Dombrovsky et al, 2009).

The polarization effects due to scattering of radiation by water droplets are negligible, and one can use the scalar radiative transfer theory. With the use of transport approximation, the 1-D radiative transfer equation (RTE) across the mist layer can be written as follows (Dombrovsky and Baillis, 2010; Howell et al, 2010; Modest, 2013):

$$\mu \frac{\partial I}{\partial y} + \beta_{\mathrm{tr}} I = \frac{\sigma_{\mathrm{tr}}}{2} \int_{-1}^{1} I(y,\mu) d\mu \qquad \mu = \cos\theta \qquad 0 < y < d \tag{5}$$

where $I(y,\mu)$ is the spectral radiation intensity at point y in direction μ (after the integration over the azimuth angles), $\beta_{\mathrm{tr}} = \alpha + \sigma_{\mathrm{tr}}$ is the transport extinction coefficient. The boundary conditions at two surfaces of the mist layer are written as follows:

$$I(0,\mu) = 2\pi\varepsilon_{\mathrm{f}} I_{\mathrm{b}}(T_{\mathrm{f}}) \qquad I(d,-\mu) = 0 \qquad \mu > 0 \tag{6}$$

where I_{b} is the Planck function. The above boundary condition at the irradiated surface of the mist denotes that we use the simplest assumption of an optically gray fire radiation. In other words, the external spectral radiative flux is assumed to be directly proportional to the blackbody radiation at temperature T_{f}. The coefficient ε_{f} is the conventional hemispherical emissivity of the flame. It means that integral radiative flux from unit surface area of the flame is expressed as follows:

$$q_{\mathrm{f}} = \varepsilon_{\mathrm{f}} \int_{0}^{\infty} \pi I_{\mathrm{b}}(T_{\mathrm{f}}) d\lambda = \varepsilon_{\mathrm{f}} \sigma_0 T_{\mathrm{f}}^4 \tag{7}$$

where σ_0 is the Stefan–Boltzmann constant. This approach is often used in engineering calculations of fire radiation (de Ris et al, 2000). It was shown in recent paper by Parent et al (2016) that assumption of optically gray flame radiation may lead to significant computational errors and the real emission spectrum should be taken into account. The physical explanation of this effect is the reabsorption of thermal radiation emitted by water vapor at the absorption band in a part of the mist layer containing significant volume fraction of steam. The latter can be done in the frame of the present approach, but this effect is not considered in the present paper.

The diffuse irradiation of the mist makes the problem much simpler than the problem of shielding of solar radiation by water mist considered by Dombrovsky et al (2011) because there is no need in a separate consideration of directed and diffuse radiation and the two-flux method can be employed immediately (not only to the diffuse component of the radiation field):

$$I(y,\mu) = 2\pi\varepsilon_{\mathrm{f}} I_{\mathrm{b}}(T_{\mathrm{f}}) \cdot \begin{cases} J^{-}(y), & \mu < 0 \\ J^{+}(y), & \mu > 0 \end{cases} \tag{8}$$

After integration of the RTE over two hemispheres, one can obtain the following boundary-value problem for the dimensionless spectral irradiance $g(y) = J^{-}(y) + J^{+}(y)$ (Dombrovsky and Baillis, 2010):

$$-(Dg')' + \alpha g = 0 \qquad D = 1/(4\beta_{\mathrm{tr}}) \tag{9a}$$

$$y = 0\,, \quad Dg' = (g-2)/2 \qquad y = d\,, \quad Dg' = -g/2 \tag{9b}$$

where $D = 1/(4\beta_{\mathrm{tr}})$ is the spectral radiation diffusion coefficient. The dimensionless spectral radiative flux from the shadow side of the mist layer is

$$\bar{q} = q(d)/[2\pi\varepsilon_{\mathrm{f}} I_{\mathrm{b}}(T_{\mathrm{f}})] = g(d)/2 \tag{10}$$

The normalized profile of integral (over the spectrum) radiation power absorbed in the mist and the integral transmitted radiative flux are determined as follows:

$$\overline{W}(y) = \int_0^\infty \overline{w}(y) d\lambda \qquad \overline{w}(y) = \alpha(y) g(y) \qquad q_{\mathrm{t}} = 2\pi\varepsilon_{\mathrm{f}} \int_0^\infty \bar{q} I_{\mathrm{b}}(T_{\mathrm{f}}) d\lambda \tag{11}$$

The radiative transfer calculations of (Dombrovsky et al, 2016a) showed that the mist containing relatively small droplets looks more promising because of greater attenuation of the flame radiation but the volumetric absorption of the radiation near the irradiated surface of the mist and small velocities of the falling droplets will lead to high rate of the mist evaporation. In the opposite case of very large droplets, the radiation is not practically reflected from the mist because of low transport scattering and a considerable attenuation of the fire radiation can be reached only in the case of a geometrically thick mist layer with high flow rate of water. Of course, the latter variant is also not the optimal one. Most likely, the droplets of an average size may be a good choice.

One should recall that thermal conditions near the irradiated surface of the mist and the conditions at the opposite shadow side of the mist are quite different. This makes interesting the use of more sophisticated engineering solution with a variable size of supplied water droplets across the mist layer. It is natural to have relatively large droplets at the irradiated side and much smaller droplets at the shadow side of the mist layer.

TRANSIENT HEAT TRANSFER MODEL

Strictly speaking, the heat transfer model for water mist exposed by thermal radiation from fire should be based on CFD modeling of the flow field and convective heat transfer in combination with radiative transfer modeling. The general problem is too complicated especially because of possible dynamic and thermal non-equilibrium of evaporating water droplets. On the other hand, the practical sense of detailed modeling is not obvious at the moment because of great uncertainty in many parameters of particular processes. Therefore, a simplified problem statement is considered without some details which can be ignored at this stage of the research.

First of all, it is assumed that the shape of the main stream region can be presented as a plane-parallel layer (see Fig. 1) and the effects of viscous interaction with ambient air can be ignored. Following the above principal suggestion and preliminary computational results of recent paper (Dombrovsky et al, 2016a) for the two-layers mist, we consider a multi-layered mist with droplet size decreasing from the flame side. For simplicity, the variation of size of water droplets is assumed to be linear. Some special features of the mist flow in the entrance region and also in the vicinity of the ground surface are not considered. This is a natural assumption because the region of the mist formation may be positioned at a greater height that the fire and the part of fire characterized by a significant thermal radiation is usually observed at some distance from the ground. In other words, we consider a middle part of the long mist layer. The following modes of heat transfer are included in the computational model: the heating of water droplets by external radiation from fire, partial evaporation of these droplets, and the downward flow of the mist. It is assumed that water droplets are isothermal and their temperature is the same as that of ambient gas. It means that radiation power is spent to heat both droplets and gas and also to evaporate the droplets. The simplest equilibrium evaporation model is considered and the evaporation at temperatures less than the saturation temperature at normal atmospheric conditions, $T_s = 373\,\text{K}$, is neglected. Possible overheating of water droplets is also not considered in the model. Strictly speaking, the assumption of negligible evaporation rate at $T < T_s$ is acceptable only in the case of 100% relative humidity of ambient air. The latter value is expected to be sufficiently high at every cross section of the quasi-steady water mist layer. Therefore, the simplified evaporation model is not expected to be critical for the reliability of the computational results. The recent paper by Talbot et al (2016) can be recommended to study the transient evaporation process of a spherical water droplet in more detail. The nonuniform volumetric heating of large water droplets and more accurate analysis of droplet evaporation in presence of thermal radiation are not considered in the present paper. The details of some comprehensive models can be found in the literature (Dombrovsky and Sazhin, 2004; Dombrovsky, 2004; Sazhin, 2006; Tseng and Viskanta, 2006; Miliauskas and Sabanas, 2006; Brewster, 2015). The evaporation is treated as the only effect resulting in a significant change of the droplet size. In other words, possible effects of agglomeration or fragmentation of droplets are also not considered.

In the case of negligible turbulent heat transfer across the mist layer, the approximate mathematical formulation of a heat transfer problem for every horizontal layer is as follows:

$$(\rho c)_{\mathrm{j}} u(y) \frac{T^*_{\mathrm{j+1}}(y) - T_{\mathrm{j}}(y)}{\Delta H} = W_{\mathrm{rad,j}}(y) \qquad T_1(y) = T_0 \qquad j = 1,\ldots, N-1 \tag{12a}$$

where

$$u(y) = u_1 - (u_1 - u_2)\, y/d \qquad (\rho c)_{\mathrm{j}} = (\rho c)_{\mathrm{g}} + f_{\mathrm{v,j}}(y)(\rho c)_{\mathrm{w}} \tag{12b}$$

Equation (11a) can be considered as a result of the use of an explicit finite-difference scheme for the obvious differential equation. In the case of $T^*_{\mathrm{j+1}}(y) \le T_{\mathrm{s}}$, the value of $T^*_{\mathrm{j+1}}$ is the real temperature and $T_{\mathrm{j+1}}(y) = T^*_{\mathrm{j+1}}(y)$. When the formal calculation gives $T^*_{\mathrm{j+1}}(y) > T_{\mathrm{s}}$, it is assumed that $T_{\mathrm{j+1}}(y) = T_{\mathrm{s}}$. As to the current volume fraction of water droplets, it can be estimated using the following relation:

$$f_{v,\mathrm{j+1}}(y) = f_{v,\mathrm{j}}(y)\left[1 - \rho_{\mathrm{g}} \frac{W_{\mathrm{rad,j}}(y)}{L} \frac{\Delta H}{u(y)} \frac{T^*_{\mathrm{j+1}} - T_{\mathrm{s}}}{T^*_{\mathrm{j+1}} - T_j}\right] \tag{13}$$

It was assumed that a variation of volumetric heat capacity of gas mixture due to evaporation of water is insignificant, the local volume fraction of water droplets is small ($f_{\mathrm{v,j}} << 1$), and the initial variation of the average radius of droplets across the mist layer can is described by the following linear function:

$$a_{32}(y) = a_{32}^{(1)} - \left(a_{32}^{(1)} - a_{32}^{(2)}\right) y/d \tag{14}$$

SOLUTION TO THE EXAMPLE PROBLEM

The following values of input parameters were used: $H = 10\,\mathrm{m}$, $d = 1\,\mathrm{m}$, $T_0 = 300\,\mathrm{K}$, $T_{\mathrm{f}} = 1500\,\mathrm{K}$, $\varepsilon_{\mathrm{f}} = 0.9$, $\rho_{\mathrm{w}} = 10^3\,\mathrm{kg\ m^{-3}}$, $\rho_{\mathrm{g}} = 1\,\mathrm{kg\ m^{-3}}$, $f_{\mathrm{v,1}} = 10^{-4}$, $c_{\mathrm{w}} = 4.18\,\mathrm{kJ\ kg^{-1}\ K^{-1}}$, $c_{\mathrm{g}} = 1\,\mathrm{kJ\ kg^{-1}\ K^{-1}}$, $L = 2.26\,\mathrm{MJ\ kg^{-1}}$. Note that the radiative flux from the flame is equal to $q_{\mathrm{t,inc}} = \varepsilon_{\mathrm{f}} \sigma_0 T_{\mathrm{f}}^4 = 258\,\mathrm{kW\ m^{-2}}$. Some results of calculations for the example problem are presented in Figs. 2 and 3.

One can see in Fig. 2 that sufficient protection with the use of a uniform mist layer (curve 2) is possible only in the case of relatively large droplets with radius about 100 μm and great water supply rate, whereas the same effect can be reached using the multi-layered mist curtain at much smaller flow rate values (curves 3 and 4, see the parameters for these curves in the figure caption).

The drawback of the mist layer containing relatively small droplets with radius about 30 μm is obvious from curve 1 in Fig. 3. These small droplets are evaporated too fast and cannot be used for radiation shielding in the case of a significant height of the flame. The latter is additionally confirmed by relatively high values of radiative flux at $z > 7\,\mathrm{m}$ for curve 1 in Fig. 2.

A general view of spatial variation for the volume fraction of water droplets is presented in Fig. 4. The decrease in the value of f_v in the lower part of the mist layer is explained by evaporation of water droplets. As one can expect, this effect is especially strong at the irradiated side of the mist layer.

One can see that the results obtained appear to be realistic and physically sound. At the same time, it should be recalled that the model developed is based on several assumptions, and some of them may lead to considerable quantitative errors. It would be good to obtain the experimental results for the multi-layered mist curtains and to suggest some corrections to the approximate computational model.

CONCLUSION

A simplified theoretical model for attenuation of fire radiation by water mist has been developed. This spectral model is based on the computed absorption and scattering characteristics of water droplets, the local 1-D solutions for radiative heat transfer through the mist layer, and transient heat transfer model taking into account heating and evaporation of the droplets. The example problem for the fire radiation protection by water mist showed that the suggested decrease in size of supplied water droplets with the distance from the hot side of the mist layer leads to a significant economy in the required water supply rate.

The model developed is based on several assumptions, and some of them may lead to considerable quantitative errors. Therefore, an experimental study of the suggested multi-layered mist curtains is recommended to examine the predicted advantages of this engineering solution and to correct the approximate computational model.

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Figure captions

Figure 1. Scheme of the problem.

Figure 2. Radiative flux transmitted through the water mist layer: *1* – $a_{32}^{(1)} = a_{32}^{(2)} = 30\,\mu\text{m}$, $u_1 = u_2 = 0.2\,\text{m s}^{-1}$; *2* – $a_{32}^{(1)} = a_{32}^{(2)} = 100\,\mu\text{m}$, $u_1 = u_2 = 3\,\text{m s}^{-1}$; *3* – $a_{32}^{(1)} = 100\,\mu\text{m}$, $a_{32}^{(2)} = 30\,\mu\text{m}$, $u_1 = 3\,\text{m s}^{-1}$, $u_2 = 0.2\,\text{m s}^{-1}$; *4* – $a_{32}^{(1)} = 60\,\mu\text{m}$, $a_{32}^{(2)} = 30\,\mu\text{m}$, $u_1 = 1\,\text{m s}^{-1}$, $u_2 = 0.2\,\text{m s}^{-1}$.

Figure 3. Volume fraction of water at the lower cross section of the mist layer. The designations see in Fig. 2.

Figure 4. Volume fraction of water in the computational region. Calculations for the variant of $a_{32}^{(1)} = 60\,\mu\text{m}$, $a_{32}^{(2)} = 30\,\mu\text{m}$, $u_1 = 1\,\text{m s}^{-1}$, and $u_2 = 0.2\,\text{m s}^{-1}$ (variant 4 in Figs. 2 and 3).

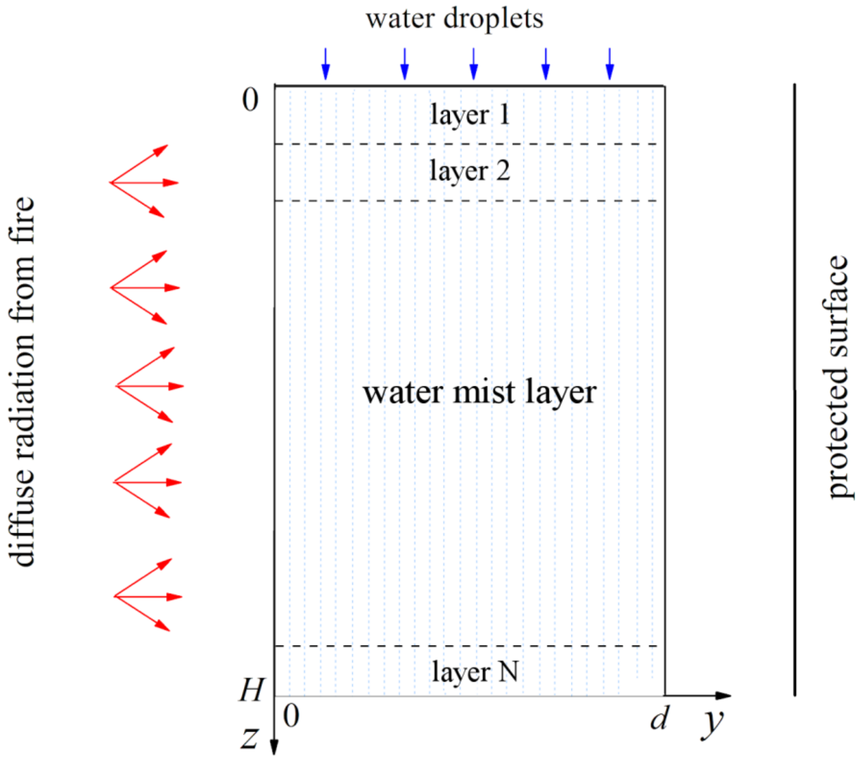

water droplets
0
layer 1
layer 2
diffuse radiation from fire
water mist layer
protected surface
layer N
H
0
z
d
y

Figure 1

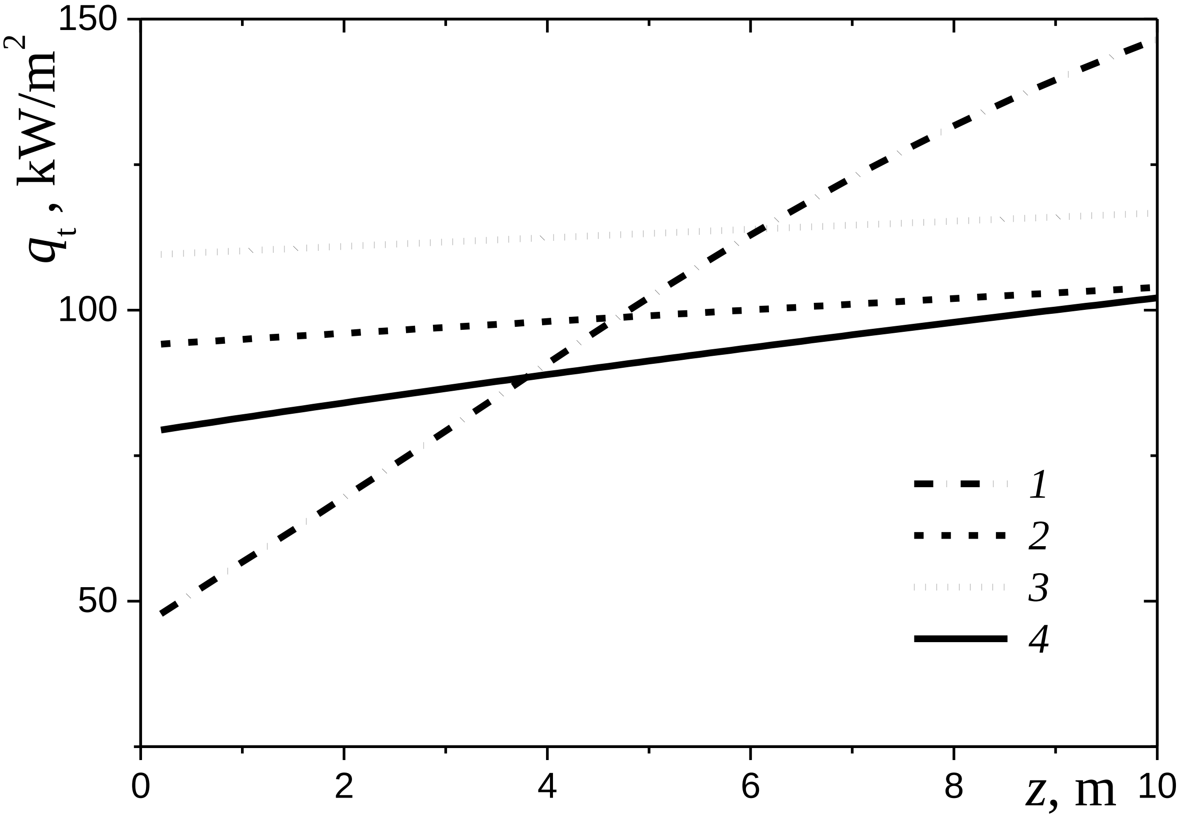


Figure 2

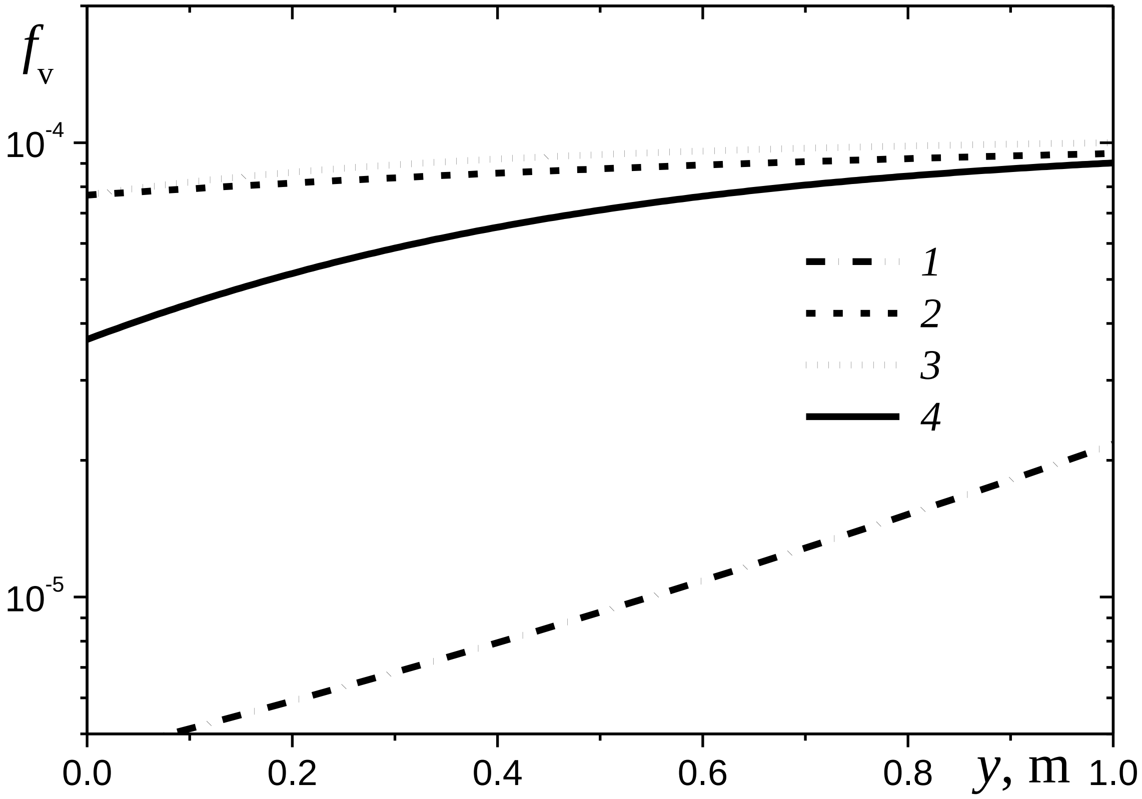
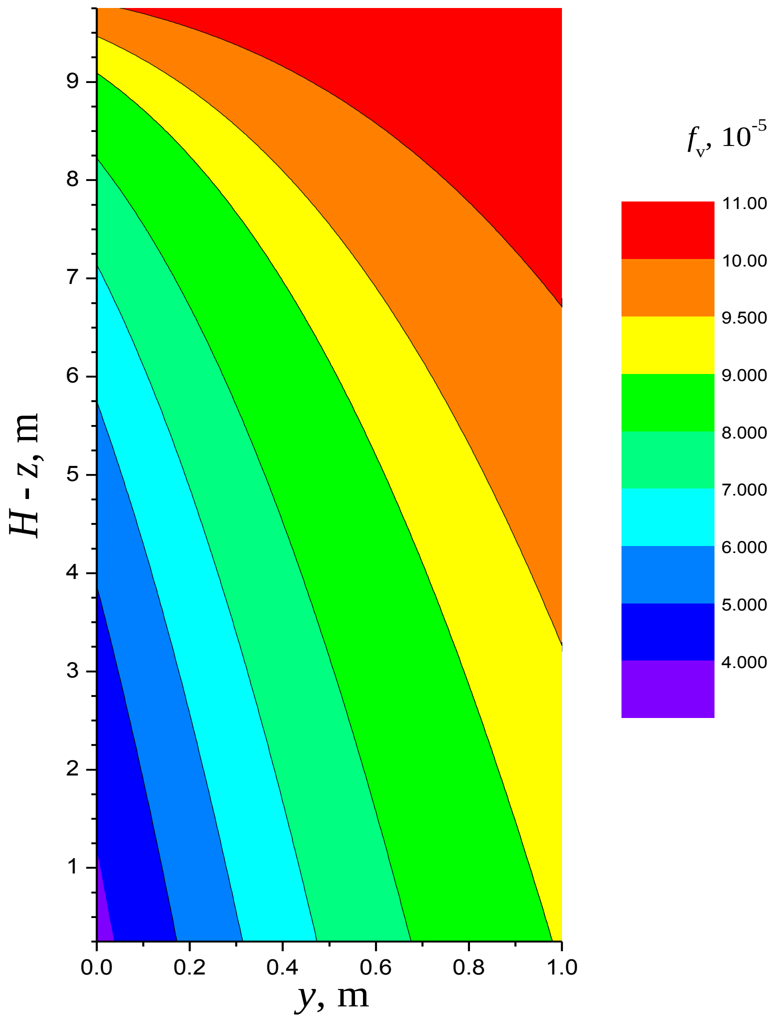


Figure 3



f_v, 10^{-5}
11.00
10.00
9.500
9.000
8.000
7.000
6.000
5.000
4.000
H - z, m
y, m
0.0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5
6
7
8
9

Figure 4