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Heat transfer by radiation from a hot particle to ambient water through the vapor layer

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Abstract

Heat transfer by thermal radiation from a hot spherical particle to ambient water through the concentric vapor shell is analyzed by the use of different theoretical models. In the case of the vapor layer thickness Δ comparable with the radiation wavelength, the wave effects are taken into account. For greater values of Δ, the problem solution is derived by combination of the Mie theory for the particle emissivity, the Fresnel's equations for radiation reflection/refraction on the vapor–water interface, and the radiation transfer equation for calculation of heat absorption profiles in water. A justified approximate description of the radiation heat transfer between corium melt particles and boiling water, as applied to vapor explosion analysis in the case of nuclear reactor severe accident, is proposed. Numerical examples illustrate effects of the particle size and the vapor shell thickness. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Heat; Radiation; Particle; Wave effects

1. Introduction

Theoretical investigation of the core melt interaction with ambient water in the case of nuclear reactor severe accident is a very important up-to-date problem [1]. At the same time, the existing physical models of the thermal interaction of small single droplet of the melt with boiling water donot take into account heat transfer by thermal radiation which may be considerable due to very high temperature of the melt (~3000 K) [1,2]. Note that in the case of experimental simulation of vapor explosion, which is often performed at a low temperature and in the presence of other substances, one must likewise analyze the differences between the simulated and full-scale conditions of radiation heat transfer.

Because of the inertia of liquid, the vapor envelope of a hot particle is subjected to high-frequency oscillation and, in some cases, it may collapse, which leads to a small-scale vapor explosion. In doing so, the vapor shell thickness at different stages of the process may range from several to hundreds of microns [2]. Obviously, the radiative flux is less sensitive to the variation of the shell thickness than the heat flux due to thermal conductivity of vapor. As a result, thermal radiation effects the average intensity of heat transfer from a particle to liquid and has a damping effect on the oscillation of the vapor envelope of the particle. The wide range of variation of the vapor shell thickness necessitates the development of a rather general theoretical description of the radiation transfer.

The objective of this paper is to present theoretical models for calculating the radiative heat flux from a

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Nomenclature

a	particle radius
a_k, b_k, c_k, d_k	mathematical functions, Eq. (3)
B_λ	Planck's function
	$i = \sqrt{-1}$
K	coefficient, Eq. (19)
m	complex index of refraction
n	index of refraction
P	specific absorbed power
q	specific radiative flux
Q	dimensionless integral absorption function, Eq. (12)
Q_a	absorption efficiency factor
r	radial coordinate
r_0	particle radius
Δr	distance from the vapor–water interface
R	Fresnel's reflection coefficient
s	distance along the ray
T	temperature
u_k, v_k	mathematical functions, Eq. (3)
W	dimensionless absorption function, Eq. (9)
x	diffraction parameter of the particle
y	diffraction parameter of the cavity
z	complex variable, Eq. (4)

Greek symbols

α_k, β_k, ζ_k	mathematical functions, Eq. (4)
γ	relative radius of the vapor–water interface
δ	relative thickness of the vapor layer
Δ	thickness of the vapor layer
ε	effective emissivity
κ	index of absorption
λ	radiation wavelength
μ	angular variable, Eqs. (8) and (9)
Σ_a	absorption coefficient
φ_k	mathematical function, Eq. (4)
ψ_k, ζ_k	Riccati–Bessel functions

Subscripts

1, 2	options
e	external
i	interface
k	order of mathematical functions
m	black-body radiation maximum
λ	spectral dependent
$*$	limiting value

hot particle through the vapor shell and also the distribution of the absorbed radiation power in surrounding water. The following special physical features of the problem are taken into account:

- the geometrical optics approximation is incorrect for small thickness of the vapor layer Δ, in the case of $\Delta \sim \lambda$ (λ is the characteristic wavelength of the thermal radiation) the wave effects take place;
- because of the specific spectral dependence of the water absorption index, the short-wave infrared radiation penetrates deep into water whereas the long-wave radiation is absorbed in very thin water layer near the vapor–water interface.

The physical models being treated and the mathematics employed are fairly general. At the same time, the performed numerical analysis is restricted with respect to the optical properties of the materials: the interaction between molten oxide particles and water is treated, which is of most interest as regards the safety of nuclear reactors.

Having in mind that calculation of the radiation heat transfer is only one part of a general multiphase flow model, special attention is given to approximate computational procedures.

2. General wave solution for radiative flux

We consider a single spherical particle of radius r_0 in a concentric cavity of radius r_i. The particle and water in the volume $r_i < r < \infty$ are isothermal, their temperatures are equal to T_0 and T_e ($T_0 > T_e$) correspondingly, complex indices of refraction, $m = n - i\kappa$ and $m_e = n_e - i\kappa_e$. The specific spectral radiative flux on the particle surface is defined as follows:

$$q_\lambda = \varepsilon_\lambda \pi \left[B_\lambda(T_0) - B_\lambda(T_e) \right] \tag{1}$$

where the function $\varepsilon_\lambda(x, y, m, m_e)$ is the spectral emissivity of the system "particle–cavity", the diffraction parameter of the particle and that of the cavity are defined as usually:

$$x = 2\pi r_0/\lambda \qquad y = 2\pi r_i/\lambda \tag{2}$$

The general solution to the problem under consideration at arbitrary values of parameters may be derived by use of the fluctuation–dissipation theorem [3]. Similar solutions for narrow clearance and layered structures are employed in radiation heat transfer calculations in microscale electronics when the wave effects prove very significant [4,5]. For a single spherical particle in a concentric cavity, the analytical solution for the spectral emissivity ε_λ was derived in papers [6,7]. This solution may be written using the notations of the Mie theory [8] in the following form:

$$\varepsilon_\lambda = -\frac{2}{x^2}\sum_{k=1}^{\infty}(2k+1) \times \left\{ \frac{\mathrm{Im}\big[m\alpha_k(mx)\big]\mathrm{Im}\big[m_e\beta_k(m_e y)\big]}{|a_k u_k - b_k/u_k + a_k b_k v_k|^2} + \frac{\mathrm{Im}\big[m^*\alpha_k(mx)\big]\mathrm{Im}\big[m_e^*\beta_k(m_e y)\big]}{|m_e c_k u_k - m d_k/u_k - c_k d_k v_k|^2} \right\} \tag{3}$$

$$a_k = m\alpha_k(mx) - \alpha_k(x)$$

$$b_k = m_e\beta_k(m_e y) - \alpha_k(y)$$

$$c_k = m\alpha_k(x) - \alpha_k(mx)$$

$$d_k = m_e\alpha_k(y) - \beta_k(m_e y)$$

$$u_k = \psi_k(x)/\psi_k(y)$$

$$v_k = \psi_k(y)\varphi_k(x) - \psi_k(x)\varphi_k(y)$$

Here

$$\alpha_k(z) = \psi_k'(z)/\psi_k(z), \quad \beta_k(z) = \zeta_k'(z)/\zeta_k(z), \quad \zeta_k(z) = \psi_k(z) + i\varphi_k(z) \tag{4}$$

ψ_k, ζ_k are the Riccati–Bessel functions.

Note that in the special case of nonabsorbing medium ($\kappa_e = 0$), the known solution for radiation absorption by a two-layer spherical particle in vacuum [8,9] may be used and the spectral emissivity is calculated as follows:

$$\varepsilon_\lambda = n_e^2\gamma^2 Q_a \tag{5}$$

where $\gamma = r_i/r_0 = y/x$, Q_a is the efficiency factor of absorption for a two-layer particle, which consists of the kernel with the diffraction parameter $x' = n_e x$ and the complex refractive index $m' = m/n_e$ and of the nonabsorbing shell with the diffraction parameter $x'' = n_e y$ and the index of refraction $n'' = 1/n_e$ [10]. One can see that in the absence of the vapor layer between the particle and water ($\gamma = 1$), the value of ε_λ proves to be n_e^2 times greater than the value $\varepsilon_\lambda^{(0)}$ for the same particle in vacuum.

3. Solution for large thickness of vapor layer

3.1. Radiative flux and heat absorption profile

In the case of large thickness of the vapor shell (in comparison with the wavelength), the particle emissivity does not depend on the optical constants of water. Note that in the case of $m_e = 1$, $\gamma = 1$ one can derive from the general equation (3), the following relation for spectral emissivity of a single particle [11,12]:

$$\varepsilon_\lambda^{(0)} = \frac{2}{x^2}\sum_{k=1}^{\infty}\frac{2k+1}{|\zeta_k(x)|^2}\left\{ \frac{\mathrm{Im}\big[m\alpha_k(mx)\big]}{|\beta_k(x) - m\alpha_k(mx)|^2} + \frac{\mathrm{Im}\big[m^*\alpha_k(mx)\big]}{|m\beta_k(x) - \alpha_k(mx)|^2} \right\} \tag{6}$$

The quantity derived by Eq. (6) is nothing but the absorption efficiency factor $Q_a(x, m)$ for a single spherical particle in the Mie theory [11].

The spectral emissivity of the system particle–water in the case of negligible wave effects may be calculated by the regular formula

$$\varepsilon_\lambda = \frac{1}{1/\varepsilon_\lambda^{(0)} + \left(1/\varepsilon_\lambda^{(i)} - 1\right)/\gamma^2} \tag{7}$$

where varepsilon $\varepsilon_\lambda^{(i)}$ is the hemispherical emissivity of the water surface. The latter value is determined using the Fresnel equations for unpolarized radiation [13]:

$$\varepsilon_\lambda^{(i)} = 2n_e^2\int_{\mu_i}^{1}\big[1 - R(\mu)\big]\mu\,\mathrm{d}\mu, \quad \mu_i = \sqrt{1 - 1/n_e^2},$$

$$R = \frac{1}{2}\left[\left(\frac{\mu - n_e s}{\mu + n_e s}\right)^2 + \left(\frac{n_e\mu - s}{n_e\mu + s}\right)^2\right], \quad s = \sqrt{1 - n_e^2\left(1 - \mu^2\right)} \tag{8}$$

Note that $1 - \varepsilon_\lambda^{(i)} \ll 1$, and therefore one can use the approximate equality $\varepsilon_\lambda \approx \varepsilon_\lambda^{(0)}$ even for not so large values of γ.

From the known value of the spectral radiative flux on the particle surface, one can calculate the radial profile of heat absorption in surrounding water. In doing so, one must keep in mind that radiation intensity in the region $r > r_i$ is not isotropic, but the radiation is concentrated in a solid angle, whose magnitude depends on the geometric parameter γ and on the index of refraction n_e. Having in mind that reflection of the thermal radiation from the vapor–water interface is small, the heat absorption profile may be characterized by the following dimensionless function:

$$W_\lambda(r) = \int_{\mu_*}^{1} \exp\left[-\Sigma_a s(r,\mu)\right] \mathrm{d}\mu, \quad \Sigma_a = 4\pi\kappa_e/\lambda$$

$$\mu_* = \sqrt{1-\left(\frac{r_0}{n_e r}\right)^2}, \quad s = \mu r - \sqrt{r_i^2 - r^2\left(1-\mu^2\right)}, \tag{9}$$

(Σ_a is the spectral absorption coefficient of water) and the specific power of absorbed radiation is determined by integration over the spectrum:

$$P(r) = 2\int_0^\infty n_e^2 \Sigma_a q_\lambda W_\lambda(r)\,\mathrm{d}\lambda \tag{10}$$

Note that the following energy balance equation takes place:

$$\int_{r_i}^\infty P(r) r^2\,\mathrm{d}r = q r_0^2, \quad q = \int_0^\infty q_\lambda\,\mathrm{d}\lambda \tag{11}$$

where q is the integral radiative flux on the particle surface, and it is convenient to use the dimensionless function, which characterizes a part of the integral radiative flux absorbed in the spherical water layer (r_i, r):

$$Q(r) = \frac{1}{q r_0^2}\int_{r_i}^{r} P(r) r^2\,\mathrm{d}r \tag{12}$$

4. Optical properties of substances

A review of the literature failed to yield the spectral optical constants $n(\lambda)$, $\kappa(\lambda)$ not only for the core melt but also for molten pure UO_2. The only approximation for uranium oxide has been proposed in paper [14]: index of refraction $n = 2.3$ (independent of wavelength) and the Rosseland averaged absorption coefficient $\Sigma_a = 50\ \mathrm{cm}^{-1}$ for the temperature interval from 3138 to 3760 K. The quantity Σ_a is related to the index of absorption used in the present paper by the following equation:

$$\Sigma_a = \frac{4\pi \displaystyle\int_0^\infty \frac{\partial B_\lambda(T)}{\partial T}\,\mathrm{d}\lambda}{\displaystyle\int_0^\infty \frac{\lambda}{\kappa}\frac{\partial B_\lambda(T)}{\partial T}\,\mathrm{d}\lambda} \approx 4\pi\kappa_m/\lambda_m \tag{13}$$

where one can assume $\lambda_m = 1.1$ μm for estimating the average absorption index κ_m. It is important that the value of $\kappa_m \approx 4\times10^{-4}$ from Eq. (13) is typical for metal oxides in the near infrared.

In this paper, we also use the constant value of $n = 2.3$. To determine the role of this parameter some additional calculations were performed for variable $n(\lambda)$ as that for aluminum oxide at 3000 K [9]. Two options are treated for the oxide index of absorption, namely, option 1 with a pronounced region of semitransparency in the near infrared (as for molten Al_2O_3) and option 2 with stronger absorption. The corresponding relations are [9]:

$$\begin{aligned} \kappa_1 &= \kappa_2 - 0.006\lambda/\left(\lambda^2+1\right) \\ \kappa_2 &= 0.002\left(0.06\lambda^2 + 0.7\lambda + 1\right) \end{aligned} \tag{14}$$

where λ is expressed in microns. A difference between

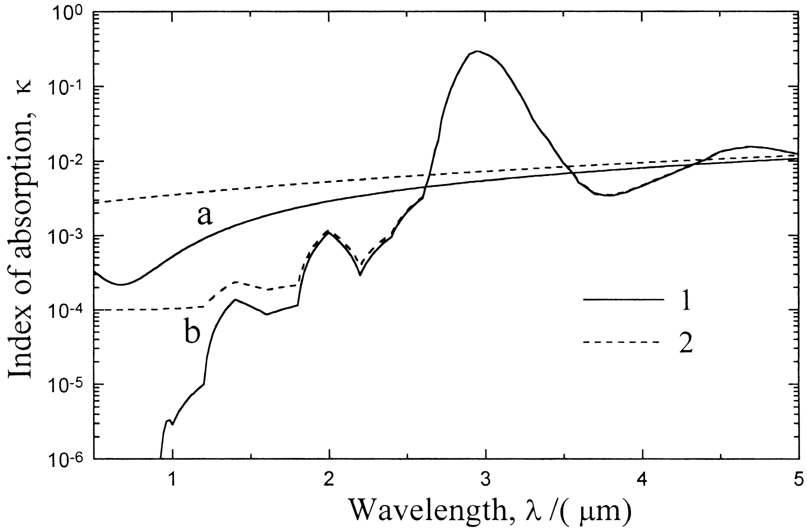

Fig. 1. The spectral absorption indexes of oxide (a) and water (b), as used in the calculations; 1, 2 — numbers of options.

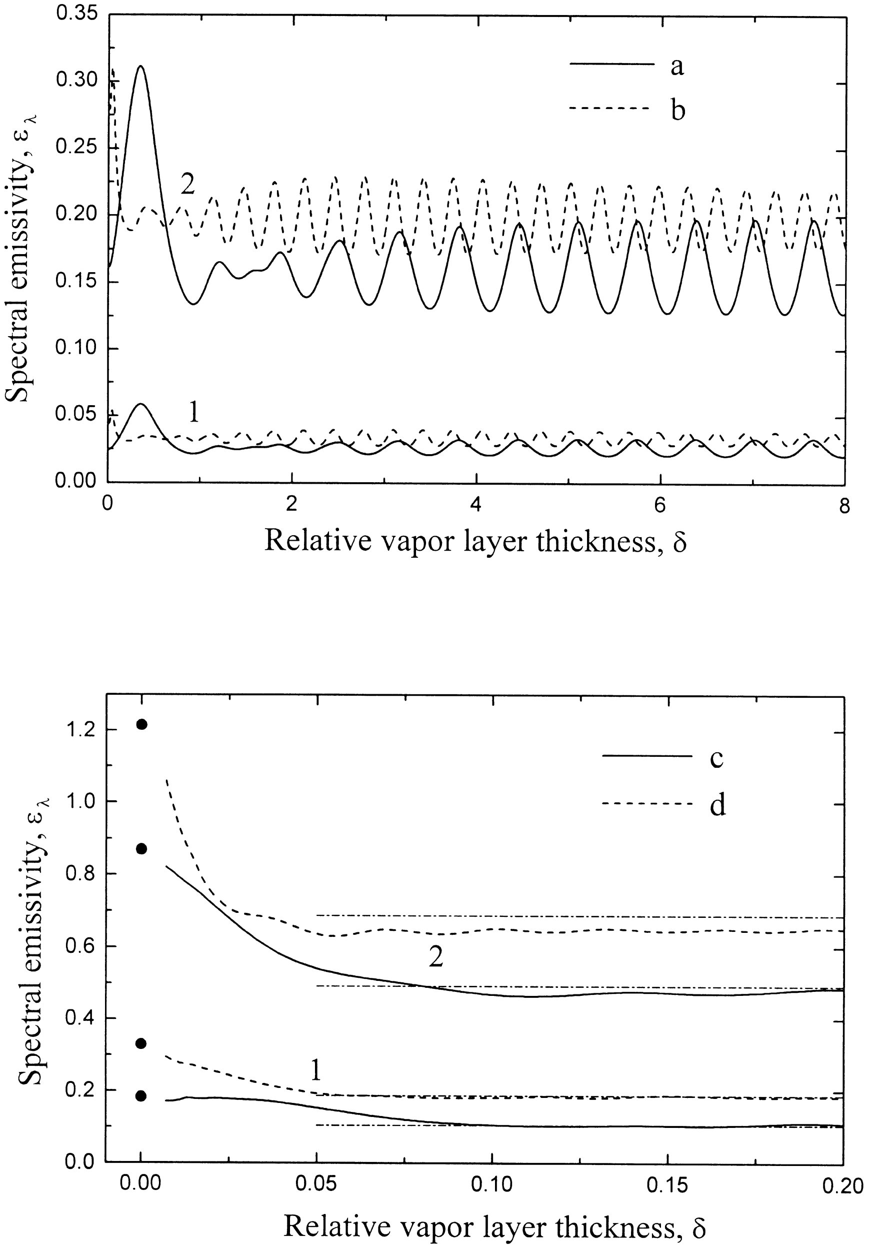

Fig. 2. The spectral emissivity of a particle in a concentric cavity at the wavelength $\lambda = 1$ μm for different values of the diffraction parameter: (a) $x = 5$, (b) $x = 10$, (c) $x = 50$, (d) $x = 100$; 1, 2 — numbers of options for the oxide absorption index. Dots at $\delta = 0$ and horizontal asymptotes — Mie theory calculations.

computational results for $\kappa = \kappa_1$ and $\kappa = \kappa_2$ should be considered as an effect of uncertainty in the absorption index data.

Optical constants of pure water in the infrared are obtained by interpolation of the experimental data [15] for spectral range $0.2 < \lambda < 7$ μm (see Fig. 1, option 1). It should be noted that radiation absorption depends significantly on the water purity. Effect of possible contamination of water (option 2) is characterized by a higher absorption index $\kappa_2 = \kappa_1 + 10^{-4}$.

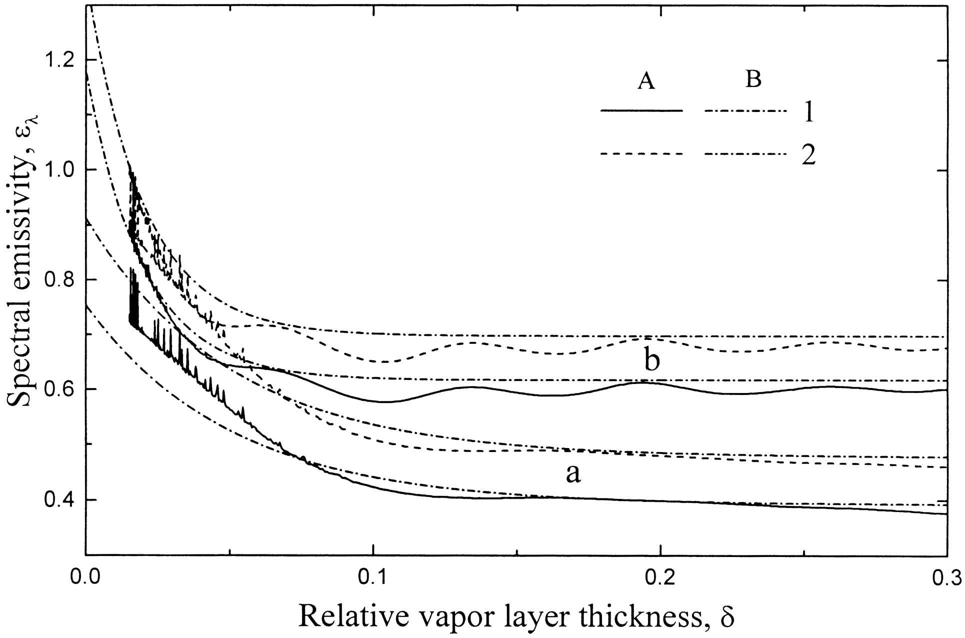

Fig. 3. The spectral emissivity of a particle in a concentric cavity at the wavelength $\lambda = 3$ μm for different values of the diffraction parameter: (a) $x = 20$, (b) $x = 50$; A — exact solution with the wave effects, B — approximation (15) based on the Mie solution for a single particle; 1, 2 — numbers of options for the oxide absorption index.

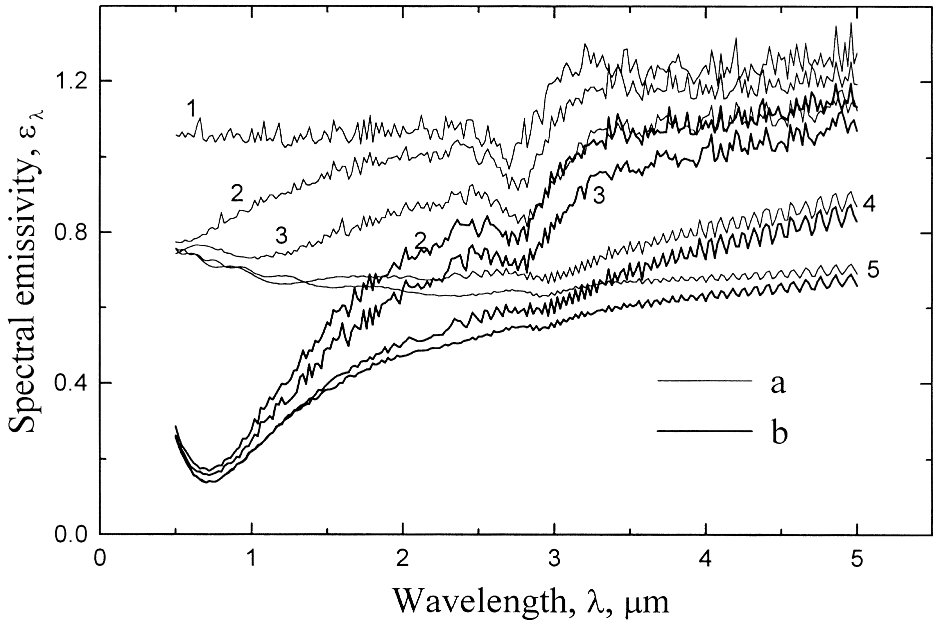

Fig. 4. The spectral emissivity of oxide particle of radius 20 μm for different values of the absorption index ((a) option 1, (b) option 2) for a varying relative thickness of the vapor shell: 1 — $\delta = 0.001$, 2 — $\delta = 0.01$, 3 — $\delta = 0.02$, 4 — $\delta = 0.05$, 5 — $\delta = 0.1$.

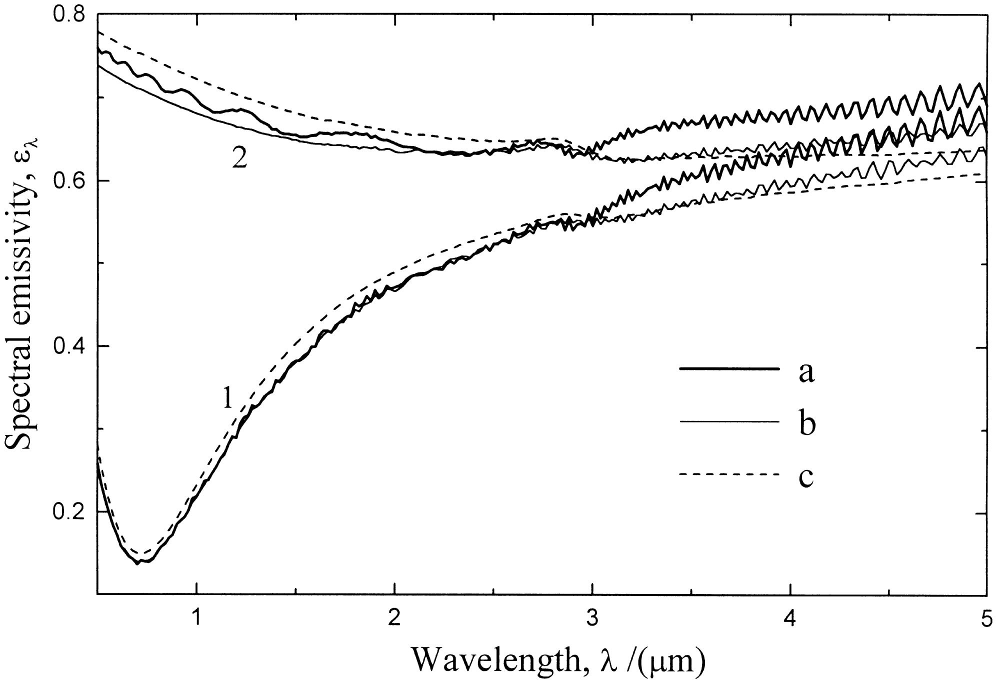

Fig. 5. The evaluation of accuracy of approximate solutions for the spectral emissivity of an oxide particle of radius $r_0 = 20$ μm with the relative thickness of the vapor shell $\delta = 0.1$: (a) exact solution, (b), (c) calculations by approximate relation (7) with $\varepsilon_\lambda^{(0)}$ determined by the Mie theory (b) or by formula (16).

5. Results of calculations

5.1. Spectral emissivity

Numerical data on spectral emissivity of the system "particle–concentric cavity" obtained by account for wave effects are presented in Figs. 2 and 3 in the form of $\varepsilon_\lambda(\delta)$ correlations, where $\delta = \gamma - 1$ is the relative thickness of the vapor shell. The value of ε_λ is weakly dependent on the water absorption index. Therefore, only the results for option 1 (pure water) are given. One can see in Fig. 2 that the emissivity, generally speaking, is a complex nonmonotonic function of the vapor shell thickness, although two limiting cases of zero shell ($\delta = 0$) and solitary particle ($\delta \to \infty$) are described by the Mie theory. As a rule, the value of ε_λ increases with the particle radius. This effect is more pronounced for weakly absorbing oxide (option 1). For comparably large particles ($x \geq 50$) dependencies $\varepsilon_\lambda(\delta)$ are more simple and one can use the following exponential approximation:

$$\varepsilon_\lambda = \varepsilon_\lambda^{(1)} - \left(\varepsilon_\lambda^{(1)} - \varepsilon_\lambda^{(0)}\right)\left[1 - \exp(-\delta x)\right]$$

$$\varepsilon_\lambda^{(0)} = Q_a(x, m), \quad \varepsilon_\lambda^{(1)} = n_e^2 Q_a(n_e x, m/n_e) \tag{15}$$

The asymptotic value of $\varepsilon_\lambda = \varepsilon_\lambda^{(0)}$ in the limit $\delta = \gamma - 1 \gg 1/x$ corresponds to a single particle in vacuum, whereas the value $\varepsilon_\lambda = \varepsilon_\lambda^{(1)}$ when $\delta = 0$ is determined as that for the particle immersed in the reflecting but nonabsorbing medium. One can see in Fig. 3 that the results of calculation by formula (15) are in good agreement with the exact solution including the wave effects.

Some more complete presentation of the spectral emissivity is given in Fig. 4 where two groups of curves, i.e. those with an approximately constant emissivity and those with a pronounced minimum in the short-wave region, correspond to different options of the spectral dependence of the oxide absorption index. One can also see that degeneration of the general solution is not uniform over the spectrum.

The calculations by Eq. (15) or (7) may be simplified even further if we employ the following approximate relation instead of the Mie theory [9]:

$$Q_a = \frac{4n}{(n+1)^2}\left[1 - \exp(-5\kappa x)\right] + 5\kappa x(n-1)^2 \exp\left[-x(n-1)/5\right] \tag{16}$$

Eq. (16) has been earlier verified only in the interval $1.5 \leq n \leq 2$, $0.002 \leq \kappa \leq 0.02$ [9]. Nevertheless, the computational results presented in Fig. 5 confirm a fairly high accuracy of this approximation in the whole spectral range.

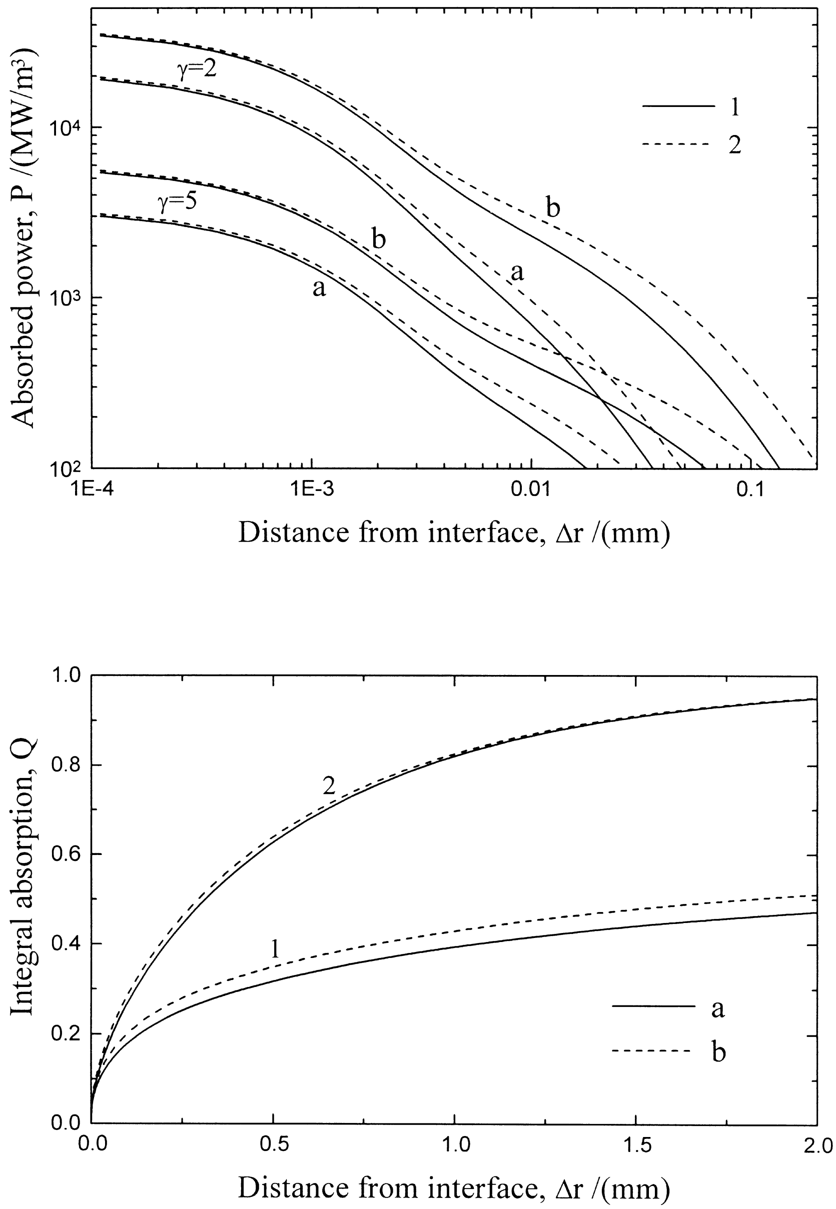

Fig. 6. The local specific absorbed power P and absorbed part of the total radiative flux Q for oxide particles of radius $r_0 = 10$ μm (a) and 50 μm (b). Particle temperature $T_0 = 3000$ K, index of absorption — option 2; 1, 2 — numbers of options for the absorption index of water.

5.2. Profiles of absorbed power

The numerical results on absorption of the particle thermal radiation in surrounding water are presented in Fig. 6 in the form of dependences of the specific absorbed power P and the integral absorption function Q on the distance to the vapor–water interface $\Delta r = r - r_i$. The calculations are performed for a relatively strongly absorbing oxide (option 2). One can see that the values of P for $\Delta r < 0.01$ mm are approximately the same for pure and contaminated water. It is explained by only the long-wave absorption in the thin surface layer of water. The initial parts of these curves for particles of different radius and for different values of γ are similar to one another. This result becomes apparent from the following relations for $W_i = W_\lambda(r_i)$

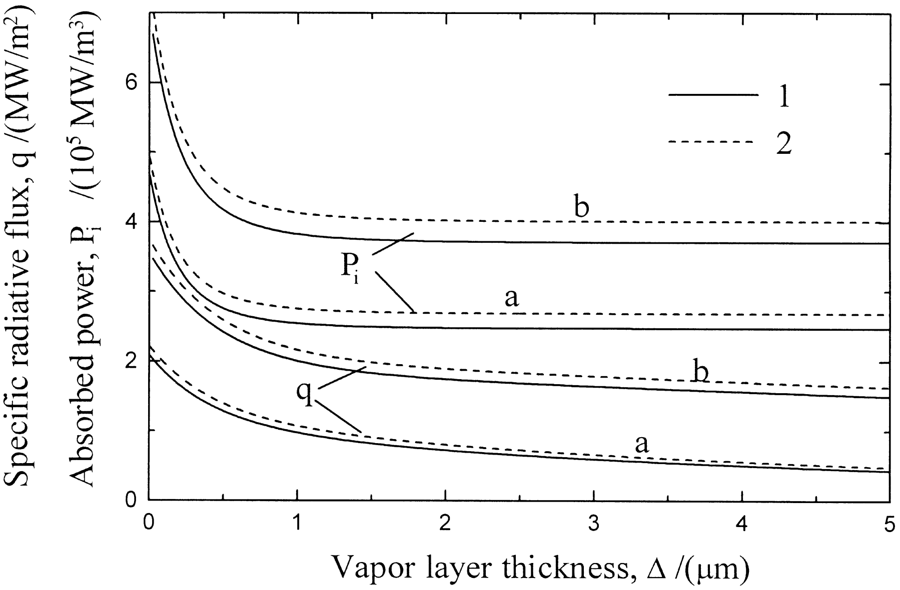

Fig. 7. The specific integral radiative flux on the particle surface q and the specific absorbed power on the water surface P_i for oxide particles of radius $r_0 = 10$ μm (a) and 50 μm (b): 1 — $n = 2.3$ (uranium oxide), 2 — $n(\lambda)$ as for molten aluminum oxide [9]. The particle temperature $T_0 = 3000$ K, the absorption indexes are those of option 2.

and $P_\mathrm{i} = P(r_\mathrm{i})$:

$$W_\mathrm{i} = 1 - \sqrt{1 - 1/(\gamma n_\mathrm{e})^2} \approx \frac{1}{2(\gamma n_\mathrm{e})^2}, \quad \gamma \geq 2 \tag{17}$$

$$P_\mathrm{i} \approx \frac{4\pi}{\gamma^2} \int_0^\infty \frac{\kappa_\mathrm{e}}{\lambda} q_\lambda \, \mathrm{d}\lambda \tag{18}$$

One can see that P_i does not depend on n_e and it is inversely proportional to γ^2. The increase in P_i by a factor of almost two as the particle radius increases from 10 to 50 μm (see Fig. 6) is attributed to the respective increase in the particle emissivity.

Approximate equation (18) explains the very weak dependence of function $Q(\Delta r)$ on the geometrical parameters r_0, γ and on the index of refraction n_e. Note that curves for $\gamma = 2$ and $\gamma = 5$ in Fig. 6 coincide within the line thickness. At the same time, the data in Fig. 6 point to a considerable difference between the options corresponding to pure and contaminated water. In the former option, half the integral radiative flux is absorbed in a water layer of thickness $\Delta r \approx 2$ mm, and in the latter option it is absorbed in a water layer of thickness $\Delta r \approx 0.3$ mm. Note that, quantitatively, the obtained result depends on the oxide absorption index κ. In the case of small κ (option 1) calculations give $\Delta r = 0.5$–0.8 mm for pure water and 0.20–0.25 mm for contaminated water (the lower values correspond to $r_0 = 10$ μm and the higher ones to $r_0 = 50$ μm).

One can readily see that the calculated curves $Q(\Delta r)$ are adequately approximated by the function:

$$Q = 1 - \exp(-K\Delta r) \tag{19}$$

where the coefficient K is proportional to some average absorption coefficient for water. For semitransparent particles ($\kappa x \ll 1$) [12], this coefficient depends further on the oxide absorption index. From the practical standpoint, it is important that the correlation $Q(\Delta r)$ needs no recalculation as the vapor shell thickness varies in the course of interaction between a particle and surrounding water.

6. Approximate radiation transfer model for particle cooling calculations

The radiation heat transfer model should be considered as a part of a general computational model including all modes of thermal and hydrodynamic interaction of the core melt particles with boiling water. For this reason, one needs the most simplified approximate algorithm both for the integral radiative flux and for the radiation absorption in water.

As mentioned above, the thickness of the water layer in which a certain part of the integral radiative flux is absorbed depends weakly on the vapor shell thickness which may vary rapidly (and nonmonotonically) during the interaction between a droplet of corium melt and water [2]. Therefore, only the values of q

and P_i should be recalculated at every time step. The spectral value q_λ can be calculated by means of approximate equations (15) and (16) for the spectral emissivity. The specific integral radiative flux and the power absorbed in a thin surface layer of water are then determined by Eqs. (12) and (19). An example of such calculation is illustrated in Fig. 7. One can see the effect of particle radius: for larger particles the values q, P_i are greater. The wave effects are significant only at very small vapor layer thickness: $\Delta < 1$ μm. Nevertheless, approximately twofold increase in q and P_i may be considerable on the initial (hydrodynamic) stage of the particle–water interaction [2]. Fig. 7 shows only insignificant influence of the oxide index of refraction. It will be recalled that there is another aspect of the same problem with a much more pronounced effect of refractive index: the radiation of comparably large semitransparent nonisothermal particles [12,16].

7. Conclusions

Computational models of different complexity levels have been treated for the radiation heat transfer from a hot spherical particle to surrounding water through the concentric vapor shell of arbitrary thickness. The most general solution includes the wave effects, which are considerable for the vapor layer thickness of the order of the radiation wavelength. For a much greater distance between the particle and the water surface, the solution of the problem is derived by combination of the Mie theory for the particle emissivity, the Fresnel's equations for the radiation reflection/refraction on the vapor–water interface, and the radiation transfer equation for calculation of the heat absorption profiles in water. In all instances, the problem is solved as spectral, with subsequent integration over the spectrum.

Numerical study of the problem for uranium oxide particles in water made it possible to propose approximate relations of the known accuracy both for the integral radiative flux (including wave effects) and for the heat absorption in water. The residual error of the radiative flux calculations for particles of radius less then 50 μm is caused by significant uncertainty of the core melt index of absorption in the near infrared range. It is also important that calculated value of the absorbing layer thickness of water strongly depends on water purity. As a result, the accuracy of the radiation heat transfer calculations is mainly determined by reliability of the experimental data on the near-infrared absorption index of the core melt and also of the process water.

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