This paper is concerned with radiation heat transfer modeling in multiphase disperse systems, which are formed in high-temperature melt–coolant interactions. This problem is important for complex interaction of the core melt with water in the case of a hypothetical severe accident in light-water nuclear reactors. The nonlocal effects of thermal radiation due to the semitransparency of water in the visible and near-infrared spectral ranges are taken into account by use of the recently developed large-cell radiation model (LCRM) based on the spectral radiation energy balance for single computational cells. In contrast to the local approach for radiative heating of water by particles (OMM—opaque medium model), the LCRM includes radiative heat transfer between the particles of different temperatures. The regular integrated code VAPEX-P, intended to model the premixing stage of FCI, was employed for verification of the LCRM in a realistic range of the problem parameters. A comparison with the OMM and the more accurate $P_1$ approximation showed that the LCRM can be recommended for the engineering problem under consideration. The effects of the temperature difference in solidifying particles are analyzed by use of the recently suggested approximation of transient temperature profile in the particles. It is shown that the effect of the temperature difference on heat transfer from corium particles to ambient water is considerable and should not be ignored in the calculations. An advanced computational model based on the LCRM for the radiation source function and subsequent integration of radiative transfer equation along the rays is also discussed.

INTRODUCTION

The radiation heat transfer computational modeling presented in this paper was stimulated by an important engineering problem in nuclear reactor safety. A plant’s containment is the last barrier of environment protection from fission products release in the case of a hypothetical severe accident in a boiling water reactor (BWR) with core melting, reactor pressure vessel failure, and subsequent melt discharge to the ex-vessel cavity. BWR plants in Sweden and Finland adopt cavity flooding to prevent direct core
melt attack on concrete structures of the containment. Corium ejected to a deep-water pool is expected to fragment, solidify, quench, settle, and form a debris bed. The case for coolability of the so-formed decay-heated debris bed is, however, contingent on the bed’s properties (such as particle size distribution, porosity, etc). These properties are dependent on a number of complex phenomena (Kudinov et al., 2007), including molten fuel–coolant interaction (FCI) and the settlement and presettlement state of solidifying debris particles. Therefore, accurate modeling of the hydrodynamics and heat transfer, including radiation in multiphase disperse systems, is a must for reliable prediction of further propagation or termination of a severe accident.

Various aspects of combined hydrodynamic and thermal FCI have been widely investigated during last two to three decades with an aim to solve a problem of energetic steam explosion (Theofanous, 1995; Fletcher, 1995; Berthoud, 2000; Dinh, 2007). The efforts of many researchers have been focused on hydrodynamic simulation of melt jet breakup (Dinh, 1999a; Bürger, 2006; Pohlner et al., 2006). At the same time, the radia-
tion heat transfer in the multiphase medium containing polydisperse corium particles of temperature of about 2500–3000 K was not a subject of detailed analysis. The papers by Dinh et al. (1999b), Fletcher (1999), and Dombrovsky (1999) were probably the first publications where the important role of radiation heat transfer has been discussed. It was noted that a part of the thermal radiation emitted by particles can be absorbed far from the radiation sources because of the semitransparency of water in the shortwave range.

The general problem of radiation heat transfer between corium particles and ambient water can be divided into the following problems of different scale: thermal radiation from a single particle through a steam blanket to ambient water and the radiation heat transfer in a large-scale volume containing numerous corium particles, steam bubbles, and water droplets. The single-particle problem has been analyzed in some detail by Dombrovsky (1999, 2000b). The main attention was paid to the significant contribution of electromagnetic wave effects in the case of a very thin steam layer. The effect of semitransparency of nonisothermal oxide particles on their thermal radiation has also been studied (Dombrovsky, 2000a, 2002b). The resulting physical pictures of particle solidification have been reported recently by Dombrovsky (2007a) and Dombrovsky and Dinh (2008). The large-scale problem of radiation heat transfer in FCI can be solved on the basis of detailed modeling of both the spectral radiative properties and radiative transfer in an absorbing, scattering, and emitting multitemperature medium. But implementation of advanced computational models for thermal radiation into the problem-oriented multiphase flow codes is unpractical at the moment. For this reason, a simplified approach based on spectral radiation balance in the computational cells (the so-called large-cell radiation model—LCRM) has been recently developed by Dombrovsky (2007b). This model is sufficiently simple to be easily implemented into CFD codes for multiphase flow calculations.

The present-day codes used in FCI calculations are based on the known methods of multiphase medium dynamics (Nigmatulin, 1991). The state of the art in computational modeling of mixing and fragmentation of the melt in FCI has been discussed in some detail by Nourgaliev et al. (2003). We do not consider the theoretical model, numerical methods, and computational techniques in this field. A reader can be referred to a general study by Dinh et al. (1999a) as well as to recent papers by Abe et al. (2006) and Pohlner et al. (2006), which are concerned with particular models of the melt fragmentation. In our paper, we use the regular integrated code VAPEX-P developed at Electrogorsk Research & Engineering Center on NPP Safety (Russia). One should distinguish the code VAPEX-D for vapor explosion modeling (Melikhov et al., 2002b) and the code VAPEX-P for the so-called premixture stage or nonexplosive FCI modeling [see papers by Melikhov et al. (2002a, 2007) and Davydenko et al. (1998) for more details]. In the VAPEX-P code, three phases are considered: the liquid water, the vapor (it may be a mixture of steam and hydrogen), and the melt. The Eulerian approach is used for water
and vapor dynamics and heat transfer, while the Lagrangian approach is used for the melt dynamics and cooling. In the current version of VAPEX-P, as well as in other theoretical models of FCI and debris bed formation [e.g., Abe et al. (2006) and Pohlner et al. (2006)], thermal radiation of core melt particles is considered on the basis of too crude models, without account for real optical properties of water, melt particles, steam bubbles, and water droplets in the visible and near-infrared spectral ranges.

In this paper, we are reporting the results of LCRM implementation into the code VAPEX-P. The verification of the LCRM for a realistic range of the problem parameters and analysis of alternative approaches are the main objectives of the present study. It would be great to validate the complete computational model by use of some experimental data; but, to our mind, it is problematic at the moment because of two reasons. The first one is very limited measurements of the local parameters for representative comparison with theoretical predictions. The second reason is not so detailed and reliable hydrodynamic and thermal FCI models realized in the code VAPEX-P. To improve the thermal model, we consider not only the specific radiation effects, but also the effect of temperature difference in large solidifying particles. The approximate model suggested recently by Dombrovsky and Dinh (2008) is modified to account for the temperature profile after solidification. The modified model is implemented into VAPEX-P, and the numerical results are presented in the paper.

Having in mind the importance of comparison between the computational predictions and the measurements, we discuss an advanced radiation model based on the LCRM for the source function and subsequent integration of the radiative transfer equation along a set of rays. This combined model can give us the spectral radiation flux from the zone of melt–coolant interaction.

**MODEL PROBLEMS OF MELT–COOLANT INTERACTION**

The model problems of FCI considered in this paper are not very close to the conditions of the known experiments because we are not going to compare our results with some experimental data. The choice of the model problem parameters was determined by the methodological task of verification of simplified radiation models. It was expected that the problem scale is an important parameter. Therefore, we consider two model problems with the same physical parameters but different initial diameters $d_j$ of the melt jet falling into water. Hereafter we call these model problems “variant 1” ($d_j = 0.1 \, \text{m}$) and “variant 2” ($d_j = 0.02 \, \text{m}$). In both variants, the discharge of the melt through the orifice in the pressure vessel is assumed to be at a height $H_j = 1 \, \text{m}$ above the water pool, the depth and diameter of the water pool are $H_w = 8 \, \text{m}$ and $d_w = 1 \, \text{m}$, the total mass and initial temperature of corium (80% UO$_2$, 20% ZrO$_2$) are $m_c = 300 \, \text{kg}$ and $T_{c0} = 3000 \, \text{K}$, the temperature of water is $T_w = 373 \, \text{K}$, and the initial pressure is $p = 0.1 \, \text{MPa}$. In the calculations, we assumed that heat losses through the walls of the water pool are negligibly small. Note that the small jet diameter in the second variant
may be interesting not only for a realistic scenario of the pressure vessel failure, but also for conditions of laboratory experiments on debris formation after FCI (Kudinov et al., 2007).

The data for thermophysical properties of corium have been reported by Harding et al. (1989), Petukhov et al. (1995), Fink (2000), and Journeau et al. (2004). In our calculations, we have used the data by Annunziato et al. (1996) and Okkonen and Sehgal (1996). The integral hemispherical emissivity of bulk corium was assumed to be equal to $\varepsilon_c = 0.7$ as in earlier versions of the code VAPEX. As was reported by Harding et al. (1989) and Fink (2000), this value is about $\varepsilon_c = 0.85$. We do not give the results for both values of the corium emissivity and our calculations at $\varepsilon_c = 0.7$ can be treated as a lower estimate of the contribution of thermal radiation. A time variation of some integral parameters of the model problems are illustrated in Fig. 1. In variant 1, practically all

**Figure 1.** Time variation of corium mass (calculation by use of the LCRM): 1, melt jet; 2, suspended particles; 3, debris bed on the pool bottom; 4, total mass of corium.
the corium particles reach the pool bottom during 10 s from the process beginning. The detailed calculations showed that ~2% of the total mass is found in corium particles of size ~0.1 mm. The sedimentation of these fine particles is very slow and they remain suspended in water during a long time. The parameters of variant 2 appear to be very different from those of variant 1: the process takes ~45 s and all the particles reach the pool bottom during this time. In contrast to the first variant, the deposition of particles is close to being quasi-steady and the current mass of suspended particles is comparably small. One can see that the chosen model problems are characterized by really different conditions of the melt-water interaction.

**COMPUTATIONAL MODELS FOR THERMAL RADIATION**

To suggest an adequate model of radiation heat transfer in water containing hot corium particles and steam bubbles, one should take into account specific optical properties of water in the visible and near-infrared spectral ranges. It is well known that water is semitransparent in the shortwave range of \( \lambda < \lambda_s \approx 1.2 \ \mu m \) and practically opaque at \( \lambda > \lambda_s \) (Hale and Querry, 1973). In the range of water semitransparency, there is a radiative transfer between corium particles, and one can use the traditional radiative transfer theory to calculate the volume distribution of the radiation power. In the opacity range, the radiative transfer problem degenerates because of strong absorption at distances comparable with both particle sizes and distances between the particles. One can assume that radiation emitted by corium particles in this spectral range is totally absorbed in ambient water.

The radiative transfer equation (RTE) for an emitting, absorbing, and scattering medium containing \( N \) components of different temperatures can be written as follows [see monographs by Siegel and Howell (2002), Modest (2003), and Dombrovsky (1996a) for the details]:

\[
\vec{\Omega}_\lambda \nabla I_\lambda (\vec{r}, \vec{\Omega}) + \beta_\lambda I_\lambda (\vec{r}, \vec{\Omega}) = \frac{\sigma_\lambda}{4\pi} \int I_\lambda (\vec{r}, \vec{\Omega}') \Phi_\lambda (\vec{\Omega}, \vec{\Omega'}) d\vec{\Omega}' + n_\lambda^2 \sum_{i=1}^{N} \alpha_{\lambda,i} B_{\lambda} (T_i) \tag{1}
\]

The physical meaning of Eq. (1) is evident: variation of the spectral radiation intensity \( I_\lambda \) in direction \( \vec{\Omega} \) takes place due to extinction by absorption and by scattering in other directions, as well as due to scattering from other directions (integral term) and thermal radiation of the medium. The extinction coefficient \( \beta_\lambda \) is defined as follows:

\[
\beta_\lambda = \alpha_\lambda + \sigma_\lambda \quad \alpha_\lambda = \sum_{i=1}^{N} \alpha_{\lambda,i} \tag{2}
\]

where \( \alpha_{\lambda,i} \) is the absorption coefficient of the medium component with temperature \( T_i \) and \( \sigma_\lambda \) is the scattering coefficient of the composite medium. In the general case, the
spectral coefficients $\alpha_{\lambda,i}$, $\sigma_{\lambda}$, $\beta_{\lambda}$, scattering (phase) function $\Phi_{\lambda}(\hat{\Omega}\hat{\Omega}')$, and temperatures $T_i$ depend on the coordinate $\vec{r}$.

By writing the last term on the right-hand side of the RTE (1), we have assumed that every component of the medium is characterized by a definite temperature. This is not the case for large corium particles with considerable temperature difference in the particle. Nevertheless, the problem formulation should not be revised for opaque particles. It is sufficient to treat the value of $T_i$ as a surface temperature of the particles of the $i$th fraction. An essentially more complex problem should be considered for semitransparent particles when thermal radiation comes from the particle volume. It is a realistic situation for particles of aluminum oxide or other light oxides used as simulant substances in experimental studies of the core melt–coolant interaction (Huh-tiniemi et al., 1999; Dinh, 2007). The problem of thermal radiation from semitransparent nonisothermal particles has been studied in some detail by Dombrovsky (2000a, 2002b, 2007a), and a differential approximation was developed for the total radiation power and radiation field in the particle. This approach has been recently applied to the problem of cooling and solidification of the metal oxide melt droplet in water (Dombrovsky and Dinh, 2008). The solution obtained can be combined with the large-scale problem under consideration. But it is beyond the scope of this paper focused on the specific case of the melt particles, which are totally opaque for thermal radiation.

It is very difficult to use the complete description of the radiation heat transfer based on the RTE (1) in the range of water semitransparency. Therefore, the simplified radiation models should be considered for engineering calculations. The integration of Eq. (1) over all values of solid angle yields the following important equation of spectral energy balance:

$$\nabla \bar{q}_\lambda = p_\lambda - \alpha_\lambda I_0^\lambda (\vec{r}), \quad p_\lambda = 4\pi n_\lambda^2 \sum_{i=1}^{N} \alpha_{\lambda,i} B_\lambda (T_i), \quad I_0^\lambda (\vec{r}) = c_0 E_\lambda (\vec{r}) \quad (3)$$

where $\bar{q}_\lambda$ is the spectral radiation flux, $p_\lambda$ is the spectral radiation power emitted in a unit volume of the medium, $E_\lambda (\vec{r})$ is the spectral radiation energy density, and $c_0$ is the velocity of light. For brevity, the name “spectral radiation energy density” is often used for the quantity $I_0^\lambda$. The spectral radiation flux and radiation energy density are expressed as follows:

$$I_\lambda^0 (\vec{r}) = \int I_\lambda (\vec{r},\hat{\Omega}) \hat{\Omega} d\Omega, \quad \bar{q}_\lambda (\vec{r}) = \int I_\lambda (\vec{r},\hat{\Omega}) \hat{\Omega} d\Omega \quad (4)$$

The spectral balance equation [Eq. (3)] is considered as a starting point for simplified models for radiation heat transfer in multiphase disperse systems.
Opaque Medium Model

In the case of not-too-hot particles, the main part of the thermal radiation is emitted in the range of water opacity. Therefore, it is reasonable to ignore the specific feature of the process in the shortwave range and assume water to be totally opaque over the whole spectrum. This approach can be called the opaque medium model (OMM). According to the OMM, thermal radiation emitted by single hot particles is absorbed in water at very small distances from the particle. In this case, the total power absorbed by water in a unit volume is equal to the power emitted by particles in this volume,

$$P_w = P_c = \int_{\lambda_1}^{\lambda_2} p_\lambda d\lambda$$  \hspace{1cm} (5)

where \(\lambda_1\) and \(\lambda_2\) are the boundaries of the spectral range of significant thermal radiation. Obviously, this model overestimates the heat absorbed in water. Besides, it cannot be employed to distinguish the radiation power absorbed at the steam-water interface near the particle and the power absorbed in the volume. The latter may be important for detailed analysis of heat transfer from corium particles to ambient water in calculations of water heating and evaporation.

Simple estimates showed that contribution of shortwave radiation increases rapidly with the particle temperature and one cannot ignore the spectral range of water semi-transparency when corium particles have a temperature greater than 2500 K. In other words, one can expect the OMM error to be considerable in this case.

At the same time, the present-day computer codes for multiphase flows use computational cells of size about 5–10 cm or greater. All parameters of the multiphase flow are assumed to be constant in every cell. This means that the OMM is really applied to the large (almost opaque) cell and may give fairly good results, especially at low volume fraction of corium particles when the average distance between the neighboring particles is greater than the mean free path of near-infrared radiation in water. It is a favorable situation for the OMM that it ignores the radiation heat transfer between the particles of different temperature.

Note that the formal use of the OMM for the cells with high void fraction (volume fraction of steam) seems to be problematic even for big cells because steam in the cell at not-too-high pressure is practically transparent for thermal radiation, and water droplets cannot totally absorb the radiation emitted by corium particles.

Large-Cell Radiation Model

The large-cell radiation model (LCRM) suggested recently by Dombrovsky (2007b) is based on the assumption of negligible radiation heat transfer between the cells. In the
range of water semitransparency, the local radiative balance in every cell yields the following relation for the radiation energy density instead of Eq. (3):

\[ I_\lambda^0 = \frac{p_\lambda}{\alpha_\lambda} \tag{6} \]

This means that the divergence of the spectral radiation flux is assumed to be zero in the cell. As a result, the expressions for the integral radiation power absorbed in water can be written as

\[ P_w = P_c = P_w^{(1)} + P_w^{(2)}, \quad P_w^{(1)} = \int_{\lambda_1}^{\lambda_2} \alpha_{\lambda,w} \frac{p_\lambda}{\alpha_\lambda} d\lambda, \quad P_w^{(2)} = \int_{\lambda_1}^{\lambda_2} p_\lambda d\lambda \tag{7} \]

where \( \alpha_{\lambda,w} \) is the spectral absorption coefficient of water containing steam bubbles. The components \( P_w^{(1)} \) and \( P_w^{(2)} \) of the absorbed power correspond to the ranges of water semitransparency and opacity. One can assume that \( P_w^{(1)} \) causes volume heating of water, whereas \( P_w^{(2)} \) only causes surface heating and evaporation of water near the hot particles. Obviously, the predicted contribution of the semitransparency range to the total absorbed power appears to be less than the corresponding value estimated by use of the OMM. Note that the LCRM does not include any characteristics of radiation scattering in the medium.

**Radiation Model Based on \( P_1 \) Approximation**

The radiation balance equation [Eq. (3)] can also be employed without ignoring the radiation flux divergence. To realize such a possibility, one should find a relation between the spectral radiation flux and radiation energy density. In the diffusion approximation, the following representation of the radiation flux is assumed to make the problem statement complete:

\[ \vec{q}_\lambda = -D_\lambda \nabla I_\lambda^0 \tag{8} \]

where \( D_\lambda \) is the radiation diffusion coefficient. Sometimes, as in the monograph by Zeldovich and Raizer (1967), the term “diffusion approximation” is related only to the case of the Eddington approximation when

\[ D_\lambda = \frac{1}{(3\beta^r_\lambda)^{1/2}}, \quad \beta^r_\lambda = \alpha_\lambda + \sigma^r_\lambda, \quad \sigma^r_\lambda = (1 - \bar{\mu}_\lambda) \sigma_\lambda \tag{9} \]

where \( \sigma^r_\lambda \) and \( \beta^r_\lambda \) are the transport coefficients of scattering and extinction, and \( \bar{\mu}_\lambda \) is the asymmetry factor of scattering, defined as

\[ \bar{\mu}_\lambda = \frac{1}{4\pi} \int_{4\pi} \left( \Omega' \cdot \Omega \right) \Phi_\lambda \left( \Omega' \cdot \Omega' \right) d\Omega' \tag{10} \]
It is known that Eqs. (8) and (9) can be derived by assuming the linear angular dependence of the radiation intensity,

\[
I_{\lambda}(\vec{r}, \vec{\Omega}) = \frac{1}{4\pi} \left[ I^0_{\lambda}(\vec{r}) + 3\vec{\Omega} \cdot \vec{q}_{\lambda}(\vec{r}) \right] \tag{11}
\]

Therefore, this approximate model is also known as the first approximation of spherical harmonics method or the P\textsubscript{1} approximation [e.g., Dombrovsky (1996a) or Modest (2003)]. Substituting Eq. (8) into Eq. (2), we obtain nonhomogeneous modified Helmholtz equation for the spectral radiation energy density,

\[
-\nabla \left( D_\lambda \nabla I^0_{\lambda} \right) = p_{\lambda}(\vec{r}) - \alpha_{\lambda} I^0_{\lambda}(\vec{r}) \tag{12}
\]

The Marshak boundary condition can be used to complete the boundary-value problem,

\[
-D_\lambda \nabla I^0_{\lambda} \cdot \vec{e}_n = I^0_{\lambda} \tag{13}
\]

The condition (13) is written here for the case of zero external radiation and no reflection from the boundary surface. The assumption of linear angular dependence of radiation intensity seems to be rather good for the problem under consideration because of the large optical thickness of the medium and the smooth variation of the physical parameters. Therefore, we consider the P\textsubscript{1} approximation instead of the RTE to analyze the quality of the LCRM in this paper.

Note that the boundary-value problem [Eqs. (12) and (13)] is formulated for the complete computational region (not for single cells). After solving this problem for several wavelengths in the range of \(\lambda_1 < \lambda < \lambda_\text{\#}\), one can find the radiation power absorbed in water as

\[
P_w(\vec{r}) = P_w^{(1)} + P_w^{(2)}, \quad P_w^{(1)}(\vec{r}) = \int_{\lambda_1}^{\lambda_\text{\#}} \alpha_{\lambda,w} I^0_{\lambda}(\vec{r}) \, d\lambda, \quad P_w^{(2)}(\vec{r}) = \int_{\lambda_\text{\#}}^{\lambda_2} p_{\lambda}(\vec{r}) \, d\lambda \tag{14}
\]

The total radiative heat loss from the corium particles is

\[
P_c(\vec{r}) = P_c^{(1)} + P_c^{(2)}, \quad P_c^{(1)}(\vec{r}) = \int_{\lambda_1}^{\lambda_\text{\#}} \left\{ p_{\lambda}(\vec{r}) - \alpha_{\lambda,c}(\vec{r}) I^0_{\lambda}(\vec{r}) \right\} \, d\lambda \tag{15}
\]

where \(\alpha_{\lambda,c}\) is the absorption coefficient of polydisperse corium particles. It is important that \(P_c^{(1)} \neq P_w^{(1)}\) due to heat transfer by radiation in a semitransparent medium,
\[
P_c^{(1)} - P_w^{(1)} = \int_{\lambda_1}^{\lambda_r} \left[ p_\lambda(\mathbf{r}) - \alpha_\lambda f_\lambda^0(\mathbf{r}) \right] d\lambda, \quad \alpha_\lambda = \alpha_{\lambda,w} + \alpha_{\lambda,c} \quad (16)
\]

The $P_1$ approximation takes into account the radiative transfer between all the computational cells. It is an important advantage of this model, especially in the case of semi-transparent “steam” cells. A long-time experience in the use of $P_1$ for solving various engineering problems has showed that the predicted field of radiation energy density is usually very close to the exact RTE solution. One can see that $P_1$ gives also the radiation flux at the boundary of the computational region. In contrast to the radiation energy density, the radiation flux error may be significant (Dombrovsky 1997). Therefore, a more sophisticated approach should be employed to determine the radiation coming from the FCI region. This problem is discussed in the last section of this paper.

The complete solution to the 2D radiation heat transfer problem in a multiphase flow typical of fuel–coolant interaction is too complicated even in the case when the $P_1$ approximation is employed. The main computational difficulty is related to the wide range of optical thicknesses of the medium at different wavelengths. One should consider not only the visible radiation when the optical thickness of the medium is determined by numerous particles, but also a part of the near-infrared range characterized by large absorption coefficient of water. As a result, the numerical solution of the boundary-value problem [Eqs. (12) and (13)], generally speaking, cannot be obtained by using the same computational mesh at all wavelengths. There is no such difficulty in the LCRM, which is simply an algebraic model and can be easily implemented into any multiphase CFD code.

Approximate Relations for Radiative Characteristics of a Multiphase Disperse Medium

In the computational cells with a not-too-high volume fraction of steam $f_v^s < 0.7$ (hereafter called “water cells”), it is assumed that water contains separate bubbles of steam and polydisperse corium particles separated from ambient water by thin steam layers. In the opposite case of “steam cells,” when $f_v^s \geq 0.7$, the multiphase medium is treated as steam containing water droplets and corium particles.

To simplify the estimates, we assume that all the particles and bubbles are ideal spheres. It is also assumed that absorption and scattering characteristics of a small element of the medium can be determined on the basis of the far-field single-scattering approximation (Mishchenko et al., 2004). There is no doubt that the latter assumption, which is known also as the independent scattering approximation (ISA), is correct for the engineering problem under consideration because particle positions are random and uncorrelated and the distances between particles are usually greater than the particle size. In our problem, the majority of particles and bubbles are much greater in size than
the wavelength. The latter simplifies an estimate of the ISA applicability as it was done by Coquard and Baille (2004) by use of direct Monte Carlo simulation for randomly located large opaque spheres. It was shown that the ISA underestimates the extinction coefficient of the disperse medium, but this effect is less than about 11% at a volume fraction of particles $f_v < 0.1$. The correction factor $S$ is well described by the mean-beam-length approach suggested by Brewster (2004). This approach gives the following simple formula for packed beds of large opaque spheres:

$$ S = \frac{1}{1 - f_v} $$

which appears to be a fairly good approximation at $f_v < 0.3$.

Since the simplified models for radiation heat transfer are used in this paper, we do not consider the detailed angular characteristics of radiation scattering by particles and bubbles. According to the above formulation, only two characteristics of the composite medium are considered: the absorption coefficient and the transport scattering coefficient. The general expressions for these quantities are as follows (Dombrovsky 1996a, 2004, 2007b) (for brevity, hereafter we omit subscript $\lambda$):

$$ \alpha = \alpha_w + \alpha_c, \quad \alpha_w = \alpha_0^w + 0.75 \frac{f_v^s}{a_3^b} \int_0^\infty Q^b_a a^2 F_b(a) \ da $$

$$ \alpha_c = 0.75 \frac{f_v^c}{a_3^c} \int_0^\infty Q^c_c a^2 F_c(a) \ da $$

$$ \sigma_{tr} = \sigma_{tr}^s + \sigma_{tr}^c, \quad \sigma_{tr}^s = 0.75 \frac{f_v^s}{a_3^c} \int_0^\infty Q_{ac}^{b, tr} a^2 F_b(a) \ da $$

$$ \sigma_{tr}^c = 0.75 \frac{f_v^c}{a_3^c} \int_0^\infty Q_{ac}^{c, tr} a^2 F_c(a) \ da $$

$$ \alpha = \alpha_w + \alpha_c, \quad \alpha_w = 0.75 \frac{f_v^w}{a_3^w} \int_0^\infty Q^w_a a^2 F_w(a) \ da $$

$$ \alpha_c = 0.75 \frac{f_v^c}{a_3^c} \int_0^\infty Q^c_a a^2 F_c(a) \ da $$

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$$\sigma_{tr} = \sigma_t^w + \sigma_t^c, \quad \sigma_{tr}^s = 0.75 \frac{f_v^w}{a_{30}} \int_0^\infty Q_{tr}^{w, tr} a^2 F_w(a) \, da$$

$$\sigma_{tr}^c = 0.75 \frac{f_v^c}{a_{30}} \int_0^\infty Q_{tr}^{c, tr} a^2 F_c(a) \, da$$

Equations (18a) and (18b) refer to the “water” cells and Eqs. (19a) and (19b) to the “steam” cells. The value $\alpha_0^w$ is the absorption coefficient of pure water (without any particles and bubbles), $\alpha_w$ is the absorption coefficient of water with bubbles (18a) or water droplets (19a), $f_v^s$, $f_v^c$, $f_v^w$ are the local volume fractions of steam, corium, and water ($f_v^s + f_v^c + f_v^w = 1$), $F_b$, $F_c$, $F_w$ are the normalized size distributions of steam bubbles, corium particles, and water droplets, and $Q_a$ and $Q_{tr}^tr$ are the efficiency factor of absorption and the transport efficiency factor of scattering for single particles in the host medium, while the parameter $a_{30}$ can be computed from the following definition of $a_{ij}$:

$$a_{ij} = \frac{\int_0^\infty a^2 F(a) \, da}{\int_0^\infty a^2 \, da}$$

Steam bubbles: The radiative properties of gas bubbles in a refracting and weakly absorbing medium have been studied by Dombrovsky (2004) on the basis of the rigorous Mie theory [e.g., Bohren and Huffman (1983)]. It was shown that the efficiency factors of large steam bubbles in water can be approximated as follows:

$$Q_a^b = -\frac{4\alpha_0^w}{3}, \quad Q_{tr}^b = 0.9 (n_w - 1)$$

Equations (21) overestimate the absolute values of $Q_a^b$ and $Q_{tr}^b$ by < 5% when $a > 10\lambda/\pi$ and $\alpha_0^w a < 1$. Obviously, these conditions are satisfied for the majority of steam bubbles in the range of water semitransparency. The resulting approximate expressions for the absorption coefficient and transport scattering coefficient of water containing polydisperse steam bubbles are as follows:

$$\alpha_w = (1 - f_v^s) \alpha_0^w, \quad \sigma_{tr}^s = 0.675 (n_w - 1) \frac{f_v^s}{a_{32}^s}$$

It is important that absorption does not depend on the bubble size distribution and scattering does not depend on absorption coefficient of water. The only parameter related to the bubbles that affects the transport scattering coefficient of the medium is the ra-
tio of steam volume fraction to the average radius of bubbles: \( f_v^s/a_{32}^b \). Note that these equations have been verified by Dombrovsky et al. (2005) in the experimental study of radiative properties of fused quartz containing gas bubbles.

**Corium particles:** In this paper, we consider only opaque particles. It significantly simplifies the analysis, but one should remember that the assumption of the particle opacity is inapplicable for some metal oxides considered as simulants of corium in experimental studies of nuclear fuel–coolant interaction (Dombrovsky and Dinh, 2008). Note that the data for the spectral absorption coefficient of corium are very limited, and our assumption concerning the opacity of corium particles is based on early experimental studies by Anderson (1976) and Bober et al. (1981, 1984), as well as recent data reported by Ruello et al. (2004) for pure uranium dioxide.

In the case of water cells, we assume that every particle of corium is surrounded by a concentric steam layer that separates the particle from ambient water. It was shown by Dombrovsky (2007b) that one can use the following simple formula when the steam layer thickness is much greater than the wavelength:

\[
Q_{a}^c = \frac{Q_{a}^{c0}}{n_w^2} \tag{23}
\]

where \( Q_{a}^{c0} \) is the absorption efficiency factor of the oxide particle in a vacuum. For large opaque particles, \( Q_{a}^{c0} = \varepsilon_c \), where \( \varepsilon_c \) is the spectral hemispherical emissivity of bulk corium. In contrast to absorption, the transport efficiency factor of scattering referred to the steam bubble cross section is equal to the value of \( Q_{bc, tr}^b \) for steam bubble without oxide particle,

\[
Q_{bc, tr}^c = 0.9 (n_w - 1) \tag{24}
\]

In this paper, the thickness of the steam layer is assumed to be much less than the particle radius. Therefore, Eq. (24) can be used for the transport efficiency factor of scattering referred to as the particle radius. Note that the same corium particles in steam cells are characterized by a negligibly small transport efficiency factor of scattering.

**Water droplets:** The efficiency factor of absorption of large (as compared with the wavelength) water droplets can be approximately calculated by use of the following expression suggested by Dombrovsky (2002a) for large particles of a semitransparent substance:

\[
Q_w^a = \frac{4n_w}{(n_w + 1)^2} \left[ 1 - \exp \left( -2\alpha_w^0 a \right) \right] \tag{25}
\]

The scattering of radiation by large water droplets is characterized by a strong peak in the vicinity of the forward direction. Therefore, the transport efficiency factor of scat-
tering is negligibly small. It can be shown that the monotonic dependence of $Q_w^w$ on the droplet radius given by Eq. (25) is favorable for the use of a monodisperse approximation with the Sauter radius $a_{32}$. The resulting expression for the absorption coefficient of polydisperse water droplets is as follows:

$$\alpha_w = \frac{f_v^w}{a_{32}^2} \frac{3n_w}{(1 + n_w)^2} \left[ 1 - \exp \left( -\alpha_0^w a_{32}^w \right) \right]$$  \hspace{1cm} (26)

**Final expressions:** According to the above consideration of absorption and scattering characteristics of the multiphase medium components, one can write the following final expressions for the absorption coefficient and the transport scattering coefficient of the medium in various computational cells:

$$\alpha = (1 - f_s^v) \alpha_0^c + \alpha_c, \quad \alpha_c = 0.75 f_c^v \frac{\varepsilon_c}{a_{32}^c} \quad \sigma_{tr} = 0.675 (n_w - 1) \left( \frac{f_v^s}{a_{32}^s} + \frac{f_c^v}{a_{32}^c} \right)$$  \hspace{1cm} (27)

$$\alpha = \alpha_w + \alpha_c, \quad \alpha_w = 1 - f_v^c - f_v^s \frac{3n_w}{a_{32}^w} \left[ 1 - \exp \left( -\alpha_0^w a_{32}^w \right) \right]$$

$$\alpha_c = 0.75 \varepsilon_c \frac{f_c^c}{a_{32}^c}, \quad \sigma_{tr} = 0$$  \hspace{1cm} (28)

Equations (27) are written for water cells, and Eqs. (28) for steam cells. Note that the index of refraction is $n = n_w$ in water cells and $n = 1$ in steam cells.

**Radiation heat flux from a single corium particle:** In the Lagrangian calculations of transient temperature of corium particles, the value of the integral (over the spectrum) radiation heat flux from the unit surface of a single particle is used. In the OMM, this value is determined as follows:

$$q_{c,i} = \pi \int_{\lambda_1}^{\lambda_2} \varepsilon_c B_\lambda (T_i) \ d\lambda$$  \hspace{1cm} (29)

It is usually assumed that the emissivity of corium $\varepsilon_c$ does not depend on the wavelength. In this case, one can write

$$q_{c,i} = \varepsilon_c \sigma T_i^4$$  \hspace{1cm} (30)

where $\sigma$ is the Stefan–Boltzmann constant. In the LCRM and $P_1$, we have the following expressions for the radiation flux:
\[ q_{c,i} = q_{c,i}^{(1)} + q_{c,i}^{(2)}, \quad q_{c,i}^{(1)} = \int_{\lambda_1}^{\lambda_2} \varepsilon_c \left( \pi B_{\lambda} (T_i) - \frac{P_0}{4n_w^2} \right) d\lambda, \quad q_{c,i}^{(2)} = \pi \int_{\lambda_1}^{\lambda_2} \varepsilon_c B_{\lambda} (T_i) d\lambda \quad (31) \]

The above equations complete the formulation of the radiation problem in the OMM, LCRM, and \( P_1 \) approximations.

**NUMERICAL RESULTS BASED ON SIMPLIFIED RADIATION MODELS**

Consider first the numerical data for the integral mass of corium particles observed at a certain depth in the pool during all the processes. The calculations were performed by use of a uniform dividing of the computational region with five cells in the radial direction and 45 along the axis, so that every circular cell has the radial thickness 10 cm and height 20 cm. The typical distributions of the mass between the particles of different size fractions at the depth \( h_{w} = H_{w} = 8 \) m (the bottom level) are presented in Fig. 2.

**Figure 2.** The calculated relative mass of particles of different diameters near the pool bottom: 1, by ignoring thermal radiation; 2, radiation according to the OMM; 3, LCRM.
The calculated pictures for different values of the depth from 2 m to 8 m appear to be almost similar to each other. Therefore, keeping in mind the limited length of this paper, we consider only the data for one depth value. For convenience of presentation, only 12 fractions of particles with diameters in the ranges of \( d < 0.5 \), 0.5–1, 1–2, . . . , 9–10, and \( d > 10 \) mm are considered. The relative mass of particles of every fraction, \( \bar{m} \), was calculated as a ratio of the mass of these particles to the total mass of corium. One can see that the thermal radiation significantly affects even the integrated-over-time mass characteristics of corium particles suspended in water. The difference between calculations by use of the OMM and LCRM is also considerable. In variant 1, the relative mass of the most important fraction 4 < \( d < 5 \) mm is about 25% less in the OMM as compared with the LCRM. In variant 2, the underestimation of the same fraction mass is less (about 15%) but the OMM gives the mass of large particles of diameter \( d > 6 \) mm by 2.5 times greater than the mass predicted by use of the LCRM. But these local differences in numerical data should not be considered as a definite effect of the radiation model. One can speak only about small displacement of the size distribution maximum. Note that size distributions of corium particles obtained in these calculations are in good qualitative agreement with the known experimental data (Magallon, 2006).

Obviously, thermal radiation significantly decreases the temperature of large corium particles. This effect of radiation on heat transfer from relatively cold small particles is not so strong. It is illustrated in Fig. 3 for corium particles near the pool bottom. The difference between the OMM and LCRM is observed only for large particles of only about \( d > 6 \) mm diameter and it is not greater than 80 K. Note that all the particles are cold near the bottom: the maximum temperature is about 1300 K in variant 1 and 650 K in variant 2. This means that greater differences can be found far from the bottom, in a zone of high-temperature particles. We have an example of such difference between OMM and LCRM calculations for large particles in variant 1. For particles of diameter in the range of 9 < \( d < 10 \) mm at the depth \( h_w = 4 \) m, the OMM gives \( T = 2200 \) K instead of 2900K as in the LCRM. But the mass fraction of these large particles is very small. For a particle of average size, the difference between temperatures calculated by use of the OMM and LCRM is not large. This is illustrated in Fig. 4, where the dependences \( T(h_w) \) for particles of several sizes are shown. The presented mass-averaged temperature of corium particles was averaged also over the process time. One can see that the OMM gives fairly good prediction of this value, and corrections by using the LCRM are negligible.

The contribution of radiation to the heat transfer from corium is illustrated in Fig. 5. The values are averaged over the pool volume, including the melt jet and all the particles, are presented in this figure. As one can expect, thermal radiation is more important in the initial period of FCI. Note that the radiation absorbed by corium (this effect is taken into account in the LCRM) is relatively small.
On the basis of the presented numerical results, one can draw the following conclusions:

- The contribution of thermal radiation to heat transfer from corium is really significant, especially at the initial stage of the process; the radiation affects not only the temperature of corium particles, but also their size distribution;

- The integral effect of radiation is well described by the opaque medium model, but the LCRM gives some corrections of the particle size distribution and the temperature of large melt droplets at the initial stage of FCI.

Fortunately, the algebraic relations of the LCRM are simple and the use of the LCRM instead of the OMM leads to only about a 20% increase in the computational time of the code VAPEX-P.
In this section of the paper, we considered only the integral parameters of corium-water interaction in the particular case of water at saturation temperature. In the case of a lower temperature of water, one should take into account that a considerable part of radiation power is absorbed in water far from the steam-water interface and does not contribute to steam production. In contrast to the OMM, the LCRM includes a correct estimate of volumetric radiation absorption in water. This is an important advantage of the LCRM that can be used to improve the current model of water heating and steam production in the general case of an arbitrary temperature of water.

Both approximations, the OMM and the LCRM, are based on the assumption of negligible radiative transfer between the computational cells. This means that even a good agreement between the results obtained by use of the OMM and the LCRM cannot be considered as a confirmation of applicability of these approaches.
VERIFICATION OF THE LARGE-CELL RADIATION MODEL

To verify the main assumption of negligible radiative transfer between the computational cells, we compare the LCRM with the $P_1$ approximation. One can solve a 2D problem boundary-value problem, Eqs. (12) and (13), by use of the finite element method (FEM) and the earlier-developed computer code (Dombrovsky and Barkova, 1986; Dombrovsky, 1996a,b). But a good estimate can be also obtained on the basis of the following one-dimensional formulation for spectral radiative transfer in the radial direction:

$$-\frac{1}{r} \frac{d}{dr} \left( r D_\lambda \frac{df^0_\lambda}{dr} \right) = p_\lambda (r) - \alpha_\lambda f^0_\lambda (r)$$  \hspace{1cm} (32a)
\[ r = 0, \quad \frac{dI_\lambda^0}{dr} = 0, \quad r = r_w, \quad -D_\lambda \frac{dI_\lambda^0}{dr} = \frac{I_\lambda^0}{2} \] (32b)

where \( r_w \) is the radius of the water pool. In our particular case of constant medium properties in every computational cell, it is convenient to use an analytical solution to the problem (32). This solution can be easily obtained by use of matching of the general solutions for single cells,

\[ I_{\lambda,k}^0 (r) = C_{1_k}I_0(\chi_{\lambda,k}r) + C_{2_k}K_0(\chi_{\lambda,k}r) + \frac{p_{\lambda,k}}{\alpha_{\lambda,k}}, \quad \chi_{\lambda,k}^2 = \frac{\alpha_{\lambda,k}}{D_{\lambda,k}}, \quad k = 1, 2, \cdots, N \] (33)

where \( k \) is the current computational cell number, \( N \) is the number of cells in the radial cross section of the computational region, and \( I_0(x) \) and \( K_0(x) \) are the modified Bessel functions of the first and second kind, respectively (Abramowitz and Stegun, 1965). The matching conditions at the boundaries between the neighboring cells are the continuity of the function \( I_\lambda^0 (r) \) and the spectral radiation flux \(-D_\lambda dI_\lambda^0 / dr\). The resulting system of linear algebraic equations for the coefficients of the analytical solutions is solved by use of a standard procedure. We do not give here all the relations because of the limited space of the paper. Note that the analytical solution is preferable in our particular case because the usual finite-difference solution and factorization procedure degenerates in the limit of an optically thin computational region, i.e., in the visible spectral range.

It is interesting to consider a model problem with the following variable coefficients:

\[ D_\lambda = \frac{r^2_1}{r}, \quad \alpha_\lambda = \frac{1}{r}, \quad p_\lambda = \frac{I_{\lambda,1}^0}{r_1} \] (34)

which yields the radical simplification of the problem (32),

\[ r^2_1 \varphi'' - \varphi = -1, \quad \varphi (0) = 0, \quad \varphi' (r_w) = -\frac{r_w}{2r_1^2} \varphi (r_w) \] (35)

with the obvious analytical solution for the dimensionless function \( \varphi = I_{\lambda}^0 / I_{\lambda,1}^0 \),

\[ \varphi (\bar{r}) = 1 - \frac{\cosh \bar{r}}{\cosh \bar{r}_w + 2(\sinh \bar{r}_w) / \bar{r}_w}, \quad \bar{r} = \frac{r}{r_1}, \quad \bar{r}_w = \frac{r_w}{r_1} \] (36)

In the limiting case of \( \bar{r}_w \ll 1 \), the analytical solution (36) degenerates to the constant value of \( \varphi \equiv 2/3 \). It is a good test problem for the limit of an optically thin medium. We have used this solution to check our algorithm developed for piecewise constant medium properties.

The calculations using the P\(_1\) approximation were performed for several cross sections of the computational region at the moments corresponding to intensive heat transfer by thermal radiation. Some numerical data are presented in Fig. 6. To understand the computational results on the radiation power absorbed by water, one should analyze the fields of void fraction (volume fraction of steam) shown in Fig. 7. One can see that considerable error of the LCRM (20% in variant 1 and 25% in variant 2) in the com-
putational cells near the axis is explained by a high volume fraction of steam in these cells. Obviously, the assumption of radiative balance is not correct for these semitransparent cells. In the water cells, i.e., in the majority of the computational cells during the process, the error of the LCRM is very small. This means that the LCRM is a good approach that can be recommended for practical calculations at a realistic scale of the problem.

**APPORXIMATE MODEL FOR TEMPERATURE PROFILE IN SINGLE PARTICLES**

It is natural to assume that the temperature difference in the corium melt droplet is small due to the small time after the last droplet fragmentation and a contribution of the melt convection. But this is not the case for the period of the droplet solidification. The
thermal radiation modeling in melt–coolant interactions

Variants of simulation and calculation by use of the LCRM.

Figure 7. Volume fraction of steam; calculation by use of the LCRM.

The mathematical formulation (37) should be simplified for the use in the integrated CFD code. The problem analysis by Dombrovsky and Dinh (2008) showed that tem-
temperature profiles in the solid crust layer on the particle surface are almost linear at the initial stage of solidification and one can consider the following approximation of the temperature profiles during this period:

\[ T(r, t) = T_m - [T_m - T_i(t)] \frac{r - r_f}{a_i - r_f} \Theta(r - r_f) \]  

(38)

where \( T_i(t) = T(a_i, t) \) is the particle surface temperature and \( r_f \) is the current radius of the solidification front inside the particle. The boundary condition at \( r = 0 \) is satisfied.

Substitution of Eq. (38) into the boundary condition at \( r = a_i \) gives

\[ T_m - T_i = \frac{q_{t,i}(a_i - r_f)}{k} \]  

(39)

Equation (38) should satisfy the equation of thermal balance, which is obtained from integration of Eq. (37a) along the radius,

\[ \rho a_i \left( c \frac{dT}{dt} + 3L \bar{r}_f^2 \frac{d\bar{r}_f}{dt} \right) = -3q_{t,i} \]  

(40)

where \( \bar{r}_f = r_f/a_i \) and the average (bulk) particle temperature \( \bar{T} \) is expressed as

\[ \bar{T}(t) = \frac{3}{a_i^3} \int_0^{a_i} T(r, t) r^2 dr = T_m - \frac{T_m - T_s}{4} \left( 3 - \bar{r}_f - \bar{r}_f^2 - \bar{r}_f^3 \right) \]  

(41)

After simple transformations, we obtain the following Cauchy problem for coupled ordinary differential equations:

\[ \left[ (T_m - T_i) \frac{1}{4} + 2\bar{r}_f + 3\bar{r}_f^2 \right] \frac{d\bar{r}_f}{dt} + \frac{3 - \bar{r}_f - \bar{r}_f^2 - \bar{r}_f^3}{4} \frac{dT_i}{dt} = -3q_{t,i} \rho c a_i \]  

(42a)

\[ \frac{dT_i}{dt} = \frac{q_{t,i}}{k/a_i + h_{t,i} (1 - \bar{r}_f)} \frac{d\bar{r}_f}{dt}, \quad h_{t,i} = h + \frac{dq_{c,i}}{dT_i} \]  

(42b)

\[ \bar{r}_f(0) = 1, \quad T_i(0) = T_m \]  

(42c)

In the derivation of Eq. (42b), it was assumed that the total heat transfer coefficient \( h_{t,i} \) is almost constant during particle solidification. The subsequent numerical results confirm this assumption. Of course, we also do not consider the temperature dependence of the heat capacity and thermal conductivity of corium in this model. The problem (42) should be solved from \( t = 0 \) to \( t = t_{sol} \), which is defined by the equation \( \bar{r}_f(t_{sol}) = 0 \). It was shown by Dombrovsky and Dinh (2008) that an approximate solution gives good results when \( \bar{r}_f > 0.5 \), but the error increases in the final period of solidification and
the solidification time is underestimated in this approach. Nevertheless, one can obtain fairly good results for the particle surface temperature that is important for heat transfer calculations.

It is instructive to note that Moriyama et al. (2006) and Pohlner et al. (2006) employed the parabolic model to obtain approximate relations for the temperature difference between the center and the surface of a corium particle. The so-derived approximate relations were recommended for implementation into FCI simulation codes. It is well known that the parabolic model gives good results for quasi-steady heating or cooling of the particle with heat absorption or generation inside the particle without phase changes (Dombrovsky and Sazhin, 2003a,b; Dombrovsky and Lipiński, 2007). However, the parabolic model is not applicable to a solidifying melt droplet.

The approximate differential model (42) has two advantages over the simplest model of isothermal particles. The first obvious advantage is that calculations of heat transfer between the corium and water are more accurate. But it is also important that we obtain quantitative information on the dynamics of solidification of the corium particles. The crust layer on the surface of solidifying particles should be taken into account in the estimates of possible further fragmentation of the melt particles. The latter is especially important for predicting the melt explosivity at specific conditions of FCI. Obviously, the breakup models cannot be based only on the value of the volume-averaged temperature of the particle. A role of the surface crust layer in stability of solidifying corium droplets by action of a pressure drop in a fast expanded steam blanket has been analyzed recently by Dombrovsky (2007c). The model suggested by Dombrovsky (2007c) was based on the problem (42) solution for the initial period of the particle solidification.

In this paper, we complete the above-presented approximate model by the parabolic model for the period just after total solidification of the particle with

\[ T(r, t) = T_c(t) - [T_c(t) - T_i(t)] \left( \frac{r}{a_i} \right)^2, \quad t > t_{sol} \]  

(43)

At the initial time moment, one can assume \( T_i \) to be equal to \( T_i(t_{sol}) \) taken from the above-presented solution. Note that there is no rigorous matching condition at \( t = t_{sol} \) because it is impossible to satisfy all the physical conditions in this approximation: the conservation of energy and the absence of jumps in heat flux and surface temperature. Fortunately, this is not so important because the temperature difference in a solid particle is much less than that during the particle solidification. After obvious rewriting, one can obtain the following ordinary differential equation for the particle surface temperature:

\[ \frac{dT_i}{dt} = -\frac{3}{\rho c a_i} \frac{q_{t,i}}{1 + 0.2 (a_i/k) h_{t,i}} \]  

(44)

After solving the initial-value problem for the surface temperature, one can determine the average (bulk) temperature of the particle,
\[ \bar{T} = 0.4T_c + 0.6T_i, \quad T_c = T_i + \frac{q_{\text{rad},i}a_i}{2k} \]  

Some numerical results illustrating the role of the temperature difference in corium particles are presented in Figs. 8 and 9. We have not revised the breakup model used in the code VAPEX-P. Only the effect of particle nonisothermicity on heat transfer was taken into account in these calculations. One can see that the nonisothermicity of corium particles is an important factor, especially for prediction of the average (bulk) temperature of the particles. Note that this effect has an opposite sign with respect to the effect of thermal radiation, so that ignoring both thermal radiation and temperature difference

**Figure 8.** Bulk temperature of corium particles near the pool bottom (calculation by use of the LCRM): 1, isothermal model; 2, approximate model (42).
Figure 9. Variation of averaged bulk temperatures of corium particles with the depth (calculation by use of the LCRM): I. \(d = 3–4\) mm; II, \(d = 6–7\) mm; 1, isothermal model, 2, approximate model (42).

in the particles leads to results that are not too far from those obtained on the basis of more sophisticated models. Fortunately, the increase in computational time in comparison with the isothermal model is insignificant (less than 5%), which is acceptable for practical calculations.

A time variation of the temperature of single corium particles during their cooling and solidification is illustrated in Fig. 10, where the model calculations at a representative constant value of heat transfer coefficient \(h = 300\) W/(m\(^2\)K) (Liu and Theofanous, 1995; Dinh et al., 1999b) and two realistic values of corium emissivity \(\varepsilon_c\) are presented.
Figure 10. Comparison between surface temperature (I) and average (bulk) temperature (II) of corium particles: 1, $d = 3$ mm; 2, $d = 5$ mm; 3, $d = 7$ mm.

The surface temperature $T_i$ and average temperature $\bar{T}$ of the particles were calculated by the above-suggested approximate differential model. Small jumps on the average temperature curves at the moment of solidification completion are not physical. As was discussed above, this effect is explained by the approximate matching of solutions for solidifying and solid particles. One can see in Fig. 10 that the difference between the surface and average temperatures of corium particles during their solidification is significant. It may reach 300 K even for not-so-large particles of diameter $d = 5$ mm. The numerical results obtained at $\varepsilon_c = 0.7$ and 0.85 are similar to each other and the quantitative difference between them is relatively small. Obviously, the uncertainty of thermal
conductivity of corium near the melting temperature (in our calculations, $k = 3 \text{ W/(m K)}$) is the main source of possible considerable errors. This uncertainty makes reasonable the use of the approximate model for the temperature profile in corium particles.

**ADVANCED COMPUTATIONAL MODELS FOR THERMAL RADIATION FROM THE ZONE OF MELT–COOLANT INTERACTION**

The problem considered in this section does not concern the heat transfer calculation in FCI that can be done by use of the LCRM or other simplified radiation models. But it may be important to predict the thermal radiation exiting from the zone of intensive melt–coolant interaction. This shortwave radiation (in the visible and near infrared) is a source of additional information on the FCI parameters and, potentially, it can be used both in laboratory studies and in industrial alarm systems.

It is natural to use the field of spectral radiation energy density $I^0_\lambda(\vec{r})$ from LCRM calculations as a first step of the problem solution. This can be done by using the transport approximation of scattering phase function $\Phi_\lambda$ [e.g., Dombrovsky (1996a,b)],

$$\Phi_\lambda(\vec{\Omega}'\vec{\Omega}) = (1 - \bar{\mu}_\lambda) + 2\bar{\mu}_\lambda \delta \left(1 - \vec{\Omega}'\vec{\Omega}\right)$$

and the corresponding simplified RTE,

$$\vec{\Omega} \nabla I_\lambda(\vec{r},\vec{\Omega}) + \beta_\lambda^{tr} I_\lambda(\vec{r},\vec{\Omega}) = S_\lambda(\vec{r}), \quad S_\lambda(\vec{r}) = \frac{1}{4\pi} \left[ \sigma_\lambda^{tr} I^0_\lambda(\vec{r}) + p_\lambda(\vec{r}) \right]$$

One can see that the radiation source function $S_\lambda$ is known from the LCRM or $P_1$ solution. The subsequent integration of Eq. (47) by a ray-tracing method is not a too difficult task. It was shown by Dombrovsky (2006a,b) that the combined two-step solution gives fairly good results, even in the case of complex angular dependences of the radiation intensity.

Of course, one can use another computational model such as Monte Carlo simulation that allows the exact numerical solution of the problem for an arbitrary scattering function to be obtained. This general procedure is successfully used for thermal radiation from the exhaust plumes of solid-propellant rocket engines (Surzhikov, 2004). Note that the exhaust plume radiation in the visible and near infrared is also determined by molten and solid metal oxide particles (Laredo and Netzer, 1993). But these micron-size aluminum oxide particles are much smaller than corium particles in FCI. As a result, the optical thickness of the rocket plumes is usually very large and the continuous radiative transfer model is appropriate for this problem.

One can also consider the thermal radiation of metal oxide particles (usually, aluminum oxide or zirconium oxide) in plasma spraying (Fauchais, 2004). This problem is an example of the opposite limiting case of an optically thin medium because of the
comparably small cross-sectional size of the two-phase jet. In the optically thin limit, the radiative transfer problem degenerates and it is sufficient to consider thermal radiation from single particles (Dombrovsky and Ignatiev, 2003).

In the visible spectral range, either limiting case of an optically thin or optically thick multiphase medium can be realized in FCI problems. The optical thickness can be estimated by use of the following approximate formula:

\[
\tau = 2R (\alpha_c + \sigma_{tr}) \approx 1.5R \left( 0.8 \frac{f_{c}^c}{a_{c}^c} + 0.3 \frac{f_{s}^s}{a_{b}^s} \right)
\]

(48)

where \( R \) is the radius of the zone of intensive melt–coolant interaction. One can see that in the realistic case of \( R = 0.5 \text{ m} \), \( f_{c}^c = f_{s}^s = 0.05 \), \( a_{c}^c = a_{b}^b = 0.03 \text{ m} \), we have \( \tau \approx 1.4 \). This is an intermediate optical thickness, which allows employing alternative approaches (continuous or discrete) for the problem analysis. The authors prefer to use the continuous radiation model and the two-step approximate solution described above.

**CONCLUSION**

The recently developed large-cell radiation model (LCRM) based on the spectral radiation balance for single computational cells was implemented into the integral code VAPEX-P for multiphase flow simulation of fuel–coolant interaction (FCI) in a hypothetical severe accident of a light-water nuclear reactor. The analysis of thermal radiation effects and verification of the LCRM were performed for model problems of different scales.

The calculations for model problems showed that the role of thermal radiation in hydrodynamic and thermal interaction of the melt jet with ambient water is significant. The integral effect of radiation is well described by the opaque medium model, but the LCRM gives noticeable corrections of the particle size distribution and temperature of large melt droplets at the initial stage of FCI. The verification of the LCRM by comparison with the diffusion approximation (P1) confirmed that the LCRM is a very good approach for the majority of computational cells, which are characterized by a not-too-high volume fraction of steam. Moreover, the typical error of the LCRM is moderate, even for “steam” cells. Therefore, this model can be recommended for engineering calculations.

All the relations of the LCRM, including those for radiative characteristics of a polydisperse multiphase medium and for emitted and absorbed radiation power, are presented in this paper. This makes possible the use of this model in other multiphase CFD codes. The implementation of the algebraic LCRM into VAPEX-P was not a source of any computational difficulties and the increase in the computational time of about 20% is considered as a reasonable cost for additional possibilities of this improved radiation model. The use of the LCRM enables us to take into account the radiation heat transfer...
between corium particles of different temperatures and to determine the field of spectral radiation energy density in the computational region. It is important that the LCRM includes a correct estimate of the radiation power absorbed in water far from the steam-water interface. This radiation power does not directly contribute to steam production. The latter circumstance can be used to improve the model of water heating and steam production realized in the present-day multiphase CFD codes.

The field of radiation energy density obtained by the LCRM can be used in a combined radiation model discussed in this paper to calculate the visible and near-infrared thermal radiation in an arbitrary direction from the zone of intensive melt–coolant interaction. The corresponding additional information may be useful both for laboratory studies and industrial alarm systems.

The recently developed approximate model for solidification of a single opaque corium particle is modified to include the period of the particle cooling after complete solidification. The modified model was implemented in the code VAPEX-P to take into account the nonisothermicity of corium particles. The calculations showed that the difference between surface and average temperatures of solidifying particle of diameter 5 mm may reach about 300 K and the overall effect of particle nonisothermicity on FCI parameters is considerable. This is especially important for the predicted bulk temperature of corium particles during formation of a particulate debris bed at the pool bottom. The typical increase in computational time to account for a particle’s nonisothermicity in comparison with the isothermal model is < 5%, which is acceptable for practical calculations. The new model also includes determination of the transient position of the solidification front in the particle. The predicted thickness of a solid crust on the particle surface can be used to improve the current models for corium particles’ fragmentation at the final stage of the FCI premixing process.

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