
HEAT AND MASS TRANSFER, PROPERTIES
OF WORKING FLUIDS AND MATERIALS

Modified Relationship for Nusselt Numbers on the Side Surface of a Flat Metal Layer of Melt Heated from Below

V. D. Loktionov^{a, b, *}

^a National Research University Moscow Energy Institute, Moscow, 111250 Russia

^b Elektrogorsk Research Center for the Safety of Nuclear Power Plants (AO ENITs), Elektrogorsk, Moscow oblast, 142530 Russia

*e-mail: LoktionovVD@mpei.ru

Received April 5, 2023; revised May 26, 2023; accepted June 27, 2023

Abstract—An analysis was made of the developed modified Nusselt number ratio Nu for estimating thermal loads on the surfaces of a flat horizontal layer of metal melt (liquid-metal coolants, metal melt layers formed inside nuclear power plant (NPP) containers during a severe accident, etc.), heated along its lower surface and having an uneven radial temperature distribution. The need for such an analysis is explained by the fact that the use of known relations for the Nusselt numbers Nu for a liquid/melt layer with an uneven longitudinal temperature distribution leads to significant errors in determining the heat transfer conditions at the boundary surfaces of the layer, which is critical, for example, when implementing the concept of retaining molten materials inside the nuclear power plant in case of a severe accident (SA). In the proposed relation for the Nu number on the lateral surface of the melt layer, both traditional (Rayleigh number) and additional parameters are used, taking into account the temperature conditions on its boundary surfaces (including the lateral one) as well as the dimensions of the layer. To find the unknown coefficients in the modified ratio, the results of several series of numerical experiments were used by the domestic ANES CFD code. Using the ratio obtained for the Nu number, a parametric analysis of the heat-transfer conditions on the side surface of the metal layer of the melt formed during an SA was carried out. According to the results of the analysis, the proposed ratio gives good accuracy in calculations (on average, the error did not exceed 7%) and the predictive efficiency of the developed modified ratio for Nu numbers in the range of Rayleigh numbers from 10^6 to 10^{12} . Such a relation for the Nu numbers on the side surface of the melt layer can be used in assessing the thermal loads on the nuclear power plant container during an SA and in other problems where there is a radial nonuniformity of the temperature distribution in a flat liquid/melt layer heated from below.

Keywords: Nusselt number, corium melt layer, CFD simulation, reactor, severe accident, thermal load

DOI: 10.1134/S004060152312008X

The issues considered in this paper are closely related to the well-known problem of retention of molten materials of the core and internal devices inside the nuclear reactor container (NRC) during a severe accident (IVMR problem—In Vessel Melt Retention problem) [1–5], when in the lower part the reactor container, a stratified bath of high-temperature corium melt with a high level of residual energy release is formed. In the case of melt stratification, a less dense layer of metal components of the melt (steel, zirconium) is formed above the denser oxide (uranium and zirconium dioxide) fuel part of the corium melt. With such a configuration of the melt, the effect of focusing the thermal load [1–3, 6–11] (the so-called thermal knife) can occur in the area of contact of the NRC with the side surface of the upper metal layer of the melt, in which high-intensity thermal loads (over 1.5 MW/m^2), causing heating and melting, up to through penetration of the wall of the reactor container. At the same time, with a decrease in the thick-

ness of the metal layer of the melt, the lower surface of which is heated by the heat-generating oxide phase of the melt, the focusing effect of the thermal load increases. Since the thermal loads on the NRC determine both the dynamics of its wall melting and the possibility of external cooling of the pressure container during an SA, obtaining more accurate and timely estimates of the heat load and its distribution over the reactor pressure container is an important and urgent task.

The beginning of systematic studies of heat-transfer processes and phenomena in the corium melt bath and assessment of thermal loads at its boundaries during an SA was initiated more than 35 years ago by the famous scientist T.G. Theofanous and his colleagues [1–5]. However, the complexity of the interrelated thermophysical, thermomechanical, and thermochemical processes in the reactor container and in the melt pool and the formation of multilayer stratified structures in it [6, 7, 12] make an in-depth study of thermophysical processes in the corium melt under

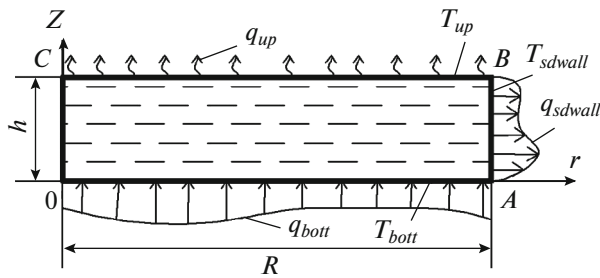


Fig. 1. Thermal scheme of the melt layer heated along the lower surface and cooled along the upper and side surfaces; h is the thickness of the melt layer; R is its radius; r is the radial coordinate of the layer; T_{up} , T_{bottom} , and T_{sdwall} are the temperatures of the upper, bottom, and side surfaces, respectively; q_{up} , q_{bottom} , and q_{sdwall} are the heat flux density on the upper, bottom, and side surfaces, respectively.

SA conditions even more relevant. One of the key problems, the solution of which determines the success of the implementation of the IVMR strategy and the prevention of the release of radioactive materials into the external environment during an SA, is the assessment of the thermal load acting on the NRC from the side of the melt pool. Only having the results of such an assessment, it is possible to reasonably apply one or another strategy for managing a severe accident: external cooling of the reactor container, internal flooding, cooling of the melt, etc.

Various methods and approaches are used to determine the thermal loads acting on the NRC under SA conditions. In particular, the numerical simulation of the thermal state of the melt pool is widely used with computational codes based on CFD technology and other approaches [1, 5–14]. The peculiarities of CFD modeling in the case under consideration are the laboriousness and time costs for preparing the initial data and obtaining numerical results. Another fairly widespread approach is based on the use of specialized calculation programs/codes for the analysis of severe accidents in nuclear power plants (for example, the domestic integrated code SOCRAT [15] and similar foreign codes RELAP/SCDAP, ASTEC, and MELCOR [16–19]). In such computational programs, the assessment of thermal loads at the boundaries of the corium melt pool is carried out, as a rule, using formulas from [1–3, 12, 20–27] for Nusselt numbers in the form of functions $Nu = f(Ra, Pr)$ and $Nu = f(Pr, Gr)$, where Ra , Gr , and Pr are the Rayleigh, Grashof, and Prandtl numbers, respectively, both for the outer surfaces of the melt bath and for its inner boundaries (between the layers of the melt).

With the obvious attractiveness of this approach to determining the heat-transfer conditions at the boundaries of the melt pool during an SA, there are several problems that need to be solved. One of these problems is a significant difference in the conditions (geometric parameters, scale factor, thermophysical

properties of the model medium, boundary conditions and flow regime of the medium, values of the characteristic Rayleigh numbers, etc.) under which the experimental data were obtained and on the basis of which the corresponding formulas were established to determine the numbers Nu under real conditions of the flow of an SA in a nuclear power plant. For example, when analyzing an SA, the well-known relation for determining the Nu number on the horizontal surfaces of a flat liquid/melt layer heated from below, which was derived by the authors of [25] more than 60 years ago, is widely used:

$$Nu = 0.069Ra^{1/3} Pr^{0.074} \quad (1)$$

Subsequently, on the basis of formula (1), similar relations were obtained [1, 5, 20, 21, 26, 27] to estimate the Nusselt numbers and heat-transfer conditions in a flat liquid/melt layer when its lower surface is heated. Thus, the well-known formula from [26],

$$Nu = \left[0.825 + \frac{0.387Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right]^2, \quad (2)$$

is used to determine the Nu numbers on the lateral surface of the horizontal layer (Fig. 1) for Ra values ranging from 0.1 to 10^{12} and any value of Pr .

It should be noted that the use of formulas of the form (1) and (2) and other similar relationships for estimating the Nu numbers and analyzing the thermal loads on the reactor pressure container during severe accidents often leads to an unjustified underestimation of the thermal loads compared to similar values obtained by numerical modeling (CFD, FEM, etc.) of the thermal state of a stratified melt pool during a severe accident [6–10, 13, 28, 29]. The reason for such differences in the values of the number Nu and the thermal load acting on the NRC during an SA can be explained, in particular, by the fact that formulas (1) and (2) were created, as a rule, on the basis of experimental data obtained on small-scale installations [25] and for media (materials) [26], the thermophysical properties of which differ significantly from the properties of melts that also form during an SA. For example, formula (1) was obtained as a result of small-scale experiments [25] on a setup in which the side wall of the vessel was made of Plexiglas, which has a low thermal conductivity. The wall thickness was such that heat removal from it to the external environment was negligible. Due to such conditions for performing experiments [25], as well as the small dimensions of the setup and the model liquid layer (the diameter of the vessel did not exceed 0.25 m), when it circulated along the lateral vertical surface, the temperature of the liquid layer remained almost unchanged. With such a heat-transfer scheme, formula (1) obtained on the basis of experimental data fully corresponds to the case when there is hardly any radial nonuniformity of the temperature distribution in the liquid layer, and the heat-transfer conditions on the lateral vertical sur-

face of this layer are to a large extent similar to the adiabatic boundary conditions.

At the same time, the conditions for the flow of a real SA in a nuclear power plant are characterized by a different picture of the interaction of a high-temperature corium melt (both its metal and oxide components) with the surface of the reactor container. In particular, the metal layer (see Fig. 1) of the melt, the average temperature over which is significantly higher (by 100–400 K) than the melting temperature of the entire composition of materials of this layer (including steel, zirconium, etc.), is in contact along its lateral vertical surface AB with a colder surface of the steel reactor container, the melting point of which is 1670–1770 K, and the outer surface of the container can be cooled during an SA. In this case, the radial nonuniformity of the temperature distribution in this melt layer [6, 7, 13] is comparable (or exceeds it) with the temperature difference of the lower OA (heated surface from the side of the oxide layer) and upper CB layer surfaces (see Fig. 1), which determines the values of the Rayleigh and Nusselt numbers according to formulas (1) and (2). In this case, relations (1) and (2) do not take into account the radial nonuniformity of the temperature distribution in such a layer of the melt.

To justify the applicability of formulas (1) and (2) to determine the Nu numbers and their “adaptation” to the conditions of the SA flow in a nuclear power plant, the values of the multipliers and exponents for the numbers Ra and Pr in these ratios vary, and their specific values for various model liquids (water, aqueous solutions of salts, molten salts, etc.) are determined on the basis of experimental data or by a calculation and analytical method [9, 11].

To obtain such data and refine the values of the parameters in formulas (1) and (2) in relation to the SA problem, experimental facilities of various scales with different geometric characteristics were created. In order to check and refine the Nusselt numbers at the boundaries of the oxide bath of the melt with NRC of the VVER and PWR (AP-600, AP-1000) reactor plants, several large research projects were implemented (RASPLAV/MASKA, COPO, ACOPO, mini-ACOPO, BALI, LIVE, etc.) [1, 23, 30–36], while a research program and a large-scale COPRA experimental facility have been developed for reactor facilities being built in the PRC [37].

During the stratification of the corium melt under SA conditions, the most heat-stressed and subjected to the most intense thermal loads $q_{sd\ wall}$ (see Fig. 1) is the lateral vertical surface AB (the zone of contact of the metal layer of the melt with the wall of the NRC), and its lower horizontal surface OA contacts with the heat-generating oxide phase of the melt. As shown by the results of numerical simulation of heat-transfer processes on the surface of the melt layer performed using the ANES [28, 29, 38] and Star-CCM [13] CFD codes, the distribution of heat loads depends not only

on the temperature difference at its bottom (T_{bottom}) and upper (T_{up}) surfaces (see Fig. 1) but also on the temperature conditions on its side ($T_{sd\ wall}$) surfaces. In this case, there is a significant difference between the results of calculations performed using numerical CFD modeling [28, 29] and integral estimates of the Nu numbers using formulas (1) and (2). As noted in [28], the most probable reason for this difference is the impossibility of using (1) and (2) to take into account the uneven temperature distribution in the layer along its radial coordinate. In order to overcome this shortcoming, it is necessary to modify (1) and (2) in such a way as to take into account the uneven distribution of the temperature field along the radial coordinate of the liquid/melt layer.

To solve this problem, an attempt was made in the present work to develop such a modification of formula (1) by which it would be possible to determine the number Nu on the side surface of a layer of metal melt, heated along its lower surface and having an uneven temperature distribution along its radial coordinate, during the formation of a stratified corium melt bath at an SA. The results of CFD modeling of several series of experiments, which were used to determine the unknown parameters in the modified ratios for Nu, were used as initial data. In the course of the experiments, the thermal state of the model layer of the melt and the parameters of the heat-transfer conditions (the values of the internal heat-transfer coefficients and Nu and Ra numbers) on its lateral and lower surfaces were studied under conditions of natural convection at high Rayleigh numbers (over 10^6) and various heat-transfer conditions on its boundary surfaces. The results of the study are presented below.

OBJECT OF INVESTIGATION AND METHOD FOR DETERMINING THE CHARACTERISTICS OF HEAT TRANSFER ON BOUNDARY SURFACES OF A LAYER OF MELTING HEATED FROM BELOW

The approach used in this work to determine the heat-transfer parameters at the boundary surfaces of a flat layer of metal melt heated from below under natural convection conditions at high Rayleigh numbers in the case of an SA in a nuclear power plant is based on the use of CFD modeling of the thermal state of the model layer (see Fig. 1) liquid/melt. It was assumed that, under SA, a less dense (approximately $5\text{--}7\text{ t/m}^3$) layer of metal (steel, zirconium, etc.) melt is heated along its lower surface OA from the oxide, denser ($8\text{--}9\text{ t/m}^3$), fuel part of the corium melt bath layer located under it. On the upper surface CB layer, heat exchange occurs with the medium located above the upper surface of the layer (in-reactor space), and its side surface AB is in contact with the inner surface of the steel reactor container.

The possibility of separate consideration of the thermal state of the upper metallic and denser oxide layers of the melt pool during an SA is due to the fact that, as is believed, on the lower surface melt metal layer OA between the lower surface of the upper layer (see Fig. 1) and the underlying oxide phase of the melt, there is a solid boundary [1, 3–5], which is formed due to a significant difference between the melting/solidification temperatures of metal (1500°C) and oxide (2500°C) components of the corium melt during its stratification during an SA. Unfortunately, there are no reliable experimental data confirming or refuting this assumption, and the possibility of accepting such a condition is determined, as a rule, on the basis of the internal consistency of this hypothesis.

Numerical simulation of the thermal state of the layer under study was performed under various conditions of heat transfer on its surfaces as well as by varying the geometric dimensions of the cylindrical layer: radius R and thickness h . In this case, the simulation of the thermal state was carried out in accordance with a specially developed matrix of numerical experiments, and the results of modeling these series of experiments were used in subsequent statistical processing when finding the parameters of functional relationships for Nusselt numbers. Such functional relations for the Nu numbers included both the thermophysical characteristics of the model melt/liquid and the dimensions of the layer as well as the temperatures on its boundary surfaces (lower, upper, and side) (see Fig. 1).

When performing numerical simulation on the lower (OA), upper (CB), and side (AB) layer surfaces, boundary conditions of the first kind were set with temperature values T_{bottom} , T_{up} , and $T_{sd\ wall}$, respectively. The temperature distributions on each of the layer surfaces were assumed to be uniform, and their values remained constant in each of the experiments but varied within the limits of a series of numerical experiments. The assumption of a uniform distribution of temperatures on the surfaces of the melt layer is generally accepted [1–6, 12, 14, 20–24] when analyzing an SA using the ratios for the Nu numbers when the calculation method uses the averaged temperatures of both the surfaces of the melt bath and volume-averaged temperatures of various phases of such a corium melt bath.

The numerical simulation of the thermal state of the melt layer was carried out by varying its geometric dimensions. Thus, changing the radius R layer was carried out in the range from 1.4 to 2.5 m, and the value of the aspect number (h/R) ranged from 0.1 to 0.8. In this case, the values of the Rayleigh number Ra ranged from 10^6 to 10^{12} . The number Ra was calculated from the known dependence

$$Ra = g\beta\Delta Th^3 / (\nu a), \quad (3)$$

where g is acceleration of gravity; β is the volumetric thermal expansion coefficient of the model melt; and

ν and a are the kinematic viscosity coefficient and thermal diffusivity of the model melt, respectively.

The value ΔT was defined as the difference between the temperatures of the lower (T_{bottom}) and upper (T_{up}) melt layer surfaces with a height h (see Fig. 1). In numerical simulation, it was assumed that the coefficient of volumetric thermal expansion and the kinematic coefficient of viscosity of the model melt were $1.5 \times 10^{-4} \text{ K}^{-1}$ and $6.65 \times 10^{-7} \text{ m}^2/\text{s}$, respectively, and the thermal conductivity λ , heat capacity c_p and density ρ were $20 \text{ W}/(\text{m K})$, $654 \text{ J}/\text{kg}$ and $6500 \text{ kg}/\text{m}^3$. The specified thermophysical characteristics of the layer corresponded to the properties of the steel melt during an SA, when a stratified melt pool is formed [1, 6–14].

Also, when performing numerical simulation, it was assumed that there is no internal heat release in the layer under consideration. However, there are reasons to believe that, under certain conditions of SA flow, internal residual heat release can occur in the upper layer of the metallic melt and reach 10% of the total heat release in the corium melt [6], and this should be taken into account in further study of such systems.

The approach that was used when establishing dependencies for Nu numbers on the side (AB) of the layer surface was as follows. Based on the results of numerical CFD modeling of the thermal state of the melt layer in each of the experiments, the averaged values of the heat flux densities on the side ($q_{sd\ wall}$), lower (q_{bottom}), and upper (q_{up}) layer surfaces (see Fig. 1), as well as the average temperature value (T_{lay}) of the model medium in terms of the volume of the layer, were determined. The averaged values of these parameters thus obtained were used in further analysis of the internal heat-transfer coefficients between the melt layer with temperature T_{lay} and its surfaces. For the side surface OA layer, internal heat-transfer coefficient ($\alpha_{sd\ wall}$) was calculated from the ratio

$$\alpha_{sd\ wall} = q_{sd\ wall} / (T_{lay} - T_{sd\ wall}) \quad (4)$$

and used in determining the values of the Nusselt number for the side surface of the layer

$$Nu_{sd\ wall} = \alpha_{sd\ wall} h / \lambda. \quad (5)$$

The values of the Nusselt number obtained by formula (5) were the initial data for constructing functional dependences for the number Nu on the side surface of the model layer of the melt during statistical analysis.

Numerical simulation of the thermal state of the model layer was performed at different values of the temperature difference between the lower and side surfaces of the layer and at different values of the temperature difference between its lower and upper surfaces. The temperature difference varied in the range from 1 to 300 K, which corresponds to the conditions of a severe accident in a nuclear power plant [6–14]. In

the numerical simulation of the thermal state of the melt layer, we used the ANES CFD calculation code [38] developed at the National Research University MPEI and successfully used in the numerical simulation of a wide range of heat-transfer problems in various fields of technology and science. This code contains an extensive library of mathematical models, including turbulence models. The simulation of the process of natural convection in the considered model layer of the melt was carried out using the two-parameter turbulence model of the type available in the code $k-\omega$ with the universal wall functions proposed by Menter. In the simulation, an asymmetric structural grid of finite volumes (FV) was used with thickening near the boundary surfaces of the computational domain according to the law of hyperbolic tangent.

To assess the sensitivity of the numerical solution to the degree of discretization of the computational domain (CD), preliminary calculations of the thermal state of the model layer of the melt were performed with varying the sampling rate both in the radial direction (N_r) and in the thickness (N_z) of the layer (Fig. 2). In each of the numerical experiments performed, the error $eps(Nu_{sd wall})$ was estimated determining the number Nu on the lateral surface of the layer relative to its base value obtained with a discretization rate of CD equal to 350 and 330 along the radial coordinate of the layer and along its thickness, respectively. Such a sampling frequency for the “basic” variant was chosen experimentally by increasing it step by step until the difference in the values of the Nusselt number for the lateral surface of the layer determined for two “neighboring” (with different CD discretization) calculation variants did not exceed 0.2%. As follows from the results presented in Fig. 2 obtained for two values (175 and 250) of the FV discretization rate (N_z) over the layer thickness and varying it along the radial coordinate of the layer from 175 to 250, the relative error in determining the number Nu for the lateral surface of the layer did not exceed 4%. Subsequently, when performing simulations in a series of numerical experiments, a FV grid was used with CD discretization parameters, which ensured a calculation error for the number Nu on the side surface of the layer of no more than 2%.

To substantiate the choice of the turbulence model and the ANES calculation code as a computational tool in solving the problem under consideration, this code was used to simulate several experiments with mercury [25], the results of which were used, in particular, in developing the well-known relation (1). Figure 3 shows the approximation line 1 experimental data in the form of the dependence of the parameter $Nu \times Ra$ (by analogy with the figure in [25]) for the horizontal surface of the mercury layer heated from below,

$$Nu \times Ra = 0.051(Ra^{4/3}), \tag{6}$$

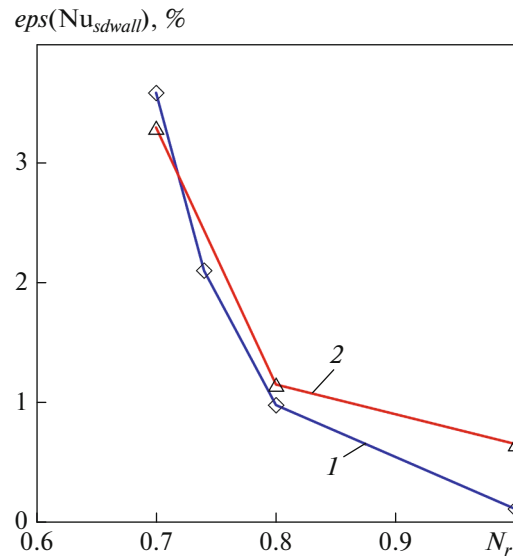


Fig. 2. Dependence of the relative error in determining the Nusselt number on the lateral surface of the melt layer $eps(Nu_{sd wall})$ on the relative grid frequency (N_r) FV by its radial coordinate at the values of the grid frequency over the layer thickness $N_z = 250$ (1) and 175 (2).

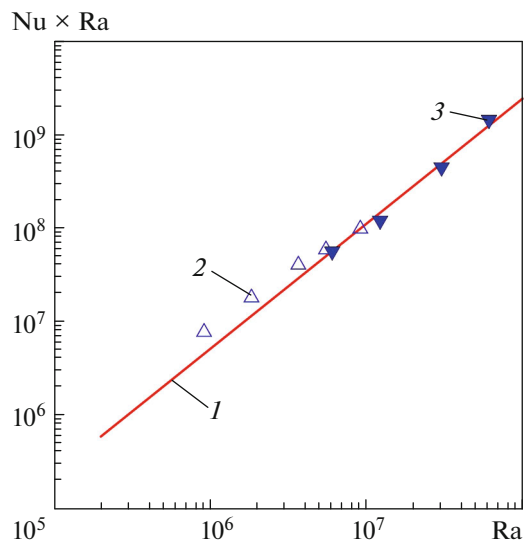


Fig. 3. Dependence $Nu \times Ra$ (1) on the Rayleigh number for horizontal surfaces of a flat layer of mercury with radius R heated from below [25] and the results of CFD simulation (2, 3) using the ANES code for different thicknesses (h/R) layer. (1) $No \times Ra = 0.051 Ra^{4/3}$; H/R : (2) 0.53, (3) 1.00.

as well as the results of numerical simulation (markers 2 and 3) of some experiments. The calculations were performed using the ANES code and the selected two-parameter turbulence model.

In Fig. 3, there is satisfactory agreement between the approximation straight line obtained from the

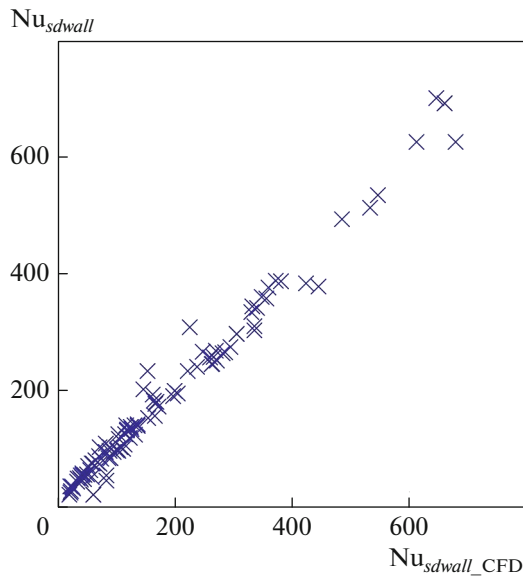


Fig. 4. Relationship between the values of the Nusselt numbers for the lateral surface of the horizontal layer of the melt determined by (8)–(10) ($Nu_{sd\ wall}$) and obtained on the basis of CFD modeling ($Nu_{sd\ wall_CFD}$).

experimental data and the results of CFD modeling for two thicknesses (h/R) of the mercury layer. With some tendency to increase, the difference between them for values of the number Ra is less than 2×10^6 .

When constructing the functional dependence for Nu on the side surface of the layer, the main problem was to choose the most convenient and accurate functional dependence that would not only allow taking into account the temperature difference between the lower and upper surfaces of the layer, as in well-known formulas (1) and (2), but also an uneven temperature distribution in its radial direction [6–8, 13, 28].

Therefore, in this work, as a functional dependence for the Nu number on the lateral surface of the melt layer, we considered a dependence of the form

$$Nu = ARa^n D(T)F(h, R), \quad (7)$$

where the first two terms are the free coefficient A and the Rayleigh number Ra and correspond to the traditional notation of similar relations for the numbers Nu , and the terms included in the additional factors $D(T)$ and $F(h, R)$ reflect the temperature conditions at the boundaries of the layer and its geometric characteristics, respectively. In this case, the choice of specific expressions for such additional factors in (7) is a separate and nontrivial problem for to be solved.

As a result of CFD modeling of several series of experiments (at least 60) for the model layer in accordance with the developed algorithms for their ghosting, initial data were obtained that were used in subsequent analysis and statistical processing to find unknown parameters in (7).

SIMULATION RESULTS AND THEIR DISCUSSION

To determine the specific type of dependence (7), functional relations of different structure for the factors $D(T)$ and $F(h, R)$ were considered. As a result, the choice was made on the following relation for the Nusselt number on the side surface of the melt layer:

$$Nu_{sd\ wall} = 0.527Ra^{0.25}D(T)F(h/R), \quad (8)$$

where

$$D(T) = \sqrt{\frac{T_{bott} - T_{sd\ wall}}{0.37(T_{bott} - T_{sd\ wall}) + 7(T_{bott} - T_{up})}}; \quad (9)$$

$$F(h/R) = \exp[(h/R)^{0.25}]; \quad (10)$$

the values of unknown parameters (exponents, coefficients) were determined on the basis of statistical processing of the results of a series of numerical experiments.

Influence of temperature conditions at the layer boundaries, represented by the factor $D(T)$ V (9), has an essentially nonlinear character and depends both on the temperature difference of the lower (T_{bottom}) and upper (T_{up}) of the horizontal surfaces of the layer and on the difference in the average temperatures of the lower (through which heat is supplied from the oxide layer) and lateral ($T_{sd\ wall}$) surfaces of this layer.

Figure 4 shows the values of $Nu_{sd\ wall}$ for lateral surface AB (see Fig. 1) determined using relations (8)–(10) (y -axis) and $Nu_{sd\ wall_CFD}$ obtained by numerical CFD simulation (abscissa axis). It should be noted that the temperatures on the layer surfaces, which were taken as boundary conditions when performing numerical CFD experiments, were used when calculating the numbers Nu according to (8)–(10).

It follows from the data in Fig. 4 that, in almost the entire range of Nu values (up to 700), there is a satisfactory agreement between the results of CFD modeling and calculation using relations (8)–(10). This indicates a fairly good predictive ability of the obtained relations (8)–(10). The error (averaged over the entire group of experiments) in determining the Nu number for the lateral surface of the melt layer does not exceed 7% in the ranges of Rayleigh numbers from 10^6 to 10^{12} and Nusselt (up to 700).

Based on the main goal of this study, it is important to evaluate the effect of boundary conditions on the surfaces of a horizontal layer of a metal melt on the heat-transfer parameters on its lateral surface on which the thermal loads on a nuclear reactor container under SA conditions largely depend.

Figure 5 shows the dependences of the Nusselt numbers on the lower Rayleigh number (curve 1) and side (2, 3) surfaces of the metal layer of the melt (steel, $Pr = 0.14$) as well as Nu numbers calculated from relations (8)–(10) for different values of the temperature

difference dT_{up} and dT_w surfaces of the considered layer (4–11). Here, the parameter $dT_{up} = (T_{bottom} - T_{up})$ corresponds to the difference between the averaged temperatures of the lower (T_{bottom}) and upper (T_{up}) surfaces of the model layer, while the parameter $dT_w = (T_{bottom} - T_{sd\ wall})$ is the difference between the averaged temperatures of its bottom and side ($T_{sd\ wall}$) surfaces. Curve 1 in this figure is constructed from dependence (1) for the Nusselt numbers on the horizontal surfaces of the layer under consideration [25], which is used in fairly wide ranges of Prandtl numbers (from 0.02 to 8750) and Rayleigh numbers (up to 10^9). Curve 2 in Fig. 5 corresponds to dependence (2) and curve 3 to the formula from [27]; the value obtained from it is the average of two values calculated using the known formulas for determining the Nu number on the side surface of the melt layer:

$$Nu = 0.5(0.6Ra^{0.19} + 0.0923Ra^{0.302}). \quad (11)$$

This choice of the structure of formula (11) is due to the fact that there are no sufficiently reliable and verified experimental data for the Nu number for the side surface of the horizontal layer of the melt.

In Fig. 5, markers 4–6 signify the calculated data corresponding to the cases of equality of the average temperatures of the surfaces of the melt layer ($dT_{up} = dT_w$). It should be noted that there is good agreement between the Nu numbers calculated from relations (8)–(10) for the lateral (vertical) surface of the considered layer (markers 4–6), and the results obtained by formula (1) (curve 1) and the Nu values for the horizontal (bottom and upper) surfaces of this layer. Moreover, the values of dT_{up} and dT_w do not have a significant effect on the degree of deviation of the Nu values calculated by (8)–(10) from those determined using (1); an increase in the absolute values of dT_{up} and dT_w (from 5 to 250 K) leads only to an increase in the Rayleigh number and, as a consequence, to an increase in the Nu number. When comparing the values of the Nusselt number for the surfaces of the melt layer, it becomes clear that the number Nu for the side surface of the layer (curve 2 in Fig. 5) exceeds the values for the lower surface (curve 1) over the entire range of the Ra number by 20–30% on average.

Significant discrepancies in the values of the Nu number determined by formulas (8)–(10) and “basic” relations (1) and (2) are observed when the values of the parameters dT_{up} and dT_w differ (curves 7–11 in Fig. 5). Moreover, with an increase in the difference between the values of dT_{up} and dT_w , there is a significant (many times!) increase in the Nu number compared to its “basic” values (curve 2) obtained by (2) for the side surface of the layer. For example, with $Ra = 10^9$, the number Nu determined using (2) (curve 2) does not exceed 100. When $dT_{up} = 5$ K and $dT_w = 250$ K, Nu is 350 (curve 7), which is more than 3.5 times higher

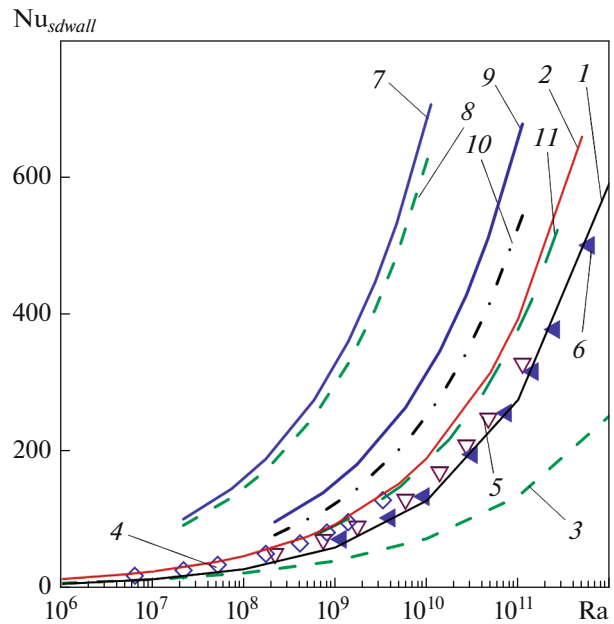


Fig. 5. Dependence of the Nusselt number $Nu_{sd\ wall}$ on the Rayleigh number Ra on the (1) bottom and (2–11) side surfaces of the metal layer of the melt at different values of temperature differences dT_{up} , dT_w , and $Pr = 0.14$. Dependence: (1) 1; (2) 2; (3) 11; (4) $dT_{up} = 5$ K, $dT_w = 5$ K; (5) $dT_{up} = 50$ K, $dT_w = 50$ K; (6) $dT_{up} = 250$ K, $dT_w = 250$ K; (7) $dT_{up} = 5$ K, $dT_w = 250$ K; (8) $dT_{up} = 5$ K, $dT_w = 150$ K; (9) $dT_{up} = 50$ K, $dT_w = 250$ K; (10) $dT_{up} = 50$ K, $dT_w = 150$ K; (11) $dT_{up} = 150$ K, $dT_w = 250$ K.

than the “basic” value. In the design case, for $dT_{up} = 50$ K and $dT_w = 250$ K, Nu does not exceed 150 (curve 9, in Fig. 5), which is 1.5 times greater than the “basic” value of Nu at $Ra = 10^9$.

As the Ra number increases, the difference between the “basic” values (curve 2) number Nu and similar values determined by relations (8)–(10) tends to increase (see Fig. 5). A significant increase in the Nu number on the side surface of the melt layer during an SA is critical with respect to thermal loads on the reactor vessel and maintaining its integrity during an SA.

It should also be noted that, with decreasing difference between the values of the parameters dT_{up} and dT_w , the difference between the numbers Nu determined by relations (8)–(10) and using (1) decreases (curve 1 in Fig. 5). Curve 1 and formula (1) corresponding to it are “asymptotes” for dependences (8)–(10) as the difference between the values of T_{up} and dT_w decreases. This phenomenon was discussed earlier and is related to the features of the experiments in [25] and the experimental data obtained on the basis of which relation (1) for the number Nu was derived.

When comparing calculated values (curves 4–11 in Fig. 5) of numbers Nu with the results obtained using (11) (curve 3), it was noted that the use of such an

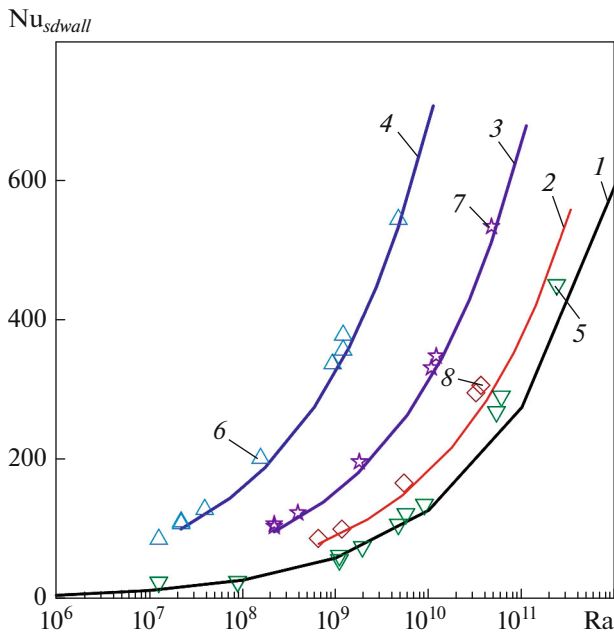


Fig. 6. Comparison of the values of the Nusselt number $Nu_{sd\ wall}$ on the side surface of the layer determined using relations (1) (1) and (8)–(10) (2–4), with CFD simulation results (markers 5, 6) at different values of the number Ra and temperature differences dT_{up} , dT_w , $Pr = 0.14$. (2) $dT_{up} = 150\ K$, $dT_w = 250\ K$; (3) $dT_{up} = 50\ K$, $dT_w = 250\ K$; (4) $dT_{up} = 5\ K$, $dT_w = 250\ K$; (5) CFD: $dT_{up} = dT_w = 5\text{--}250\ K$; (6) CFD: $dT_{up} = 5\ K$, $dT_w = 250\ K$; (7) CFD: $dT_{up} = 50\ K$, $dT_w = 250\ K$; (8) CFD: $dT_{up} = 150\ K$, $dT_w = 250\ K$.

“averaged” formula [27] to determine the number Nu on the side surface of the layer during an SA is not justified and leads to a significant underestimation of the values of Nu and the thermal loads acting on the nuclear reactor container from the metal layer of the melt under emergency conditions.

For comparison, the results of calculating the number Nu on the lateral surface of the layer according to relations (8)–(10) and (1) (for horizontal surfaces of the layer) and the data of CFD modeling using the ANES code of the thermal state of the melt layer (see Fig. 1) for calculated cases are shown in Fig. 6. Choice of ratio (1) (curve 1 in Fig. 6) to calculate the values of the Nu number on the horizontal surfaces of the layer is solely due to the convenience when comparing the results: relation (1) and the corresponding curve 1, as mentioned earlier, are the “asymptote” for dependences (8)–(10) when the temperatures of the upper and side surfaces of the layer are equal ($dT_{up} = dT_w$), which can be regarded as a limiting case.

Figure 6 also shows the results of CFD modeling (markers 5 and 6) using the ANES code of the calculated cases for different sizes of the model layer and values of the parameters dT_{up} and dT_w characterizing the temperature conditions at the layer boundaries.

The values of the number Nu determined on the basis of numerical simulation at equal temperatures of the upper and side surfaces ($dT_{up} = dT_w$) layer (markers 5 in Fig. 6) quite well coincide with the values of the Nusselt number calculated by relation (1) in the range of Rayleigh numbers from 10^7 up to 5×10^{11} . There is also a fairly good agreement between the Nu numbers determined from relations (8)–(10) (curves 2–4 in Fig. 6) and the results of CFD modeling (markers 6) for different values of the parameters dT_{up} and dT_w . Markers 6 correspond to calculated data and curves 2–4 at $dT_w = 250\ K$ and $dT_{up} = 150, 60,$ and $5\ K$, respectively.

The results in Fig. 6 allow us to conclude that the developed modified relation (8) has a good predictive ability for estimating the value of the Nusselt number on the side surface of the melt layer heated from below and the presence of an uneven radial temperature distribution in the melt in the considered range of Rayleigh numbers.

To verify the obtained modified relation (8) and the possibility of its use for estimating the number Nu on the side surface of the layer and analyzing the heat-transfer conditions in the stratified melt pool during an SA, it is extremely important to conduct experimental studies using model materials and under boundary conditions corresponding to the state of SA progression in a nuclear power plant.

It should also be noted that, in order to use relations (1) and (2) and similar ones [1, 3–5, 20–27] to estimate the Nu numbers on the boundary surfaces of the corium melt bath during an SA, additional in-depth analysis is required. The need for such an analysis is explained by the fact that many of these ratios for estimating the values of the Nu number at the boundaries of the melt pool were obtained on the basis of experimental data and under experimental conditions that differ significantly from the conditions of the SA flow, which can lead to significant errors and errors in assessment of thermal loads on the reactor container and, as a result, the impossibility of implementing the concept of in-container containment of the corium melt in an emergency in a nuclear power plant.

CONCLUSIONS

(1) The modified relation for determining the Nusselt number on the lateral surface of a horizontal layer of a metal melt makes it possible to take into account the radial nonuniformity of the temperature distribution in the layer. The modified ratio, in comparison with similar known formulas, includes additional factors that take into account both the temperatures of the lower, lateral, and upper boundaries of the melt layer and its geometric (aspect number) characteristics. Parametric analysis performed using the modified ratio for the Nu number, as well as comparison with the results of numerical CFD modeling, revealed

good accuracy (the average error does not exceed 7%) and the predictive ability of the obtained ratio for the Nu number in a wide range of Rayleigh numbers (from 10^6 to 10^{12}) and Nusselt (up to 700).

(2) When carrying out parametric analysis, a significant effect of the difference between the averaged temperatures of the upper and side surfaces of the melt layer on the Nusselt number for the side surface of the layer and, as a result, on the thermal loads acting from the melt on the reactor pressure container during a severe accident was established. An increase in the difference between the averaged temperatures of the upper and side surfaces of the layer leads to a significant increase in the Nusselt number and thermal loads acting on the side surface of the melt layer heated along its lower surface.

(3) When using the known relations for estimating the number Nu in the case of a radial nonuniformity of the temperature distribution in the liquid/melt layer heated along its lower surface, the values of the Nu number turn out to be significantly underestimated. This situation is critical in many cases, for example, when assessing the thermal loads on a nuclear reactor container during severe accidents.

(4) To confirm the performance of the developed modified ratio for the number Nu on the side surface of the horizontal layer of the melt liquid and the results obtained, it is necessary to set up and conduct additional experimental studies with prototype melts/model media under conditions close to those during severe accidents in nuclear power plants.

FUNDING

The work was financially supported by the Ministry of Science and Higher Education of the Russian Federation within the framework of the state order no. FSWF-2023-0017 (agreement no. 075-03-2023-383 dated January 18, 2023) in the field of scientific activity for 2023–2025.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. T. G. Theofanous, C. Liu, S. Additon, S. Angelini, O. Kymäläinen, and T. Salmassi, *In-vessel Coolability and Retention of a Core Melt*, DOE/ID-10460 (U.S. Department of Energy, 1996).
2. R. E. Henry and H. K. Fauske, “External cooling of a reactor vessel under severe accident conditions,” *Nucl. Eng. Des.* **139**, 31–43 (1993).
3. O. Kymäläinen, H. Tuomisto, O. Hongisto, and T. G. Theofanous, “Heat flux distribution from a volumetrically heated pool with high Rayleigh number,” *Nucl. Eng. Des.* **149**, 401–408 (1994). [https://doi.org/10.1016/0029-5493\(94\)90305-0](https://doi.org/10.1016/0029-5493(94)90305-0)
4. O. Kymäläinen, H. Tuomisto, and T. G. Theofanous, “In-vessel retention of corium at the Loviisa plant,” *Nucl. Eng. Des.* **169**, 109–130 (1997). [https://doi.org/10.1016/S0029-5493\(96\)01280-0](https://doi.org/10.1016/S0029-5493(96)01280-0)
5. T. G. Theofanous, C. Liu, S. Addition, S. Angelini, O. Kymäläinen, and T. Salimassi, “In-vessel coolability and retention of a core melt,” *Nucl. Eng. Des.* **169**, 1–48 (1997). [https://doi.org/10.1016/S0029-5493\(97\)00009-5](https://doi.org/10.1016/S0029-5493(97)00009-5)
6. V. D. Loktionov, E. S. Mukhtarov, and I. V. Lyubashevskaya, “Features of heat and deformation behavior of a VVER-600 reactor pressure vessel under conditions of inverse stratification of corium pool and worsened external vessel cooling during the severe accident. Part 1. The effect of the inverse melt stratification and in-vessel top cooling of corium pool on the thermal loads acting on VVER-600’s reactor pressure vessel during a severe accident,” *Nucl. Eng. Des.* **326**, 320–332 (2018). <https://doi.org/10.1016/j.nucengdes.2017.11.015>
7. V. D. Loktionov and E. S. Mukhtarov, “Estimation of thermal loads on the VVER vessel under conditions of inversion of the stratified molten pool in a severe accident,” *Therm. Eng.* **63**, 648–656 (2016). <https://doi.org/10.1134/S0040601516090032>
8. V. D. Loktionov, E. S. Mukhtarov, N. I. Yaroshenko, and V. E. Orlov, “Numerical investigation of the reactor pressure vessel behaviour under severe accident conditions taking into account the combined processes of the vessel creep and the molten pool natural convection,” *Nucl. Eng. Des.* **191**, 31–52 (1999). [https://doi.org/10.1016/S0029-5493\(99\)00051-5](https://doi.org/10.1016/S0029-5493(99)00051-5)
9. D. G. Grigoruk and P. S. Kondratenko, “Focusing effect in heat transfer of a multicomponent liquid with internal heat sources,” *High Temp.* **39**, 157–158 (2001).
10. N. G. Rassokhin, V. D. Loktionov, and E. S. Mukhtarov, “A combined thermal and strength analysis of the behavior of a VVER-440 reactor’s vessel during an accident involving core melting,” *Therm. Eng.* **53**, 675–681 (2006).
11. D. G. Grigoruk, V. F. Strizhov, and A. S. Filippov, “A numerical investigation of heat transfer of stratified melt with volumetric heat release in the bottom layer,” *High Temp.* **46**, 386–392 (2008).
12. A. Nieminen, “The effect of late-phase melt pool configuration on pressure vessel rupture,” in *Proc. 6th Eur. Review Meeting on Severe Accident Research (ERMSAR-2013)*, Avignon, France, Oct. 2–4, 2013 (Pregamon, Oxford, 2014).
13. N. A. Kochetov, V. D. Loktionov, and A. S. Sidorov, “Using the Star CCM+ software system for modeling the thermal state and natural convection in the melt metal layer during severe accidents in VVER reactors,” *Therm. Eng.* **62**, 663–672 (2015). <https://doi.org/10.1134/S0040601515050055>
14. P. S. Kondratenko, D. V. Nikol’skii, N. N. Samkharadze, and M. E. Chizhov, “Free convection of a heat generating fluid in a hemispherical closed volume,” *High Temp.* **49**, 725–730 (2011).
15. *Integral Code SOKRAT for Severe Accidents* (Inst. Probl. Bezop. Razvit. At. Energ. Ross. Akad. Nauk, Moscow, 2013). <http://www.ibrae.ac.ru/contents/267/>

16. L. J. Siefken, E. W. Coryell, E. A. Harvego, J. K. Horsch, *SCDAP/RELAP5/MOD 3.3. Code Manual: User's Guide and Input Manual*, NUREG/CR-6150 (U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC, 2001), Vol. 3, Rev. 2. <https://www.nrc.gov/docs/ML0103/ML010310311.pdf>
17. The ASTEC Software Package (IRSN). <https://en.irsn.fr/en/research/scientific-tools/computer-codes/pages/the-astec-software-package-2949.aspx>
18. *MELCOR Computer Code Manuals*, Vol. 3: *MELCOR Assessment Problems*, Version 2.1.7347, SAND 2015-6693 R (Sandia National Laboratories, 2015), ADAMS Accession No. ML15300A476. <https://melcor.sandia.gov/documentation.html>
19. D. Tarabelli, G. Ratel, R. Pélisson, G. Guillard, M. Barnak, and P. Matejovic, "ASTEC application to in-vessel corium retention," *Nucl. Eng. Des.* **239**, 1345–1353 (2009). <https://doi.org/10.1016/j.nucengdes.2009.02.021>
20. N. I. Kolev, "SWR 1000 severe accident control through in-vessel melt retention by external RPV cooling," in *Proc. 9th Int. Conf. on Nuclear Engineering (ICONE-9)*, Nice, France, Apr. 8–12, 2001 (Société Française d'Énergie Nucléaire, Nice, 2001).
21. N. I. Kolev, "External cooling of reactor vessels during severe accident," in *Multiphase Flow Dynamics 4: Nuclear Thermal Hydraulics* (Springer, Berlin, 2009), pp. 497–548. https://doi.org/10.1007/978-3-540-92918-5_16
22. N. Bakouta, R. Le Tellier, and L. Saas, "Assessment of advanced corium-in-lower-head models in MAAP and PROCOR codes," in *Proc. 7th Eur. Review Meeting on Severe Accident Research (ERMSAR-2015)*, Marseille, France, Mar. 24–26, 2015 (SARNET, Brussels, 2015), paper no. 003.
23. J. M. Bonnet, "An integral model for the calculation of heat flux distribution in a pool with internal heat generation," in *Proc. 7th Int. Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-7)*, Saratoga Springs, N.Y., Sept. 10–15, 1995 (U.S. Nuclear Regulatory Commission, Washington, DC, 1995).
24. H. Esmail and M. Khatib-Rahbar, "Analysis of likelihood of lower head failure and exvessel fuel coolant interaction energetics for AP1000," *Nucl. Eng. Des.* **235**, 1583–1605 (2005).
25. S. Globe and D. Dropkin, "Natural-convection heat transfer in liquid confined by two horizontal plates and heated from below," *J. Heat Transfer* **81**, 24–28 (1959). <https://doi.org/10.1115/1.4008124>
26. S. W. Churchill and H. H. S. Chu, "Correlating equations for laminar and turbulent free convection from a vertical plate," *Int. J. Heat Mass Transfer* **18**, 1049–1053 (1975). [https://doi.org/10.1016/0017-9310\(75\)90222-7](https://doi.org/10.1016/0017-9310(75)90222-7)
27. M. S. Sohal and L. J. Siefken, *A Heat Transfer Model for a Stratified Corium-Metal Pool in the Lower Plenum of a Nuclear Reactor*, Report No. INEEL/EXT-99-00763 (Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, 1999).
28. V. D. Loktionov and E. S. Mukhtarov, "The effect of heat transfer conditions at the boundary surfaces of a thin heated from below layer of metal melt on the nature of the melt flow under natural convection conditions at high Rayleigh numbers as applied to solving the problem of keeping the melt inside the nuclear reactor vessel during a severe accident," in *Proc. 8th Russian Natl. Conf. on Heat Transfer (RNTK-8)*, Moscow, Russia, Oct. 17–22, 2022, Vol. 1, pp. 169–170.
29. P. A. Bryzgunov, *Numerical Modeling of Heat Transfer Processes in Imitation Multilayer Melts with Internal Heat Release at High Rayleigh Numbers*, Bachelor's Graduation Qualification Paper (Moscow Power Engineering Inst., Moscow, 2019).
30. V. Asmolov, N. N. Ponomarev-Stepnoy, V. Strizhov, and B. R. Sehgal, "Challenges left in the area of in-vessel melt retention," *Nucl. Eng. Des.* **209**, 87–96 (2001). [https://doi.org/10.1016/S0029-5493\(01\)00391-0](https://doi.org/10.1016/S0029-5493(01)00391-0)
31. T. G. Theofanous, M. Maguire, S. Angelini, and T. Salmassi, "The first results from the ACOPO experiment," *Nucl. Eng. Des.* **169**, 49–57 (1996). [https://doi.org/10.1016/S0029-5493\(97\)00023-X](https://doi.org/10.1016/S0029-5493(97)00023-X)
32. J. M. Bonnet, "Thermal hydraulic phenomena in corium pools: The BALI experiment," in *Proc. Workshop on Severe Accident Research held in Japan (SARJ-98)*, Tokyo, Japan, Nov. 4–6, 1998 (Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken, Japan, 1999), pp. 79–86.
33. L. Bernaz, "Thermal hydraulic phenomena in corium pools: Numerical simulation with TOLBIAC and experimental validation with BALI," in *In-Vessel Core Debris Retention and Coolability: Proc. OECD/CSNI Workshop, Garching, Germany, Mar. 3–6, 1998* (OECD Nuclear Energy Agency, Paris, 1998), pp. 185–193.
34. O. Kymäläinen, O. Hongisto, E. Pessa, *COPO Experiments on Heat Transfer from a Volumetrically Heated Pool*, DLV1-G380-0377 (Imatran Voima Oy Process Laboratory, 1993).
35. M. Halle, O. Kymäläinen, and H. Tuomisto, "Experimental COPO II data on natural convection in homogeneous and stratified pools," in *Proc. 9th Int. Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-9)*, San-Francisco, Calif., Oct. 3–8, 1999 (American Nuclear Society, La Grange Park, Ill., 1999).
36. M. Buck, "The LIVE program — Results of test L1 and joint analyses on transient molten pool thermal hydraulics," *Prog. Nucl. Energy* **52**, 46–60 (2010).
37. Y. P. Zhang, L. T. Zhang, Y. K. Zhou, W. X. Tian, S. Z. Qiu, G. H. Su, B. Zhao, Y. D. Yuan, and R. B. Ma, "The COPRA experiments on the in-vessel melt pool behavior in the RPV lower head," *Ann. Nucl. Energy* **89**, 19–27 (2016).
38. *ANES/20XE: A Numerical Modeling Code of the Processes of Hydrodynamics and Heat and Mass Transfer. Description of Mathematical Models of the Code* (2015). <http://anesch12655.tmweb.ru>

Publisher's Note. Pleiades Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.