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METHOD FOR CALCULATING THE THERMAL STATE OF A DEPOSITED BED CONSISTING OF FRAGMENTS OF A DAMAGED CORE

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The steady thermal state of a deposited bed consisting of heat-evolving particles in a volume of coolant is considered. As a model of heat exchange in a porous medium, a one-dimensional model of stationary effective heat conduction is adopted. An initial differential equation with a system of boundary conditions is solved numerically using the method of explicit separation of phase boundaries. A computation program was developed and numerical results were obtained for the conditions of reactor experiments.

To secure the safety of atomic power stations it is necessary, among other measures, to consider the so-called off-design failures of nuclear reactors with an indispensable analysis of the removal of heat from the fragments of the damaged core within the reactor vessel at the last stage of the accident.

When molten materials of the core (nuclear fuel and steel) enter into interaction with the liquid coolant, they are broken up into small particles that accumulate on separate parts within the vessel. The size of the particles formed after fragmentation is for the most part below 1000 μm [1]. One of the places where porous beds are deposited is a special retaining tray meant for protection of the reactor vessel bottom (if such a tray is envisaged). The power of afterheats in fuel particles depends on the time that passed after loss of criticality of the core. Experimental investigations show that the main heat flux from the deposited heat-evolving bed is directed upward to the coolant that covers the fragments [1, 2]. In a thin bed heat is transferred by heat conduction and convection. If the thickness and/or the volumetric heat release rate are high enough, the temperature of the coolant that is in direct contact with the fuel particles attains the boiling point, with the vapor bubbles being carried out of the boiling zone. If the cooling of the fragments is insufficient, a portion of the bed may dry out and there the temperature of the fuel may, in turn, attain the melting point. Dryout occurs because of the onset of burnout, when the rate of generation of coolant vapor becomes higher than the velocity of inflow of liquid to the boiling bed. The temperature field and the phase state of the components within the heat-evolving bed are of interest, because in this bed a heat flux directed to the underlying surface is generated. Very high heat fluxes may cause high thermal stresses in the framework. Moreover, there is a danger that the molten fuel may penetrate from the bed directly to the framework. These factors may cause damage to the underlying structure.

Investigation of the conditions of heat transfer in a heat-evolving deposited bed is the concern of numerous experimental and computational works. Mathematical models are available for calculating temperature fields in a heat-evolving bed that are usually based on the phenomenological experimental information described, in particular, in [1]. Among important results of this type that were obtained, for example, in a series of reactor experiments carried out at the Sandia laboratory (U.S.) was the fact that in the absence of a liquid flow from below a dried patch appears in the lower portion of the zone with a two-phase coolant. A review of the program of experiments of series *D* is given in [3]. The most rigorous theoretical approach to the description of heat exchange in a bed of heat-evolving particles saturated with a coolant involves the solution of mass, momentum, and energy conservation equations. In [4] such a two-dimensional mathematical model is presented for analyzing heat exchange in a bed in the case of underheating, boiling, start of dryout, and evolution of a dry bed to the fuel melting temperature. However, from the first estimates the so-called method of simple heat conduction has become

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particularly widely used for calculating temperature fields in zones with a single-phase coolant. In such a model the temperature in the zone with a boiling coolant is simply assumed to be equal to the saturation temperature. To predict the start of the drying of a portion of the bed, empirical relations or computational models are used that are based on a more complex analysis of heat exchange in a boiling zone, as, for example, in [5]. Several computational relations are available for the critical heat flux from a two-phase zone at which dryout occurs. The most comprehensive survey of various dryout models and their comparative analysis for evaluating their conformity with experimental data are presented in [6]. The method of steady effective heat conduction was used to calculate the temperature in a bed with a liquid coolant, the thickness of the liquid zone with a boiling coolant in a portion of the bed, as well as the thickness of the zone dried of the coolant [7, 8]. It was found that the best agreement with experimental data is obtained when Kampf and Karsten's formula [9] is used for calculating the effective thermal conductivity of a medium consisting of solid particles and a liquid coolant, rather than other formulas presented in review [10]. A model of heat conduction that involves an asymptotic temperature field in zones with different phase states of the coolant and the fuel and in which the dimensions of all the zones are calculated with the aid of explicit mathematical expressions obtained by solving stationary heat conduction equations under corresponding boundary conditions was developed most comprehensively in [11]. A similar stationary computational model augmented with a criterion for assessing the type of boiling (in a filling or in a channel) for predicting the start of dryout is described in [12]. In computational evaluations with the use of explicit mathematical relations one has to average the values of the thermal conductivity coefficients within the limits of each computational zone because of the strong temperature dependence of the thermal conductivity of the components of the medium. Moreover, a characteristic feature of deposited beds that can be formed under the conditions of an accident is nonuniformity in diameters of particles, porosity, etc. over the bed volume (so-called stratification). In such a case, the computational process is again reduced, just as in the case of a numerical solution, to iterations. There are also nonstationary models based on the heat conduction method that are used for calculating temperature fields in deposited beds. The behavior of a porous heat-evolving bed in time from the initial moment of precipitation of particles up to the development of a steady state is described by the TRABED program [13]. Up to the start of boiling, the program takes into account internal convection of sodium, which is incorporated in the value of the effective heat conduction coefficient. The TRABED program is incapable of accounting for the melting of fuel in the dryout zone. A brief description of nonstationary models in one- and multidimensional formulations is given in [12]. These models meant for estimative computations also reduce to the solution of just the heat conduction equation (by the finite-difference method), and an effective heat conduction coefficient is also introduced in [12] for describing heat transfer in a zone with a boiling coolant. Stationary models are regarded as more accurate, since they can use experimentally verified computational relations for predicting the start of dryout in a zone with a two-phase coolant.

Consideration of the problem in a stationary formulation is correct for the case of a steady state, when the temperature field does not change in time, or for the case where the rate of its change is small enough. Therefore, this formulation is inapplicable for a certain initial period of warming up of a bed after it is formed by particles that were cooled during their sinking in the mass of cold coolant. If in the process of heating the temperature of the fuel does not exceed its boiling temperature, when the initial configuration can be disturbed, in the deposited bed a temperature field develops that corresponds to the level of heat release and to the conditions of cooling and that subsequently changes more slowly with a decrease in the rate of residual heat release in fuel particles. Such a quasistationary state can develop at a rather small thickness of the bed and level of heat release and at a sufficient intensity of heat removal from the deposited bed. In a fast reactor the time of the motion of the fuel from the core to the tray may amount to 3–5 h. In this time the rate of change of the volumetric heat-release is rather small and permits consideration of the problem in a stationary formulation. The increase in the temperature of the coolant surrounding the deposited bed should be rather slow due to the predominance of the mass of the coolant in the reactor vessel and to a certain level of coolant circulation in the loop.

In the present work, to calculate a one-dimensional temperature field in a porous heat-evolving medium we use a stationary model of effective heat conduction. The initial differential equation of concervation with a system of boundary conditions is solved numerically. This makes it possible to take account of the spatial dependence of

the effective coefficient of thermal conductivity. A specific feature of the present solution is the so-called explicit isolation of phase boundaries due to the use of a calculating scheme involving a nonuniform spatial grid with floating nodes and the method of oppositely directed pivots [14]. A computational algorithm developed for a conjugate problem of steady-state heat conduction in a plane geometry is implemented in the computation program STO for a computer. Specific conditions of heat exchange within and between the zones in the heat-evolving deposited bed considered (temperature dependences of the thermophysical properties of the components of an inhomogeneous medium, computational models for the effective coefficient of thermal conductivity, models for predicting dryout of a portion of the bed and calculating the size of the dry zone, conditions of heat exchange with the surrounding coolant, etc.) are realized in additional modules that, in conjunction with the main computation program indicated above, constitute the STO-BED program.

In the formulation adopted, the temperature field in a heat-evolving porous medium with a single-phase coolant is described by the following steady inhomogeneous heat conduction equation:

$$\frac{\partial}{\partial z}\lambda\,(z,\,T)\,\frac{\partial T\,(z)}{\partial z}+q_v\,(z)=0\,, \tag{1}$$

where $\lambda=\lambda_{\text{eff}}$ and $q_v=(1-\varepsilon)\cdot q_{vf}$. This very equation is also used to describe the temperature field in the dryout zone, including the presence of a zone of molten fuel in it. In Eq. (1) for the zone of the melt $q_v=q_{vf}$. In the zone with a two-phase coolant the temperature is simply assumed to be equal to the saturation temperature.

Equation (1) is augmented with a system of boundary conditions. On the lower and upper boundaries of the deposited bed a boundary condition of the third kind is adopted:

$$\begin{aligned}
-\lambda_{\text{eff}}\left.\frac{\partial T}{\partial z}\right|_{z=0^{+}} &= -\alpha_{\text{eff}}\,[T\,(z=0)-T_1]\,,\\
-\lambda_{\text{eff}}\left.\frac{\partial T}{\partial z}\right|_{z=H_b^{-}} &= \alpha_2\,[T\,(z=H_b)-T_2]\,.
\end{aligned} \tag{2}$$

where

$$\alpha_{\text{eff}}=\left[\frac{1}{\alpha_1}+\frac{\delta}{\lambda_\delta}\right]^{-1};$$

On the boundaries of the zones adjoining the zone with a boiling coolant the saturation temperature is adopted:

$$T\,(z=z_{LNa1})=T_{sNa}\,;\quad T\,(z=z_{LNa2})=T_{sNa}\,. \tag{3}$$

On these outer phase interfaces boundary conditions of heat transfer of the second kind are assumed. On the boundary between the lower zone and the boiling zone zero density of the heat flux is adopted according to [11]. On the boundary between the upper zone and the boiling zone it is adopted that the heat flux density is equal to the overall heat release from unit surface of the coolant boiling zone. Correspondingly, the boundary conditions are written in the form

$$-\lambda_{\text{eff}}\left.\frac{\partial T}{\partial z}\right|_{z=z_{LNa1}^{-}}=0\,;\qquad -\lambda_{\text{eff}}\left.\frac{\partial T}{\partial z}\right|_{z=z_{LNa2}^{+}}=q_s^{\text{boil}}\,, \tag{4}$$

where $q_s^{\text{boil}}=q_v\cdot H_{\text{boil}}$. Under adiabatic conditions on the lower surface of the bed the zone with boiling coolant extends to the bottom of the bed. As a criterion for the drying of a portion of the bed of the coolant we take the excess of the density of the heat flux from the boiling zone over the critical value calculated from one of the well-known formulas. In the case of detection of critical conditions the thickness of the dried zone is determined in the present calculations from the relation $H_{\text{dr}}=H_{\text{boil}}-H_{\text{boil}}^{\text{cr}}$ using a zero-dimensional model of dryout. In this

case, the critical thickness of the boiling zone can be determined approximately, as suggested in [12], from the following simple relation: $H_{\text{boil}}^{\text{cr}} = q_{\text{cr}}/(q_{vf} \cdot (1 - \varepsilon))$. On the upper boundary of the dried zone boundary conditions of the first kind are adopted with the temperature equal to the saturation temperature:

$$T\,(z = z_{v\text{Na}2}) = T_{\text{sNa}}\,. \tag{5}$$

The density of the heat flux from the dried zone to the boiling zone q_s^{dr}, calculated under this boundary condition, is taken into account in the value of the density of the heat flux from the boiling zone to the upper zone with a single-phase coolant, i.e., under condition (4): $q_s^{\text{boil}} = q_v \cdot H_{\text{boil}} + q_s^{\text{dr}}$. On the lower boundary of the dried zone, the temperature on which is taken to be equal to the saturation temperature:

$$T\,(z = z_{v\text{Na}1}) = T_{\text{sNa}}\,, \tag{6}$$

boundary conditions of the fourth kind are used:

$$-\lambda_{\text{eff}} \frac{\partial T}{\partial z}\bigg|_{z=z_{v\text{Na}1}^{-}} = -\lambda_{\text{eff}} \frac{\partial T}{\partial z}\bigg|_{z=z_{v\text{Na}1}^{+}}\,. \tag{7}$$

Conditions similar to (6) and (7) are written down for the boundaries of the zone with molten fuel. Thus, to take into account all the above-indicated configurations of the bed for different aggregate states of the components over the bed height all four types of boundary conditions are used in the present numerical solution.

In the numerical solution of Eq. (1) with a system of boundary conditions we used the finite-difference method. The finite-difference scheme was obtained by the balance method [15]. The discrete analog of the conservation equation (1) was obtained for a nonuniform spatial grid. To approximate the diffusion term we used the approximation of a piecewise-constant temperature profile on control segments. The discrete analog of Eq. (1) is written down in the form [15]

$$A_i\,T_{i-1} - C_i\,T_i + B_i\,T_{i+1} + F_i = 0\,, \tag{8}$$

whose coefficients are defined as

$$A_i = \frac{1}{\bar{h}_i\,h_i}\,\lambda_{i-1/2}\,; \quad B_i = \frac{1}{\bar{h}_i\,h_{i+1}}\,\lambda_{i+1/2}\,; \quad C_i = A_i + B_i\,; \quad F_i = q_{v_i}\,, \tag{9}$$

where

$$T_i = T\,(z_i)\,; \quad h_i = z_i - z_{i-1}\,; \quad \bar{h}_i = (h_i + h_{i+1})/2\,;$$

$$\lambda_{i-1/2} = [\lambda\,(z_{i-1},\,T_{i-1}) + \lambda\,(z_i,\,T_i)]/2\,; \quad q_{v_i} = q_v\,(z_i)\,.$$

To solve the nonlinear system of algebraic equations (8) subject to boundary conditions, we used a combination of the pivot and iteration methods [16]. We used the methods of right and left pivots [16]. Here, for the calculated zones with inner phase interfaces (for example, boundaries of the zone of molten fuel) we used the method of oppositely directed pivots [16], in which the right and left pivots were performed relative to phase interfaces [14]. The number of phase interfaces, including those within the limits of one calculation region, is not limited. The coordinates of phase interfaces are determined by the method of iterations, and a more precise determination of the coordinate of each such interface is repeated (inside the cycle of the above-indicated iterations) several times until the required difference of the calculated temperature from that needed for this boundary is attained.

The STO program developed on the basis of this solution makes it possible, in one calculation, to determine the temperature field in a deposited bed with a single-phase coolant. When the calculated temperature of the coolant is obtained to be higher than the saturation temperature, a second calculation is performed that determines more

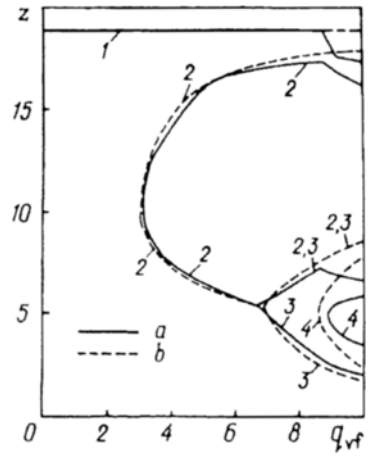


Fig. 1. Coordinates of the boundaries of the characteristic zones in a heat-evolving deposited bed calculated by different techniques: a) by analytical relations of [11]; b) by the STO-BED program; 1) top of the bed; 2) boundaries of the zone with boiling sodium; 3) boundaries of the dried zone; 4) boundaries of the zone of fuel melting. q_{vf}, W/cm^3; z, cm.

precisely the coordinates of the boundaries of the coolant boiling zone starting from the approximate values of these coordinates obtained in the first calculation. In this case the initial calculation region, which includes the segment from the bottom to the top of the bed, is divided into three calculation regions: the lower and upper zones with liquid coolant and the boiling zone. The temperature on each (lower and upper) boundary of the coolant boiling zone (at the outer phase interface) is calculated by the formula obtained from the discrete analog of the corresponding condition (4) and the corresponding pivot equation (right or left). Iterations for refining the coordinates of the indicated boundaries are continued until the calculated values of temperature do not show appreciable change from those prescribed by conditions (3). The dryout zone is included in the lower calculation region with liquid coolant on the condition of an ideal contact on their interface. Here the coordinate of this interface (inner phase interface) is refined in the third circle of iterations in calculation of the thermal state of the bed. If the temperature of the fuel in the dried zone exceeds the melting temperature, in the next circle of iterations refinement of the temperature distribution in the bed is repeated again, and the coordinates of the boundaries of the melt zone are determined. When the fuel boiling temperature is not assumed to be limiting for the existence of the deposited bed, it is possible to determine also the coordinates of the zone of fuel vapor inside the melt (we speak only of very approximate estimates of the thermal state of the bed with such a zone). Iterative calculations with the use of the STO program are carried out automatically in accordance with the algorithm of special modules of the STO-BED program.

To test the computation technique we carried out a comparison of the results presented in [11] with those obtained by applying the STO-BED program with the values of the data used in [11]. The coordinates of the boundaries of the characteristic zones calculated by the two techniques are shown in Fig. 1. The results obtained by the proposed technique agree with those obtained from the explicit expressions given in [11]. The coordinates of the boundaries of the sodium boiling and coolant dryout zones are close to one another. The difference increases with the appearance of the zone of fuel melt. The calculations made in [11] allow for sagging of the bed due to disappearance of the original porous structure in the melt zone. However, use of a $1/(1-\varepsilon)$-fold corrected value of the thermal conductivity coefficient for the fuel melt in the STO-BED program calculations ultimately gives values of the maximum temperature that closely approximate those given in [11]. In the given case the fuel temperature does not exceed the boiling point, i.e., the values of the volumetric heat release rate used in the calculation (not higher than 10 W/cm^3 of fuel) lie within admissible limits (for the adopted thickness of the bed and conditions of heat removal), for which a stationary regime of heat removal is possible.

To check the physical accuracy of the computational technique we used results of D-series experiments carried out at the Sandia laboratory. In these experiments heat was released due to the fission of heavy nuclei in

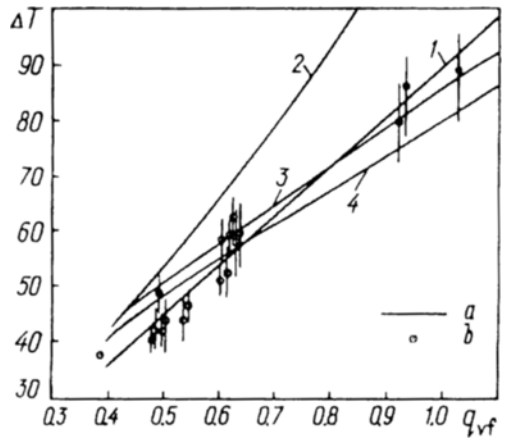


Fig. 2. Temperature drop between the locations of thermocouples at the bottom of the bed and at a height of 33 mm under the conditions of experiment D1 as a function of the volumetric heat release rate in fuel particles: a) calculated values; b) according to readings of the thermocouples; 1) $\lambda_{eff} = 31$ W/(m·deg) (the value adopted in [17]); 2) λ_{eff} was calculated from Kampf and Karsten's formula using the temperature at each point of the computational grid; 3) the same but with a correction for convection of the coolant in the volume of the bed; 4) λ_{eff} was calculated for the mean value of the temperature over the bed height. q_{vf}, W/g; ΔT, K.

a bed of enriched-uranium particles of diameter 0.1–1 mm in a volume of liquid sodium in a cylindrical vessel that was thermally insulated from below and from the sides and placed in an ACPR reactor. We used published data of experiments D1, D2, D3 [17], and D4 [8]. These works also give the parameters and the schemes of location of thermocouples throughout the bed volume that are necessary for the calculations.

In the present work, to calculate the effective thermal conductivity coefficients at each of the nodes of the spatial grid we used Kampf and Karsten's formula, which, in conformity with [9] and terminology used in [10], is written in the form

$$\lambda_{eff} = \lambda_c \left\{ 1 - \varepsilon_d^{2/3} \left[1 - \frac{1}{1 + \varepsilon_d^{1/3} (\lambda_c/\lambda_d - 1)} \right] \right\}, \qquad (10)$$

where λ_c is the thermal conductivity coefficient of the continuous medium; λ_d is the same for the noncontinuous medium (in [9] these were pores in the fuel inside fuel elements); ε_d is the volumetric fraction of the noncontinuous medium. In the present analysis, for the zones with liquid sodium $\lambda_c = \lambda_{Na}$, $\lambda_d = \lambda_f$, $\varepsilon_d = 1 - \varepsilon$. Probably, note should be taken of the erroneous presentation of this formula in [11], but the values of the coefficients given in [11] correspond to Eq. (10).

The contribution of natural convection to heat exchange in a deposited bed is taken into account in the value of the effective thermal conductivity coefficient. The corresponding correction expressed by the Nusselt number, by which λ_{eff} is multiplied, is connected with the internal Rayleigh number by the empirical formula $Nu = (Ra/0.76)^{0.34}$ [8], which corresponds to data of experiments D2 and D3 with a sodium coolant. A survey of investigations devoted to natural circulation of a single-phase coolant in a heat-evolving bed is given in [2].

The temperature drop between the top of the bed and the overlying volume of sodium is calculated, just as in [8], with the aid of a relation from [18]: $Nu = 0.0785 \cdot Ra_l^{0.32}$. As a matter of fact, the same dependence, but written in a different form, is used in the model of [12].

To predict the dryout of a portion of the bed of coolant a model of [5] was used in conformity with which the critical heat flux for $d_f < 1$ mm is determined from the relation $q_{cr} = q_0 \cdot (1 + L_c/H)$, where $H = H_{boil}$, while the formulas for q_0 and L_c are available in [5].

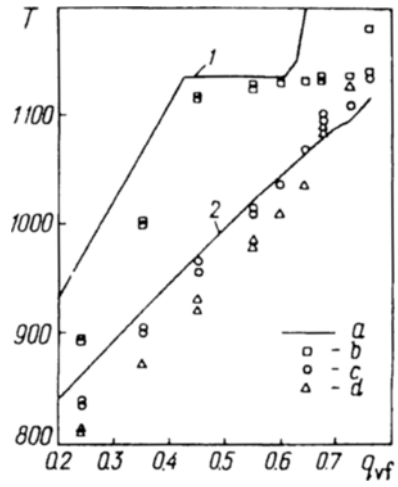


Fig. 3. Temperature in the bed under the conditions of experiment D2 as a function of the volumetric heat release rate in fuel particles: a) calculated values (1, maximum temperature; 2, temperature at a height of 65 mm); b, c, d) readings of thermocouples at the bottom of the bed, at a height of 65 mm from the bottom (at the center), and at the same height (but on the periphery), respectively. q_{vf}, W/g; T, K.

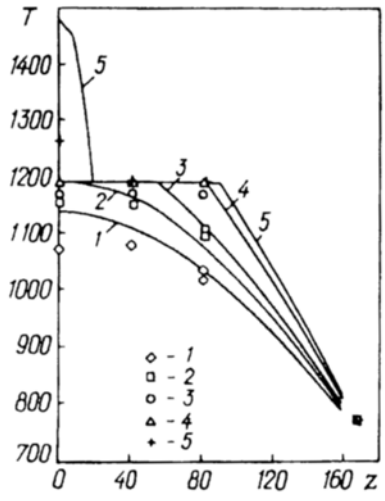
To calculate the effective thermal conductivity coefficients inside the dry zone we also used formula (10). In the present calculations we assumed that $\lambda_0 = \lambda_f$, $\lambda_d = \lambda_{vNa}$, $\varepsilon_d = \varepsilon$. This will be valid for conditions where the fuel particles are sintered at a high temperature in the dried zone, whose thermal conductivity is higher. The contribution of the radiative component to heat transfer in the dried zone is taken into account by adding to the value of the effective thermal conductivity coefficient a value calculated from a formula given in [10]: $\Delta\lambda_r = 4\sigma e(1/(1-\varepsilon)-1)d_f T^3$.

The values of the thermophysical properties of sodium that are needed for the calculations were taken from [19], those of the thermal conductivity coefficients of uranium dioxide from [20], and those of the thermal conductivity coefficients of sodium vapor as a function of temperature and pressure from [21].

Calculated and experimental values of temperature under the conditions of experiments D1, D2, D3, and D4 are presented in Figs. 2, 3, 4, and 5, respectively. In these experiments the height of the deposited bed was equal to 58, 99-113 (106 on the average), 158, and 82.5 mm, respectively. For computational estimates the heating cycles were taken for underheatings of sodium below the saturation point equal to 500, 463, 418, and 460 K (characteristic for the conditions of an off-design accident in a fast reactor).

In experiment D1 the boiling point was not attained in the bed. The values given in Fig. 2 for the temperature differences over the portion between the thermocouples calculated for $\lambda_{eff} = 31$ W/(m·deg) coincide with those given in [17]. When we calculated the effective coefficients of thermal conductivity at the nodes of the computation grid according to the values of temperature at these points obtained from Eq. (10) and corrected for convection appearing with the growth of heat release in the bed (the Ra number attains the critical value 0.76 at $q_{vf} = 0.42$ W/g), the calculated values of the temperature drop agree well with experimental results. If at all the nodes the value of the effective thermal conductivity coefficient calculated at the arithmetic-mean value of temperature over the height of the bed is the same (actually calculated in the same way as with the use of explicit expressions from an analytical solution), we obtain smaller values of the heat difference, but they are also located near the experimental values. In this case the calculated maximum values of temperature are equal in both cases, but in the latter case the values of the temperature obtained at the middle of the bed are overestimated by several degrees.

In experiment D2 at a volumetric heat release rate of about 0.5 W/g boiling-up of the coolant was noted, as indicated by the readings of all three thermocouples at the bottom of the bed. At the same time the temperature of the upper part remained below the saturation temperature. At $q_{vf} = 0.76$ W/g dryout of the bottom of the bed



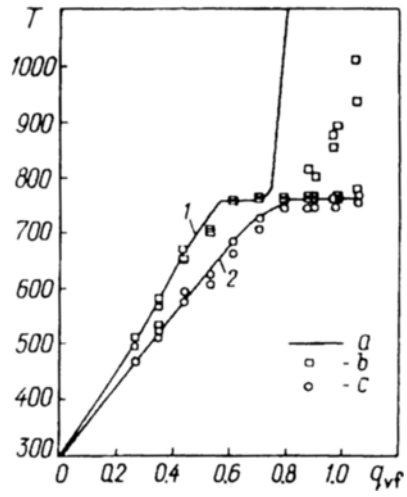


Fig. 4. Temperature field in the bed under the conditions of experiment D3 at different volumetric heat release rates (curves, calculated values; points, readings of thermocouples); 1, 2, 3, 4, 5) the volumetric heat release rate in fuel particles is equal to 0.19, 0.23, 0.27, 0.35, 0.39 W/g, respectively. z, mm; T, K.

Fig. 5. Temperature in the bed under the conditions of experiment D4 as a function of the volumetric heat release rate in fuel particles: a) calculated values (1, maximum temperature; 2, temperature at a height of 38 mm from the bottom of the bed); b, c) readings of thermocouples at the bottom and at a height of 38 mm, respectively. q_{vf}, W/g; T, K.

was noted. We obtained good agreement of the calculated and experimental values of temperature at a height of 65 mm (Fig. 3). The calculated maximum values of the temperature of the bottom of the bed are higher than the experimental values; the difference was 5% up to $q_{vf} = 0.61$ W/g, at which the calculated density of the heat flux from the zone of coolant boiling attains the calculated critical value. Because of the low thermal conductivity in the dried zone the temperature increases sharply even for an insignificant increase in heat release. At $q_{vf} = 0.76$ W/g this gives a large difference of the calculated value of temperature from that obtained experimentally (1181 K).

In experiment D3 the greatest development of convection in the bed was noted. As a result, already at the smallest heat release the temperature field in the lower part of the bed (at the location of the two lower thermocouples) becomes uniform (Fig. 4). The Rayleigh number in calculations even at $q_{vf} = 0.19$ W/g was obtained equal to 5.0 (under the conditions of experiment D1 this number attained only 2.0 at the maximum power, and under the conditions of experiment D2 it was equal to 2.2 by the start of boiling). The greatest discrepancy between the calculated and experimental temperature is noted at the bottom of the bed; in the middle of the height of the bed the calculated and experimental values are close to each other at the lowest power. As the power increases, the influence of convection increases, expanding the region of constant temperature; in this case the discrepancy between the calculated and experimental data also increases in the middle of the bed height. On the whole the calculated temperature fields agree with the experimental distributions. The maximum difference before the start of dryout of the bed is not greater than 5.5%. For this experiment better agreement is achieved for the temperature in the dried zone. The predicted start of dryout corresponds to a volumetric heat release rate of 0.36 W/g, while at 0.39 W/g the calculated temperature in the dried zone attains 1477, differing from the experimental value of 1263 K by 17%.

In experiment D4 the best agreement between the calculated and experimental temperatures in the zone with liquid coolant is obtained (Fig. 5). The temperature field corresponds well to the Fourier heat conduction law due to the late beginning of convection. Thus, Ra attains the critical value 0.76 only at $q_{vf} = 0.505$ W/g. The values of temperature obtained in the present work for the period before boiling-up of sodium are very nearly equal to

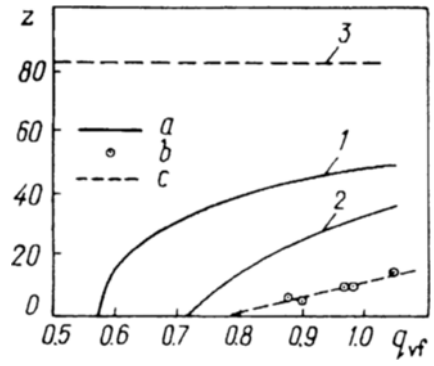


Fig. 6. Dimension of zones with different phase states of the coolant in the bed under the conditions of experiment D4 as a function of the volumetric heat release rate: a) values calculated by the one-dimensional model of the present work (1, dimension of the zone of sodium boiling; 2, dimension of the dryout zone; 3, height of the bed); b) values of the dimension of the dry zone calculated in [8] by a two-dimensional model of heat conduction on the basis of measured values of temperature; c) extrapolation [8]. q_{vf}, W/g; z, mm.

those given in [8]; the powers of the start of boiling also coincident. At a higher power we obtained better agreement than in [8] between the calculated and experimental values of temperature for the middle of the bed. The start of dryout of the bed is predicted to occur at $q_{vf} = 0.72$ W/g, while an analysis of the experimental results of [8] shows that the start of dryout should begin at $q_{vf} = 0.77$ W/g, i.e., the difference is about 7%. However, the calculated maximum values of temperature in the dried zone differ greatly from the experimental values. As noted in [8], the temperatures measured in the dry zone do not attain such high values mainly due to heat transfer from the bed to the walls of the crucible that increases strongly with the start of dryout and with the corresponding increase in the difference of heat fluxes between the volume of the dry zone and the walls. Thus, in all the experiments at the bottom of the bed only the central thermocouples recorded a temperature above the saturation point of sodium; near the crucible wall the temperature did not increase above the saturation temperature. Therefore, using a two-dimensional computational model we can obtain values of temperature in the dry zone that are closer to the experimental ones; in this case we can also obtain values for the height of the dryout zone that are smaller than those calculated with the aid of the one-dimensional technique of the present work (Fig. 6).

Thus, the STO-BED program calculations of heat transfer in heat-evolving deposited beds under the conditions of reactor experiments showed that on the whole the results obtained correspond to experimental data. Rather good agreement of the calculated values of temperature with those measured is attained before the start of the predicted dryout. But in the zone dried of coolant the values of temperature calculated with the help of a one-dimensional model greatly exceed the experimental ones. However, for the conditions in a deposited bed that forms on a tray in an accident and has a rather large radial dimension and therefore a low heat release in the lateral direction the program developed can give results on heat transfer in the dry zone that are closer to the physically accurate ones.

NOTATION

z, coordinate; T, temperature; λ, thermal conductivity coefficient; ε, medium porosity; q_v, volumetric heat release rate of a unit volume of the medium; q_{vf}, volumetric heat release rate of the fuel; λ_{eff}, effective thermal conductivity of the medium; λ_{Na}, thermal conductivity coefficient of coolant; λ_{vNa}, thermal conductivity coefficient of coolant vapor; λ_f, thermal conductivity coefficient of fuel; λ_δ, thermal conductivity coefficient of the slab under the deposited bed; α_1, coefficient of heat transfer to the coolant under the bed; α_2, coefficient of heat transfer to the coolant above the bed; T_1, temperature of the coolant under the bed; T_2, temperature of the coolant above the

bed; T_{3Na}, saturation temperature of the coolant; H_b, thickness of the deposited bed; H_{boil}, thickness of the zone with boiling coolant; H_{boil}^{cr}, critical thickness of the zone with boiling coolant; H_{dr}, thickness of the zone dried of coolant; z_{LNa1}, coordinate of the upper boundary of the lower zone with liquid coolant; z_{LNa2}, coordinate of the lower boundary of the upper zone with liquid coolant; z_{vNa1}, coordinate of the lower boundary of the dryout zone; z_{vNa2}, coordinate of the upper boundary of the dryout zone; δ, thickness of the slab; q_{cr}, critical heat flux density; ρ_{Sf}, density of the fuel; d_f, size of the fuel particles; e, emissivity of the surface of the particles; σ, Stefan–Boltzmann constant; h, spatial step of the computational grid. Subscript: i, number of the grid node.

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