RESEARCHING THE INFLUENCE OF PARAMETERS OF CONSTRUCTIONS OF FUEL RODS AND THEIR OPERATING CONDITIONS ON THE TEMPERATURE STATE OF CERAMIC NUCLEAR FUEL IN THE NUCLEAR REACTOR VVER-1000

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Yu.V. Romashov^{1,2,a}, I.Yu. Ilchenko^{1,b}

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[1] National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine
[2] V.N. Karazin Kharkiv National University, Kharkiv, Ukraine
[a] yu.v.romashov@gmail.com, [b] ilchenko970@ukr.net

Introduction. The temperature state significantly limits operability of the ceramic nuclear fuel pellets in fuel rods of modern industrial power nuclear reactors, including the VVER-1000 nuclear reactors, widely used in Ukrainian power industry. Due to this circumstance, all researches about the temperature state and theirs more precisely assessments for the ceramic nuclear fuel pellets are of current interest, considering with the trends of increasing the working parameters and using the new fuel type if the next generation nuclear reactors for example [1]. The purpose of this research is to develop the approach for evaluating the temperature state of the ceramic nuclear fuel on the base of finite differences technique for the heat conduction equation, as well as to obtain the quantitative assessments of these temperature state and influencing the parameters of constructions and operating conditions for the VVER-1000 nuclear reactor.

Simplified mathematical model of the temperature state of ceramic fuel. The ceramic fuel for nuclear reactors is ordinary made as the compact products with the shape closely to the cylinders with or without the axial central hole. To consider the temperature state we will use the theory of stationary heat conduction [2], considering the heat flows and the Fourier's law. The heat conduction in ceramic nuclear fuel is the complicated problem in general, but it is possible to simplify this problem considering some characteristic properties of the heat flows, by averaging of thermal conductivity coefficient in wide temperature interval, as well as by using the schematized imaginations about the heat transfer. As the result of these simplified assumptions the simplified mathematical model of temperature state of the compact products of ceramic nuclear fuel can be represented by the heat conduction equation and two boundary conditions [2] as follows:

$$\frac{d^2T}{dr^2}+\frac{1}{r}\frac{dT}{dr}=-\frac{Q}{\lambda_{\mathrm{f}}},\quad a_{\mathrm{f}}<r<b_{\mathrm{f}}\ , \tag{1}$$

$$\frac{dT}{dr}=0,\quad r=a_{\mathrm{f}}\,,\qquad -\lambda_{\mathrm{f}}\frac{dT}{dr}=\alpha_{\mathrm{f}}\left(T-T_{\mathrm{HC}}\right),\quad r=b_{\mathrm{f}}\ , \tag{2}$$

where $T=T(r)$ is the temperature; r is the radial coordinate; Q is the intensity of the internal heat sources due to the nuclear fission reactions; λ_{f} is the heat conduction coefficient of the ceramic nuclear fuel; a_{f} and b_{f} are the internal and external radii; α_{f} and T_{HC} are the heat transfer coefficient on the external surface of the fuel and the temperature of the heat carrier.

To research influence of parameters of constructions it is necessary to represent the members in (1), (2) as the functions of these parameters [2]:

$$Q=\frac{W}{N\pi\left(b_{\mathrm{f}}^2-a_{\mathrm{f}}^2\right)L},\quad \alpha_{\mathrm{f}}=\left(\frac{a_{\mathrm{f}}}{\lambda_{\mathrm{g}}}\ln\frac{a_{\mathrm{c}}}{b_{\mathrm{f}}}+\frac{b_{\mathrm{f}}}{\lambda_{\mathrm{c}}}\ln\frac{b_{\mathrm{c}}}{a_{\mathrm{c}}}+\frac{b_{\mathrm{f}}}{\alpha_{\mathrm{c}}b_{\mathrm{c}}}\right)^{-1}, \tag{3}$$

where W is the heat power of the reactor; N and L are the number of fuel rods in the core and the characteristic length of the core; λ_{g} and λ_{c} are the heat conduction coefficients of materials of gaseous gap and the cladding; a_{c} and b_{c} are the internal and external radii of the cladding; α_{c} is the heat transfer coefficient on the external surface of the cladding.

The mathematical model (1), (2) is applicable for the compact products of ceramic nuclear fuel made with as well as without the central axial hole.

Numerical analysis the temperature state of ceramic fuel. The simplified mathematical model (1)–(3) allows the exact analytical solution of the boundary-value problem (1), (2) representing the temperature state of the ceramic nuclear fuel, but solving the heat conduction equation is the complicated problem requiring of application only the numerical methods in general case. We will use the finite differences technique [3] for numerical solving the boundary-value problem (1), (2) considering with the purposes of this research. The main idea of this approach is to consider the separate values of the temperature in some chosen points of the fuel instead to consider the temperature as the continuous function. The grid of the nodes is introduced such as the coordinates r_k of the grid's nodes and the nodal values T_k of the temperature are:

$$r_k = a_{\mathrm{f}} + k\Delta r, \quad k = 0,1,2,\ldots,n,n+1, \tag{4}$$

$$T_k = T(r_k), \quad k = 0,1,2,\ldots,n,n+1, \tag{5}$$

where $\Delta r = (b-a)/(n+1)$ is the step of the grid; n is the number of nodes inside the domain excluding the boundary points.

To find the nodal values (5) we will reduce the differential equation (1) and the boundary conditions (2) to their discrete form using the well-known finite differences technique [3]:

$$\frac{T_{k-1} - 2T_k + T_{k+1}}{\Delta r^2} + \frac{1}{r_k}\left(\frac{T_{k+1} - T_{k-1}}{\Delta r}\right) = -\frac{Q}{\lambda_{\mathrm{f}}}, \quad k = 1,2,\ldots n, \tag{6}$$

$$\frac{-3T_0 + 4T_1 - T_2}{2\Delta r} = 0, \quad -\lambda_{\mathrm{f}}\left(\frac{3T_{n+1} - 4T_n + T_{n-1}}{2\Delta r}\right) = \alpha_{\mathrm{f}}\left(T_{n+1} - T_{\mathrm{HC}}\right). \tag{7}$$

The equalities (7) are the discrete analogue of the differential equations (1), but the equalities (7) are the discrete analogue the boundary conditions (2). The equalities (6), (7) are represented the linear algebraic equation system, which must be solved to find the nodal values (5). The number n must be sufficiently big to provide the required accuracy of temperature field representation. To solve the equations (6), (7) in the cases of large values n it is necessary to use the numerical methods; we will use the Gauss-Seidel iteration method [4].

Results for the temperature state of nuclear fuel in VVER-1000. The core of the nuclear reactors VVER-1000 is made from the Zr-1%Nb alloy and is had the well-known parameters:

$$a_{\mathrm{f}} = 3{,}765\,\mathrm{mm}, \quad a_{\mathrm{c}} = 3{,}86\,\mathrm{mm}, \quad b_{\mathrm{c}} = 4{,}55\,\mathrm{mm}, \tag{8}$$

$$\lambda_{\mathrm{f}} = 5\,\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}), \quad \lambda_{\mathrm{g}} = 0{,}3\,\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}), \quad \lambda_{\mathrm{c}} = 20{,}5\,\mathrm{W}/(\mathrm{m}\cdot\mathrm{K}), \quad \alpha_{\mathrm{c}} = 35\,\mathrm{kW}/(\mathrm{m}^2\cdot\mathrm{K}). \tag{9}$$

$$Q = 3000\,\mathrm{MW}, \quad n = 50856, \quad L = 3530\,\mathrm{mm}, \quad T_{\mathrm{HC}} = 583\,\mathrm{K}, \tag{10}$$

Some of results in the form of the temperature fields inside the nuclear fuel for nuclear fuel without the central axial hole are presented on the fig. 1 and fig. 2; influencing the central axial hole is shown on the fig. 3. All these results are obtained by using the finite differences technique for count $n = 100$ of the grid nodes, providing the full much with the analytical exact solution and smooth representations of the temperature fields on the fig. 1–3.

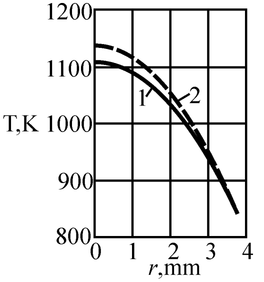

Fig. 1. Temperature field for $\lambda_{\mathrm{f}} = 5\,\mathrm{W}/(\mathrm{m} \cdot \mathrm{K})$ (1) and for $\lambda_{\mathrm{f}} = 4{,}5\,\mathrm{W}/(\mathrm{m} \cdot \mathrm{K})$ (2)

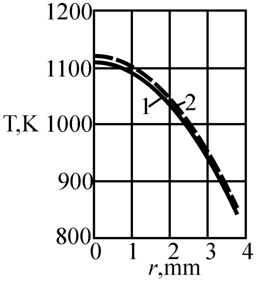

Fig. 2. Temperature field for $\alpha_{\mathrm{c}} = 35\,\mathrm{kW}/(\mathrm{m}^2 \cdot \mathrm{K})$ (1) and for $\alpha_{\mathrm{c}} = 20\,\mathrm{kW}/(\mathrm{m}^2 \cdot \mathrm{K})$ (2)

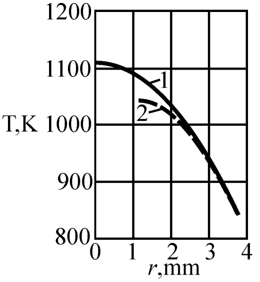

Fig. 3. Temperature field in the fuel with $a_{\mathrm{f}} = 0$ (1) and with $a_{\mathrm{f}} = 1{,}15\,\mathrm{mm}$ (2)

Obtained results (fig. 1–3) not contradict with well-known regularities of the temperature state of the ceramic nuclear fuel, but it seems, that the obtained temperatures are too high, what it seems it is the consequence of neglecting the axial heat flows.

Conclusions. The obtained results have shown that the finite differences technique can be recommended for using in further researches for researching the temperature states in the ceramic nuclear fuel considering with their design and operating conditions in the core of nuclear reactors. Significant influencing of the heat conductivity of the ceramic nuclear fuel on its temperature state was shown and it is recommended to take into account the temperature dependence of the heat conductivity coefficient, which will lead to the nonlinear heat conductivity differential equation. It is necessary to consider the axial and circumferential heat flows to provide the more precisely results for the temperatures of the ceramic nuclear fuels, which are high for the proposed simplified mathematical model.

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