Heat exchange between the fuel element of a nuclear reactor made of plutonium dioxide and its shell under boundary conditions of the fourth kind

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Abstract. The work is devoted to the heat exchange of a nuclear reactor. Attention was paid to the mathematical modeling of the temperature field of the fuel element and the thin gas layer. It is assumed that the thermal contact between the solid–interlayer system is ideal. Methods of differentiation, integration and approximate methods were used for numerical modeling. The dependence of the thermal conductivity of plutonium dioxide on temperature was also taken into account.

1 Introduction

As is known, the fuel element is the main structural element of the core of a nuclear reactor containing nuclear fuel. In it, the fission of heavy uranium 235 or plutonium 239 nuclei occurs, accompanied by the release of thermal energy, which is then transferred to the coolant. One of the key points of the NPP safety analysis is the investigation of the occurrence of emergency processes and confirmation that during the accident the main parameters do not exceed the permissible limits. For example, in order to comply with the tightness conditions, it is necessary to ensure the permissible temperature of fuel and enclosing structures when cooling storage nests due to natural air circulation in the storage.
The temperature of the cooled fuel at a given heat release and the geometry of the assembly placement in the pencil case is determined by the thermal resistance inside the storage nest and the thermal resistance at the outer boundary. In this case, the thermal resistance inside the storage nest includes the thermal resistance of the assembly inside the pencil case, the resistance of the pencil case wall, the resistance of the air gap between the pencil case and the nest, as well as the resistance of the nest wall and the resistance at its outer boundary. The design of a fuel cell is a complex process involving the combined study of many phenomena, such as the propagation of heat in the fuel core, the behavior of fuel and shell depending on temperature and irradiation history, the voltage in the fuel —shell system. The temperatures of the fuel and shells are usually very different. Therefore, it is necessary to clarify whether the temperatures of the nuclear fuel and the protective shell do not exceed the permissible or limit values. All this must be taken into account. Or, if a temperature field is established

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inside the heat-generating element, then a temperature-dependent relationship between stresses and deformation can be obtained. Therefore, solving the problem of organizing effective heat and mass transfer will significantly increase the efficiency of work, and can also reduce the cost of equipment.
The fuel element is the main element of the core of a nuclear reactor containing nuclear fuel. One of the key points of the NPP safety analysis is the investigation of the occurrence of emergency processes and confirmation that during the accident the main parameters do not exceed the permissible limits.
To perform such a calculation, data on thermal resistances on the outer surface of the foam are required. At the same time, cooling must be effective so that the temperatures of the materials of the structural elements are acceptable [1-7]. There are many computer programs for modeling processes in the core of a nuclear reactor. Many works have been devoted to the issue of calculating fuel elements, where uranium oxide serves as nuclear fuel [8-11], but few works are devoted to the calculation of fuel elements where plutonium dioxide serves as nuclear fuel.
The paper considers boundary conditions of the fourth kind. Boundary conditions of the fourth kind define the conditions of heat exchange at the boundary of the ideal contact of two bodies consisting of different substances with different physical properties. Therefore, they simulate the so-called ideal thermal contact between tightly touching bodies, and have a simple physical meaning: what amount of heat is supplied from the depth of the first body to its boundary, the same amount of heat is diverted into the depth of the second body. In this work, using the methods of differentiation and integration, the problem of heat exchange between a cylindrical heat-generating element and its shell under boundary conditions of the first and fourth kind was solved. As a result, the laws of change of temperature fields in both bodies are obtained. At the same time, the dependence of the thermal conductivity of plutonium dioxide on temperature was taken into account. Also, based on the obtained mathematical modelling, the linear coefficient of heat transfer through the shell and the linear thermal resistance for this case were determined.

2 Main Part

The temperature field of a cylindrical fuel element is described by the Poisson equation. The same heat source with a specific power of q_v operates inside. At the same time, we will consider the process stationary. In this case, the equation of thermal conductivity will take the form

$$\Delta T + \frac{q_v}{\lambda_1} = 0 \tag{1}$$

For the convenience of further calculations, we write the expression (2) in a cylindrical coordinate system

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_1 r \frac{\partial T}{\partial r}\right) = -q_v \tag{2}$$

In practice, the thermal conductivity of plutonium dioxide has a functional dependence on temperature. Therefore, it must be taken into account in thermal calculations. In the field of operating temperatures, this dependence can be represented in the following form

$$\lambda_1 = (0{,}00089T - 2{,}83)^2 \tag{3}$$

Taking into account the above, the solution of equation (2) has the form [12]

$$T_1 = 3180 + \sqrt[3]{C_1 - 9{,}46 \cdot 10^5 q_v r^2} \tag{4}$$

The temperature field of the gas layer is described by the following equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_2 r \frac{\partial T}{\partial r}\right) = 0 \tag{5}$$

where: λ_2 is the thermal conductivity coefficient of helium. The solution of equation (5) is

$$T_2 = \frac{C_2}{\lambda}\ln r + C_3 \tag{6}$$

On the surface of the shell itself , the temperature is T_0

$$T_2\big|_{r=R_2} = T_0 \tag{7}$$

from where the constant C_3 is equal to

$$C_3 = T_0 - \frac{C_2}{\lambda_2}\ln R_2 \tag{8}$$

then formula (6) will take the form

$$T_2 = T_0 - \frac{C_2}{\lambda_2}\ln(R_2 / r) \tag{9}$$

We find the constant C_2 from the following boundary condition. In this heat exchange, the boundary conditions are boundary conditions of the fourth kind. In this case, the temperatures of the contacting surfaces are the same

$$T_1\big|_{r=R_1} = T_2\big|_{r=R_1} \tag{10}$$

where: T_1 and T_2 are the temperatures of the fuel element and the interlayer. And the heat flows at the boundary of their separation should be the same

$$-\lambda_1 \frac{dT_1}{dr}\bigg|_{r=R_1} = -\lambda_2 \frac{dT_2}{dr}\bigg|_{r=R_1} \tag{11}$$

Next, we introduce a new variable n

$$n = \sqrt[3]{C_1 - 9{,}46 \cdot 10^5 q_v R_1^{\,2}} \tag{12}$$

then condition (10) will take the form

$$3180 + n = T_0 - \frac{C_2}{\lambda_2}\ln(R_2 / R_1) \tag{13}$$

a condition (11)

$$-0{,}5q_v R_1 = \frac{C_2}{R_2} \tag{14}$$

from where the required constants are equal to the following values

$$C_2 = -0{,}5q_v R_1 R_2 \tag{15}$$

$$n = T_0 + \frac{0{,}5q_v R_1 R_2}{\lambda_2}\ln(R_2 / R_1) - 3180 \tag{16}$$

$$C_1 = 9{,}46 \cdot 10^5 q_v R_1^{\ 2} + \left(T_0 + \frac{0{,}5q_v R_1 R_2}{\lambda_2}\ln(R_2 / R_1) - 3180\right)^3 \tag{17}$$

Then the expression for determining the temperature field of the fuel element will take the form

$$T_1 = 3180 + \sqrt[3]{9{,}46 \cdot 10^5 q_v (R_1^{\ 2} - r^2) + \left(T_0 + \frac{0{,}5q_v R_1 R_2}{\lambda_2}\ln(R_2 / R_1) - 3180\right)^3} \tag{18}$$

and for the shell

$$T_2 = T_0 + \frac{0{,}5q_v R_1 R_2}{\lambda_2}\ln(R_2 / r) \tag{19}$$

The resulting field of the system is shown in figure 1.

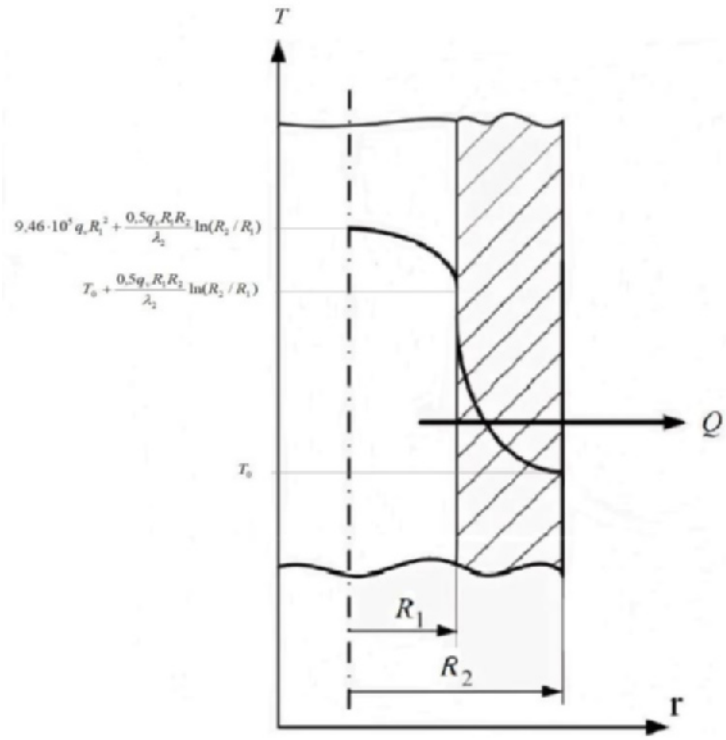

Fig. 1. A graph of the behavior of the temperature field.

As follows from the expression (18), the temperature of the fuel element changes according to the parabolic law in the direction of decreasing from the center. Which is to be expected, since the process of heat transfer to the environment is more intense at the edge. From the second expression obtained (19) it follows that the field decreases according to the logarithmic law.

3 Conclusions

In this paper, the solution of the stationary problem of the distribution of the temperature field of both the fuel element of a nuclear reactor and the helium layer is considered. Using differentiation and integration methods, a mathematical model for an axisymmetric rod was developed. This model takes into account the dependence of the thermal conductivity of plutonium dioxide on temperature. Numerical simulation of the heat release process allows you to choose the power of internal sources, which ensures the optimal operation of a nuclear reactor.

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