Simulation of a fuel element made of plutonium dioxide

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Abstract. The work is devoted to the calculation of the temperature field of the fuel element of a nuclear reactor made of plutonium dioxide. At the same time, the heat release process itself is stationary and occurs under boundary conditions of the first kind. The author obtained a solution that takes into account the dependence of the thermal conductivity of plutonium dioxide on temperature using a quadratic approximation. The result obtained can be useful for more accurate calculations in order to ensure the reactor's operability for a longer time.

1. Introduction
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. To perform such a calculation, data on thermal resistances on the outer surface of the foam are required. At the same time, cooling should be effective, so that the temperatures of the materials of the structural elements are acceptable. 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 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.

A lot of works have been devoted to the calculation of fuel elements using various methods and programs [1-8], while uranium oxide is mainly used as nuclear fuel [9], but few works are devoted to the calculation of fuel elements, where plutonium dioxide serves as nuclear fuel.

The above study is a continuation of the author's work [10].
2. Materials and methods
The paper uses the method of quadratic approximation.

3. Results
To solve this problem, we will consider a heat-generating element in the form of a cylinder, inside which the same heat source with a specific power \( qv \) operates. Then the Poisson equation describing the process itself will take the form

\[
\Delta T + \frac{qv}{\lambda} = 0 \tag{1}
\]

Next, let's move on to the cylindrical coordinate system

\[
\frac{1}{r} \frac{d}{dr} \left( r \frac{dt}{dr} \right) = -\frac{qv}{\lambda} \tag{2}
\]

or

\[
\frac{d}{dr} \left( r \frac{dt}{dr} \right) = -\frac{qv}{\lambda} r \tag{3}
\]

where from

\[
r \frac{dt}{dr} = -\frac{qv r^2}{2\lambda} + C_1 \tag{4}
\]

Take the integral

\[
\frac{dt}{dr} = -\frac{qv r}{2\lambda} + C_1 \tag{5}
\]

Due to the central symmetry of the thermal field

\[
\left. \frac{dt}{dr} \right|_{r=0} = 0 \tag{6}
\]

From where \( C_1 = 0 \). Then

\[
\frac{dt}{dr} = -\frac{qv r}{2\lambda} \tag{7}
\]

In practice, the thermal conductivity of plutonium dioxide has a temperature dependence as shown below (fig. 1). We approximate the experimental data in the form of the following dependence

\[
\lambda = 2 \cdot 10^{-5} t^2 - 0.0074 t + 8.44 \tag{8}
\]
For further calculations, we select a full square
\[ \lambda = (0.00089t - 2.83)^2 \]  
(9)

Then formula (6) will take the form
\[ (0.00089t - 2.83)^2 \, dt = -\frac{q_r \lambda}{2} \, dr \]  
(10)

Let's take the integral again
\[ 375(0.00089t - 2.83)^3 = -\frac{q_r r^2}{4} + C_2 \]  
(11)

Where from
\[ t = 3180 + \sqrt[3]{C_3 - 9.46 \cdot 10^5 q_r r^2} \]  
(12)

The integration constant \( C_3 \) is found from the boundary condition of the first kind
\[ t|_{r=R} = t_0 \]  
(13)

then
\[ t = 3180 + \sqrt[3]{(t_0 - 3180)^3 + 9.46 \cdot 10^5 q_r (R^2 - r^2)} \]  
(14)

Now let's introduce a new variable \( x \)
\[ x = \frac{r^2}{R^2} \]  
(15)

then formula (13) will take the form
\[ t = 3180 + \sqrt[3]{(t_0 - 3180)^3 + 9.46 \cdot 10^5 q_r R^2 (1 - x^2)} \]  
(16)
Figure 2 shows a graph of changes in the temperature field of the rod.

![Graph of the change in the temperature field of the rod from the dimensionless radius x.](image)

**Figure 2.** Graph of the change in the temperature field of the rod from the dimensionless radius x.

4. **Discussion**

As follows from graph 2, the law of change of the temperature field is similar to parabolic. At the same time, when moving away from the center, it decreases. This is due to the fact that the process of heat transfers to the environment itself occurs more intensively on the surface of the rod.

5. **Conclusion**

Thus, in this paper, on the basis of numerical modeling, the influence of the temperature dependence of the thermal conductivity of plutonium dioxide on the temperature field of the fuel element is investigated. The solution is obtained for the stationary case using quadratic approximation. The result obtained can be useful for engineering calculations of the construction of fuel elements.

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