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EFFECT OF DEFECTIVE FUEL ELEMENT PARAMETERS ON TEMPERATURE DISTRIBUTIONS

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Results are presented of the calculation of temperature distributions in the cross section of fuel rods with a defective contact bond. The effects of the dimensions and thermal conductivity of the defects, the dimensions of the fuel element, the heat-conduction properties of the fuel element core and cladding, and the rate of cooling are determined.

The effects of the thermal conductivity and the dimensions of defects, and the dimensions, heat-conduction properties, and rate of cooling of defective fuel rods on temperature distributions are established.

During the manufacture and use of fuel elements various defects may develop, the most important of which are local impairments of heat transfer between the core and cladding. Such defects lead to a distortion of the temperature distribution, which in turn gives rise to thermal stresses, acceleration of corrosion processes, and a loss of mechanical strength. In view of this it is necessary to develop methods for calculating temperature distributions in defective fuel elements to determine the controlling factors which have an appreciable effect on the temperature distribution.

The most accurate determination of the temperature distribution would involve the simultaneous solution of the differential equations describing the temperature distribution in the fuel element and in the coolant. However, because of the difficulty of describing the velocity distribution and the turbulent component of heat conduction most calculations have been performed by solving the heat-conduction equations in the fuel element with boundary conditions of the third kind specified at the boundary between the fuel element and the coolant.

Calculational methods or the results of temperature calculations for certain special problems have been published [1-4], but the basic rules for the effect of dimensions and thermal parameters of fuel elements and defects on the distribution of temperature fields have not been established.

If these rules were known the construction of fuel elements could be optimized so as to minimize the effect of their defects on their operating life.

With this in mind we have performed numerical calculations of temperature distributions in the cross section of a fuel rod with an infinitely long defect in the contact bond between the core and cladding.

For constant physical parameters and dimensions of the fuel element and defect, and a constant coefficient of heat transfer from the surface of the fuel element the dimensionless equations describing the steady temperature distribution in the cross section of a fuel element with a defect of width $2\varphi_D R_1$ have the form

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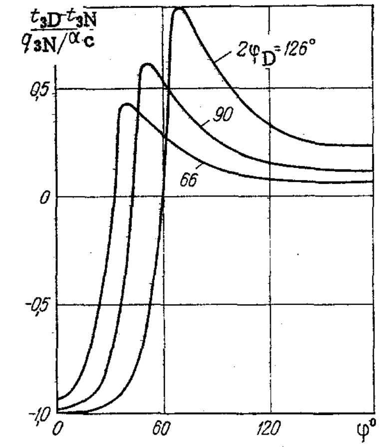

Fig. 1

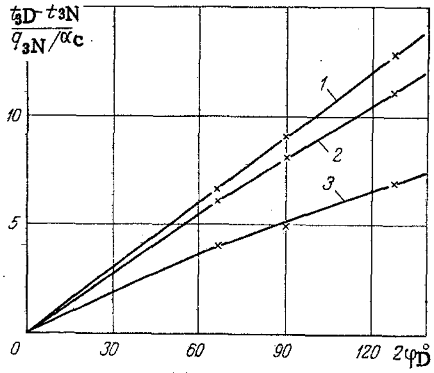

Fig. 2

Fig. 1. Distribution of overheating of outer surface of fuel element cladding for $\alpha_c R_1/\lambda_1 = 8.6$; $\alpha_D R_1/\lambda_1 = 0$; $\lambda_3/\lambda_1 = 2.15$; $R_3/R_1 = 1.14$.

Fig. 2. Maximum overheating of surface of fuel element core as a function of the size of the defect in the azimuthal direction for $\alpha_c R_1/\lambda_1 = 8.6$; $\lambda_3/\lambda_1 = 2.15$; $R_3/R_1 = 1.14$. 1) $\alpha_D R_1/\lambda_1 = 0$; 2) 0.12; 3) 0.88.

$$\nabla^2 T_1 = -1 \text{ for } L \leqslant 1{,}0, \tag{1}$$

$$\nabla^2 T_2 = 0 \text{ for } 1.0 < L \leqslant R_2/R_1, \tag{2}$$

$$\nabla^2 T_3 = 0 \text{ for } R_2/R_1 < L \leqslant R_3/R_1; \tag{3}$$

with the boundary conditions

$$-\frac{\partial T_1}{\partial L} = \frac{\lambda_2}{\lambda_1}\frac{\partial T_2}{\partial L} \text{ for } L = 1.0,\ \varphi > \varphi_D, \tag{4}$$

$$-\frac{\partial T_1}{\partial L} = \mathrm{Bi}_D (T_1 - T_3)\frac{R_2}{R_1} \text{ for } L = 1.0,\ \varphi \leqslant \varphi_D, \tag{5}$$

$$-\frac{\lambda_2}{\lambda_1}\frac{\partial T_2}{\partial L} = -\frac{\lambda_3}{\lambda_1}\frac{\partial T_3}{\partial L} \text{ for } L = R_2/R_1,\ \varphi > \varphi_D, \tag{6}$$

$$T_1 = T_2 \text{ for } L = 1.0,\ \varphi > \varphi_D, \tag{7}$$

$$T_2 = T_3 \text{ for } L = R_2/R_1,\ \varphi > \varphi_D, \tag{8}$$

$$-\frac{\partial T_3}{\partial L} = \mathrm{Bi}_c \frac{\lambda_1}{\lambda_3} T_3 \text{ for } L = R_3/R_1 \text{ and any } \varphi. \tag{9}$$

Thus, the dimensionless temperature is in general a function of the following combinations:

$$T = f\left(\frac{\alpha_D R_1}{\lambda_1};\ \frac{\alpha_c R_1}{\lambda_1};\ \frac{\lambda_2}{\lambda_1};\ \frac{\lambda_3}{\lambda_1};\ \frac{r}{R_1};\ \varphi;\ \varphi_D\right). \tag{10}$$

The temperature distributions were calculated numerically on an M-220 computer using the method of partial factorization [5].

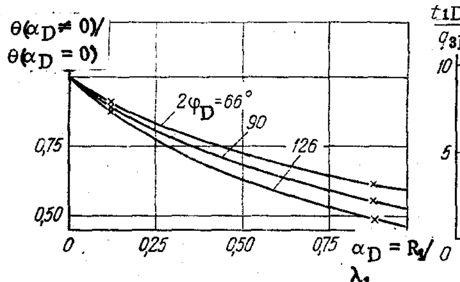

Fig. 3

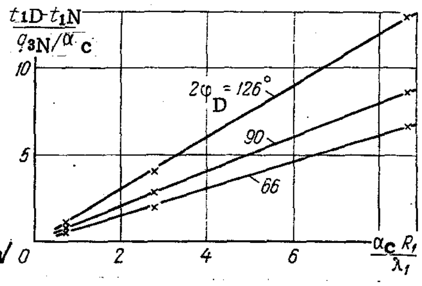

Fig. 4

Fig. 3. Effect of thermal conductivity of defect on the maximum overheating of the surface of the core and the outer surface of the fuel element cladding for $\alpha_c R_1/\lambda_1 = 8.6$, $\lambda_3/\lambda_1 = 2.15$, and $R_3/R_1 = 1.14$.

Fig. 4. Maximum overheating of surface of fuel element core as a function of $\alpha_c R_1/\lambda_1$ for $\alpha_D R_1/\lambda_1 = 0$, $\lambda_3/\lambda_1 = 2.15$, and $R_3/R_1 = 1.4$.

Some of the temperature distributions calculated numerically were compared with data obtained by electronic modelling and analytically [4]; the difference did not exceed ~5%.

The results of calculations performed for a wide range of parameters are presented in the form of graphs of the dependence of the ratio of the temperature difference in a fuel element with and without a defect, i.e., overheating, to the thermal head on a number of combinations.

In a fuel element with a defect in the contact bond [4] the temperature of the core surface is above nominal, especially in the region of the defect. At the boundary of the defective region there is an abrupt change in temperature.

The temperature of the surface of the cladding in the defective region (Fig. 1) is below nominal, and the decrease in temperature increases with a decrease of the thermal conductivity of the defect. However, the minimum calculated value of the surface temperature of the cladding cannot be below the mean coolant temperature as a consequence of the assumed boundary condition of the third kind (9). Outside the region of the defect the surface temperature of the cladding is above nominal, particularly at the boundaries of the defective region where there is a thermal spike.

An abrupt change in temperature at the boundary of the defective region can lead to appreciable thermal stresses in the fuel element core and cladding.

As the defective region increases in the azimuthal direction the maximum overheating of the core increases linearly for values of $\alpha_D R_1/\lambda_1 < 0.12$ (Fig. 2). For larger values of $\alpha_D R_1/\lambda_1$ the increase in overheating is slowed down as the size of the defective region increases.

The maximum overheating of the outer surface of the cladding varies with the size of the defective region in a similar way.

Naturally the distortion of the temperature distribution in a cross section of the fuel element decreases with increasing thermal conductivity of the defect. However, the curves in Fig. 3 for the ratio of the maximum overheating of the surface of the core and the outer surface of the cladding of a fuel element with a nonconducting defect to that of a fuel element with a conducting defect as functions of $\alpha_D R_1/\lambda_1$ show that the thermal conductivity of the defect has little effect. Thus, an increase in $\alpha_D R_1/\lambda_1$ from 0.12 to 0.88, i.e., by more than a factor of 7, which corresponds to changing from gases with a low thermal conductivity to helium, leads to a decrease of overheating by only a factor of ~1.6. The effect of the thermal conductivity decreases with a decrease in the size of the defect.

Figure 4 shows that the maximum overheating of the surface of the fuel element core increases linearly with $\alpha_c R_1/\lambda_1$, and more rapidly the larger the angle of the defect. The linear character of the variation of the dimensionless overheating with $\alpha_c R_1/\lambda_1$ shows that the temperature difference between the core surface of a defective fuel element and that of a nondefective one does not depend on the rate of cooling.

In fact

$$\frac{t_{1D} - t_{1N}}{q_{3N}/\alpha_c} = A\,\frac{\alpha_c R_1}{\lambda_1}, \tag{11}$$

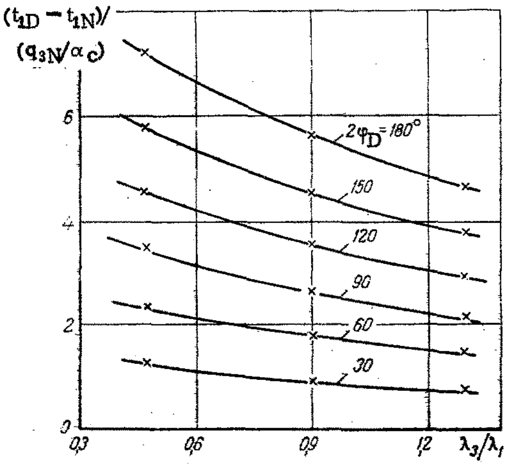

Fig. 5. Maximum overheating of core surface as a function of the ratio of the thermal conductivities of cladding and core for $\alpha_c R_1/\lambda_1 = 2.04$, $\alpha_D R_1/\lambda_1 = 0$, and $R_3/R_1 = 1.09$.

from which $t_{1D} - t_{1N} = A(R_1 q_{3N}/\lambda_1)$, where A is a coefficient of proportionality.

The variation of the maximum dimensionless overheating of the surface of the cladding is more complicated: as $\alpha_c R_1/\lambda_1$ increases, the increase in overheating is slowed down.

The effect of the ratio of the thermal conductivities of the cladding and core on the maximum overheating of the surface of the core is shown in Fig. 5. The maximum overheating decreases as λ_3/λ_1 increases, and this dependence is the more pronounced the larger the size or the lower the thermal conductivity of the defective region.

The maximum overheating of the outer surface of the cladding varies in a similar way with the ratio of the thermal conductivities of the cladding and the core.

Thus, one can say that a defect of a definite size and thermal conductivity in a fuel rod leads to a smaller distortion of the temperature distribution for small values of $\alpha_c R_1/\lambda_1$ and for high values of $\alpha_D R_1/\lambda_1$ or λ_3/λ_1.

The error in the calculation of temperature distributions under the assumptions made does not exceed ~5%.

NOTATION

r, φ, t	are the running values of the radius, angle, and temperature measured from the mean coolant temperature;
φ_D	is the angle determining size of defective portion of perimeter;
R_1, R_2, R_3	are the outside radii of core, contact layer, and fuel element cladding;
λ_1, λ_2, λ_3	are the thermal conductivities of core, contact layer, and fuel element cladding;
α_D	is the thermal conductivity of defective region;
α_c	is the coefficient of heat transfer from fuel element surface to coolant;
q_{3N}	is the heat flux density;
$T = t\lambda_1/q_1R_1^2$	are the dimensionless temperature;
Bi_D, Bi_c	are the Biot numbers.

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