Determination of the optimal size of the fuel element of the elliptical cross-section of a nuclear reactor

Aleksandr Kanareykin[1*]

[1]Sergo Ordzhonikidze Russian State University for Geological Prospecting, 117997, Miklouho-Maclay St. 23., Moscow, Russia

Abstract. The work is devoted to the process of heat exchange of a nuclear reactor. Attention was paid to improving the reliability of the fuel rods of the nuclear reactor. At the same time, two cases of the cross section of the rod shell were considered: cylindrical and elliptical. Based on the application of the differentiation method, it was shown that the level of thermal stresses arising during the transition from a circular cross-section to an elliptical one decreases. Which confirms the choice of the section of the reduced elements in the form of an ellipse. The optimal size of the section itself was also obtained. The obtained result is useful because by varying the geometric shape of the cross-section, it is possible to reduce the level of thermal stresses that occur, and, consequently, to increase the reliability and durability of nuclear rocket engine designs.

1 Introduction

The main fuel elements traditionally used in nuclear power plants can be classified into three types, namely a plate-type element (all shapes), a cylindrical element elongated in the direction of the axis (usually having a round or annular section), which forms a rod element, and a spherical element, usually in the form of a small particle diameter [1-7].

In addition, composite fuel elements formed from spherical particles enclosed in an inert matrix are known to exist in the three geometric shapes mentioned above, namely: balls, plates and compact shapes used in high-temperature reactors [8-12].

Cylindrical fuel elements are, for example, cylindrical containers with nuclear fuel used in graphite-gas reactors, rods used in water-water power reactors, or rod-type fuel elements in fast neutron nuclear reactors.

The design of these cylindrical elements is characterized by the presence of a radial gap between the nuclear fuel in the form of tablets and the shell inside which these tablets are stacked to form a column, which makes it possible to compensate for various deformations between the nuclear fuel and the shell; this gap is capable of at least compensating for various expansions during the first rise in the power of the fuel element, as well as part of the swelling fuel, which cannot be resorbed by itself due to fluidity and re-compaction in its internal cavities, in other words, in the cavities formed by the central hole and pores in the

[*] Corresponding author: kanareykins@mail.ru

fuel. Nuclear fuel must also operate at a temperature at which it can activate deformation compensation mechanisms.

On the other hand, it releases a certain amount of gaseous fuel fission products.

The second expansion volume is formed inside the shell at the end of the column of nuclear fuel tablets (fuel tablets) in order to limit the amount of internal pressure in the fuel element.

The main optimization parameters of these cylindrical elements are the initial radial gap between the nuclear fuel and the shell, in other words, the radial assembly gap, the quality of the thermal connection between the nuclear fuel and the shell using a fluid (gas seal or molten metal seal), the actual density of filling the shell section with nuclear fuel, determined by the radial gap, pores, voids, such as the central hole or lens-shaped depressions at the ends of the tablet, the rigidity of the shell (thickness), mechanical properties (maximum strength and ability to plastic deformation) and the patterns of behavior of the shell and nuclear fuels (buckling and creep).

The thermal resistance changes during operation, since there is a change in the radial gap and a deterioration in thermal conductivity due to the release of gaseous products of nuclear fission. The change in thermal resistance complicates the control over the maximum fuel temperature, which consists in the fact that nuclear fuel should not reach its melting point under any operating conditions. In addition, the use of this type of element in the "pressure chamber" mode involves the use of a material capable of holding the fuel element in the working position without the risk of sudden rupture under pressure. To achieve this result, a circular cross-section is usually used, since it best resists the action of pressure. Thus, in the situation of mechanical interaction between the nuclear fuel and the shell, the shell, being under the action of annular tension, exhibits high ring stiffness. As a result, the fuel in two radial directions is kept from moving, only in the axial direction it partially has freedom, and this partial freedom depends on the adhesion between the tablets and the shell.

It should be noted that spherical fuel elements are used only in high-temperature and gas-cooled reactors.

The main mode of their residual destruction corresponds to a strong interaction between the fissile core and the covering layers (the creation of mechanical stress at a given deformation of the shell), which can cause the destruction of the protective shell; based on this, the spherical shell is the worst form of shell, since it leaves no direction for deformation of nuclear fuel (in addition to maximum compaction) to weaken the interaction forces (creation of hydrostatic pressure in the inner volume of the shell).

The considered type of spherical fuel element is also used in various composite forms, in which the particles are dispersed in a matrix through which heat is transferred to the coolant, with a very small content of nuclear fuel in the reactor reaction volume, about several l% per unit volume. In addition, with the help of such a design, the danger of shell destruction at high burning rates of nuclear fuel is reduced Gorenje.

The main purpose of the work is to reduce the probability of deformation of the rod shell and the release of fission products into the coolant.

2 Main Part

The determination of thermal stresses in a heat-generating element is reduced to solving a planar thermoelasticity problem. The stress function F is found from the solution of the equations [13]

$$\Delta\Delta F = \frac{\alpha E q_v}{\lambda(1-\nu)}, F = \frac{\partial F}{\partial n} = 0 \tag{1}$$

where λ is the coefficient of thermal conductivity of concrete, α is the coefficient of linear expansion, E is the Young's modulus, v is the Poisson's ratio.

We will conduct a comparative analysis of the corresponding components of the thermal stress tensor for circular or elliptical sections. In a circular cylinder, the components of the stress tensor have the form

$$\sigma_{xx} = \frac{\alpha E q_v R^2}{64\lambda(1-\nu)}\left(\frac{x^2+3y^2}{R^2}-1\right) \tag{2}$$

$$\sigma_{yy} = \frac{\alpha E q_v R^2}{64\lambda(1-\nu)}\left(\frac{3x^2+y^2}{R^2}-1\right) \tag{3}$$

In an elliptical cylinder

$$\sigma_{xx} = \frac{4A}{b^2}\left(\frac{x^2}{a^2}+\frac{3y^2}{b^2}-1\right) \tag{4}$$

$$\sigma_{yy} = \frac{4A}{a^2}\left(\frac{3x^2}{a^2}+\frac{y^2}{b^2}-1\right) \tag{5}$$

where

$$A = \frac{\alpha E q_v}{\lambda(1-\nu)\left(3\frac{a^4+b^4}{a^2b^2}+2\right)}\frac{a^2b^2}{8} \tag{6}$$

For further analysis, let's consider the behavior of one of the tensor components. The ratio of the considered thermal stresses is equal to [14]

$$\frac{\sigma_{xx}^{ell}}{\sigma_{xx}^{cir}} = \frac{8\left(\frac{x^2}{a^2}+\frac{3y^2}{b^2}-1\right)}{\left(3\left(\frac{b}{a}\right)^3+2\left(\frac{b}{a}\right)+3\left(\frac{a}{b}\right)\right)\left(\frac{x^2+3y^2}{R^2}-1\right)} \tag{7}$$

where σ_{xx}^{ell} - thermal stresses in a cylindrical body, σ_{xx}^{cir} - thermal stresses in a cylindrical body.

We will conduct a study of the behavior when the maximum value of tensors (x = 0) is reached

$$\frac{\sigma_{xx}^{ell}}{\sigma_{xx}^{cir}} = \frac{8}{3\left(\frac{b}{a}\right)^3 + 2\left(\frac{b}{a}\right) + 3\left(\frac{a}{b}\right)} \quad (8)$$

Multiply the numerator and denominator by the ratio b/a

$$\frac{\sigma_{xx}^{ell}}{\sigma_{xx}^{cir}} = \frac{8\left(\frac{b}{a}\right)}{3\left(\frac{b}{a}\right)^4 + 2\left(\frac{b}{a}\right)^2 + 3} \quad (9)$$

Taking b/a =t, we get a function depending on t

$$f(t) = \frac{8t}{3t^4 + 2t^2 + 3} \quad (10)$$

We investigate the resulting function at the extremum using differential analysis

$$f'(t) = 8\frac{-9t^4 - 2t^2 + 3}{\left(3t^4 + 2t^2 + 3\right)^2} \quad (11)$$

From where t = 0.69.

It follows that the ratio of the considered thermal stresses takes the maximum value with the following ratio of the semi-axes of the ellipse b = 0.69a.

Below is a drawing of the heat-generating element with an indication of the optimal dimensions (Fig. 1).

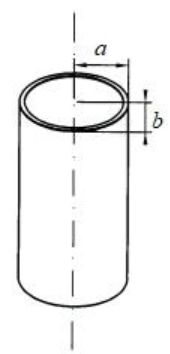

Fig. 1. Drawing of the heat-generating element indicating the semi-axes.

3 Conclusions

In this paper, the analysis of publications devoted to the choice of fuel rods is carried out. The study of the basic physical and mechanical properties of fuel elements directly related to the mechanics of a deformable solid is carried out. It is established that the transition to an elliptical cross-section of the fuel elements reduces the level of thermal stresses arising. Which confirms the choice of the section of the reduced elements in the form of an ellipse. The optimal size of the section itself was also obtained. Thus, by varying the geometric shape of the cross-section, it is possible to reduce the level of thermal stresses that occur, and, consequently, to increase the reliability and durability of nuclear rocket engine designs.

References

1. S.A. Panfilov, O.V. Kabanov, International Journal of Advanced Biotechnology and Research **7(4)**, 1395–1402 (2016)
2. A.I. Kanareykin, IOP Conference Series: Earth and Environmental Science **990**, 012012 (2022)
3. R.L. Williamson, Journal of Nuclear Materials **423(1)**, 149-163 (2012)
4. J.D. Hales, Computational Materials Science **99**, 290-297 (2015)
5. Y. Rashid, R. Dunham, R. Montgomery, *Fuel analysis and licensing code: FALCON MOD0. EPRI Report1011308* (2004)
6. A.I. Kanareykin, IOP Conference Series: Earth and Environmental Science **1045**, 012070 (2022)
7. H.C. Kim, Y.S. Yang, Y.H. Koo, KSME **38**, 157–166 (2014)
8. C. Newman, G. Hansen, D. Gaston, Journal of Nuclear Materials **392(1)**, 6-15 (2009)
9. E.A. Gomin, VANT: Physics of nuclear reactors **1**, 6–32 (2006)
10. J. Knight, *Conflict in Society* (John Wiley & Sons, 2009)
11. J.C. Ramirez, M. Stan, P. Cristea, Journal of nuclear materials **359(3)**, 174-184 (2006)
12. B. Mihaila, Journal of Nuclear Materials **394(2)**, 182-189 (2009)
13. A.I. Kanareykin, Journal of Physics: Conference Series, 012013 (2021)
14. A.I. Kanareykin, AIP Conference Proceedings **2762**, 020007 (2022)