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Research Article

Investigation of the influence of the fuel element design parameter on the VVER-1000 reactor axial power peaking factor*

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Abstract

The paper presents the results of a numerical study into the efficiency of the fuel element operation in the pressurized water reactor (VVER) core filled with uranium dioxide (UO_2) pellets. The investigation results were obtained from a three-dimensional simulation of the fuel element power density. The dependencies of the fuel and fuel cladding temperatures on specific power per cubic meter of fuel are compared. Uranium metal and uranium dioxide have been studied as fuel. Engineering constraints on the safe operation of fuel assemblies have been selected as the determining parameters. The paper analyzes the extent of the radiation heat transfer effects on the fuel element specific power. Equations have been obtained that reflect the dependencies of specific power per cubic meter of fuel on the size of the fuel pellet hole diameter in the maximum heat flux conditions. The COMSOL Multiphysics code, a numerical thermo-physical simulation package, was used for the study. Calculations show that an additional uranium-235 enrichment with an increase in the fuel pellet hole diameter at a fixed fuel thermal power leads to a reduced reactor axial temperature field peaking factor.

Keywords

VVER-1000, fuel element, fuel pellet, temperature field, specific thermal power, power peaking factor

Introduction

Modern fuel assemblies (TVSA-T, TVSA-12, TVSA-12PLUS, TVS-2M) for VVER-1000 reactors allow improving the NPP performance thanks to a longer lifetime and extended fuel cycles. The core of such reactor type is formed by fuel assemblies consisting of rod-type fuel elements (Kolpakov and Selivanikova 2009; Leskin et al. 2011) б which are filled, in turn, with fuel pellets of U-235 uranium dioxide (UO_2). The maximum temperature of nuclear fuel and the zirconium fuel cladding has been stringently limited to ensure the nuclear reactor operating safety (Chirkin 1968; Gorbunov 2019).

Calculating the temperature fields inside the reactor core requires solving conjugate problems for determining the internal power density in the fuel element based on neutronic characteristics (Perimov et al. 2004). Dedicated software for such calculations is not accessible for a broad

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range of users (Velesjuk and Morgunov 1990; Golcev et al. 2009; Kartashov and Bogoslovskaya 2012; Starkov and Marihin 2013; Design Codes of New Generation 2022). Extensively used are numerical packages for thermophysical simulations available for educational or noncommercial applications (Heat Transfer Module User's Guide 2005; Biryulin 2006; Gorbunov 2008, 2011), including Elcut, Flow Vision, Ansys Fluent and COMSOL Multiphysics.

The VVER reactor core model has a simple cylindrical shape. The origin of coordinates is at the core center. Two coordinates are used for the cylinder: radius r and height z along the cylinder axis. The core has an effective radius, R_e, and an effective height, H_e. In a homogeneous core with fuel and other materials distributed uniformly through the volume (Dementiev 1990; Ilchenko 2005; Gorbunov et al. 2019), the reactor power density inside the volume is proportional to the neutron flux density.

The reactor power density is not uniform in the process of operation. It changes in accordance with the zero-order Bessel functions in the radial direction, and according to the cosinusoidal law in the axial direction. Coefficients are introduced to allow for the power peaking defined by the maximum to average power density ratio. The core peaking factor, k_r, (Dementiev 1990; Ilchenko 2005; Gorbunov et al. 2019) is used to allow for the power peaking in the radial direction:

$$k_r = Q_0 / Q_r \,, \tag{1}$$

where Q_0 is the maximum value of the power density at the reactor center, W; and Q_r is the core radial average power density, W. The maximum value of the power peaking factor, $k_r^{\max}$, is 2.32. The factor value shows that the central channel's thermal load is 2.32 times higher than the radial average value.

The core axial power peaking factor, k_z, is used to allow for the power peaking in the axial direction:

$$k_z = Q_0 / Q_z \,, \tag{2}$$

where Q_0 is the maximum value of the power density at the reactor center, W; and Q_z is the reactor axial average power density, W. The maximum value of the factor is $k_z^{\max} = 1.57$.

Widely used in practice is the volumetric power peaking factor, k_V, determined from the following expression

$$k_V = k_r \cdot k_z. \tag{3}$$

For a homogeneous cylindrical reactor core without a reflector, the maximum volumetric power peaking factor exceeds by more than three times the reactor core average value and amounts to $k_V = 3.64$. This leads to stressed conditions of the fuel element operation and the safety constraints for the fuel element operation reduce the permissible reactor power. The permissible heat flux shall not exceed the maximum value. Flattening the power density through the core makes it therefore possible to obtain a larger power with other conditions being equal (Velesjuk and Morgunov 1990). The partially flattened core radial power density is achieved through the core layout. In practice, as a rule, more enriched fuel assemblies are installed around the reactor periphery and further reinstalled nearer to the center in the process of operation.

It is occasionally proposed that the core axial power density be flattened via a non-uniform axial distribution of the burnable coolant. Another flattening method under consideration is to insert control rods from below and position them in the maximum thermal neutron density region.

The accumulated experience of the VVER-1000 reactor operation has shown that the core axial power density flattening is a topical issue.

The purpose of the study is to search for ways to increase the efficiency of fuel element operation by reducing the VVER-1000 core axial power peaking factor (Dementiev 1990; Dolgov 2016; Gorbunov 2019).

The following needs to be done as part of the study for its objective to be achieved.

1. Analyze the peculiarities of the fuel power density in the VVER-1000 reactor, and build 3D models for the fuel temperature field determination using the finite element method and the COMSOL Multiphysics code.
2. Investigate fuel elements in conditions of the maximum thermal load and as the temperature limits are reached.
3. Build the 3D model for the fuel element temperature field determination and numerically calculate it further. The model includes a thermal conductivity equation with an internal source of energy, and takes into account the temperature effects on the thermophysical properties of uranium fuel, helium and the cladding of a zirconium alloy (Gorbunov et al. 2019, 2021).
4. Investigate the effects of the fuel pellet material (UO_2 uranium dioxide and U uranium metal) for the fuel element with a different heat conductivity coefficient on the core axial power peaking factor (Leskin et al. 2011; Gorbunov et al. 2021).
5. Investigate the effects of the heat exchange radiation component inside the fuel pellet holes and in the gap between the fuel and the fuel cladding during 2D simulations using the radiative heat exchange algorithm offered in the COMSOL Multiphycics code.
6. Compare the results from investigating the effects of the heat exchange radiation component inside the fuel pellet holes and in the gaps between the fuel and the fuel cladding using 2D and 3D models.
7. Investigate the effects of the radiation component for fuel elements with the same thermal power but with different levels of additional uranium-235 enrichment and different fuel pellet hole diameters based on the maximum fuel and cladding temperature limits.

Investigation methodology

The VVER-1000 reactor is designed to generate thermal energy at the expense of the nuclei fission chain reaction. Water is heated in the core due to heat release from the fuel elements.

A fuel element is a cylinder with a fuel column of the outer diameter 7.6 mm and the height 3.68 m made of uranium dioxide (UO_2). The UO_2 fuel column is positioned coaxially inside the cladding of a zirconium-niobium alloy. The outer diameter of the tube is 9.1 mm, and the wall thickness is 0.65 mm. The gap between the fuel and the cladding is 0.1 mm. When the fuel element's end plugs are sealed, its internal cavity is filled with helium up to a pressure of 2.0 MPa. The volumetric power density changes from 100 to 600 MW/m^3 in steps of 100 MW/m^3.

The temperature of the fuel element with UO_2 pellets shall not reach 1690 °C (1963 K). If the temperature exceeds this limit, the emission of gaseous products increases greatly (Gorbunov 2019). The average temperature of the water that flows about the fuel element is 285 °C (578 K). The external cladding temperature shall not exceed 350 °C (623 K). A temperature growth to over 350 °C leads to the fuel cladding alloy strength properties decreasing abruptly and the plastic properties increasing. The coefficient of heat transfer from the fuel outside to coolant is ~ 50000 W/(m^2·K).

The following conditions were assumed for solving the problem:

- the thermophysical properties of UO_2, the H1 zirconium alloy and helium depend on temperature;
- the calculation is done for the fuel elements being in operation with the maximum thermal loading at the reactor center;
- no effects of the liquid flow current pattern on the fuel element surface heat exchange are taken into account;
- it is taken into account that the fuel burnup in fuel elements is uniform (a stationary problem).

To allow for the change in the thermophysical properties, data arrays are defined for heat conductivities as a function of temperature (Chirkin 1968; Vargraftik 1972; The Density of Uranium and its Thermophysical Properties at Various Temperatures). The paper uses the thermophysical properties of UO_2, U, the H1 alloy and He at a pressure of 2 MPa depending on temperature.

The following geometrical parameters were assumed for the study: rod half-length of $l = 1.84$ m; rod radius of $R_0 = 0.00455$ m.

We shall present the initial and boundary conditions that define the solution.

1. Initial rod temperature

$$T(r, z, 0) = T_0 = 592\text{ K}, r \in [0, R_0], z \in [-l, l], \quad (4)$$

where $T(r, z, 0)$ is the temperature of the rod points with coordinates (r, z) at time $\tau = 0$.

2. Ambient temperature $T_{amb} = 592$ K.
3. Second-order boundary conditions on the rod ends:

$$q_1(r, -l, \tau) = 0, r \in [0, R_0], \quad (5)$$

$$q_2(r, l, \tau) = 0, r \in [0, R_0], \quad (6)$$

where $q_1(r, -l, \tau)$ is the flux (power density) on the rod's lower end at a point with coordinate r at time τ, W/m^2; and $q_2(r, l, \tau)$ is the flux (power density) on the rod's upper end at a point with coordinate r at time τ, W/m^2.

4. Second-order boundary conditions (adiabatic condition):

$$q_3(r, l, \tau) = 0, r = 0, z \in [-l, l], \quad (7)$$

where $q_3(r, l, \tau)$ is the flux (power density) inside the rod at a point with coordinate r at time τ, W/m^2.

5. Third-order boundary condition on the rod's side surface (Gorbunov 2019):

$$q_4(R_0, z, \tau) = \alpha(T(R_0, z, \tau) - T_{oc}), z \in [-l, l], \quad (8)$$

where $q_4(R_0, z, \tau)$ is the heat flux on the rod's side surface, W/m^2; $T(R_0, z, \tau)$ is the temperature of the rod's side surface points at time τ, K; T_{amb} is the ambient temperature, K; and α is the coefficient of heat exchange with the environment, W/(m^2·K).

To found the coefficient of heat transfer, α, from the fuel cladding surface to the heated water, a formula is used in Gorbunov 2019 to calculate the external heat exchange in the fuel lattices. The calculation includes the computation of the Nusselt criterion using the following relationship:

$$\text{Nu} = \text{A}\cdot\text{Re}^{0.8}\cdot\text{Pr}^{0.4}, \quad (9)$$

where Pr is the Prandtl criterion; Re is the Reynolds criterion; and A is the empirical coefficient.

The empirical coefficient is found as follows:

$$\text{A} = [0.0165+0.02(1\text{-}0.91/(s/d)^2](s/d)^{0.15}, \quad (10)$$

where s is the distance between the fuel element centers, m; and d is the external fuel element diameter, m.

Reynolds criterion

$$\text{Re} = \omega\cdot d_r/\nu, \quad (11)$$

where ω is the average coolant velocity in the cell, m/s; d_h is the hydraulic diameter of the regular triangular fuel element cell, m; and ν is the kinematic viscosity of liquid with the preset temperature and pressure, m^2/s.

The hydraulic diameter of the regular triangular fuel element cell is computed as follows:

$$d_r = d[(2(3/\pi)^{0.5}(s/d)^2 \text{ - } 1], \quad (12)$$

where d is the external diameter of fuel elements, m; and s is the distance between the fuel element centers, m.

The physical parameters are taken with the coolant temperature in the assembly's regular cells being equal to the arithmetic mean value of the regular cell inlet and outlet coolant temperature value. Formula (12) is valid if $1.06 \leq s/d \leq 1.80$, $0.7 \leq \mathrm{Pr} \leq 20$, and $5000 \leq \mathrm{Re} \leq 5 \cdot 10^5$.

6. Second-order boundary conditions for conductive heat exchange on the helium calculated region boundary:

$$q_5(r, z, \tau) = \lambda_{He}(T)(\partial T/\partial r),\ r = 0.0038,\ z \in [-l, l]. \quad (13)$$

7. Second-order boundary conditions for conductive heat exchange on the fuel element calculated region boundary:

$$q_6(r, z, \tau) = \lambda_{Zr}(T)(\partial T/\partial r),\ r = 0.0039,\ z \in [-l, l]. \quad (14)$$

The study uses a heat conductivity equation with variable thermophysical properties of the fuel element materials. The heat conductivity equation is solved by the finite element method. It is taken into account in the heat conductivity equation that

$$\nabla(-\lambda \nabla T) = q, \quad (15)$$

where λ is the heat conductivity coefficient, W/(m·K); and T is the temperature, K.

For a homogeneous reactor, the specific power density through the volume is proportional to the neutron flux density and can be determined by the expression

$$q(r, z) = q_0 J_0(2.405 r/R_э)\cos(\pi z/H_э), \quad (16)$$

where $q(r, z)$ is the specific amount of thermal energy generated in the reactor core with current coordinates (r, z), MW/m^3; q_0 is the specific maximum power density value at the reactor center, MW/m^3; J_0 if the zero-order Bessel function; R_e is the effective radius, m; and H_e is the effective height, m.

Investigation results

An axially symmetrical model was built in the study. A half of the fuel element is considered to reduce the number of the mesh nodes and, as a sequence, the resources for its calculation. For a better visual effect, the radius-related dimensions are given in millimeters, and those related to the fuel element height are given in meters. The study was conducted based on the 2D and 3D models built and the fuel element temperature field calculation. The 3D models are solid-body.

To identify the extent to which the heat exchange will improve as the result of refueling, we shall undertake a numerical experiment with the UO_2 replacement for uranium metal. The use of uranium metal in power is highly limited due to its swelling in the course of service and, therefore, by the low service temperature (≤ 500 °C).

The results of the numerical experiments to estimate the effects of specific power on the fuel element operating limits are presented in Table 1.

Table 1. Effects of specific power generated in one cubic meter of fuel

Specific power generated by one cubic meter of fuel, MW/^{m}3	100	200	300	400	500	600	1000
Maximum UO_2 fuel temperature, K	717.9	857.8	997.7	1137.6	1277.4	1417.3	1976.9
Maximum UO_2 cladding temperature, K	587.4	596.7	606.1	615.0	624.8	634.1	671.5
Maximum uranium metal temperature, K	675	773.8	871	989.5	1067.4	1165.3	1556.8
Uranium metal cladding temperature, K	587.4	596.7	606.1	615.0	624.8	634.1	671.5

With internally generated energy, the fuel element service limit is reached as the fuel failure temperature is reached. For uranium metal, which is more heat conductive, the limit is reached at a temperature of 773 K and a specific power density of 200 MW/m^3.

An analysis of Fig. 1 shows that the UO_2 fuel replacement for uranium metal does not lead to any advantages. Using UO_2 in fuel elements makes it possible to achieve a higher specific power density.

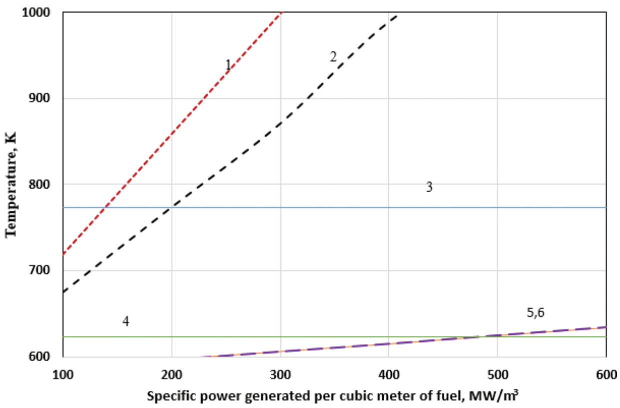

Figure 1. Fuel and cladding temperatures as a function of specific power generated in one cubic meter of fuel: 1 – maximum temperature of UO_2 fuel; 2 – maximum temperature of uranium metal; 3 – permissible fuel temperature for uranium metal; 4 – permissible temperature for fuel cladding of H1 alloy; 5, 6 – maximum temperature for fuel cladding with UO_2 and uranium metal fuel.

Improving the efficiency of the fuel element operation requires increasing the effective heat conductivity of fuel in the fuel element with which two types of heat exchange (conductive and radiative) are taken into account. To do this, it is necessary to estimate the effects of the radiative heat exchange inside the fuel hole on the temperature limits for the maximum temperature of using UO_2 and the fuel cladding material.

The effects of radiative heat exchange were calculated using the COMSOL Multiphysics software package. It is taken into account by the "countergradient method". We adopt the emissivity factor, which is approximate to the absolutely black body, for the external surfaces of the fuel pellet column, the fuel wall surfaces inside the fuel hole, and the cladding's inner walls involved in the radiative heat exchange.

To allow for the boundary conditions in the 3D model, an "algorithm of radiative heat transfer from surface to surrounding space" is used. The ambient environment has a constant average temperature, T_{amb}.

These assumptions make it possible to express the heat flux incident to the surface as

$$E_{inc} = \sigma \cdot (T_{amb})^4, \tag{17}$$

where E_{inc} is the heat flux incident to the surface, W/m^2; $\sigma = 5.67 \cdot 10^{-8}$ W/(m$^2 \cdot$K^4) is the Stefan-Boltzmann constant; and T_{amb} is the ambient temperature, K.

For the absorbed emissive heat flux from the surface to the surrounding space, the following equation is used:

$$q = \varepsilon \cdot \sigma \cdot [(T_{amb})^4 - T^4], \tag{18}$$

where ε is the total emissivity of the body; and $T = T_0$ is the temperature on the boundary (first-order boundary conditions), K.

Fig. 2 presents the fuel temperature as a function of specific power generated per cubic meter of fuel. Lines 4 and 5 show the specific power at which the maximum fuel temperature limit is reached for a fuel element with a hole of 2.3 mm without radiative heat exchange taken into account. The percent difference is 38.16 MW/m^3 (6.1%), which confirms the effects of radiative heat exchange of fuel in the fuel element.

An analysis of Fig. 2 shows that the effect of radiative heat exchange cannot be taken into account in full in the 2D problem statement. Each point will emit and absorb energy not only in the direction of the axis, as in the 2D model, but some of the thermal radiation will be also go onto the surfaces having an offset against the direction along the axis.

Values of specific power density for a fuel element with a 2.3 mm hole taking into account the radiative heat transfer differ significantly when obtained using the 2D and 3D models. The difference is 222.87 MW/m^3 (26.2%).

The calculation results for the hole diameter effects on the fuel temperature limit are presented in Fig. 3, and the calculation results for those on the cladding temperature limit are presented in Fig. 4.

A conclusion can be made from the diagrams that increasing the fuel pellet hole diameter moves away the

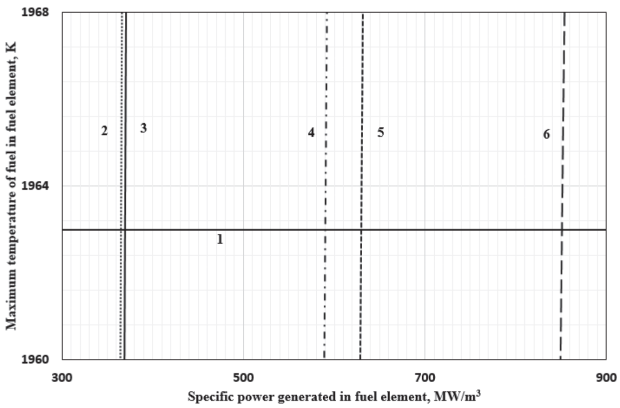

Figure 2. Maximum fuel temperatures (MFT) as a function of specific power generated in one cubic meter of fuel: 1 – permissible fuel temperature for UO_2; 2 – MFT without taking into account radiative heat exchange, K; 3 – MFT with taking into account radiative heat exchange in the gap between fuel and cladding, K; 4 – MFT for a fuel element with a hole of 2.3 mm without taking into account radiative heat exchange, K; 5 – MFT for a fuel element with a hole of 2.3 mm with taking into account radiative heat exchange, K; 6 – MFT for a fuel element with a hole of 2.3 mm with taking into account radiative heat exchange obtained on the 3D model, K.

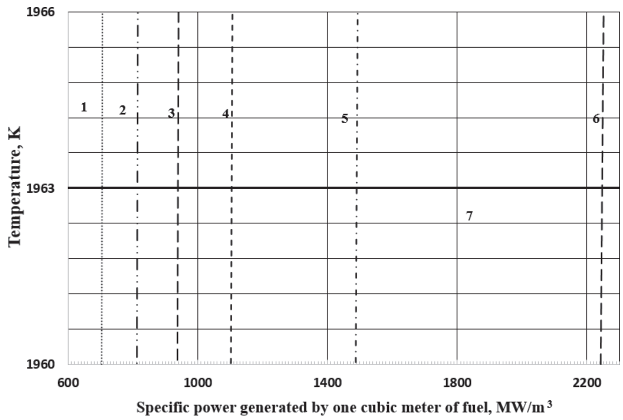

Figure. 3. Dependences of the maximum fuel temperatures (MFT) on specific power generated in one cubic meter of fuel obtained based on the 3D model taking into account radiative heat exchange: 1 – MFT for a fuel element with no hole, K; 2 – MFT for a fuel element with a hole of 1.5 mm, K; 3 – MFT for a fuel element with a hole of 2.3 mm, K; 4 – MFT for a fuel element with a hole of 3 mm, K; 5 – MFT for a fuel element with a hole of 4 mm, K; 6 – MFT for a fuel element with a hole of 5 mm, K; 7 – permissible fuel temperature for UO_2.

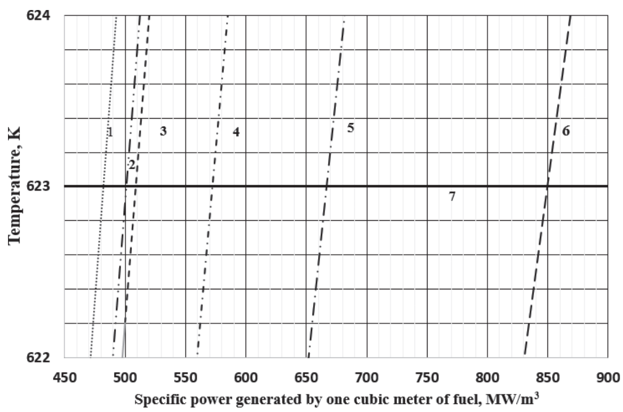

Figure 4. Dependences of the maximum fuel cladding temperatures on specific power generated in one cubic meter of fuel obtained based on the 3D model taking into account radiative heat exchange: 1 – for a fuel element with no hole, K; 2 – for a fuel element with a hole of 1.5 mm, K; 3 – for a fuel element with a hole of 2.3 mm, K; 4 – for a fuel element with a hole of 3 mm, K; 5 – for a fuel element with a hole of 4 mm, K, 6 – for a fuel element with a hole of 5 mm, K; 7 – permissible fuel cladding temperature.

boundary for the fuel and cladding temperature limits. This makes it possible to increase the fuel element specific power.

Table 2 presents the results from investigating the effects of the maximum specific fuel element power, Q_{sp}, generated in one cubic meter of fuel taking into account radiative heat exchange in the 3D fuel element model on different parameters depending on the hole diameter.

It can be seen from the table that an increase in the fuel pellet hole diameter leads to a reduction in the permissible fuel and cladding temperature limit.

Table 2. Results from investigating the effects of the maximum specific fuel element power, Q_{sp}, MW/m^3

Pellet hole diameter, mm	0	1.5	2.3	3	4	5
Q_{sp} for fuel temperature, MW/m^3	715	820	950	1118	1500	2275
Q_{sp} for cladding temperature, MW/m^3	434	472	509	563	668	862
Fuel volume in fuel element, m^3	1.67E-4	1.60E-4	1.52E-4	1.41E-4	1.21E-4	9.47E-5
Share of increased uranium-235 content in UO_2 fuel for preserving energy margin in fuel element	1.000	1.040	1.100	1.180	1.380	1.760
Q_{sp} for fuel temperature with similar energy margin inside fuel element, MW/m^3	715.0	788.5	863.6	947.5	1087.0	1292.6
Q_{sp} for cladding temperature with similar energy margin inside fuel element, MW/m^3	434.0	453.8	462.7	477.1	484.1	489.8

Calculations show that an additional enrichment with uranium-235 and an increase in the fuel pellet hole diameter reduces the reactor core axial power peaking factor with a fixed thermal power of the fuel element (Gorbunov et al. 2021). The best possible fuel element parameters have been found as the result of the study which ensure the smallest possible core axial power peaking factor: the fuel pellet hole diameter is 5 mm, and the share of fuel enrichment with uranium-235 has been increased by a factor of 1.76.

Fig. 5 presents the dependences of specific power generated in one cubic meter of fuel and in fuel cladding on the fuel element hole diameter.

Following the approximation of the numerical simulation results, dependences of specific power generated in the fuel element on the fuel pellet hole diameter have been obtained as

$$q_{max} = a_1 d^2 + a_2 d + a_3. \quad (19)$$

The values of coefficients a_i for fuel (1) and fuel cladding (2) in the diagrams in Fig. 5 are presented in Table 3.

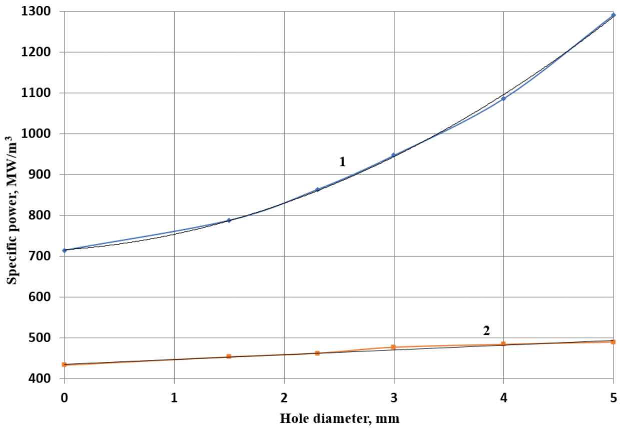

Figure 5. Specific power generated in one cubic meter of fuel and in fuel cladding as a function of the fuel element hole diameter: 1 – permissible specific power generated in UO2 fuel; 2 – maximum specific power generated in a fuel element without permissible fuel cladding temperature being exceeded.

Table 3. Values of coefficients a_i for fuel and fuel cladding

Coefficient	Fuel (1)	Cladding (2)
a_1	19.11	0
a_2	18.76	11.56
a_3	716.4	436.5

Conclusions

It has been shown by the results of investigating the effects of the fuel pellet materials (UO_2 uranium dioxide and U uranium metal) with different heat conductivity coefficients on the reactor core axial power peaking factor that the UO_2 fuel replacement for uranium metal does not offer any advantages.

Calculations of the fuel element specific power confirm the effects of radiative heat exchange, and the percent difference in specific power with the radiative component of heat exchange taken and not taken into account amounts to 38.16 MW/m^3 (6.1%).

The specific power density values obtained using the 2D and 3D models built for a fuel element with a hole of 2.3 mm, taking into account radiative heat exchange, differ noticeably in favor of the 3D model and the difference amounts to 222.87 MW/m^3 (26.2%).

The best possible fuel element parameters have been found as the result of the study which ensure the smallest possible reactor core axial power peaking factor: the fuel pellet hole diameter is 5 mm, and the share of fuel enrichment with uranium-235 has been increased by a factor of 1.76.

It has been found to be theoretically possible to increase the power of nuclear reactors by reducing the power peaking factor through the volume.

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