Research of the temperature state of nuclear fuel with various fuel rod design modifications

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***Abstract*—The temperature distribution in a fuel pallet consisting of uranium dioxide was researched depending on the thickness of the fuel-clad gap and the size of the central hole at various points in the nuclear reactor campaign. The fuel element of the VVER-1200 was selected as a model. It has been established that a reduction in the fuel-clad gap leads to a decrease in the maximum temperature of the fuel since the fuel-clad gap has lower thermal conductivity in comparison with the cladding and the fuel. The composition of the gas in the gap changes during the fuel campaign due to the release of gaseous fission products, which leads to a reduction of thermal conductivity. Reducing the center hole also decreases the maximum fuel temperature, but to a lesser degree than the reduction of the fuel-clad gap.**

Keywords—nuclear fuel, fuel elements, maximum temperature of the fuel rod

I. INTRODUCTION

Nuclear power occupies a significant share in the production of electricity [1]. Its indisputable advantages are environmental friendliness, efficiency and stability of work [2]. The specificity of the nuclear source of electricity is the possibility of release of radioactive substances into the environment in case of an accident. Consequently, increased safety and reliability requirements are imposed on nuclear power facilities.

According to the modern concept of safety of nuclear power plants, there are several safety barriers that prevent the occurrence of radioactive contamination, the first of which is the fuel matrix [3]. The fuel is manufactured in such a way as to reduce the possibility of release of fission products under the fuel element cladding. The classic version of the fuel rod design is a rod in which fuel in the form of pellets is placed in a cylindrical shell of a corrosion-resistant alloy. To collect gaseous fission products and compensate for swelling in the center of the fuel pellet, an opening is made, and a gap is left between the fuel and the casing [4].

The most common type of reactor in the world is a pressurized-water reactor, and the most common type of fuel is uranium dioxide (UO_2) [5]. Uranium dioxide has a high melting point (about 2800 °C), but low thermal conductivity [6], which decreases with increasing temperature. During the operation of this fuel there is a high temperature gradient in the fuel core.

Fuel rod capacity increases to improve the efficiency of the reactor. With constant geometric parameters, this leads to the achievement of high temperatures in the center of the fuel element, which may contribute to the destruction of the fuel matrix. To improve the reliability of the fuel, measures should be taken to reduce the maximum temperature in the core. Thus, it is necessary to investigate the possibility of increasing the power of the fuel element taking into account changes in its design, namely the modification of the shape and size of the fuel pellet.

The effect of changing the geometric parameters (internal hole and gas gap thickness) of the fuel core on the maximum temperature reached in the fuel element depending on the campaign time and various calculation options (at a constant volume energy release and at a constant power of a fuel element) is researched in this paper.

II. DESCRIPTION OF THE FUEL ELEMENT MODEL

The calculation of the maximum temperature of a fuel element of a nuclear reactor was carried out using the program TVEL, developed on the basis of [7, 8].

The fuel model of the VVER-1200 reactor [9] was chosen as the model under study, since this reactor is modern and developed on the basis of the VVER-1000 reactor, which is the most accepted and mastered in Russia. The main parameters of a fuel rod are given in Table 1. The structure of a fuel rod is shown in Figure 1.

The temperature of the outer surface of the shell is assumed to be equal to the temperature of the coolant, which does not change in the calculation. In the calculation model, it is assumed that heat is transferred by heat conduction.

In the manufacture of a fuel element, helium (He) gas is pumped between the fuel and the cladding under a pressure of 2 MPa to increase the thermal conductivity of the gas layer [4]. During operation, the characteristics of the fuel element change, including the composition of the gas under the shell due to the release of gaseous fission products. In particular, xenon (Xe) accumulates, which has worse thermophysical

TABLE I. THE PARAMETERS OF STUDIED FUEL ELEMENT [9]

Parameter	Value
Cladding material	E110
Fuel	UO_2
Gas in the gas gap	He; Xe; 50% He + 50% Xe
Temperature on the outer surface of cladding t_{clad}^{out}, °C	314,1
Fuel element diameter d_{fe}, mm	9,1
Cladding thickness δ_{cl}, mm	0,65
Gas gap thickness δ_g, mm	0,1
Pellet diameter d_p, mm	7,6
Inner hole diameter d_h, m	1,2
Volumetric energy release q_v, MW/m^3	110
Power of the fuel element N, MW	18,68

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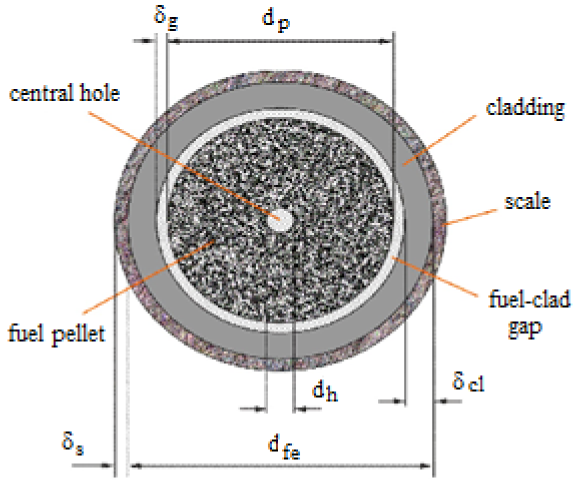

Fig. 3. Fuel element composition

properties compared to helium, which impairs the operation of the fuel element [4]. The composition of the gas sweep reflects the moment of the fuel campaign. He corresponds to the beginning of the campaign, 50% He + 50% Xe corresponds to the middle of the campaign and Xe corresponds to the end.

The operation of a fuel element is considered in two versions of the calculation: at a constant volume energy release (constant volume heat flux) and constant power (or at a constant linear heat flux). The volume energy release q_v = 110 MW/m^3 (the energy release at the nominal operating parameters of a fuel rod) corresponds to the power N = 18.68 MW (for a given length l = 3.84 m).

III. Results Of Calculation

A. The influence of the thickness of the gas gap

In the first series of calculations, the impact of the gas gap thickness on the maximum temperature in the pellet was studied, taking into account the composition of the gas in the gas gap under various calculation modes.

The results of calculations with a constant energy release are displayed in Fig. 2 and the results with constant power are displayed in Fig. 3.

The gas has a lower thermal conductivity than the fuel material, while xenon has worse thermal and physical properties than helium. Increasing the gas gap at a constant coolant temperature results in that the maximum temperature in the pellet increases due to the occurrence of a larger temperature differential in the gas layer. The numerical results of the calculations are given in table 2.

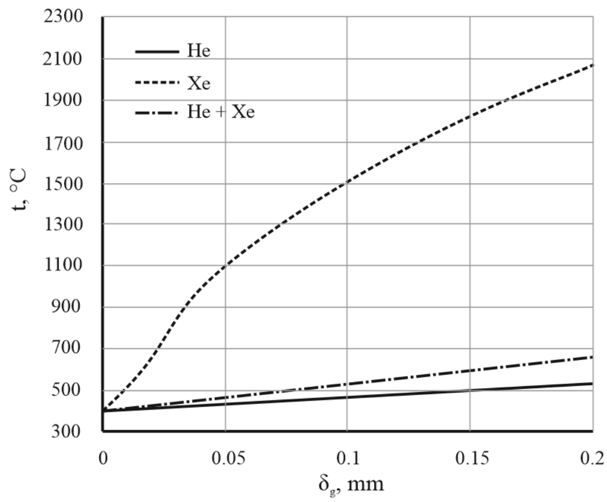

Fig. 2. The maximum temperature depending on the thickness of the gas gap at a constant volumetric energy release

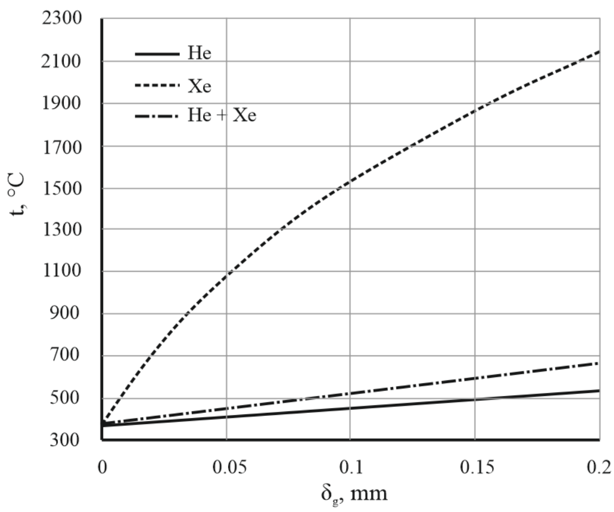

Fig. 1. The maximum temperature depending on the thickness of the gas gap at a constant power level

B. The influence of central hole size

In the second series of calculations, the dependence of the maximum temperature in the pellet on the diameter of the inner hole was considered. The results of the calculation with a constant energy release are reflected in Fig. 4, with constant power in Fig. 5.

TABLE II. THE VALUE OF THE MAXIMUM TEMPERATURE IN THE FUEL PELLET DEPENDING ON THE GAS GAP THICKNESS, °C

Gas	q_v = const					N = const				
	δ_g, mm					δ_g, mm				
	0	0.04	0.08	0.12	0.16	0	0.04	0.08	0.12	0.16
He	388.5	421.5	452.0	480.3	507.3	384.4	417.9	450.5	482.2	513.9
50%He + 50% Xe	388.5	452.2	510.0	562.7	611.3	384.4	447.6	507.8	565.5	621.1
Xe	388.5	985.7	1371.2	1649.1	1886.9	384.4	966.6	1362.1	1659.3	1921.9

TABLE III. THE VALUE OF THE MAXIMUM TEMPERATURE IN THE FUEL PELLET DEPENDING ON DIAMETER OF THE INNER HOLE, °C

Gas	q_v = const					N = comst				
	d_h, mm					d_h, mm				
	0	0.6	1.2	1.8	2.4	0	0.6	1.2	1.8	2.4
He	478.0	474.2	466.4	455.8	443.4	473.7	471.1	466.4	460.7	454.4
50%He + 50% Xe	550.9	546.4	536.9	523.7	507.8	544.8	542.0	536.9	530.7	523.9
Xe	1557.4	1545.7	1518.0	1484.2	1429.6	1534.2	1528.3	1518.0	1505.0	1491.0

The temperature increase in the pellet occurs according to a parabolic law, since it contains an internal source of heat [4], and the maximum temperature is reached in the center.

The temperature on the inner surface of the pellet is determined using (1) [4].

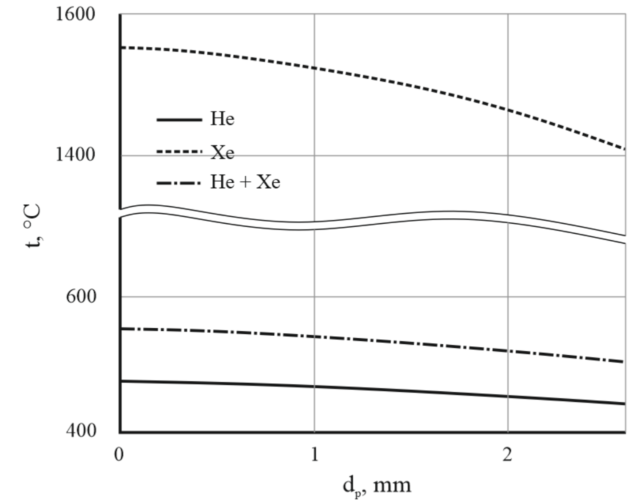

Fig. 4. Maximum temperature depending on the diameter of the inner hole at a constant volumetric energy release

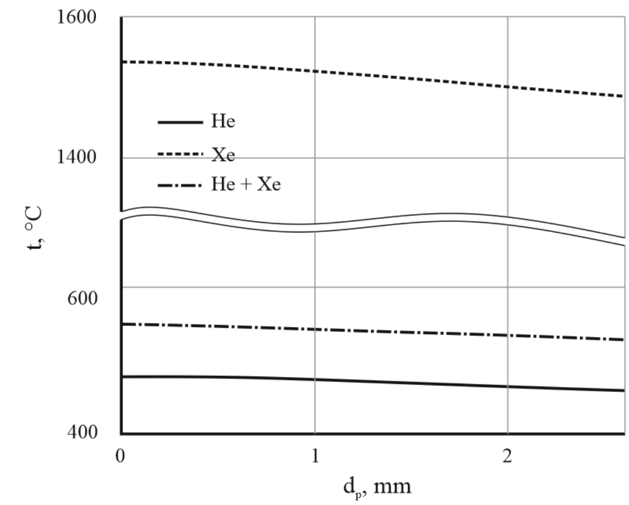

Fig. 5. Maximum temperature depending on the diameter of the inner hole at constant power level

$$t_p^{in} = t_p^{out} + q_v \cdot \frac{d_p^{\ 2} - d_h^{\ 2}}{16 \cdot \lambda_{fuel}}, \quad (1)$$

where t_p^{out} is the temperature on the outer surface of the fuel pellet, °C; q_v is the volumetric energy release, W/m^3; d_p is the outer diameter of the pellet, m; d_h is the diameter of the inner hole, m; λ_{fuel} is the thermal conductivity of fuel, W/(m·°C).

The temperature of the inner surface can also be obtained depending on the power using (2) [4].

$$N = q_v \cdot V = q_v \cdot l \cdot \frac{\pi \cdot \left(d_p^{\ 2} - d_h^{\ 2}\right)}{4}, \quad (2)$$

where q_v is the volumetric energy release, W/m^3; V is volume of the fuel, m^3; l is length of the fuel rod, m; d_p is the outer diameter of the pellet, m; d_h is the diameter of the inner hole, m.

The thermal conductivity of the fuel is determined using the tables from [6].

As the diameter of the inner hole in the fuel pellet increases, the maximum temperature decreases. Increasing the inner hole means removing a portion of the fuel material, so the maximum temperature reached in the core drops. At a constant energy release, the temperature is determined by the change in the inner hole. At a constant power level, the volumetric energy release increases with decreasing fuel volume, but the temperature is proportional to the difference of the squares of the outer and inner diameter of the core, so the temperature in the center decreases. Numerical results of calculations are given in table 3.

IV. Conclusion

The integrity of fuel elements of a nuclear reactor is one of the key points of safe operation of a nuclear power plant. Overheating of the fuel is not allowed under any operating conditions of the reactor in order to avoid its melting.

The temperature state of the fuel rod depends on the geometrical dimensions of each layer. The thickness of the gas layer has the highest influence on it, since the gas has a lower thermal conductivity compared to the cladding material and fuel. With increasing gas gap thickness, the maximum fuel temperature increases. This influence is enhanced during operation, as the composition of the gas changes with the during campaign, and the heat transfer deteriorates.

The size of the inner hole of the fuel pellet also affects the temperature distribution of the fuel: the larger the inner hole, the lower the temperature in the center of the fuel rod. However, the diameter of the inner hole has a smaller effect on the maximum temperature value than the size of the gas layer.

Also, the change in the temperature field is influenced by the calculation mode — at a constant volumetric energy release or at constant power. At a constant energy release, the maximum temperature is affected only by the geometry of the fuel element. At constant power, the volumetric heat flow varies inversely with the volume of the fuel pellet, and the temperature changes depending on the size of the fuel, and on the magnitude of the volumetric heat flow.

A promising option for the design of a fuel element in terms of temperature distribution is the absence of a gas gap and a central hole. This design variant is supposed to be used for IV generation fuel - a core with a diameter of 7.8 mm without a central hole with a fuel rod diameter of 9.1 mm [10]. At the same time, a sufficient gas collector is required to collect gaseous fission products that appear during the entire fuel campaign. In addition to improving the working conditions of the fuel element and increasing its operational reliability, the performance of the fuel pellet increases the fuel load, which allows the nominal reactor power to be raised by 7-10% [10].

References

[1] BP energy outlook, 2019 edition, BP Energy Economics, 2019.

[2] Rosatom nuclear energy generation, Rosatom, URL: https://rosatom.ru/production/generation (15.06.2019).

[3] Safety systems of russian nuclear power plants, Rosatom, URL: https://rosatom.ru/about-nuclear-industry/safety-russian-npp (16.06.2019).

[4] B. A. Dementyev, Nuclear Power Reactors, 2nd ed., Moscow: Energoatomizdat, 1990.

[5] Operational & Long-Term Shutdown Reactors, IAEA world statistics.

[6] P. L. Kirillov, M. I. Terentieva, N. B. Deniskina, Thermal-physical Properties of Nuclear Industry Materials, 2nd ed., Moscow: IzdAt, 2007.

[7] G. N. Kolpakov, O. V. Selivanikovam, Design of Fuel Elements, Channels, and Cores of Power Reactors: Tutorial, Tomsk: TPU, 2009.

[8] S. T. Leskin, A. S. Schelegov, V. I. Slobodchuk, Physical features and design of reactor WWER-1000: Tutorial, Moscow: NRNU MEPhi, 2011.

[9] TVEL Nuclear Fuel Booklet: The Energy of Growth.

[10] A. Dolgov, Modern WWER Fuel, 2013.