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THERMAL HYDRAULIC METHOD OF OPTIMIZING THE THERMAL RESISTANCE OF NUCLEAR FUEL OF REACTOR INSTALLATIONS

An original thermal-hydraulic method for optimizing the thermal resistance of thermal conductivity of fuel rod matrix upgrades has been developed to achieve the maximum burnup depth of nuclear fuel while ensuring safety conditions in operating and emergency modes of nuclear power plants. Based on the developed method, the boundaries of the optimization area for upgrades of the thermal resistance of the fuel rod matrix thermal conductivity are determined in accordance with the accepted optimization criteria and safety conditions. It is established that when optimizing upgrades to the thermal resistance of nuclear fuel, it is necessary to take into account both normal operating conditions and emergency conditions with impaired heat removal from the reactor core. It is established that the optimal values of thermal resistance of nuclear fuel thermal conductivity depend on the design and technical parameters of reactor installations, composition, and condition of nuclear fuel, accident management systems, and other factors.

Keywords: reactor, thermal resistance of nuclear fuel.

1. Introduction

One of the current approaches to improve the efficiency of nuclear power plant (NPP) operation is to increase the depth of nuclear fuel (NF) burnup [1 - 7] and others. Increasing the depth of nuclear fuel burnup (DNFB) can be achieved by modernizing the thermophysical properties of NF, in particular, in well-known experimental studies, reviewed, for example, in [8]; it was found that DNFB ~ λ_F^{-n} ($n > 0$, λ_F is the parameter of thermal conductivity of NF).

Thus, an "artificial" decrease in core thermal conductivity NF increases DNFB (ceteris paribus). In practice, an "artificial" decrease in λ_F can be achieved by chemically adding to NF elements with reduced thermal conductivity [8]. The consequence of a relative decrease in λ_F (ceteris paribus) is a relative increase in temperature of NF $\left(T_F\right)$ and, accordingly, in DNFB.

However, the negative consequences of a relative increase of T_F may be:

increased damage/degradation of NF;

reaching the maximum permissible temperature at the beginning of intensive melting/destruction of the fuel matrix $\left(T_{Fm}\right)$.

One of the approaches to reduce surface damage to the NF is associated with the development of a "two-layer" fuel matrix: a central zone of the NF with reduced thermal conductivity and a surface zone (rim zone) with increased thermal conductivity of the NF (e.g., [8]). A relative "artificial" increase in the thermal conductivity of the core (e.g., by the same chemical method) determines the corresponding decrease of T_F and surface damage to the fuel matrix. However, the negative consequences of a relative increase in the thermal conductivity of the rim zone may be (ceteris paribus) a relative increase in the fuel cladding temperature $\left(T_b\right)$. Under certain conditions (e.g., heat transfer crisis (boiling) and/or accidents with impaired heat removal from the reactor core), T_b may reach the maximum permissible temperature for the start of intensification of the zirconium vapor reaction with impulsive hydrogen and heat release $\left(T_{bm}\right)$.

Thus, it is necessary to optimize the modernization of thermophysical properties and thermal resistance of NF conductivity to achieve maximum DNFB while ensuring the necessary safety conditions in NPP operating and emergency modes.

At present, these issues are not sufficiently studied, which determines the relevance of the presented work.

The work aims to develop a method for optimizing the modernization of thermal properties and thermal resistance of the NF while ensuring safety conditions for maximum permissible temperatures of the NF element and fuel cladding in operating and emergency modes of NPPs.

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2. Basic provisions and models of the optimization method

1. The optimization criterion is the maximum permissible DNFB while ensuring nuclear safety conditions:

$$T_{Fo} < T_{Fm}, \tag{1}$$

$$T_b < T_{bm}, \tag{2}$$

where T_{Fo} is the maximum temperature of the NF in the central part of the fuel rod matrix.

For zirconium fuel element claddings, the maximum permissible temperature is $T_{bm} = 1473\,\text{K}$. The maximum melting/fracture onset temperature for UO_2 NF is $T_{Fm} = 3113\,\text{K}$ [8]. Depending on the level of NF enrichment, concentration of accumulated plutonium, and other effects, the temperature of intensive melting/damage of NF can be significantly lower than 3113 K.

2. The optimization parameter is the thermal resistance of the fuel matrix thermal conductivity:

$$R_F = \frac{\delta_r}{\lambda_r} + \frac{\delta_0}{\lambda_{F0}}, \tag{3}$$

where δ_r, δ_0 are the thicknesses of the rim zone and the central zone of the fuel matrix; λ_r, λ_{F0} are the thermal conductivity parameters of the rim zone and the central zone of the fuel matrix.

3. The DNFB optimization method is based on thermal-hydraulic models of fuel assemblies in two boundary conditions:

normal reactor operating conditions (NOC);

maximum design basis accident with the main circulation pipeline (MDBA) separation.

In the NOC mode, the intensity of heat transfer from the fuel rod surface is maximal, and in the MDBA mode, it is minimal.

The equations of fuel rod heat balance in quasi-stationary and one-dimensional heat transfer by thermal conductivity approximations for the NOC and MDBA modes [9 - 11]:

$$\alpha_{max} \cdot \left[T_b - T_T\left(\alpha_{max}\right)\right] = \frac{T_{Fo} - T_b}{R_F + R_{g\text{в}}} = N_o, \tag{4}$$

$$\alpha_{min} \cdot \left[T_b - T_T\left(\alpha_{min}\right)\right] = \frac{T_{Fo} - T_b}{R_F + R_{g\text{в}}} = N_a, \tag{5}$$

where α_{max}, α_{min} are the maximum and minimum parameters of the heat transfer intensity on the fuel rod surface in the NOC and MDBA modes; T_T is the coolant temperature; N_o, N_a are the fuel rod thermal power in the NOC and MDBA modes; $R_{g\text{в}}$ is the thermal resistance parameter of the thermal conductivity of the gas gap and the fuel rod shell:

$$R_{gb} = \delta_g / \lambda_g + \delta_b / \lambda_b, \tag{6}$$

where δ_g, δ_b are the thicknesses of the gas gap and fuel rod cladding; λ_g, λ_b are the thermal conductivity parameters of the gas gap and fuel rod cladding.

Taking into account the adopted provisions, after the transformations (1) - (5), we obtain the conditions for optimizing the upper and lower limits of R_F :

$$R_{F1} = \frac{T_{Fm} - T_b\left(\alpha_{max}\right)}{\alpha_{max} \cdot \left[T_b(\alpha_{\max}) - T_T\left(\alpha_{max}\right)\right]} - R_{ga}, \tag{7}$$

$$R_{F2} = \frac{T_{Fo}\left(\alpha_{min}\right) - T_{bm}}{\alpha_{min} \cdot T_{bm} - \alpha_{min} \cdot T_T\left(\alpha_{min}\right)} + R_{ga}. \tag{8}$$

The area of acceptable optimization

$$R_{F2} < R_F < R_{F1}. \tag{9}$$

When ensuring safety conditions in operating and emergency modes

$$T_{Fo}\left(\alpha_{min}\right) < T_{Fm};\; T_b\left(\alpha_{max}\right) < T_{bm}. \tag{10}$$

Safety conditions for preventing a boiling crisis on the surface of the fuel cell:

$$T_T < T_S\left(P\right), \tag{11}$$

where $T_S\left(P\right)$ is the saturation temperature of the coolant at the current pressure *P*.

3. Results and discussion

The analysis of the established area of permissible optimization of R_F and the necessary conditions for the safe modernization of thermal resistances of NF (7) - (11) lead to the following conclusions:

1. In NOC modes, relative increases in thermal resistances of the central zone of the fuel matrix (ceteris paribus) increase the maximum core temperature of NF and, accordingly, the DNFB (positive effect for operation). However, the relative increase in T_F (ceteris paribus) determines the relative increase in fuel cladding temperature $\left(T_b\right)$ and the possibility of safety violations (negative effect).

2. In NOC modes, a relative decrease in thermal resistance of the thermal conductivity of the rim zone

of the fuel matrix (ceteris paribus) determines positive safety effects of a relative decrease in maximum T_F and surface damage of the NF. But in this case, there is a relative decrease in DNFB and a relative increase in T_b (negative effects).

3. In emergency modes with impaired heat removal from the reactor core due to relatively increased initial values of T_b and or T_{Fo} as a result of core upgrades, safety conditions (1), (2) may be violated. For example, the results of MDBA modeling in NPPs with VVER-1000 by different deterministic codes and code users established that the maximum fuel rod cladding temperature with an unmodernized core can reach 1373 K during an accident, which meets safety conditions (2) [8]. However, if, as a result of R_F modernization, the fuel cladding temperature in NOC modes was 100 K higher than in unmodernized NF, then safety condition (2) would be violated.

Thus, when upgrading R_F of a NF, it is necessary to take into account not only NOC but also the conditions of emergency modes.

The method presented in this paper determines the region of optimal values R_F of NF upgrades to achieve maximum DNFB while ensuring the required safety conditions in NOC and emergency modes with violations of heat removal from the reactor core.

Optimal values R_F of NF depend on the design and technical parameters of the NPP and reactor core, composition and condition of the NF, accident management systems, and other factors.

4. Conclusions

1. The original thermal-hydraulic method for optimizing the thermal resistance to the thermal conductivity of fuel rod upgrades was developed to assess and achieve the maximum DNFB depth while ensuring safety conditions under normal operation and at the maximum design basis accident at NPPs.

The optimization criterion is the maximum burnup depth of NF permissible under safety conditions. The optimization parameter is the thermal resistance to the thermal conductivity of the fuel rod matrix. Safety criterion – maximum permissible temperature of the beginning of intensive melting/destruction of NF; the maximum permissible temperature of the fuel rod cladding at the beginning of intensification of the vapour-zirconium reaction, conservative conditions for the beginning of the coolant boiling crisis on the fuel rod surface.

2. The thermal-hydraulic method makes it possible to determine the boundaries of the optimization area for upgrades of the thermal resistance to the thermal conductivity of the fuel rod matrix in accordance with the optimization criteria and safety conditions.

3. The analysis of the study results showed that when upgrading the thermal resistance of NF, it is necessary to take into account both NOC and emergency conditions (including the maximum design basis accident) with a violation of heat removal from the reactor core.

4. The dependence of optimal values of thermal resistance to the thermal conductivity of NF on the structural and technical parameters of reactor installations, composition and condition of NF, accident management systems, and other factors is established.

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ТЕПЛОГІДРАВЛІЧНИЙ МЕТОД ОПТИМІЗАЦІЇ ТЕРМІЧНОГО ОПОРУ ЯДЕРНОГО ПАЛИВА РЕАКТОРНИХ УСТАНОВОК

Розроблено оригінальний теплогідравлічний метод оптимізації термічного опору теплопровідності модернізацій паливних матриць твелів для досягнення максимальної глибини вигоряння ядерного палива при забезпеченні умов безпеки в робочих та аварійних режимах ядерних енергоустановок. На основі розробленого методу визначені межі області оптимізації модернізацій термічного опору теплопровідності паливної матриці твела відповідно до прийнятих критеріїв оптимізації та умов безпеки. Встановлено, що при оптимізації модернізацій термічного опору ядерного палива необхідно враховувати як режими нормальних умов експлуатації, так і аварійні режими з порушенням відведення тепла від активної зони реактора. Оптимальні значення термічного опору теплопровідності ядерного палива залежать від конструкційно-технічних параметрів реакторних установок, складу та стану ядерного палива, систем управління аваріями та інших факторів.

Ключові слова: реактор, термічний опір ядерного палива.

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