Experimental device design justification for radiation resistance tests of single-mode optical fibers and FBG-based sensors at the IVG.1M reactor

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Abstract. One of the most important stages in the development of an experimental device is to carry out a series of computational studies to substantiate the compliance of device design with the objectives of the experiment, such as the choice of test modes and the study of standard and hypothetical emergency modes of its operation. Result of these studies is the neutron-physical, thermal, strength and hydrodynamic characteristics of the structural elements of the device and working bodies. During this work, a series of neutron calculations was conducted using the MCNP6 code and thermal-physical calculations using the ANSYS software package of two configurations of the experimental device. A feature of the calculated studies is the presence of specific requirements for the thermal state of the experimental device sleeve. Namely, ensuring a predetermined temperature gradient between its ribs, which should not exceed 4°K during the reactor tests.

Keywords: experimental device, single-mode optical fibers, FBG-based sensors, IVG.1M reactor, MCNP6, Ansys Fluent, computer modeling.

1. Introduction

Currently, equipping fission and fusion reactors with fiber-optic sensors based on a fiber Bragg grating (FBG) [1-5] is a growing trend in the development of nuclear industry [3, 6], in the creation of embedded systems for self-diagnosis of aircraft structures, as well as the whole a number of other branches of science [7]. FBGs installed in such strong in-core radiation fields are currently being intensively developed. The well-known principle of FBG operation consists in measuring the wavelength shift of light reflected from the FBG (i.e., the shift of the FBG resonance wave), which is uniquely related to the measured physical quantity (for example, temperature). The resonant wavelength depends on the refractive index of the optical fiber, which in turn can be altered by ionizing radiation (fast neutrons and/or gamma rays), causing the radiation to interfere with the sensor reading. It is necessary to determine in advance to what extent this unwanted radiation-induced effect will degrade the accuracy of the sensor. Another undesirable factor that will occur in the fiber transporting the probe light signal...
is the radiation-induced effect in the FBG and the reflected signal from the FBG. The effect consists in the appearance of attenuation of light in the fiber (radiation-stimulated attenuation (RSA)), which reduces the signal-to-noise ratio of the sensor and thereby degrades its accuracy, up to complete failure. Investigations of the phenomena arising from the action of ionizing radiation on fiber optical sensors are presented in [8-11].

The IVG.1M research reactor (Kurchatov, Kazakhstan) [12, 13] was chosen as a combined source of neutrons and gamma radiation, which allows carrying out in-situ studies directly during the irradiation of investigated samples [14-19]. For testing under conditions of combined $\gamma$-n radiation, radiation-resistant single-mode optic fibers (SMF) from different manufacturers and fiber-optic FBG-based sensors were selected. One of the important requirements for the experimental device (ED) design was that the SMF samples and FBG-sensors should be placed in such a way, that during the reactor experiments the temperature gradient of all investigated samples did not exceed 4 K.

2. Experimental part

The purpose of research was to substantiate the design of the ED by calculation to achieve the required heat balance during irradiation of test samples at the IVG1.M reactor. The research tasks were logically divided into the following groups: neutron-physical and thermal-physical calculations of the initial and modernized configuration of the ED; selection of material and geometric parameters of the ED to ensure the difference in temperature values of test samples of no more than 4 K.

2.1. Initial configuration of the experimental device

As a result of design and engineering studies, the following design of the ED was proposed, scheme of which is presented in [20]. ED consists of the following main units: sealed evacuated irradiation capsule (environment: vacuum); inner segment of the capsule on which 6 fiber-optic temperature sensors, 8 coils of optical fiber (coated with Cu, Al and uncoated) and 8 reference coils of fiber optic, 3 Cr-Al type thermocouples are installed; the pipe, hermetically connected to the capsule, through which optical fibers and thermocouples will be removed from the inner segment of the capsule outside the physical protection of the reactor; an external unit, hermetically connected to the pipe, on which a fiber-optic sealed lead-in will be mounted and a branch pipe is provided for connecting the ED with the gas-vacuum system of the LIANA test bench [21-24]. Also, a cooling cover with a cooling gas (nitrogen) supply pipe is installed on the irradiation capsule, which, when blown through the annular gap, cools the capsule walls. A sketch drawing of the sleeve is shown in [20]. The sleeve height can be varied from 43 to 50 mm. The inner segment of the capsule is made of a metal sleeve made of copper or stainless steel (12Cr18Ni10Ti) with an internal hexagon (for mounting sensors) and external horizontally cut slots for laying optical fiber. The optical fiber is pulled out of the slot either through one oval hole with a diameter that is orders of magnitude larger than the fiber diameter, or through two holes drilled at an angle of 60 degrees (input-output, respectively).

3. Results and Discussion

3.1. Computer modelling results with an initial configuration of the experimental device

3.1.1. Calculation of neutron characteristics of the initial configuration of experimental device

At the first stage, neutron calculations were performed, the results of which served as input data for thermal simulation. The calculations were performed using the MCNP6 code [25] and the ENDF/B-VII.1 nuclear constant libraries [26]. The neutron-physical calculation was carried out under the following boundary conditions: the temperature of the IVG.1M reactor is taken to be 300$^\circ$K (during start-up it can rise to 50$^\circ$K at the reactor inlet); the stationary thermal power level of the IVG.1M reactor is 6 MW and is determined by the fission energy of uranium and the activation energy of non-fuel elements in the reactor core.
For calculations, a combined model was developed (Figure 1), created on the basis of the IVG.1M model [27] and the design model of the experimental device (Figure 1).

**Figure 1.** Combined computational model of the IVG.1M reactor and experimental device

The high-altitude (18 parts) and azimuthal (6 sectors) distribution of energy release according to the ED materials, due to the absorption of $\gamma$-radiation and neutrons, in the calculation process was determined. Table 1 presents the results of calculating the average distribution of energy release in materials of the device body and the sleeve when the reactor is operating at a stationary thermal power level of the IVG.1M reactor, equal to 6 MW.

| Specific power, $10^6$ W/m³ | Power, W |
|-----------------------------|----------|
| Steel elements              | 10.4·687 |
| Steel sleeve                | 10.4·301 |
| Copper sleeve               | 12.2·353 |

According to the results of neutron-physical calculations, the non-uniformity of the altitude distribution of energy release in the sleeve is about 8%, and the azimuthal non-uniformity of the energy release distribution, due to the core asymmetry due to the presence of two low-enriched fuel, was less than 0.3% and is at the level statistical calculation error. In this regard, the irregularity of the azimuthal distribution of energy release was not taken into account in calculations. In order to reduce the high-altitude non-uniformity of energy release distribution, it is recommended to install the sleeve in the area with the least non-uniformity of the $\gamma$-ray flux distribution.

### 3.1.2. Calculation of thermal-physical characteristics of the initial configuration of the ED

The main task of the thermal-hydraulic calculation at this stage was to determine the thermal state of the device in a steady-state regime of heat exchange between the sleeve and the coolant at a stationary level of reactor power. To accomplish this task, using the ANSYS software package [28], a 3D model was developed that allows calculating the required parameters taking into account the distribution of the coolant velocity field, corresponding to the required values of the mass flow rate of nitrogen in the cooling cover of the device, and a given distribution of specific power in materials of the ED. The average distribution of the specific power in body materials of the ED and the sleeve is taken according to Table 1. The initial data for carrying out thermal-hydraulic calculations: Coolant consumption 0.1 kg/s, coolant temperature and pressure at the inlet, 300 K and 1.0 MPa, respectively. The coolant flow rate was determined as a result of preliminary calculations using the values of energy release in the structural elements of the device and in the cooling cover, in such a way that the wall temperature of the device does not exceed 423 °K at the IVG.1M reactor core center. This is 50 °K less than the value
determined in the research tasks. This flow rate also provides a turbulent flow of the coolant in the cooling path \((\text{Re} > 10000)\). The flow turbulence was taken into account using the standard \(k-\varepsilon\) model.

On the outer wall of the model, conditions of convective heat transfer with an ambient temperature of \(300\ \text{K}\) and a heat transfer coefficient of \(5\ \text{W/(m}^2\text{K)}\) are set. The material properties used in calculations were taken from reference sources [29].

According to the results of preliminary thermal-hydraulic calculations, the device design of the initial configuration does not allow for a uniform temperature distribution on the ribs and in slots of the sleeve. The resulting non-uniformity of the temperature distribution was \(~12\ \text{K}\), which exceeds the permissible values. In this case, the wall temperature of device was less than \(370\ \text{K}\). It is recommended to use the design of the ED with a lower central supply of the coolant in order to level the azimuthal irregularity of the temperature distribution in slots of the sleeve.

### 3.2. Computer modelling results with the modernized configuration of the experimental device

Based on the results of calculating the initial configuration of ED, it was decided to make changes to the device design. Namely, the transfer of the cooling gas outlet pipe was carried out in order to align the axial distribution of the coolant flow, and the device was displaced in altitude relative to the center of the reactor core by \("-50\ \text{mm}\)". To confirm the possibility of conducting studies with the design of an experimental device with a lower central supply of the coolant, a thermal-hydraulic calculation was carried out with an average distribution of energy release in materials of ED body and sleeve according to Table 1 with sleeves made of steel and copper. According to the results of thermal calculations, it was obtained that when using a steel sleeve in the upgraded device configuration, the difference between the maximum and minimum temperatures recorded in the sleeve slots will be about \(9\ \text{K}\), while the radial unevenness in the slots exceeds \(10\ \text{K}\). This unevenness does not meet the set requirements, since as many times exceeds this value for a copper sleeve.

Therefore, the further calculations were made to determine the thermal-hydraulic parameters for a modernized device configuration using a sleeve made of M1 copper.

#### 3.2.1. Calculation of the neutron-physical characteristics of the modernized ED

Table 2 shows the results of the energy release distribution for three options of the ED with different heights of the copper sleeve.

| Height layer | Energy release, W | Option 1 | Option 2 | Option 3 |
|--------------|------------------|----------|----------|----------|
| 5            | 12.77            | 12.77    | 12.79    |
| 6            | 12.80            | 12.83    | 12.83    |
| 7            | 12.71            | 12.72    | 12.67    |
| 8            | 12.69            | 12.73    | 12.73    |
| 9            | 12.75            | 12.75    | 12.73    |
| 10           | 12.78            | 12.66    | 12.68    |
| 11           | 12.71            | 12.65    | 12.64    |
| 12           | 12.64            | 12.60    | 12.66    |
| 13           | 12.63            | 12.61    | 12.62    |
| 14           | 12.64            | 12.59    | 12.65    |
| 15           | 12.60            | 12.57    | 12.59    |
| 16           | 12.46            | 12.42    | 12.41    |

In order to reduce the altitude non-uniformity of the energy release distribution in the sleeve, it was decided to install the device in such a way that the sleeve center was \(50\ \text{mm}\) below the center of the IVG.1M reactor core. According to the tasks set, it is necessary to carry out calculations for three sizes
of sleeve (43 mm, 47 mm and 50 mm), while the number and height of slots in it remains unchanged. During the neutron-physical calculation, the influence of the device on the reactor reactivity was determined, which was $0.37 \pm 0.05 \beta_{\text{eff}}$ without taking into account the influence of sensors and communications of the test device. The average flux of thermal neutrons in the slots of the copper sleeve is $7.58 \times 10^{13}$ n/cm$^2$·s. The average flux of $\gamma$-particles is $2.77 \times 10^{14}$ $\gamma$/cm$^2$·s.

### 3.2.2. Calculation of the thermal-physical characteristics of the modernized ED

The main tasks of this thermal-hydraulic calculation of ED were the following: determination of the thermal state of ED using a sleeve made of copper M1, with a steady-state mode of heat exchange between the sleeve and the coolant; determination of the thermal state of ED with a possible decrease in the coolant flow rate through the cooling jacket; determination of the time to reach the destruction temperature of samples during emergency shutdown of the coolant flow.

For thermal-hydraulic calculation, the altitude distribution of energy release in the sleeve was taken, according to Table 2. The initial data for the thermal-hydraulic calculations are similar to the initial configuration of the device. On the model of outer wall, conditions of convective heat transfer with an ambient temperature of 300 K and a heat transfer coefficient of 5 W/(m$^2$·K) are set. Table 3 shows the calculated thermal parameters of the copper sleeve at different heights. The minimum temperature difference in slots of the radiator is 2.6 K for a 43 mm high.

| Parameter                                      | Value    |
|-----------------------------------------------|----------|
| Copper sleeve height, mm                      | 43, 47, 50 |
| Temperature difference in slots of the radiator, K | 2.6, 2.8, 3.1 |
| Maximum radiator temperature, K               | 361.3, 362.0, 363.2 |
| Maximum device temperature, K                 | 360.3, 361.0, 362.3 |
| Nitrogen outlet temperature, K                 | 309.2, 309.6, 309.8 |

According to calculations results of the thermal-hydraulic parameters of the ED using a copper sleeve, it can be seen that for all three options of the device configuration, the temperature difference in the sleeve slots will not exceed 4 K. Consequently, the height of the upper and lower layer of the sleeve located above and below the slots does not affect the altitude temperature gradient.

Based on the results of calculations of the modernized design of ED, the following conclusions and recommendations can be made:

- the possibility of conducting studies with ED design with a lower central coolant supply when using a copper sleeve was confirmed, while the use of a stainless steel sleeve is not recommended;
- thermal-hydraulic parameters were determined for three options of a copper sleeve, different heights of 43, 47 and 50 mm at the same nitrogen flow rate of 100 g/s in the cooling path of the device. In all three configurations of a copper radiator in the device, the temperature difference in slots of the sleeve will not exceed 4 K, which fully meets the requirements. The height influence of radiator on the results is minimal, which means that any of the considered options can be used for experiments;
- the thermal state of ED was determined at different coolant flow rates in the cooling path of the ED (nitrogen flow rate 100, 20, 5 and 3 g/s). When implementing these cooling modes, it is possible to regulate the temperature of the copper sleeve in the range from 360 K to 700 K;
- the requirements for performing a reactor experiment with the ED are achieved in the design of the device with a lower central location of the nitrogen supply pipe to the cooling jacket at a flow rate of 100 g/s and using a copper sleeve of any of the considered configurations.

The position of the optical fibers in the ED was not taken into account. Thin fibers must quickly heat up to the temperature of the surrounding material, regardless of the energy release. When placing materials in a vacuum under conditions of irradiation with $\gamma$-particles and neutrons, they will be heated up to complete destruction. Therefore, the optical fibers going to the copper heat sink must be in contact with the cooled surfaces throughout the entire length of the core.
The results of computer simulation were subsequently used to carry out further tests of the radiation resistance of fibers and fiber-optic sensors conducted at the WWR-K [30-36] nuclear reactor.

Conclusion
Within this work, a series of neutron and thermal calculations of two configurations of the ED was carried out. Also, the results were achieved with the set requirements. The altitude and azimuthal energy release in materials of the ED was determined for two options of the device configuration. The possibilities of numerical simulation for solving thermal problems associated with the choice and justification of the optimal design of the device are demonstrated. It is shown that the requirements for performing a reactor tests with ED are achieved in the option of the modernized configuration with a lower central location of the nitrogen supply pipe to the cooling jacket at a flow rate of 100 g/s and using a copper sleeve. In this case, the height of the sleeve can be selected from the range of 43 - 50 mm. The assessment of the possibility of increasing the device temperature by reducing the flow rate of the cooling gas to 3 g/s is carried out. Calculations have shown that this is possible, but a decrease in flow rate will be accompanied by an increase in the temperature gradient. According to studies results, all the necessary parameters of the ED were determined. It was provided a given temperature gradient at the most critical element, justified the choice of design, material, location in the reactor and the flow rate of the cooling gas. Therefore, the stage of computational studies of the experimental device for testing at the IVG.1M reactor has been completed.

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