

Coolant temperature distribution in the model of the fuel assembly peripheral area

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Abstract. To evaluate the interchannel temperature transfer, the test section was created, the working section of which is a model of two neighboring cells of the peripheral region of the fuel assembly. The experimental setup is equipped with three fuel rod simulators 500 mm long. During the work, the fuel rods were connected in turn to the power source. This made it possible to determine the features of the temperature distribution in the model with uneven energy release. The power of each fuel rod simulator was up to 2000 W. A movable thermocouple and an IR camera were used for measurements.

Introduction

Improving the efficiency and safety of nuclear power plants can be done by optimizing the designs of existing power units of thermal neutron nuclear power plants and creating a new type of fast neutron reactors with liquid metal coolants. To improve nuclear power complexes of a new generation, detailed measurements of local hydrodynamic characteristics and heat transfer in the elements of nuclear power plants are required.

A significant problem is the limited database on the regularities of thermophysical phenomena in the flow of coolants with low Prandtl numbers. Due to the complexity of the experimental study of the operation of reactor plants in normal and emergency modes, the coolant flow is modeled on the basis of calculations. Currently existing system thermal-hydraulic codes are based on empirical information and theoretical assumptions. There is a possibility of incorrect prediction due to the imperfection of models, nodalization effects and other factors. Their refinement and verification are required, taking into account the latest achievements in the field of experimental hydrodynamics and heat transfer.

Studies of the structure of flows in fuel assemblies of the reactor plant have been carried out for many years. Data on local hydrodynamics under the conditions of fuel assemblies were obtained, correlations were proposed for calculating the coefficients of resistance and heat transfer.

The introduction of measurements with high temporal resolution to study the hydrodynamics of fuel assemblies: the method of thin-film anemometry [1], laser Doppler velocity meters [2] and in recent years - digital tracer imaging [3-5] makes it possible to measure in local areas of the flow, which are important from the point of view of the formation of local flow disturbances, and, along with the averaged flow

parameters, to obtain the components of the pulsating flow velocity of the coolant, Reynolds stresses, spectral characteristics of the flow, etc. The measurements were mainly carried out in scaled rod assemblies, i.e. with an increase in their diameters and a proportional increase in the remaining elements of the experimental models, as well as assemblies with a small number of fuel rod simulators.

Along with the study of parameters that can be determined to some extent in the channel approximation, an important issue is the interchannel interaction and mixing. This problem is extremely important in connection with the probability of formation of superheated zones in areas with increased energy release. This can lead to a heat transfer crisis and an emergency situation, up to the destruction of fuel elements. Works [6-9] refer to the study of such effects.

Comprehensive studies of interchannel mass and heat exchange in bundles of smooth and ribbed fuel rods, as well as with spiral wire winding, have been carried out. The transverse mass transfer in an assembly of rods was measured during the flow of a liquid metal coolant, heat transfer features. Based on these measurements, formulas have been proposed for the coefficients of interaction between cells by thermal conduction, turbulent diffusion [10].

Verification of computational methods based on modern approaches, including the development of a methodology for creating efficient RANS models using machine learning methods, requires experimental data obtained using various coolants.

To reduce the hydraulic resistance, increase the reserve before the heat transfer crisis and its intensification, increased attention should be paid to local flows in the subchannels of fuel assemblies. An important task is to study the peripheral subchannels of fuel cassettes and flows in the region of the inter-cassette gap [11-13].

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In this work, an experimental study was carried out in a fairly simple geometry, consisting of three vertical simulators of fuel rods with a diameter of 10 mm, arranged in a line with a relative step of 1.4. The working section of the measuring section corresponds to two adjacent subchannels of the peripheral region of the fuel assembly. The length of the fuel rod simulators is 500 mm. The use of simple geometry allows us, on the one hand, to apply various methods of experimental research, including panoramic high-speed optical methods and high-speed thermal imaging, and, on the other hand, to use direct numerical simulation methods or eddy-resolving methods without significant computational costs. [14].

1 Experimental setup

In this work, distilled water was used as the test liquid. The water temperature in the inlet of the test section of the experimental setup was maintained within 25 ± 0.2 °C using an automatic thermal stabilization system situated in the tank.

The scheme of the test section is shown in Figure 1. To reduce heat losses, fuel rod simulators 1 were placed in a cradle made of heat-insulating material 2. The fuel rod simulators are equipped with individual electrical power supplies, which makes it possible to carry out studies with uneven energy release in neighboring subchannels. The WSD-20H50 power source with the maximum electrical power of 10000 W was utilized. This makes it possible to determine some patterns of interchannel exchange by monitoring the temperature distribution in the flow. The diameter of each fuel pin simulator is $D = 10$ mm, their spacing is $S = 14$ mm.

The experiments were carried out in the turbulent mode of the coolant flow at the Reynolds number of the coolant flow determined by the hydraulic diameter $Re = 10000$. The liquid flow rate was controlled by the ultrasound flow meter Multical 402 with the measurement uncertainty 2%. Fluid flux was organized in the cross section of test section 3.

To prevent overheating of the fuel rod simulators, their temperature in the area not washed by the liquid flow was controlled using individual thermocouples. These three thermocouples were connected to the industrial controller TRM-138. The positions of thermocouples are shown in fig. 1.

The experimental model is equipped with the necessary measurement systems for temperature fields using thermal imaging and thermocouple probes. The measurements in the coolant flow were carried out using a thermocouple moved with the help of a coordinate device. Thermocouple wires were in a stainless steel casing with an outer diameter of 1.5 mm. Wire diameters 0.3 mm, junction size 0.6 mm. Temperature profiles were measured along line 4 (see Fig. 1).

The outer wall temperature was measured using a Fluke T32 infrared camera. The thermal imager was mounted on a tripod. The outer wall of the test section 5 was made of stainless steel foil. The wall thickness is 0.5 mm. The outer surface is painted with black matte paint. To prevent the foil from being buckled by the coolant

flow, ribs with a thickness of 8 mm were regularly installed.

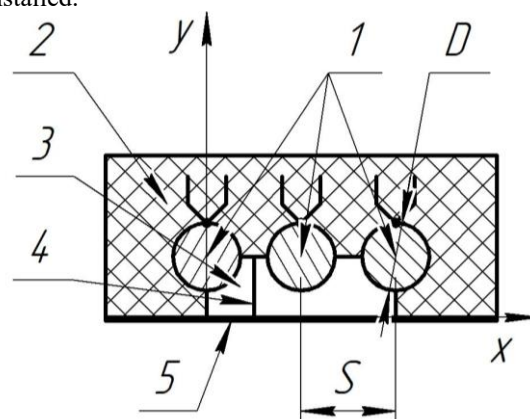


Fig. 1. Scheme of the experimental setup: 1 – fuel pins; 2 - heat insulator; 3 - channel cross-section; 4 – thermocouple displacement line; 5 - stainless steel foil.

2 Experimental results

Thermograms of the wall temperature distribution obtained with a stationary liquid with only the central and peripheral fuel rod simulators turned on are shown in Figure 2. Data are given on the relative wall temperature distribution $T/T_{\max}$, where $T_{\max}$ is the maximum temperature in the sample. Horizontal regions with a constant temperature correspond to the location of the stiffeners, which prevented the thin-walled foil from bending during experimental studies with a forced fluid flow.

With an increase in height from the beginning of the working section, for the case of heating of the central fuel element simulator, heating of the central region is observed with redistribution of heat over the entire cross section of the channel. To connect only a peripheral fuel element simulator, there is an uneven distribution of the outer wall of the test section. In this case, the maximum temperature is observed in the subchannel in which the heated fuel rod simulator is located. Moreover, a rather pronounced boundary is also preserved for the uppermost segment of the working area.

When carrying out experiments with liquid motion, the situation changes quite strongly; sufficiently high temperatures were recorded in the immediate vicinity of the heated fuel rod simulator (see Fig. 3). At the same time, this trend was characteristic of both the overheating of the central and peripheral fuel rod simulators.

The results of processing the thermograms obtained in the upper part of the working section during heating of the central and peripheral fuel rod simulators, located to the right and left of the central one, are shown in Figure 4. For each case, 10 thermograms were processed. The data are given in dimensionless form. Here x is the distance from the left edge of the test section X is the width of the test section ($X=2S=28$ mm). The maximum temperature difference between the liquid in the inlet of the test section and the channel wall was about 0.5 degrees of Celsius.

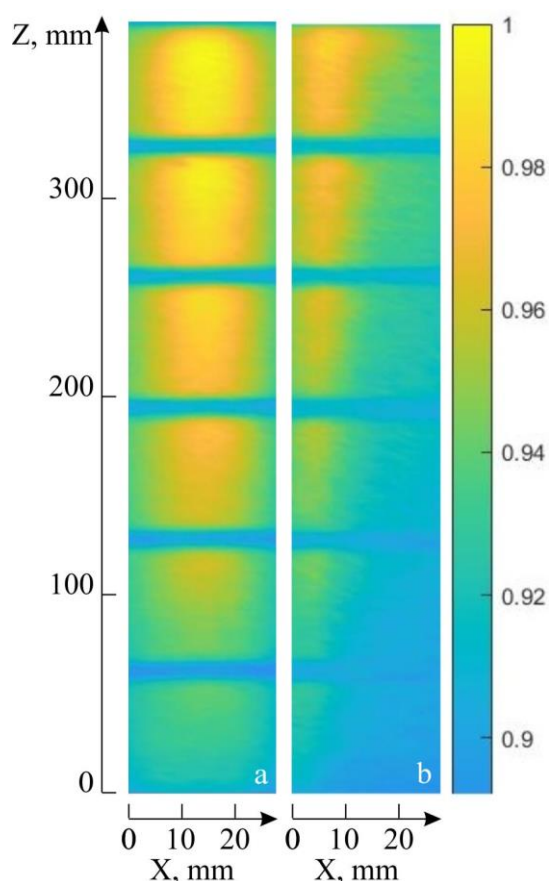


Fig. 2. Temperature distribution on the wall in the channel with stationary coolant: a – heating of the central fuel pin initiator; b – heating of the peripheral fuel pin initiator.

One can see a significant difference in the temperature distribution in a subchannel containing a heated fuel element from the opposite one.

To carry out measurements inside the flow, a chromel-kopel thermocouple (type L) mounted on a coordinate device was used. The measurements were carried out along the center of one of the subchannels along line 4 shown in Figure 1. The measurements were carried out during heating of the central and peripheral fuel rod simulators during the flow of the working fluid with $Re = 10000$. Since the washed area of the peripheral fuel rod simulators is two times lower than that of the central one, the power supplied to them was reduced by half.

The data obtained are shown in Figure 5 in a dimensionless form. Here y is the distance from the outer wall of the working area, Y is the subchannel depth. The thermocouple was located at a distance $Z/Dh = 45$ from the beginning of the test section. The relative temperature was calculated as $T_r = (T - T_{min})/T_{max}$.

In general, for the cases of heating of the central and peripheral fuel element simulators, a similar trend is observed, with a minimum temperature at the outer wall of the working section and a temperature maximum in the depth of the subchannel. When the heated fuel element simulator was located outside the cell, the temperature was fixed along the entire length of the profile, which differed little from the measurement error, which also shows a rather weak temperature transfer between the cells along the channel height.

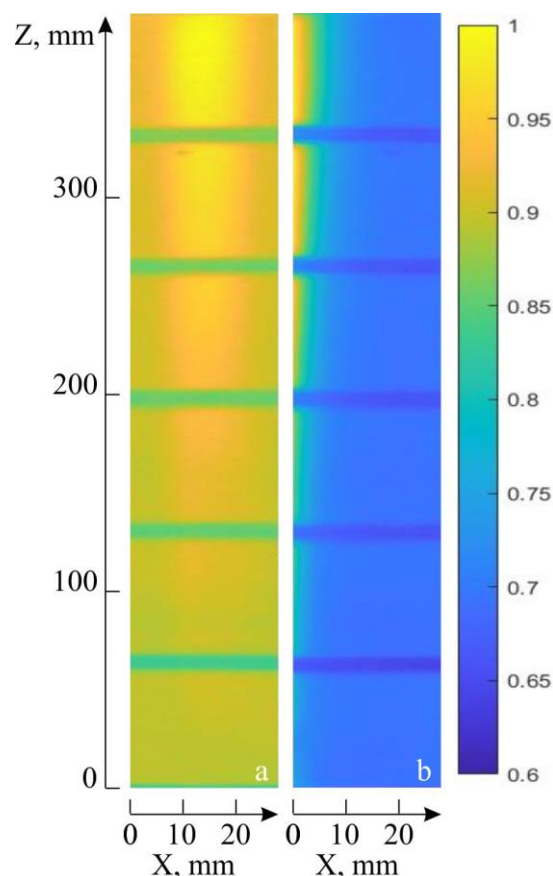


Fig. 3. Temperature distribution on the wall in the channel at $Re = 10000$: a – heating of the central fuel pin initiator; b – heating of the peripheral fuel pin initiator.

The maximum temperature difference between the liquid in the inlet of the test section and the temperature registered in the profile was about 3 degrees of Celsius.

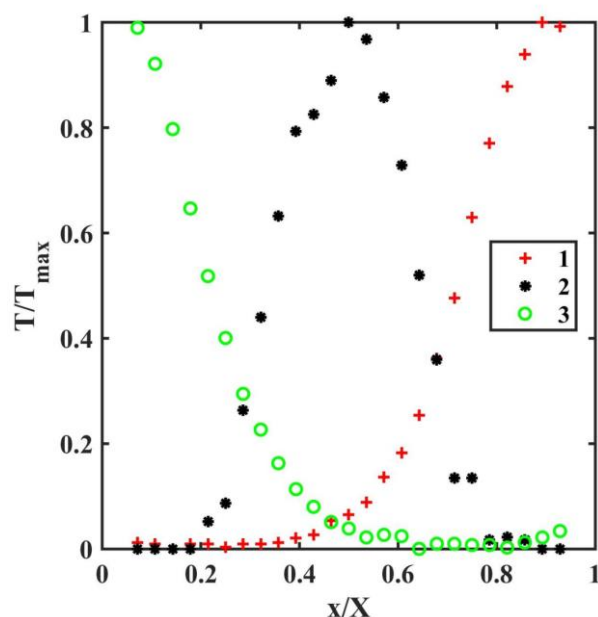


Fig. 4. Mean temperature in higher part of the test section for various options for organizing energy release: 1 – power on the left fuel pin initiator; 2 – power on the central fuel pin initiator; 3 – power on the right fuel pin initiator.

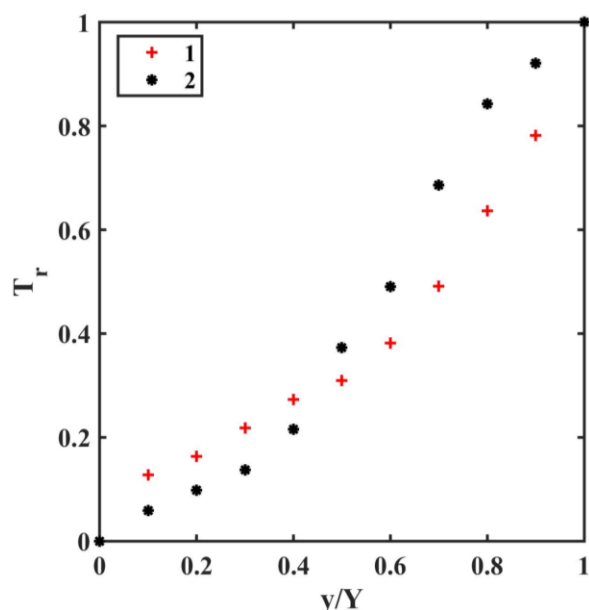


Fig. 5. Temperature distribution inside the flow: 1 – power on the central fuel pin imitator; 2 – power on the peripheral fuel pin imitator.

Conclusions

An experimental study of the temperature distribution in a simple model of the peripheral region of a fuel assembly was carried out using thermocouple measurements and IR camera. Conditions for uneven energy release have been created in the test section. Studies have shown that the temperature transition between the subchannels is rather weakly expressed, and a rather significant temperature imbalance is formed and maintained throughout the working section.

Further research will be performed to the study of temperature distribution when using lead bismuth eutectic as test coolant. Thus, the analysis of the features of flows with different Prandtl numbers will be carried out.

It is planned to use the obtained experimental data to create effective numerical models for describing the turbulent coolant flow at low Prandtl numbers based on machine learning methods.

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