Heat transfer at high energy density in nuclear power plants

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Abstract. A review is given of the works of the Department of General Physics and Nuclear Fusion NRU «MPEI» in the thermophysical as applied to nuclear energy, performed over the past 30 years. Some basic results of these studies and some bibliographic references are given.

1. Introduction
In the 80s, the physical justification for the possibility of implementing the idea of controlled thermonuclear fusion (TCF) was completed. The tasks of the technical implementation of this brilliant idea have come to the fore. One of these tasks is to protect the structural elements of the first wall from the effects of neutron and ion fluxes, and abstraction their energy. The heat flux density in the blanket of the reactor reaches 10 MW/m², and in the divertor - 10²-10⁴ MW/m². These structures have a large area and heat removal by traditional methods is not possible.

2. Heat transfer in subcooled swirl flow under conditions of one-side heating
In 1986, a stand was created at the department to organize research in this direction. The key point of the stand is the energy source, which is able to provide the necessary energy density. It would be natural for these purposes to use an ion source. However, a characteristic property is inherent in the ion source: this device is poorly tuned from mode to mode and is intended for use in stationary conditions. It was decided to use an electron beam apparatus (EBA), which includes an electron gun, as an alternative source. The initial purpose of EBA is electron beam welding. Our task was to ensure uniform distribution of energy over the exposed surface of the target. To meet this requirement, an electron beam scans the surface of the target with a frequency of 10 kHz. To this end, an additional control coil has been developed. In addition, to turn off the power unit in emergency mode, a thermal process control unit (TPCU) was developed. Schematic diagram of the stand, its detailed description is given in [1]. The first scientific results were obtained in 1995-97. One-sided heating was carried out by electron beam scanning the surface of the target with a high frequency, and the heat was removed using a swirling flow of water not heated to the saturation temperature. Energy was supplied to the heat exchange surface during one-sided heating according to the law

\[ q = q_0 \cos \varphi, \]

where \( q_0 \) is the heat flux density in the central axial section, \( \varphi \) is the angle between the axis of the electron beam and the normal to the section under consideration. The results of these studies can be found in [2-6]. In the studies performed, the heat transfer conditions in the energy receivers of the injection heating system of plasma were simulated. One-sided heating leads to a substantially non-uniform
distribution of the heat flux density and wall temperature along the inner perimeter of the channel (Fig. 1). We found a negative effect of pressure on the intensity and crisis of heat transfer.

The family of obtained typical boiling curves at various mass velocities is shown in Fig. 2.

![Figure 1. Change in heat flux density and temperature along the inner perimeter of the pipe. $q_{in}=34 \text{ MW/m}^2$, $\rho w=8800 \text{ kg/(m}^2\text{s})$, $T_{in}=20^\circ \text{C}$; 1–$p=0.7 \text{ MPa}$, 2,3–$p=1.5 \text{ MPa}$](image1.png)

![Figure 2. Boiling curves of water in subcooled swirl flow, $p = 1.0 \text{ MPa}$, $x = -0.24$](image2.png)

Analysis of the entire array of experimental data showed:

- at mass flux $\rho w < 2500 \text{ kg/(m}^2\text{s})$ on the characteristics of heat transfer during boiling, the effect of speed is practically absent;
- at mass flux $\rho w > 4000 \text{ kg/(m}^2\text{s})$ the influence of speed is clearly expressed up to the average values of heat fluxes;
- in the region of high heat fluxes ($q > 30 \text{ MW/m}^2$), the effect of the mass flux on heat transfer is smoothed out (boiling curves tend to merge);
- subcooled of the coolant does not affect the heat transfer coefficient during boiling.

It was shown that more than 80% of the total heat flux is diverted due to single-phase convection. Boiling heat transfer becomes predominant only with heat fluxes exceeding 8 MW/m$^2$. Taking into account the independence of heat transfer mechanisms by single-phase convection and boiling in an subcooled high-speed flow, a simple superposition was used to calculate the total heat flux: $q = q_{\text{conv}} + q_{\text{boil}}$. V.V.Yagov's modified equation was used to calculate $q_{\text{boil}}$ and B.S.Petukhov's equation was used to calculate $q_{\text{conv}}$. According to this technique was generalized own data for a swirling flow and Araki data for a direct subcooled freon flow during one-side heating. In Figure 3 shows the contribution of single-phase convection and boiling mechanisms to the total heat flux. It can be seen that the calculations give quite satisfactory agreement with the experimental data, and linear interpolation is justified.
In Figure 4 shows typical dependencies $q(\Delta T_s)$ at different mass flux. The entire array of experimental data was generalized by this method, the maximum deviation of 30% was observed at low mass flux.

As a result of research, data were obtained that testify to the possibility of heat removal of record high heat fluxes. Moreover, in the vicinity of the “frontal” point, a boiling crisis occurs, which does not lead to the destruction of the pipe walls. On the whole, the effect achieved in these experiments can be explained by the simultaneous influence of factors: one-sided heating, strong underheating to the saturation temperature, and swirling of the flow. The thickness of the steam blanket upon reaching critical loads during boiling in a high-speed subcooled swirl flow at relatively high pressures is about 10 μm. The resulting steam blanket in a swirling flow is shifted in the azimuthal direction to the cold zone of the channel perimeter, where it condenses. The reason that the thickness of the vapor blanket is not growing, apparently, is also the process of condensation of steam on the upper part of the blanket in contact with the core of the cold stream.

It was shown in [3] that under experimental conditions, when critical heat fluxes (CHF) increase by more than an order of magnitude and the shape of the boiling curve changes strongly, the heat transfer crisis has a thermodynamic origin. The use of the condition $T_w = T_{L.S}$ for $q_{boil}$, where $T_{L.S}$ is the temperature of the limiting superheat of the liquid, determines the thermodynamically limiting values of heat fluxes due to the mechanisms of single-phase convection and boiling. In the studied pressure range, the temperature of the limiting superheat changes little ($T_{L.S} = 310–312.5$ °C). This means that the contribution of $q_{conv}$ to the CHF does not depend on pressure. At the same time, the saturation temperature $T_S$ in the pressure range under consideration changes by 33 °C, which explains that $q_{kip}$ and CHF decreases with increasing pressure.

3. Fuel assembly

One of the key points of the Nuclear Energy Development Strategy was the principle of natural safety. A possible way to increase the safety of nuclear power plants while ensuring competitiveness against the background of extending the life of existing VVER reactors is to replace fuel assemblies (FA) with rod fuel elements (fuel rods) to fuel assemblies with microfuel elements (MT).

An experimental stand “Fuel Assembly” was developed in 2007. This project was among the winners of the Innovative Educational Program In 2008. As part of this program, an experimental stand was created...
at the Department of General Physics and Nuclear Fusion, on which, among other things, a cycle of studies of the thermohydraulic parameters of tubular fuel elements was carried out. The layout of the stand is given in [7], and the design of the intensifier in [8].

At this stand, studies were carried out on tubular fuel rods, the effectiveness of which, compared with rod fuel rods, is determined by the fact that heat removal is carried out from two sides: internal and external. The heat transfer on the outer surface of the fuel element is lower than on the inside. A variety of methods for intensifying heat transfer are known. However, in relation to a convex surface, these methods of intensification are ineffective, and sometimes even lead to a negative result. To solve this problem, a new type of intensifier was developed, the effectiveness of which is due to the interaction of swirling and transit flows. It was experimentally established that the dependences of heat transfer and hydraulic resistance on design parameters have pronounced maxima. The size range of the relative height of the supporting rib was determined [8,9], in which the ratio of the flow rates of swirling and transit flows is optimal, and the use of such an intensifier gives the maximum effect (see fig. 5,6).

Figure 5. The dependence of the hydraulic resistance coefficient on the parameter \( \dot{H} \) (Re = 60000): 1 – \( t = 40 \times 10^{-3} \) m; 2 – \( t = 50 \times 10^{-3} \) m; 3 – \( t = 100 \times 10^{-3} \) m

Figure 6. The dependence \( Nu/Nu_0 \) on the parameter \( \dot{H} \) for ribs (Re = 45000): 1 – \( t = 40 \times 10^{-3} \) m, 2 – \( t = 50 \times 10^{-3} \) m, 3 – \( t = 60 \times 10^{-3} \) m, 4 – \( t = 100 \times 10^{-3} \) m, 5 – smooth annular channel

Fuel assemblies with microfuel (MT) differ from fuel assemblies with fuel rods. In MT fuel assemblies, microfuels are placed in the form of pebble bed between perforated covers and are directly washed by the coolant. Such an assembly is a collector system with pebble bed. To minimize pressure drop, a radial flow of the coolant is implemented. The fuel assemblies with microfuel in external geometrical parameters can fully correspond to traditional assemblies with rod fuel elements. There are very few studies of hydrodynamics and heat transfer during radial flow of a coolant through pebble bed. Therefore, to test the experimental technique and validate the mathematical model, an experimental low-pressure stand was created [10]. For the model of fuel assemblies MT on this stand, studies of pressure drops and temperature fields were performed. Based on these data, a mathematical model was validated for numerical calculations [11].

The data obtained on the model of fuel assemblies at low pressures and the results of numerical simulations are the initial base for studies at the “Fuel Assembly” stand with operating parameters of VVER-1000.
**Conclusion**

A creative team of the research thermophysical laboratory was created at the Department of General Physics and Nuclear Fusion, which continues research in the field of urgent tasks of modern nuclear energy.

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