Study of heat transfer during cooling of highly loaded structural elements with a two-component heat carrier flow

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Abstract. One of the promising directions for the development of energy in the 21st century is thermonuclear energy. To implement this method of generating energy, experimental thermonuclear reactors have been operating for decades, the largest of which is currently being built in Cadarache (France). At the moment, one of the unsolved problems of such reactors is the creation of systems that provide reliable heat removal of heat fluxes from intracameral objects, such as a limiter, blanket, and divertor. In addition to high energy density, these objects have quite significant dimensions. Today, cooling of such objects is carried out mainly by water under pressure. This paper considers the possibility of using a dispersed two-component coolant flow as an alternative method of cooling such objects. A description is given of an experimental bench simulating uniform heating along the perimeter of the test section and its main systems. The paper presents the design of a spray device for forming a two-component dispersed coolant flow with its technical characteristics and a working area for conducting research. Experimental data were obtained on the temperature of the wall of the working area at various operating parameters of the coolant and power input.

1. Introduction

According to forecasts, it is expected that the world's population will reach 9-10 billion by the middle of the 21st century. According to Academician E.P. Velikhov, by this time, global energy consumption will increase several times. One of the promising directions of satisfying the need for such a colossal amount of energy could be fusion energy.

To date, specially designed units (tokamaks and stellarators) have been created and are operating in different mills, the main purpose of which is to test various systems and study the processes necessary to create a stationary fusion reactor.

Undoubtedly, one of the main problems in thermonuclear experimental installations is the stationary long-term confinement of plasma inside the chamber, but, along with this global task, several technological difficulties arise that are not yet solved or require additional research and justification of the possibility of their use.

One of these problems is the creation of a reliable cooling system for high-temperature surfaces, which will be effective both in the thermonuclear energy of the future and in other industries.

One of the most promising methods of cooling a high-temperature surface is the use of a dispersed two-component coolant flow [1–2]. Obtaining a dispersed mixture of drops is ensured through the use of devices designed for fine and, if possible, uniform distribution of fluid over the jet cross-section, i.e.
“injectors”, which, to date, have acquired a huge number of various types and designs, differing both in the operating principle and purpose [3].

2. Description of the test bench and main systems
The test bench consists of three main systems: a heating system, based on VCH-60AV high-frequency generator, a cooling, collection, and information processing systems built on L-Card equipment.

An induction heating method was chosen to heat the working area. For long-term continuous operation of the VCH-60AV high-frequency generator, including at high powers, a cooling circuit had to be developed. Figure 1 shows the cooling scheme of a high-frequency (HF) generator. Its main elements are as follows:

- distilled water tank;
- frame-mounted distilled water cooling unit;
- HF-generator cooling unit.

![Figure 1. HF-generator cooling scheme.](image)

The use of a frame design for water cooling is due to the mobility and multipurpose use of the cooling unit.

The wiring diagram of the cooling unit is shown in figure 2. A mechanical filter is used to purify the water coming from the dispensing unit. A pressure gauge and a float flow rate are used respectively to control flow parameters (pressure $p_w$ and flow rate $G_w$). Through dispensing manifold 34, water is distributed to cool a transformer unit, control unit, and inductor. Wastewater is collected using manifold 37 and then fill the tank. Thus, the HF-generator cooling circuit is closed.

To cool the working area, a dispersed flow is used, formed using a pneumatic atomizer due to air and tap water mixing.

Figure 3 shows a schematic diagram of the cooling circuit of working area 9. The maximum pressure of water and gas is $p_w = 5.0 \cdot 10^5 \text{ Pa}$ and $p_g = 10.0 \cdot 10^5 \text{ Pa}$ respectively. To control operational parameters of the dispersed flow components, pressure sensors, float flow meters, and cable chrome-alumel (type K) thermocouples are used.
To conduct experimental studies, a design was developed and a working section was made consisting of a heated element which was a tube with an external diameter of 24 mm and a wall thickness of 4 mm, and holders made of stainless steel grade 12X18H10T (figure 4). The connection between the elements of the working area is carried out by welding. The free end of the upper holder allows installing and sealing the spray device, a general view of which is shown in Fig. 5. The length of the upper holder was selected so that the dispersed stream formed by the spray device cooled the entire working area. The energy supply to the heated element was provided by a VCH-60AV high-frequency generator employing a prefabricated inductor. To minimize heat loss and complicate the process of convective heat transfer along the outer surface, the working section was isolated from the environment with fiberglass.

The main element of the hydraulic circuit responsible for the formation of a two-component dispersed flow is a pneumatic spray device mounted in the upper part of the working section. The spraying device consists of a nozzle for spraying liquid 1, the outer body of the nozzle 2, inlet channels, and elements, in which turbulization and swirling of the coolant component flow occurs, air supply unit, unit water supply, as well as fixing and sealing elements. A collapsible design, replaceable nozzles, as well as a movable rod allow moving the nozzle along the axis of the channel and change the geometry of the torch, which allows adjusting the cooling efficiency of the inner sited working portion. The nozzle is designed so that the inner diameter of the working channel is within the range \( d_{in} = (16 \div 20) \, \text{mm} \).

The parameters of the dispersed flow generated by the spray device are as follows:
- used components: 1 - distilled water, 2 - air (non-aggressive or inert gases: \( \text{N}_2, \text{Ar} \));
- components pressure: 1 - \( p = (1 \div 5) \cdot 10^5 \, \text{Pa} \), 2 - \( p = (1 \div 10) \cdot 10^5 \, \text{Pa} \);
- mass consumption of components: 1 - \( G_{water} = (0.014 \div 0.070) \, \text{kg/s} \), 2 - \( G_{air} = (0.4 \div 3.0) \cdot 10^{-3} \, \text{kg/c}\);
- diameter of water droplets: \( d = (10 \div 100) \, \text{microns} \);
- jet opening angle: \( \alpha = (5 \div 10) \, ^\circ \).
3. Experimental results

The studies were conducted, and arrays of experimental data were obtained on the cooling of the working section No. 1 with a dispersed heat carrier flow in the following range of operating parameters: mass flow rates of water and air $G_{\text{water}} = (0.014 \div 0.070) \text{ kg/s}$, $G_{\text{air}} = (0.4 \div 3.0) \cdot 10^{-3} \text{ kg/s}$, the pressure of the components of the $p_{\text{water}} = (1 \div 5) \cdot 10^5 \text{ Pa}$, $p_{\text{air}} = (1 \div 10) \cdot 10^5 \text{ Pa}$, the water temperature at the inlet to the working section $T_{\text{in}} = (5 \div 15)\degree \text{C}$, the electric power $N = (1 \div 16) \text{ kW}$. In the course of the experiments, the readings of all thermophysical parameters (flow rates, pressures, and temperatures of the coolant components, the wall temperature of the working section) as well as electrical parameters (current strength and voltage of the high-frequency generator) were recorded. All temperature measurements were recorded on a personal computer using an information collection system based on L-Card equipment. In total, about 170 experimental points were obtained at various operating parameters. An example of the time-dependent temperature during the experiment is presented in figure 6.
Conclusions
This paper describes the design of an experimental installation for studying the thermal-hydraulic characteristics of the working area cooled by a two-component dispersed coolant flow under conditions...
of uniform heating along the perimeter. The paper presents the design of a new atomizing device to form a two-component dispersed flow with its technical characteristics and a working area intended for research. Experimental data on the wall temperature of the working area were obtained in the following range of operating parameters: mass flow rates of water and air $G_{\text{water}} = (0.014\div0.070) \text{ kg/s}$, $G_{\text{air}} = (0.4\div3.0)\cdot10^{-3} \text{ kg/s}$, the pressure of the components $p_{\text{water}} = (1\div5)\cdot10^5 \text{ Pa}$, $p_{\text{air}} = (1\div10)\cdot10^5 \text{ Pa}$, the water temperature at the inlet to the working section $T_{\text{in}} = (5\div15)\degree\text{C}$, the electric power $N = (1\div16) \text{ kW}$.

Preliminary analysis of the results shows that the use of this cooling method allows cooling effectively the working area without its damage at thermal loads of $\approx (2\div2.5) \text{ MBt/m}^2$.

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