Investigation of the cooling of a high-temperature surface by a dispersed coolant flow

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Abstract. A modernized experimental setup diagram is presented for studying the cooling of a high-temperature surface with a dispersed coolant flow. The results of an experimental study of unsteady heat removal from a target with a temperature exceeding the Leidenfrost temperature are presented. The cooling curves are obtained, the regions of effective heat transfer are determined. The primary experimental data were obtained during stationary heat transfer in the following range of operating parameters of the coolant: mass water flow rate 0.0038 ÷ 0.0145 kg/s; water pressure 0.4 ÷ 0.2 MPa, induction heating power 7 ÷ 20 kW.

1. Introduction
To ensure a given thermal state of the elements of power equipment, the method of cooling surfaces with a dispersed heat carrier flow generated by nozzles of various designs is widely used. This method of cooling has two extremely important advantages over cooling with a continuous flow of coolant: it can significantly increase the efficiency of heat transfer and reduce the pressure in the cooling system, which reduces the risk of emergency situations. Dispersed cooling is considered as a promising method for highly loaded elements in nuclear and thermonuclear installations and reactors. Various dispersed cooling techniques may be used. For fast-neutron nuclear reactors, the paper [1] proposes the use of a dispersed flux in a channel. In experimental thermonuclear setups, it is proposed to use capillary-porous structures (CPS) saturated with liquid lithium on the plasma side to protect the surface of elements interacting with plasma, such as the limiter and divertor [2-5]. The peculiarities of the operation of the chamber elements are one-sided heating with a high heat flux density (reaching 20 MW/m²), as well as the need to maintain the temperature in the range at which lithium is in a liquid state. All these requirements are satisfied quite well by the dispersed coolant flow cooling. For cooling the limiters, dispersed flow studies in the channel are carried out [5-8], these studies confirm high efficiency of dispersed cooling. In this paper, we present some results of an experimental study as applied to the divertor model, which is a vertical flat surface. The dispersed coolant flow is directed perpendicular to the surface.

2. Description of the experimental setup
A detailed description of the hydraulic circuit is given in [9]. In the present work, the heating element in the experimental chamber is modernized. The scheme of the experimental chamber is shown in Fig. 1.
Figure 1. The design of the experimental chamber: 1 – body, 2 – nozzle, 3 – heated element, 4 – inductor, 5 – target, 6,7 – taps, 8 – condenser.

The experimental chamber is made of stainless steel and is sealed. For visual observation, viewing windows are provided in the chamber. The nozzle (2) is connected to the hydraulic circuit, and the unit of the sealed nozzle attachment to the chamber body allows changing the position of the nozzle for accurate hit of the spray torch on the target. The chamber has two differentiated fluid discharges (6.7). One (6) of them is designed to collect droplets condensed on a steam condenser (8). The second (7) is designed to collect droplets of non-evaporated liquid. A flat target (5) has direct contact with a low thermal resistance with heated element (3). The heating of the element (3) is carried out in the inductor (4). The inductor is connected to a high frequency generator with an electric power of 20 kW. In [9], the heated element (3) had the form of a solid cylinder with a diameter of 60 mm made of steel 12H17. However, using such a heated element, due to the low thermal conductivity of the steel, it was not possible to enter the stationary mode at a given power. Therefore, the heated element has been modernized (see Fig. 2). In this work, we use a heated element, which has the form of a solid cylinder of copper with 11 steel rods 08H18N10T.
3. Experimental study of unsteady heat transfer

According to experimental data on cooling of a surface heated to a temperature exceeding the Leidenfrost temperature, cooling curves are constructed. From the obtained cooling curves, the regions of effective heat transfer are determined. The experimental technique is as follows: the target is heated by induction heating to a temperature close to 400°C, then the heating is turned off and the process of cooling the surface with a dispersed water stream with the specified parameters (pressure, mass flow rate) begins. At the same time, the readings of thermocouples, pressure sensors and coolant flow rate
are recorded. The experiments are carried out using a hydraulic nozzle. The pressure of the coolant in front of the nozzle varies within $0.15 \div 0.40$ MPa, the mass flow rate of the coolant is $0.016 \div 0.033$ kg/s. An example of a cooling curve is shown in Fig. 4. Similar cooling curves are obtained for other operating parameters.

![Cooling Curve](image)

**Figure 4.** Dependence of the target temperature on time: $p = 0.40$ MPa, $G = 0.022$ kg/s, black line – readings of thermocouples located at a distance of 2.5 mm from the cooled surface, red line – 17.5 mm.

From the cooling curves, quite definite conclusions can be drawn about the change of heat transfer modes: 1 - the region of linear decrease in temperature corresponding to film boiling; 2 - region of a sharp increase in the rate of cooling, there is a transitional and bubble boiling mode; 3 - the region of a noticeable decrease in the cooling rate, which indicates the transition to the convective heat transfer mechanism. The most intense heat transfer is carried out in region 2.

### 4. Experimental data for stationary heat transfer

To conduct experimental studies, hydraulic nozzles of the same design developed for different nominal mass flow rates were used. Preliminary experiments for fluid mass flow rates $G = 0.0038; 0.0044; 0.0145$ kg/s (corresponding to the fluid pressure in front of the nozzle $p = 0.32; 0.40; 0.20$ MPa) with induction heating power $P = 7\div 21$ kW. The experimental technique in the stationary mode consisted in heating the target and simultaneously cooling it with a dispersed stream of water with given pressure and flow parameters. At the same time, the readings of thermocouples, pressure sensors and coolant flow were recorded. The experiments show the performance of the modernized installation. For the given parameters, steady-state regimes have been achieved and primary experimental data have been obtained.

A typical temperature distribution over the target thickness is shown in Fig. 5. As follows from this figure, a linear temperature distribution takes place for the studied modes. Firstly, it allows obtaining the values of the heat flux density transmitted through the target, and, secondly, obtaining the
temperature value of the cooled target surface by extrapolation. The experimental results for the three coolant mass flow rates are summarized in table 1.

![Graph](image)

**Figure 5.** Temperature distribution over target thickness: $G = 0.0044 \cdot 10^{-3} \text{kg/s}$, $P = 7 \text{ kW (●)}$, $P = 11 \text{ kW (■)}$, $P = 13 \text{ kW (●)}$, $P = 17 \text{ kW (▲)}$.

| $p$, MPa | $G$, kg/s | $P$, kW | $T_w$, °C | $q$, MW/m$^2$ |
|----------|-----------|---------|-----------|--------------|
| 0.32     | 0.0038    | 7       | 114.59    | 0.38         |
|          |           | 10      | 131.73    | 0.45         |
|          |           | 13      | 164.84    | 0.62         |
|          |           | 17      | 202.26    | 0.74         |
| 0.40     | 0.0044    | 7       | 112.13    | 0.35         |
|          |           | 11      | 134.59    | 0.48         |
|          |           | 13      | 155.06    | 0.60         |
|          |           | 17      | 184.50    | 0.73         |
| 0.20     | 0.0145    | 11      | 109.96    | 0.74         |
|          |           | 14      | 117.35    | 0.80         |
|          |           | 17      | 125.86    | 1.12         |
|          |           | 20      | 134.80    | 1.60         |

### Table 1. Experimental data.

**Conclusions**

A modernized scheme of an experimental setup for studying the cooling of a high-temperature surface by a dispersed coolant flow was presented. An experimental study of unsteady heat removal from a target with a temperature exceeding the Leidenfrost temperature allowed us to obtain cooling curves and to determine the effective heat transfer regions.

The first experimental data obtained in stationary mode proved the operability of the setup and the possibility of applying the method under consideration for the thermal stabilization of heat receiving
elements. In order to generalize the data on the thermal stabilization of a flat target by a dispersed coolant flow and to develop recommendations on the application of this cooling method in modern thermonuclear installations, detailed studies will be continued at higher values of the heat flux density in a wide range of operating parameters of the coolant.

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