Development of the design of a new working section cooled by a dispersed coolant flow for a stand with induction heating

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Abstract. The paper presents a description of the design of a new working section cooled by a dispersed coolant flow for a stand with induction heating. The choice of the material of the working area and the method of spraying has been substantiated. The first commissioning experiments were carried out in a stationary cooling mode, with the parameters of the coolant $p = 1.7 \cdot 10^5$ Pa, $G = 3.8 \cdot 10^{-3}$ kg/s.

1. Introduction

In modern technology, it is often necessary to remove heat fluxes with an energy density of several MW/m$^2$. This is typical for such areas as aerospace and nuclear technology, microelectronics, and energy. At the same time, the cooled objects are very diverse in terms of their weight and size parameters: from compact ones, which are found in computer and laser technology, to bulky and voluminous ones, such as, for example, rolled products of the steel industry during quenching and cooling. One of the most promising ways to cool a high-temperature surface is to use a dispersed coolant.

Obtaining a polydisperse mixture of droplets is ensured through the use of nozzles - devices that generate a dispersed flow of the coolant, while it is necessary to achieve a uniform distribution of the liquid over the cross section of the spray plume. Cooling with a dispersed coolant has proven itself in power engineering, mechanical engineering, metallurgy, but its application is not limited only to these areas of industry. Due to its high efficiency and relative ease of implementation, it may well be applicable for cooling the structures of modern thermonuclear power systems exposed to high-density thermal loads.

The process of heat transfer during cooling by sputtering is poorly understood: complex physics, involving the simultaneous interaction of sputtered droplets with a cooled surface, their evaporation, convection and vapor condensation [1, 2]. Models are known that describe these complex processes [3-5], but it is hardly possible to consider them exhaustive. That is why experimental research in this area is of great relevance.

The most detailed review of all relevant works on the topic of dispersed cooling is presented in [6].

The purpose of this work is to study the cooling of a high-temperature surface by a dispersed stream of water, on an experimental bench that simulates the energy-loaded elements of thermonuclear installations.
2. Description of the experimental stand

To cool the heated target, a closed hydraulic circuit was designed and installed (Fig. 1). Distilled water is used as a heat carrier, which is circulated by a pumping system (3). To control the temperature of the heated target, 6 thermocouples are installed. The L-CARD information collection system (4) is connected to thermocouple sensors, a digital flow meter (5) and a pressure meter (6). The scheme provides for the necessary fittings for regulating flow and pressure, measuring them, as well as a condenser for the formed water vapor.

Tanks 1 and 2 with level gauges are designed to measure the flow rate of the evaporated and non-evaporated parts of the dispersed stream.

![Figure 1](image)

**Figure 1.** Schematic diagram of the stand: 1 – experimental chamber, 2 – nozzle, 3 – pumping system, 4 – L-CARD information collection system, 5 – pressure meter, 6 – digital flow meter, 7 – condenser, 8 – target, 9 – ferrite core, 10 – induction coil

3. Description of the induction heating circuit of the target

A nickel cylinder 50 mm in diameter and 10 mm thick (Fig. 2) is a heated element that is attached to the chamber wall using a magnetically transparent ceramic flange with low thermal conductivity.

Between the flange and the chamber wall there is a graphite o-ring, which has sufficient ductility and is resistant to high temperatures, which fully satisfies the experimental conditions.

On the outside of the heated element there is an induction coil connected to the RF generator and the cooling system. In order to increase the inductance, the coil is double wound. A magnetic concentrator in the form of a cylinder, made of ferrite 10000NM, is placed in the coil. This ferrite core allows for efficient one-sided heating with high energy density.
The choice of nickel as a material for the heated element is due to its ferromagnetic properties, high Curie temperature (~ 358°C), relatively high thermal conductivity ($\lambda = 91 \text{ W/(m} \cdot \text{K)}$ at a temperature of 20°C), as well as corrosion resistance [7]. This working section, due to its small thickness, has a low thermal inertia, which makes it possible to obtain the highest quality results when studying a stationary cooling mode with a dispersed flow.

**Figure 2.** Induction heating circuit for a nickel target

Below is a layout of thermocouples in a nickel target (Fig. 3), for the possibility of calculating heat fluxes and controlling the rate of cooling, as well as getting an idea of its uniformity. The temperature field in the target is measured by six thermocouples in two sections. In each of the two sections, three thermocouples are installed, located in the target radially at different depths. Cable thermocouples with a diameter of 1 mm are used.

**Figure 3.** Layout of thermocouples in the target
4. Hydraulic nozzle

A hydraulic centrifugal nozzle from Fluidics (Fig. 4) is investigated as a dispersed flow generator as the most economical in terms of energy consumption for spraying a liquid [8] with a diameter of 0.7 mm. The average droplet diameter declared by the manufacturer is 35 microns.

![Figure 4. Nozzle with conical insert: 1 – nozzle (Ø 0.7 mm), 2 – swirler, 3 – body, 4 – limiter, 5 – filter](image)

5. Technique of the experiment

The procedure for conducting an experiment on thermal stabilization in a stationary mode with a dispersed flow is as follows:

1) setting the required parameters for the pressure and flow rate of the coolant;
2) setting the required power of the RF generator;
3) after establishing a stationary temperature distribution in the target for 60 seconds, at a frequency of 10 Hz, the values of the pressure and flow rate of the coolant, and the target temperatures are recorded. The maximum temperature deviation in stationary mode was no more than 2°C. Subject to this condition, a stationary mode was recorded.

An example of recording measurements in an experiment with stationary modes selected on them at different powers is shown in Fig. 5, which shows the readings of two thermocouples located in different coordinates along the target thickness for different operating parameters.

![Figure 5. From the experiment protocol: coolant parameters $p=1.7\times10^5$ Pa, $G=3.8\times10^{-3}$ kg / s , – readings of thermocouples T1 and T4, respectively](image)
6. Technique for processing primary experimental data

Primary experimental data processing scheme consists of:

1. Time averaging of the readings of thermocouples, which measure the temperature of the working section and the coolant flow in a stationary mode, is performed.

2. Target temperatures calculation averaged over the sections \( x_1 = 1 \text{ mm} \) and \( x_2 = 3 \text{ mm} \) (see Fig. 3), using the temperatures averaged over time in step 1

\[
\bar{T}_1 = \frac{T_1 + T_2 + T_3}{3}, \quad \bar{T}_2 = \frac{T_4 + T_5 + T_6}{3}.
\]

3. Since in the considered temperature range the thermal conductivity along the thickness of the target changes insignificantly, \( \lambda \approx \text{const} \) can be considered, while the temperature field is described by a linear dependence, and the wall temperature, determined by the extrapolation method (see Fig. 6).

![Figure 6. Temperature distribution over the target thickness](image)

4. Heat flux density calculation for a given stationary mode \( = \frac{q}{x_2 - x_1} \), according to Fourier law.

5. Calculation of the heat transfer coefficients according to the Newton-Richman law:

\[
\alpha = \frac{q}{\Delta T_S} = \frac{q}{T_w - T_S}.
\]

Table 1 shows the primary data of adjustment experiments averaged over time for each stationary mode. Table 2 shows the calculated thermophysical values.

Table 1. Primary data of adjustment experiments

| \( p \cdot 10^5 \), Pa | \( G \cdot 10^6 \), \( \text{m}^3/\text{s} \) | \( P, \text{kW} \) | \( T_1, ^\circ \text{C} \) | \( T_2, ^\circ \text{C} \) | \( T_3, ^\circ \text{C} \) | \( T_4, ^\circ \text{C} \) | \( T_5, ^\circ \text{C} \) | \( T_6, ^\circ \text{C} \) |
|-----------------|-----------------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 |                 |       | \( x=1 \text{ mm} \) | \( x=1 \text{ mm} \) | \( x=1 \text{ mm} \) | \( x=3 \text{ mm} \) | \( x=3 \text{ mm} \) | \( x=3 \text{ mm} \) |
|                 |                 |       | \( R=20 \text{ mm} \) | \( R=15 \text{ mm} \) | \( R=10 \text{ mm} \) | \( R=20 \text{ mm} \) | \( R=15 \text{ mm} \) | \( R=10 \text{ mm} \) |
| 2.5             | 121.12          | 122.84| 121.05          | 156.67          | 154.38          | 153.74          |
| 3.0             | 131.32          | 130.42| 129.55          | 170.12          | 172.16          | 170.03          |
| 3.5             | 138.21          | 137.4 | 132.54          | 182.31          | 180.96          | 178.74          |
| 4.0             | 143.05          | 138.96| 135.92          | 190.51          | 187.37          | 181.53          |
| 4.5             | 149.27          | 146.91| 141.43          | 203.21          | 196.08          | 192.97          |
| 5.0             | 158.30          | 153.03| 150.85          | 214.64          | 210.27          | 204.28          |
| 5.5             | 166.47          | 161.2 | 158.03          | 226.39          | 220.47          | 215.93          |
Table 2. Calculated thermophysical values

| $p \times 10^5$, Pa | $G \cdot 10^6$, m$^3$/s | $P$, kW | $\bar{T}_1$, °C | $\bar{T}_2$, °C | $T_{cr}$, °C | $q$, kW/m$^2$ | $\alpha$, kW/(m$^2$K) |
|------------------|------------------|---------|----------------|----------------|------------|----------------|----------------|
| 1.7              | 3.8              | 2.5     | 121.67         | 154.93         | 111.1      | 1370.0        | 271.9          |
|                  |                  | 3.0     | 130.43         | 170.77         | 113.1      | 1636.8        | 159.5          |
|                  |                  | 3.5     | 136.05         | 180.67         | 116.8      | 1793.2        | 130.4          |
|                  |                  | 4.0     | 139.31         | 186.47         | 118.2      | 1885.1        | 119.9          |
|                  |                  | 4.5     | 145.87         | 197.42         | 118.9      | 2038.0        | 101.4          |
|                  |                  | 5.0     | 154.06         | 209.73         | 119.9      | 2172.3        | 82.8           |
|                  |                  | 5.5     | 161.90         | 220.93         | 120.7      | 2275.9        | 70.3           |

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