Development of the experimental stand for research heat removal with a high power density by a dispersed heat carrier flow

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Abstract. A schematic and measuring diagram of an experimental stand has been developed for research heat removal with a high power density by a dispersed heat carrier flow. Methods for measuring thermophysical and electrical parameters are determined. The design of the experimental chamber is developed. The scheme and design of the induction heating system and steam condenser have been developed. An experimental setup for research the evaporation time of a droplet has been created. An experimental study of the droplet evaporation time was carried out. The experimental data were processed and compared with the theoretical dependence.

1. Introduction

Nowadays, one of the urgent problems of power engineering is the cooling of high-temperature surfaces at extremely high heat flux densities. That kind of problem in particular arises while creating experimental thermonuclear power plants which are related with stationary long-term plasma confinement, that requires the development of new highly efficient methods for cooling intracameral elements of the first wall (limiters, blanket, divertor).

One of the most promising methods of cooling a high-temperature surface is the use of dispersed liquid.

Generating a polydisperse mixture of drops is ensured by the use of nozzles - devices designed for small and, if possible, equipartition of liquid over the jet cross section. The method of fine cooling has already established itself in the energy sector, mechanical engineering, metallurgy, but its application is not limited to only these areas of industry. Due to its high efficiency and relative ease of implementation, it might be applicable for cooling the components of modern thermonuclear energy systems that are subjects to powerful thermal loads.

The aim of this project being implemented at the department is to develop a cooling system of high-temperature surfaces by a dispersed water stream, the surface simulates the energy-loaded structural elements of thermonuclear plants. The purpose of the experimental stand under development is to research the possibility of removal of high-density heat fluxes and thermal stabilization in a given temperature range of energy-loaded structural elements. In contrast to [1], in which a pneumatic nozzle was used, in this work a hydraulic nozzle will be used.
2. Description of the experimental stand

To cool the heated target, a closed hydraulic circuit was designed (fig. 1.). Distilled water is used as a heat carrier which circulation is carried out by a pump (3). To control the temperature of the heated target, 12 thermocouples were installed, connected to the L-CARD information collection system (4), to which a pressure gauge (5) and a flowmeter (6) are also connected. The circuit provides the necessary fittings for adjusting the flow and pressure, measuring them, as well as a condenser for the generated water vapor.

![Figure 1. Schematic diagram of the stand: 1 - experimental chamber, 2 - hydraulic circuit, 3 - pump, 4 - L-CARD information collection system, 5 - pressure meter, 6 - digital flow meter](image)

3. Experimental chamber design

Figure 2. The design of the experimental chamber: 1 – body, 2 – nozzle, 3 – induction heating unit, 4 – condenser, 5,6 - fluid outlets, 7 – induction coil, 8 – target

Visual observation of the evaporation process will be carried out in a sealed chamber (1) (fig. 2), equipped with viewing windows made of optical glass. The nozzle (2) is connected to the hydraulic circuit with the ability to change the position of the nozzle in the chamber. The project uses induction heating as a heat source using an RF generator VCH-60AV with an operating frequency of 50 kHz and an electric power of 60 kW. The heated element in the form of a metal cylinder (3) made of steel AISI 430 with a diameter of 60 mm is placed in an induction coil (7).

The chamber has two differentiated fluid outlets (5,6). One of them is designed to collect droplets of condensed vapor on a condenser (4). The second is designed to collect drops of non-vaporized liquid.
4. Thermocouples installation chart
The layout of thermocouples in the heated target (8) (Fig. 2) is shown in Fig. 3. A total of 12 thermocouples are provided. Holes of different depths (5, 15, 25 mm) were made, to install thermocouples in the target. Thermocouples are installed in two sections across the thickness of the target.

![Thermocouples installation chart](image)

**Figure 3.** The layout of thermocouples in the heated target

5. Investigation of the evaporation time of a single drop on a surface with a high temperature
In the process of developing an experimental stand for studying cooling by fine flows, an applied problem arose of researching the interaction of a single drop with a heated surface and the time of its evaporation.

Using analysis result given in [1], an equation is derived for calculating the evaporation time of a single drop:

\[
\tau (t_{\text{surf}}, r_0) = \frac{1}{1.25^{0.25} \left( 1 + \frac{4\lambda_{\text{st}}^3 (t_{\text{surf}} - t_s)^3 g}{9V_{\text{st}}^3 \rho_{\text{liq}}^3 r^3} \right)^{0.25} r_0^{1.25}}, \tag{1}
\]

where \(\lambda_{\text{st}}\) – thermal conductivity of steam, \(t_{\text{surf}}\) – surface temperature, \(t_s\) – saturation temperature, \(V_{\text{st}}\) – kinematic viscosity of steam, \(\rho_{\text{liq}}\) – density of saturated liquid, \(r\) – heat of vaporization, \(r_0\) – radius of a spheroid before direct interaction with a cooled surface.

During the experimental research, the dependences of the evaporation time of the droplet on the surface temperature and on the droplet diameter were obtained, and a comparison was made with the theoretical dependence (1).

In fig. 4 is a diagram of an experimental setup for determining the time of evaporation of a droplet of different diameters on a surface with a high temperature of copper and stainless steel.
Figure 4. Experimental setup: 1 – a container with a distillate, 2 – discrete water valve, 3 – a capillary, 4 – a heated surface, 5 – a spiral heater, 6 – a thermocouple, 7 – a meter TRM200, 8,9 – video cameras

The surface temperature is recorded using a thermocouple (6) connected to the meter (7). The process of droplet evaporation is recorded by the video camera (8) (frequency 120 frames/s). The video camera (9) is used to record temperature changes on the TRM200 meter, which allows one to simultaneously register the process of droplet evaporation and surface temperature changes. To control the diameter of the droplet, when processing the results, a scaled grid was programmed (fig. 5).

Figure 5. Example shot frame

Fig. 6 presents data on the time of evaporation of water droplets of various diameters on the surface of a target made of copper. Fig. 7 shows the data on the time of evaporation of water droplets of the same diameter from the surface temperature of a target made of stainless steel AISI304.
The equation of approximation of experimental data in fig. 6 can be represented in a general way

$$\tau = a + b r_0^n$$

where $n = 1.25$, $r_0 = \frac{d_{\text{drop}}}{2}$ that is in good match with (1).
In fig. 7, various modes of droplet boiling can be distinguished: bubble (~120-180 °C), transitional (~180-240 °C), and film (>240 °C).

Next, we will consider in more detail the transition to film boiling upon evaporation of a drop.

**Figure 8.** A fragment of the dependence of the time of evaporation of a drop with a diameter of 2.2 mm on the temperature of a steel target made of steel AISI304.

In fig. 8 shows the initial portion of the dependence of the time of evaporation of the droplet on a steel target made of steel AISI304. The transition from the bubble boiling to the less effective – film mode is clearly visible. At a relatively small temperature increase of ~3 °C, which is ~1.5% of the surface temperature, the drop in the evaporation time of the droplet is more than 2 orders of magnitude.

**Figure 9.** Comparison of the theoretical dependence (solid line) with an experiment on a steel plate:
- ● - data of the author, ▲ – data of the [2], ─ – calculation of the theoretical dependence (1)

Fig. 9 compares the theoretical dependence of the evaporation time on the surface temperature (1) with the experimental results. The mismatch of the experimental curves is due to different characteristics of the surfaces on which the experiment was carried out.
As can be seen from the graph in the range 300 - 700 °C, the theoretical dependence qualitatively reflects the nature of the change in the evaporation time and can be used to estimate it, with considering some correction of a numerical constant.

**Conclusion**

- A schematic diagram and an experimental stand has been created has been developed for research heat removal with a high power density by a dispersed heat carrier flow. Methods for measuring thermophysical and electrical parameters are determined.
- Experimental data on the time of droplet evaporation on the droplet size and surface temperature were obtained.
- A comparison of the obtained experimental dependences on the time of evaporation of the droplet with the data [3] and calculation by formula (1) showed their quality match.

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