Experimental determination of the cooling efficiency of a high-temperature surface by a pneumatic nozzle

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Abstract. The cooling of surfaces that perceive high heat fluxes (more than 7 MW/m²) at the current pace of development of the energy sector will become one of the main problems of the near future. In this paper, as one of the options for effective cooling of high-temperature surfaces of various geometries, the results of an experimental study of the cooling process by a spray flow directed perpendicular to the cooled surface are presented. Two different types of nozzles are used for cooling. Water consumption varied in the range \((8.3 \div 25.0) \cdot 10^{-3} \text{kg/s}\), air consumption in the range \((0.3 \div 1.1) \cdot 10^{-3} \text{kg/s}\). The maximum value of the density of the removed heat flux for one of the nozzles is 11.3 MW/m² at a water flow rate \(25.0 \cdot 10^{-3} \text{kg/s}\), the average value of the heat transfer coefficient during spray cooling was about 100 kW/m²K.

1 Introduction

In modern technology, it is often necessary to divert heat flows with an energy density of hundreds of kW/m² or even several MW/m². At the same time, the cooled objects are very diverse in their weight and size parameters: from compact, which take place in computer and laser technology, to bulky and bulky, such as, for example, rolled products of the steel industry during quenching and cooling. Currently, this problem is solved by using various methods of heat exchange intensification, which are divided into 2 main groups – active and passive [1-3].

As an alternative to the existing methods widely used for cooling high-temperature surfaces, it is proposed to use a two-component dispersed water-gas coolant flow [4-10]. Previously conducted experimental studies [7-8] of the features of the cooling process with such a coolant have so far concerned the case when the coolant flow interacted with the cooled surface at an acute angle (~ 3-5 degrees). However, it was found [9] that the efficiency of the heat sink with such a longitudinal supply scheme decreases depending on the distance of the cooled area from the place of the coolant input. In addition, such a coolant input scheme is not optimal for the case of cooling large flat surfaces and channels of complex configuration. For this reason, in this work, as in [10], the process of heat removal was investigated when a coolant flow was applied perpendicular to the cooled surface of the target, which seems to be a more promising approach. The process of heat transfer during spray cooling by a dispersed flow (DP) of the coolant is schematically presented in Fig. 1 [11].

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determining the possibilities of cooling by a dispersed flow.

2 Installation description

In order to conduct experiments to study the possibilities of effective cooling of a high-temperature surface with a dispersed flow using various models of spraying devices, the modernization of the "One-way heating" stand was carried out, created on the basis of the Department of General Physics and Nuclear Fusion of "MPEI". The experimental installation consists of 3 main systems: a heating system, a cooling system and a system for collecting and processing information.

2.1 Heating system

The target is heated by a sanitizing electron beam, the source of which is an electron beam gun EBG manufactured by the company "THETA", with a capacity of 60 kW. The EBG can operate both in stationary (τ > 10000 c) and in pulsed heating mode. The system of the beam forming unit and the accelerating voltage generation units of the EBG allows you to adjust and maintain a stable value of the beam current in the range from 1 to 1000 mA in increments of 1 mA at a maximum accelerating voltage of 60 kV. Smooth adjustment of the electron current strength at a constant accelerating beam voltage ensures a change in the value of the supplied power in a wide range.

Scanning of the electron beam along the outer surface of the target is provided by the deflection and focusing unit. To create a uniform heat flow on the surface of the working area, a raster scan is used, which forms 100 lines with a refresh rate of 120 frames. Thus, the total frequency of the electron beam displacements is 12 kHz.

The electron beam gun is installed on a vacuum chamber with a volume of 0.8 m³, inside which there is an experimental module connected to the cooling system.

2.2 Cooling system

During the experiments, the effect on the cooling efficiency of a high-temperature surface when using two nozzles with different nozzle geometries was investigated. A nozzle with a diameter of the central water supply hole of 1.4 mm (hereinafter nozzle № 1) and a diameter of 2.4 mm (hereinafter nozzle № 2).

An important task of the conducted research was to determine the influence of the operating parameters of the flow and pressure of the coolant components on the cooling efficiency, which led to the creation of a cooling system, the schematic diagram of which is shown in Figure 2. The cooling system provides for the possibility of adjusting the flow rate of coolant components, pressure control, compressed air preparation. Water is supplied to the nozzle by means of a centrifugal pump. The water pressure at the nozzle inlet can take values in the range \((10 \div 400) \cdot 10^3 Pa\). Air is supplied to the nozzle by means of a compressor, the air pressure at the nozzle inlet can take values in the range \((50 \div 850) \cdot 10^3 Pa\).

2.3 Information collection and processing system

During the experiment, special attention was paid to the accuracy of measuring thermophysical and electrical parameters, such as target temperature, volumetric flow rates, pressure of coolant components, etc. For this purpose, an information collection and processing system was used, created on the basis of National Instruments equipment in conjunction with LabVIEW software. The system operates with a channel polling frequency of 1 Hz, the readings of all sensors are recorded in the resulting file of the experiment protocol.

2.4 Experimental module description

The experimental module (Fig. 3), installed in a vacuum chamber, is a sealed cylindrical vessel, 260 mm high, made of AISI 304 stainless steel, consisting of three main elements: the upper flange, the body and the lower flange. In the center of the upper flange, a target made of C11000 grade copper is hermetically installed, the scheme of which is shown in Fig. 4.
The rectangular shape of the target and the significantly different thermophysical characteristics of the materials being connected created some difficulties in its reliable fixation with the upper flange, which was helped to solve by the team from the National Research Nuclear University MEPhI. To install the target into the flange, the MEPhI-AMETO solder technology of the STEMET 1202 brand was used, which provides a vacuum-tight connection at high thermal loads up to a value of 750 °C.

In this work, a pneumatic nozzle with a full spray cone was used as a source for the formation of a dispersed coolant flow to ensure uniform cooling of the inner surface of the target. The choice of this type of nozzle is due to the need to obtain finely dispersed liquid droplets (with a diameter of about 30-100 microns) and a slight dependence of the quality of spraying on the flow rate of the liquid. Two-phase water-air pneumatic nozzles are used with a spray angle of 12-16 degrees, which depends on the flow rate of water or air. The distance from the cooled surface to the outlet channel of the nozzle is 140 mm.

A spiral condenser is installed inside the experimental module, the purpose of which is to condense the vapor formed during the cooling of the target.

3 Methodology of the experiment

Experimental studies on target cooling were carried out on nozzles that allow adjusting the operating parameters of the dispersed flow components at the nozzle inlet in the following range: water flow $G_{\text{water}} = (8.3\times25.0) \times 10^{-3}$ kg/s; water pressure $p_{\text{water}} = (40\times350) \times 10^3$ Pa; air flow $G_{\text{air}} = (0.3\times1.1) \times 10^{-3}$ kg/s; air pressure $p_{\text{air}} = (50\times340) \times 10^3$ Pa, initial water temperature $T_{\text{in water}} = 10^\circ$C. During each experiment, electrical and thermophysical parameters were determined: accelerating voltage and the strength of the anode current of the EBG, the volumetric flow rate of cooling water on the condenser, the temperatures of the coolant components at the inlet and outlet to the working module and condenser, etc.

The aim of the experiments was to determine the modes of the most effective cooling of the surface with a different ratio of distilled water and air in a two-component dispersed coolant flow and the maximum thermal load, above which there is a sharp increase in the temperature of the target wall and there is a risk of its destruction. Each mode included an array of experimental points characterized by a pre-selected pair of values of the mass flow rate of water and air, as well as the electrical power of the electron beam. The method of conducting the experiments consisted in a step-by-step increase in the supplied electrical power and monitoring the stabilization of the temperature of the target wall at fixed parameters of the coolant. The experiment was stopped in case of a sharp increase in the temperature of the target wall (at least 5 °C per second). The corresponding value of the specific power was considered critical and corresponded, according to the authors, to the crisis of heat exchange on the inner surface. The second condition for stopping the experiment was the achievement of a critical temperature associated with an increased risk of destruction of the working module.

The photo of the target after the next series of experiments is shown in Figure 5. The characteristic traces of the scanning electron beam are visible on the surface. The area of the heated surface in the series of experiments was unchanged and amounted to $S_{\text{surf}} = 0.76 \times 10^{-3}$ m².

Under significant thermal loads, the electron beam significantly changed the surface of the target, forming irregularities, microcracks and melting on it (especially at the boundary of the scanned surface due to local overheating during the forward and reverse course of the beam).
4 Discussion of the results

The geometry of the working area used and the heating-cooling conditions suggest a linear nature of the temperature distribution in the cross section of the target. Using Fourier's law in the flat wall approximation

\[ q = \lambda \frac{dT}{dx} \]  

(it is possible to determine the temperatures of the heating and cooling surfaces and the local value of the heat flux density at a point located directly under the thermocouples. The results of the method used to determine the target temperatures are shown in Figure 6.

\[ T_{liq} = \frac{T_{water} + T_{wall}}{2}, \]  

The above method of determining the temperature of the liquid near the surface is associated with a high contribution of preheating of the cooling water and condensation on the droplets of the cooling spray of steam formed as a result of cooling the surface.

Defining the value of the temperature drop as the temperature difference between the temperature of the coolant at the inlet and the temperature of the cooling surface

\[ \Delta T = T_{wall} - T_{liq}, \]  

the dependences of the heat flux density on the temperature drop were obtained (Fig. 7).

According to the results obtained, several conclusions can be drawn. Firstly, with the help of the nozzle №2, it is possible to divert the heat flux density more than 10 MW/m² in stationary cooling mode with water flow \( G_{water} = 20.8 \cdot 10^{-3} \text{ kg/s} \) and air flow \( G_{air} = 0.5 \cdot 10^{-3} \text{ kg/s} \) for the nozzle №2.

Secondly, when using the nozzle №1 with a lower value of the temperature drop, a heat transfer crisis develops.

5 Conclusion

According to the experimental results obtained, the following conclusions can be drawn:

- the nozzle №2 with a large diameter of the central hole, with the same flow rates of the liquid and gas phases of the coolant, it allows you to divert large values of the heat flux density. At water flow \( G_{water} = 20.8 \cdot 10^{-3} \text{ kg/s} \) and air flow \( G_{air} = (0.52 \div 0.54) \cdot 10^{-3} \text{ kg/s} \), the cooling efficiency of each of the nozzles can be indirectly determined by calculating the value of the heat transfer coefficient using the Newton-Richman equation:

\[ \alpha = \frac{q}{\Delta T} = \frac{2q}{T_{wall} - T_{in}}, \]  

Figure 8 shows the dependence of the heat transfer coefficient on the heat flux density.

According to the obtained graph, it can be concluded that higher values of the heat transfer coefficient when using the nozzle №2. The average value of the heat transfer coefficient for nozzle № is 80 kW/m²K, for the nozzle №2 – 120 kW/m²K. The reference value of the heat transfer coefficient when boiling water in the channel is taken in the range 20 ÷ 50 kW/m²K.
\[0.5 \cdot 10^{-3} \text{ kg/s}\] the value of the heat flux density \( q \) exceeds 10 MW/m\(^2\); the average value of the heat transfer coefficient is about 100 kW/m\(^2\)K. In this case, the reference value of the heat transfer coefficient when boiling water in the channel is of the order of 20 ÷ 50 kW/m\(^2\)K. From all the above we can conclude about the effectiveness of the proposed cooling method.

In the future, the team of authors proposes to conduct a study of the influence of the size of the central hole of the nozzles on the shape, size and distribution of droplets in the section of the spray torch.

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References