Innovative method of cooling and thermostabilization of tokamak elements with capillary-porous structures

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Abstract. The paper describes and considers the possibility of using the method of cooling by a gas-water spray of a working area heated by a beam of charged particles. The design of a gas-water spray generator and an experimental installation for visualizing the process of outflow of the working environment from it has been developed, the necessary components of the system have been prepared, and an experimental setup has been installed. The cooling of the surface is carried out by evaporation of the impalpable drops of water from spray flow. Photographs of coolant outflow from the gas-water spray generator were obtained. The experiments revealed that the dispersion of liquid drops in the spray flow increases with air pressure rise, with a constant water consumption. It was concluded from the experiments carried out that the optimum dispersity of drops is achieved at air pressure (2÷3)·10⁵ Pa and water flow (50÷100) g/s.

1. Introduction
When creating experimental energy systems and thermonuclear systems of the near future, such as, for example, a thermonuclear neutron source (TNS) and a demonstration thermonuclear reactor DEMO (DEMO-C), in addition to problems associated with stationary long-term plasma retention, a number of technological difficulties arise. They have not been solved yet or require additional research and justification of the possibility of their use.

One of such problems is the provision of reliable thermal protection of the elements of the thermonuclear reactor design – the divertor, limiter, blanket, injection additional heating systems that contact with the plasma and high-energy particle flows and their cooling at different temperature levels.

The use of solid materials (tungsten, beryllium, graphite and composites based on it) as materials that contact with the plasma, and in particular the receiving elements of the tokamak reactor divertor, as the experimental studies and estimates showed, will not provide high resource characteristics of this device because of a high rate of erosion of materials under the influence of high thermal loads and corpuscular flows, impurities entering the main plasma, accumulation of dust, accumulation of tritium and a number of other problems. A promising engineering-physical solution is the use of liquid metals (lithium, tin, tin-lithium eutectic composition) as a material that contacts with the plasma in the divertor in combination with the use of capillary-porous structures (CPS) for effective stabilization of the surface of a liquid metal under conditions of the experimental systems work. Easy-melting metal,
and lithium in the first place, can combine the functions of a coolant, a tritium reproducing material, a material capable of providing the necessary characteristics of the main plasma and the protective material of the receiving divertor devices and the first wall.

Until now, however, the testing of intracameral elements of thermonuclear installations, the construction of which is based on the use of lithium-based CPS, was carried out under conditions of plasma discharges of relatively short duration – not more than 1.5 s (FTU). The excess energy supplied to the receiving lithium cell under these conditions was absorbed by the heat accumulator, which is an integral part of the construction of such an intracameral element.

In thermonuclear installations of the near future, the situation will be different because they are aimed at developing the regimes of stationary (quasi-stationary) plasma combustion with large energy flows outgoing from it to the receiving intracameral elements of such installations. Thus, the ITER thermonuclear reactor, which is currently being under construction in France, will operate with a plasma discharge duration of 400 s. The T-15MD thermonuclear installation, which is being built under the Federal Program of the YaENP at the Research Center “Kurchatov Institute” and is to be operational in 2018, is designed for operation with a plasma discharge duration of up to 30 s. This requires the mandatory use of receiving internal system elements in its design based on lithium-based CPS systems of active high-efficiency cooling, which must ensure their operation in a stationary mode. Such systems are subject to the requirements formulated in [1-3]

One of the ways to effectively cool the limiters of tokamaks with lithium CPS can be the use of a gas-water spray, proposed in JSC “Krasnaya Zvezda”. The cooling of the surface is carried out by evaporation of the impalpable drops of water from a spray flow washing the surface, which lowers the surface temperature to an acceptable value (250° C). At the same time the system operates at low pressures, the specific volume of water does not exceed 10% and can be easily regulated.

2. Visualization of the gas-water spray flow in the open air

For the qualitative determination of the interaction of a two-component mixture at various pressures, an experimental setup was designed and manufactured, its principal scheme is shown in Figure 1.

The following tasks were solved with the help of this installation:

- visualization of a two-component environment flow at the outlet of the gas-water spray generator;
- determination of the torch parameters in relation to the mass consumption and pressure of air and water entering the gas-water spray generator;
- selection of the optimal ratio of the two-component flow parameters for cooling the inner surface of a pipe of a given diameter.

The main element of the gas-water spray generator is an injection device with tubes supplying it with the mixture components. The injector forms a torch of spray, the geometric characteristics of which, as well as the speed of water drops and their dispersion are determined by the regime parameters of the input components.

Figure 1(a) shows a photograph of a spray generator with an injection device and Figure 1(b) shows a photograph of a spray generator with the supply components of the tubes assembled.
Figure 1. The layout of the gas-water spray generator: (a) elements, (b) assembled

The diagram of the supply to the water and gas generator is shown in Figure 2.

Figure 2. The experimental installation diagram

After assembly of the experimental facility, the operation of the spray generator and the influence of the input parameters (pressure, mass consumption) of air and water on the dispersion and drops size were analyzed. Figure 3 shows the view of the spray flow outgoing from the generator, depending on the air consumption at constant water consumption.
(b)

**Figure 3.** View of "torch" depending on the air flow at a constant flow of water: (a) only water, (b) water and gas

The experiments carried out showed that the dispersion of liquid drops in the spray flow increases with the rise of air pressure, however, the water consumption in the flow is noticeably reduced. Optimal dispersion of drops is achieved at an air pressure of $2 \times 10^5$ Pa and water consumption ($50\div100$) g/s. The photographs of the obtained "torch" are shown in Figure 4.

**Figure 4.** Photographs of the obtained "torch"

3. **Description of the working area and the test-bed for experimental research**

Experimental studies for determining the thermal and hydraulic characteristics of a two-component environment are carried out in the “One-side heating” installation in model working areas. The energy receiver is a copper insert of rectangular cross-section, which is fastened between two tubes made of 12X18H10T steel. One of the tubes supplies a spray torch, which provides heat dissipation from the inner surface of the receiver channel. The steam-water-air mixture is discharged through the other tube.

The main conditions of the model experiment are:

- maintenance of heat flow density on the external surface of the receiver from 2.0 to 20.0 MW/m² at one-sided heating;
ensuring the heat dissipation efficiency in a level that would allow the temperature of the outer surface of the receiver not exceed $t_{\text{h}} = 550^\circ \text{C}$, from the inner surface it would not be lower than $t_{\text{m}} = 250^\circ \text{C}$.

To perform the estimated calculations for the heat transfer coefficient in the central section of the receiver, thermocouples are mounted on the vertical from the frontal point, which make it possible to evaluate the nature of the temperature field. Under the assumption of a homogeneous field, it is possible to extrapolate the temperature distribution to the frontal point that makes it possible to estimate the wall temperature. It is also possible to estimate the density of the heat flow on the wall. When the temperature of the spray coming to cool the receiver wall is known, we can calculate the heat transfer coefficient.

High density of heat flow from 2.0 MW/m$^2$ and above with one-sided heating is provided by electron beam equipment ELA-60/15T. The main elements are:
- high-voltage power supply (up to 60 kV) and control units;
- cathode node;
- systems of focusing and scanning of the electron beam;
- auxiliary systems (vacuum, cooling system of separate elements).

Maximum output characteristic of ELA-60/15T are: output power of the beam is 15 kW, maximum current $I_{\text{max}} = 0.250$ A, which allows to solve the tasks given.

In order to select the optimum characteristics of the spray components (water consumption, air pressure), a model with a working insert made of a glass tube has been made. In this case, the basic geometric characteristics of the model correspond to the geometric characteristics of the working area. Based on the conducted experiments, the intervals of technological parameters for further basic experimental studies were chosen. Figure 5 shows the type of torch in one of the modes.
Figure 5. View of a torch at pressure $2 \cdot 10^5$ Pa: (a) without water, (b) water consumption 100 g/s

Conclusion
A gas-water spray generator has been designed and an experimental mounting has been installed to visualize the processes of spray torch formation with different geometric and physical characteristics of the mixture. An installation for supplying the mixture components to a gas-water spray generator at various technological parameters has been created. The experiments carried out made it possible to determine the area of the technological parameters of the components, which provide the optimum characteristics of the spray torch. The main working area with pre-installed and mounted thermocouples has been prepared.

The work was supported by the Russian Science Foundation under the agreement no. 16-19-10457.

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