Cooling of the inner-chamber elements of a thermonuclear reactor with a dispersed flow

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Abstract. A method of temperature stabilization of the limiter of the Tokamak T-10 with capillary-porous structure on the side facing the plasma and saturated with liquid lithium, by dispersed gas-liquid flow is considered. The spray pattern, formed by the spray generator, is directed along the axis of the divertor. The results of experiments for determining the geometric characteristics of a torch, a dispersed flow, the distribution of the velocity and the size of water droplets in dependence on the pressure of water and air entering the generator nozzle are presented. The technique developed by the authors for processing experimental data is presented, which makes it possible to calculate the density of the heat flux, the temperature on the outer (heated) and internal (cooled) surface of the target walls. The design of the working area -divertor simulator is developed. It was experimentally established that the temperature of the target sharply decreased when air was supplied to the generator nozzle. The main experiments were carried out at excess water pressures \((1.0 - 3.5) \times 10^5\) Pa, air \((1.0 - 4.0) \times 10^5\) Pa, and heat flux densities of up to 8 MW/m\(^2\) applied to the target.

1. Introduction

One of the issues to be solved at constructing the fixed thermonuclear tokamak reactor is design engineering of its intrachambers (ICs). Structural components of the thermonuclear reactor are exposed to destructive action of a neutral flow with the energy of 14.1 MeV, high temperature plasma with the energy of tens of keV, electromagnetic and heat radiation. All this results in the structure degradation and scatteration of material in structures turned to plasma. For the time being, conventional design solutions and materials (including high-melt) cannot provide the creation of ICs able to withstand the exposure to heat flows with density of 10 – 20 MW/m\(^2\) during the commercially acceptable period of operation.

An alternative solution of this issue is the use of platelet structures (PSs) saturated with molten metals with low (for example, Li) or high Z number, but with low steam pressure (for example, Sn). This will allow creating a long-lived, non-damageable and self-renewing IC surface with a slight contaminating influence on plasma [1-4].
One of the main challenges emerging at molten metal use is selecting the IC cooling circuit and a type of heat carrier that would meet the safety requirements to the thermonuclear reactor.

Experimental studies carried out by the authors [5] on IC cooling with water insufficiently heated to saturation temperature at high pressures demonstrated good results. Despite this fact, using high pressures in cooling systems can be considered only for small research systems due to high potential hazard of the cooling system depressurization which is inadmissible for fixed tokamak type installations.

As an alternative heat removal method, the use of lithium PSs from the IC side turned to plasma, and cooling with finely dispersed water and gas mixture. When such approach is used, the system operates at low pressure, specific water holdup in the heat carrier does not exceed 10% and can be easily regulated. In terms of design, the system is simple and can be manufactured from common steel of austenite class of X18H10T type.

2. The description of the generator and experimental study of heat transfer in the limiter model

For work in this direction, the authors developed the working site and the cooling system hydraulic circuit on the basis of the available equipment.

The working section, the thermophysical model of the limiter, is placed in a vacuum chamber. The source of energy is the electron-beam aggregate ELA-60/15T. The laboratory bench is equipped with a high-frequency scanning system of the electron beam over the exposed surface, which ensures a predetermined, including uniform, heating of the target. A more detailed description of the experimental facility is given in [5, 6]. In figure 1 is a schematic diagram of a working section consisting of two carrier tubes 2 made of steel 12X18H10T and a copper target 1, which is a receiver of the electron beam energy. Seating places 3 are intended for installation of a working unit into a hydraulic circuit by means of sealing modules. Four chromel-alumel cable thermocouples $T_1 - T_4$ are mounted in the target, allowing to fix the temperature field in the target wall. The coordinates of the location of the thermocouples are indicated in the cross-sectional drawing of the target.

![Image](image1.png)

**Figure 1.** Scheme of the working area – the thermophysical model of the limiter: 1 – the target, 2 – the carrier tubes, 3 – the seats.

In figure 2 shows the diagram of the hydraulic circuit in which the working section 1, the cooling spray generator is installed (in the figure, only the injector 2 is shown). To measure the flow rate of the
generated steam, the hydraulic circuit comprises a separator 22 in which the vapor and liquid phases are separated, the condenser 21, and the measuring container 19 for measuring the steam flow.

**Figure 2.** Scheme of the hydraulic circuit for cooling the working area: 1 – working section, 2 – nozzle (gas-water spray generator), 3 – thermocouple at the inlet to the working area of the reactor, 4 – thermocouple at the outlet from the working area of the reactor, 5 – pressure vessel with working gas, 6,8,14,17,18,20,23-gate shut-off valve, 7 – gas flow meter, 9 – compressor, 10 – gas pressure gauge at the injector inlet, 11 – gauge of water inlet pressure in the reactor, 12 – water flow meter, 13 – water pump, 15 – coarse filter, 16 – tank, 19 – measuring container, 21 – capacitor, 22 – separator.

3. Experimental study results

Experimental study has been carried out in the following range of mode parameters: water pressure $p_{\text{water}} = (1.0\div3.5)\cdot10^5$ Pa, air pressure $p_{\text{air}} = (1.0\div4.0)\cdot10^5$ Pa, mass water flow $G_{\text{water}} = 0.025\div0.058$ kg/sec, mass air flow $G_{\text{air}} = 0.001\div0.0023$ kg/sec, heat flow density on the target wall $q = 1\div9$ MW/m$^2$.

A typical temperature distribution over the target is shown in figure 3. As follows from this figure, for the regimes under study, an almost linear temperature distribution takes place, which allows, first, to determine the density of the heat flow transmitted through the target; and, secondly, by extrapolation method, to obtain the temperature of the inner surface of the target wall, which, in turn, makes it possible to calculate the heat transfer factor. It can be seen from the figure that with increasing specific consumption of gas: $x = \frac{G_{\text{gas}}}{G_{\text{water}}}$ in a dispersed gas-liquid spray (with a constant flow of water), the target temperature is fairly markedly reduced.

**Figure 3.** The distribution of the wall temperature along the thickness of the working section in different cooling regimes ($G_{\text{воды}} = 0.0416$ kg/sec, $q = 4.2$ MW/m$^2$):

1 – $g = 0.032$; 2 – $g = 0.035$; 3 – $g = 0.039$; 4 – $g = 0.045$.

Figure 4 represents the dependence of the target wall temperature ($T_w$) on mass flow gas content for mass water flow value $G_{\text{water}} = 0.0416$ kg/sec. For any water flow and input power level, the wall...
temperature considerably decreases (to 200°C) with mass flow gas content, and when reaching the certain threshold value, further decrease of the surface temperature and, consequently, heat removal efficiency increase, ceases.

**Figure 4.** The dependence of the target wall temperature ($T_w$) on mass flow gas content ($G_{\text{water}} = 0.0416$ kg/sec): 1 – $q = 4.2$ MW/m$^2$; 2 – $q = 5.8$ MW/m$^2$; 3 – $q = 7.1$ MW/m$^2$; 4 – $q = 8.3$ MW/m$^2$

Figure 5 presents experimental data on the dependence of the heat transfer coefficient (thermal transmittance value) on the specific consumption of gas of a dispersed gas-liquid spray pattern at a fixed water flow rate.

**Figure 5.** Heat removal factor dependency on mass flow gas content $x$ ($q = 4.2$ MW/m$^2$): 1 – $G_{\text{water}} = 0.033$ kg/sec; 2 – $G_{\text{water}} = 0.042$ kg/sec; 3 – $G_{\text{water}} = 0.050$ kg/sec
Conclusions
A hydraulic circuit was designed and manufactured for carrying out experimental studies on the divertor model. Experimental data on thermal exchange at cooling with the dispersed pipe flow at one-sided heating have been obtained. As the result of studies conducted, the considerable decrease of the target wall temperature has been established at adding gas portions into the heat carrier (distilled water) flow. At the increased mass flow gas content, the wall temperature tangibly decreases at the respective heat loss increase. With the further mass flow gas content increase, heat loss increase rate decreases, and at values of $x \geq 0.055$, heat loss increase ceases.

For the most modes studied, the wall temperature exceeded the Leidenfrost temperature at which the steam and air film exists between the wall and the liquid phase. For this reason, the heat removal process is performed by means of evaporation of the smallest dispersion flare drops which explains the heat removal high intensity.

Experimental data analysis shows that the use of the dispersed flow with a nozzle of the given geometry allows maintaining the admissible temperature level (up to 550°C) at the work site at heat flow densities to 9 MW/m².

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References
[1] Lyublinski I, Vertkov A, Mirnov S and Lazarev V 2015 J. Nucl. Mater. 463 1156–9
[2] Mirnov S, Belov A, Djigailo N, Kostina A, Lazarev V, Nesterenko V and Vertkov A 2013 J. Nucl. Mater. 438 224–8
[3] Mirnov S, Belov A, Djigailo N, Dzhurik A, Kravchuk S, Lazarev V, Lyublinski I, Vertkov A, Zharkov M and Shcherbak A 2015 Nuclear Fusion 55 123015
[4] Lyublinski I, Vertkov A, Zharkov M, Mirnov S, Vershkov V, Glazyuk Y, Notkin G, Grashin S, Kislov A and Komov A 2017 J Nuclear Fusion 57 066006
[5] Varava A, Dedov A, Komov A and Yagov V 2006 High Temperature 44 669
[6] Vertkov A, Komov A, Lyublinski I, Mirnov S, Varava A, Dedov A, Zaharenkov A, Frick P 2018 Problems of Atomic Science and Technology, Series Thermonuclear Fusion 41 57–64