Experimental investigation of heat transfer of highly loaded structure elements upon cooling by a two-component gas-liquid flow

S V Mirnov, A T Komov, A N Varava, I E Lyublinski, A V Dedov, A V Vertkov and A V Zakharenkov

1 General Physics and Nuclear Fusion Department, National Research University "Moscow Power Engineering Institute", 14 Krasnokazarmennaya Street, Moscow, Russia
2 JSC “SRC RF TRINITI”, 12 Pushkovykh street, Troitsk, Moscow, Russia
3 JSC “Red Star”, 1A Elektrotitniy proyezd, Moscow, Russia

E-mail: ZakharenkovAV@mpei.ru

Abstract. The paper considers a method of temperature stabilization of the limiter in the T-10 Tokamak with capillary-porous structure on the side facing the plasma and saturated with liquid lithium, by dispersed gas-liquid flow. The spray pattern, formed by the spray generator, is directed along the axis of the limiter. The results of preliminary experiments for determining the geometric characteristics of a torch, a dispersed flow, the distribution of the velocity and the size of water droplets depending on the pressure of water and air entering the generator nozzle are presented. The paper presents the technique developed by the authors for processing experimental data, which makes it possible to calculate the heat flux density, as well as the temperature on the outer (heated) and internal (cooled) surface of the target walls. The design of the working area - limiter 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 \((0.5 \div 1.0) \times 10^5\) Pa, air \((0.3 \div 2.8) \times 10^5\) Pa, and heat flux densities of up to \(4.9\) MW/m\(^2\) applied to the target.

1. Introduction
The structural elements of the first wall of the nuclear fusion reactor are exposed to the destructive effects of high-temperature plasma: 14.1 MeV neutrons, 3.5 MeV \(\alpha\)-particles, tens of keV ions, electromagnetic and thermal radiation. All these impacts lead to the degradation of the structure and the spraying of the material of the first wall. At an early stage of studies on controlled thermonuclear fusion it was believed that for the solution of the problem of the first wall it would be sufficient to use refractory materials such as, for example, tungsten. However, at present, the prospects for the use of churlish materials are becoming less obvious due to the extremely negative consequences of the entry of atoms with a large \(Z\) into the plasma. For this reason, the surface of the first wall of thermonuclear reactor created by the efforts of the international community is planned to be covered with beryllium tiles. However, subsequent prospects for the use of beryllium are also very uncertain for a variety of reasons, including ones of medical origin.

In recent years, studies on the feasibility of using capillary-porous structures saturated with liquid lithium as structural elements facing the reactor plasma have been rather intensively conducted in the
Russian Federation [1-4]. Description of the limiter in T-10 Tokomak with liquid lithium is presented in [4]. Table 1 shows the main parameters of the lithium limiter.

**Table 1. Main parameters of the lithium limiter**

| Parameter                          | Value       |
|------------------------------------|-------------|
| Maximal power flux, MW m⁻²         | 5           |
| Limiter size $H \times D \times L$, mm | $95 \times 450 \times 48$ |
| Length of lithium element, mm      | 323         |
| Diameter of lithium element, mm    | 34          |
| Area of lithium surface, cm²       | 324         |
| Limiter radial moving $(r_1-r_3)$, mm | 150       |
| Operating temperature, °C           | 200-550     |
| Heater power, W                    | 500         |
| Lithium amount, g/cm³              | ~50 (100)   |

An important problem arising with the use of lithium-based capillary-porous systems is their effective cooling, which prompts to seek innovative approaches to solving the problem of cooling lithium-based capillary-porous systems, as applied to their use for thermostabilization of in-chamber tokamak elements operating in a stationary mode.

This approach may include cooling of the in-chamber tokamak devices and, in particular, lithium-based limiters, with a finely dispersed mixture of water and gas with low pressures in the cooling system. With this approach, the above requirements are met: the system operates at low pressure, the specific volume content of water in the coolant does not exceed 10% and can be regulated, and the system is simple and can be made of ordinary stainless steels of the austenitic class.

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

The authors of this work have developed the design of a generator of a dispersed gas-liquid flame (spray), whose schematic diagram is shown in figure 1.

![Figure 1. The schematic diagram of the gas-liquid spray generator: 1 - test section, 2 - sealing unit, 3 - nozzle, 4 - air (gas) supply line, 5 - water supply line.](image)

The test section, the thermophysical model of the limiter, is placed in a vacuum chamber. The energy source is the ELA-60/15T electron-beam aggregate. 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]. Figure 2 shows 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, which allow measuring 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.

![Cross-sectional drawing of the target](image)

**Figure 2.** Schematic diagram of the working area - the thermophysical model of the limiter: 1 - the target, 2 - the carrier tubes, 3 - the seats.

Figure 3 shows the schematic diagram of the hydraulic circuit in which the test 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 3. Schematic diagram of the hydraulic circuit for cooling the working area: 1-test 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.

A typical temperature distribution over the target is shown in figure 4. As follows from this figure, for the regimes under study, an almost linear temperature distribution takes place, which allows, first, determining the heat flux density transmitted through the target; and, secondly, by extrapolation method, obtaining 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: \( g = \frac{G_{\text{gas}}}{G_{\text{water}}} \) in a dispersed gas-liquid spray (with a constant flow of water), the target temperature is fairly markedly reduced.
Figure 4. The distribution of the wall temperature along the thickness of the test section in different cooling regimes: 1 - $g=0$; 2 - $g=0.027$; 3 - $g=0.037$

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. Dependence of the heat transfer coefficient on the specific consumption of gas of the dispersed spray pattern

3. Conclusions
We have performed investigations of the parameters of the gas-liquid spray pattern created by the developed spray generator. A hydraulic circuit was designed and manufactured for carrying out
experimental studies on the limiter model. An experimental facility with electronic heating of the target surface has been used for the investigations. The parameters of the experimental bench are given in [5]. The results of the performed studies show that this design of the spray generator is able to provide the specified parameters of the limiter \((q = 5 \text{ MW} / \text{m}^2, T = 200-550\, ^\circ\text{C})\).

The temperature of the target wall when it is cooled by a dispersed gas-liquid flow decreases noticeably, and the heat transfer is correspondingly very significant in comparison with the cooling of a single-phase liquid jet with the same parameters. To confirm the first results on the efficiency of heat removal and heat setting of the limiter by a dispersed flow, it is necessary to continue detailed investigations in this direction. In modes with low specific consumption of gas, the temperature of the inner surface of the test section exceeds the temperature of the superheat limit, which under the experimental conditions is equal to \(T_{\text{max}} = 306.6\, ^\circ\text{C}\) [5]. The mechanism of heat transfer, stability of heat-removal regimes at such high temperatures requires additional and careful study.

**Acknowledgments**

This work was supported by the Russian Science Foundation No. 16-19-10457.

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