Studying in-vessel component materials under heat and plasma loads relevant to fusion installations

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Abstract. The results of studies of materials under extreme thermal and plasma-beam loads, carried out to justify existing technological solutions in the design of thermonuclear reactors, are presented. The study of materials under plasma and beam loads and the intensifying heat transfer of in-vessel cooled components of fusion devices is reported. Tests of limiter and divertor mock-ups irradiated with high heat fluxes in electron beam and plasma facilities are described. Methods for cooling in-vessel components using advanced approaches with dispersed gas-liquid flow for heat removal, including at loads of up to 15 MW/m² have been developed and tested.

1. Introduction
To estimate thermal loads in thermonuclear reactors and the to develop engineering approaches to the design of cooling systems for in-vessel components of hybrid thermonuclear reactors [1], a description of the heat transfer in materials under the high plasma, beam and neutron loads is required. The key issues of the fusion projects are the problems of material surviving under extremely high heat plasma and beam loads [2,3]. The results of studies of materials under extreme thermal and plasma-beam loads carried out to justify existing technological solutions in the design of fusion reactors are presented.

2. Description of experimental facilities
E-beam tests of materials and the divertor mock-ups were carried out at the facilities at NRU “MPEI” providing loads of up to 300 MV/m², which simulates thermal loads on the walls and divertor plates in a tokamak reactor [4, 5]. Industrial facilities for electron beam welding were used as two installations. The first installation had an electric power of 200 kW and a vacuum chamber volume of 6 m³, and the second one had an electric power of 15 kW and was equipped with a hydraulic loop. This experimental setup described in detail in [6, 7] included the following basic components: a system of electron heating, hydraulically and vacuum systems, and an automatic system for data acquisition and processing. The horizontally arranged target was heated in a vacuum chamber by a scanning electron beam, generated by an electron gun with an accelerating voltage of up to 60 kV and current of up to 250 mA. The specially developed electron beam sweeps the heat-absorbing surface of the target provided for its uniform heating. The hydraulic system provides for the stable parameters of
air-water flow in the following range: water pressure $p_{\text{water}} = (1.0 \div 3.5) \cdot 10^5$ Pa, air pressure $p_{\text{air}} = (1.0 \div 4.0) \cdot 10^5$ Pa, water flow $G_{\text{water}} = (0.015 \div 0.038) \text{ kg / s}$, air flow $G_{\text{air}} = (0.001 \div 0.002) \text{ kg/s}$ and heat flux of up to 11 MW/m$^2$ applied to the target.

Figure 1 shows diagram of the test section, consisting of two carrier tubes 3 made of stainless steel 12X18N10T, a copper target 2, and tungsten plates 1, being an electron beam energy receiver. Seats 4 are intended for installing the working section in the hydraulic loop by means of sealing units. Eight chromel-alumel cable thermocouples were mounted in the copper target, which enabled the temperature field recording along the target cross section of the test section.

![Figure 1. Scheme of the test section: 1 – tungsten target; 2 – copper target; 3 – carrier tubes; 4 – seats.](image)

The PLM installation [8, 9] is a linear plasma trap with a multi-cusp configuration of a magnetic field and a stationary plasma discharge that provides the powerful plasma-thermal load of up to 5 MW/m$^2$ on test materials. At the PLM installation, modules of various grades of tungsten (including ITER grade, etc.) were tested in stationary plasma discharges lasting for more than 200 minutes with parameters: plasma density of $(0.5-5) \times 10^{12}$ cm$^{-3}$, temperature of electrons of the main fraction of 2-5 eV with a fraction of hot electrons of up to 50 eV, ion fluxes per material of up to $10^{21}$ m$^{-2}$s$^{-1}$, power from 0.5 to 5 MW / m$^2$, ion energy per sample of up to 200 eV at biasing to the sample of up to -300 V, magnetic field of 0.01 T, and up to 0.2 T in cusps. Such parameters provide adequate conditions for stationary plasma tests of thermonuclear materials.

3. Experimental results

Experimental results are presented for materials under beam and plasma load and for dispersed flow cooling of divertor modules.

The experimental data on heat transfer in divertor modules cooling by a dispersed air-water flow under conditions of one-sided heating were obtained with the following parameters: input heat flux $q = (8-17)$ MW/m$^2$; water pressure at inlet $1.3 \cdot 10^5$ Pa; air pressure at inlet $1.8 \cdot 10^5$ Pa; water mass flow rate $G_{\text{water}} = 56 \cdot 10^{-3}$ kg / s; air mass flow rate $G = 1.9 \cdot 10^{-3}$ kg / s. The temperature of the air-water mixture at the inlet was maintained at 22 °C. Two series of experiments were conducted. The
differences between the series consisted in the arrangement of the electron beam on the surface of test section. The arrangement of the electron beam is shown in Figure 2.

Figure 3 shows typical temperature distribution over the cross section of the copper part of the target (figure 1). The temperature field is close to be linear, which enables extrapolation to obtain the heat flux density from experimental data and to determine the temperature of the inner surface of the target wall, which, in turn, allows us to estimate the heat transfer coefficient. Figure 4 shows the heat transfer coefficients determined in two series of experiments.

**Figure 2.** The arrangement of the electron beam on the surface of test section:
   a) 1st series of experiments; b) 2nd series of experiments.
Figure 3. Temperature distribution over the cross section of the copper part of the target: heat flux $q$: 1 – 13.6 MW/m$^2$, 2 – 11.4 MW/m$^2$, 3 – 8.2 MW/m$^2$.

Figure 4. The heat transfer coefficient depending on the heat flux at constant flow rates of water and air: $G_{\text{water}} = 56 \cdot 10^{-3}$ kg/s, $G_{\text{air}} = 1.9 \cdot 10^{-3}$ kg/s, 1 – 1st series, 2 – 2nd series.
According to figure 4, it can be determined that with an increase in the heat flux, the heat transfer coefficient decreases, but after reaching 9–11 MW/m² for the second series and 12 MW/m² for the first series, the heat transfer coefficient reaches a “plateau”. A further increase in the heat flux does not lead to any significant decrease in the heat transfer coefficient. The temperature of the inner surface increases in the range from 150 to 270 °C with an increase in the heat flux from 6 to 15 MW/m².

Tests of uncooled models in the combined scheme of plasma-beam tests were carried out, namely, (1) thermocyclic tests in electron beam facilities with the load of 1 to 40 MW/m² or more (Figure 5); and then (2) testing in PLM plasma device with stationary plasma loads of 0.5–2 MW/m² or more [10–11]. These combined tests simulated variable loads in the divertor of a tokamak reactor, including ELMs load. The combined loads led to erosion, cracking, a significant change in the surface microstructure (Figure 5) and tungsten recrystallization to the depth of more than 20 micrometers.

As a result of tests with stationary plasma flows, layers with fibers with a diameter of 20-50 nanometers were formed on the tungsten surface; the layer depth reaching 1.6 μm,

Figure 5. SEM micrograph of the surface of ITER-grade tungsten after thermocycling with e-beam load of 40 MW/m².

The experimental results will be used to predict the erosion of plasma-facing components and to develop the designs of the cooling systems of a hybrid fusion reactor with loads on in-vessel components of more than 10 MW/m².

Conclusions
The data on heat transfer in real divertor modules for water-air flow cooling have been presented. Thermal stabilization of the receiving devices of thermonuclear installations with a heat flux of up to 15 MW/m² using a water-air flow has been shown for the first time. The possibility in principle of achieving the necessary temperature of the inner surface at the level of (150-250) °C, which is impossible with water cooling, has been illustrated. To achieve the desired temperature of the receiving devices may be possible by controlling the flow of water and air. The combined test of ITER-grade tungsten with powerful e-beam and steady-state plasma has led to erosion, cracking, and a significant change in the surface microstructure. The experimental results will be used to develop the design of the cooling systems of a hybrid fusion reactor with loads on in-vessel components of more than 10 MW/m².

Preliminary analysis of the results shows that the use of this cooling method allows effectively cooling the work area without its damage at thermal loads of \( \approx (2 \div 2.5) \) MW/m².
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