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High-heat-flux-exposure-experiments of a tungsten-test-limiter at TEXTOR-94

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Abstract

To test the performance of tungsten as a plasma facing material, a small test limiter made of solid pure W was immersed in a TEXTOR plasma. A surface temperature in excess of 3000 K and the rate of temperature increase close to 2000 K/s was measured for the auxiliary heating conditions. These values corresponded to a power flux density of more than 40 MW/m^2 based on the calculations of a heat transfer model. The test limiter showed no observable degradation after exposure to this high heat flux density. The oxygen flux from the test limiter showed an increase during intense plasma exposure. However, no enhancement in the normalized W yield was observed when the W release was normalized to the C and O flux to the limiter, and the W release appeared to be dominated by physical sputtering.

1. Introduction

High Z materials may be used as plasma facing materials (PFM) in future fusion devices [1] but their performance under high power-loading in a plasma has yet to be confirmed. To obtain insight into how high Z materials behave in the edge plasma of a tokamak discharge, experiments to test the material performance of a small test limiter made of pure Mo and W metal have been performed at TEXTOR-94 [2]. The position of the test limiter determines the amount of the plasma energy deposited onto the limiter, and the heat load onto the test limiter can be controlled by changing the position of the test limiter as well as changing the input power to the ohmic and auxiliary heatings [3]. The distributions of temperature on the limiter surface are measured and used to estimate the power flux density. The time evolution of the temperature at the hottest part of the test limiter can be reasonably represented by a one-dimensional heat transfer model, and the local heat flux can be obtained from simple calculations. A good agreement has been achieved between the heat load evaluated from the heat transfer calculation and that estimated from the measured electron temperature and the electron density [4].

It has been confirmed with a Mo limiter that a local melting of the high Z element does not cause a serious deterioration of the core plasma parameters [4,5]. Because W has a much higher melting point than Mo, it can be better as the PFM subject to a large heat loading. One of the main concerns is the performance of W as PFM at high temperatures. At extremely high temperatures, the current density of thermionically emitted electrons should become large enough to change the floating potential of the surface immersed in the plasma. With a higher current density from the thermionic

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electron emission, the floating potential shifts toward the plasma potential, and the average energy of electrons impinging on the surface becomes higher, causing a greater heat load to the surface [6]. Another concern is the effect of a high rate of temperature change. If the molecules adsorbed on the surface are released during the heating stage, the rate of desorption of the molecules should increase with increases in the rate of heating. This will change the recycling of atoms and molecules at the plasma edge and is important in estimating the erosion rate of PFM. In this paper, we report the experimental results obtained by exposing a W test limiter to a plasma radiation with a power density of more than 40 MW/m^2. The results are compared with a simple three-dimensional heat transfer calculation.

2. Experimental

The experimental setup is schematically illustrated in Fig. 1. The major radius of TEXTOR-94 was 1.75 m. The minor radius was set to 0.46 m by the graphite ALT-II limiter and the W test limiter with radii of 8.5 cm in the toroidal direction and 6.5 cm in the poloidal direction was inserted into the plasma through the limiter lock system [7]. To measure the ion and neutral species that were emitted from the plasma and then reflected at the test limiter surface, a grating spectrometer monitored the intensities of line spectra from various ions and neutrals. The spatial distribution of neutral W in a plasma near the test limiter was measured as a two-dimensional picture taken by a CCD camera through a 1.5 nm band interference filter at the 400.8 nm wavelength of the line spectrum emission from neutral W. Another CCD camera was used to measure the spatial distribution of the surface temperature of the test limiter. It observed the top surface of the limiter through an infrared filter transmitting 850–1100 nm coupled with neutral density filters. From the measured distribution of the infrared radiation, the temperature distribution was reconstructed from the calibration table. To measure the total heat absorbed by the limiter, two thermocouples were inserted into the limiter through drilled holes. These thermocouples measured the temperatures of the ion drift and electron drift sides.

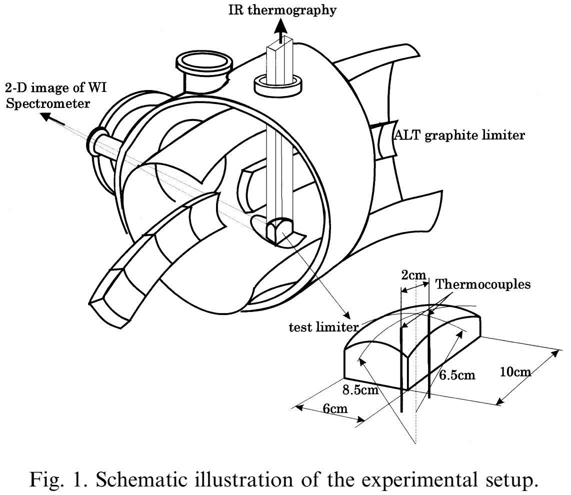

Fig. 1. Schematic illustration of the experimental setup.

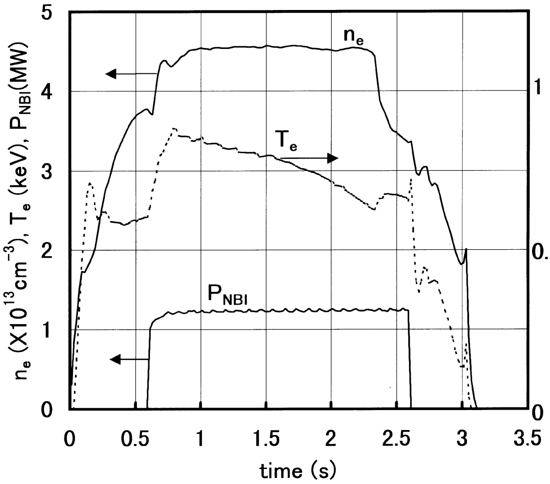

Fig. 2. The electron density, and the electron temperature during high-heat-flux exposure experiment of the W test limiter.

The high heat flux experiment was performed with the usual TEXTOR operating condition with a 2.24 T toroidal field and a 340 kA plasma current. The plasma was heated from 0.6 to 2.6 s with 1.3 MW neutral beam heating. The gas introduction system adjusted the electron density to 4.5×10^{13} cm^{-3} density from 0.6 to 2.3 s. Typically observed variations in the electron density and temperature at the plasma center are shown in Fig. 2. The temperature of the limiter prior to the discharge was controlled by a heater to keep it higher than 600°C, which is above the ductile brittle transition temperature of W.

3. Heat transfer model

Assuming no heat source is present in the limiter, a simple heat conduction equation given by

$$\rho C_{\mathrm{p}} \frac{\partial T}{\partial t} - k\nabla^2 T = 0 \tag{1}$$

was solved with the boundary condition,

$$q_n = -k\nabla_n T = P(r) - \varepsilon(T)\sigma(T^4 - T_a^4). \tag{2}$$

The most important part of the calculation is to set up a proper model for the heat flux normal to the surface, q_n, which determines the spatial derivative of the temperature in the direction normal to the surface, $\nabla_n T$. The emissivity of the W surface, $\varepsilon(T)$, is a function of the surface temperature, T, and is computed from Ref. [8] as well as other heat conduction parameters like the mass density, ρ, the specific heat, C_p, and the thermal conductivity, k. The heat flux density due to the plasma irradiation, $P(r)$, is assumed to decrease exponentially from the last closed flux surface determined by the head of the test limiter. The equation was numerically solved by the time-dependent finite element method (FEM). The power density from the plasma was reiteratively adjusted so as to realize the observed temperature distribution on the surface.

4. Results and discussion

4.1. Temperature distribution for moderate heat loading

To illustrate the distribution of the surface temperature in a simple way, a one-dimensional temperature distribution taken at the center of the limiter in the toroidal direction was studied. In Fig. 3, a comparison between the result of the model calculation and the measured distribution of the surface temperature is shown at the time $t = 2.3$ s. The distribution of the surface temperature allows for a discharge with the limiter located at 45 cm from the center. The FEM calculation shows the result for 1 cm power decay length, 36 MW/m^2 maximum heat loading, and 30% more heat load to the ion drift side compared to the electron drift side. The discrepancy on the ion drift side seems to indicate a larger e-folding length for the power decay on that side. The fit of the temperature profile for the electron drift side is quite satisfactory, except near the center of the limiter. The model seems to show a smaller thermal diffusion than that obtained in the experimental results, which may be attributable to improper constants employed to calculate the heat conduction at high temperature.

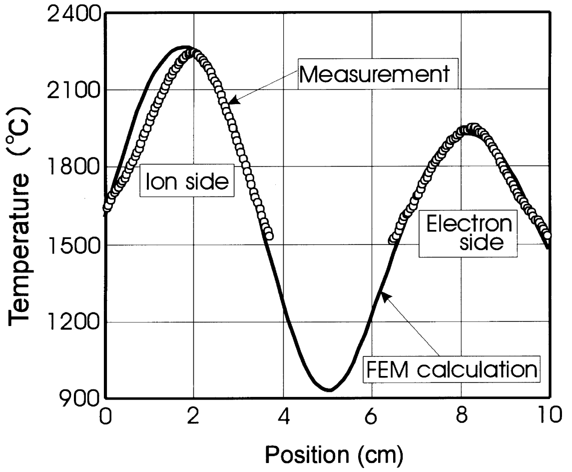

Fig. 3. Comparison of the measured distribution of the surface temperature (open circles) and the calculated distribution (solid line) for the condition of test limiter positioned at 45 cm from the plasma center.

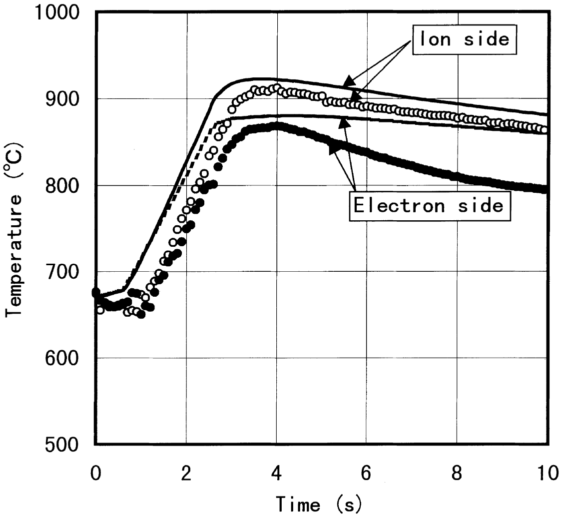

Fig. 4. The temperature evolution of the test limiter measured with the thermocouple embedded in the ion drift side (open circle), and in the electron drift side (closed circle). The results of the calculation by FEM are given with the solid (ion drift side) and dashed (electron drift side) lines in the figure. The limiter is located at 45 cm from the plasma center.

The temperature at the position of the thermocouple can be also computed by the model. The experimental results are compared with the calculation results in Fig. 4. The rate of temperature increase and the temperature difference between the ion side and the electron side at the time of the appearance of the maximum temperature are similar. However, a substantial difference in the cooling phase is observed, and the heat conduction along the thermocouple wire is a possible explanation for this discrepancy. If this is the real reason for observing the faster cooling of the limiter temperature, we need some correction in estimating the plasma energy absorbed by the test limiter.

4.2. Temperature distribution at the maximum heat loading

When the limiter is inserted 2.5 cm deeper into the plasma from the LCFS determined by ALT-II, a very rapid increase was observed in the surface temperature's rate of change. This is shown in Fig. 5. The maximum rate of temperature increase was about 2000 K/s. To obtain a temperature distribution similar to that shown

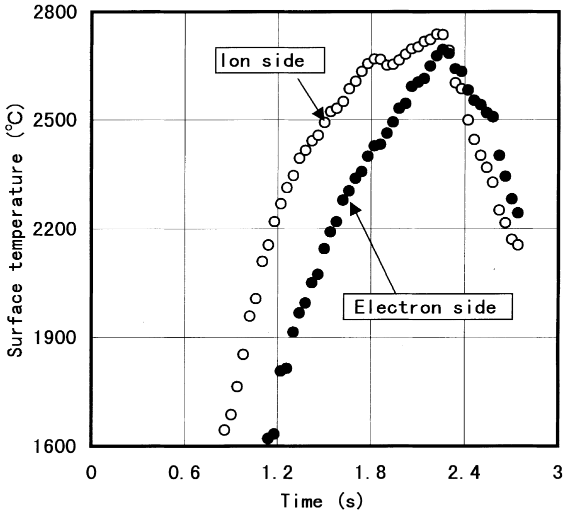

Fig. 5. Measured surface temperatures in the ion (open circle) and electron (closed circle) drift sides plotted as functions of time.

in Fig. 5 from the results of the heat transfer calculation, the maximum heat flux density onto the limiter should be more than 50 MW/m^2. Meanwhile, in order to realize a rate of temperature increase as high as the one shown in the figure by adjusting the power density used as the input parameter for the calculation, the required power density is even higher than 50 MW/m^2. Even with exposure to this high power density heat flux, the test limiter showed no observable degradation when it was investigated after the experiment.

According to Fig. 5, the heat load to the limiter should be higher in the electron drift side, toward the end of the discharge period. The temperature distribution measured by the CCD camera with an infrared filter at the time of the maximum local temperature is shown in Fig. 6. A complete two-dimensional distribution of the surface temperature showed a strong asymmetry in the poloidal as well as the toroidal directions. A movement of the high temperature spot similar to the one observed on a C limiter surface was observed [9]. The switch of the heat load from one side to the other was observed for most of the shots with high heat load with the limiter location more than 1 cm deeper than the LCFS. The pattern of rotation in the plasma may be the reason for the observed different heat flux distribution from one limiter location to the next. As shown in Fig. 6, some part of the limiter had been heated up to a temperature in excess of 3000°C. At this temperature, the current density of the electron emission from the surface should be more than 10 A/cm^2, which may alter the potential difference between the limiter and the plasma. This can change the direction of the plasma drift and the distribution of the heat flux onto the limiter.

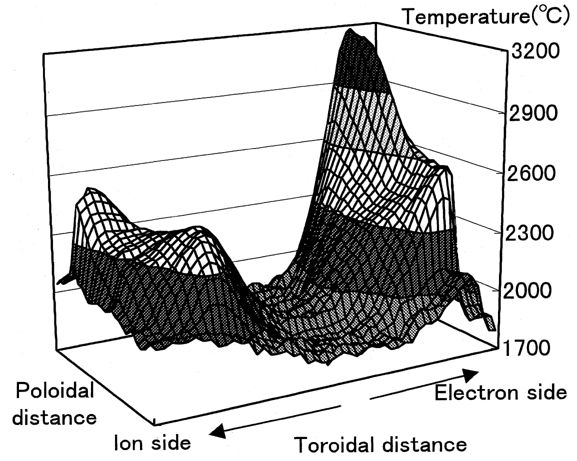

Fig. 6. A two-dimensional plot of the surface temperature toward the end of the discharge period for a high-heat-flux experiment. The limiter is positioned at 43.5 cm minor radius, or 2.5 cm deeper than the LCFS.

4.3. Impurity release from the high-temperature limiter

The release rate of impurities from the heated W test limiter was investigated by spectroscopically measuring the flux. When the limiter was heated, an increase in the OII intensity was observed. In the result shown in Fig. 7, it can be seen that the O flux normalized to Dγ flux increased by a factor of 3.5 as the temperature of the limiter exceeded 2000°C. A similar trend for the O flux

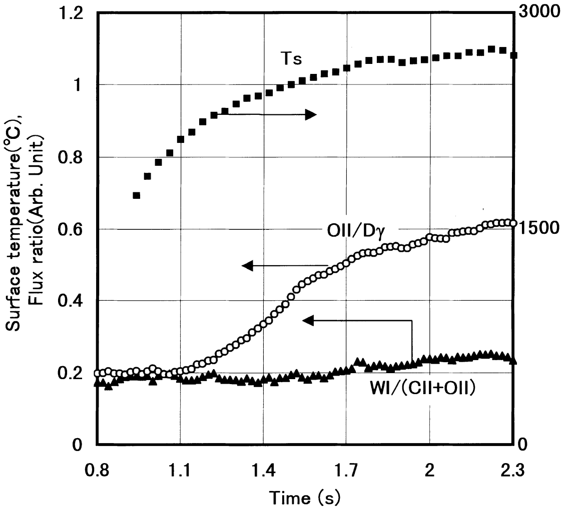

Fig. 7. Neutral W flux normalized to the total flux of CII and OII, the OII flux normalized to the Dγ flux, and the surface temperature of the ion drift side during the quasi-steady-state of the neutral beam heated discharge. Evaluations of WI, CII and OII are made spectroscopically at the ion drift side of the limiter.

was observed at the diagnostics installed at the poloidal limiter, and the ALT-II limiter, but they were not as pronounced as was observed at the test limiter surface. Therefore, O were probably released from the heated part of the test limiter. Fig. 7 shows the W flux normalized to the total flux of O and C. It shows that the normalized W flux had increased toward the end of the discharge period, but did not increase by more than 20%. The release of W can be enhanced if there is a mechanism like the evaporation or chemical sputtering of oxidized tungsten due to an increase in the surface temperature. The results shown in Fig. 7 indicate that the release of W from the limiter surface is governed by the physical sputtering due to the C and O ions.

5. Conclusions

The performance of the pure W limiter immersed in the TEXTOR-94 edge plasma was investigated. When the heat load to the limiter is not high, the surface temperature distribution can be well simulated with a simple heat transfer model. Even at the highest temperature of 3000 K, the local release of W was shown to be governed by the physical sputtering of C and O ions and no sign of the enhanced chemical sputtering of W was observed. Thus, the performance of tungsten as the PFM can be predicted from simple models based on a normal heat transfer and physical sputtering. The limiter did not show any signs of damage in response to a maximum heat flux density exceeding 40 MW/m^2. At the highest heat flux density, the distribution of the surface temperature on the limiter changes in a complicated way. Investigations of local electric field, plasma flow, as well as the impact of W material onto the plasma–wall interaction are necessary to clarify the changes in heat flux distribution onto the limiter at the high-heat-flux density.

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