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Evaporation and vapor shielding of CFC targets exposed to plasma heat fluxes relevant to ITER ELMs

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ABSTRACT

Carbon fibre composite NB31 was tested at plasma gun facility MK-200UG by plasma heat fluxes relevant to Edge Localised Modes in ITER. The paper reports the results obtained on the evaporation threshold of carbon fibre composite, the velocity of carbon vapor motion along and across the magnetic field lines, and the parameters of carbon plasma such as temperature, density and ionization state. First experimental results on investigation of the vapor shield onset conditions are presented also. The obtained experimental data are compared with the results of numerical modeling.

1. Introduction

Some key issues remain in the ITER design associated with the response of the divertor armour materials to thermal energy deposited during Type I Edge Localised Modes (ELMs). They include the erosion effects in the armour materials, the resultant production and transport of impurities in tokamak plasma during and after the ELM, and the potential for plasma contamination during the inter-ELM phase. These effects are not fully understood and require further experimental and theoretical studies.

During Type I ELMs the divertor targets in ITER will be exposed to the plasma heat loads of $q = 0.5–4\ \mathrm{MJ/m^2}$ in timescales of $t = 0.1-1$ ms [1,2]. The expected heat fluxes are not achievable in the existing tokamak-machines. Therefore the divertor armour materials are tested by use of other devices such as powerful plasma guns [3–5] and e-beam facilities [6], which are capable to simulate, at least in part, the loading conditions of interest. Experimental results are used for development and validation of numerical models simulating behavior of the armour materials during the transient tokamak processes [7–9].

Carbon fibre composite (CFC) and tungsten are foreseen as candidate armour materials for ITER divertor target. The present work refers to investigation of CFC armour. CFC NB31 was tested at plasma gun facility MK-200UG by plasma heat fluxes relevant to the ITER Type I ELMs. A threshold of CFC evaporation has been experimentally determined, i.e., there was measured a minimum plasma heat flux causing CFC evaporation. The measured threshold has been analyzed numerically for evaluation of CFC thermal conductivity. Properties of the evaporated carbon such as temperature, density and ionization state have been studied. There were investigated also conditions when the evaporated carbon acts as a thermal shield protecting the target from the incoming energy flux.

2. Experimental techniques

MK-200UG facility consists of a pulsed plasma gun, long drift tube and target chamber (Fig. 1). In the present experiment the plasma gun was fed from 1152 μF capacitor bank at operating voltage 13 kV.

The plasma gun injects a hydrogen plasma stream into the drift tube, consisting of 6.5 m cylindrical part and conical one with a length of 3 m. Diameter of the cylindrical tube is 30 cm. At the conical section, the tube diameter reduces towards its exit from 30 cm to 15 cm. The cylindrical tube is filled with a 0.7 T longitudinal magnetic field. The magnetic field rises from 0.7 T up to 2.5 T along the conical part. The plasma stream is magnetized in the magnetic cone.

The CFC targets are tested by varying plasma load. The plasma load changes by variation of magnetic field in the target chamber. The load varies due to plasma density changing while the plasma stream velocity, impact ion energy and plasma pulse duration remain unaltered. Plasma stream parameters are listed in Table 1.

MK-200UG reproduces well such parameters of ITER ELMs as the impact ion energy, plasma density, pressure, and energy flux coming onto the divertor target. Being equipped by a strong magnetic field $B = 2-3$ T the facility is suitable for experimental simulation of impurity production and their transport during ELMs.

Carbon fibre composite NB31 has been tested. The targets have a flat rectangular shape with a face surface 25 × 25 mm and thickness 10 mm. The targets are equipped by thermocouples for the measurement of absorbed energy.

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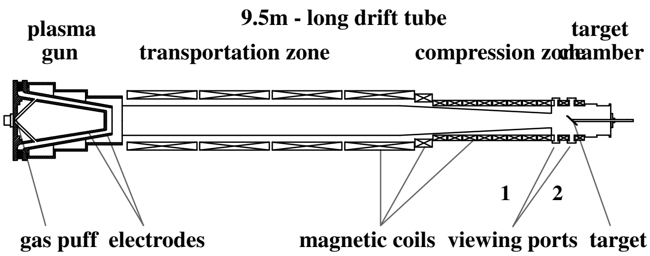

Fig. 1. Basic scheme of MK-200UG facility.

Temperature of the exposed target surface is measured by infrared pyrometer with time resolution 100 ns. Visible (4000–7000 A) and EUV (10–400 A) spectrometers with time resolution about 1 μs and space resolution of 1 mm are applied for analysis of the evaporated carbon.

3. Experimental results and discussion

For investigation of evaporation threshold the CFC target was tested by plasma shots with increasing heat load. Visible spectroscopy was applied for detection of carbon vapor appearance near the target. Infrared pyrometer was used for online measurement of the target surface temperature $T_s(t)$.

The measurements have shown that the evaporation is absent at the plasma load $q = 0.1$ MJ/m^2 ($T_s \leqslant 2200$ K); weak evaporation takes place at $q = 0.15$ MJ/m^2 ($T_s \approx 3000$ K); intense evaporation starts at $q = 0.2$ MJ/m^2 ($T_s \approx 4000$ K). The surface temperature grows with the plasma load, it runs up to a peak value of $T_s \approx 4000$ K at $q = 0.2$ MJ/m^2 and remains unaltered with further increase of the plasma load. It indicates that the load $q = 0.2$ MJ/m^2 corresponds to a threshold of intense carbon evaporation when the CFC surface heats up to a sublimation point. Fig. 2 presents the temperature $T_s(t)$ evaluated from the surface radiation measured by infrared pyrometer at $q = 0.24$ MJ/m^2. As the CFC emissivity is not known exactly there are uncertainties in the measured temperature.

The evaporated carbon is ionized quickly and carbon plasma arises. Spectrum of carbon plasma consists of spectral lines of C^{+1}–C^{+5} ions, continuous spectrum is observed near the target surface at distances below 1 mm. Electron density n_e of carbon plasma was evaluated from Stark broadening of spectral line CIV (4658.3 A°).

Density of carbon plasma increases with the plasma load q (Fig. 3). At first, the density rises steeply: small variation of q from 0.17 to 0.20 MJ/m^2 results in increase of n_e by a factor of 10. At $q > 0.20$ MJ/m^2 the density grows slightly and keeps at a level of $n_e = 2 \times 10^{23}$ m^{-3}. These measurements confirm also that a threshold of intense CFC evaporation is about $q = 0.2$ MJ/m^2.

At $q = 0.15$ MJ/m^2 the density of carbon plasma was too small to be measured by the applied diagnostics (Fig. 3). But after the target was exposed to 200 plasma shots the density increased to the measurable magnitude $n_e = 3$–4×10^{21} m^{-3} at the same plasma load.

Table 1
ELM simulation condition at MK-200UG.

Energy density	$q = 0.05$–1 MJ/m^2
Power density	$w = 1$–20 GW/m^2
Pulse duration	$\tau = 0.05$ ms
Impact ion energy	$E_i = 2$–3 keV
Plasma density	$n = (0.1$–$2) \times 10^{20}$ m^{-3}
Plasma pressure	$P = 0.03$–0.5 bar
Stream diameter	$D = 0.06$–0.1 m

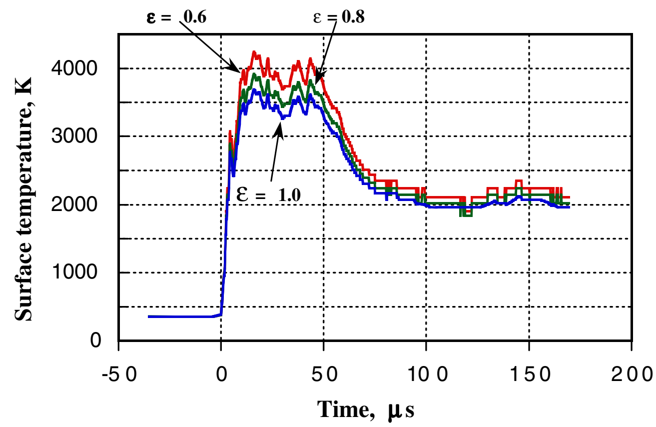

Fig. 2. Surface temperature of CFC target evaluated for surface emissivity $\varepsilon = 1$, 0.8, 0.6. Plasma heat load 0.24 MJ/m^2.

Properties of CFC seem to be degraded during multiple plasma exposures that lead to intensification of vaporization.

Numerical simulation for NB31 surface temperature evolution under the plasma exposure has been done using PEGASUS-3D code [8]. Temperature dependence for NB31 thermal conductivity at $T = 2500$–4000 K was taken from analytical extrapolation of the thermoconductivity measured at $T \leqslant 2500$ K [10]. The performed simulation reveals that the reference thermal conductivity λ_{ref} is incompatible with the measured temperature (Fig. 4). According to numerical modeling an intense evaporation of NB31 with λ_{ref} should start at $q = 0.3$ MJ/m^2 while in the experiment it happens at $q = 0.2$ MJ/m^2. It was assumed that a real thermal conductivity differs from the reference one because of degradation of CFC properties during plasma irradiation. Most probable reason for this degradation is brittle CFC destruction caused by multiple thermal shocks [8]. It was found that the best fit for the experimental results corresponds to the reduction of λ_{ref} by a factor about 3. Time dependence of the surface temperature simulated using $\lambda(T) = 0.35\lambda_{ref}(T)$ is shown in Fig. 4.

Parameters of the evaporated carbon have been studied by spectroscopy. It was measured that carbon vapor emits mainly in the visible spectral range at plasma load $q < 0.2$ MJ/m^2. EUV spectral lines CV (40.3A) and CVI (33.7A) appear at $q = 0.2$ MJ/m^2 and $q = 0.3$ MJ/m^2 correspondingly. Analysis of the obtained spectral

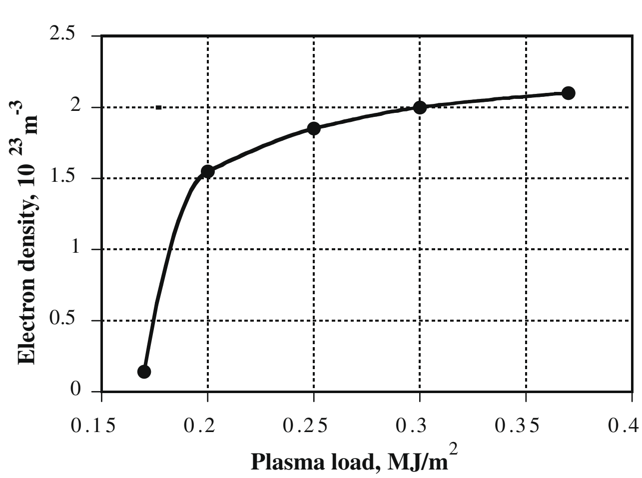

Fig. 3. Electron density of carbon vapor plasma vs plasma load. (0.5 cm distance from target surface, 10–15 μs after start of plasma/target interaction).

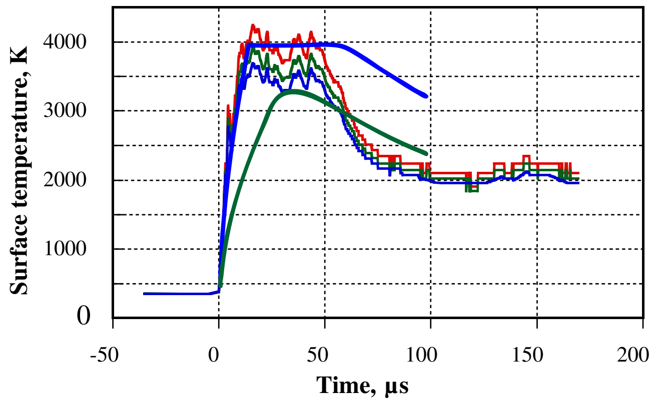

Fig. 4. Comparison of numerical and experimental results. Lower simulated curve – reference thermal conductivity λ_{ref}, Upper curve – thermal conductivity $\lambda(T) = 0.35\lambda_{ref}(T)$.

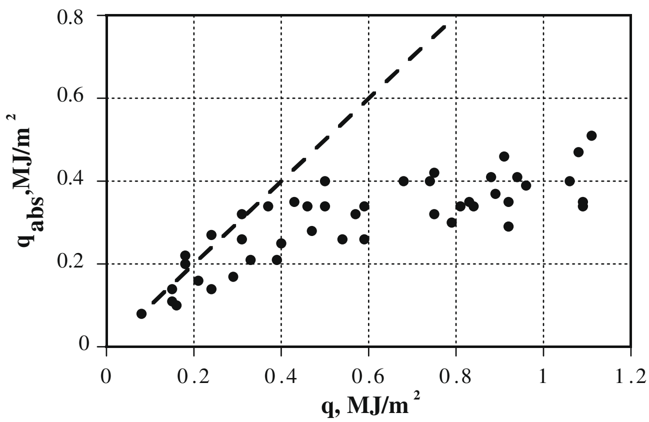

Fig. 6. Energy absorbed by CFC target at varying plasma load.

data gives a temperature of carbon plasma about $T = 10$ eV for $q = 0.2$ MJ/m^2 and $T = 30$ eV for $q = 0.3$ MJ/m^2.

Fig. 5 shows a space distribution of electron density in front of the target. Carbon target plasma consists of a dense near-surface plasma ($n_e = 2 \times 10^{23}$ m^{-3}) and carbon plasma corona ($n_e = 1$–2×10^{22} m^{-3}), which expands from the target surface with a velocity $V = 1$–2×10^4 m/s. Carbon corona moves along the magnetic field lines, transverse motion is inhibited. Taking into account that the plasma corona consists mainly of C^{+3} ions we can conclude that a density of carbon ions is $n_c > 10^{21}$ m^{-3} that is larger than a density of tokamak plasma. It means that during ELMs large amount of carbon impurities might move from the divertor to main chamber causing contamination of tokamak plasma.

The evaporated material forms a cloud of dense carbon plasma, which may act as a thermal shield protecting the target from a direct action of hot plasma. Carbon plasma shield absorbs the incoming energy and dissipates it partly into outgoing photon radiation thereby reducing the surface heat load. Onset condition of the vapor shield has been studied.

Flat carbon target of 2 cm diameter and calorimeter (cylindrical copper cup of 2 cm diameter and 7 cm length) were exposed to identical plasma loads. The calorimeter was applied for the measurement of plasma stream energy q and the flat target equipped by thermocouple – for the measurement of energy q_{abs} delivered through the evaporated carbon to the exposed surface and consumed then for target heating (energy spent for evaporation $q_{ev} << q_{abs}$). The obtained results are presented in Fig. 6. The measured q_{abs} is practically always less than the incoming plasma energy q but at the plasma load $q < 0.2$ MJ/m^2 when the intense evaporation does not occur this difference is small and it might be explained by inaccuracy of the measurement. The difference between q_{abs} and q becomes absolutely evident at $q = 0.4$ MJ/m^2. This point corresponds to a threshold of strong vapor shielding.

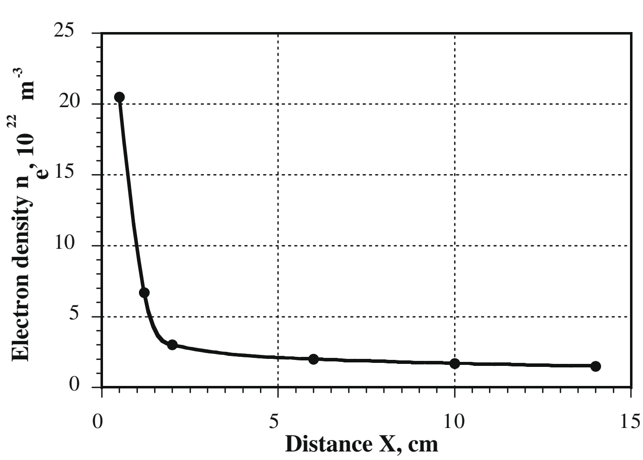

Fig. 5. Space distribution of electron density in front of CFC target ($q = 0.3$ MJ/m^2, $t = 13$ µs).

4. Summary

CFC NB31 was tested by plasma heat fluxes relevant to ITER ELMs. The CFC targets were exposed to hot magnetized plasma streams at heat loads $q = 0.05$–1 MJ/m^2 and pulse duration 0.05 ms. CFC evaporation and properties of the evaporated carbon have been studied experimentally and analyzed numerically.

According to the measurements, intense evaporation of CFC starts at $q = 0.2$ MJ/m^2 and surface temperature $T_s \approx 4000$ K. At $q = 0.2$–03 MJ/m^2 the evaporated carbon has a temperature 10–30 eV and consists of C^{+1}–C^{+5} ions. Density of carbon plasma is maximal near the target surface – $n = 2 \times 10^{23}$ m^{-3}. Carbon plasma with ion density $n_c > 10^{21}$ m^{-3} moves from the target along the magnetic field lines with a velocity 1–2 $\times 10^4$ m/s. Due to a high density of carbon plasma a significant impurity contamination of the edge tokamak plasma can occur in ITER during ELMs.

Numerical simulation of CFC evaporation and evolution of CFC surface temperature has revealed that the measurements are definitely incompatible with the reference thermoconductivity of NB31. The measurements are fit with the simulations if the real thermoconductivity is three times lower than the reference value. Degradation of the thermoconductivity could be caused by brittle CFC destruction during multiple plasma exposures. The effect of thermal conductivity degradation is important for the ITER divertor operation and needs further investigation.

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