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ABSTRACT
Power flux deposition during ELMs and disruptions need to be controlled in ITER to avoid damage to the Plasma Facing Components (PFC). In the present tokamaks, the power and energy deposited on the tile during ELMs is calculated from the surface temperature measurements which are affected by the presence of deposited layers. Thermal behaviour of deposited layer under high heat load exposure has been investigated and thermal properties of the layer have been determined from experimental data and modelling results obtained with CAST3M code.

1. INTRODUCTION

Heat load deposition during transient events such as ELMs and disruptions is a critical issue for ITER. In the present ITER design, very different materials such as Tungsten, Carbon and Beryllium are used as Plasma Facing Components (PFC) and distributed at different location depending on the plasma wall interaction and in particular on the heat load deposition expected during ELMs. Thus, power and energy flux impinging on the PFC during ELMs and disruptions need to be measured in tokamaks in order to validate the ITER material choice. In today's tokamaks, power flux is usually deduced from surface temperature obtained from infrared camera measurements and energy is deduced from temperature measured by means of thermocouples inserted in the bulk of the PFC. Unfortunately, due to the long time constant ($\tau = l^2/D$, where l is the distance between the thermocouple location and the surface of the tile and D the thermal diffusivity of the material), transient events such as ELMs with a duration in the range of 100-400 μs in JET, cannot be timely resolved and energy impinging on the divertor cannot be measured with thermocouples for an individual ELM. Moreover, due to carbon layer deposition on the tile occurring during plasma operation, the surface temperatures are higher than expected on initial material. Additionally, the carbon layers are not homogenously distributed on the tiles and these effects induce large uncertainties on the power flux calculated from the surface temperature evolution. In order to characterize the thermal behaviour of the PFC with carbon layers, experiments under high heat load have been conducted on divertor MkIIa tiles using the JET Neutral Beam Test Bed Facility. In the following sections, we describe the experimental set-up and the numerical model used for comparison to experimental data. The results at low and high power flux exposures are presented and discussed.

2. EXPERIMENTAL SET-UP

Carbon Fibre Composite (CFC) tiles covered with deposited layers have been placed at the centre line of the JET Neutral beam Test Bed in the Beryllium Rig at a distance of 4.3 meters from the beam source. Experiments have been conducted on inner (tile 4) and a outer tile (tile 7) of the MKIIa divertor. These tiles have been exposed to JET plasma during the 1995 and 1996 campaigns. Surface analysis of divertor tiles in the MKII-GB divertor indicated that the thickness of the deposited layer can be up to 90 μm [1]. Due to beryllium evaporation performed in JET, these tiles were beryllium contaminated and showed in some case a large Be content, with a Be/C ratio of one [2]. Both tiles were exposed to particles beams with peak power density ranging between $5MW/m^2$ and

100MW/m^2 with pulse duration between 10 milliseconds and 2 seconds. The power density distribution is usually measured by an in situ inertial calorimeter. Unfortunately, due to technical problems, power density distribution could not be measured and has been obtained from simulation of the neutral beam parameters and from data obtained in similar conditions on the test bed. Deuterium and Helium beam have been used for comparison. Since no difference was noticeable between both gases, we will not discuss furthermore this point.

The CFC bulk temperature is measured by means of 12 thermocouples inserted at different depth from 5 to 20 mm from the surface, in order to evaluate the thermal diffusivity and the total energy deposited in the tile. Surface temperature is measured by using an infrared camera with a time resolution of 20ms. CCD camera is also used for visible observation.

3. NUMERICAL MODEL

A detailed 3-D model with true geometry of the tiles, taking into account the inconel dumbbell, was developed using the CAST3M code (finite element code developed at CEA [3]) to calculate the surface and in-depth temperature distribution. Thermal properties of the CFC have been measured on samples taken on MKIIa batches [4]. Parallel (to the CFC weave direction) and perpendicular thermal conductivity and specific heat capacity are temperature dependent and are taken from reference [5]. A deposited layer, with a thickness of 40µm, has been implemented in the model. The adjustable parameters are the thermal conductivity of the layer (assumed to be isotropic) and the heat exchange coefficient between the layer and the bulk material. The initial temperature is assumed to be uniform (this is confirmed with the different thermocouples) and is adjusted to the real initial temperature of the target before the pulse. The power flux is applied on the upper tile surface with a time dependence. Radiative conditions towards environment at 20°C are considered for all the surfaces of the tile. Two heat load conditions have been applied in the simulations:

- a low power density case with a 5MW/m^2 flux density during 2s on and 2s off for 3 cycles
- a high power density case with a 50MW/m^2 flux density during 17ms on and 43ms off for 10 cycles

The Fig 1. shows a schematic view of the model and the time dependence of the flux for the low power case.

RESULTS AND DISCUSSION

First experiments have been conducted at a peak power flux of 5 MW/m^2 during 3 cycles of 2s. Preliminary simulations using bulk material properties without layer indicated an increase of the surface temperature in the range of 350°C per cycle with a maximum temperature of 900°C reached at the end of the third pulse. The thermagram (infrared image) acquired during the beam exposure is shown on Fig.2(a) and exhibits a complete different behaviour than expected with a quasi-uniform power flux deposition [6]. Two parallel vertical lines along the direction of the tile (which corresponds also to the toroidal magnetic field direction when the tile was in the tokamak) can be observed and present much higher temperature than the rest of the tile. This image has been obtained 40ms (+0/-20ms) after the beginning of the heat pulse; at this time, the increase of temperature δT on a bulk CFC material should be less than 40°C while δT ranging between 170°C and 460°C are measured on the different points of the tile. This behaviour is typical of what is observed on the JET divertor during the power step discharges [7]. On this image, there are also a horizontal stripe across the image and a less distinct stripe near the bottom edge. These stripes correspond to the area where tape tests were performed during the surface analysis campaign [8]. Several tape tests have been done across the tile and every time the tape came off with black band of carbon dust. The stripe in the middle has had probably tens of microns of carbon layer removed but no absolute measurement was done.

When the beam are switched off, the surface temperature steps down also very rapidly with the same time constant (< 40 ms) and then the surface temperature reflects the footprint of the neutral beam power flux distribution, as shown on Fig.2(b).

Modelling the temperature evolution of the tile without additional layer and changing only the thermal properties of the CFC (ρ, λ, Cp) cannot reproduce neither the thermocouples nor the surface temperature measurements. A contrario, using the thermal properties from the reference [5], modelling data fit well the thermocouples measurements, as shown or Fig.3(a) confirming the value of the thermal properties measured on the samples. It should be noted that in many cases in our experiments several thermocouples did not respond correctly due to a bad thermal contact with the tile. Even though the time evolution could not be used in such a case, the temperature equilibrium, achieved about 30 seconds after the pulse, was measurable and allowed to calculate the total energy deposited on the tile. The surface temperatures evolution measured at different locations on the tile are plotted on Fig.3(b). Simulations have been performed with an additional carbon layer of 40 μm with density and specific heat similar to the bulk values. The thermal conductivity was set at 10% of the CFC and the heat exchange coefficient was varied between 5 and 50 $kW/m^2.K$. The Fig.3(c) shows the surface temperature evolution calculated with CAST3M for a heat exchange coefficient of 20 and 50$kW/m^2.K$ and, for comparison, without additional layer. The curves reproduce very well both the amplitude and the time constant of the experimental temperatures. Nevertheless, it should be pointed out that the inverse problem of the heat conduction is a problem including more variables than measurables and therefore a unique solution cannot be found [9]. In particular, it not possible to determine from such experiments all the relevant parameters which are: thickness, density, thermal conductivity, heat capacity of the layer and heat exchange coefficient between the bulk and the layer. For instance, the offset of the surface temperature compared with the bulk material can be attributed to a combination of two conductances :

$$1/h_{eq} = 1/h + 1/h_1 \quad (1)$$

where h is the heat exchange between the layer and the bulk and h_1 is the heat exchange in the layer itself, defined by :

$$h_1 = \lambda/e \quad (2)$$

where e is the thickness and ª is the thermal conductivity of the layer. From the analysis of the simulated and experimental data, we can deduce that the equivalent heat exchange coefficient h_{eq}

on different points is between 15 and 50 $kW/m^2.K$ m. Other set of parameters for λ, ρ, e, Cp and h can produce the same value of h_{eq} and this does not imply that the layer is really 40μm thick. Additionally to the offset, the rising time of the surface temperature gives also an information on the thermal properties of the layer. When the power flux is applied, the temperature in the layer is governed by:

$$e\rho\, Cp \frac{\partial T}{\partial t} = \varphi - hT \tag{3}$$

and the time constant of the temperature increase in the layer is, τ:

$$\tau = \frac{e\rho\, Cp}{h} \tag{4}$$

Using the parameters introduced in the code, we obtained =2.6ms, in agreement with the experimental observations. Higher time resolution would be suitable to measure precisely the time constant and consequently gives a relationship between ρ, e and h (assuming Cp is known).

Experiments with high heat load exposure at $50MW/m^2$ during 10ms for 10 cycles have also been performed in similar conditions. Due to the short length and the frequency of the pulses (18Hz), the thermocouples could not resolve in time the individual heat load. Nevertheless, the equilibrium temperature achieved about 20s after the end of the power flux exposure, gives accurate measurement of the energy deposited on the tile. Simulations (with the same parameters as the low power case) show a very good agreement with the thermocouples data, as can be seen on Fig.4(a). The Fig.4(b) shows the surface temperature evolution at different location on the surface. The power flux duration being smaller than the acquisition rate of the IR camera, only one measurement could be acquired per pulse. On the deposited layer, the temperature reaches more than 2000°C at the first pulse and ~2300°C at the tenth pulse while it varies only from 800°C to 1200°C at other locations on the tile. Simulated surface temperature evolutions of bulk material and with additional layer are shown on Fig.4(c). Both simulated curves, bulk and layer with heat exchange coefficient of $50kW/m^2.K$, fitted very well the experimental results.

Additionally, several identical shots have been reproduced and it was noticeable that the maximum temperature decreased slightly with the shot number. The Fig.5 shows the difference in the temperature achieved at the end of two similar shots, performed at few days of interval. The map of the temperature variation corresponds to the deposited layer area. This evolution of the surface temperature, up to 500°C, is due to the modifications of the surface layer properties. Erosion can be excluded, due to the high energy of the incoming particles (130keV) and sublimation of carbon at 2300°C, during a very limited time (~10s), could not explain a so large effect. Therefore, this evolution of the surface temperature is likely due to annealing of the layer at high temperature, inducing structural modification (graphitisation) and increase of the thermal properties of the deposited layer. This evolution of the properties of the deposited layer during time adds further complexity to the system and will induce additional uncertainties in the determination of the power flux from the surface temperature evolution.

CONCLUSION

Thermal behaviour of the deposited layer under power flux exposure has been characterized by using the JET Neutral beam test bed. Surface and thermocouples temperature have been successfully modelled using CAST3M code, with an additional layer with low thermal conductivity and a heat exchange coefficient between the bulk and the layer. The deposited layer is non uniform and a unique heat exchange coefficient cannot reproduce the 2D surface temperature. Comparison of modelling results and experimental data allows determining the heat exchange coefficient and values between 15 and 50 $kW/m^2.K$ have been found. The thickness of the layer can also be estimated but require surface temperature measurements with time resolution lower than 1ms. Modifications of the thermal properties of the layer occur when the temperature exceed 2000°C. In such conditions, the power flux calculated from the surface temperature measurements can only be determined with large uncertainties.

REFERENCES

[1]. J.P. Coad et al, J. Nucl Mat., **313-316** (2003) 419-423
[2]. M. Rubel et al, J. Nucl. Mat., **313-316** (2003) 321-326
[3]. CAST3M, see http\\www-cast3m.cea.fr
[4]. H. Altmann et al, Proc. Of the 16th SOFE, (1995)
[5]. V. Riccardo et al, PPCF, (2001)
[6]. J. Matheus, E. Gauthier, M. Missirlian, note CEA CFP/NTT-2002-027 (2002)
[7]. Y. Corre et al, 30th EPS Conference, St Petersburg, 2003
[8]. J.P. Coad, private communication, (2003)
[9]. C. Martinsons, M. Heuret, High temp.-High pressures, (1999), vol **31**, 99-104

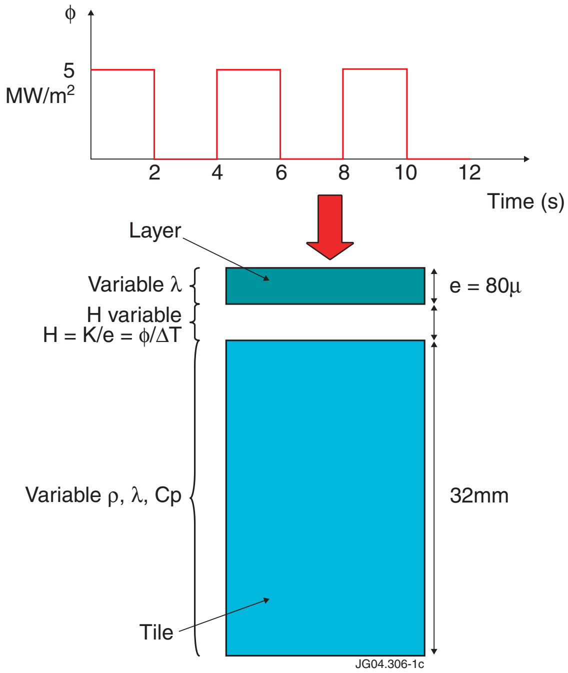

Figure 1: Schematic view of the model and of the power flux.

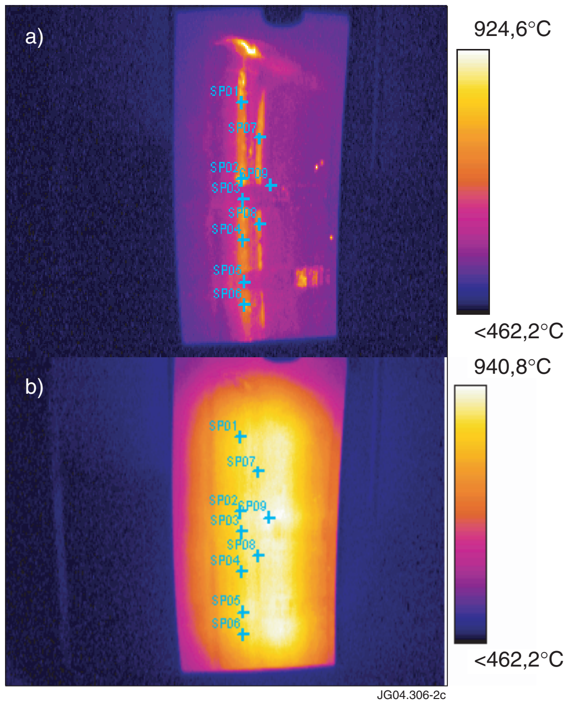

Figure 2: Surface temperature during (a) and after (b) power flux exposure.

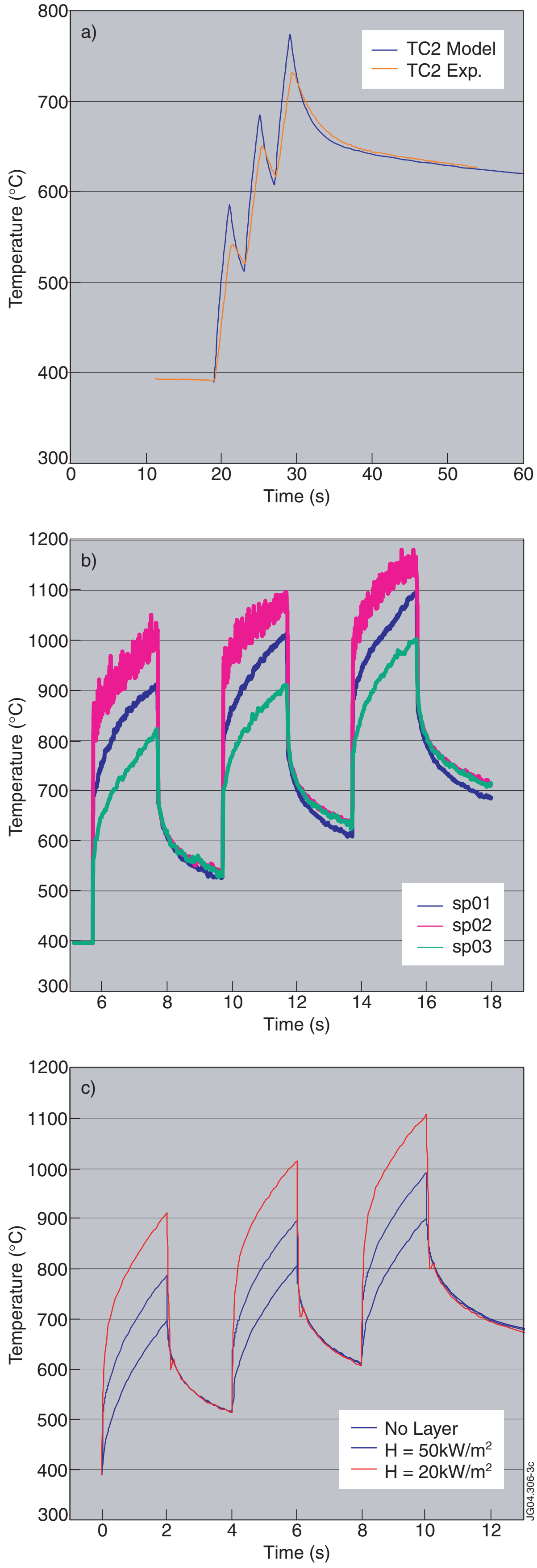

Figure 3: Experimental (b) and modelled (c) temperature evolutions at surface and thermocouple (a) location with φ = 5MW/m² flux exposure (2s on /2s off; 3cycles).

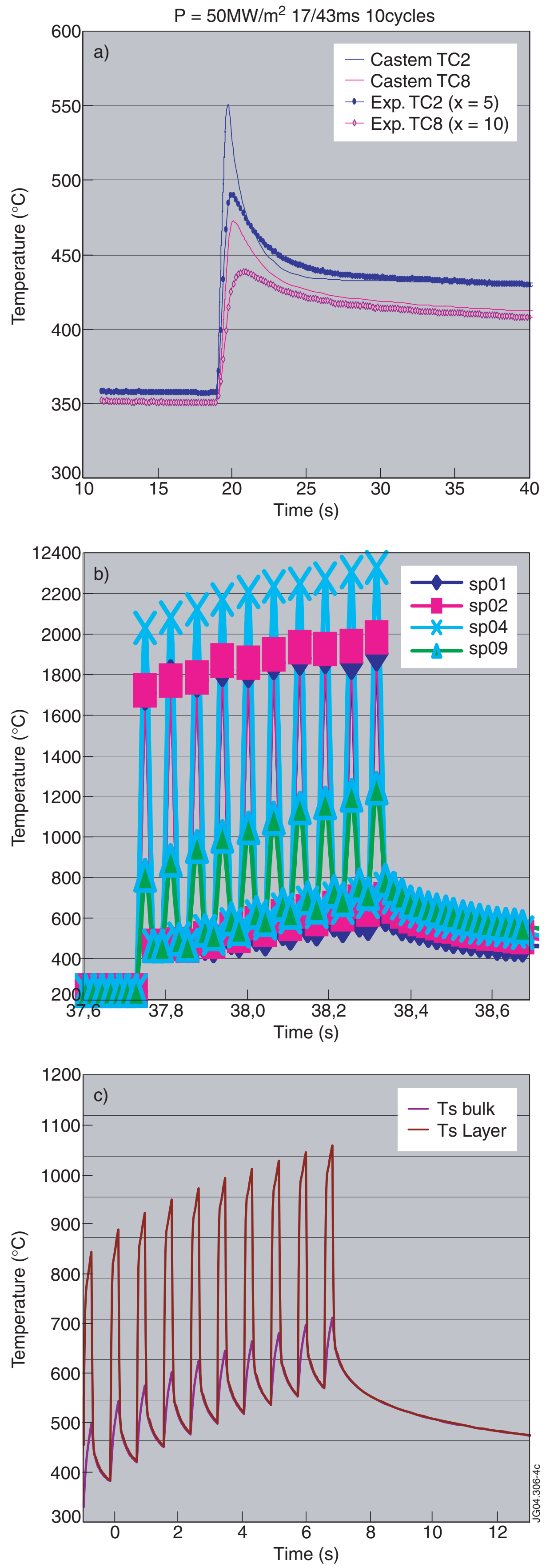

Figure 4: Experimental (b) and modelled (c) temperature evolutions at surface and thermocouple location with φ = 50MW/m² flux exposure (17ms on /43ms off; 10cycles).

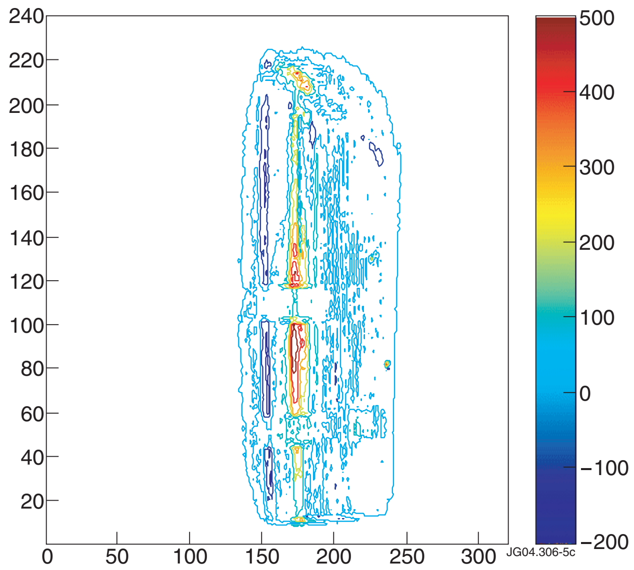

Figure 5: Surface temperature variation for two similar shots, induced by modifications of the thermal properties of the surface layer.