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Determination of a thermal property of carbon layers from IR measurements in JET NBI test bed using optimisation methods

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ABSTRACT

An optimisation algorithm is used to realize an automated determination of a carbon layer thermal property from IR temperature measurements. This algorithm is based on a 1D linear thermal model of the plasma facing component. It is tested on measurements from two MkIIa JET divertor tiles placed in the NBI JET test bed. Heat fluxes of 5–100 MW/m^2 were applied on those tiles. The resulting surface distribution of the carbon layer is discussed, including its evolution through the experiment, and its influence on the computed surface heat loads. Heat fluxes computed from IR and thermocouple temperature measurements are compared to the previous results. First computation of heat loads during short high flux NBI pulses simulating ELMs using previously determined carbon layer properties are also presented.

1. Introduction

The computation of heat fluxes received by Plasma Facing Components (PFCs) is a key element for the development of future fusion devices. The knowledge of such fluxes is needed to ensure tokamak safety, to determine the component lifespan and to choose a correct material for PFCs in future devices of increasing power. These heat fluxes can be computed from PFC surface temperature (measured with IR thermography) and through a modelling of the PFC whose thermal properties are well known. In most tokamaks, using carbon parts, erosion, transport and re-deposition of the carbon by the plasma leads to the formation of thick carbon layer on the PFCs. Those layers have a strong influence on the PFC surface temperature, about 100 °C; therefore correct modelling is crucial for the computation of the heat fluxes. In this paper, the carbon layer is modelled through a unique parameter called equivalent thermal resistance (R_e in K m^2 W^{-1}) which will be described in the next section. The thermal properties of the layers are unknown and may vary with time and location [1]. Therefore, the R_e parameter must be determined on a regular time basis and for every pixel on which the flux computation is applied. In the following section, an algorithm which simultaneously computes this parameter and the heat load is described. This algorithm is used on experimental data acquired during a JET neutral beam test bed experiment on two MKIIa JET divertor tiles (see Section 3).

2. Thermal models and numerical algorithm

2.1. Carbon layer model

The layer is here modelled as purely resistive; the difference of temperature between the surface of the layer T_d and the surface of the PFC T_{PFC} under the layer is proportional with the received heat flux Φ: $T_d - T_{PFC} = R_e \cdot \Phi$.

R_e is linked to the carbon layer thermal properties: $R_e = R_{tc} + \frac{e_d}{\lambda_d}$ where λ_d is the thermal conductivity, e_d the thickness and R_{tc} the thermal contact resistance which represents the quality of the thermal contact between the layer and the PFC. This parameter is similar to the inverse of the heat transmission coefficient α used in the THEODOR code [1].

This model can be used only if the layer diffusive time $\tau_d = e_d^2/a_d$ (a_d being the thermal diffusivity of the layer) is smaller than any characteristic time of the heat flux. Thermal behaviour of the carbon layer under heat load shows that τ_d is less than 10^{-2} s. The algorithm is applied after 0.15s following any change of heat load.

2.2. R_e determination algorithm

Simultaneous determination of R_e and the heat flux function $\Phi(x,y,t)$ (W m^{-2}) may be done using parameter identification methods on the IR temperature measurements T_{IR}. The heat flux value at each time step and the R_e cannot be computed at once with only T_{IR}. There are N equations corresponding to N measurement time steps but $N+1$ unknown parameters with R_e. An assumption on the heat flux is needed to solve the issue. The heat

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flux function $\Phi(x,y,t)$ can be expressed as a product of a time depending function $g(t)$ and a space depending function $\Phi_{max}(x,y)$: $\Phi(x,y,t) = \Phi_{max}(x,y) \cdot g(t)$. It is assumed that $g(t)$ can be well evaluated from the temporal shape of the heating applied. In that case, only two parameters have to be determined Φ_{max} and R_e. This estimation is done with a minimization of the difference between T_{IR} and a simulated temperature T_{model} computed as a function of the parameters R_e and Φ_{max}. The minimization is realized with an ordinary least square method. T_{model} is computed using a 1D model along the depth of the tile. The tile will be considered finite in that direction (see Fig. 1). The 1D property of the model requires the applied heat flux to be sufficiently homogeneous for not considering transverse conduction. The thermal problem is considered linear, which means the thermal properties of the tiles are assumed not to be function of temperature. In linear system theory, the surface temperature can be expressed as the convolution of the surface heat flux with the impulse response (the tile response after a Dirac function of heat flux) which is computed with the method of the thermal quadrupoles [2]. The radiated flux at the surface (maximum about 50 kW m^{-2}) can be calculated from the temperature measurement and is taken into account in the model.

The minimization between T_{IR} to the T_{model} is applied during the two thermal transient regimes, either during the heating and the cooling process. In the first case, T_{model} is a function of the two parameters Φ_{max} and R_e; therefore they must be determined simultaneously using an alternate direction method on them. In the second case, T_{model} is only a function of the heat load previously applied. Φ_{max} is computed independently from R_e. The heating period is then used to compute R_e knowing Φ_{max}.

The algorithm has the advantage of automatically determining the best value of both the heat flux and the equivalent resistance. This operation is easily repeated on each pixel of an IR picture and for a great number of measurements, giving spatial determination of R_e for different shots.

2.3. Uncertainties in the algorithm

Several assumptions were made in computing T_{model}, the main ones being linearity and 1D model. Those assumptions are not fully reliable and therefore may introduce errors on the computed value of the two parameters Φ_{max} and R_e. These errors were studied through a CEA finite-element computing code, CASTEM [3], with a 3D non-linear thermal model of the tiles. Effects of uncertainty in tile model parameters and measurement noise were also taken into account to determine the error bars on the results of the algorithm. The results show that this uncertainty is highly dependent of the location considered on the tile and the computed value of R_e. However, this study showed that the uncertainty can be considered less than 10% on the heat flux, and less than 15% on R_e on 90% of the surface of the tile.

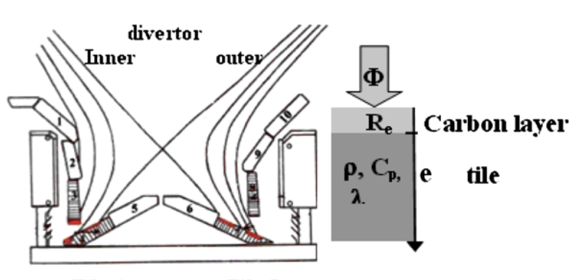

Fig. 1. Section of the JET MKIIa divertor (left) and1D thermal model of the tile (right).

3. Experimental set-up

The previous method was tested on the data collected during the FT3.1 task done at JET in 2003 [4]. During this experiment, two Carbon Fibre Composite (CFC) tiles from the JET divertor MkIIa were put on the JET neutral beam test bed. Those tiles were removed from the tokamak and therefore, have been exposed to the erosion and deposition mechanisms. One tile comes from the inner divertor (tile 4, see Fig. 1) which is considered as a predominant re-deposition zone [5], the other one comes from the outer divertor (tile 7) and more likely exposed to erosion. During the experiments, those tiles were exposed to fluxes from 5 MW/m^2 up to 100 MW/m^2, precisely controlled with the neutral beam. The spatial flux distribution of the neutral beam was configured to have a parabolic shape. The PFCs surface temperatures were measured using an IR camera (20 ms acquisition time, pixel size around 1.6 mm). 12 thermocouples (Tc) were used to measure the internal temperature at different locations and depths into the tiles (from 5 mm to 20 mm). 2 s-long exposures of the tiles to 5 MW/m^2 particle fluxes were done to simulate regular tokamak shots. Repeated 17 ms-long pulses of 50 MW/m^2 were used to simulate short transient effects such as ELMs.

4. Results and discussion

4.1. Calculated distribution of Φ_{max} and R_e

The algorithm was applied to every pixel of the IR picture taken during the experiments, creating a 2D cartography of R_e on the surface of tiles. The results clearly show a toroidal symmetry of the layer. In poloidal direction, there is high differences of many orders on R_e. For example on the tile 4, R_e varies from 10^{-6} K m^2 W^{-1}, on the outer side of the tile to $4 \cdot 10^{-4}$ K m^2 W^{-1}, on the inner side (see Fig. 2(a)). This wide range of values highlights the necessity to determine R_e for every pixel of the IR picture. A R_e value above 10^{-5} K m^2 W^{-1} clearly shows the presence of a layer which cannot be ignored for flux computation. The surface can be considered clear of a layer for R_e being lower than $7 \cdot 10^{-6}$ K m^2 W^{-1}. Such R_e does not have any influence on the surface temperature in the range of the heat loads applied here. At this scale, the algorithm cannot differentiate a clear surface from a very thin layer. R_e measured on the tile 7 (see Fig. 3) is much weaker than on tile 4. Only a 6 cm wide strip of carbon layer was observed, with a R_e value around $5 \cdot 10^{-5}$ K m^2 W^{-1}. The other part of the tile appears as clear of carbon layer ($R_e < 7 \cdot 10^{-6}$ K m^2 W^{-1}), which agree with the assumption of erosion on this tile in opposition with tile 4.

This figure also shows the computed R_e for several pulses. The comparison of the determined R_e values, for consecutive pulses, shows reproducibility of the results. The evolution of the layer during about 1 min of neutral beam heating at 5 MW/m^2 does not imply measurable changes of R_e. It should be possible to use one value of R_e during this period of time. If R_e stay within the error bars during this period, the maximum error induced on the computed heat flux is less than 10%. Between the two sets of consecutive shots, over 1000 short 17 ms pulses of 50 MW/m^2 neutral heating were applied on the tile. An important change in the R_e value is observed between the two sets corresponding to a possible transformation of the layer. This results leads to consider it may be necessary to frequently recalculate R_e during H-mode program to adapt to such variations of the layer possibly introduced by ELMs.

The Fig. 2(b) shows that the spatial profile of the computed flux is comparable to the one which has been applied to the tile with the neutral beam (maximal Flux ∼5 MW/m^2 with a parabolic profile). The temporal profile of the Fig. 2(c) is computed by deconvolution of the IR temperature with the impulse response of a 1D

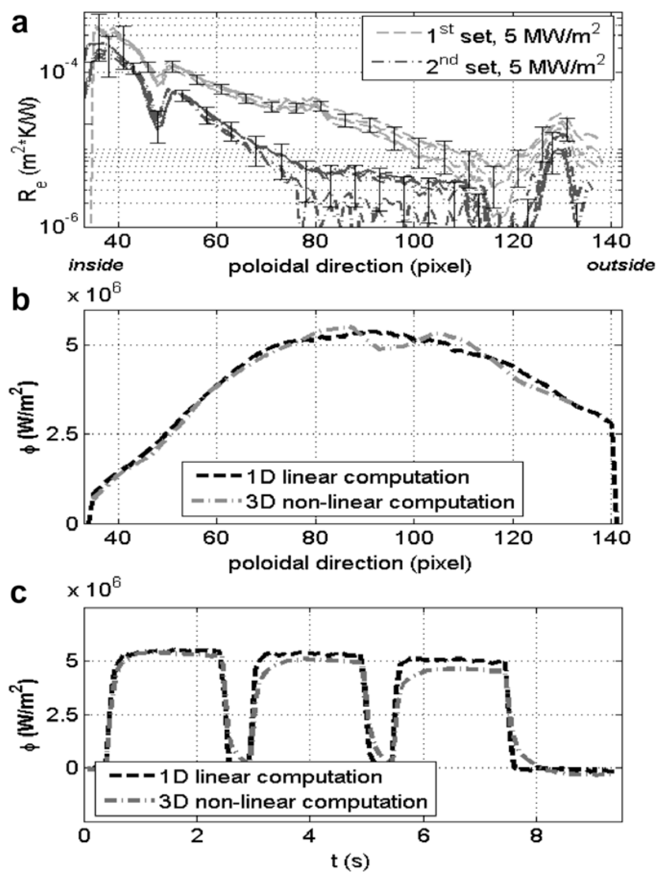

Fig. 2. (a) Determined equivalent thermal resistance values computed on the same poloidal section of the tile 4 for several consecutive 5 MW/m^2 neutral beam injection pulses (1000 $\times$ 17 ms of 50 MW/m^2 pulses between the two series). (b) Heat load computed with 1D linear model and 3D non-linear model on the same poloidal section. (c) Corresponding temporal evolution of the heat load (previously determined R_e is used).

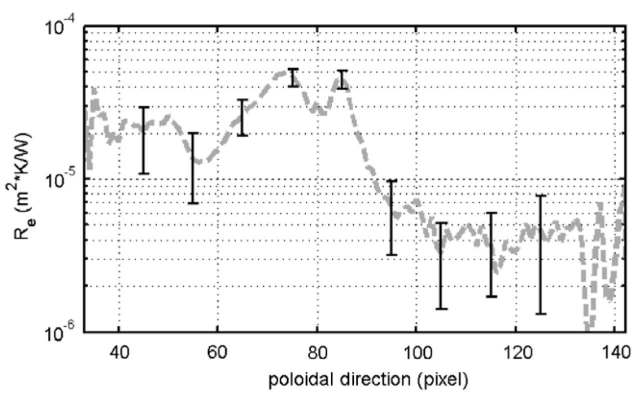

Fig. 3. Determined equivalent thermal resistance values on the tile 7.

linear model of the tile with a carbon layer. The R_e used was determined only with the temperature measurement of the first step of heat load. The results show that a R_e determined on a fraction of the measurement can be extended to the whole pulse. Consequently, during an ELMs pulse, it might be possible to determine the carbon layer property from the beginning of the pulse, during a heating period clear of ELMs, and use it to compute the heat load on the whole pulse time. The 2D R_e computed with the algorithm presented here was also used to compute the heat load with a complete 3D non-linear model of the tile under ANSYS. The comparison between the fluxes calculated with a 1D linear or a 3D non-linear method show little difference on both spatial and temporal profile (Fig. 2(b) and (c)). It means that for those experiments, the linear and 1D assumptions are sufficiently reliable. In the case of in-situ application, the method should be adapted to a 3D non-linear model due to the great variation of fluxes in the scrape off-layer in the poloidal direction.

4.2. Comparison between IR and thermocouples measurements

Heat loads are also computed by inversion of the thermocouple temperature measurements with a step response of the same 1D linear model of the tile. The impulse response is computed with the method of thermal quadrupoles [2,7]. The thermocouple response time ($\sim$0.7 ms) introduced by an imperfect contact between the soldering and the tile are taken into account. Computation of surface heat loads from inside temperature measurements is an ill-posed problem which solution is subject to instabilities. It is essential to introduce a Tikhonov regularisation [6,7] to obtain more stable heat flux estimation. The heat fluxes computed with IR and thermocouples (Fig. 4) show a good accor-

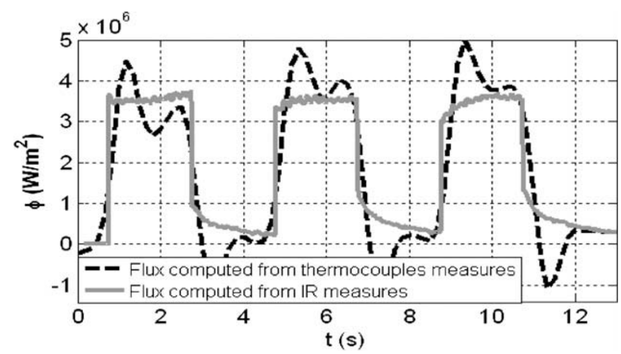

Fig. 4. Comparison of heat loads computed from the IR and thermocouples temperature measurements on tile 7.

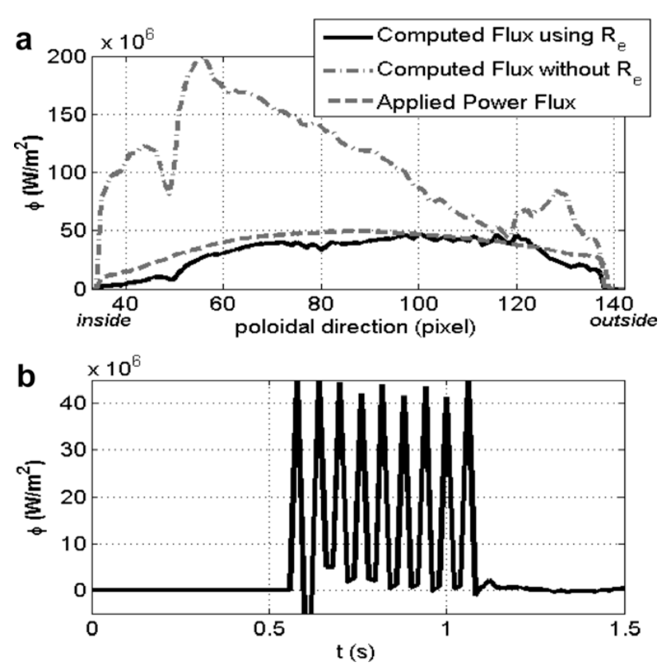

Fig. 5. 9 $\times$ 17 ms neutral beam pulses of 50 MW/m^2 (a) heat load computed on a tile 4 poloidal section. (b) Corresponding temporal evolution of the heat load (previously determined R_e is used).

dance in amplitude. Thermocouples are not influenced by surface carbon layer [8], therefore this result gives confidence in the IR-computed heat loads. The effects of numerical instabilities are visible on the graph and are responsible for the oscillations on the thermocouple solution.

4.3. High heat loads results

Simulation of PFC behaviour under ELM loads were made during experiments by applying 50 MW/m^2 fluxes on the tiles during 17 ms. The previous algorithm cannot be applied on such short pulses. In that case, heat loads were computed using a deconvolution of the temperature with the impulse response of a linear 1D model of the tile. The R_e used was computed on a 5 MW/m^2 shot, just following the 50 MW/m^2. The Fig. 5(a) shows that the flux profile is correctly determined, and in accordance with the imposed profile from the neutral beam (parabolic shape with a maximum at 50 MW/m^2). No negative flux appears on the temporal profile at the end of time, confirming the idea that the R_e used is correct for this shot (see Fig. 5(b)). The large difference between flux profiles calculated with and without R_e shows the crucial importance of this parameter and highlights the necessity to consider it heterogeneous.

5. Conclusion

The algorithm presented here is able to compute simultaneously the heat load and a value for the R_e property of the carbon layer. This parameter is determined for every pixel of the IR picture automatically and its value does not need to be assumed. The test made on the JET neutral beam test bed shows good results of this algorithm. The calculated heat loads are in good agreement with both the programmed neutral beam power and the heat loads computed from the thermocouple measurements. A correct computation of heat load was also possible during short high flux injections similar to ELMs. The determined R_e shows a great spatial variation of the property of the layer over the surface of a tile. The experiment also shows the variation of this property during time, especially when the layer is submitted to high heat loads. This algorithm should be adapted in order to be applied on measurement during plasma operation. It will be necessary to use a 3D non-linear model because of the heterogeneous distribution of heat loads on the tiles into the tokamak.

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