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R. Guigon, C. Le Niliot, M. Missirlian, X. Courtois, F. Cismondi. Innovative image processing techniques applied to the thermographic inspection of PFC with SATIR facility. *Fusion Engineering and Design*, 2009, 84 (2-6), pp.859 - 863. 10.1016/j.fusengdes.2008.11.034 . cea-04746876

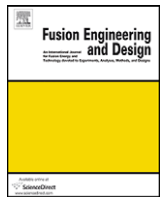
HAL Id: cea-04746876

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Submitted on 21 Oct 2024

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Innovative image processing techniques applied to the thermographic inspection of PFC with SATIR facility

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ARTICLE INFO

Article history:

Available online 8 January 2009

Keywords:

Plasma Facing Component
Spatial autocorrelation
Inverse Heat Conduction Problem
BEM
SVD

ABSTRACT

The components used in fusion devices, especially high heat flux Plasma Facing Components (PFC), have to withstand heat fluxes in the range of 10–20 MW/m². So, they require high reliability which can be only guaranteed by accurate Non Destructive Examinations (NDE). The SATIR test bed operating at Commissariat à l'Energie Atomique (CEA) Cadarache performs NDE using transient infrared thermography sequence which compares the thermal response of a tested element to a Reference element assumed to be defect free. The control parameter is called $DT_{ref\ max}$. In this paper, we present two innovative image processing techniques of the SATIR signal allowing the qualification of a component without any Reference element. The first method is based on a spatial image autocorrelation and the second on the resolution of an Inverse Heat Conduction Problem (IHCP) using a BEM (Boundary Element Method) technique. After a validation step performed on numerical data, these two methods have been applied to SATIR experimental data. The results show that these two techniques allow accurate defect detection, without using a Reference tile. They can be used in addition to the $DT_{ref\ max}$, for the qualification of plasma facing components.

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1. Introduction

The development of suitable Non Destructive Examinations (NDE) is essential for the manufacturing of reliable Plasma Facing Components (PFC) and in particular, for the inspection of the delicate armour to heat sink joint [1]. A transient infrared facility named SATIR, operating in Cadarache, was found to be well adapted to give quantitative information on the global heat transfer capability of the component. The principle consists in recording the surface temperature evolution of the component with an infrared device during the circulation of an alternate flow of hot and cold water into the cooling channels of the components [2,3]. The surface transient temperature is recorded and compared pixel to pixel to a reference sequence, the maximum of the temperature difference (so-called $DT_{ref\ max}$) is stored and the presence of a faulty behaviour is detected by a slower surface temperature response. Using this technique, the reliability of the diagnostic is dictated by the quality of the assumed defect-free Reference element. In this paper, we present two innovative image processing techniques allowing the qualification of components without using any Reference element. The first one is

based on a spatial image autocorrelation using a signal processing technique and the second one on the resolution of Inverse Heat Conduction Problems (IHCP) using a Boundary Element Method (BEM) formulation.

2. Spatial image autocorrelation: NO REF method

The spatial autocorrelation of the thermosignal SATIR, also called surface energy $E(x,y)$, is fully explained in [4].

2.1. Validation step on simulated numerical data

In a first step, this method has been applied on numerical data. We present here results on a monoblock geometry (representative of a ITER geometry), where a defect is localised by its angle θ and its extension $\Delta\theta$ (see Fig. 1). Finite Element (FE) simulations of SATIR tests were performed on monoblocks with various calibrated defect. The calculated surface temperature evolution (which stands for IR measures) was therefore processed by the NO REF method. An illustration of the surface tile defect mapping is given in Fig. 2. On this figure, we can clearly observe a high contrast in the autocorrelation energy value at the level defect, in the middle of the tile. This example shows the capability of this method to detect and localise interface defects.

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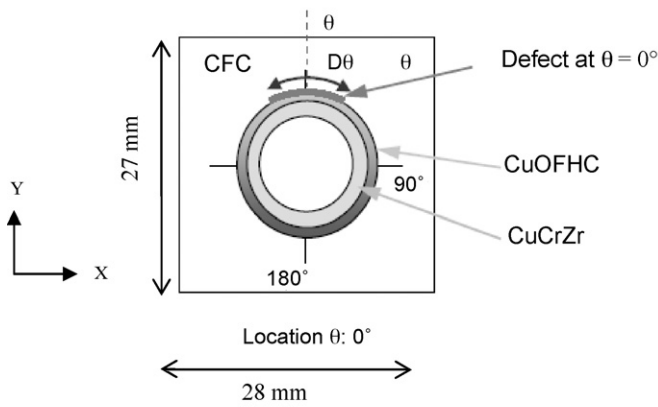


Fig. 1. Localisation of the defects on ITER monoblocks.

2.2. Application on experimental data

After the validation step performed on numerical data, the NO REF method was applied on experimental data. So, SATIR tests have been performed on several CFC ITER monoblocks with various calibrated defects. For instance, Fig. 3(a) shows the surface tile defect

mapping of a monoblock with the same defect as the one used for the illustration of the validation step: we observe the same contrast in the defect location (i.e. in the middle of the tile). The Fig. 3(b) gives the result concerning a monoblock with a non-centred defect ($\theta=45^\circ$), and the Fig. 3(c) shows the application of the NO REF technique on a component without any calibrated defects. These maps clearly prove the defect detection capability of the NO REF method on SATIR experimental data. This innovative image processing method won't replace the $DT_{ref\ max}$ criterion but can help the reliability of the decision-making during the qualification phase [5].

3. IHCP using BEM formulation for SATIR data processing

The direct problem in heat conduction consists in the resolution of the fundamental heat transfer equation in order to calculate the temperature variations in time and space. In contrast, the resolution is inverse when one of the conditions necessary to solve the direct problem is missing. In this paper we present the transient IHCP which consists in estimating unknown boundary conditions: the heat flux and the temperature at the CFC/CuOFHC interface of a PFC, the surface temperature evolution being recorded by an infrared camera. It is therefore possible to inverse these temperatures for the evaluation of heat flux and temperatures in order to estimate the

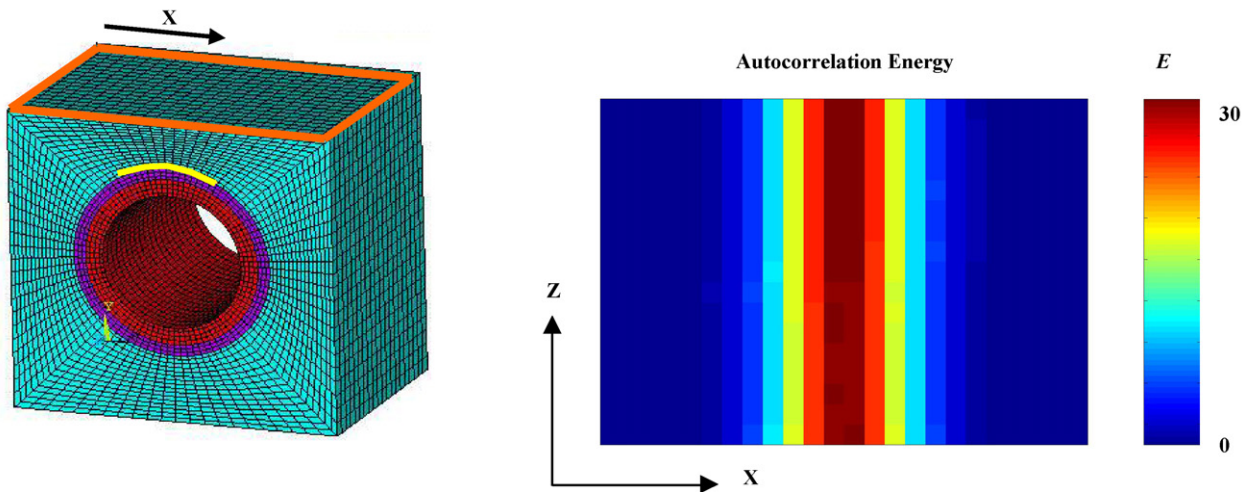


Fig. 2. Validation of the NO REF method on numerical data (ITER monoblock with a calibrated defect $\theta=0^\circ$ and $\Delta\theta=65^\circ$ at the CFC/CuOFHC interface, represented in yellow).

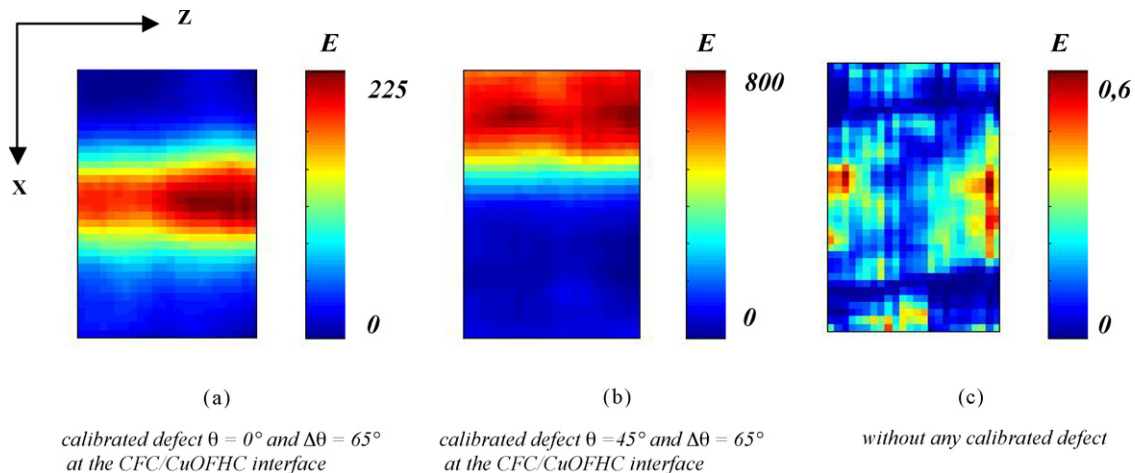


Fig. 3. Application of the NO REF method on experimental SATIR data (results given in terms of autocorrelation energy). (a) Calibrated defect $\theta=0^\circ$ and $\Delta\theta=65^\circ$ at the CFC/CuOFHC interface, (b) calibrated defect $\theta=45^\circ$ and $\Delta\theta=65^\circ$ at the CFC/CuOFHC interface, and (c) without any calibrated defect.

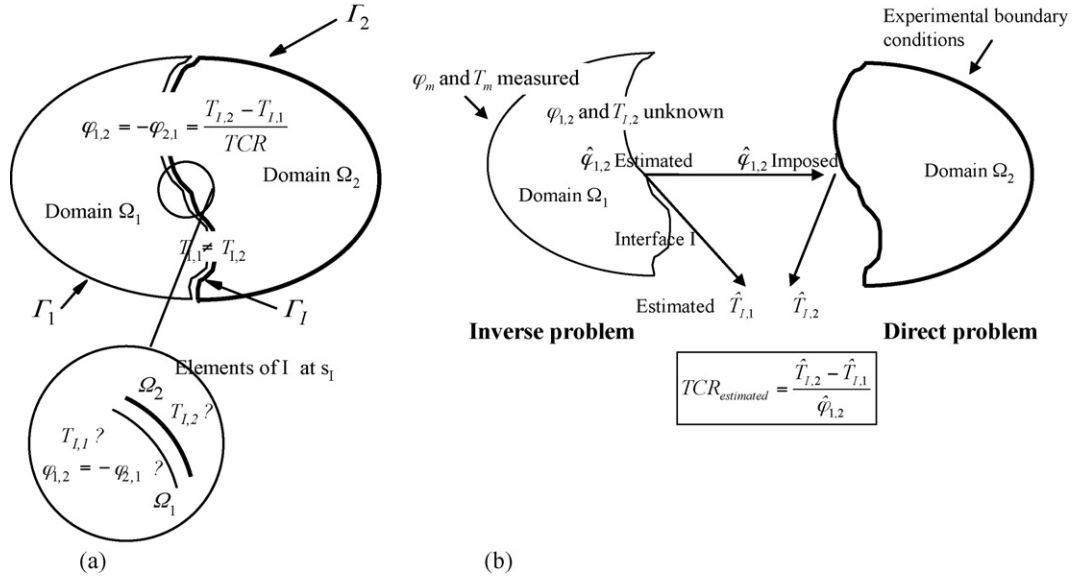


Fig. 4. Thermal contact resistance as a boundary condition between two domains. (a) The basic concept, and (b) scheme of the TCR estimation procedure.

Thermal Contact Resistance (a specific thermal parameter) between the different layers of a PFC.

3.1. Some elements of theory

As shown in Fig. 4, this inverse method requires two steps. We solve in a first step an IHCP for estimating interface temperatures and heat flux by the BEM approach [7,8,9,10]: at resolution time t_f , if the geometry and the diffusivity are known, it is possible to calculate some matrices \mathbf{H}_f , \mathbf{G}_f by applying a discrete form of the Boundary Integral Equation [6,7] to all N boundary elements. If we use a global resolution procedure providing that we apply the discrete Boundary Integral Equation from the initial time t_0 to the final time t_f , we obtain the following simultaneous equations (f there is no heat source term):

$$\sum_{f=1}^F \mathbf{H}_{f,F} T_f = \sum_{f=1}^F \mathbf{G}_{f,F} P_f \quad (1)$$

Here $\mathbf{H}_{f,F}$ ($\mathbf{G}_{f,F}$) is a $(N \times N)$ dimensioned matrix of pre-calculated coefficients from initial time t_0 to resolution time t_f (F time steps Δt such as $t_f = \Delta t \times F$), T_f (P_f) is the (N) dimensioned vector of temperatures (heat flux) at the N boundary elements on the boundary nodes at time t_f . This system contains N equations and a variable number M of unknowns depending on the set of boundary conditions. In order to solve the problem, it is convenient to have more equations than unknowns ($M > N$), in our application we have $M = N$. This means that we have as many pixels at the scanned surface that we have elements at the interface. Eq. (1) can be written for each time step of the SATIR IR sequence, we obtain consequently a macro matrix system presenting $(N \times F)$ equations and $(N \times F)$ unknowns. Rearranging the unknowns in a vector X , the known boundary conditions and measurements in a vector B leads to the following system of linear equations:

$$\mathbf{A} X = B \quad (2)$$

where \mathbf{A} is a square matrix of dimension $((N \times F); (N \times F))$ composed of the $\mathbf{H}_{f,F}$ and $\mathbf{G}_{f,F}$ of Eq. (1). Since the IHCP is ill-posed, matrix \mathbf{A} is ill conditioned. As a result the numerical solution of the Eq. (2) is very sensitive to measurements errors introduced in vector B . In order to obtain a stable solution, we have to use a regularisation procedure. The Singular Value Decomposition (SVD) technique

is a general purpose method for solving discrete ill-conditioned problems [11].

In our problem, SVD method consists in removing the too small singular values which affect the stability of the system in order to find one solution among several, which best corresponds. According to SVD definition, the matrix \mathbf{A} can be built into a product of squares matrices (\mathbf{U} and \mathbf{V} are orthogonal matrices and \mathbf{W} is the diagonal matrix of the singular values w_j , exponent T denotes the transposed matrix operator) as shown:

$$\mathbf{A} = \mathbf{U} \mathbf{W} \mathbf{V}^T \quad (3)$$

$$X = \left(\mathbf{U}^T \text{Diag} \left(\frac{1}{w_j} \right) \mathbf{V} \right) B \quad (4)$$

By using SVD, \mathbf{W}^{-1} is truncated from the too high $(1/w_j)$ to obtain a stable solution. The truncated inverse matrix \mathbf{W}_t^{-1} can be built up as

$$\mathbf{W}_t^{-1} = \begin{bmatrix} 1/w_1 & \dots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \dots & 1/w_p & \vdots \\ 0 & \dots & \dots & 0 \end{bmatrix} \quad (5)$$

The estimate solution vector \hat{X} is function of the new truncated matrix \mathbf{W}_t^{-1} :

$$\hat{X} = (\mathbf{U}^T \mathbf{W}_t^{-1} \mathbf{V}) B \quad (6)$$

Thanks to this regularisation procedure, we observe a smoothing of the solution, which has to be minimised for the conservation of a physical solution. The level of truncation is determined by the technique known as the “L”-curve [11].

After this first step, temperature evolution $\hat{T}_{I1}(t, s_i)$ and thermal heat flux $\hat{\phi}_{12}(t, s_i)$ are evaluated at the CFC/CuOFHC interface, on the CFC hand side (see domain Ω_1 Fig. 4(a)). We assume that the presence of an interface defect can be symbolised by a non-capacitive Thermal Contact Resistance. Consequently, there is thermal flux conservation, through the interface. In this condition, the surface temperature evolution $\hat{T}_{I2}(t, s_i)$ on the interface (on the copper hand side) can also be computed, by solving during a second step a direct problem (see Fig. 4(b)). If the CFC/CuOFHC interface is defect free, there is continuity in the surface temperature evolution. But, if

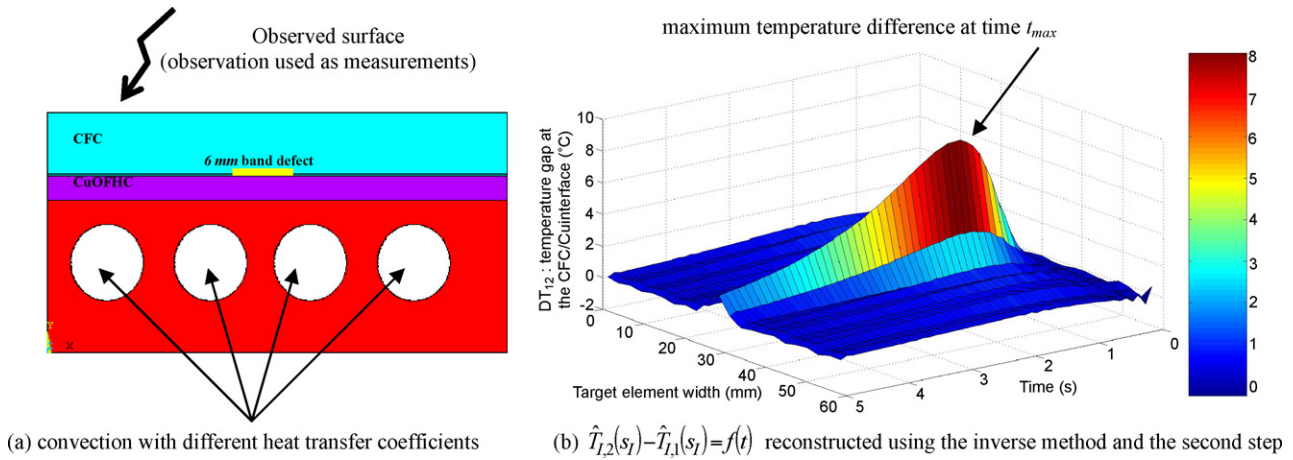


Fig. 5. Validation of the inverse method on numerical data: defect effect in terms of temperature gap. (a) Convection with different heat transfer coefficients and (b) $\hat{T}_{I,2}(s_I) - \hat{T}_{I,1}(s_I) = f(t)$ reconstructed using the inverse method and the second step.

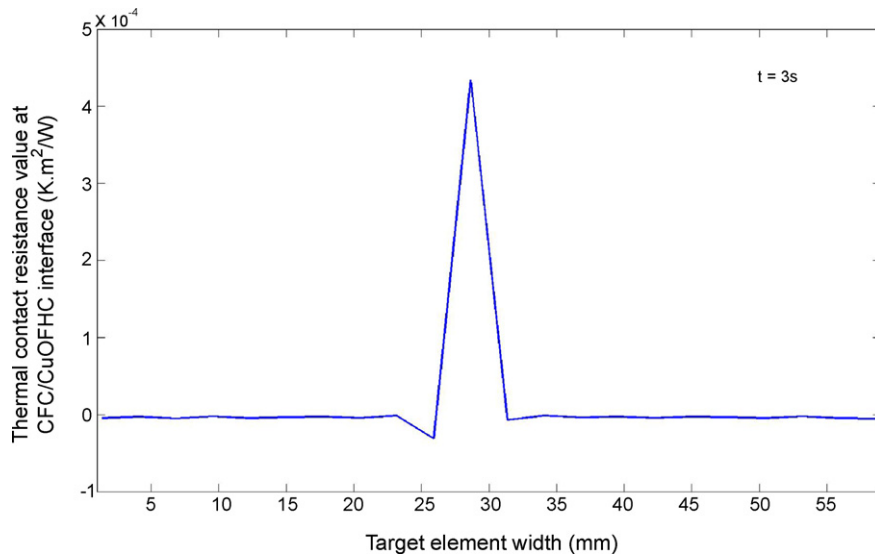


Fig. 6. Validation of the inverse method on numerical data: defect effect in terms of thermal contact resistance. Results obtained using simulated data, resistance calculated using $T_{I,1}(t_{max}), T_{I,2}(t_{max}), \varphi_{I2}(t_{max})$.

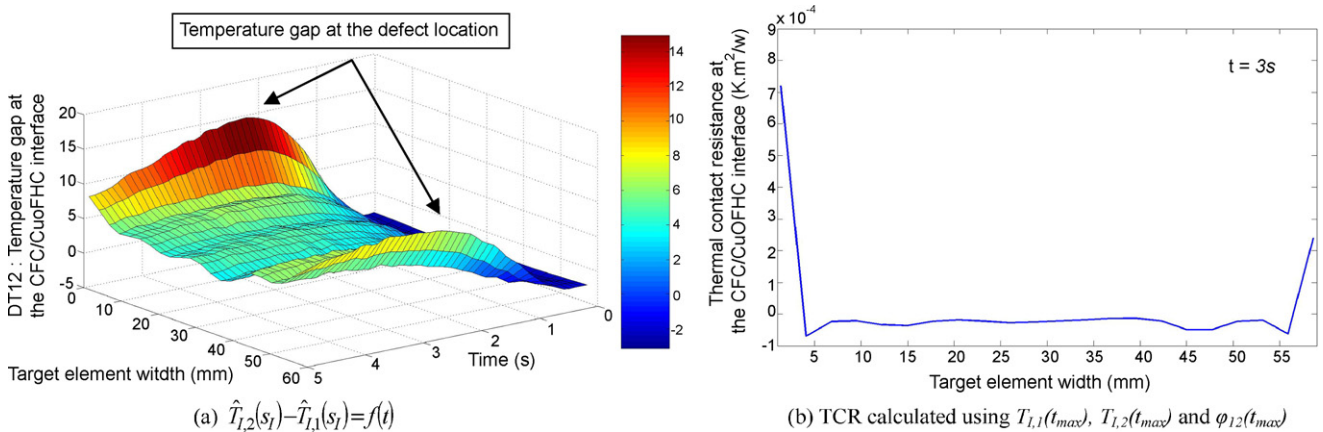


Fig. 7. Application of the inverse method on experimental data. (a) $\hat{T}_{I,2}(s_I) - \hat{T}_{I,1}(s_I) = f(t)$ and (b) TCR calculated using $T_{I,1}(t_{max}), T_{I,2}(t_{max}),$ and $\varphi_{I2}(t_{max})$.

there is a defect, there is therefore a temperature gap, which can be expressed in terms of Thermal Contact Resistance estimated value TCR_{est} :

$$TCR_{est}(t_F, S_I) = \frac{\hat{T}_{1,2}(t_F, S_I) - \hat{T}_{1,1}(t_F, S_I)}{\hat{\varphi}_{1,2}(t_F, S_I)} \quad (7)$$

3.2. Validation step on simulated numerical data

The inverse method has been tested using numerical data produced by a direct ANSYS® simulation. An illustration of this validation step is given in Fig. 5(a) for the case of a 6-mm band defect at the CFC/CuOFHC interface of a 2D flat tile geometry (W7-X Target Elements type 4B). We observe temperature continuity at the interface, except at the defect location where we clearly observe a temperature gap. As a result, we can calculate the TCR as described by Eq. (7). As we can see in Fig. 6, a non-zero TCR can be observed at the defect location. On the other hand we have temperature continuity at the interface where there is no defect. We obtain $(T_{1,2} - T_{1,1}) = 0$ as shown in Fig. 5(b). Defect detection and localisation is therefore possible.

3.3. Application on experimental data

After the validation step performed on numerical data, the inverse method had been applied on SATIR experimental tests. The application of the inverse method on surface temperature evolution of a W7-X target element with calibrated defects (two 6 mm band defects at the CFC/CuOFHC interface, at $x=0$ mm and $x=60$ mm) allows the identification of the defect morphology, as showed on the Fig. 7. Compared to the results of the validation step, results are noisier, due to measurements uncertainties. However, the orders of magnitude of the estimated TCR are roughly the same in the validation and application step. It proves the reliability of this image processing technique.

4. Conclusion

In the frame of NDT of PFCs, the SATIR test bed operating at CEA Cadarache is based on transient IR thermography. Advanced image processing techniques on thermosignals coming from SATIR, in order to improve its sensitivity in terms of PFCs defect detection and qualification, are proposed. They are based on the autocorrelation energy and the thermal contact resistance evaluation. These two methods process the thermosignal by itself, without using a

reference signal coming from a supposed defect free tile. The application of these two techniques on experimental SATIR data showed accurate defect detection. In consequence, they are suitable to PFC qualification and can be employed, for instance, in addition to the fully operational $DT_{ref\ max}$ criterion, in order to help the decision-making during a qualification phase.

In light of these encouraging results, it is expected to extend these two techniques to other geometries and to upgrade the inverse method by the development of a 3D BEM formulation allowing the detection of coin defects.

Acknowledgements

This work, supported by the European Communities under the contract of Association between EURATOM and CEA, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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