

Application of Infrared Thermography in NDT of Plasma-Facing Components for Tokamaks

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Abstract

Plasma-facing components (PFCs), consisting of plasma-facing materials (PFMs) and heat sink, are the first wall facing directly tokamak plasma, subjected to high heat flux (HHF) and bombardment of particles from the high temperature plasma. The exposure to the HHF and particles may damage the structural integrity of PFCs and shorten their service lives significantly if the connection of PFMs to heat sink is not satisfactory. Suitable non-destructive testings (NDTs) are thus necessary to evaluate the connection quality reliably.

Infrared (IR) thermography has been used successfully in evaluating the connection by e-beam welding between CFC tiles and Cu alloy heat sink on the French tokamak Tore Supra, and now is being used for the similar connection on the German stellarator W-7X, and will be used for the International Thermonuclear Experimental Reactor (ITER) being built in France. Various types of IR thermography NDTs are now under development to test the PFCs before installation and to monitor them in-field between campaigns. The Experimental Advanced Superconducting Tokamak (EAST), one of Mega-Science Projects in China, will also employ the NDTs for inspection of its PFCs. In this report, to be presented is the R & D state of the art in the field in China and other countries.

Keywords: IR thermography, NDT, Tokamak, PFCs, Nuclear Fusion

1. Introduction

The Experimental Advanced Superconducting Tokamak (EAST) is an advanced steady-state plasma physics experimental device that has been built at the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). As a part of the device, the plasma facing components (PFCs) are designed to protect the vacuum vessel, injection power system and diagnostic components from the plasma particles and heat loads. It must be designed to withstand the particle and heat load fluxes with a peak value up to 10MW/m^2 in future operation^[1]. The exposure to such fluxes may damage the structural integrity of the PFCs easily and shorten their service life significantly if heat conduction from the plasma-facing materials (PFMs) to the heat sink is insufficient. Therefore suitable non-destructive testings (NDTs) are quite important to evaluate reliably the connection quality between the PFM and the heat sink.

Infrared (IR) thermography as one of NDTs has been widely used over the decades to

evaluate the integrity of joints in a wide range of industries as well as in research fields^[2]. It provides a fast, safe, non-destructive and noncontact detection of subsurface defects, and can be used as an alternative or complement to conventional inspection technologies^[3,4]. It is an examination of an object with technology that does not affect the object's future usefulness and provides an excellent balance between quality control and cost-effectiveness. In IR inspection, the material surface is heated by a heat source and an IR camera monitors the evolution of surface temperature. Heat flow into the material is perturbed by the presence of subsurface defects, causing a temperature contrast on the surface. This feature is exploited in many applications of NDTs to check the reliability and quality of the joints, with particular attention to dissimilar material joints in PFC structures in fusion devices^[5-7].

Recent improvements on the IR thermography with high precision IR detectors have brought about remarkable progresses into thermographic NDT techniques, which make it possible to detect flaws and defects with good resolution^[8]. In this paper, three main IR thermography methods being used and/or developed in fusion community are to be introduced. Among them, transient IR thermography has been developed for almost 20 years, and pulse heating and lock-in IR thermographic inspections as effective NDT techniques are still under development.

2. PFCs of EAST

As shown in Fig. 1, the EAST PFCs mainly consist of divertor (outer plate, dome, inner plate), high field side (HFS), passive plate, and movable limiter, also shown are some possible configurations of plasma in future operation.

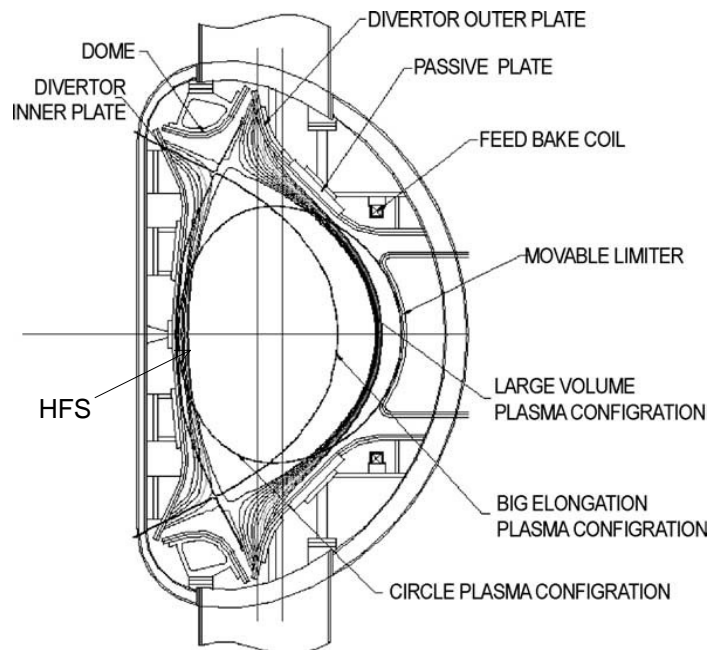


Fig. 1. Elevation view of EAST PFCs^[1].

The PFCs were initially stainless steel plates bolted directly to the supports, and are now

under upgrading into graphite tiles bolted to Cu alloy heat sink with built-in cooling channels as shown in Fig.2. A thin sheet of flexible graphite is placed between graphite tile and heat sink to ensure better thermal contact between them. The PFCs will be further upgraded into tungsten coated Cu alloy with increasing the input power for heating and driving the plasma, simulating the ITER construction and operation phases.

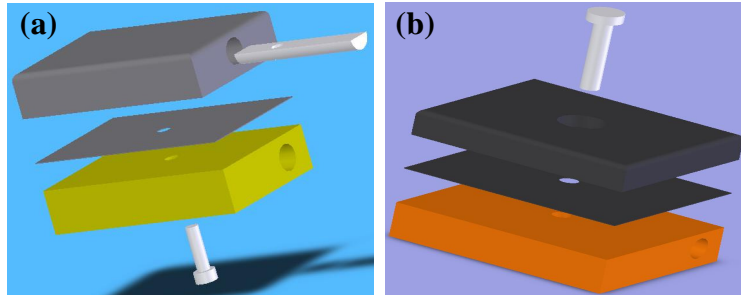


Fig. 2. Schematic figures of two types of PFC modules with active cooling, (a) for areas of high heat load (divertor), and (b) for areas of low heat load (HFS, passive plate, etc.), expecting to withstand heat fluxes less than 1 and 3 MW/m², respectively.

3. IR Thermography NDT Methods

The basic principle is that flaws in the bonds between PFM and heat sink modify the heat transfer in the component. To generate a heat transfer through the part to be inspected, a temperature gradient needs to be established inside the component. The technique for the thermal activation defines the different IR-NDT procedures^[9].

3.1 Transient thermography

SATIR is a test-bed established at CEA, France to perform non-destructive examination of actively cooled plasma facing components. Majority of PFCs (CFC tiles welded onto Cu heat sink) of the French tokamak, Tore Supra, are actively cooled with the built-in cooling channels that make it possible to thermally activate heat transfer in the components with hot or cold water during IR thermography testing^[6]. The testing protocol is based on a thermal transient induced by an alternative hot and cold water flow in the heat sink through the cooling tubes. As shown in Fig. 3, the design of the system allows controlling two elements in parallel, one to be tested and the other defect-free (so-called reference, verified by high heat flux (HHF) testing^[6]). The surface temperatures of both elements are monitored simultaneously by an IR camera. The temporal evolution of the surface temperature difference at each corresponding pixel of both elements is calculated and the areal maxima (so-called DTref_max) distribution can be obtained. A bonding flaw between heat sink and PFM can be judged from the distribution on the areas with values of DTref_max higher than a critical value verified by HHF testing beforehand. The SATIR is used for the reception examination of the PFCs, providing quantitative information on the global thermal efficiency of the component prior to its installation into the fusion machine^[10].

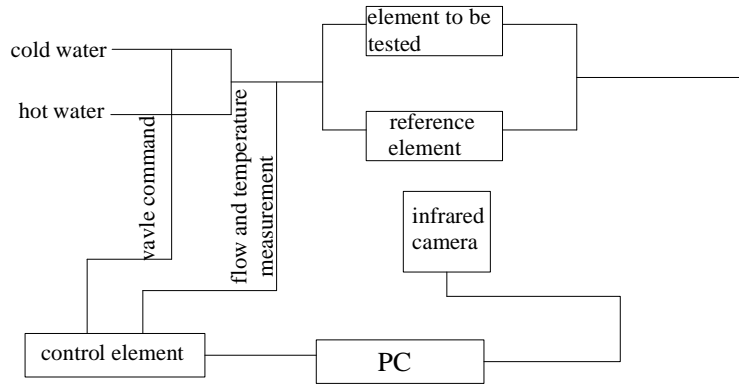


Fig. 3. Test-bed diagram

The shortcoming of SATIR is the use of a reference element. A new method without use of a reference component, i.e., innovative data processing based on energy distribution at the CFC/Cu bonding, is being developed at CEA^[11].

3.2 Lock-in thermographic NDT

The principle is shown on the left of Fig. 4^[12]. The lock-in thermography method is based on propagation and reflection of modulated thermal waves in solids that are applied at the surface of element. As this thermal wave undergoes reflections at CFC/Cu interlayer bond, the temperature modulation at the surface is modified by the thermal waves coming back from the first interface of the component^[13,14]. In the application to PFCs, the sinus thermal excitation is provided by four lamps each bearing a maximum power of 1 kW, as shown on the right of Fig. 4 by Courtois et al^[15]. As the surface temperature is monitored with an IR camera during the modulated illumination, Fourier analysis performed at each pixel provides magnitude and phase of the local response. The detection sensibility of the lock-in depends on several parameters such as the frequency (0.7 Hz optimum) and the background noise of local response. Under optimized testing conditions, the detectable defect size is about 6mm (4.5° phase) for a corner defect and 2mm for a strip defect^[16].

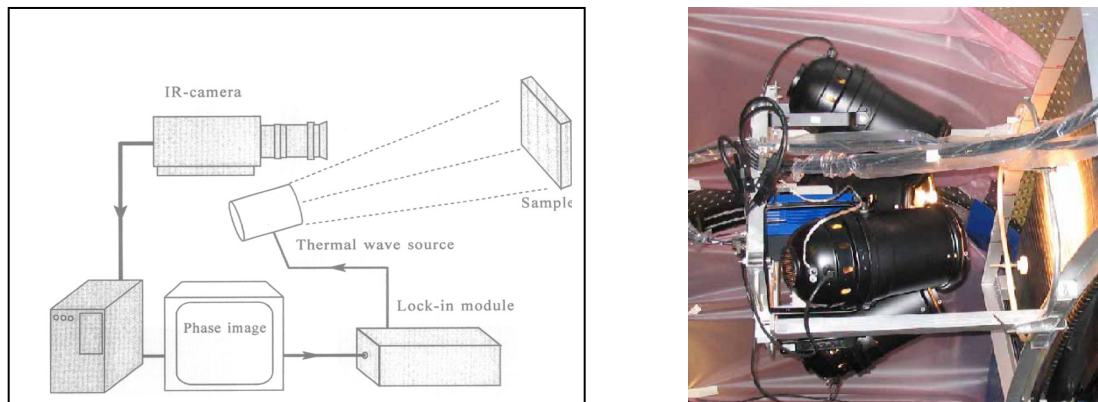


Fig. 4. Left: principle schematic of lock-in thermography^[12]; right: an in-filed lock-in^[15]

3.3 Pulsed thermography

In the case of pulsed thermography, the temperature gradient necessary for NDT is established by a single powerful flash of light which is directed towards the surface of the CFC tiles, as visualized in Fig. 5^[17]. The light source of the ARGUS setup releases energy of 12 kJ within 0.1 s. The cool-down of the CFC surface is observed applying an IR camera with good temperature resolution (NETD at 20°C = 20mK) and high image frequency (up to 150 Hz). For each pixel, a frequency analysis based on the fast Fourier transform algorithm (FFT) is calculated on the cool-down behavior after the flash. The defect detection is not based on the power spectrum of the FFT, but on the phase-shift of the basic frequency of the FFT (f_1) and its higher harmonics (f_2, f_3, f_4, \dots). The basic frequency (f_1) is adjusted to obtain a penetration depth reaching the interface of Cu interlayer/Cu heat sink, whereas the penetration of the first harmonic frequency (f_2) is limited to the interface of CFC/Cu interlayer. This means that the phase image of each frequency addressed by the FFT carries information about the depth of the defect detected.

The method can be applied to the components without using the cooling system and the bonding quality can be assessed at any stages of the manufacturing route, allowing an earlier detection to defects of the bond. This is an important feature for a manufacturer of PFCs to develop a reliable quality-control tool, which can be efficiently integrated in an industrial process. Since there is no need for a reference element, the test setup is quite simple and the evaluation for rating the bonding quality under inspection can be finished within a few seconds^[9].

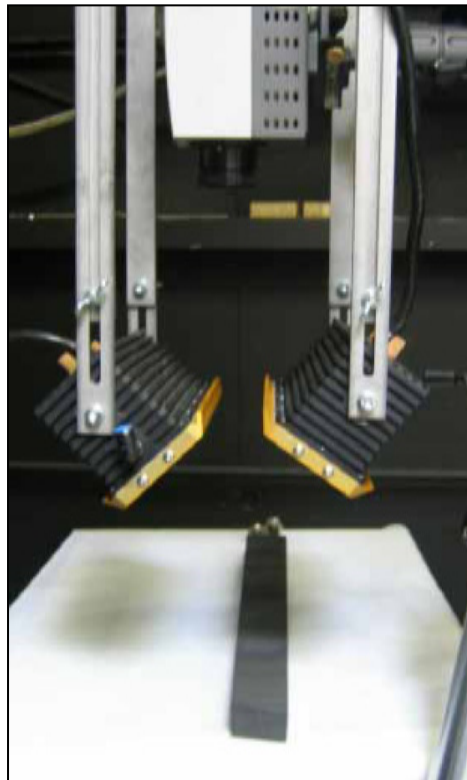


Fig. 5. The ARGUS set-up for pulsed IR thermography^[17]

4. IR NDT at ASIPP

4.1 Construction of a test-bed

IR inspection by means of hot/cold water is being developed for testing interface quality of the EAST PFCs at the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). Fig. 6 shows a picture of the experimental set-up similar as SATIR, consisting of hot water tank and cool water tank for water supply at a constant temperature, and an IR camera connected to a PC for data storage and processing. The testing principle is similar with SATIR. Due to some constraints, we can only give qualitative analysis for defects for the present.

For evaluation of thermal contact of the PFCs designed for the first phase of EAST by means of bolting connection as shown in Fig. 2, the first step is to calibrate the system in order to judge properly the bonding quality of the target elements. Defects of known sizes and geometries will be introduced into the thin sheet of flexible graphite inserted in between the PFM and the heat sink for the purpose of calibration.



Fig. 6. The experimental set-up at ASIPP.

4.2 Test procedure and FE simulations

In Fig. 6, hot water flows through the test section at first. When the temperature distribution on the sample surface becomes stable, the water supply is switched to the loop of cold water that cools the heated test section by flowing cool water through the cooling channels. The surface temperature and the flow rate of cooling water are monitored and stored in a data logger.

Fig. 7(a) gives an image from the IR camera and Fig. 7(b) simulation results by a commercial ANSYS code. Three-dimensional finite element (FE) simulation has been performed to understand the surface temperature distribution in the case of existence of an artificial defect at the corner in between PFM and heat sink. From the two images, one can see a good correlation between the actual situation and simulation result.

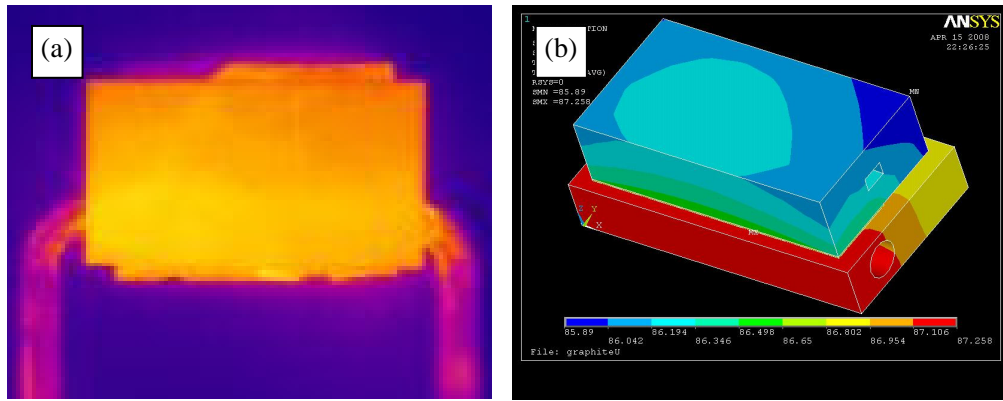


Fig. 7. (a) image from IR camera; (b) simulation results by ANSYS

5. Summary

NDTs are among the key issues in developing high quality PFCs for fusion devices. The most critical step is the examination of the bonding between PFM and heat sink. The transient IR thermography has been used successfully in evaluating the connection by e-beam welding between CFC tiles and Cu alloy heat sink on the French tokamak, Tore Supra, and is now being used on the German stellarator W-7X, and will be used on ITER being built in France. The lock-in and pulsed thermography methods, being developed as portable and in-field testing methods, are quite useful in detecting bonding flaws at earlier stage during or in between operation campaigns.

The transient IR thermography, as a more mature technique, is also being developed at ASIPP for quality control of the PFCs for EAST. An experimental device has been constructed and calibration work is underway. And the in-field testing methods will also be developed in the near future.

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