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HEAT TRANSFER PHENOMENA IN THE FIRST WALL OF THE RFX FUSION EXPERIMENT

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ABSTRACT

The thermal analysis of the first wall (FW) of the RFX machine is presented. RFX is a large fusion experiment under construction at Padua, Italy. The RFX FW is briefly described, together with the critical thermal conditions it has to withstand. The numerical analyses performed to predict the FW thermal behaviour are presented. 1-D and 2-D finite element models give accurate predictions of the FW temperatures and of the thermal exchanges in the machine inner environment.

INTRODUCTION

The RFX Project (an EURATOM-CNR-University of Padua Association) is among the major current projects on controlled thermonuclear fusion based on plasma confinement with magnetic fields. Like many other research machines presently in operation or design, RFX will have a toroidal geometry, and will operate with a particular configuration for the magnetic fields used for plasma confinement, known as Reversed Field Pinch (RFP). The basic goal of RFX is to prove the suitability of the RFP configurations for fusion reactors [1].

On increasing the performances of the fusion research machines, the deposition of energy released from the plasma onto the first wall (defined here as any reactor component that has physical contact with any segment of the plasma, for any length of time) is also increased, thereby originating one of the major feasibility problems of fusion.

The most severe thermal loads on the first wall (FW) occur when the plasma becomes instable, resulting in a sudden termination of the plasma configuration, called disruption. The energy stored in the plasma is then transferred to the FW in a very short time interval. The FW shall withstand the thermal power flux of normal pulses without erosion or any other significant damage and, moreover, assure the vacuum vessel (VV) integrity in the event of a sudden disruption of the plasma configuration.

Also, the plasma shall be protected against contamination with particles released from the FW, in order to not intensify the loss of plasma energy by radiation. This will be of major concern in the forthcoming fusion reactors, because the loss of energy by radiation makes it more difficult, or impossible, to establish a self-sustaining fusion reaction.

The RFX first wall design is such that the VV safety is assured even in conditions of a hard disruption, since the FW will recover the whole vessel. The numerical analyses here presented were restricted to the normal operational conditions of RFX. Though extremely important, the study of disruption conditions involves so many unknowns that complex numerical analyses are not undertaken.

The RFX first wall will be made up by rectangular graphite tiles, each supported at its centre by an austenitic steel clamp. The clamps will be bolted to the 72 massive rings of the VV (fig. 1) [2]. Tiles will have dimensions varying from a minimum of 90mm x 126mm inside the torus, to a maximum of 90mm x 208mm at the outside, and will have a thickness of about 20 mm.

Heat transfer from the FW towards the VV will occur by radiation from the rear tile surface and by conduction through the metallic support. Cooling by forced convection is sometimes adopted in similar machines but cannot be employed in RFX. The energy shall then be extracted by the VV cooling system which will be able to keep the VV temperatures bellow 90 C.

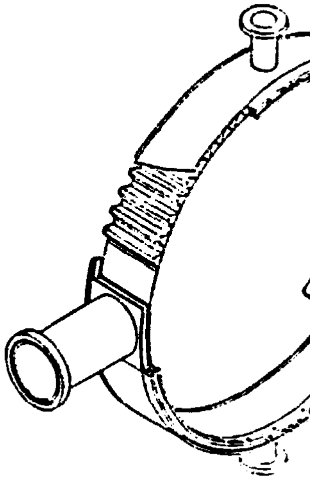

Fig. 1 Wedge shaped vessel element

THERMAL LOADS ON THE FIRST WALL

The energy dumped onto the FW during a full-performance pulse (I_p= 2 MA) is estimated to be 6 MJ during the rise of the plasma current, which lasts about 30 ms. Part of this energy is transferred by radiation and transport of neutrons, with uniform distribution, and part by charged particles, with a flux distribution that depends on the eccentricity of the plasma with respect to the FW toroidal axis. During the flat-top of the plasma current (250 ms), the energy deposited on the FW is about 9 MJ, which are presumed to be transferred to the wall mainly by transport of charged particles. At the end of the pulse, the energy stored inside the plasma, about 5 MJ, is dumped onto the FW. In a controlled rundown of the plasma pulse, the current termination may be soft, with a timescale similar to that of current rise, that is, 30 ms.

Fig. 2 shows the poloidal distribution of the thermal flux, symmetrical with respect to the equatorial plane and independent of the toroidal coordinate. It assumes a plasma displacement of 3.0 cm from the machine axis and the whole thermal flux coming from particle transport.

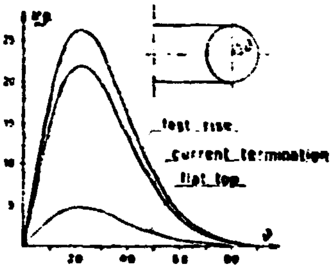

Fig. 2 Thermal load on the first wall

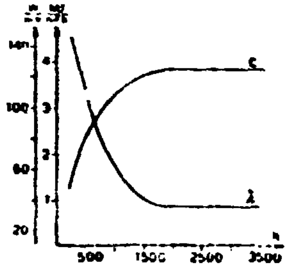

Fig. 3 Physical properties of graphite

NUMERICAL ANALYSIS

Due to the geometrical and loading complexities as well as the many types of heat transfer process and the nonlinear material properties involved, the analysis of the thermal behaviour of the RFX first wall had to be performed by means of numerical methods.

One dimensional analysis. An 1-D model, with the ADINAT code [3], determined the operational temperature range of the FW and considered the variations of the thermal response as function of the properties of the tile materials. The dependence of the graphite physical properties on temperature is shown in fig. 3.

In order to correctly describe the high thermal gradients near the tile surface facing the plasma (front surface), the distances between the nodes near the surface were kept very small.

As fas as the temperature range in a single pulse was concerned, the FW could be approximated by a semi-infinite solid [4]. However, over larger time-scales, the energy transferred during several plasma pulses causes the FW temperatures and radiation towards VV to rise. After some cycles, a balance is achieved between the heat absorved by the FW during the pulse and the heat drained by the VV during the dead time. The minimum dead time prescribed to RFX is 10 minutes.

Initially, radiative heat exchange between grey surfaces, given by Lambert's Law, Eq. (1), was assumed to occur between FW and VV.

$$q = f_{12} \cdot \varepsilon_{12} (T_1^4 - T_2^4) \qquad (1)$$

where T_1 and T_2 are the temperatures of surfaces L_1 and L_2 , ε_{12} is an exchange coefficient between the surfaces and f_{12} is a shape factor, a function of the surfaces geometry. The FW-VV exchange factor is mainly influenced by the Inconell (the VV material) emissivity, for it is considerably lower than graphite one. Varying the Inconel emissivity form 0.4 to 0.3, typical values, the time needed to reach thermal equilibrium rises from two to two and a half hours from the beginning of the operation, that is, 12 to 18 plasma discharges (fig. 4). The transients were determined applying a simplified thermal flux (such that the incident energy and pulse duration were preserved). When the thermal equilibrium was achieved, the model was loaded with a more refined stepped transient, in order to determine the peak temperatures. With the former Inconel emissivity, the maximum temperature at the tile surface rose up to 1450 K, at the end of the pulse. After about 3 seconds, the temperatures along the tile thickness became practically uniform at 740 K, decaying then to 640 K, after 10 minutes of dead time. With the second value, these characteristic temperatures increased to about 1500 K, 790 K and 690 K, respectively. Fig. 5 shows temperatures at several depths along the tile, with the Inconel emissivity equal to 0.4.

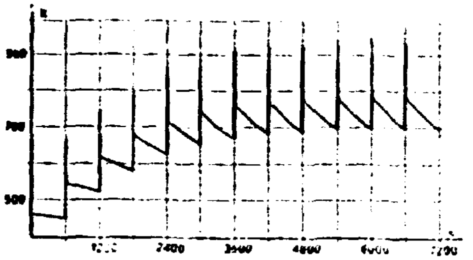

Fig. 4 Long time analysis of graphite tile temperature in the hottest zone

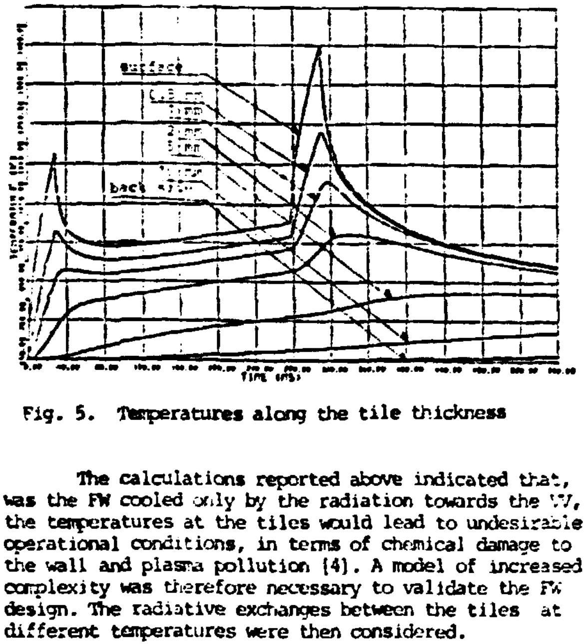

Fig. 5. Temperatures along the tile thickness

The calculations reported above indicated that, was the FW cooled only by the radiation towards the VV, the temperatures at the tiles would lead to undesirable operational conditions, in terms of chemical damage to the wall and plasma pollution [4]. A model of increased complexity was therefore necessary to validate the FW design. The radiative exchanges between the tiles at different temperatures were then considered.

The model was assumed to radiate to a black body, which assimilated the whole FW, and wich temperature followed the equilibrium temperature transient of the FW under the average thermal load (if the plasma is perfectly centred with respect to the machine torus, the FW is submited to an uniform average load and its behaviour is perfectly described by the 1-D model. Equilibrium is reached after three hours of opperation, the FW temperature rising up until 625 K, at the end of the pulse, then falling until 505 K at the end of the dead time).

Now the temperature at the wall surface rose up to 1310 K at the end of the discharge; after some seconds it was equal to 660 K and decrease to 560 K at the end of the dead time.

2-D models. Considerable simplifications were introduced in the 1-D model, so that the previous results could only be taken in their magnitude. An accurate analysis should consider the radiative heat exchanges between several mutually irradiating surfaces, disposed in a well defined geometry.

Due to the geometrical and loading axissimmetry, the general, 3-D thermal problem was reduced to a two dimensional one. On the other hand, the equatorial symmetry was not considered, because it holds only for the specific load case under examination [5].

Radiative exchanges between tiles at different temperatures depend upon the fourth power of their temperatures and upon their mutual shape factors. The shape factors have been analytically calculated, after approximating the toroidal enclousure with a cylindrical one. Integration of expression (2) over the whole FW inner surface, for every radiative segment, led to the determination of the required values.

$$f_{ij} = \frac{1}{L_i}\int_{L_i}\int_{L_j} \frac{\cos\theta_i . \cos\theta_j}{2.d}\, dL_i . dL_j \qquad (2)$$

where θ_i and θ_j are the angles between the normals to the line segments i and j and the line connecting their centres, and d is the distance between them.

It was assumed that the FW screened the whole VV and that its meridional section had the shape of a circular ring 20 mm thick. Between two adjacent tiles, no heat transfer was considered, since they are separated by vacuum and their mutual radiative heat exchange is negligible. The FW rear surface considered radiative exchange with the VV wall. Each rear radiative segment had an unit shape factor and the VV temperature was 363 K. Conduction through the tile supports was initially disregarded. Graphite was considered to behave like a grey body.

The phenomenon was simulated with the code TOPAZ [6]. The model had a mesh with 1200 nodes, and the whole FW was divided into 840 2-D solid elements with nonlinear material properties. Each tile was defined by 28 elements regularly disposed in a set of 4 x 7 elements with different sizes in the radial direction (very thin near the front tile surface and thicker towards the the rear surface); the poloidal width of the tile was equal to 3 degrees.

Beginning with the whole FW at 505K (equilibrium temperature just before a plasma shot, when the average thermal load is applied), a series of pulses was simulated, until another state of equilibrium was achieved. The temperature transients obtained were in agreement with those calculated with the 1-D model. For the more stressed tile, the maximum equilibrium temperature reached 1250 K at the end of the pulse. After some seconds the temperatures along the thickness became uniform at 635 K, falling until 545 K at the end of the dead time. The front surface temperatures are shown in fig. 6, for several instants during the thermal cycle. It is remarkable that the temperatures in the internal zone of the torus are practically uniform and constant in time, at 475 K.

The maximum flux towards the inside (fig. 7) is 93 KW/m² at the end of the discharge, falls to about 5 KW/m² after some seconds and returns to 1.3 KW/m² when the thermal cycle is completed. The radiative exchanges among the tiles do not contribute to damp the rise of surface temperatures during the pulse, for the radiative flux is three orders of magnitude lower than the incident flux. However, their contribution does become important during the dead time between two successive pulses, cooling the hottest tiles by redistribution of the incident heat.

Whilst the flux towards the inside of the cavity has an abrupt variation during the pulse, the flux towards the VV (fig. 8) has a much softer variation. Even if the VV temperature is lower than that of the FW, in the zones of maximum temperatures the flux towards the inside is always higher than the flux towards the outside. Therefore, for the hottest tiles, the redistribution of heat by radiation towards the inside of the FW cavity counts more than the flux towards the VV. This happens because the exchange coefficient between graphite and Inconel is very low, due to the low Inconel emissivity.

In overall scale, the energy transfer from FW to VV is almost linear with time and fairly uniform in space. The FW provides an efficient thermal shield to the VV, absorbing heat impulsively and releasing it continuously.

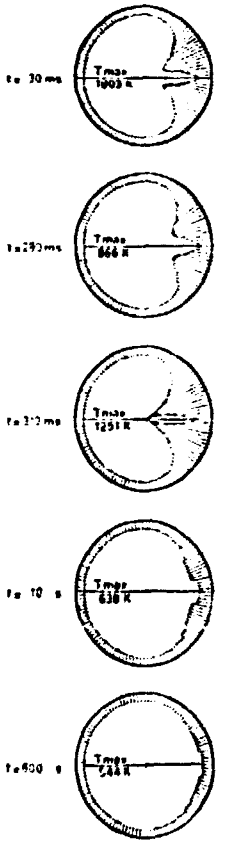

Fig. 6 Inner surface temperature distribution

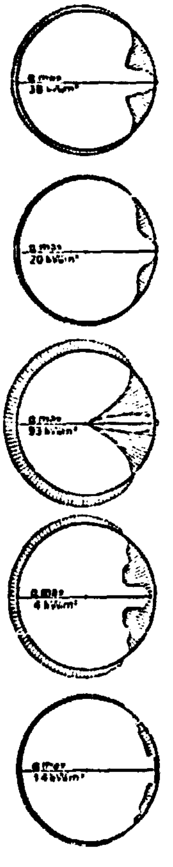

Fig. 7 Radiation heat flux towards the inside

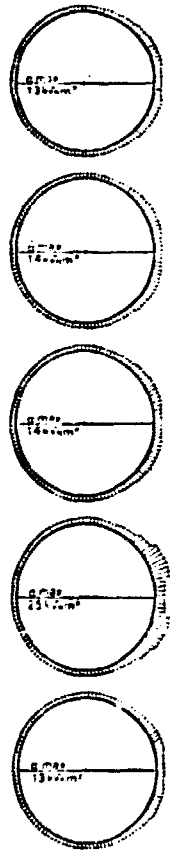

Fig. 8 Radiation heat flux towards the vessel

The effects of thermal conduction. Thermal conduction through the tile supports was evaluated with a 2-D model of a single tile, using the code ADINAT, (fig. 9). The model had 108 nodes, and was constituted by 3 groups of elements. Graphite was divided into a group of 56 elements with nonlinear material behaviour, the stainless steel clamp into a group of 20 linear elements and the contact resistance between graphite and steel into a group of 6 thin elements with a suitable thermal conductivity.

Compared to the case in which only radiation was assumed to act, inclusion of conductive heat transfer led to equilibrium temperatures nearly 100 K lower. With a contact conductance of 1000 W/m.K, the maximum temperature rose to 1100 K; as the temperatures became uniform along the tile thickness, they fell to 545 K; at the end of the dead time, they were about 450 K.

This substantial decrease in the equilibrium temperatures tends to reduce the radiative flux among the tiles, thus the actual fluxes towards the VV are not so uniform as determined before. Disregarding conduction is, however, a conservative figure to the FW verifications.

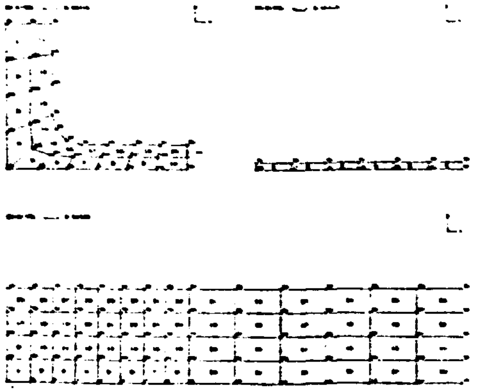

Fig. 9. 2-D model of a single tile

VERIFICATIONS OF THE FIRST WALL

The calculations allowed to assert that, under normal operational conditions, the FW has a satisfactory thermal performance [4].

The tiles may freely undergo the thermal expansion , and it is known that in such cases graphite resists well stresses due to thermal shock; the FW will remain at temperatures considerably bellow the sublimation limits of graphite; erosion of the FW due to evaporation will not be expressive and no problems of plasma polution are to be expected.

Erosion due to methane production is expected to become somewhat important, but in less than 10 percent of the whole FW surface area, in the limit case studied herein.

CONCLUSION

The thermal behaviour of RFX first wall under the heat fluxes due to the plasma pulses was analysed by means of finite element codes.

The temperature transients related to the assumed thermal flux define the upper bound of the FW temperatures and was calculated with a 2-D model. The lower bound corresponds to a perfectly centred plasma, and was studied in an 1-D model. Starting with the FW at the same uniform temperature of the W, the FW heats until a cyclic equilibrium is reached, after 2 or 3 hours of operation, with a temperature field bounded by the two limit cases. Good mechanical and thermical performances are expected under this thermal field.

The radiative heat flux from the hottest to the coldest tiles was shown to be essential to cool the hottest tiles themselves. Although its intensity is very low, compared to the incident flux, the radiative flux among the tiles subsists all along the time, and constitutes the more important phenomenon in cooling the more stressed tiles.

The heat flux towards the W is low, if compared to the energy flux released from the plasma. It has a very soft variation in space and time. This confirms the shielding effect of the FW, which transforms the pulsed thermal load from the plasma into a continuous load, globally linear, towards the W.

FINAL REMARKS

All the computational work presented herein was performed during the author's enrolment in the Specialization Course on Plasma and Controlled Thermonuclear Fusion Engineering, held at the University of Padua. The author whishes to thank PROMON Engineering for making available time during his activities there to work in the preparation of this paper.

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