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Analysis of sweeping heat loads on divertor plate materials *

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The heat flux on the divertor plate of a fusion reactor is probably one of the most limiting constraints on its lifetime. The current heat flux profile on the outer divertor plate of a device like the International Thermonuclear Experimental Reactor (ITER) is highly peaked with narrow profile. The peak heat flux can be as high as 30–40 MW/m^2 with full width at half maximum (FWHM) of the order of a few centimeters. Sweeping the separatrix along the divertor plate is one of the options proposed to reduce the thermomechanical effects of this highly peaked narrow profile. The effectiveness of the sweeping process is investigated parametrically for various design values. The optimum sweeping parameters of a particular heat load will depend on the design of the divertor plate as well as on the profile of such a heat load. In general, moving a highly peaked heat load results in substantial reduction of the thermomechanical effects on the divertor plate.

1. Introduction

The heat flux on the divertor plate of a magnetically confined fusion reactor is probably one of the most limiting constraints on its lifetime. Heat loads as high as 30–40 MW/m^2, with full width at half maximum (FWHM) in the order of a few centimeters, are expected on the divertor plate of a device like ITER. Sweeping the plasma separatrix point magnetically along the divertor plate is one of the options proposed to accommodate high heat loads and/or to reduce the thermomechanical effects of a given heat load. During the sweeping process, each location on the divertor plate will experience miniperiodic cycles in both the heat and the particle fluxes. The period of such minicycles is inversely proportional to the sweeping frequency. These minicycles are superimposed on the main reactor on- and off-cycles. The minicycles will result in additional temperature fluctuations over the main cycles which may have the effect of reducing the divertor fatigue life. On the other hand, sweeping the heat load substantially reduces the temperature rise in the structural material which greatly enhances the component fatigue life.

The computer code A*THERMAL-2 [1] is used in this study for the thermal analysis of the divertor plate due to a moving heat source. The analysis can be done for any divertor structure composed of several layers of different materials. The work presented in this paper assumes a divertor plate constructed from a 1 cm carbon-fiber-composite armor bonded to a 3 mm copper alloy which is the heat sink material. The input heat flux profile on the divertor plate can be described by either a histogram or by analytical functions [2]. The sweeping wave can also have different time profiles. In this study sweeping is done linearly in time and starts from the origin [2].

Carbon-fiber-composite (CFC) is still seriously considered as an armor material for the initial phase of operation in fusion devices for several reasons. One reason is the extensive operating experience in the current tokamaks which suggests a strong preference for low z materials. Another reason is that CFCs have demonstrated excellent thermomechanical properties against thermal shocks during abnormal events like disruptions and runaway electrons. In additions, CFC can be designed to achieve high thermal conductivity and irradiation resistance. The CFC used in this analysis is the CX-2002U composite which is currently available commercially.

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2. Thermal analysis

The heat flux profile on the outer plate of a double null divertor used in this analysis can be described as [3]

$$h = h_1\,e^{x/\lambda_1} + h_2\,e^{x/\lambda_2}, \qquad x \le 0, \tag{1}$$

and

$$h = h_3\,e^{-x/\lambda_3} + h_4\,e^{-x/\lambda_4}, \qquad x \ge 0, \tag{2}$$

where x is the origin. The total power to the outer divertor plate, P_T, can then be given by

$$P_T = 2\pi R \sum_{i=1}^{4} \lambda_i h_i, \tag{3}$$

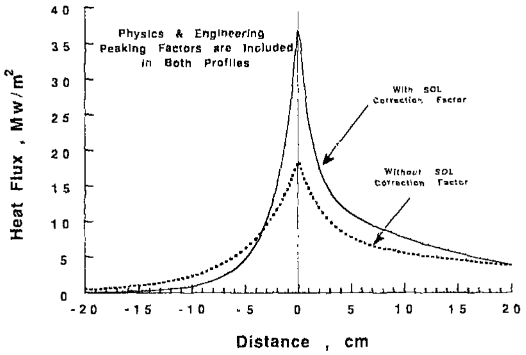

Fig. 1. Heat flux profile with different peaking factors.

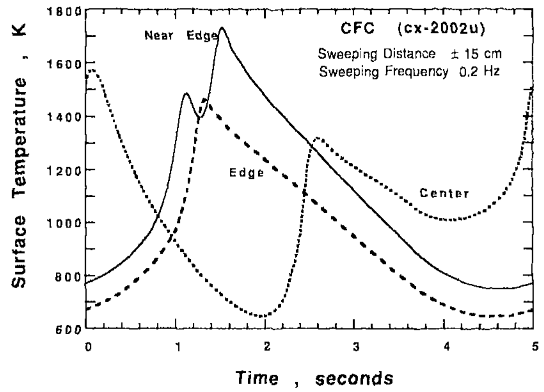

Fig. 2. Surface temperature variation during sweeping at different locations.

where R is the major radius of the reactor. The parameters h_i and λ_i are determined from the total power expected at the divertor plate as well as from different engineering, physics, and safety factors.

Fig. 1 shows two different heat flux profiles used in this analysis that have the same total power on the divertor plate. The peak heat flux in normal operation on the inclined divertor plate include estimated physics and engineering peaking factors for uncertainties in asymmetries and geometrical alignment, power variation, and for safety considerations. The uncertainties in the scrape-off layer (SOL) width may also contribute to the peaking factor by narrowing the profile as shown in fig. 1, such that the total power to the divertor plate remains the same. The resulting peak heat flux value in a device like ITER can be as high as 40 MW/m^2 with a FWHM of only 4–5 cm. There is no available material that can withstand such high heat fluxes over extended periods of time. Because of this peaked nature of the heat flux, a modest movement around the origin can substantially reduce the effective heat flux on the divertor to an acceptable level from material performance points of view. The maximum acceptable surface temperature for a graphite-based material is assumed to be about 1400 K in order to avoid runaway erosion by self-sputtering at plasma edge temperatures up to 100 eV.

It was recently recommended for a device like ITER, based on physics considerations, that the sweeping frequencies of the heat load should be such that the sweeping distance times the sweeping frequency should be about 3 Hz cm. It was further recommended, due to design configuration and space limitations, that the sweeping in ITER be done within a distance of ± 15 cm from the origin. Fig. 2 shows the surface temperature variation at three different locations on the divertor surface during one complete sweeping cycle of ± 15 cm distance and 0.2 Hz frequency. This temperature profile is repeated every period ($t = 1/\text{frequency}$), i.e., every 5 s for this frequency during the main on-cycle of the reactor. If for example the duration of the main on-cycle of the reactor is 200 s, there will be 40 additional minicycles in this case. The near edge location, where the maximum temperature is expected to occur, is defined as one-half of the FWHM distance to the left of the edge location. The edge location is where the sweeping heat load is reversed toward the center of the sweeping. The temperature profile within the sweeping cycle varies substantially at each location on the divertor plate. The profile near the edge, for example, has a double hump and has the maximum expected temperature because the maximum heat load passes twice through this location in a very short time as it reverses at the edge.

Fig. 3 shows the spatial distribution of the maximum temperature occurred at each point along the divertor plate. Again, it can be seen that the highest temperature occurs near the edge location. It is noted that these maximum temperatures occur at different times as the heat load moves along the divertor plate. It can also be seen that the maximum temperature on the divertor plate exceed the 1400 K limit set to avoid runaway erosion. This means that the sweeping parameters of ± 15 cm distance and 0.2 Hz frequency are not

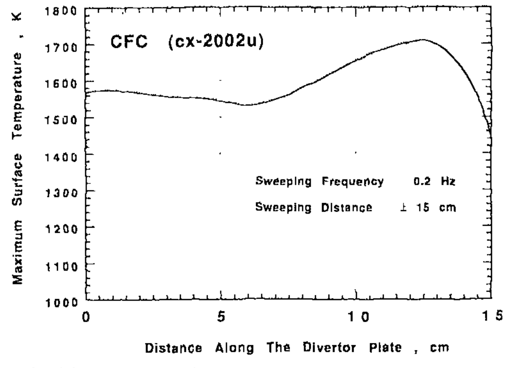

Fig. 3. Maximum surface temperature occurred along the divertor plate.

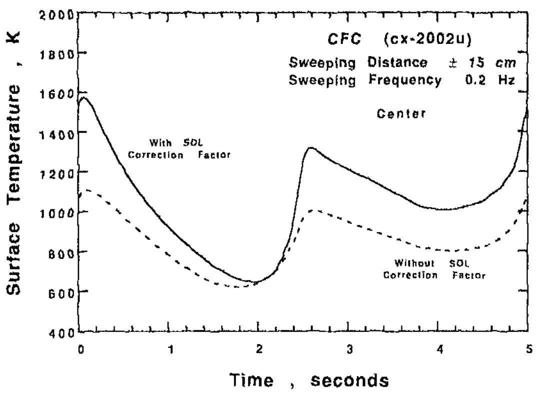

Fig. 4. Surface temperature variation for different heat flux profile.

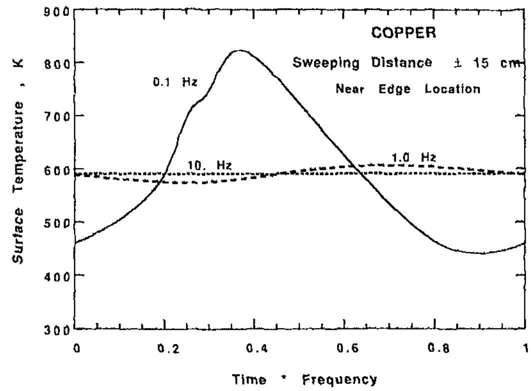

Fig. 6. The effect of different sweeping frequencies on the substrate structure.

sufficient for the narrow peaked heat flux profile shown in fig. 1. For the less peaked heat flux distribution, with the same power content but without the scrape-off uncertainty factor, the surface temperature rise is always much less than that of the peaked profile as shown in fig. 4.

The effect of increasing the sweeping frequency on the armor surface temperature is shown in fig. 5. Increasing the sweeping frequency from 0.1 to 10 Hz will reduce the maximum surface temperature by a factor of about 2. Not only the higher sweeping frequency reduces the peak surface temperature, it also reduces the temperature change (ΔT) within the sweeping cycle. This is more important for the heat sink substrate structure because it reduces the thermal stresses and fatigue damage. Fig. 6 shows the corresponding copper substrate surface temperature rise for the different sweeping frequencies. Although increasing the frequency from 0.1 to 1.0 Hz will increase the number of cycles by a factor of 10 (this is in addition to the total main reactor on- and off-cycles) it will reduce the ΔT from 400 K to only a few degrees. This will result in an increase in the fatigue lifetime.

The near edge maximum surface temperature as a function of the sweeping distance for different sweeping frequencies is shown in fig. 7. The required sweeping distance for each sweeping frequency such as to keep the maximum surface temperature at 1400 K is also shown. To keep the sweeping frequency at 0.2 Hz, one should sweep the heat load at ± 25 cm from the origin. However, if one can sweep the heat load at a frequency of 1.0 Hz, the sweeping distance need only be ± 14 cm. The decision whether to use higher sweeping frequencies or larger sweeping distances should be based on several factors such as the required sweeping power, design constraints, space limitations and other factors.

The effect of the sweeping frequency on the predicted maximum temperature near the edge location is shown in fig. 8 for two different sweeping distances. A large reduction in the armor surface temperature predicted when increasing the sweeping frequencies to 1.0

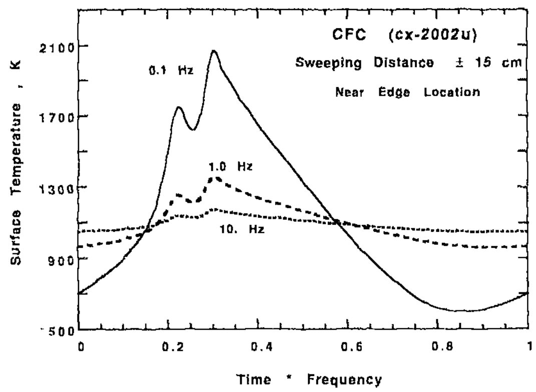

Fig. 5. The effect of different sweeping frequencies on the armor surface temperature.

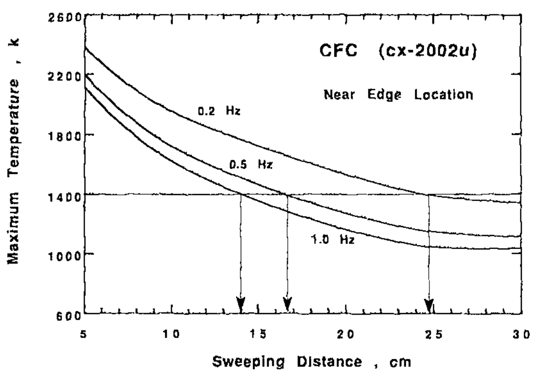

Fig. 7. Maximum armor surface temperature as a function of sweeping distance.

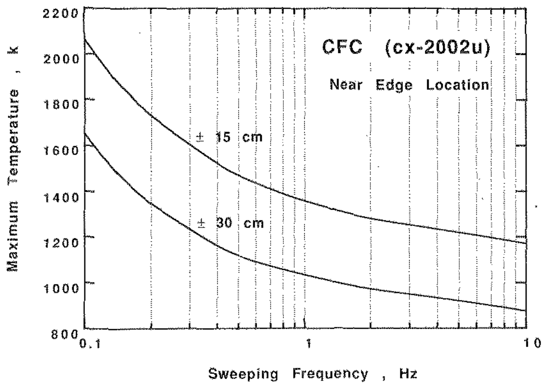

Fig. 8. Maximum armor surface temperature as a function of sweeping frequency.

Hz. Further increase in the sweeping frequencies does not substantially reduce the temperature and may require a larger power supply. However, longer sweeping distances always result in large temperature reductions because of the narrow nature of the predicted heat flux distribution on the divertor plate. In addition, longer sweeping distances may have other advantages such as spreading both sputtering and disruption erosion over larger areas. This will result in a much longer lifetime for the divertor plate.

3. Conclusions

Sweeping the heat loads over the divertor plate may be required to mitigate and reduce the effects of the highly peaked heat fluxes. Higher sweeping frequencies and longer sweeping distances substantially reduce the resulting armor and substrate surface temperature. Lower temperatures also allow the use of thicker armor and coating materials which tend to increase the erosion lifetime. The maximum temperature during sweeping will roughly occur about one-half the FWHM (of the heat flux) to the left of the sweeping edge. Longer sweeping distances have the additional advantage of spreading disruption and sputtering erosion over larger areas, thus, substantially increasing the divertor lifetime.

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