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THERMAL SWEEPING ANALYSIS FOR DIVERTOR PLATE MATERIALS*

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ABSTRACT

Magnetically sweeping the separatrix along the divertor plate is proposed to accommodate higher heat loads or to reduce the maximum armor/coating surface temperature for a given heat flux distribution. During the sweeping, each position on the divertor plate will experience periodic heat and particle flux variations. The magnitude of these variations with time will depend on the location as well as on the time shape of the sweeping wave. Consequently, the shape of the sweeping pulse and the sweeping frequency will determine the maximum surface temperature as well as the spatial distribution of the temperature along the sweeping distance. Sweeping is also expected to increase the lifetime due to reduction in both physical sputtering and chemical and radiation enhanced erosion for materials such as graphite or carbon composites.

I. INTRODUCTION

The heat flux to the divertor plate of a magnetically confined fusion reactor such as ITER may be one of the most limiting constraints on the lifetime of such components. Particular attention has recently been focused on methods to extend the capability of the divertor plate to withstand higher heat fluxes. Magnetically sweeping the separatrix along the divertor plate has been proposed as one of the ways to reduce the thermomechanical effects of the highly localized surface heat flux and to reduce the erosion of the plate resulting from the associated particle fluxes of energetic ions.

During the sweeping, each position along the divertor plate experiences periodic fluctuations in both the heat and the particle fluxes. The magnitude of these variations with time will depend on the location as well as on the shape and the frequency of the sweeping wave. The main disadvantage resulting from the sweeping process is associated with the additional internal cycles (due to the temperature fluctuations) that is superimposed on the main reactor on- and off-cycles. However, the advantages resulting from the sweeping overcome these concerns.

The computer code A*THERMAL-2[1] is modified and used in the thermal analysis of the divertor plate due to moving heat loads. The maximum surface temperature is calculated for various sweeping frequencies and different sweeping wave shapes. The code can handle both one and two dimensional geometry and up to four different layers of materials such as for coatings and substrates. The original heat flux distribution on the divertor plate surface can be described by either a histogram or by analytical functions. Various boundary conditions are incorporated in the code to account for possible surface radiation and surface recession due to erosion and/or melting.

Although similar analysis can be done for any potential divertor material, most of the work presented in this paper assumed that the divertor plate was constructed of graphite armor bonded to a Cu-alloy as a heat sink material. Parametric studies were conducted comparing different types of graphite subject to a range of heat flux distributions in order to account for peaking factors for both physics and engineering uncertainties.

II. THERMAL ANALYSIS

Parametric studies were conducted comparing different types of graphites such as nuclear grade (H451), as deposited pyrolytic graphite (PG), and carbon-fiber-composites (CFC) [CX-2002U]. This particular type of CFC was adopted in this study because it is the only type that has actual published data on its thermophysical properties. The divertor plate was assumed to be constructed of 1 cm thickness of graphite tiles over 3 mm of Cu-alloy, cooled with water of a temperature

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around 50°C. The heat flux profile used in this analysis is shown in Fig. 1. This heat flux has a peak of about 10 MW/m^2. The dashed heat flux profile shows the anticipated sweeping process around the center point along the divertor plate. The bottom illustrations in Fig. 1 show the possible shapes of the sweeping wave. A triangular, as well as a sinusoidal sweeping waves were proposed as a different mechanisms to perform the sweeping process.

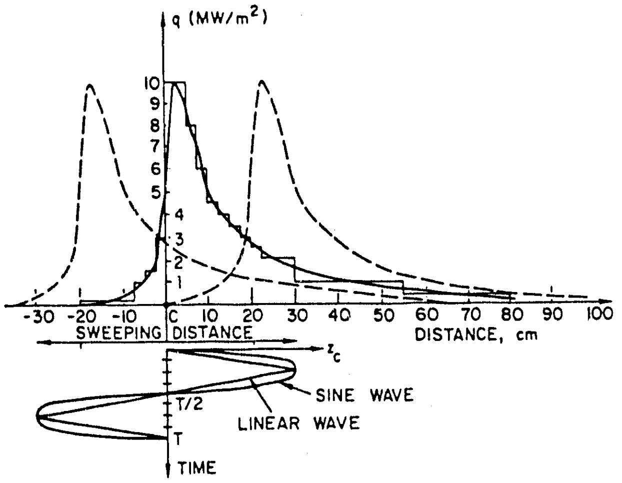

Figure 1. Typical heat flux distribution on the divertor plate.

The thermal analysis was done for stationary (no sweeping) as well as for sweeping heat loads with different peaks, i.e., 10, 15, and 20 MW/m^2 to account for both physics and engineering uncertainties. A maximum surface temperature limit of about 1100°C (1400 K was assumed for graphite tiles based on erosion and redeposition calculations.[2] The irradiated thermophysical properties of graphite tiles are used in this analysis since these properties reach the saturation level in less than 1 dpa. In a device such as ITER this corresponds to one-to-one and half months of continuous operation.

The temperature at the end of the sweeping distance, i.e., the edge temperature, is usually higher than that at the center of the sweeping wave.[3] This is mainly because the time exposure of the peak heat flux at the edge is longer than that at the center. For the same reason, a sinusoidal sweeping wave will result in higher temperatures at the edge and lower temperatures at the center of the sweeping compared to the linear or triangular sweeping wave. The actual sweeping wave configuration will be determined by the design of the sweeping coils and the power required to sweep and reflect the wave at the end of the sweeping distances. The maximum possible surface temperature as a result of the sweeping is expected to be at the edge of an irradiated material resulting from a sinusoidal sweeping wave. However, if it is possible to sweep linearly, that will result in a little lower surface temperature rise at the edge.

The spatial sweeping amplitude is another important factor to determine the peak surface temperature as well as the temperature profile over the divertor plate. Larger sweeping distances are expected to substantially reduce the surface temperature rise for both the tile and the substrate materials. This is mainly because of the expected narrow nature of the heat flux distribution over the divertor plate. However, the maximum sweeping amplitude is constrained by the actual divertor geometry and configuration. A parametric sweeping amplitudes of ±10 cm, ±20 cm, and ±30 cm is analyzed in this study.

A typical surface temperature profile for both the tile and the substrate due to the sweeping process is shown in Fig. 2. For this case the sweeping frequency is 0.1 Hz and the sweeping distance is ±20 cm. The on-cycle of the reactor is assumed to be 200 seconds. The fluctuations or the mini-cycles superimposed on the temperature profile throughout the main on-cycle is due to the sweeping of the heat load. The period and the magnitude of each mini-cycle depend on the sweeping parameters. In this case the period of each mini-cycle is 10 seconds making the total number of these mini-cycles to be 20 over one main on-cycle of the reactor.

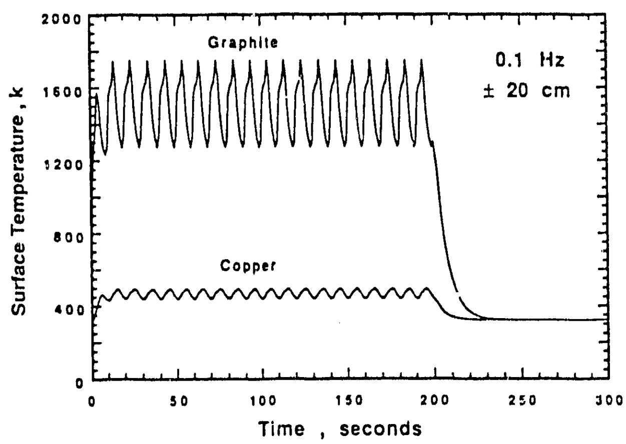

Figure 2. Surface temperature profile due to the sweeping process.

The effect of the sweeping frequency on the maximum surface temperature rise for an irradiated nuclear grade graphite (H451) tiles is shown in Fig. 3. This temperature profile is repeated every time t=1/frequency (seconds), during the main on-cycle of the reactor. The peak surface temperature for a stationary heat flux of 10 MW/m^2 (i.e., no sweeping or the sweeping frequency = 0) is calculated to be about 2700 K for the same divertor configuration. It can be seen that increasing the sweeping frequency will substantially reduces the maximum surface temperature. A sweeping frequency of 1 Hz will reduce the peak temperature by about a factor of 2. Not only a higher sweeping frequency reduces the peak surface temperature, it also reduces the temperature change within a given sweeping cycle. This is more important for the substrate or the heat sink structure because it reduces the thermal stress fatigue damage.[3] Figure 4 shows the corresponding copper substrate surface temperature response as a result of the sweeping process. It can be seen that higher sweeping frequencies almost eliminate the copper surface temperature fluctuation during the sweeping cycle.

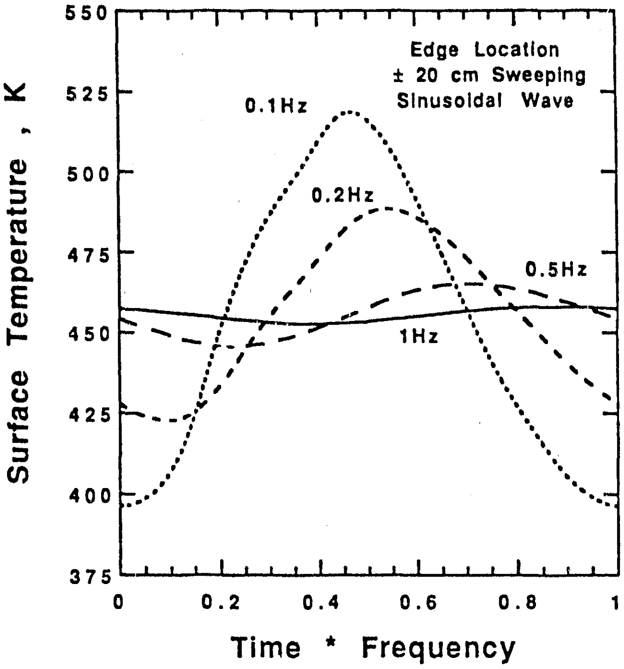

Figure 4. Copper surface temperature rise for different sweeping frequencies.

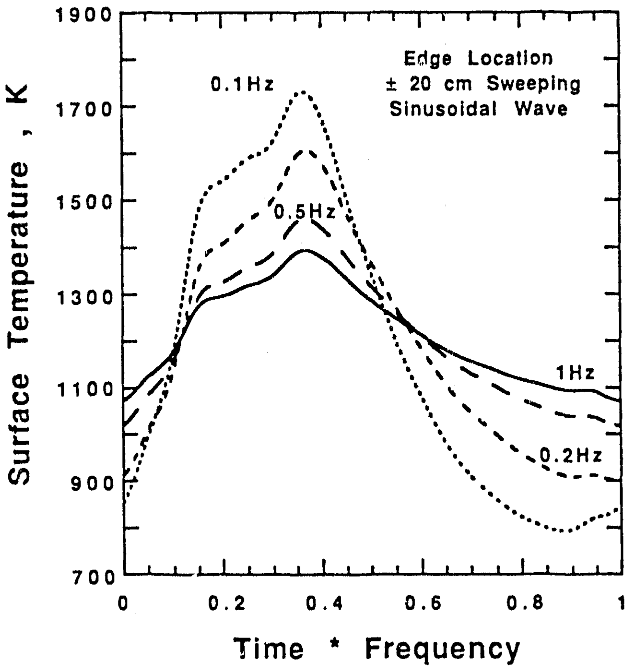

Figure 3. Surface temperature rise of nuclear grade graphite for different sweeping frequencies.

The effect of the sweeping distance on the temperature rise for a sweeping frequency of 1 Hz is shown in Fig. 5. Larger sweeping distances will always result in lower surface temperature profile. However the maximum possible sweeping distance may again be limited by the divertor plate configuration and design constraint as well as by the power required for the sweeping process.

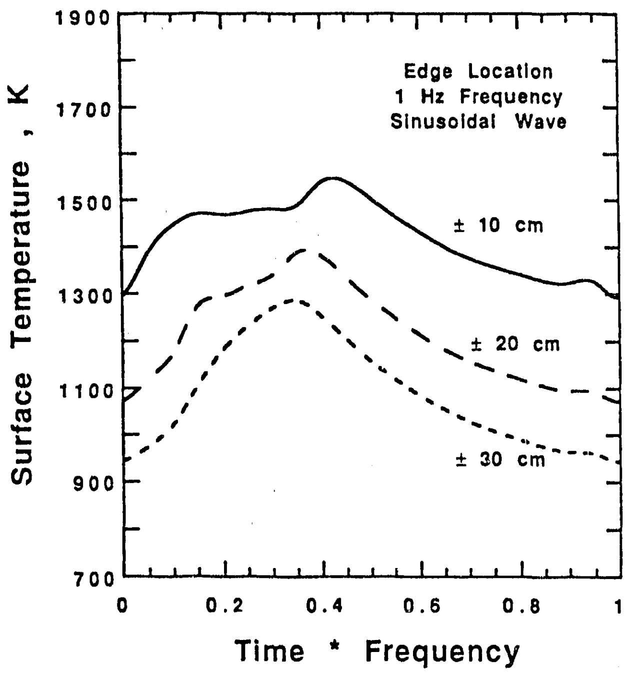

Figure 5. Surface temperature rise of nuclear grade graphite for various sweeping distances.

The calculation for the tile surface temperature is performed in this analysis assuming a radiating boundary condition at the surface. The radiating heat flux is assumed towards locations which operate at or close to the coolant temperature. However, if the entire first wall is radiatively cooled, or the surface emissivity is very low, or other geometrical factors such that to reduce the radiation heat flux, the resulting surface temperature from the sweeping process will be much higher than those presented here. In other words, the effect of the surface radiation can be very important in lowering the surface temperature and enhance the effectiveness of the sweeping process.[3]

It was recently recommended for a device like ITER, based on physics considerations, that the sweeping frequencies are given such that the sweeping distance times the sweeping frequency should be around 3 Hz•cm. It was also recommended that linear sweeping may be feasible. Linear sweeping is expected to slightly reduce the peak temperatures at the edge.[3] Since the effect of neutron irradiation on the thermophysical properties at high temperatures is not well known on different graphite materials, the calculation for this section is done for unirradiated properties. Figure 6 shows the maximum surface temperature as a function of the sweeping distance (such that distance × frequency = 3 Hz•cm) for different graphite candidate materials. For this case the divertor plate is assumed to be 1 cm thickness of graphite tiles over 3 mm of Cu-alloy as a heat sink material. It can be seen that all different types of graphite result in a maximum surface temperature lower than the 1400 K limit for all the sweeping distances and frequencies considered. It is also clear that a larger sweeping distance with a lower frequency is more effective in reducing the maximum temperature than a shorter sweeping distance with a higher frequency. This is mainly because of the narrow nature of the given heat flux distribution along the divertor plate. Larger sweeping distances are also better for erosion and disruption lifetime. However for the case of a heat flux profile with a peak of 20 MW/m^2, only pyrolytic graphite can satisfy the temperature limit for all the sweeping distances and frequencies considered as shown in Fig. 7. It should also be mentioned that a sweeping with a peak heat load of 20 MW/m^2 may result in heat transfer coefficient being in the boiling regime at the water coolant interface. This may substantially enhance the heat transfer and hence result in further reduction of the tile surface temperature at the surface.

It was further recommended, based on design configurations and limitations, that the sweeping in ITER be done within a distance of ±15 cm. Figure 8 shows the maximum tile surface temperature as a function of sweeping peak heat flux for a sweeping distance of ±15 cm and a corresponding frequency of 0.2 Hz. It can be seen that the maximum tolerable heat flux for H451 and CFC to stay within the temperature limits of 1400 K is about 12 and 16 MW/m^2, respectively. Pyrolytic graphite stays well within the temperature

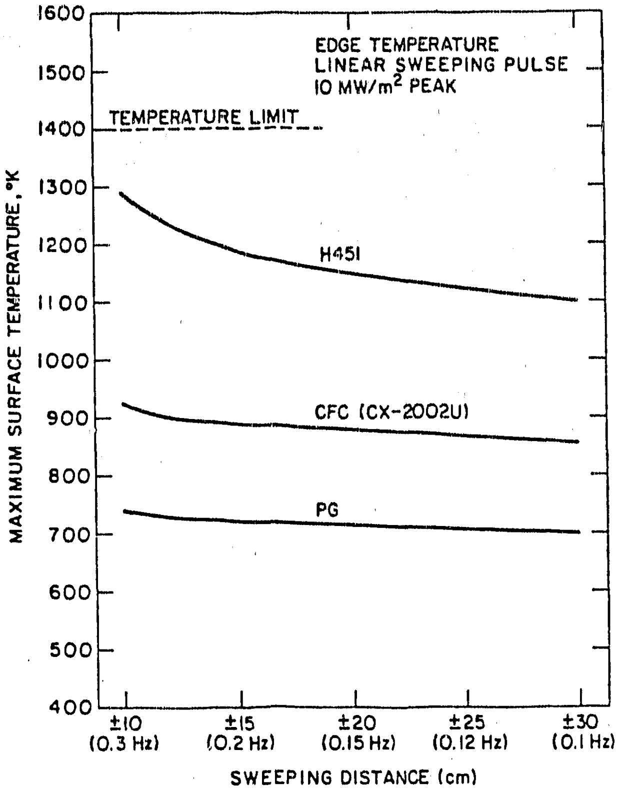

Fig. 6. Tile surface temperature as a function of sweeping distance and frequency.

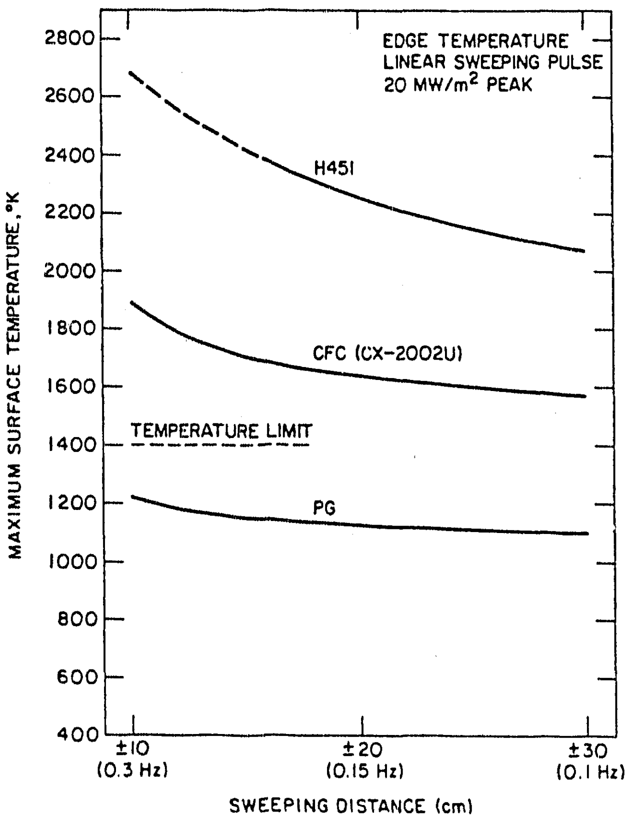

Fig. 7. Tile surface temperature as a function of sweeping distance and frequency.

limits for these sweeping conditions for peak heat fluxes even higher than 20 MW/m^2. However, the effect of neutron irradiation on the properties at high temperatures needs to be examined.

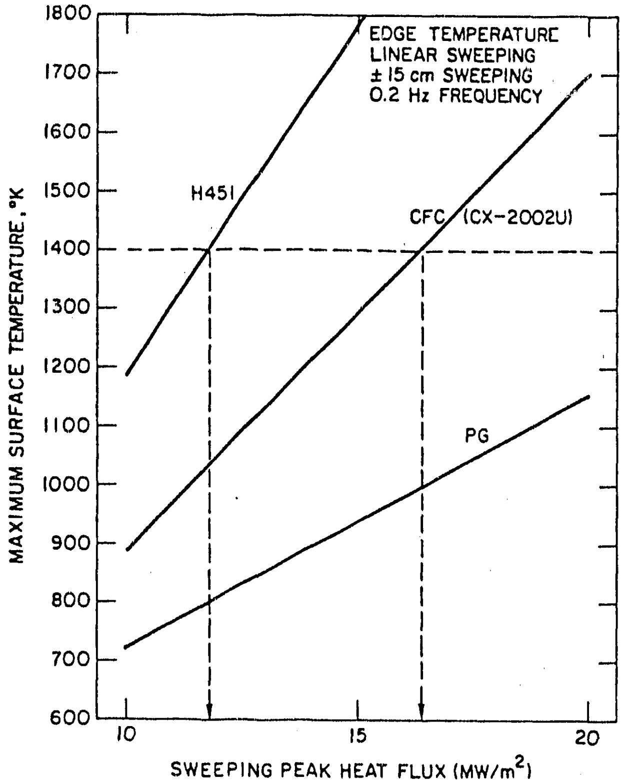

Figure 8. Maximum tile surface temperature as a function of sweeping peak heat flux for sweeping distance of ±15 cm and a frequency of 0.2 Hz.

Pyrolytic graphite is still far better than other graphite in accommodating higher heat fluxes because of its high thermal conductivity. However, it is believed that carbon-fiber-composites can be made with conductivity as high as pyrolytic graphite if not higher. This is especially important since there are some concerns of using pyrolytic graphites resulting from delamination of its planes when exposed to high heat fluxes. With high thermal conductivity graphites, the resulting surface temperature is low enough to do without sweeping for the range of heat fluxes considered in this analysis. For example a 1 cm pyrolytic graphite tile on a 3 mm Cu-substrate can withstand up to 16 MW/m^2 stationary heat flux, and with the enhanced boiling heat transfer coefficient this heat flux can be even higher, up to 20 MW/m^2.[4] However, sweeping may be beneficial in other aspects such as producing uniform erosion along the divertor plate from both sputtering and disruption and therefore result in longer lifetime of the plate.

III. CONCLUSION

Sweeping the separatrix along the divertor plate surface can substantially reduce the surface temperature rise compared to stationary heat loads for both tile and heat sink materials. The higher the sweeping frequency and the larger the sweeping distance, the lower the resulting surface temperature. The maximum temperature at the edge of the sweeping distance is usually higher than that at the center of the sweeping wave. A sinusoidal sweeping wave can result in higher temperatures at the edge and lower temperatures at the center of the sweeping compared to a linear sweeping. Pyrolytic graphite, whether it is compressed annealed or as deposited, still results in much lower temperature rise than other graphites or current fiber composites. In general, sweeping allows higher heat loads on the divertor plate or allows the use of much thicker tiles which offers longer lifetime against erosion.

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