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Hot spot formation on electron-emissive target plate with plasma potential variation across magnetic field

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Abstract

Nonlinear dynamic behavior of hot spot formation on tungsten (W) material surfaces is numerically investigated by introducing a transient heat pulse into the local area of the hot W sheet immersed in high heat flux plasma. It is found that the formation and development of hot spot depend not only on plasma parameters (plasma heat flow, plasma potential variation) and the energy and time scale of heat pulse but also sensitively on electron-emission characteristics of the tungsten surface as well as the size of hot spot in a nonlinear way. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Heat pulses; Heat spot; High-Z materials; Plasma sheath; Numerical simulation

1. Introduction

High heat flux plasma in fusion devices sometimes leads to a local hot spot on plasma-facing materials caused by reduction of the sheath voltage due to thermoelectron emission [1–4], resulting in enhanced erosion on the divertor plate. This can result in increased impurity contamination of the core plasma. Electron emission is one of several key factors which determine the energy transmission through the sheath [5–10]. A general nonlinear thermal bifurcation induced by electron emission has been studied both in experiments and the 0-D numerical analysis [11,12]. The formation of hot spot on tungsten (W) plate has been observed in experiments on NAGDIS-I [13], and is explained by enhancement of the local heat flow by a thermal contraction induced by cross-field potential variation in a plasma and thermoelectron emission [14].

In tokamaks, on the other hand a divertor target plate receives repetitive heat pulse due to minor disruption and edge localized modes (ELMs) in case of H-mode [15]. Measurements of the ELMs heat pulse on a number of tokamaks indicate that peak divertor heat flux during ELMs is as high as 50–100 MW/m^2. The ELMs deposition time varies from about 0.1–1.0 ms. Such a high transient heat flux from each ELM may lead to divertor plate damage. Therefore, the divertor design requires the transient heat flux from individual ELMs to remain below the threshold for ablation of the divertor target surface. So it is of great interest to investigate the dynamic behavior of hot spot formation on the target plate responding to a heat pulse in a variety of conditions in such a nonlinear system.

In this paper, we will discuss some dynamic behaviors of hot spot formation on the W sheet which is heated locally by introducing a transient heat pulse into such a system composed of the high heat flux plasma and the hot W surface, in which we consider the plasma potential variation across the magnetic field and the thermoelectron emission from the W surface. A correct emission current expression under space charge limited condition for arbitrary sheath voltages [5] is used in our numerical analysis. The results of numerical analysis indicate some interesting nonlinear relations among the plasma potential variation, the formation and development of hot spot on the W plate, and the energy, the pulse width and the irradiation area of heat pulse. Finally, effects of modified tungsten surface irradiated by high heat flux plasma on the hot spot formation is discussed.

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2. Model and basic equations

Fig. 1 shows essential features of the model for our numerical analysis. We assume a cylindrical symmetry plasma with the uniform electron temperature of T_e and the electron density of n_e. The plasma potential $\phi_p(r)$ is assumed to have a hollow radial distribution across the magnetic field, $e\phi_p(r)/T_e = -\Phi_0(1 - r^2/a^2)$, and not to change due to the existence of the conductive plate and the thermoelectron emission, where Φ_0 (>0) is the normalized potential drop at the center of plasma column, and a is the radius of plasma column. Such a hollow radial distribution is considered just for comparing numerical analysis with the experiment which will be carried out on a linear divertor simulator NAGDIS-I in which a fairly deep hollow structure of plasma potential is created due to the PIG (Penning ionization gauge) configuration for plasma production. The magnetic field is normal to the surface, and the charged particles in the sheath are assumed to be collisionless. The target plate satisfies the floating condition as a whole, that is, the total current flowing into the target plate should be zero. It should be noted that it is not necessary to match the ion and electron current density locally in the case of a conductive target plate. The thermoelectron current $j^-_{TH}(r)$ is determined by the smaller value of either the Richardson Dushman temperature limited formula $j^-_{TH_t}(r) = AT^2 \exp[-e\phi_w/(kT)]$, or the space charge-limited current [5] $j^-_{TH_s}(r) = G(l + G)^{-1} n_{se} e\sqrt{-2\Phi T_e/m_e}$, where A is Dushman's constant, ϕ_w is the work function of the material, n_{se} is the electron density at the sheath edge and assumed to be equal to 0.5 n_e, $\Phi = e\phi/T_e$ is the normalized sheath voltage in front of the target plate. G is the function of Φ.

In order to investigate the dynamic behavior of hot spot formation a transient heat pulse is introduced into the central area of the target plate immersed in the high heat flux plasma in the form $q_{hp} = E_{hp}/(\Delta t_{hp} S_{hp})$, where E_{hp}, Δt_{hp} and S_{hp} are the energy, the pulse width and the irradiation area of heat pulse, respectively. $S_{hp} = \pi r^2_{hp}$, where r_{hp} is the radius. When the central area of the target plate is heated locally by a transient heat pulse up to a temperature high enough to generate the thermoelectrons, the surface potential tends to decrease so that it may approach more to the plasma potential. This positive feedback may lead to a transition to have a strong hot area near the center.

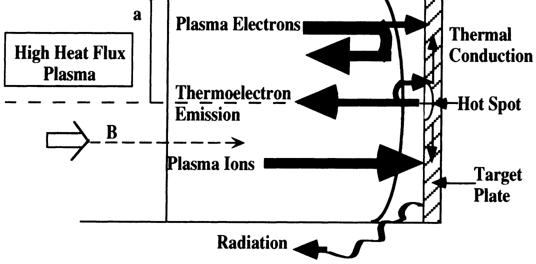

Fig. 1. Schematic diagram for the numerical analysis model.

The time evolution of the temperature distribution $T(r)$ on the target plate, which is obtained by solving the 2-D heat conduction equation as follows [14], $\rho C_p \partial T/\partial t = \lambda \nabla^2 T + (q_{in} - q_{loss})/\delta$ where ρ and C_p are the mass density and the specific heat of the plate material; λ and δ are the heat conductivity and thickness of the plate material; we neglect the dependence of ρ, C_p and λ on T. $q_{in} = 2q_0 + q_p + q_{hp}$, where q_0 is determined by initial plate temperature T_0, q_p is the heat flux distribution from plasma to the plate and determined by the sheath voltage. The loss term q_{loss} includes the losses of the thermal radiation, the emission of thermoelectrons and the evaporation.

3. Dynamic behavior of hot spot formation responding to a transient heat pulse

A numerical analysis is carried out for a helium plasma with the W target plate. Dushman's constant $A = 6.0 \times 10^5$ [$A/(m^2\ K^2)$], the emissivity $\varepsilon = 0.42$, the work function $\phi_w = 4.5$ eV, $\rho = 1.935 \times 10^4$ (kg/m^3), $C_p = 137$ [J/(kg K)], and $\lambda = 163$ [W/(m K)] for W. The radius of the plasma column a is assumed to be 0.05 m, and the thickness of the W plate $\delta = 0.1$ mm. We chose He plasma parameters $n_{se} = 1.0 \times 10^{19}$ m^{-3}, $T_e = 10$ eV and $\Phi_0 = 5$. The central T on the tungsten plate arrives to 2983 K in steady state by such a high heat flux plasma. This surface T is not large enough to generate enough thermoelectron emission to make the transition. Then we introduce a heat pulse q_{hp} to the central area of the tungsten plate. A dynamic behavior of hot spot formation is investigated responding to such a transient heat pulse by the numerical analysis in various conditions. These results give some interesting phenomena as follows.

3.1. Effect of pulse width of transient heat input

We fix the energy of the heat pulse $E_{hp} = 40$ J and the radius of the heat area with $r_{hp} = 1$ cm. The dynamic behavior of the formation and development of the hot spot were studied with different widths of the heat pulse. The time response of the central temperature T of the W surface to the heat pulse corresponding to $\Delta t_{hp} = 0.5$ s, 0.1 s and 0.05 s are shown by dashed line, solid line and dotted line respectively, in Fig. 2(a). The heat pulse starts at $t = 1.5$ s. In the case of $\Delta t_{hp} = 0.5$ s, T increases slowly during heat pulse up to 3070 K at $t = 2.0$ s, then goes back to the original temperature before the input of heat pulse. The time evolution of the central normalized sheath Φ and the central electron heat flux q_e are shown by the dashed lines in Fig. 2(b). It shows that the heat pulse can not induce a thermal transition since the central T value of 3070 K is not high enough to generate the electron emission to make large reduction of the sheath voltage at the center.

In the case of $\Delta t_{hp} = 0.1$ s, on the other hand, we find that a heat pulse induces a thermal transition of the central area of the W plate; T arrives at 3220 K at $t = 1.6$ s, as shown by the solid line in Fig. 2(a), and Φ at the center decreases to a smaller steady state value leading to a space charge limited current condition, as shown by the solid line in Fig. 2(b). After the termination of heat pulse at $t = 1.6$ s, the central temperature is kept at a new steady state of 3110 K although the temperature T decreases slightly. This is because an enhancement of the central plasma heat flux is maintained due to the small Φ compared with that before the heat pulse application, as shown by the solid line in Fig. 2(b).

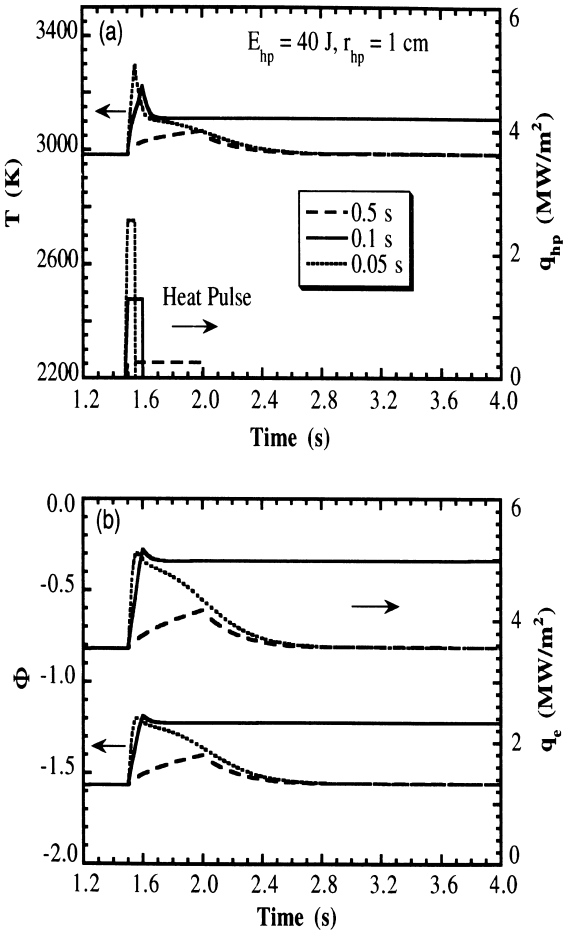

Fig. 2. Dynamic response of the temperature T and the normalized sheath voltage Φ at the center, and the electron heat flux q_e to the center of W plate to the heat pulse q_{hp} with three values of pulse width $\Delta t_{hp} = 0.5$ s, 0.1 s, and 0.05 s.

If we further shorten Δt_{hp}, let us see what happens. In the case of $\Delta t_{hp} = 0.05$ s. The central T increases much rapidly to a higher temperature of 3330 K. However, it decreases rapidly to a lower value due to a large radiation energy loss during high T after the end of the heat pulse. The system finally goes slowly back to the original state. The time response of Φ and q_e at the center are shown by the dotted lines in Fig. 2(b). It shows that the sheath potential becomes deep again and the central q_e decreases with decrease in T, leading to the state before the heat pulse input. These results show that the transition induced by the heat pulse occur only in certain range of the time scale of the heat pulse in the case of a fixed energy of the heat pulse. Beyond the range of the time scale the heat pulse may not induce the stable formation of the hot spot.

3.2. Effect of area of heat pulse on the hot spot formation

We fix the energy of the heat pulse $E_{hp} = 60$ J and $\Delta t_{hp} = 0.5$ s. The dynamic behavior of the formation and development of the hot spot were studied with different sizes of hot spot.

The temporal behavior of T for $r_{hp} = 2$ cm, 0.5 cm and 0.3 cm are shown in Fig. 3(a) by dashed, solid and dotted lines, respectively. The heat pulse starts again at $t = 1.5$ s. It is found that the heat pulse can induce the thermal transition only in the case of $r_{hp} = 0.5$ cm among three sizes. Although the central T decreases slightly at the end of the heat pulse $t = 2.0$ s, the temperature still increases again gradually to 3400 K from $t = 2.7$ s and is kept at high temperature, as shown by the solid line in Fig. 3(a). The time response of Φ and q_e to the heat pulse are shown by the solid line in Fig. 3(b). It shows clearly that when the center area of the tungsten plate is heated locally by a transient heat pulse up to a temperature high enough to generate the thermoelectrons, the surface potential tends to decrease so that it may approach more to the plasma potential, as shown by the solid line in Fig. 3(b). The central electron heat flux is greatly enhanced by such a small sheath voltage, finally leading to a stable hot area near the center.

Fig. 4 shows the horizontal distributions of the W plate temperature and emission current density J_{TH} at two times $t = 1.4$ s and 4.0 s corresponding to the beginning and after the removal of the heat pulse, respectively. It is found that a stable hot region with the center $T = 3400$ K is formed by the heat pulse, as shown by solid line ($t = 4.0$ s). The dashed line in Fig. 4 shows the horizontal distributions of J_{TH} in the hot spot area near the center. It is found to be determined by space charge limited current condition, in which a hollow profile in the center region comes from a hollow plasma potential profile assumed in our numerical analysis.

In the cases of $r_{hp} = 2$ cm and 0.3 cm, the time response of T of the W surface, Φ and q_e at the center are shown by dashed line and dotted line, respectively, in Fig. 3. It is found that the heat pulse can not make the transition in both these two cases. In the case of $r_{hp} = 2$ cm, T has only a little increase by the heat pulse because S_{hp} becomes large corresponding to a small heat flux density q_{hp} compared with that of $r_{hp} = 0.5$ cm. But in the case of $r_{hp} = 0.3$ cm, corresponding to a large q_{hp} compared with $r_{hp} = 0.5$ cm, the central T decreases rapidly to the temperature before heat pulse input although the central T increases to 3300 K at the end of heat pulse, as shown by dotted line in Fig. 3(a). This phenomena can be understood by the time behavior of Φ and q_e shown by dotted lines in Fig. 3(b). Φ and q_e have only a small change compared with that as in the case of $r_{hp} = 0.5$ cm. This is because the thermoelectron emission from a small area does not make a large emission current. When the tungsten plate satisfies the floating condition as a whole, the floating potential of tungsten plate is determined by the zero condition to the total current flowing into the target. The emission current from a small area is too small to make a large change of the floating potential of the tungsten plate. So, Φ has only a small change. This result indicates that the size of the hot area will have an important effect on the transition to a stable hot spot formation.

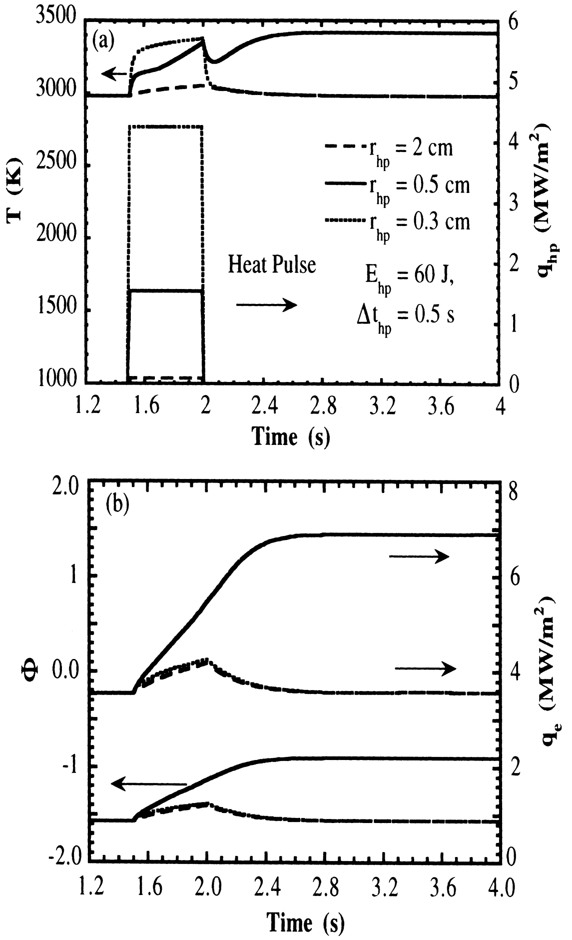

Fig. 3. Dynamic response of the temperature T and the normalized sheath voltage Φ at the center, and the electron heat flux q_e to the center of W plate to the heat pulse q_{hp} with three different sizes of heat pulse, $r_{hp} = 2$ cm, 0.5 cm, and 0.3 cm.

3.3. *A modification of tungsten surface on electron emission characteristics*

The electron emission characteristics on the material surface is very sensitive to the work function and the temperature of the materials. Some experimental results indicate that microstructure of tungsten surface can be modified by irradiation of high heat flux plasma [13]. The electron emission characteristics from such a modified surface may be changed due to the changes of work function, Dushman's constant and emissivity of tungsten material. Fig. 5 gives a comparative numerical analysis for two different values of work function $\phi_w = 4.5$ eV and 4.54 eV for W with same parameters corresponding to $E_{hp} = 80$ J, $\Delta t_{hp} = 0.5$ s, $r_{hp} = 1$ cm, $n_{se} = 1.0 \times 10^{19}$ m^{-3}, $T_e = 10$ eV and $\Phi_0 = 5$. Fig. 5 shows that we have quite different results although the work function has a change by only less than 1%. The heat pulse does induce the transition for $\phi_w = 4.50$ eV and does not induce the transition for $\phi_w = 4.54$ eV. Therefore the effect of modification of material surface on electron emission should be taken into account for the explanation of the experimental phenomena.

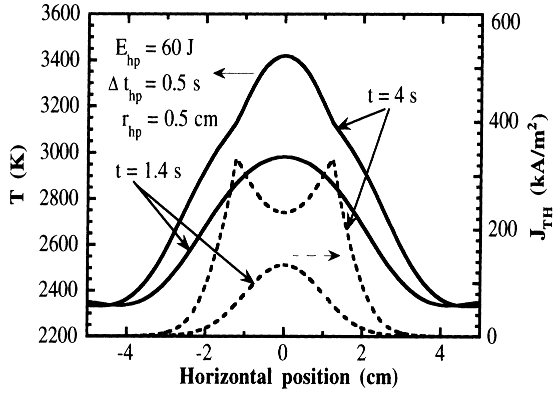

Fig. 4. Horizontal distributions of the W plate temperature T and emission current density J_{TH} at two times $t = 1.4$ s and 4.0 s.

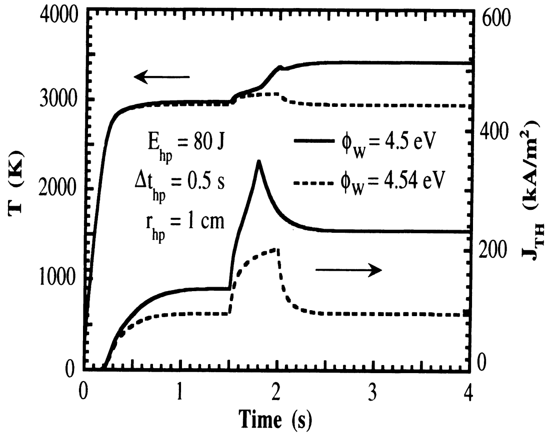

Fig. 5. Dynamic response of the central temperature T and emission current density J_{TH} corresponding to two different work functions $\phi_w = 4.5$ eV and 4.54 eV.

4. Summary

Dynamic behavior of hot spot formation on tungsten plates due to a transient high heat pulse is investigated. From our numerical analysis, the conclusions are summarized as follows:

1. It is found that the formation and development of hot spot depends not only on plasma parameters (plasma heat flow, plasma potential variation) and the energy and time scale of heat pulse, but also depends sensitively on the electron-emission characteristics of the tungsten surface as well as the size of hot spot in a nonlinear way. For a certain energy heat pulse the transition induced by the heat pulse occur only in certain range of pulse width of the heat input. Beyond the range of the time scale, the heat pulse may not induce the stable formation of the hot spot. The size of the hot area will have an important effect on the transition to have a stable hot spot formation.
2. The effect of modification of material surface irradiated by high heat flux plasma on the electron emission characteristics should be taken into account for the quantitative comparison between experiments and numerical analysis.

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