THEORETICAL STUDY OF THE W-TH CATHODE ON PLASMA ARC TORCHES

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A problem of major concern still restraining the use of plasma systems over long periods of time is cathode erosion. The more common cathode materials used are the binary alloys like W-Th and Cu-Cr, in which diffusion processes drive the life improving mechanism.

Our principal aim in the present work is to create a working model of this type of cathode, which later will be used to set the optimum operation parameters. In particular we are mainly concerned with adsorbate dynamics on the spot, which is the basic physical process determining the temperature distribution and therefore the cathode life time.

We use a one-dimensional model of a W-Th cathode of length L. The dependence of the temperature with time t and position x, $T(x,t)$, inside the cathode is governed by the following non-linear equation:

$$\rho c_p \frac{\partial T}{\partial t} = \sum \frac{\partial}{\partial x}\left(\kappa(T) \frac{\partial T}{\partial x} \right) + S, \tag{1}$$

where the specific heat c_p, the thermic conductivity κ and electrical resistivity ρ_e (present in the S term which takes account of Joule heating effect) are experimentally known functions of the temperature T. The cathode base is maintained refrigerated at a constant temperature $T_{o,}$ whereas the spot temperature satisfies the general boundary condition:

$$\kappa \frac{\partial T}{\partial x}\bigg|_{x=0} = q_{rad} + q_{Nott} + q_{ion} + q_{evap}, \tag{2}$$

where the terms on the right account for the energy flows due to: radiation (q_{rad}), the Nottingham effect (q_{Nott}), heating by ion impinging (q_{ion}) and to cooling by evaporation of the cathode material (q_{evap}).

The dopant concentration $n(x,t)$ is set by the following equation:

$$\frac{\partial n}{\partial t} = \sum \frac{\partial}{\partial x}\left(D(T) \frac{\partial n}{\partial x} \right), \tag{3}$$

where the temperature dependence of the diffusion coefficient is $D(T) = D_0 \exp(-Q/kT)$, and D_o and Q depends of the cathode material.

This is important due to the wide range of temperatures present inside the cathode. The concentration n_0 of Th in the base of the cathode remains unchanged during its functioning, whereas in the spot, it initially fall at a constant rate until reaching a negligible level, where it stays essentially null during the rest of the cathode lifetime.

The key physical parameter in the functioning of the doped cathodes is θ: the degree of the dopant coverage of the surface of the spot, which determines the value of the work function $\varphi(\theta)$. The dependence of φ as a function of θ is known from experiments (Fig.1). The time evolution of θ is determined by

$$N_o \frac{d\theta}{dt} = -\Gamma(T_S)U(\theta)\xi + D(T_S)\left.\frac{\partial n}{\partial x}\right|_{x=0}. \qquad (4)$$

The first term on the right hand side of this equation accounts for the desorption of Th on the spot, while the last term refers to the dopant supply by diffusion from the cathode bulk. In (4) T_S is the spot temperature. The evaporation rate of the thorium atoms is $\Gamma(T) = \Gamma_o \exp[-H(\theta)/kT]$ where H is the heat of adsorption, N_0 is the surface density of available sites for adatoms, the function $U(\theta) = \theta$ if $\theta < 1$ and equals unity otherwise, and the factor ξ gives the fraction of atoms that do not return to the cathode.

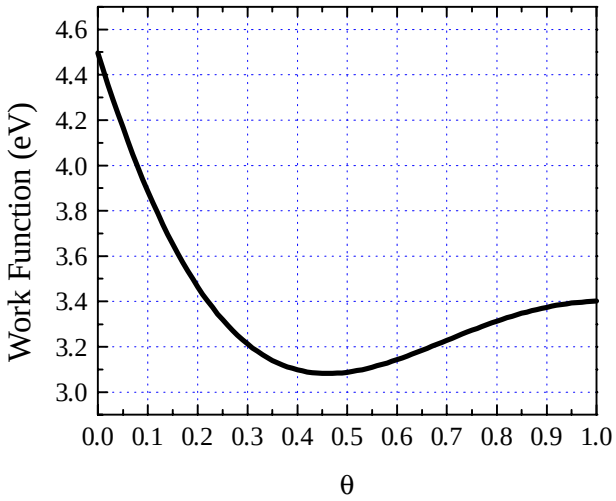

Fig. 1. Work function versus grade of coverage

The Equations (1), (3) and (4) are a system of non-linear differential equations that will be solved numerically. In order to do that the boundary condition (2) will be simplified: In Fig. 2, the power density extracted by electrons emitted from the spot is shown. As can be seen in the work area (Region I) of the doped cathodes studied, the electronic emission is essentially thermionic, and the power associated with the extracted electrons is relatively low. This allows for dismissing the Nottingham effect and describing the electronic emission through the Richardson-Dushman expression. Furthermore as the arc works at constant intensity, the density of emission current, j_0, will be constant as well. Therefore, instead of equation (2) we can use the simpler boundary condition

$$j(T_S,\theta) \equiv A{T_S}^2 \exp[-\varphi(\theta)/kT_S] = j_0, \qquad (5)$$

which determines the spot temperature if the degree of coverage θ is known.

In obtaining the numerical solution of the system of equations we have used finite-

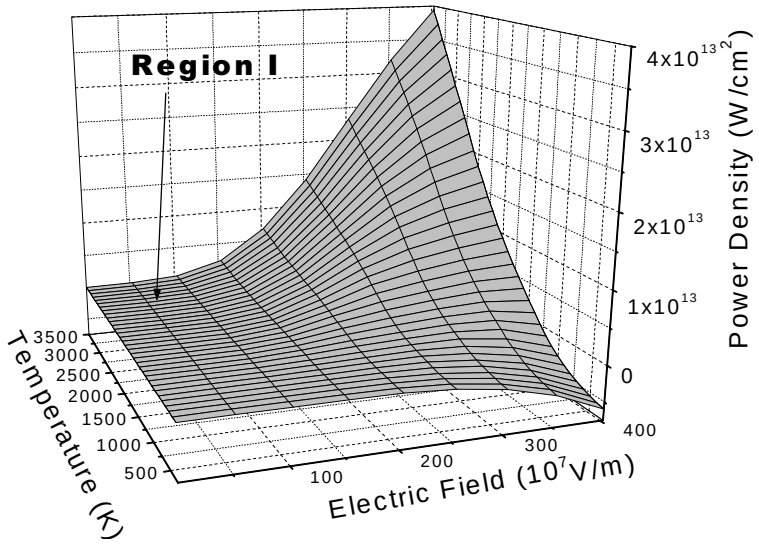

Fig. 2. Power extracted by electrons.

difference methods with a fully implicit scheme for the partial differential equations and a 4-order Runge-Kutta method with adaptative stepsize control for the θ equation. We have solved the two stages of the cathode life: (i) The first stage is characterized by an initial uniform distribution n_0 of dopants, and by thorium atoms accumulation on the spot that maintain $\theta > 1$. This makes the work function correspond with that of thorium, therefore it is not necessary to take into consideration the Eq. (4). In spite of the fact that very few thorium atoms are lost to the plasma by evaporation, the supply of atoms by diffusion coming from the bulk is very slow, so that eventually the concentration n on the spot drops to zero and θ diminishes to 1, facts that mark the end of this stage. (ii) In the second stage the concentration of dopant on the spot remains null, whereas the coverage of thorium atoms might be less than a monolayer, making the work function and the speed of thorium disorption vary, which at the same time will change the temperature distribution and the diffusion speed. The combination of these factors will determine the time spent by the cathode in this stage.

To approach the problem from the beginning of the functioning of the cathode allows us to determine unambiguously the initial condition in both stages. In the first stage $n(x, t = 0) = n_0$. Moreover, the equation for the temperature decouples, and the temperature rapidly reaches a stationary distribution independent from the initial condition. The state of the cathode at the end of this stage forms the initial condition for the final stage.

In the calculation we used usual values for thoriated tungsten cathodes (at 2% wt.) in argon: $T_0 =$ 400 K, $D_0 = 1.1\ \ cm^2/s$, $Q = 4.1\text{eV}$, $\Gamma_0 = 4.4\times10^{26}\ cm^{-2}s^{-1}$, $\xi = 1.8\times10^{-3}$, $N_0 = 4\times10^{14}\ cm^{-2}$ and $j_0 = 10\ \text{kA}/cm^2$.

The main results we obtained are the following: The cathode remains in the first stage of work approximately 10% of its life time (we consider the cathode life time equal to the time elapsed until the temperature reaches the melting point of tungsten). At the end of this stage the concentration profile goes from $n = 0$ at the spot to $n = n_0$ in a distance less than

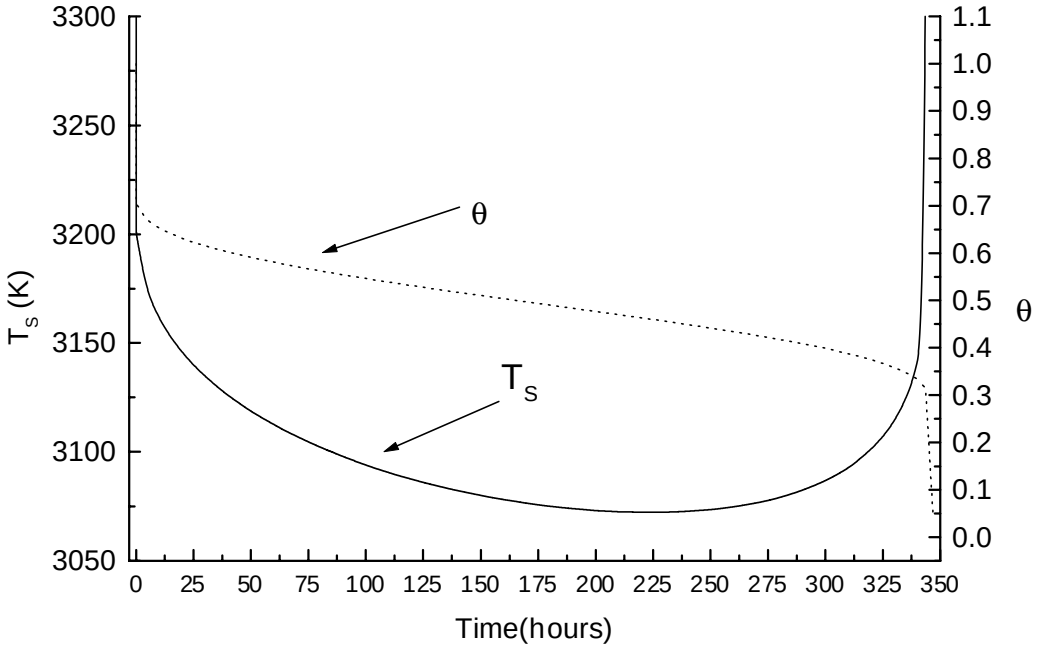

Fig. 3. Temperature of the spot and grade of coverage θ versus time.

20% of the cathode length. The slope of n/n_0 is near to 1 on the spot. The time needed to reach this concentration profile is very sensitive to the desorption factor ξ, increasing approximately twice if we reduce the ξ value by a third.

The evolution of both the temperature of the spot and θ after reaching the monolayer of thorium on the spot is shown in Fig. 3. The layer of thorium drops dramatically to 0.65. From this point a softly sloping plateau is reached where the cathode spends the greatest part of its working time. On this plateau the spot temperature reaches its minimum value. For $\theta = 0.35$ the temperature increases quickly reaching the melting temperature for tungsten, while a rapid depopulation of thorium atoms on the cathode surface occurs.