Mode changes on thermionic cathodes: I. Sensitivity study

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A numerical study of effect of control parameters on the mode of attachment of a high pressure arc discharge to a cathode is performed in the framework of the model of nonlinear surface heating. Both steady-state and non-stationary regimes of current transfer to the cathode were modeled. Calculations reveal that the appearance of both steady-state and transient spots on thermionic cathodes is strongly affected by the cathode geometry and thermal conductivity of the cathode material. Dynamic transitions between the diffuse and spot modes provoked by a current jump are strongly affected by the target current.

1. Introduction

A crucial point in ensuring a stable and lasting operation of arc devices consists in controlling the mode of attachment of the arc to the cathode. In most case, the diffuse attachment is preferred, however it may be unstable and spots appear on the cathode surface.

It is quite difficult to obtain in the experiment a reproducible transition between diffuse and spot modes of arc-cathode attachment. This suggests that this transition is highly sensitive to discharge and electrode parameters and it is this sensitivity that complicates the experiments. On the other hand, this sensitivity, if properly understood, promises a possibility of control of transitions between different modes and ensuring a desired mode.

In this work, the effect of three kinds of control parameters is studied: of cathode geometry, of thermal conductivity of the cathode material, and of target current in a current jump. The effect of power supply on non-stationary mode changes provoked by a current jump is studied numerically and experimentally and the possibility of prevention of appearance of spots is demonstrated in the second part of this work [1].

2. Model and Numerics

A time dependent temperature distribution T in the body of a cathode is considered. Joule heat production in the body of the cathode is neglected. The base of the cathode is maintained at a fixed temperature T_c and the rest of the cathode surface is in contact with the plasma or the cold gas and is heated or, respectively, cooled.

Mathematically, the problem amounts to solving the transient thermal conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) \qquad (1)$$

with the boundary condition

$$T = T_c \qquad (2)$$

at the base and with the nonlinear boundary condition

$$\kappa \frac{\partial T}{\partial n} = q(T_w, U) \qquad (3)$$

at the rest of the cathode surface. Here ρ, c_p and κ are the density, specific heat and thermal conductivity of the material of the cathode, respectively; n is a direction locally orthogonal to the cathode surface and directed outside the cathode; and $q(T_w, U)$ is a given function of the cathode surface temperature T_w and of the near-cathode voltage drop U which describes the energy exchange between the cathode surface, on one hand, and the arc plasma and the cold gas, on the other hand. In particular, the function $q(T_w, U)$ takes into account radiation energy losses from the cathode surface.

The function $q(T_w, U)$ and the function $j(T_w, U)$ describing the density of electric current to the cathode surface are calculated by means of equations given in [2-4] and summarized in [5]. (Some additional theoretical materials and an online tool for simulation of the diffuse mode of current transfer developed in the framework of this theory can be found on the Internet [6].)

The code developed for numerical solution of the nonlinear boundary-value problem (1)-(3) is similar to one used in [7] to solve a stationary temperature distribution problem in the body of a cathode. Shortly, the code consists of two modules. The first module, written in FORTRAN, calculates functions $q(T_w, U)$ and $j(T_w, U)$ by means of solving equations describing the near-cathode layer in a high-pressure arc plasma. The second module calculates the temperature distribution inside the cathode body and at the surface by means of solving the problem (1)-(3) in the cathode. This module is realized by means of the commercial finite element software COMSOL MULTIPHYSICS.

Control parameters of the model are cathode geometry, thermal conductivity, emissivity and work function of the cathode material, the plasma pressure and species of the plasma-producing gas. Numerical results given in this work refer to cathodes made of tungsten operating in the argon plasma. Tungsten cathodes operating in the mercury plasma will be considered in the second part of this work [1]. Data on thermal conductivity, emissivity and specific heat capacity of tungsten was taken from [8], [9] and [10], respectively; the values of 4.55eV and 19300$Js^{-1}K^{-1}$ were assumed for the work function and specific heat of tungsten, respectively. We have also considered data on thermal conductivity taken from [11] which refers to thoriated tungsten but also used to modeling cathodes made of pure tungsten [12,13].

3. Examples of modeling results

The effect of cathode geometry, thermal conductivity of the cathode material and target current of a current jump on cathodic arc attachment mode have been studied considering a cathode in the form of a rod of radius 0.5mm and a height 12mm, operating in the argon plasma under the pressure of 2bar; the temperature of the base of the cathode was set to 1000K. This geometry is convenient for purposes of illustrations.

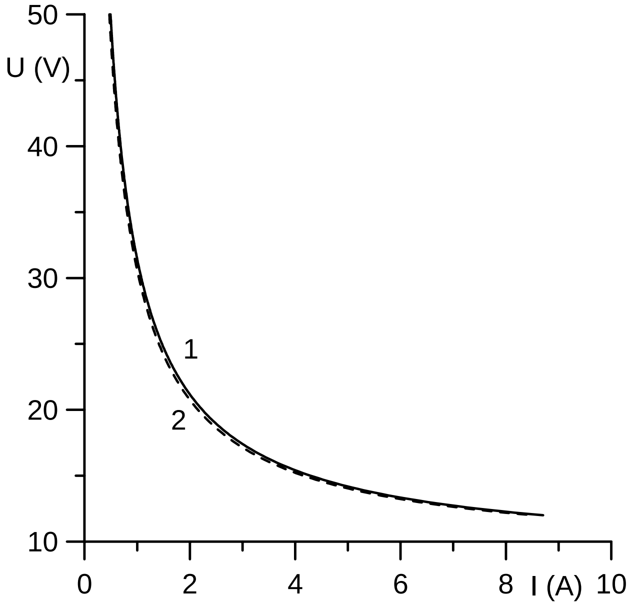

Figure 1. Current-voltage characteristics of the diffuse mode. 1: thermal conductivity of tungsten taken from [8]. 2: thermal conductivity of tungsten taken from [11].

Stationary current–voltage characteristics of the diffuse mode and of the spot mode (mode with a spot at the edge of the front surface of the cathode) of current transfer to a tungsten cathode, with above mentioned parameters, are shown in figures 1 and 2, respectively. As it was established in [3] the current-voltage characteristic of the stationary spot mode consists of two branches, a high-voltage branch (solid lines in figure 2) which exists in the current range from zero up to a current corresponding to the turning point (the point at which a solution reaches a limit of its existence region and then turns back), and a low-voltage branch (dotted lines in figure 2) which exists in the current range between the bifurcation point (the point at which the spot branch off from the diffuse mode) and the turning point. For the presented case, the bifurcation point is positioned in the region of very high voltages (well in excess of 200V), while the current corresponding to the turning point is around 1.95A.

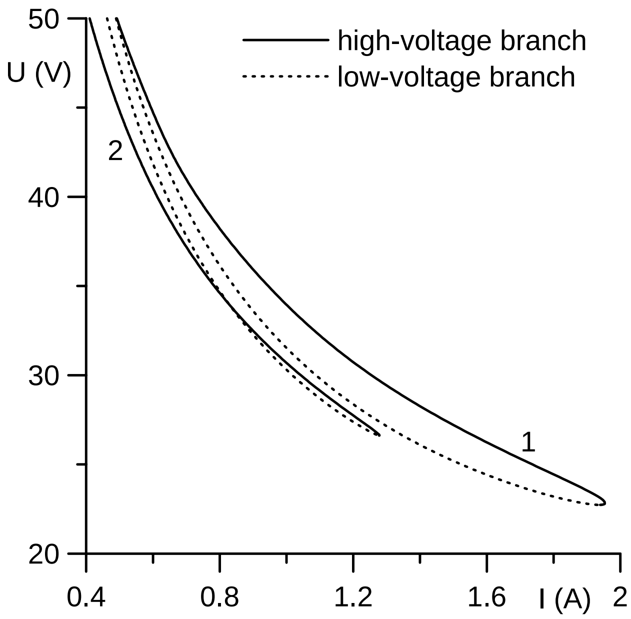

Figure 2. Current-voltage characteristics of the spot mode. 1: thermal conductivity of tungsten taken from [8]. 2: thermal conductivity of tungsten taken from [11].

One can see from figures 1 and 2 that a change in the thermal conductivity of the cathode material has no appreciable effect on the characteristic of the diffuse mode while the turning point of the spot mode has changed considerably. This effect can be interpreted taking into account that the thermal conductivity taken from [11] is nearly the same as the one taken from [8] at low temperatures and appreciably higher at high temperatures. Thermal conductivity has no appreciable effect on the characteristic of the diffuse mode because the temperature attained by the cathode when operating in the diffuse mode is relatively low compared with the one attained in the spot mode. On the other hand, the temperature attained by the spot calculated with thermal conductivity taken from [11] is less than the one attained by the spot calculated with thermal conductivity taken from [8] (according simulation results not shown in this work). This explains the decreasing of the current corresponding to turning point of the spot calculated with thermal conductivity taken from [11].

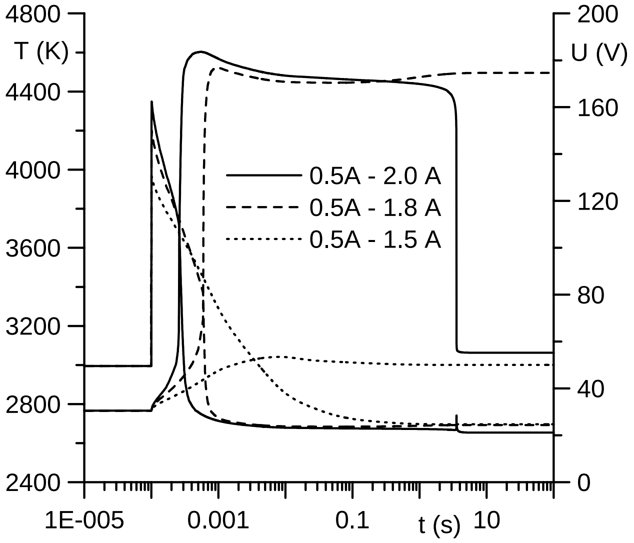

Figure 3. Maximum temperature on the cathode surface and near-cathode voltage drop for different current jumps. Cathode in the form of a rod with a flat front surface.

Figures 1 and 2 refer to steady-state current transfer. The rest of this paper deals with non-stationary effects. Following [12,13], we will study non-stationary effects provoked by a current jump. Let us assume that the discharge burns in the steady-state diffuse mode at $I = I_1 = 0.5\text{A}$. At the moment $t = 100\mu\text{s}$ the current starts growing. It grows linearly with time and in $1\mu\text{s}$ (i.e., at $t = 101\mu\text{s}$) attains a target value $I = I_2$, after which the current remains constant. The temperature distribution in the cathode body and the near-cathode voltage drop will undergo a transition process and then a new steady state will be reached.

Figure 3 shows results of simulation of the temporal variation of the maximum temperature of the cathode surface and near-cathode voltage drop for current jumps with the target current of 1.5A, 1.8A and 2.0A. In the case $I_2 = 1.5\text{A}$, the temperature distribution during the whole transition process remains axially symmetric. The maximum temperature of the cathode surface remains around 3000K. One can say that the transition process in this case occurs in the diffuse mode.

In the case $I_2 = 1.8\text{A}$ the axial symmetry breaks down during the transition process and a hot current spot is formed. The formation of the spot is accompanied by a steep decrease of the near-cathode voltage. Once having been formed, the spot continues to exist at all times. In other words, the final steady state belongs to a spot mode. A more detailed investigation shows that this state belongs to the high-voltage branch of the first spot mode.

A spot appears also in the case $I_2 = 2.0\text{A}$, however in this case it does not exist at all times but rather disappears, around $t = 3\text{s}$. Its disappearance is accompanied by a small voltage peak. In other words, the spot is transient in this case and the final steady state in this case belongs to the diffuse mode.

In our simulations, a transient spot is formed for target currents above 1.95A. More specifically, a stationary spot is formed at $I_2 = 1.94\text{A}$, and a transient spot occurs at $I_2 = 1.96\text{A}$. Note that the current corresponding to the turning point of the stationary mode with one spot, shown in figure 2, is 1.95A.

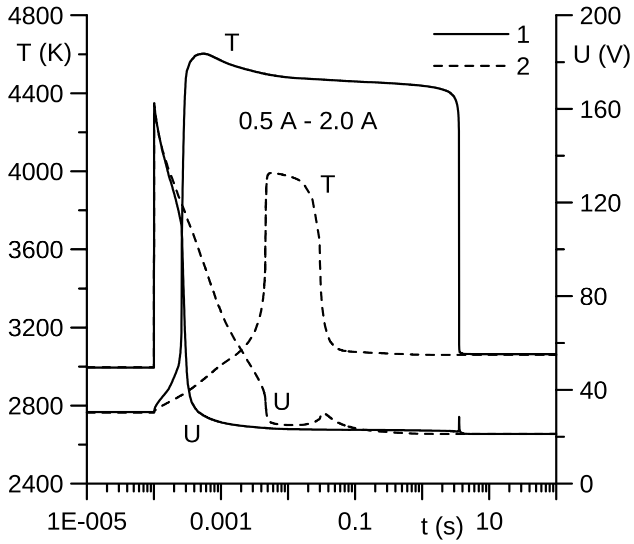

Figure 4. Maximum temperature on the cathode surface and near-cathode voltage drop for a current jump. 1: cathode in the form of a rod with a flat front surface. 2: cathode in the form of a rod with a rounding edge at the front surface.

One can conclude that there is a threshold value of arc current which coincides with the current corresponding to the turning point of the steady-state mode with one spot: a stationary spot belonging to the high-voltage branch of the first spot mode is formed at currents below this threshold and a transient spot occurs at currents above the threshold.

The effect of the cathode geometry on the formation of transient spots was studied by performing simulations for a cathode in the form of a rod with the same dimensions above considered but with a rounding edge at the front surface of $100\mu m$ radius. The temporal variation of the maximum temperature of the cathode surface and near-cathode voltage drop for a current jump with $I_2 = 2.0A$, for this geometry, are shown in figure 4. The spot on a rounded cathode is formed considerably later, is considerably less hot and lives much shorter, than the spot on a cathode with the flat front surface. This difference can be interpreted as a consequence of better cooling conditions on a rounded edge.

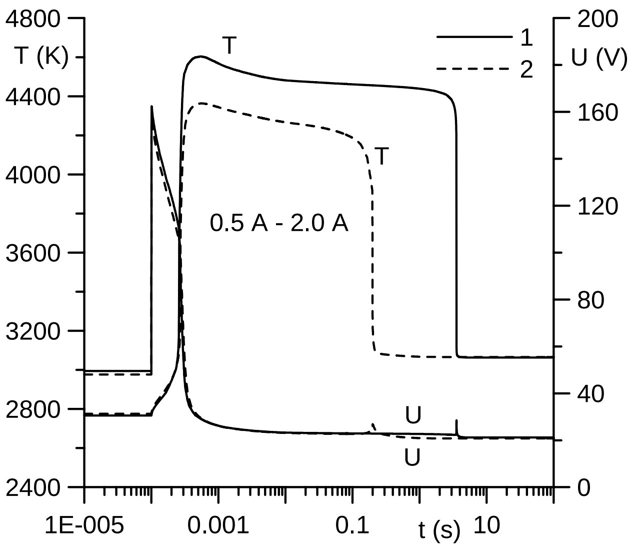

Figure 5. Maximum temperature on the cathode surface and near-cathode voltage drop for a current jump on a cathodes in the form of a rod with a flat front surface. 1: thermal conductivity of tungsten taken from [9]. 2: thermal conductivity of tungsten taken from [2].

Calculations reveal that the spot formation is strongly affected also by the thermal conductivity of the cathode material. Figure 5 shows the effect of this parameter on the temporal variation of the maximum temperature of the cathode surface and near-cathode voltage drop for a current jump with $I_2 = 2.0A$. When the thermal conductivity of tungsten taken from [8] is replaced by the one taken from [11], the lifetime of the spot considerably decreases and the spot temperature also decreases, although the time formation of the spot remains virtually unchanged. Again, this variation is a consequence of better cooling conditions for a spot on a material with higher thermal conductivity.

Acknowledgments

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