Patterns of current transfer to thermionic cathodes in a wide range of conditions

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Changes of the pattern of steady-state modes of current transfer to thermionic cathodes induced by variations of the cathode geometry and temperature of the cooling fluid are studied numerically. For some combinations of control parameters, only one stable mode in a wide current range exists, which combines features of spot and diffuse modes. There is a reasonable agreement between the modelling and the experiment on cathodes of both low- and high-current arcs. The conclusions on existence under certain conditions of only one stable mode in a wide current range and of a minimum of the dependence of the temperature of the hottest point of the cathode on the arc current, manifested by this mode, may have industrial importance and admit a straightforward experimental verification.

1. Introduction

Thermionic cathodes of complex geometries can exibit different patterns of current transfer and of its stability quite different from the one previously established [1,2] for a cathode with a flat front surface. This work is concerned with studying these patterns in a wide range of conditions and with finding out in what conditions each pattern occurs and how a transition between different patterns happens.

2. Numerics

The modelling is performed by means of the model of nonlinear surface heating; e.g., review [3] and references therein. Axially symmetric tungsten cathodes of different shapes and with different temperatures T_c of the cooling fluid are treated. All the results unless otherwise specified refer to an arc operating in argon under the pressure of 1 bar. Numerical calculations have been performed with the use of the commercial finite element software COMSOL Multiphysics. The stability of different modes of current transfer was investigated in the framework of the linear theory as decribed in [2, 4].

3. Results and discussion

Modelling results refer to axially symmetric cathodes which consist of a cylindrical section, a tip in the form of the half of spheroid at the top of the cylindrical section, and a hemispherical protrusion at the top of the tip; see figure 1. The radius and height of the cylindrical section are designated by R and $h - d$, respectively. The horizontal and vertical semi-axis of the spheroid are R and d, respectively. The radius of the protrusion is R_p. A cathode with a hemispherical tip without protrusion with $h = 10\,\mathrm{mm}$, $R = d = 1\,\mathrm{mm}$, $T_c = 1000\,\mathrm{K}$, is chosen as basic variant.

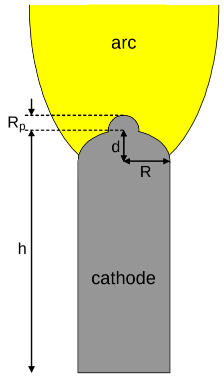

Figure 1: Geometry of the problem.

The dependence of the maximum temperature (T) of the cathode surface on the arc current (I) for cathodes with oblate tips ($d < R$) is shown in figure 2. The indices 1 and 2 designate the diffuse and, respectively, the first axially symmetric spot modes. Stable and unstable sections of each mode in this figure (and figure 3) are depicted by solid or, respectively, dotted lines. A decrease of the curvature of the cathode tip (i.e., a decrease of d) has virtually no effect on the diffuse mode and its stability. The Z-shape which is present on the low-temperature branch of the spot mode in the basic variant (figure 2a) becomes less pronounced with a decrease of d. There is a dramatic effect over stability of the spot mode. As d decreases, states of the high-temperature branch lose stability against the first mode of 3D perturbations. The state at which this change of stability occurs is marked in figure 2 by a circle. As d decreases the point of change of

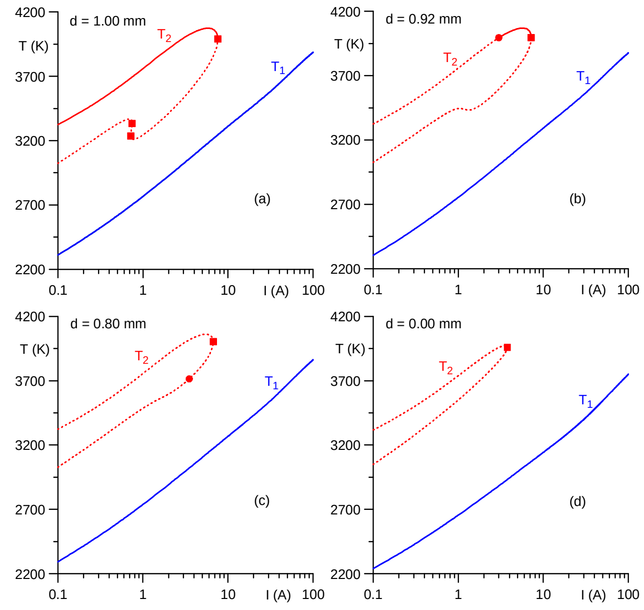

Figure 2: Effect of curvature of the cathode tip on the pattern of steady-state modes of current transfer to cathodes with oblate spheroidal tips (b, c) and a flat tip (d). Circle: state at which the change of stability against the first mode of 3D perturbations occurs. Square: turning point. $R = 1\,\mathrm{mm}$, $h = 10\,\mathrm{mm}$, $T_c = 1000\,\mathrm{K}$.

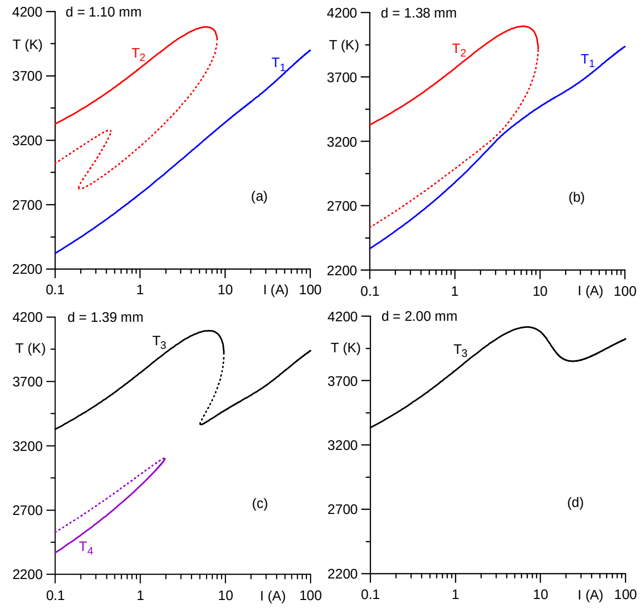

Figure 3: Effect of curvature of the cathode tip on the pattern of steady-state modes of current transfer to cathodes with prolate spheroidal tips. $R = 1\,\mathrm{mm}$, $h = 10\,\mathrm{mm}$, $T_c = 1000\,\mathrm{K}$.

stability moves in the direction of the turning point; the stable section of the high-temperature branch shrinks. At $d \approx 0.88\,\mathrm{mm}$ the point of change of stability passes over the turning point and moves to the low-temperature branch; the whole of the high-temperature branch becomes unstable: a situation familiar from simulations for the cathode with a flat front surface [2]. These results reveal the first possible scenario of variation of the pattern of current transfer to thermionic cathodes: a change of stability of the first axially symmetric spot mode which occurs through a travel of the point of change of stability against the first mode of 3D perturbations along the whole mode.

The dependence of the maximum temperature of the cathode surface on the arc current for prolate tips, $d > R$, are shown in figure 3. As d increases from 1 mm upwards, the above-mentioned Z-shape is shifted in the direction of low currents. Another effect caused by an increase of d is approaching of the diffuse and spot modes. At $d \approx 1.383\,\mathrm{mm}$ the two modes become connected: there is a state, corresponding to $I \approx 3.63\,\mathrm{A}$, which belongs to both modes. In other words, a bifurcation occurs. There are two disconnected modes once again as d grows further (figure 3c). The mode to which the index 3 refers exists in the whole current range under consideration and possesses a Z-shape. It is stable with exception of the "retrograde" section of the Z-shape. The mode to which the index 4 refers exists only at low currents and comprises two branches separated by a turning point. The low-temperature branch is stable in this case while the high-temperature branch is unstable. As d increases, the Z-shape on the mode 3 becomes less pronounced and eventually is extinguished (figure 3d). The mode 4 is shifted in the direction of low currents and only one mode exists in the whole current range considered (figure 3d). Since this mode possesses no Z-shapes, only one thermal regime of the cathode is possible at any current value within the range considered.

Temperature distributions in the body of the cathode for several states belonging to the mode 3 are shown in figure 4. While high-current states are characterized by smooth temperature distributions typical for the diffuse mode, there is a well-defined spot in the low-current states. States belonging to the stable branch of the mode 4 are characterized by smooth temperature distributions typical for the diffuse mode and there is something resembling a poorly pronounced spot on the unstable branch. Each of the two modes of steady-state current transfer existing in this geometry embraces diffuse states and states with spots; a result similar to the one reported in [5] for a cathode with a protrusion on the top of a hemispherical tip.

The above-described bifurcation involves modes

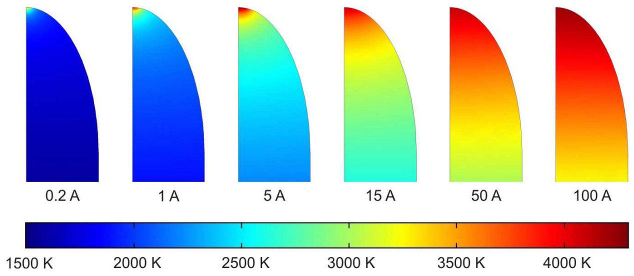

Figure 4: Distributions of the temperature inside a cathode with a prolate spheroidal tip in states belonging to mode 3. $d = 2\,\mathrm{mm}$, $R = 1\,\mathrm{mm}$, $h = 10\,\mathrm{mm}$, $T_c = 1000\,\mathrm{K}$.

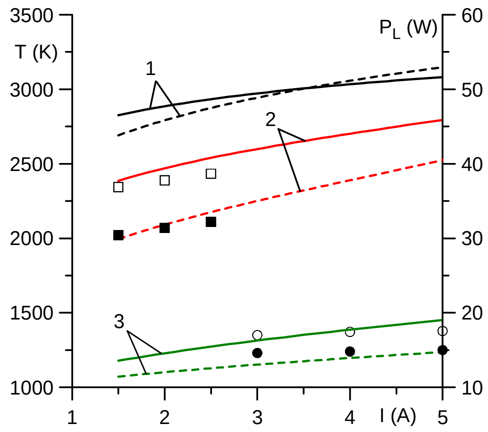

Figure 5: Characteristics of tungsten cathodes operating in a xenon plasma. Lines: modelling. Points: experiment [6]. 1: diffuse mode. 2 and squares: spot mode. Circles: super spot mode. 3: mode 3. Solid, open squares and open circles: Global cathode tip temperature. Dashed, full squares and full circles: Total power losses.

of the same symmetry and occurs at only one value of the parameter d. In this aspect, this bifurcation is fundamentally different from the pitchfork (symmetry-breaking) and saddle-node bifurcations. One can see from figures 3b and 3c that the modes exchange branches at this point, and this is why each of the two modes at $d > 1.383\,\mathrm{mm}$ embraces states typical for both diffuse and spot modes.

Results obtained for prolate tips reveal the second possible scenario of variation of the pattern of current transfer to thermionic cathodes: a bifurcation that is not symmetry-breaking occurs at a particular value of a control parameter (d, in this case) and is accompanied by an exchange of branches.

The effects of increase of R from 1 mm upwards and of decrease of h from 10 mm downwards are both quite similar to the effect of increase of d at fixed R and h. In other words, the second above-described scenario occurs.

The effect of increase of R_p, for a cathode of the same geometry that in the basic variant, is similar to the effect of d at fixed R and h with a hemispherical tip. In other words, the second above-described scenario occurs.

A third scenario of variation of the pattern of current transfer can be identified when T_c is decreased from 1000 K downwards: a junction of the diffuse and spot modes, the result being a single mode existing in a wide current range and comprising states characteristic of the spot mode at low current and of the diffuse mode at high currents. This mode is similar to the mode 3 in the second scenario, however there is a difference in the two scenarios as far as the way of its appearance is concerned: through a junction of the diffuse and spot modes that enters the considered range of I from the region of very low currents in the third scenario, or through a bifurcation that is not symmetry-breaking and occurs at a certain value of I inside the current range being considered in the second scenario. No analogue of the mode 4 exists in the third scenario.

A pattern with two distinct modes may be viewed as a manifestation of self-organization, while a pattern with one mode is governed by a non-uniformity of the current-collecting surface of the cathode. All the above-mentioned variations of control parameters contribute to the diffuse mode becoming less uniform along the front surface. Therefore, the second and third scenarios may be interpreted as a disappearance of self-organization due to an increasing non-uniformity of current-collecting surface.

The conclusions on existence under certain conditions of only one stable mode in a wide current range, which combines features of both spot and diffuse modes, and of a minimum of the dependence of the temperature of the hottest point of the cathode on the arc current, manifested by this mode, may have industrial importance and admit a relatively straightforward experimental verification.

4. Comparison with the experiment

Data of thermal measurements in the spot and super spot modes, in tungsten cathodes operating in a xenon plasma under the pressure of 2.6 bar, taken from figure 15 of [6] and modelling results are shown in figure 5. In accordance with the experimental observations, three variants of the cathode geometry were considered: a rod with a flat front surface; a rod with a front surface which is flat at the center and rounded at the edge, the radius of rounding being 100 μm; a cathode with a hemispherical tip and a protrusion in the form of half of a prolate

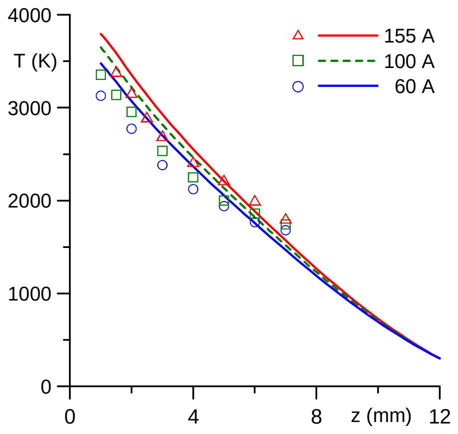

Figure 6: Axial distributions of the surface temperature of a 1 mm-radius rod cathode at arc currents of 50, 100, and 155 A. Lines: modelling, mode 3. Points: experiment [7], diffuse mode.

spheroid with minor and major semi-axes of 50 μm and 150 μm, respectively. It was set $R = 0.75$ mm, $h = 19$ mm, $T_c = 300$ K in all the variants.

In the first and second variants two separate modes were found, the diffuse mode and a 3D spot mode with a spot at the edge of the front surface of the cathode localized in the current ranges $I \lesssim 10.4$ A and, respectively, $I \lesssim 6.8$ A. In the third variant, mode 3 was found with two Z-shapes localized in the current range $15.6\,\mathrm{A} \lesssim I \lesssim 39.2$ A. Lines 1 in figure 5 represent modelling data on the diffuse mode under conditions of the first variant, lines 2 represent the high-temperature branch of the 3D spot mode under conditions of the second variant, and lines 3 represent mode 3 under conditions of the third variant.

There is a good agreement between the modelling and the experiment on the spot mode. According to the modelling, protrusions cause reductions of the global tip temperature and the power losses, and these reductions are comparable to those measured in the super spot mode provided that the protrusion is elongated. Thus, the super spot mode observed in [6] may be explained as mode 3 of the present work attached to an elongated protrusion.

Data on axial distributions of the cathode surface temperature measured at three values of I on a tungsten cathode operating in the diffuse mode taken from figure 6 of [7] and modelling results are shown in figure 6 (z is the distance measured along the cathode axis from the tip in the direction inside the cathode body). Three variants have been treated: a rod cathode of a height of 12 mm with a hemispherical tip; a rod cathode of a height of 12 mm with a flat tip; and a rod cathode of a height of 10 mm with a hemispherical tip. The cooling temperature T_c was set equal to 300 K.

Only one mode of current transfer was found in each variant for the current values to which data in figure 6 refer, and this is the diffuse mode or the high-current section of the mode 3 which comprises states typical for the diffuse mode. The lines in figure 6 represent modelling data under conditions of the first variant. According to both the experiment and the modelling, dependence of the temperature of the cathode surface on arc current is relatively weak, and the quantitative agreement is reasonable. As far as the spot is concerned, the modelling correctly describes trends observed in the experiment. However, the range of existence of the spot mode in the experiment considerably exceeds the range in which two modes are obtained in the modelling. Therefore, further work is clearly required, and this work should involve planning of experiments with account of modelling results.

Acknowledgments Work performed within activities of the project PTDC/FIS/68609/2006 of FCT and FEDER and of the project Centro de Ciências Matemáticas of FCT, POCTI-219 and FEDER. M. J. Faria appreciates financial support from FCT through grant SFRH/BD/35883/2007.

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