Effect of Joule heat generation in cathodes of high-pressure arc discharges

M. S. Benilov and M. D. Cunha

Departamento de Física, Universidade da Madeira, Largo do Município, 9000 Funchal, Portugal

Abstract

Considerable advances have been attained during the last decade in the theory and modelling of plasma-cathode interaction in high-pressure arc discharges; e.g., review [1] and references therein. In particular, available simulation methods allow one to self-consistently compute distributions of temperature and electric current density over the cathode surface in cases where the current transfer occurs both in the diffuse and spot modes; see, e.g., the free Internet tool [2].

There is, however, an important aspect that has not been investigated in sufficient detail up to now, namely, the effect of Joule heat generation in the cathode body: in most models this effect was neglected compared to the energy flux coming from the plasma. This simplification can be justified when the current transfer occurs in the diffuse mode and the current is low; on the other hand, it is *apriori* unclear what the role of Joule heating is in the spot mode and at higher currents in the diffuse mode.

In this work, the effect of Joule heat generation in the body of thermionic cathodes of high-pressure arc discharges is investigated by means of numerical simulation. The model is obtained by introducing an account of Joule heat production in the cathode body into the model of nonlinear surface heating, which is a widely used tool of simulation of plasma-cathode interaction in high-pressure arc discharges (e.g., [1] and references therein). To this end, the electric current continuity equation supplemented with Ohm's law is solved jointly with the equation of heat conduction in the cathode body. COMSOL Multiphysics commercial software is used. Special attention is paid to investigation of thermal balance of the cathode and of energy balance of the near-cathode plasma layer.

Calculation results are reported for tungsten cathodes and argon arcs under the following conditions, which are typical for experiments with high-pressure arc discharges [3-5]: plasma pressure 2.6 bar, cylindrical cathode of radius 0.75 mm and height 24 mm, current transfer occurs in the diffuse mode; plasma pressure 2.6 bar, cylindrical cathode of radius 0.75 mm and height 20 mm, current transfer occurs in the spot mode; plasma pressure 1 bar, cylindrical cathode with a hemispherical tip of radius 1 mm and height 12 mm, current transfer occurs in the mixed mode (a mode which embraces states with a diffuse temperature distribution at high currents and states with a hot spot at low currents [6]). Also reported are results on a solitary spot on an infinite planar cathode [7] in the atmospheric-pressure plasma.

It was found that the voltage drop inside the cathode is much smaller than the voltage drop in the near-cathode plasma region in all the cases and at all currents investigated, which justifies the model being used. The Joule heat generation has virtually no effect on thermal and electrical characteristics of the diffuse mode at low currents, of the spot mode on the cylindrical cathode, and of the solitary spot mode.

On the other hand, the Joule heat generation produces a significant effect on characteristics of the diffuse and mixed modes at high currents. In particular, the current-voltage characteristic of the diffuse mode becomes Z-shaped in the current range 105A $\lesssim I \lesssim$ 130A. The maximum of the temperature of the cathode, which in the case without Joule heating is positioned at the edge of the front surface of the rod cathode and at the center of the front surface of the cathode with the hemispherical tip, is shifted to the lateral surface and its value is significantly reduced, in many cases to values below the melting point of tungsten. At high currents, $I \gtrsim$ 270A, the power dissipated in the cathode due to Joule heating exceeds the power coming to the cathode from the plasma.

Acknowledgments The work was supported by FCT of Portugal (projects PTDC/FIS/68609/2006 and PEst-OE/MAT/UI0219/2011).

References

[1] Benilov M S 2008 Understanding and modelling plasma-electrode interaction in high-pressure arc discharges: a review *J. Phys. D: Appl. Phys* **41** 144001

[2] http://www.arc_cathode.uma.pt

[3] Luhmann J, Nandelstädt A, Barzik A and Mentel J 1999 Measurements of the cathode fall in a high pressure argon model lamp *Contr. Papers XXIV ICPIG* (Institute of Plasma Physics and Laser Microfusion, Warsaw), 13-14

[4] Dabringhausen L, Langenscheidt O, Lichtenberg S, Redwitz M and Mentel J 2005 Different modes of arc attachment at HID cathodes: simulation and comparison with measurements *J. Phys. D: Appl. Phys*. **38** 3128-42

[5] Mitrofanov N K and Shkol'nik S M 2007 Two forms of attachment of an atmospheric-pressure direct-current arc in argon to a thermionic cathode *Tech. Phys*. **52** 711-720

[6] Benilov M S, Cunha M D and Faria M J 2009 Simulating different modes of current transfer to thermionic cathodes in a wide range of conditions *J. Phys. D: Appl. Phys*. **42** 145205

[7] Benilov M S and Cunha M D 2003 Heating of refractory cathodes by high-pressure arc plasmas: II *J. Phys. D: Appl. Phys*. **36** 603-614