Modelling non-equilibrium near-cathode plasma layers at ignition of high-pressure arcs on refractory cathodes

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One of the important unsolved problems in the theory of high-pressure arc discharges is the lack of self-consistent methods for numerical modelling of the ignition of high-current arcs on refractory electrodes. The most difficult is the self-consistent description of the current transfer to the cathodes at the initial stage of arc ignition when the cathode surface is not yet hot enough for thermionic emission.

Various hypotheses on the dominating mechanism of current transfer to the surfaces of cold arc cathodes have been proposed in the arc discharge literature, and the theoretical conclusion that the ion current and secondary electron emission from the cathode are the most important mechanisms of current transfer to cold cathodes of arc discharges was confirmed by specially designed experiments [1]. Thus, this conclusion has by now been substantiated both theoretically and experimentally and there appears to be no reason to doubt it.

The development of an approximate model of non-equilibrium near-cathode plasma layers (NCPL) in high-pressure arc discharges, applicable over a wide range of cathode surface temperatures and near-cathode voltages, is the objective of this work. The model takes into consideration thermionic electron emission from the cathode and secondary electron emission resulting from ion impact. The applicability of the model will be limited to cathode surface temperatures below the boiling point of the cathode material, when the vaporization of the cathode material is not a dominating effect, and the arc may be considered as burning in the ambient gas.

The model is based on the previous work [2], which was supplemented with the secondary electron emission current. The density of electric current from the plasma to the cathode surface in the modified model is evaluated as

$$j_c = j_T + (1+\gamma)j_i - j_{CD},$$

where j_T is the density of emission current caused by high values of the cathode surface temperature and/or electric field directed to the cathode surface, γ is the so-called effective secondary emission coefficient, j_i is the density of electric current transported to the cathode surface by the ions coming from the plasma, and j_{CD} is the density of current of fast plasma electrons counter-diffusing to the cathode surface against the sheath electric field.

The quantities involved in this expression are shown in Fig. 1 as functions of the cathode surface temperature T_c for two values of the near-cathode voltage drop U. Also shown is the electron temperature in the near-cathode layer, T_e. The conditions of the model are: the cathode is made of tungsten, the plasma-producing gas is atmospheric-pressure argon. j_T is determined by means of the Richardson-Schottky formula, values of the work function and the Richardson constant are 4.55 eV and 6×10^5 $\mathrm{Am^{-2}K^{-2}}$, respectively. The secondary electron emission is 0.1. Also shown in Fig. 1 is parameter α characterizing the ratio of the scale of thickness of the ionization layer to the mean free path for collisions between the neutral atoms and the ions [3].

Let us first consider the case where U is small. For low and moderate values of T_c, the ion current density is roughly proportional to the thermionic emission current density. In this regime, the ion current to the cathode is limited not by a finite rate of diffusion of the ions from the ionization layer to the cathode surface, but rather by a finite rate of supply of the ionization energy to the ionization layer. This regime occurs on thermionic arc cathodes when they are not hot enough for the plasma in the near-

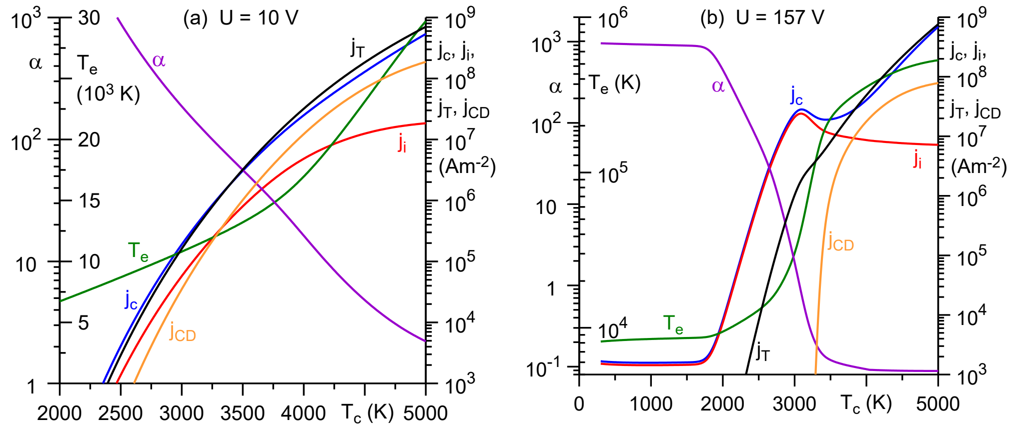

Fig. 1 Characteristics of the non-equilibrium NCPL on a tungsten cathode in atmospheric-pressure argon arc.

cathode layer to attain full ionization. In the case where U is high enough the ion current can be significant even for low cathode surface temperatures, when j_T is negligible. In other words, the secondary electron emission is strong enough to supply the necessary ionization energy to the near-cathode plasma; the glow discharge regime. The dependence of j_i on T_c is weak in this regime.

As T_c increases, the electron temperature in the ionization layer, T_e, increases as well and the ionization degree of the plasma also increases. As the plasma at the edge of the ionization layer approaches full ionization, the ion current j_i becomes saturated and is no longer proportional to j_T. For high values of U a maximum in the dependence $j_i(T_c)$ appears. After the maximum, the dependence $j_i(T_c)$ monotonically decreases and saturates. This causes a decrease in j_c. This decrease of the density of ion current is unrelated to the account of the secondary electron emission, introduced in this work. The detailed description of the reason for this decrease is provided in [3].

A comparison of results given by the approximate and unified models is shown in Fig. 2. The solid lines depict characteristics of the cathodic part of a steady-state arc on a 1 cm-high tungsten cathode in atmospheric-pressure argon. The dashed lines in in Fig. 2 represent results obtained with the use of the unified model [4]. The computation domain in this case included 1 cm-high tungsten cathode, 1 cm-high tungsten anode, and a 1 mm-long arc. T_e shown by the dashed line was evaluated in the unified model at an "edge" of the space-charge sheath, defined as a point where the charge separation is 10%. There is a good agreement between the two models.

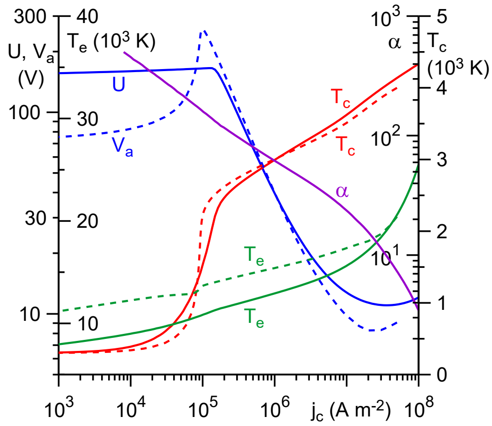

Fig. 2 Characteristics of the cathodic part of a steady-state arc on a 1 cm-high tungsten cathode in atmospheric-pressure argon.

The introduction of secondary electron emission into the approximate model of non-equilibrium NCPL of high-pressure arc discharges [2] allows one to self-consistently describe, in the framework of a single model, glow-like discharges on cold cathodes and thermionic arc discharges on hot cathodes. This is an essential step in the development of practicable self-consistent multidimensional modelling methods of ignition of high-current arcs on cold refractory cathodes.

Acknowledgments The work was supported by FCT - Fundação para a Ciência e Tecnologia, I.P. under projects UIDB/50010/2020, UIDP/50010/2020, LA/P/0061/2020 and by European Regional Development Fund through the Operational Program of the Autonomous Region of Madeira 2014-2020 under project PlasMa-M1420-01-0145-FEDER-000016.

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