Modeling of DC Discharges in Argon at Low Pressures

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Introduction: Low pressure discharge plasma has various applications in material processing, lasers and power electronics to name a few. In this work, the DC plasma discharges are modeled in argon at gas pressures ranging from 1 to 20 mTorr. The discharge tube size is large with the diameter ranging from 0.2 to 0.5 m and the length ranging from 0.3 to 0.6 m. Both 1D and 2D axisymmetric models are considered. The model scheme shown schematically in **Figure 1** includes the cathode and anode at opposite ends of the axisymmetric discharge tube and external electrical circuit. The discharge current ranges from 0.1 to 100 A and the power supply voltage ranges from 100V to 300V with a low external resistance of 0.5 Ohm. Two mechanisms of electron emission are considered: one is self-sustained DC glow discharge based on secondary electron emission and another is low pressure DC arc in which electrons are emitted by a thermionic cathode. In this model, we are comparing 3 different conditions on the discharge wall; a charge balance condition associated with a dielectric discharge tube and two boundary conditions associated with a metal discharge tube: one is a floating potential tube and another one is a discharge tube serving as an anode in the discharge electrical circuit. Plasma distribution across the discharge tube as well as electrical characteristics of the discharge plasma in the relationship to the discharge pressure, thermionic current density and boundary conditions are discussed.
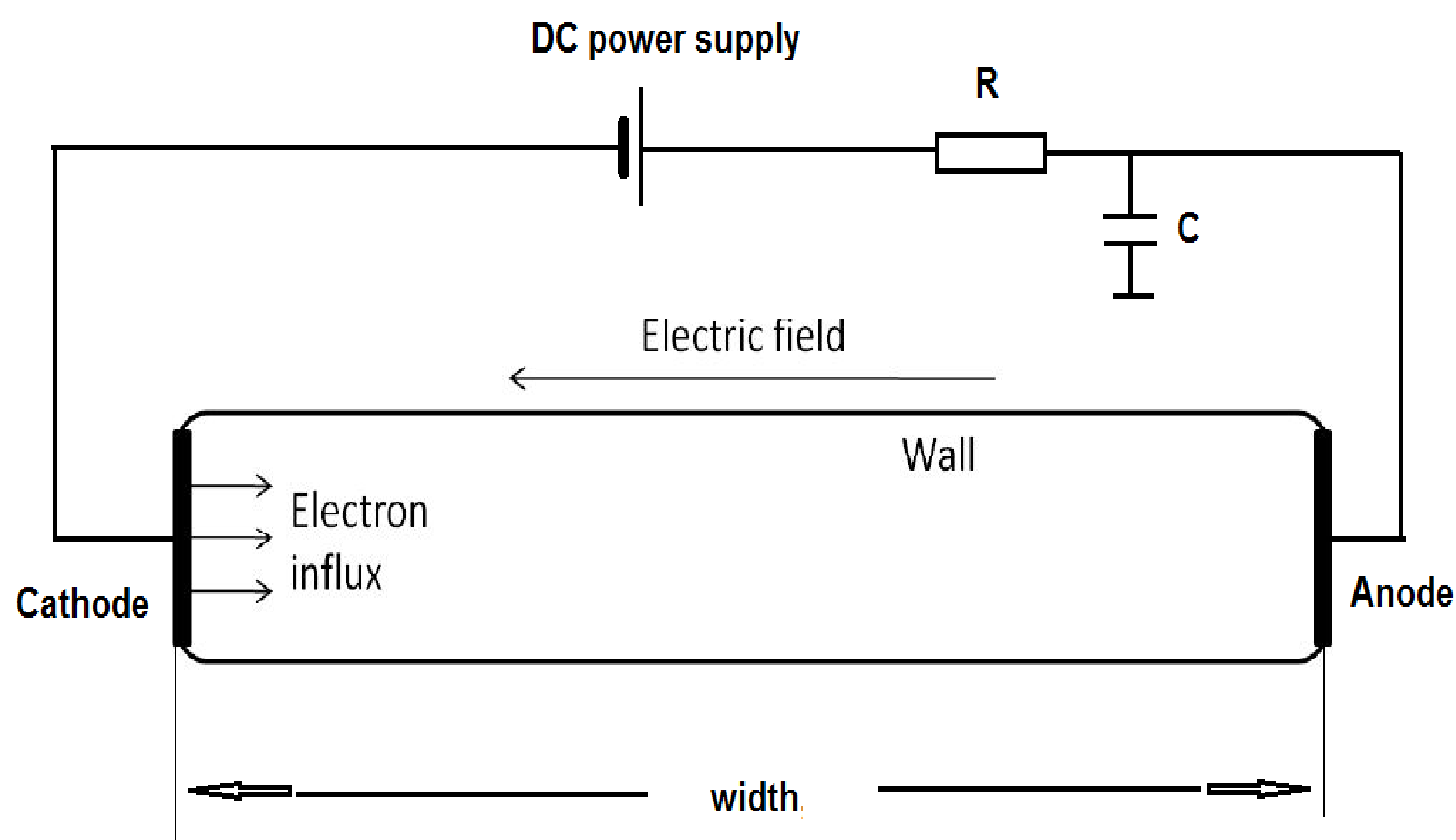

Figure 1. Axisymmetric DC plasma discharge scheme.

Computational Methods: COMSOL Plasma Module [1] was used in this work. In this module, the electron density and mean energy are computed by solving a pair of drift-diffusion equations using a Drift Diffusion Interface. Transport of the heavy species is determined by solving a modified form of Maxwell-Stefan equations using The Heavy Species Transport Interface. The Maxwellian electron energy distribution function is used for calculation of the cross-sections of reactions in argon plasma. In the plasma module, a set of transport equations is coupled via DC Discharge Interface, while the Electrical Circuit Interface is used to add an external electric circuit to the plasma model. The electron emission from the cathode was modeled by two different approaches: one consisting of a secondary electron emission mechanism in which electrons are emitted by ion bombardment of the cathode surface supporting a self-sustained discharge mode and another mechanism consisting of thermionic emission in which the electron influx was provided as an input parameter of the model [2,3]. Two different types of boundary conditions on the walls of discharge tube were used to mimic the dielectric vs. metal tubes. In the case of dielectric tubes, the Electrostatic Interface was used to calculate a surface charge accumulating on dielectric surfaces [1,4]. In the case of metal discharge tubes, two different approaches were used. In the first approach, the metal discharge tube was considered as an anode in the discharge electric circuit. In the second approach, the floating metal discharge tube was modeled by balancing to zero the total flux of charged particles (ions and electrons) conveyed from the discharge plasma toward the discharge wall.

Results: The thermionic arc plasma distribution in the floating metal discharge tube at 4 mTorr, a thermionic current density of 15000 A/m², tube size 0.2 dia x 0.6 m length shown in **Figure 2** is compared to the thermionic arc plasma distribution in metal tube-anode shown in **Figure 3**. These are shown in the same discharge geometry and thermionic current density but with the metal discharge tube serving as an arc anode. For these two cases, the plasma distribution is quite different. In the case of the floating metal wall, the plasma is concentrated near the anode in an anodic arc discharge mode. Whilst in the case of the discharge tube wall-anode, the plasma is concentrated around the thermionic cathode; in cathodic arc discharge mode. The I-V characteristics of the self-sustained DC glow discharge vs. low pressure thermionic arc discharge were calculated using a 1D model (**Figures 4,5**) and a 2D model (**Figure 6**). The 2D model also predicts a peak in thermionic arc discharge current in a pressure range 1-20 mtorr (**Figure 7**). The results of 1D modeling are in good agreement with axisymmetric 2D modeling results, both showing the rising trend of I-V shape in DC glow discharge vs. the falling trend of I-V shape in low pressure thermionic arc.
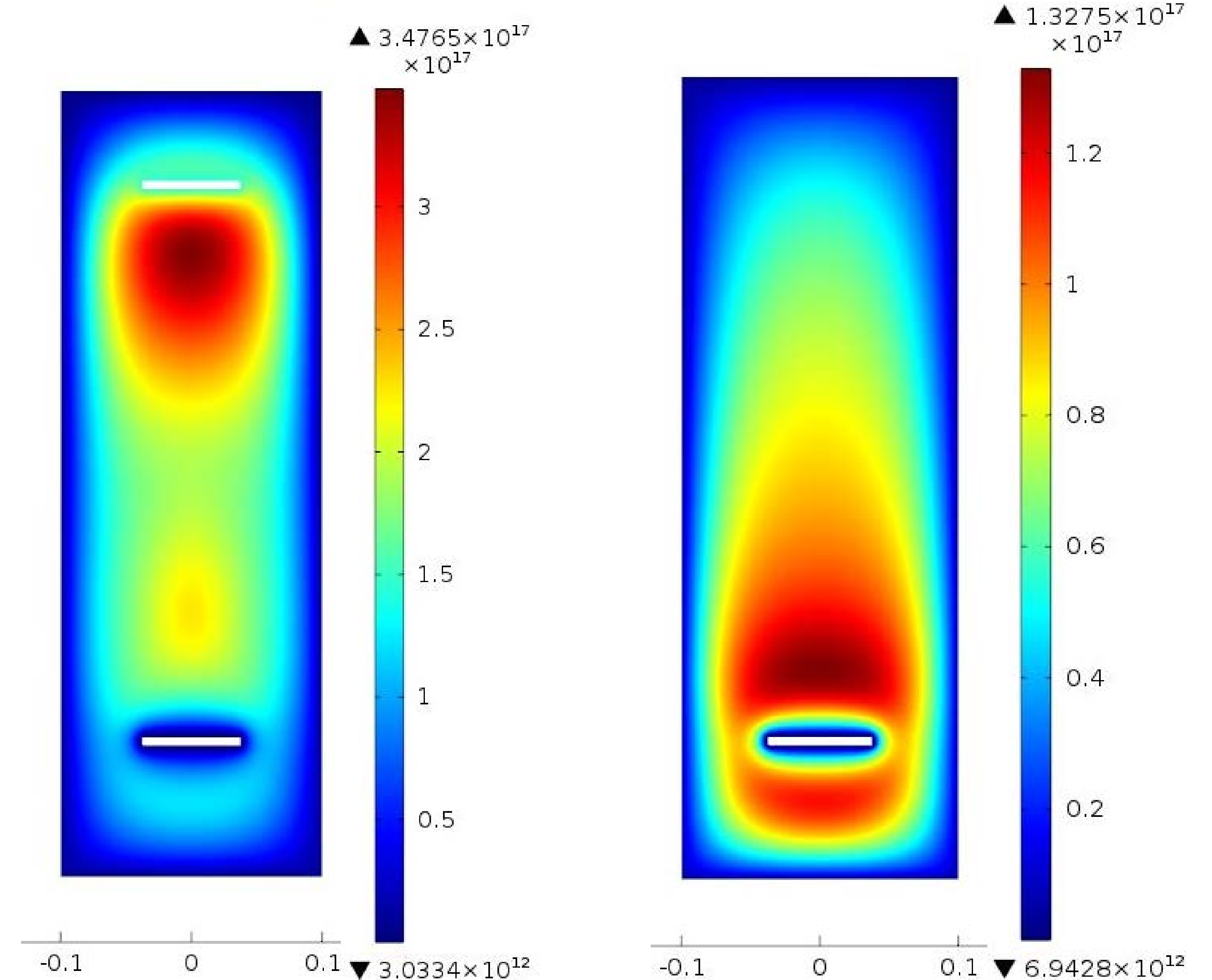

Figure 2. Plasma distribution in the floating metal discharge tube.

Figure 3. Plasma distribution in the metal discharge tube-anode.
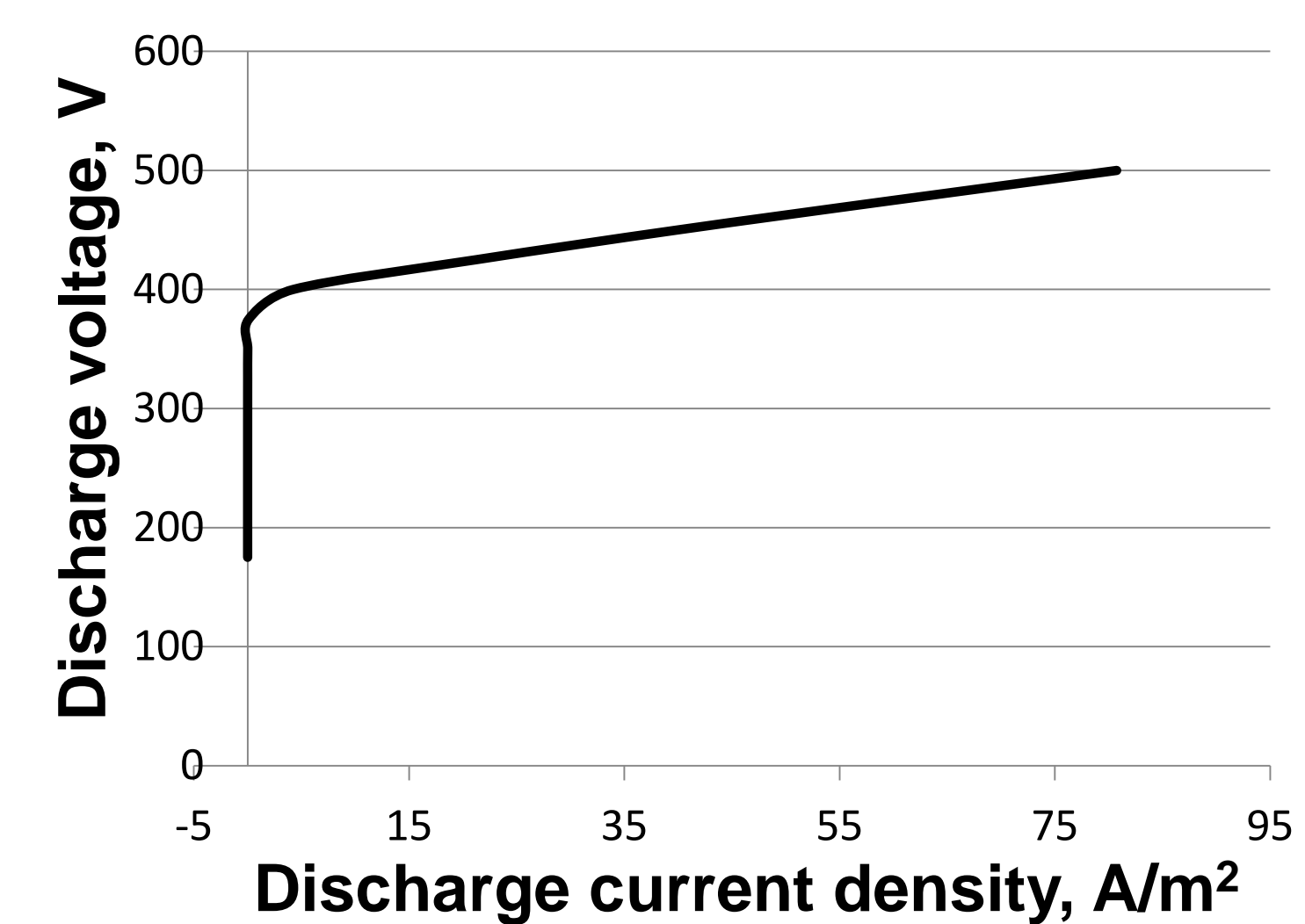

Figure 4. Discharge voltage vs. discharge current for self-sustained 1D model with secondary electron emission.
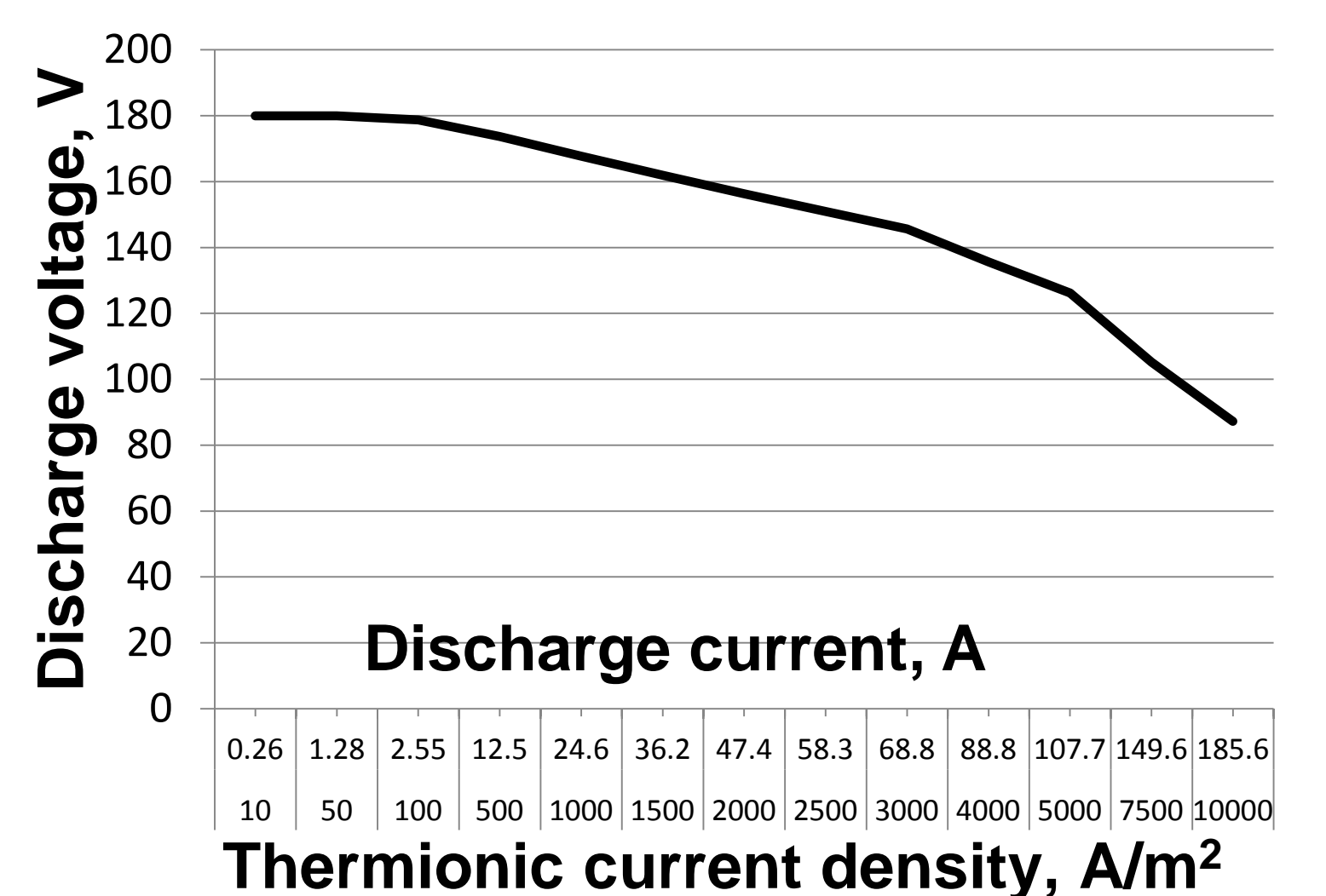

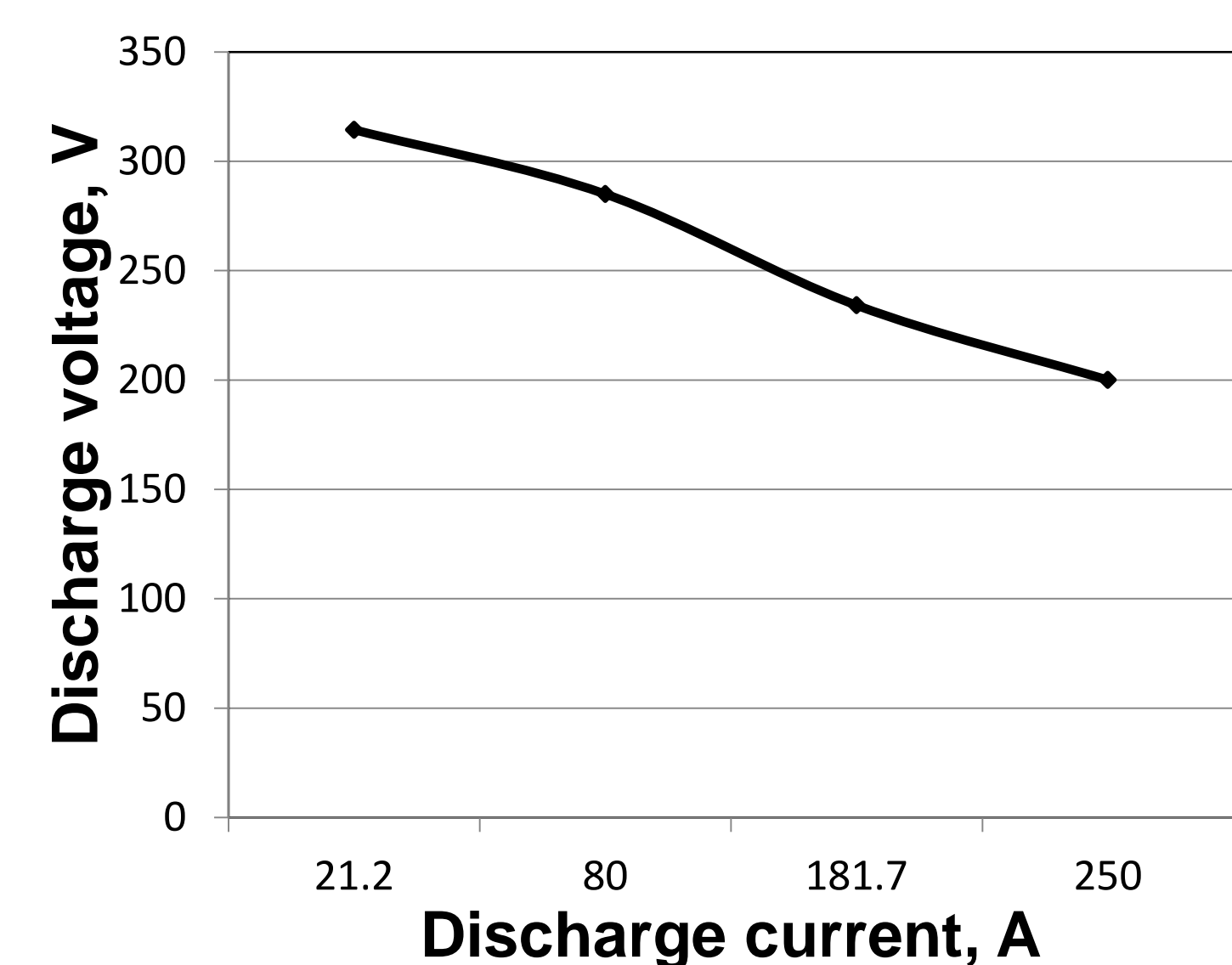Figure 5. 1D modeling of I-V characteristics of thermionic discharge.

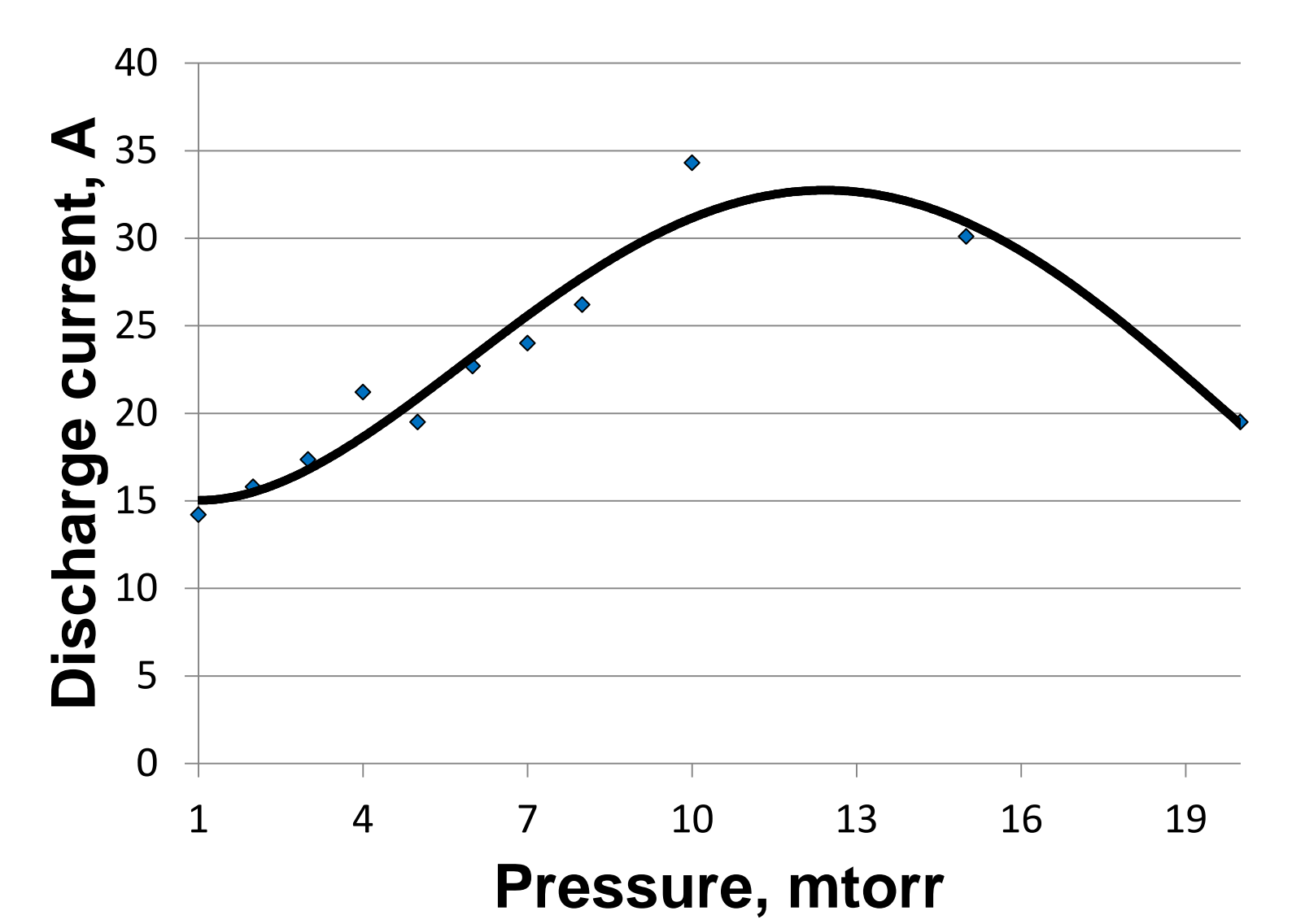Figure 6. Discharge voltage vs. discharge current for 2D axisymmetric thermionic low pressure arc.

Figure 7. 2D modeling of low pressure thermionic arc: arc current vs. pressure at thermionic current density 1000 A/m².

Conclusions: Low pressure DC discharges were modeled using Plasma Module of the COMSOL FEM software package. Modeling revealed that electron emission mechanisms (secondary emission vs. thermionic emission) as well as boundary conditions on discharge tube walls strongly influence both the plasma distribution and the electrical characteristics of the discharges. Moreover, the self-sustained DC glow discharge has a rising trend of I-V characteristics with positive differential resistance, having an apparent voltage threshold associated with the secondary emission cross-section. Alternatively, the thermionic discharge has a falling trend of I-V characteristics with negative differential resistance typical of gaseous arc plasmas [3].

References:
1. COMSOL Plasma Module User's Guide. 2012.
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4. I. Rafatov, E. A. Bogdanov, A. A. Kudryavtsev, "On the numerical modeling of a dc driven glow discharge plasma" Proceedings of the 30th International Conference on Phenomena in Ionized Gases (ICPIG 2011), August 28th-September 2nd, 2011, Belfast, UK.