NUMERICAL STUDY OF CHARACTERISTICS OF ATMOSPHERIC PRESSURE GLOW DISCHARGE IN HELIUM GAS

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Glow discharges are a classic subject of low-temperature plasma physics [1, 2]. Currently, atmospheric pressure glow discharges (APGDs) are of interest due to their simple design and practical applications (see, e.g. [3]). Here, we report results of one- and two-dimensional numerical studies of APGD in helium gas. The numerical model is based on the drift and diffusion theory of gas discharges and includes a detailed description of plasma-chemical kinetics [4].

Table 1: Species that are considered in the numerical model.

No	Term	Energy (eV)	Designation
0	He	0	1^1S_0
1	He^* (1)	19.82	2^3S_1
2	He^* (2)	20.62	2^1S_0
3	He^* (3)	20.96	$2^3P_0{}^0$, $2^3P_0{}^1$, $2^3P_2{}^0$
4	He^* (4)	21.22	$2^1P_0{}^1$
5	He^* (5)	23.02	3^3S_0, 3^1S_1, $3^3P_0{}^2$, $3^3P_0{}^1$, $3^3P_0{}^0$, 3^3D_3, 3^3D_2, 3^3D_1, 3^1D_2
6	He^+	24.59	He^+
7	He_2^*	17.97	He_2 ($^3\sum_u{}^+$)
8	He_2^{**}	18.36	He_2 ($^1\sum_g{}^+$)
9	He_2^+	22.24	$He_2{}^+$
10	He_3^+	22.12	$He_3{}^+$

To verify the performance of the model, the current-voltage characteristic (CVC) and current density-voltage characteristic (CDVC) curves have been obtained and analyzed. The effects of the following factors were investigated: the temperature regime (cooled vs uncooled) on the cathode, the value of the secondary electron emission (SEE) coefficient, and the thermal diffusion. The effect of the thermal diffusion manifests itself from very low values of the discharge current; it leads to an upward shift of the CVC curves by a few tens of volts (see Fig. 1). The effect of cathode heating on the CVC begins to show up at sufficiently high discharge currents, of the order of one tenth of an ampere. It leads to a significant distortion (up to several tens of volts) of the part of the CVC corresponding to a normal discharge, which in the case of a cold cathode has a flat profile usual for the normal discharge mode.

In the case of microdischarge at atmospheric pressure, due to intense heating of the plasma at sufficiently high currents, it becomes necessary to identify the

discharge mode. The question is whether it is positioned to the left of the minimum of the Paschen curve and, therefore, whether it is in obstructed mode.

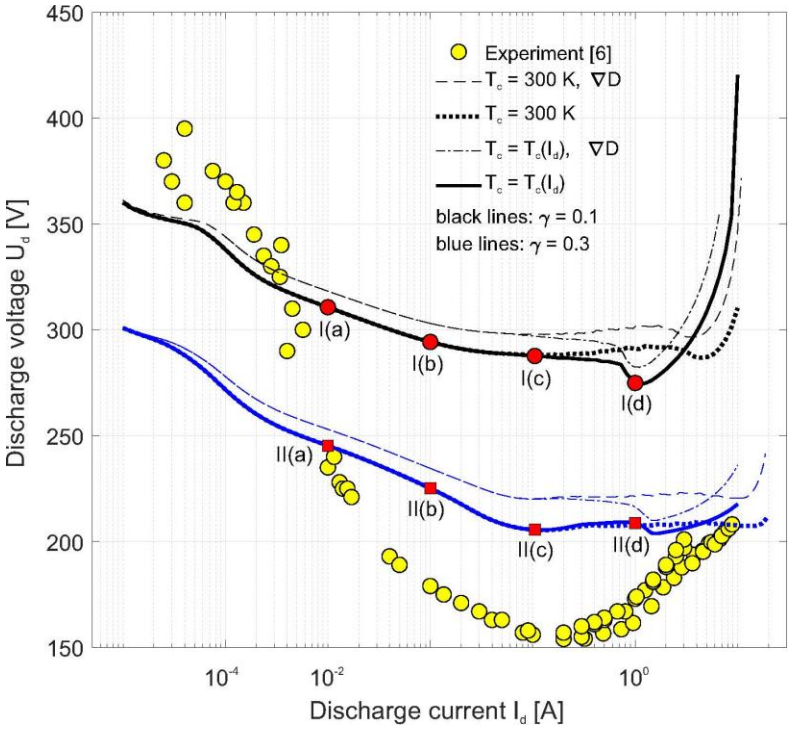


Figure 1: CVCs obtained from 2D simulations in helium APGD. Calculations were performed for $\gamma = 0.1$ and 0.3, and imposing constant (300 K) and varying (linearly with the discharge current) temperature T_c on the cathode. The inclusion of thermal diffusion in the model is indicated by '∇D' term in the legend. The experimental data is taken from [6].

With this in mind, the patterns of transition of helium APGD to the obstructed regime with increasing current were investigated. The results revealed that this transition differs from that observed in APGD in argon [5]. In particular, for a microdischarge in argon, on the right branch of the CVC, the current density, the total ionization rate, and the maximal electron density saturate or even decrease with an increase in the discharge voltage, accompanied by an increase in the gas temperature. On the contrary, in a microdischarge in helium, the current density, as well as the total ionization rate, increase monotonically with increasing discharge voltage. The analysis showed that for gas gaps of $d = 0.5$ mm and 1 mm, the helium APGD is not obstructed. With a gas gap of $d = 0.1$ mm, the discharge state is very close to obstructed regime, and with $d = 0.05$ mm it is obstructed.

Calculations have shown that the numerical model is capable of reproducing the formation of a normal glow discharge in atmospheric pressure helium in the correct parameter regime (see Fig. 2). An analysis revealed good agreement between the calculated values of the current density and electric field on the cathode surface and the experimental data. However, formation of a classical normal glow discharge, with current density on the cathode surface nearly constant with increasing discharge current, is observed in the case of a cooled cathode. In the case of an uncooled cathode, at sufficiently high discharge currents, the current density on the cathode surface no longer remains approximately equal to the normal current density, known from the literature [1],

but drops drastically.

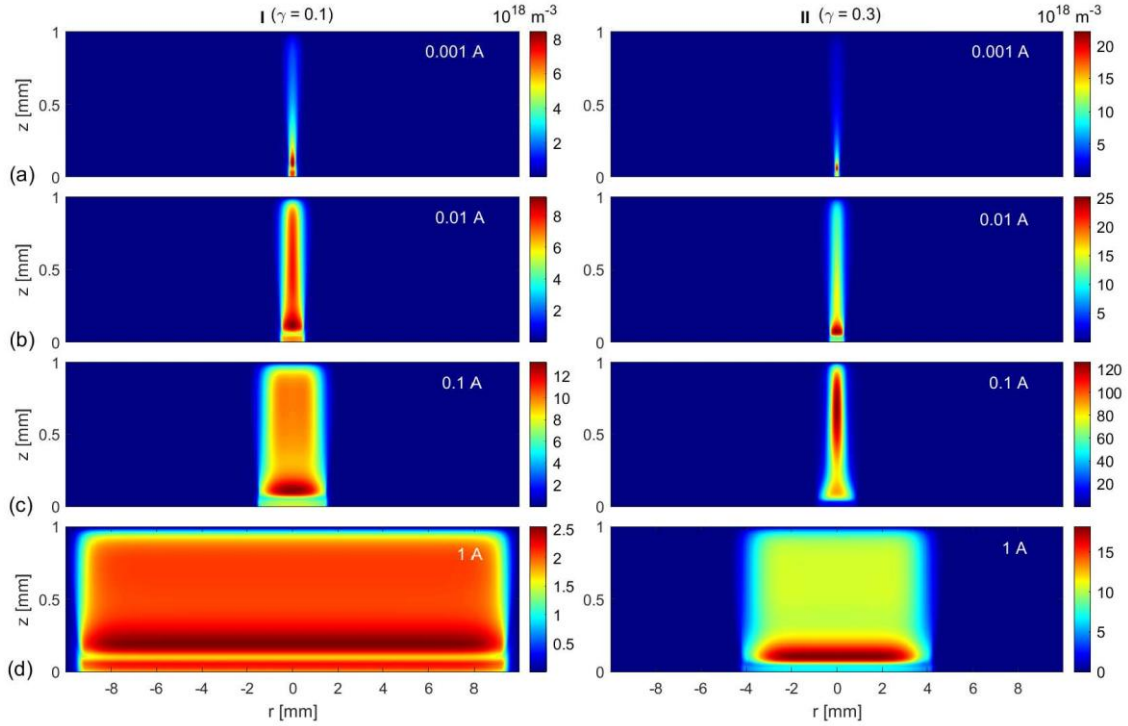
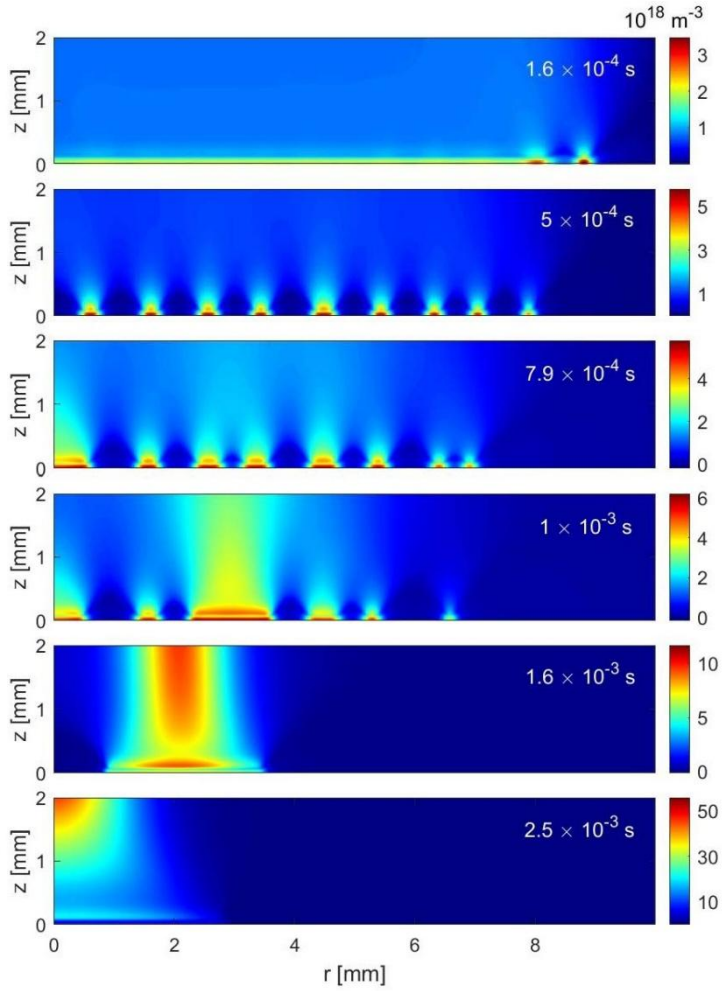


Figure 2: Profiles of the total ion density n_i in helium APGD. The left column "I" corresponds to $\gamma = 0.1$ and the right column "II" corresponds to $\gamma = 0.3$. The values of discharge current are $I_\mathrm{d} = 0.001$ A, 0.01 A, 0.1A and 1 A, from (a) to (d), in each column. The discharge states correspond to those designated from I(a) and II(a) to I(d) and II(d) on CVC curve in Fig. 1. The gas gap is $d = 1$ mm, the radius of the discharge tube is $l = 10$ mm.

As usual in fluid models of glow discharges, the effective value of the SEE coefficient from the cathode, without having a noticeable qualitative effect on the helium APGD parameter profiles, exhibits a significant quantitative effect on them (see Fig. 2). Recall that the SEE is generally considered as one the main sources of uncertainty in fluid models of glow discharges.

The above analysis concerned regular discharges formed along the axis of the system. The spontaneous emergence of cathode spots was also observed. In particular, multiplication of the cathode spots with increasing current was identified (see Fig. 3). In this case, for each individual spot, the average current density on the cathode surface remained approximately equal to the normal current density for helium APGD. Calculations have shown that due to the intense heating of plasma at relatively high discharge currents (of the order of tens of mA or more), cathode spots do not form dynamically stable patterns at these discharge currents [4]. We have observed that an increase in the discharge current can lead to an increase in the number of cathode spots by either of two ways. The first one is the pattern 'self-completion' process. It is accompanied by the growth of perturbation in the region surrounding the primary spots, followed by the



emergence of new spots in the vicinity of old ones. Another scenario that was observed at sufficiently high discharge currents is that the number of spots increases via the division of existing spots.

Figure 3: Temporal evolution of the ion density n_i on the cathode surface in helium APGD with gas heating taken into account. The discharge state depicted in the bottom panel is in a steady state. The discharge current is $I_d = 0.5$ A, the gas gap $d = 5$ mm, the radius of the discharge tube $l = 10$ mm, and $\gamma = 0.1$. The cathode temperature is set to $T_c = 300$ K. A part of the gas gap along the cathode surface, limited by a distance of 2 mm from its surface, is shown.

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