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Characteristics of stationary negative corona discharge in atmospheric air

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Abstract. The paper presents a 2D-axisymmetric multi-fluid model of a stationary negative corona discharge in atmospheric-pressure air in the needle-to-plane diode. Discharges with a cathode tip with a curvature radius of 20–200 μm, a gap length of 3–10 mm, and a power source voltage of 5–35 kV were studied. The spatial distribution of the discharge plasma at a current level of 2.2 mA with a gap voltage of 5.8 kV, gap length of 10 mm, tip radius of 100 μm is described in detail. This corona discharge has a glow discharge structure with a subnormal current density of 5 A/cm^2.
Keywords: corona discharge, glow discharge, hydrodynamic approach, numerical simulation.

1. Introduction

Corona discharge is a specific type of self-sustained discharge. To form a corona discharge, a sufficiently high voltage must be applied to an electrode with a small radius of curvature. However, there is a range of applied voltage value, at which the corona discharge has an unstable mode. Our previous work [1] has shown that the negative corona discharge in atmospheric-pressure air has three evolution stages: unstable mode (mode of Trichel pulses), stationary glow and unstable-to-stationary transition. Characteristics of stationary mode are of interest for practical application. The transition from the unstable mode to glow discharge was studied for a long time. Dordizadeh et al. believed that the strong electric field plays a key role in the transition [2]. The experimental and simulation results indicate that the Trichel pulse-glow transition occurs when the electric field around the cathode is strong enough to keep the negative ion space charge at a sufficient distance from the cathode. In this paper we investigate the characteristics of negative corona discharge's stationary mode and unstable-to-stationary transition.

2. Theoretical model

To calculate the plasma characteristics of the non-stationary gas discharge, a theoretical model of corona discharge in atmospheric pressure air was formulated. The model describes plasma evolution using the hydrodynamic drift-diffusion equations. Plasma components described by the following system of continuity equations:

$$\frac{\partial n_{\mathrm{e}}}{\partial t}+\nabla\cdot\boldsymbol{j}_{\mathrm{e}}=R_{\mathrm{e}}, \tag{1}$$

$$\frac{\partial n_{\varepsilon}}{\partial t}+\nabla\cdot\boldsymbol{j}_{\varepsilon}+\boldsymbol{j}_{\mathrm{e}}\cdot\boldsymbol{E}=R_{\varepsilon}, \tag{2}$$

$$\frac{\partial n_k}{\partial t}+\nabla\cdot\boldsymbol{j}_k=R_k, k=1\ldots M, \tag{3}$$

where n_e and n_ε are electron number and energy densities, n_k is number density of k-th ions, M is total number of ions, $\boldsymbol{j}_e$ and $\boldsymbol{j}_\varepsilon$ are drift-diffusion electron mass and energy fluxes, R_e is electron rate expression, R_ε is electron energy loss or gain due to inelastic collisions, R_k is rate expression of k-th ions, $\boldsymbol{E}$ is electric field strength.

The equations for electrons (1), (2) and ions (3) are coupled to the Poisson's equation in order to take into the account the electric field self-consistently:

$$\nabla\cdot\boldsymbol{E}=\frac{e}{\varepsilon_0}\left(\sum_{k=1}^{M}z_k n_k-n_\mathrm{e}\right),\quad \boldsymbol{E}=-\nabla\varphi,\tag{4}$$

where e is elementary charge, ε_0 is vacuum permittivity, z_k is charge number of k-th ions, φ is electrostatic potential. Discharge voltage U_d and current I_d are calculated by the following equations:

$$U_\mathrm{d}=U_0-IR_\mathrm{b}-R_\mathrm{b}C_\mathrm{b}\frac{dU_\mathrm{d}}{dt},$$
$$I_\mathrm{d}=\int_S\left[\sum_{k=1}^{M}\boldsymbol{n}\cdot\boldsymbol{j}_k+\boldsymbol{n}\cdot\boldsymbol{j}_\mathrm{e}+\boldsymbol{n}\cdot\left(\varepsilon_0\frac{\partial\boldsymbol{E}}{\partial t}\right)\right]dS,\tag{5}$$

where U_0 is source voltage, R_b is ballast resistance, C_b is blocking capacitance.

A gas discharge diode includes a thin tip high-voltage electrode with a small radius of curvature r_{curv} and a plane anode at a distance d from the tip (Fig.1). A computational domain is relatively wide so that the open boundaries does not affect the plasma processes at the tip.

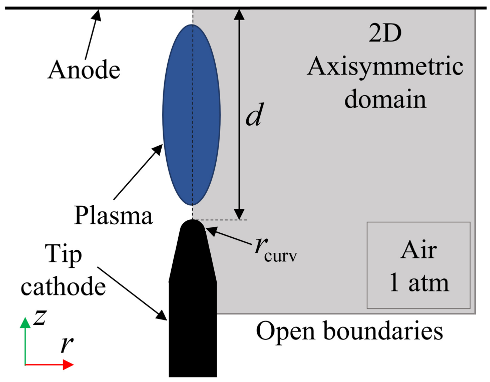

Fig.1. Scheme of gas discharge gap.

In the model, nine kinds of particles: free electrons, N, N_2, N_2^+, O, O_2, O_2^+, O_4^+, O_2^- and 23 reactions are considered. A plasma-chemical set includes the most important reactions: production of single charged ions, ions recharging and important conversion reactions, as well as various electron energy losses. The full plasma-chemical reaction set in air can be found in [1].

The numerical solution of the gas discharge equations system (1)–(3) was performed using the nonstationary finite element method implemented in Plasma Module of COMSOL Multiphysics software [3].

3. Numerical results

The simulation of the negative corona discharge in atmospheric pressure air was carried out under the following input parameters of the model: radius of curvature $r_{curv} = 100$ µm, interelectrode distance $d = 10$ mm, source voltage $U_0 = -8$ kV, ballast resistance $R_\mathrm{b} = 1$ MΩ, blocking capacitance $C_\mathrm{b} = 100$ pF, gas temperature 300 K and uniform quasi-neutral initial distributions of the plasma components density.

Fig.2 shows temporal dependencies of discharge current I_d and gap voltage U_d. Unstable mode continues up to 80 µs and discharge goes to a transient mode. Unstable and transient modes are characterized by a very low average discharge current (level 10–20 µA). Due to such a low current, the blocking capacitance charges almost linearly up to a voltage of 5.7 kV, and an oscillatory transition to the stationary mode occurs. Fig.3 shows the spatial distribution of free electrons in the stationary mode. Duration of the unstable-to-stationary transition decreases as the applied dc voltage U_0 increases.

Numerical calculations have been shown that the stationary discharge structure consists of a positive space charge (mainly of N_2^+ and O_2^+ ions) layer (the cathode layer is clearly visible on Fig.3 and 4) with characteristic width of ~20 µm, an intermediate 1 mm region with a monotonically decreasing plasma density, and a long discharge column in the remaining part of the gap.

In our recent work [4], the corona discharge in the Trichel pulse mode was studied in detail. Although even at the maximum of the Trichel pulsed current (~200 µA), this current is an order of magnitude lower than the current of the stationary stage (~2 mA), but the spatial distribution of charged particles in these two different regimes is almost the same.

During the transition, plasma in the discharge channel is redistributed and a uniform electric field distribution is established (Fig.5). In the transition region from the space charge layer to the discharge column, a small local minimum is observed in the spatial profile of the field strength.

The discharge column is formed by three-component quasi-neutral plasma consisting of positive ionic charges O_4^+, and an approximately equal number of negative charges of O_2^- ions and free electrons (Fig.4). Due to the high mobility of free electrons, it is they that provide a high level of plasma conductivity in the discharge column.

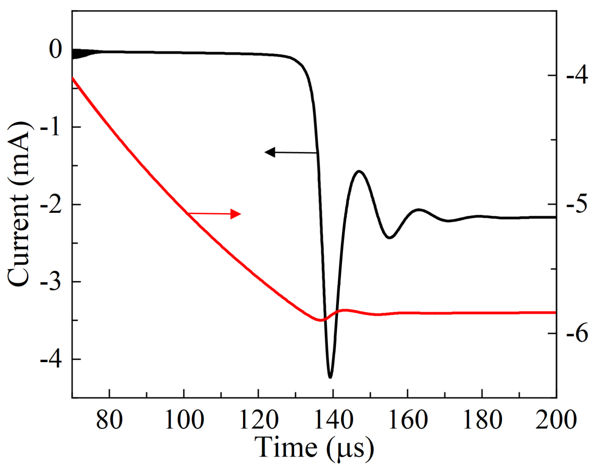

Fig.2. Current & voltage time profiles.

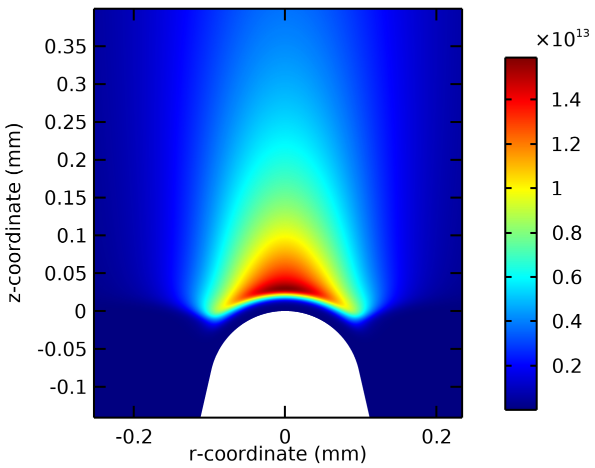

Fig.3. Electron number density distribution (in 1/cm^3).

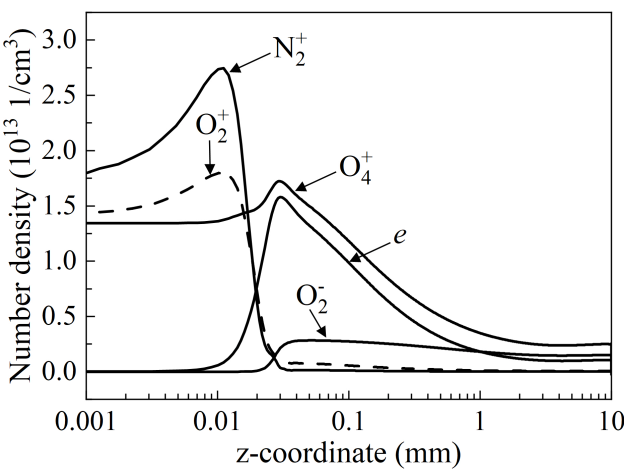

Fig.4. Plasma distribution at symmetry axis.

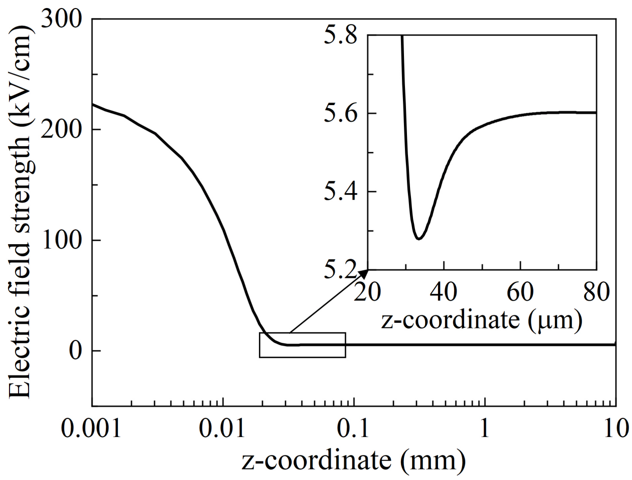

Fig.5. Electric field distribution at symmetry axis.

The resulting picture of a stationary corona discharge can be characterized as a kind of glow discharge regime with its typical spatial structure: ion cathode layer + transition region + positive column. The calculated discharge current density on the axis of the system near the tip (z = 100 μm) is ~5 A/cm^2. If these values are compared with the corresponding characteristic of a normal glow discharge in air at atmospheric pressure (~200 A/cm^2), then this will correspond to the mode of a deep subnormal glow discharge. In this mode, the main voltage drops on the discharge column (~5.5 kV), and the near-cathode drop of ~300 V is concentrated in the near-cathode layer 20 μm thick.

4. Conclusion

A 2D-axisymmetric hydrodynamic model of the negative corona discharge in atmospheric-pressure air is presented. Numerical results are demonstrated that the evolution of corona discharge at constant applied voltage includes a transition from the unstable mode to the stationary glow discharge.

In the final mode at a current of 2.2 mA, the corona discharge burns in the subnormal range of the glow discharge current, the number density of three-component plasma in the discharge column is ~$2\cdot10^{12}$ cm^{-3}, the main types of ions in the plasma are O_4^+ and O_2^-, but the conductivity of the plasma column is controlled by free electrons. These results are in good agreement with experimental data.

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