Simulation of Initial Stage of Nanosecond Volume HighPpressure Gas Discharge

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The initial stage simulation of a nanosecond volume gas discharge under high pressures is presented. The ionization phenomena and charged particles transfer are investigated in the context of the local-field model base on the 1D system of hydrodynamic equations. The continuity equations are solved numerically, and the electric field is calculated from quadrature solution of Poisson's equation. The new details of the formation mechanism of the glow discharge were discovered.

Keywords: glow discharge, gas discharge formation, cathode layer of glow discharge

1 INTRODUCTION

There are three approaches to numerical modeling of plasma - kinetic [1], hydrodynamic [2] and hybrid methods [3]. Model selection is determined by mean free path for each type of particles. Hydrodynamic interpretation requires that the characteristic scales of discharge in homogeneities have to be significantly greater that corresponding particles free path. As for the numerical simulations of atmospheric discharges drift-diffusion approximation is commonly used. It includes continuity equations for each particle type with non-zero source term and Poisson's equation for the electrostatic potential distribution.

Our paper presents the results of 1D numerical simulation of the glow discharge development in a wide range of pressures. Problem formulation allows us to consider the overall process of a steady state gas discharge formation as well as the development of pre-breakdown phase under high discharge gap overvoltage.

2 SIMULATION

One-dimensional drift-diffusion fluxes have the form

$$\Gamma_e = -\mu_e n_e E - D_e \frac{\partial n_e}{\partial x}, \quad \Gamma_i = \mu_i n_i E - D_i \frac{\partial n_i}{\partial x} \quad (1)$$

where n_e, n_i – electrons and ions densities; μ_e, μ_i – electrons and ions mobilities; D_e, D_i – electrons and ions diffusion coefficients; E – electric field strength. The continuity equation which correspond to above fluxes

$$\begin{aligned} \frac{\partial n_e}{\partial t} + \frac{\partial \Gamma_e}{\partial x} &= -\beta n_i n_e + \alpha \mu_e |E| n_e \\ \frac{\partial n_i}{\partial t} + \frac{\partial \Gamma_i}{\partial x} &= -\beta n_i n_e + \alpha \mu_i |E| n_i \end{aligned}, \quad (2)$$

where β is three-body recombination coefficient; α is Townsend ionization coefficient:

$$\alpha / P = A \exp(-BP/E), \quad (3)$$

where P is gas pressure; A, B are the constants which depends on kind of gas. System of equations (2) is supplemented by one-dimensional Poisson's equation in order to calculate an electric potential φ, and a field strength, E

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{q}{\varepsilon_0}(n_e - n_i), \quad E = -\frac{\partial \varphi}{\partial x}, \quad (4)$$

where ε_0 is permittivity of free space; q is absolute value of electron charge.

Boundary conditions of system (2)-(4) are formulated in term of border flux values. The electrons flux at cathode is determined by gamma processes intensity, and the ions flux is equal to drift flux

$$\begin{aligned} \Gamma_e(0,t) &= -\gamma \Gamma_i(0,t), \\ \Gamma_i(0,t) &= \mu_i n_i(0,t) E(0,t), \end{aligned} \quad (5)$$

where γ is effective coefficient of a secondary electron-ion processes at the cathode.

Due to the drift flux is greater than diffusion one, electron flux to the anode is equal to the drift flux component and the ion flux vanishes

$$\Gamma_e(d,t) = -\mu_e n_e(d,t) E(d,t), \quad \Gamma_i(d,t) = 0, \quad (6)$$

where d is a length of gas-discharge gap.

Conditions for the electric potential corresponds common Dirichlet boundary conditions for Poisson's equation

$$\varphi(0,t)=0,\quad \varphi(d,t)=U(t)-I(t)R. \qquad (7)$$

Here, $U(t)$ is a voltage source, R is a ballast load, $I(t)$ is a discharge current.

Solution of equations system (2), (4) with boundary conditions (5) – (7) is numerical-quadrature process, because Poisson equation can be solved quadrature, and equation (2) is solved numerically. Electric field strength is found to be

$$E(x,t)=-\frac{U(t)-I(t)R}{d}- \\ -\frac{q}{\varepsilon_0}\frac{1}{d}\int_0^d\int_0^x\left(n_+(x',t)-n_-(x',t)\right)dx'dx+. \qquad (8) \\ +\frac{q}{\varepsilon_0}\int_0^x\left(n_+(x',t)-n_-(x',t)\right)dx'$$

Numerical solution of (2) is related to the specific discretization procedures. The purpose of this method is to reduce partial differential equations system to the system of ordinary differential equations (method of lines) [4] and solve them using common ODE solvers (i.e. RKF45). As for the fluxes discretization at continuity equations (2) we apply WENO-3-LF [5] scheme in the context of finite volume method [6] for convective terms. Numerical solution was implemented in Mathworks MATLAB.

3 DISCUSSION

We investigate a steady-state of glow gas discharge at constant voltage. Following calculations were performed for the discharge gap connected serially to the source voltage and ballast load. Gas pressure was chosen at about 760 Torr, the discharge gap length is 0.5 cm, the voltage source value 17 kV. Calculations are performed for nitrogen gas. Fig. 1 shows the voltage-current characteristic (VCC) of the discharge.

Discharge begins with a homogeneous ionized gas. The initial concentration of charged particles is $5\cdot10^{10}\,cm^{-3}$. Initially, the current decreases due to rapid movement of initial electrons toward the anode. Then current increases abruptly due to the impact ionization in cathode layer with the increasing electric field. At this moment the current commutation is established. Fig. 2 shows time variation of the current in the circuit. The electron and ion density distributions and electric field strength in discharge gap are depicted in fig. 3. This draws corresponded to points from fig. 2.

Afterward, there is a relatively long transition time to the steady-state regime whether the ions motion forms final plasma distribution in the gap. The stationary discharge structure and VCC are conformed to the theoretical model [7].

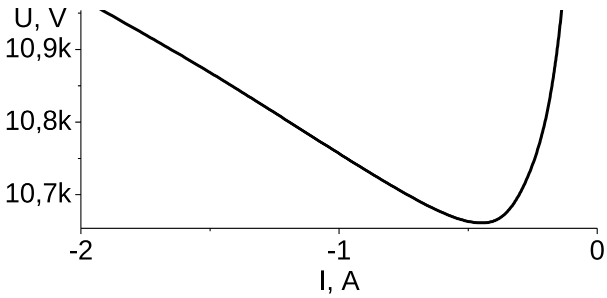

Fig. 1. Calculated voltage-current characteristic of a gas discharge gap. Pressure of nitrogen is 760 Torr, gap length is 5 mm, discharge cross-section square is 1 cm^2.

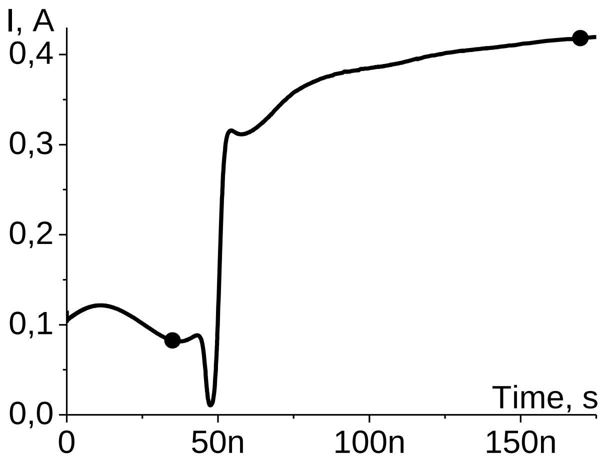

Fig.2 The time dependence of current an initial stage of discharge formation. The points are corresponded to plots at fig. 3.

4 CONCLUSION

Numerical model of 1D stationary discharge is created. We receive the stationary VCC, the time dependencies of discharge current, concentration of charged particles, and the electric field distributions in the gap. It was shown in the figure below that ions distribution has two peaks, one of them further decreases and converts to the positive column of discharge. We don't know publications which exhibit similar feature of the discharge.

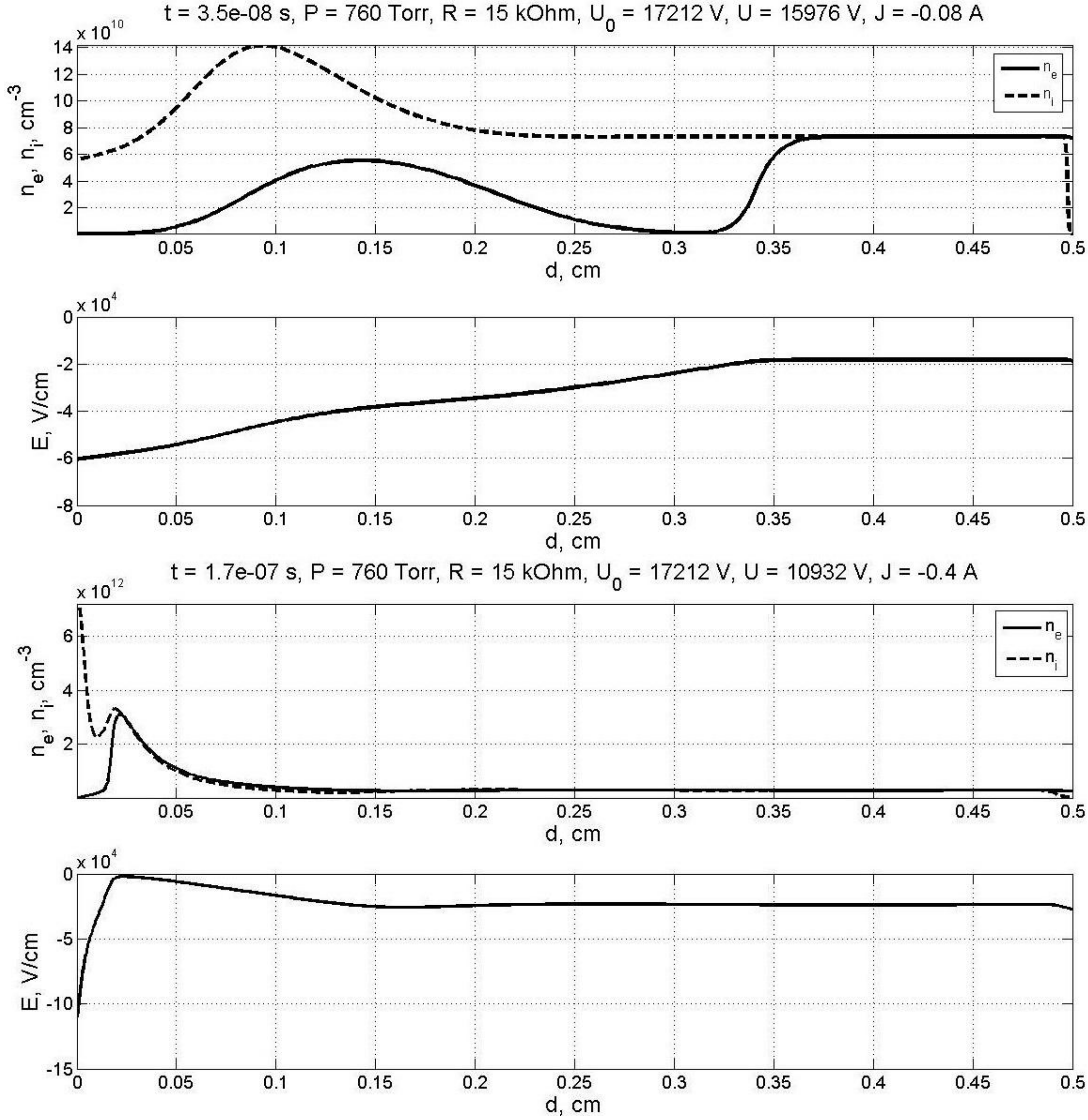

Fig. 3. Electron and ion densities and the electric field strength distributions (two different stages of discharge are shown). Running time, t, pressure, P, ballast resistance, R, voltage of source, U_0, and voltage on gap, U, current, J, are shown at the top as well.

It's a consequence of hydrodynamic equations of continuity and Poisson's equation. In contrast, stationary structure and VCC are consistent with other work [8].

REFERENCES

[1] Birdsall C K, IEEE Trans. Plasma Sci. 19 (1991) 65-85.

[2] Georghiou G E, Papadakis A P, Morrow R, Metaxas A C, J. Phys. D: Appl. Phys. 38 (2005) R303-R328.

[3] Kushner M J, J. Phys. D: Appl. Phys. 38 (2005) 1633-1643.

[4] William E. Schiesser. A compendium of partial differential equation models. Method of Lines Analysis with Matlab, Cambridge University Press, USA, New York, 2009.

[5] Xu-Dong Liu, Stanley Osher, Tony Chan Xu-Dong Liu, Journal of computational physics 115 (1994) 200-212.

[6] Versteeg H. K, Malalasekera W, An introduction to computational fluid dynamics. The finite volume method, Longman Scientific & Technical, New York 1995.

[7] Kozhevnikov V. Yu., Kozyrev A. V., Korolev Yu. D., Plasma Physics 32 (2006) 1027-1038 (in Russian).

[8] Raizer Yu. P., Physics of Gas Discharge (Intellect, Dolgoprudnyi, 2009) (in Russian).