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# Computer modeling of plasma formation generation in the non-self-sustained glow discharge mode

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**Abstract.** The results of computer modeling of plasma formation generation in non-self-sustained glow discharge mode at low pressure in a large-volume hollow cathode are presented. The dependencies of discharge current and plasma concentration on the gas (argon, nitrogen) pressure and electron beam current from one and two sources are obtained. The agreement between the results of computer modeling and experiments indicates the possibility of using the drift-diffusion approximation in the development of plasma sources with the lowest degree of distribution inhomogeneity of main (glow) discharge plasma in the large-volume hollow cathode (more than 0.2 m$^3$).

**Keywords:** non-self-sustaining glow discharge, hollow cathode, plasma concentration, distribution of charged particle concentration, plasma source, computer modeling, drift-diffusion approximation.

## 1. Introduction

Ion-plasma treatment is the most promising method for modification and strengthening the surface of products with large area or complex shape. To ensure stable ignition and combustion of the glow discharge, as well as to achieve discharge currents of hundreds of amperes, in the large-volume (more than 0.2 m$^3$) hollow cathode of plasma source, a non-self-sustained combustion mode of a low-pressure glow discharge (1.0–0.025 Pa) is realized when electrons are injected from the electron source based on a pulsed auxiliary arc discharge with a cold hollow cathode [1, 2]. In the pulsed combustion mode of a non-self-sustained glow discharge with independent current regulation at relatively low, up to several hundred volts, combustion voltages, the concentration of charged particles can be an order of magnitude higher than in self-sustained glow discharge combustion mode [3, 4]. However, to ensure uniform ion-plasma treatment of large-sized extended products, it is necessary to resolve the issue of ensuring a low degree of distribution inhomogeneity of charged particles in a hollow cathode. Inhomogeneity of plasma distribution in such sources depends on the geometry of the system (hollow cathode and anode) and is reduced due to additional sources of electron beam injection [5, 6].

This work presents the results of numerical modeling and experimental measurements. The possibility of using the drift-diffusion approximation in studying of mechanisms and patterns of plasma formation generation in non-self-sustained combustion mode of a low-pressure discharge in a large-volume hollow cathode is shown.

## 2. Hollow cathode model diagram

Hollow cathode model diagram of a plasma source with an electric circuit is shown in fig. 1. The glow discharge is ignited between the anode and the cathode, located under the ground potential, and is supported by an external circuit, both in the main (self-sustained) combustion mode and in the mode of maintaining the discharge by an electron beam extracted from electron source (auxiliary arc discharge plasma). Power supply allows to stabilize the voltage (or current) of the discharge combustion [3] and is located under the cathode potential. The hollow cathode geometry, the shape of the emission electrode and anode, their location in the chamber are determined from the condition of the lowest degree inhomogeneity of plasma concentration in the hollow cathode and the density of ion current.

In non-self-sustained arc discharge of low gas pressure, effective ionization and excitation of gas molecules is carried out due to oscillations in the cathode cavity and multiple reflection from the near-cathode barrier ($U_c = U_d - U_a \approx U_d$) of gamma-electrons emerging due to ion-electron emission from the cathode surface with coefficient γ, and current electrons from an external source, $U_a$ – negative anode potential drop.

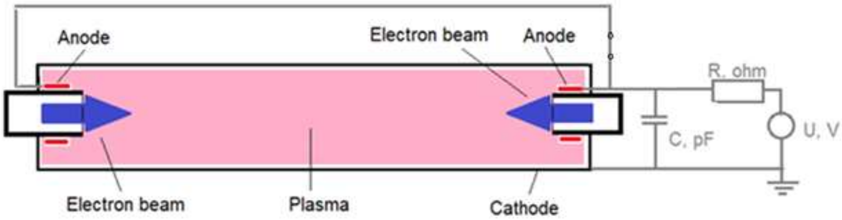



Fig. 1. Diagram of the discharge model and the electric circuit.

## 3. Computer model

Gas discharge processes are described by a system of hydrodynamic equations for the electron density $n_e$ and the average electron energy $n_\varepsilon = n_e \bar{\varepsilon}$ , a multicomponent diffusion relation

$$\frac{\partial n_{e,\varepsilon}}{\partial t} + \nabla \cdot \mathbf{\Gamma}_{e,\varepsilon} + a_{e,\varepsilon} \boldsymbol{E} \cdot \mathbf{\Gamma}_{\boldsymbol{e}} = R_{e,\varepsilon}, \tag{1}$$

$$\rho \frac{\partial}{\partial t} w_m = \nabla \cdot \boldsymbol{j_m} + R_m, \tag{2}$$

and the Poisson's equation for the electrostatic potential $\Delta\varphi = f/\varepsilon_0$, where $f$ – volumetric charge density of all charged particles. Here $\Gamma_{e,\varepsilon} = -\mu_{e,\varepsilon} \boldsymbol{E} n_{e,\varepsilon} - \nabla(D_{e,\varepsilon} n_{e,\varepsilon})$ – flows of electrons and energy, $\boldsymbol{E} = -\nabla\varphi$; $\mu_{e,\varepsilon}$ и $D_{e,\varepsilon}$ – mobility and diffusion coefficients of electrons and energy (indexes $e,\varepsilon$ denote quantities describing electrons and their average energy), $a_e$ = 0, $a_\varepsilon$ = 1, $m$ – numbers of the components (ions, neutrals and excited atoms), $\boldsymbol{j}_k$ – vector of the diffusion flow, $R_m$ and $w_m$ – reaction rate constant and mass fraction of the $k$th component, $\rho$ – mixture density, $R_{e,\varepsilon}$ – sources of elementary processes and inelastic collisions that occur both in the discharge volume and on the walls, $\bar{\varepsilon}$ – average electron energy of the entire ensemble of the electrons, $T_e = 2/3\bar{\varepsilon}$ – electron temperature.

Secondary electron emission and losses on the walls of the electron flow and electron density of the energy are accounted for on the boundary of the hollow cathode:

$$\boldsymbol{n} \cdot \mathbf{\Gamma}_{\boldsymbol{e}} = \frac{1}{4} v_{ch} n_e - 2\gamma \mathbf{\Gamma}_i \cdot \boldsymbol{n}, \ \boldsymbol{n} \cdot \mathbf{\Gamma}_{\boldsymbol{\varepsilon}} = \frac{1}{4} v_{ch} n_\varepsilon - 2\gamma \bar{\boldsymbol{\varepsilon}}_{\boldsymbol{i}} \mathbf{\Gamma}_i \cdot \boldsymbol{n}. \tag{3}$$

Here $\boldsymbol{n}$ – unit normal vector, $v_{ch}$ – average chaotic electron velocity, γ – coefficient of the secondary electron emission, $\Gamma_i$ – flow of the positive ions onto the wall. On the emission boundary of the electron source, electron flows and energy density corresponding to the arc discharge plasma potential of the additional source are specified:

$$\boldsymbol{n} \cdot \mathbf{\Gamma}_{\boldsymbol{e}} = -\frac{j_b}{e}, \boldsymbol{n} \cdot \mathbf{\Gamma}_{\boldsymbol{e\varepsilon}} = -\frac{j_b}{e} \varepsilon_b \ . \tag{4}$$

## 4. Modeling of the non-self-sustained glow discharge in the hollow cathode

Model 1. In the glow discharge in the cathode area processes responsible for its existence are concentrated: ion-electron emission and emission of the electrons from an external source, surface reactions. Boundary condition on the cathode for the Poisson's equation is $\varphi = 0$, on the anode $\varphi = U_c$, where $U_c$ is determined from the electron circuit equation by Kirchhoff's law (fig. 1). In the boundary conditions for the electron source (4), the initial energy of the electrons corresponds to the arc discharge emission plasma potential [7].

Model 2**.** Processes in the charge separation layer near the surface of the cathode are not considered, energy density $\varepsilon_b$ of electrons in the boundary condition (4) corresponds to the accelerating voltage $U_d$. When the law of continuity of flows (currents) on the boundaries of the computational area are satisfied, the model allows one to study the characteristics of the plasma generated in the non-self-sustained mode in the hollow cathode. Plasma potential relative to the wall of the discharge area is evaluated from comparison of the density of chaotic electron current in the near-electrode layer [8].

Mathematical models (Model 1 and Model 2) have their advantages and disadvantages, complementing each other, making it possible to determine basic patterns and mechanisms of non-self-sustained low-pressure glow discharge generation in large-sized hollow cathodes. Computer modeling is carried out using a professional software package Comsol Multiphysics, that allows to process the complex relationship of the electrostatic field with transport of electrons and heavy particles in drift-diffusion approximation. Argon is used in calculations in Model 1, based on a fairly good study of the parameters for the glow discharge problem in this gas and available experimental data on plasma formation generation in non-self-sustained combustion mode in the hollow cathode with one electron beam source [5]. Calculation are carried out for argon and nitrogen in Model 2, discharge coefficients are determined using Bolsig+ program [9].

*4.1. Model 1*

Figures (2–4) show the results of calculations using Model 1. Calculations show that discharge current and plasma concentration increase linearly with the increase of beam emission current when operating one and two beam sources (fig. 2). Figure 3 shows dependencies of the discharge current on gas pressure when operating 1 and 2 sources at discharge combustion voltage of $U_d$ = 90, 180 and 250 V, $p$ = 0.65 Pa, $I_b$ =10 A. At voltages of $U_d$<180 V discharge current weakly depends on gas pressure, gas concentration $n(p)$ increases due to increase in discharge current.

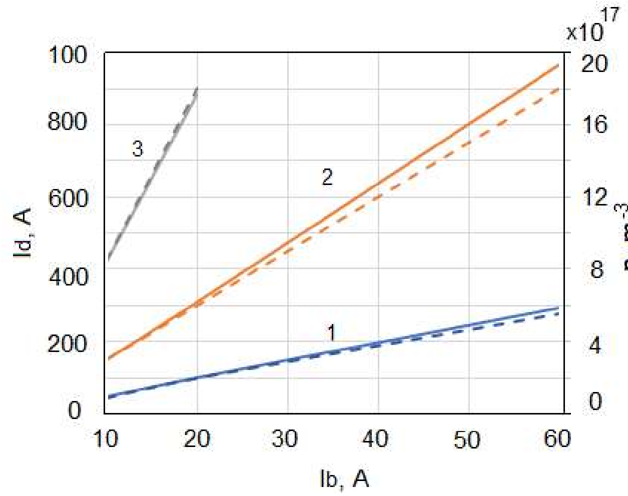



Fig. 2. Dependency of discharge current (solid lines) and plasma concentration on the symmetry axis (dotted lines) on beam emission current, 1 – $U_d$ = 90 V, 2 – 180 V, 3 – 250 V.

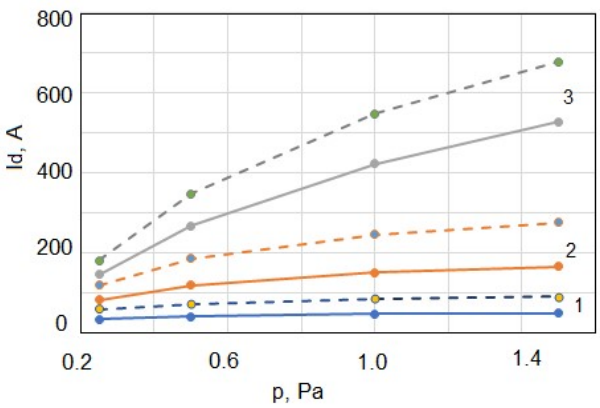
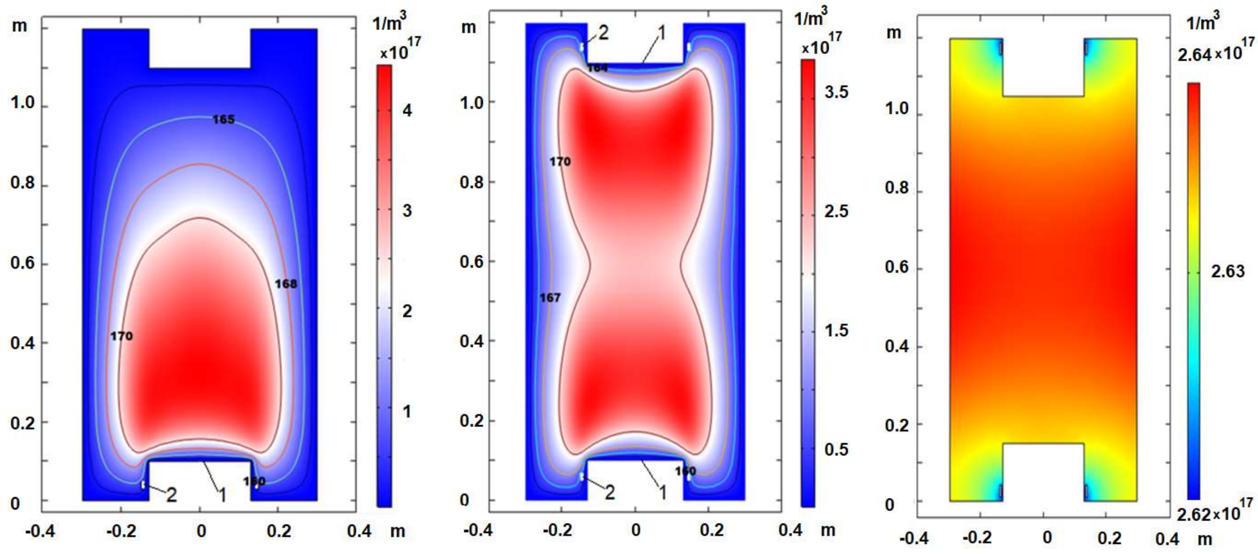



Fig. 3. Dependency of discharge current on gas pressure when operating one source (solid lines) and two sources (dotted lines); 1 – $U_d$= 90 V, 2 – 180 V, 3 – 250 V, $I_b$=10 A.

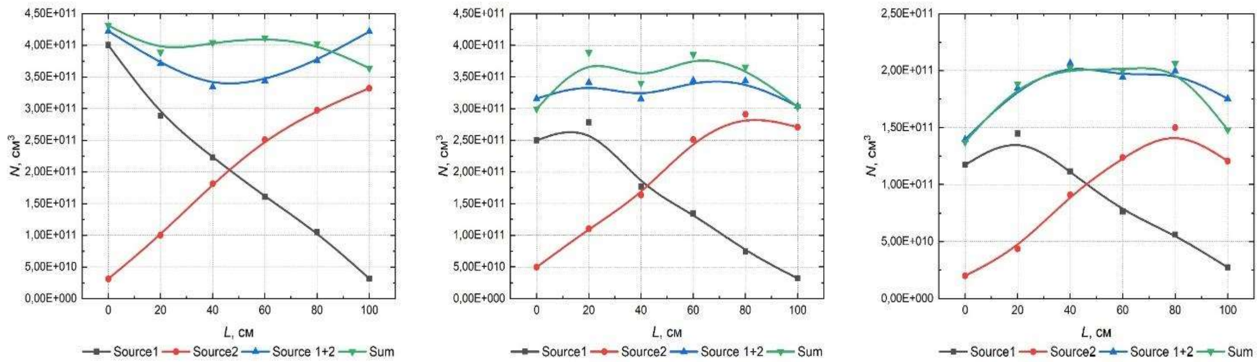
Spatial distribution of plasma concentration is shown in fig. 4 a,b at $p$ = 0.65 Pa. Distribution of plasma concentration in glow discharge is inhomogeneous due to the need to maintain plasma quasi-neutrality under conditions of directed motion of plasma electrons in the direction of the anode and the beam electrons (beams) accelerated in near-cathode layer.



(a) (b) (c)

Fig. 4. Plasma potential level lines relative to the cathode (a, b) and spatial distribution of plasma concentration; Model 1 – (a, b), Model 2 – (c), 1 – emitter, 2 – anode.

Figure 5 shows experimental distributions of plasma concentration density. The total charge density of colliding beams $\rho_\Sigma$ increases when two sources are turned on relative to single sources $\rho_{1,2}$, accordingly, electric field and electron temperature increase, which causes an increase in particle diffusion rate. The bigger the difference between $\rho_\Sigma$ and $\rho_{1,2}$, the bigger the violation of the superposition principle of plasma concentration distribution, which is observed in the experiment with the increase in discharge current, related by linear dependence to the beam emission current. Stronger inhomogeneity of plasma density concentration in calculations (fig. 4a, 4b) and excessive plasma temperature values (5–7 eV) relative to experimental measurements are explained by hydrodynamic approximation of the electron beam in the model.



(a) (b) (c)

Fig. 5. Experimental linear plasma concentration distribution: a – $r$ = 0 cm, b – 13 cm, c – 26 cm.

*4.2. Model 2*

The results of numerical calculations using Model 2 are shown in fig. 6–7. The linear dependencies of the discharge current on the beam current (fig. 6) when operating one and two sources at gas (nitrogen and argon) pressure of $p$ = 0.65 Pa and discharge combustion voltage of 160 V matches the calculations for Model 2 (fig. 2) and experimental measurements [3].

Figure 7 shows the dependence of plasma concentration on source beam current. The values of discharge current, plasma concentration and their change rate with the increase in $I_b$ for argon is higher than it is for nitrogen. The plasma concentration distribution in the hollow cathode is almost homogeneous (fig. 4c), the energy of fast electrons (secondary and beam) is spent on interaction with gas molecules and in the pressure range of (0.025–1.5) Pa the plasma temperature varies in the range of (1.4–0.7).

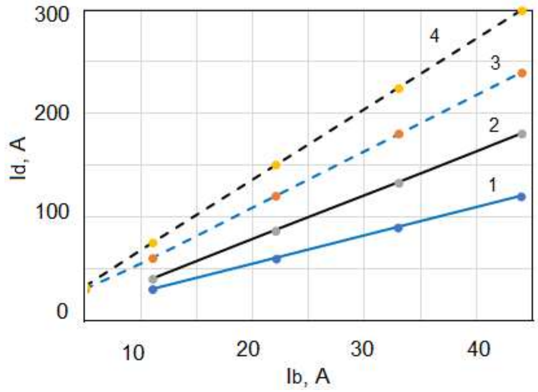



Fig. 6. Dependence of discharge current on beam current when operating one (1, 2) and two sources (3, 4); 1, 3 – nitrogen, 2, 4 – argon, $p = 0.65$ Pa, $U_d = 160$ V.

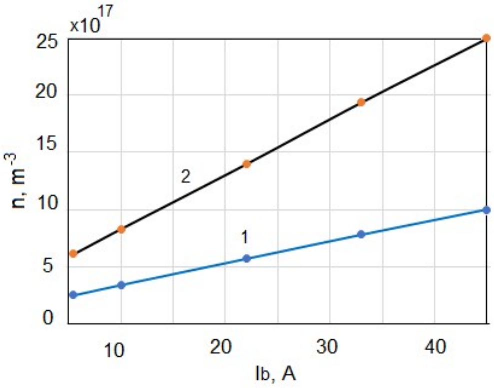



Fig. 7. Dependence of plasma concentration on source beam current, 1 – nitrogen, 2 – argon $p = 0.65$ Pa, $U_d = 160$ V.

Thus, computer modeling of plasma formation generation in a large-sized volume in non-self-sustained mode of low-pressure discharge combustion can be carried out in drift-diffusion approximation taking into account physical principles of glow discharge and hollow cathode. Model 1 describes basic patterns of the parameters and the mechanism of inhomogeneous plasma formation generation in non-self-sustained glow discharge in a large-sized discharge volume. Model 2 more correctly describes the hollow cathode mode during non-self-sustained combustion of a gas discharge and, in the presence of processed parts located in it, is more preferable.

## 5. Conclusion

Comparison of the experiment results and numerical modeling shows that numerical models (Model 1 and Model 2) reflect basic mechanisms of non-self-sustained low-pressure glow discharge plasma generation when operating one and two electron beam sources. The accuracy of the execution of the plasma concentration superposition principle is decreased in Model 1 with the increase in influence of electron beam on electric field distribution and plasma particle dynamic. Model 2 more correctly describes the mechanism of the hollow cathode in non-self-sustained mode of plasma generation. The agreement between the results of computer modeling and experimental measurements provides grounds for the use of drift-diffusion approximation when solving problems of reducing the degree of distribution inhomogeneity of a non-self-sustained high-current glow discharge plasma in hollow cathodes with multiple electron beam sources in the presence of processed parts located in cathode cavity

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