CONTROL OF THE DISTRIBUTION OF THE INTERNAL CHARACTERISTICS OF THE DISCHARGE USING SUPERSONIC GAS PUMPING

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Abstract. Theoretical studies of the distribution of glow discharge parameters in a supersonic nitrogen gas flow between the central body of the nozzle and an annular electrode around the central body are carried out. Distributions of charged particle concentrations, potential, and electric field strength are obtained. The possibility of compaction or stretching of the cathode zones has been demonstrated. In the case of the organization of a supersonic gas flow near the central body—the anode, all the near-electrode zones are pressed against the anode. In this case, the cathode is located in the area of reduced pressures. Such a way of organizing the discharge can find application in the processes of applying functional coatings.

1. Introduction

A smoldering discharge is a self-organizing discharge in the sense that after the discharge occurs in the interelectrode gap, a specific distribution of its parameters is established, such as the potential and intensity of the electric field, the concentration of charged particles, the glow pattern, which corresponds to the principle of least action. It is almost impossible to influence this distribution.

The relevance of the search for ways to control the distribution of internal discharge parameters is dictated by practical applications of glow discharge. One of the most popular applications of glow discharge is the application of protective, functional, anticorrosive coatings, in which cathode atoms knocked out by discharge gas ions are deposited on the substrate [1-3]. This process is not fast, but the quality of the coating, if the appropriate conditions are met, can be close to ideal. One of the necessary conditions for providing a high-quality coating is a strong vacuum of the working gas, in which an atom knocked out of the cathode can reach the substrate without colliding with others. On the other hand, the existence of a glow discharge requires the presence of at least five ionizing collisions of electrons in the cathode region. In this case, the condition of self-maintenance of the discharge will be fulfilled: the ions created by one primary electron in the cathode layer, when falling on the cathode, must ensure the output of at least one electron.

Thus, on the one hand, a low pressure of the working gas is required to obtain high-quality coatings, on the other hand, at such a low pressure, a glow discharge is difficult to initiate and maintain. One of the solutions to this problem is the use of a magnetic field in the cathode region. The action of the Lorentz force increases the residence time of an electron near the cathode and, accordingly, the number...
of collisions of electrons with gas atoms in the cathode region, as a result of which the main condition for maintaining a glow discharge is fulfilled.

An alternative method of solving the problem is to create regions with different concentrations of neutral particles in the interelectrode gap. As it was shown in [4-5], the organization of supersonic gas flow in a limited area of the interelectrode gap makes it possible to control the distribution of discharge parameters between the cathode and the anode. Pumping gas at supersonic speed allows you to create regions with different values of gas concentrations in the interelectrode space and in this way change the distribution of concentrations of electrons and ions, as well as the potential and intensity of the electric field. In [6], an axisymmetric supersonic flow created by an axisymmetric supersonic nozzle with a central body was used for this purpose. One of the electrodes was a central body completely immersed in the supersonic flow, and the second electrode was an axisymmetric ring with the first electrode, which was carried outside the supersonic gas flow. At the same time, an inhomogeneous gas density is created in the interelectrode space.

The aim of this work is to numerically simulate the distribution of parameters of a glow discharge with supersonic gas pumping near the central electrode at various discharge pressures and currents. As the initial distribution of the concentration of gas particles, the results of calculations performed in [6] are accepted.

2. Description of the model
The system of equations for the glow discharge plasma was written in the diffusion-drift approximation, these are k equations for the concentrations of \( n_k \) of all kinds of particles under consideration (neutral, excited particles, electrons and ions):

\[
e_0 \nabla E = \rho ,
\]

\[
E = -\nabla V ,
\]

\[
\frac{\partial n_k}{\partial t} + \nabla \Gamma_k = R_k ,
\]

\[
\Gamma_{e,i} = Z_{e,i} \mu_{e,i} n_{ke,i} E - D_{e,i} \nabla n_{e,i} ,
\]

\[
\Gamma_n = -n \nabla n \n ,
\]

\[
\frac{\partial n_e}{\partial t} + \Delta \Gamma_e = R_e ,
\]

\[
\Gamma_e = -\mu_e n_e E - D_e \nabla n_e ,
\]

Here \( e_0 \) - is the electric constant, \( E \) - is the electric field strength, which is determined by the Poisson equation (2) for the potential \( V, \rho = \sum_k Z_k n_k - n_e, Z_k \) - is the charge of the particle of grade \( k \), \( n_k \) - is the concentration of particles, \( \Gamma_k \) - is the flow of concentrations of particles of grade \( k \) (\( k = e, i, n \) for charged, excited and neutral particles), \( \Gamma_e \) - the flow of density electron energies, \( \mu_e, \mu_i \) and \( D_e, D_i \) - mobility and diffusion coefficients of electrons and ions, \( \mu_e = \frac{5}{3} \mu_e \) - "energy" mobility and \( D_e = \frac{5}{3} D_e \) - energy diffusion coefficient, \( \mu_e = \frac{e}{m_e} \frac{1}{v_d}, v_d = k n(N_2) \) - drift velocity, \( k \) - elastic collision constant, \( n(N_2) \) - concentration of neutral molecules \( N_2 \), \( D_e = \mu_e \frac{k_B T}{q} \) - electron charge, \( k_B \) - Boltzmann constant, \( T \) - temperature, \( n_e = n_e \bar{e} \) - electron energy density, \( \bar{e} = \frac{3}{2} T \) - average electron energy, \( T_e = \frac{2}{3} \bar{e} \) - electron temperature (understood as 2/3 of the average energy of the total ensemble), \( n \) - is a single vector directed towards the anode. \( R_e \) - the rate of birth and destruction of particles in reactions, \( R_e \) - the
loss of electron energy due to inelastic collisions, which are determined by plasma-chemical reactions. If M reactions occur in the plasma, as a result of which the electron density decreases or increases and $P$ inelastic collisions of electrons with neutral particles, then the value can be calculated from the equation $R_e$:

$$R_e = \sum_{j=1}^{M} R_j = \sum_{j=1}^{M} x_j k_j N_n n_e,$$  \hspace{1cm} (8)

where $R_j$ - is the reaction rate $j$, $x_j$ - is the molar fraction of the target particles for reaction $j$, $k_j$ - is the reaction rate constant of the corresponding inelastic process involving the electron, $N_n$ - is the total density of neutral particles (concentration of molecules $N_2$). Energy losses $R_e$ due to inelastic collisions of electrons and heavy plasma particles are calculated by summing up the energy losses during collisions for all reactions:

$$R_e = \sum_{j=1}^{P} x_j k_j N_n n_e \Delta \epsilon_j = \sum_{j=1}^{P} \Delta \epsilon_j R_j$$  \hspace{1cm} (9)

where $\Delta \epsilon_j$ - is the loss (or gain, if $\Delta \epsilon_j < 0$) of energy in the reaction $j$.

Calculations were carried out for nitrogen, 73 plasma-chemical reactions from the works were used [7-9].

3. Boundary conditions

For the Poisson equation, it was believed that the anode is grounded: $V_a = 0$, on the cathode $V_c = -V_0$, where $V_0 = V_{00} - IR_b$, here $V_{00}$ - is the voltage at the source, $R_b$ - is the ballast resistance, $I = \int_S j \, n dS$ - is the current in the circuit, $j$ the current density.

For metal electrodes, the boundary conditions for the flow of electrons $\Gamma_e$, for the energy flux density of electrons $\epsilon$, for ions $\Gamma_i$, as well as excited and neutral plasma particles are:

$$n \Gamma_e \bigg|_{x=0,L} = \frac{1}{4} v_{t,e} n_e - \left(1 - \alpha\right) \sum_{l=1}^{N} \gamma \Gamma_l n,$$  \hspace{1cm} (10)

$$n \Gamma_e \bigg|_{x=0,L} = \frac{1}{4} v_{t,e} n_e 2 k_B T_e - \left(1 - \alpha\right) \sum_{l=1}^{N} \gamma \Gamma_l n,$$  \hspace{1cm} (11)

$$n \Gamma_i \bigg|_{x=0,L} = \frac{1}{4} v_{t,i} n_e + \alpha \mu_i n_i E n,$$  \hspace{1cm} (12)

$$n \Gamma_n \bigg|_{x=0,L} = \frac{1}{4} v_{t,n} n_e,$$  \hspace{1cm} (13)

where $v_{t,e}, v_{t,i}, v_{t,n}$ the average thermal velocities of electrons, ions, excited and neutral particles of the gas plasma $\gamma = 0.2$ are the coefficient of secondary emission of electrons from the cathode, $\alpha = 1$ on the anode, $\alpha = 0$ on the cathode. The average energy of the emitted electron as a result of the impact of the $k$-th grade of particles:

$$\bar{\epsilon} = \Delta \epsilon - 2 W_f,$$  \hspace{1cm} (14)

$\Delta \epsilon$ = 15.6 eV - ionization energy of ion $N_2$, $W_f$ - energy Fermi.

4. Calculation results

The system of equations (1)-(7) was solved with boundary conditions (10)-(13) in geometry 1D with axial symmetry. The cathode radius is 1.5 mm, the anode radius is 25 mm (Figure1).
Figure 1. 1D geometry with axial symmetry.

Figure 2 shows the distribution of particle concentrations depending on the distance from the cathode center with a constant concentration of gas particles corresponding to a pressure of $p_0 = 5$ Torr, a power supply voltage of 1000 V, a ballast resistance of $R_b = 100$ kOhm.

Figure 2. Distribution of electron and positive ion concentrations in the interelectrode space for a constant concentration of neutral particles.

Figure 3. Distribution of electron and positive ion concentrations in the interelectrode space for the case when supersonic gas pumping is organized near the cathode—the central body, which led to a 9-fold increase in the concentration of gas particles.
This is the classical distribution of electron and ion concentrations in the interelectrode gap, corresponding to the axisymmetric geometry of the electrode arrangement. The areas of Astanov dark space, cathode glow, cathode dark space, negative glow, Faraday dark space, positive column and the area of anode potential drop are clearly visible.

When the pressure drops to 0.05 Torr at the same $V_0 = 1000$ V and $R_b = 100$ kOhm, there is no discharge. In the presence of a supersonic gas flow near the cathode-the central body, an additional concentration of neutral nitrogen molecules appears. Figure 3 shows the distributions of the concentration of ions and electrons for the case when the central electrode is a cathode and the area of increased concentration of nitrogen molecules is located near it at a distance of up to 10 mm. The concentration of neutral particles is increased by 9 times compared to the rest of the region. It follows from the figure that large concentrations of charged particles are also observed in the area of increased concentration of neutral molecules. When moving to a region with a lower concentration of neutral particles, the concentrations of charged particles also decrease. But this decrease is mainly due to the cylindrical symmetry of the electrode system. At the same time, the total current is preserved, since in this area there are high values of the electric field strength and the cross-sectional area of the discharge area.

In Figure 4a and 4b show the distributions of the concentrations of electrons, positive ions and the electric field strength in the interelectrode space for the case when the central electrode is an anode, and the area of increased concentration of nitrogen molecules is located near it also at a distance of 10 mm ($n=9n_0$).

![Figure 4. a) Distribution of electron and positive ion concentrations in the interelectrode space.](image1)

![Figure 4. b) Distribution of electric field strength.](image2)

As expected, this arrangement of the electrodes and the organization of supersonic gas flow led to the displacement of all near-electrode zones to the anode. There are practically no ionization processes in the area of reduced electron concentration. In this region, the probability of collision of electrons with
neutral molecules is extremely low. Therefore, the electrons released from the cathode run through this region freely, gain energy, and, falling into an area with an increased concentration of gas particles, intensively ionize gas molecules. The concentration of both electrons and ions is increasing. The ions are pulled out of this region by the applied electric field and, just like the electrons, reach the cathode without reducing their concentration. Recombination of these ions at the cathode leads to the appearance of new electrons.

5. Conclusion

As can be seen from Figure 4b, the distribution of the electric field also has a specific character. In the region of small concentrations of gas particles, the field is high, which contributes to the rapid collection of energy by electrons sufficient for repeated ionization of molecules by an electron shock.

Conclusions. As can be seen from the above analysis, an increase in the concentration of nitrogen molecules in various regions of the interelectrode space of the glow discharge significantly affects the nature of the discharge. Of particular interest is the discharge with the organization of an increased concentration of gas particles near the central body—the anode. In this case, the cathode region becomes collisionless and this type of discharge can find effective application in coating processes by cathode sputtering without magnetron effect. The proposed method allows you to control the parameters of the glow discharge.

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