Control of glow discharge parameters using transverse supersonic gas flow - numerical experiment

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Abstract. A low pressure glow discharge in a transverse supersonic gas flow was studied by numerical modelling for the case where the flow only partially fills the interelectrode gap. It’s shown that by organizing a supersonic gas flow in a limited region of the interelectrode space can be controlled combustion conditions of the glow discharge, and its parameters. It is shown that it is possible to achieve stable combustion glow discharge at low and superlow pressures, when the parameter $pL$ lies on the left branch of the Paschen curve.

1. Introduction
The control of the parameters of the DC glow discharge’s plasma is of considerable fundamental and applied interest. Glow discharges at low pressures and long discharge gaps are promising for the application of coatings, plasma surface modification and others.

As is known [1, et al.], one of the necessary conditions for the existence of glow discharge is the presence of all near cathode regions. The length of these regions increases with decreasing pressure. This is due to the fact that the length of each zone is mainly determined by the number of ionizing collisions of electrons with neutral gas particles. As a result, under high vacuum for self-organization glow discharge may be not enough distance between the electrodes. In this case, the discharge becomes difficult that is combustion conditions correspond to a point belonging to the left branch of the Paschen curve [1], or does not lights up.

To solve this problem, the article [2] proposed a method which consists in the organization of a supersonic gas flow in the direction of perpendicular to the electric field in the area next to the cathode layer CS. In this case, on the way of the electrons, which gain energy in CS, in the narrow part of the interelectrode space in which is organized transverse supersonic flow, by artificial means created "the stockade" of neutral gas particles, i.e., to create conditions similar increase in the concentration of neutral particles, which leads to increase the number of ionizing collisions. As a result, all main regions of glow discharge are formed, including the positive column and PC.

It is worth noting works [3-8], which been studied in detail glow discharge in longitudinal and transverse supersonic gas flow.

The aim of this work is to demonstrate by using of numerical experiments in the approach of hybrid model the new method for controlling parameters of glow discharge by using transverse supersonic gas flow.
2. The model description
One of the most common methods of modeling the spatial structure of the glow discharge is diffusion-drift (fluid) approximation [1, 3, 6, and others]. However, at low pressures, when clearly observed the near cathode regions of the discharge, in particular, the region of the negative glow NG and the Faraday dark space FDS must be considered non-locality of the ionization processes occurring in these areas. Different approaches to describe the near cathode regions of the discharge have been proposed earlier in papers [7, 8-11].

In this paper, for the numerical experiments are formulated hybrid model [9], glow discharge, based on the balance equations for the concentrations of electrons \( n_e \), positive \( n_+ \) and negative ions \( n_- \), heat balance equation of electrons \( \rho \), which takes into account not only the bulk processes, but also the spatial transfer by conduction and Poisson equation for finding the self-consistent electric potential \( \phi \). The calculations were performed for air (77% \( \text{N}_2 \), 23% \( \text{O}_2 \)) with a set of plasma-chemical reactions described in [14-15]. In the energy balance equation for the electrons were taken into account members of the excitation and elastic losses.

The system of equations describing the structure of the glow discharge, is written as follows:

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = S_e, \quad \Gamma_e = -D_e \nabla n_e + z_e \mu_e E n_e, \quad (1)
\]

\[
S_e = (\nu_{\text{ion}} - \nu_{\text{att}}) n_e + \nu_+ n_- - \beta_e n_e n_+, \quad S_- = \nu_{\text{att}} n_e + \nu_- n_+ - \beta_0 n_- n_+, \quad (2)
\]

\[
\frac{3}{2} \frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{Q}_\rho = -e \nabla \cdot \mathbf{E} + S_{\text{el}} + S_{\text{in}} , \quad \mathbf{Q}_\rho = -D_e \nabla n_e - \mu_e E n_e, \quad (3)
\]

\[
\frac{\partial (\rho T)}{\partial t} - \nabla \cdot \mathbf{Q}_T = e \Gamma_e \cdot \mathbf{E}, \quad (4)
\]

\[
\Delta \phi = -\frac{q_e}{\varepsilon_0} \left( n_e - n_- - n_+ \right). \quad (5)
\]

where \( \Gamma_e \) are fluxes of electrons, positive and negative ions, \( \mathbf{Q}_\rho \) are the energy flux of the electrons; \( z_e \) is the electric charge of the particle; \( D \) and \( \mu \) with index «ke» are the diffusion coefficients and the mobility of electrons, positive and negative ions, respectively; with index «ke» are the diffusion coefficient and the mobility of electron energy; \( \mathbf{E} = -\nabla \phi \) is the electric field strength, \( \nu_{\text{ion}}, \nu_{\text{att}}, \nu_\text{-} \) are the ionization, attachment and detachment frequencies; \( \beta_\text{e}, \beta_\text{-} \) are the coefficients for electron-ion and ion-ion recombination. The ionization frequency calculated by convolution with a Maxwellian distribution function with section \( \sigma(w) \) of the corresponding process [13].

The first term on the right hand side of the first expression (3) corresponds to the Joule heating of the electrons in an electric field. The second term \( S_{\text{el}} \) describes the energy loss due to elastic collisions of electrons with atoms and molecules. The third term \( S_{\text{in}} \) describes the inelastic energy loss of an electron gas.

Mobility is determined as follows:

\[
\mu_e = q_e / m_e v_{\text{el}} \rho_0, \quad \mu_+ = \left(1.7 \cdot 10^{-4} / p\right) m^2 / s, \quad \mu_\text{-} = (5/3) \mu_e, \quad (6)
\]
where \( v_{el} \) – is frequency of elastic electron-atom strikes, \( p \) – pressure (Torr). The diffusion coefficients were calculated by means of the Einstein relation:

\[
D_k = T \mu_k, \quad D_e = T \mu_e, \quad D_e = T \mu_e. \tag{7}
\]

Boundary conditions were set at the cathode and anode for the electron density, the energy density of the electrons and the ion concentration and the electric potential

\[
n \cdot \Gamma_{e|0} = \frac{V_{th} \cdot n_e}{2} - \gamma n \cdot \Gamma_k, \quad n \cdot \Gamma_{e|L} = \frac{V_{th} \cdot n_e}{2},
\]

\[
n \cdot Q_{|0} = \frac{5}{6} V_{th} \cdot n_e, \quad n \cdot Q_{|L} = \frac{5}{6} V_{th} \cdot n_e,
\]

\[
n \cdot \Gamma_{k|0} = v_{th} n_k, \quad n \cdot \Gamma_{k|L} = v_{th} n_k + \mu_k n \cdot E,
\]

\[
\varphi(0,r) = 0, \quad \varphi(L,r) = U_0. \tag{11}
\]

Where \( \gamma = 0.1 \) – is the coefficient of secondary electron emission from the cathode, \( V_{th} = \sqrt{8k_B T_e / \pi m_e} \)

and \( v_{th} = \sqrt{8k_B T_e / \pi M} \) – are the average thermal velocity of the electrons and the atoms of the gas, respectively, \((T-\text{in eV})\).

3. The results of numerical experiments.

Equations (1)-(5) with boundary conditions (8)-(11) were solved for a one-dimensional geometry with the distance between the electrodes \( L = 4 \text{ cm} \). Picture of the distribution of the plasma parameters of a glow discharge at a pressure \( p = 0.15 \text{Torr} \) and the voltage between the electrodes \( U = 500 \text{V} \) is shown in Fig. 1. Clearly observed the near cathode region of the discharge – cathode layer CS, a region of negative glow NG and the Faraday dark space FDS. The positive column PC is missing. Under these conditions, the discharge parameter \( pL = 6.0 \text{Torr} \cdot \text{cm} \) belongs to the minimum of the Paschen curve for air [1].

![Fig.1. The distribution parameters of a glow discharge at a pressure \( p = 0.15 \text{Torr} \), with the distance between the electrodes \( L = 4 \text{cm} \) without making a supersonic airflow.](image-url)

Through supersonic gas flow perpendicular to the direction of the electric field in a limited region of the interelectrode space, and varying the gas flow rate \( G = \rho V_{sup} S \), which is related to the density
of the supersonic flow $\rho$ and its speed $V_{\text{sup}}$ (assuming that the gas density and flow rate does not vary across the cross section) can thereby increase the concentration of neutral particles in the selected area of the discharge gap is several times. Furthermore, when implementing the supersonic gas flow possible to light discharge in conditions when the parameter $pL$ shifted to the left side of the Paschen curve for the same voltage between the electrodes.

Thus in Fig. 3 shows the structure of a glow discharge at a pressure $p = 0.1\text{Torr}$ in the discharge chamber and the implementation of a supersonic gas flow region $x \in (0.25 - 0.35)\text{ cm}$. It is worth noting that the implementation of the supersonic gas flow possible to light the discharge in conditions when the parameter $pL$ displaced in the left branch of the Paschen curve at the same voltage between the electrodes. It is seen that NG and FDS narrowed and focusing entirely in the area with a supersonic flow. In addition, the formed PC, a small part of which is localized in the region with a supersonic flow and the remainder (the majority) after area with a supersonic flow. Similar results are observed in laboratory experiments [2].

Fig.2. The distribution parameters of the discharge at a pressure of $p = 0.1\text{Torr}$ considering supersonic gas flow in the region from 2.5 cm to 3.5 cm with a gas consumption corresponding increased concentrations of neutral particles 10 times.

4. Conclusions
Thus, it is shown that organizing a supersonic gas flow in a limited region of the interelectrode space can be controlled as a glow discharge conditions, and its parameters. In particular, it is shown that it is possible to achieve stable combustion glow discharge at low and superlow pressures, when the the parameter $pL$ lies on the left branch of the Paschen curve. In this case, there is an extended cathode layer and the plasma region - negative glow NG, Faraday dark space and positive column FDS PC concentrated in a limited region with a supersonic gas flow. The obtained results allow to conclude that found a new effective way to control the longitudinal structure of the discharge, which can have a variety of applications, both in the region of the plasma coating, and in gas lasers.

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