Abnormal Glow Discharge between Two Electrodes on Plane with Transverse Magnetic Field

S T Surzhikov
Ishlinsky Institute for Problems in Mechanics, RUSSIAN Academy of Sciences, Vernadsky Street 101(1), Moscow, 119526, Russia
Dukhov Research Institute of Automatics (VNIIA), Suschevskaya Street 22, Moscow 127055, Russia

E-mail: surg@ipmnet.ru

Abstract. Surface glow discharge in the abnormal mode of its burning at pressure 5 Torr is numerically studied at a voltage drop of ~650 V between electrodes, located on plate surface at a distance of 2 cm. The drift-diffusion two-dimensional model of gas discharge plasma is used for the description of electrodynamic parameters of the discharge. It is shown that external transverse magnetic field of induction about 0.2 T occurs significant influence on the gas discharge plasma configuration, squeezing or expanding electric current channel between electrodes depending on the magnetic field polarization. Two-dimensional fields of electrodynamic functions, such as the volume concentrations of charged particles, electric potential and the force lines of electric field strength without and with external magnetic field are presented and analyzed.

1. Introduction

In this paper, we are considering the glow discharge configuration in the abnormal mode, which is of the greatest practical interest, when two electrodes are arranged on the same plane, as it is shown in figure 1. It is obvious, that such scheme of discharge is most acceptable for supposed schemes of discharge disposition on various streamline surfaces [1].

![Figure 1](image-url)

**Figure 1.** Schematic of the abnormal glow discharge on the plate surface.

The glow discharge of this kind has the following important peculiarities:
1. The discharge cannot exist in a condition of normal current density because it is limited by boundaries of the cathode and anode sections;  
2. It is necessary to expect abrupt growth of electric field strength near to boundaries of the electrode sections;  
3. The glow discharge region becomes non-symmetric: one its border is located on a dielectric surface, and another one is a non-disturbed gas of external gas flow.  

The specified properties of the surface direct current glow discharges are manifested in the formulation of the calculation model and boundary conditions.

2. The equations of the drift-diffusion model for surface glow discharge

The surface glow discharge is considered in molecular nitrogen between two flat electrodes (see figure 1). The glow discharge is described by the drift-diffusion model of the motion of electrons and ions together with the Poisson equation for the definition of electric potential \( \phi \) and electric field strength \( E = -\nabla \phi \):

\[
\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial x} \left( \mu_{eE} n_e E_{e,x} - \frac{D_e}{1 + b_e^2} \frac{\partial n_e}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_{eE} n_e E_{e,y} - \frac{D_e}{1 + b_e^2} \frac{\partial n_e}{\partial y} \right) = \alpha [\Gamma_e] - \beta n_e n_i, \tag{1}
\]

\[
\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x} \left( \mu_{iE} n_i E_{i,x} - \frac{D_i}{1 + b_i^2} \frac{\partial n_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_{iE} n_i E_{i,y} - \frac{D_i}{1 + b_i^2} \frac{\partial n_i}{\partial y} \right) = \alpha [\Gamma_i] - \beta n_e n_i, \tag{2}
\]

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 4\pi e (n_e - n_i), \tag{3}
\]

\[\Gamma_e = u_e n_e = -D_e \text{grad} n_e - n_e \mu_e (E + u_e \times B),\]

\[\Gamma_i = u_i n_i = -D_i \text{grad} n_i + n_i \mu_i (E + u_i \times B),\]

where \( n_e, n_i \) are the volumetric concentration of electrons and ions; \( \Gamma_e, \Gamma_i \) are the vectors of densities of electron and ion flows; \([\Gamma_e] = \sqrt{\Gamma_{e,x}^2 + \Gamma_{e,y}^2} \); \( B \) is the external magnetic field (its configuration is shown in figure 1); \( \alpha (E) \) and \( \beta \) are the coefficients of ionization and recombination; \( \mu_e, \mu_i \) are the mobilities of electrons and ions; \( u_e, u_i \) are the averaged velocities of electrons and ions; \( D_e, D_i \) are the diffusivities of electrons and ions;

\[
b_e = \frac{\mu_e B_z}{c}, \quad b_i = \frac{\mu_i B_z}{c}, \quad \alpha_e = \frac{\omega_e}{v_e}, \quad \alpha_i = \frac{\omega_i}{v_i}, \quad \omega_e = \frac{eB_z}{m_e c}, \quad \omega_i = \frac{eB_z}{m_i c}, \quad \omega_e = \frac{eH_z}{m_e c}, \quad \omega_i = \frac{eH_z}{m_i c},
\]

are the Hall parameters and the Larmor frequencies for electrons and ions.  

Components of the external effective electric field are expressed by the following relations:

\[
E_{e,x} = \frac{b_i E_y - E_x}{1 + b_i^2}, \quad E_{e,y} = \frac{b_i E_x + E_y}{1 + b_i^2}, \quad E_{i,x} = \frac{E_x + b_i E_y}{1 + b_i^2}, \quad E_{i,y} = \frac{E_y - b_i E_x}{1 + b_i^2}.
\]

It is supposed, that the glow discharge does not distort an external magnetic field.  

To define the diffusion coefficients of charged particles the Einstein’s formula is used

\[
D_e = \mu_e (p) T_e, \quad D_i = \mu_i (p) T
\]

while other constitutive parameters of the model are defining by empirical correlations as follows:
$$\mu_{e}(p) = \frac{4.4 \times 10^5}{p} \text{cm}^2 \text{s}^{-1}, \quad \mu_{i}(p) = \frac{1440}{p} \text{cm}^2 \text{s}^{-1}, \quad \beta = 2 \times 10^{-7} \text{cm}^3 \text{s}^{-1}, \quad T_e = 11610 \text{K}, \quad T = 300 \text{ K}.$$  

where: $p$ is the pressure in non-disturbed gas (in Torr); $T_e$ is the electronic temperature; $T_e = 11610 \text{ K}, T = 300 \text{ K}$. 

The coefficient of ionization is defined as follows (the first Townsend coefficient):

$$\alpha(E) = pA \exp \left[ -\frac{B}{(|E|/p)} \right], \frac{1}{\text{cm} \times \text{Torr}},$$

where: $A = 12 \frac{1}{\text{cm} \times \text{Torr}}, B = 342 \frac{V}{\text{cm} \times \text{Torr}}.$

The equations (1) – (3) are solved together with the equation for an external electric circuit, which in the stationary case looks like this

$$E = V + IR_0,$$

where: $V$ is the voltage drop on the electrodes; $I$ is the discharge current; $E$ is the emf of the power supply; $R_0$ is the external ballast resistance.

The total current in the discharge is calculated under the formula

$$I = \int_{0}^{l} \left( j \hat{n} \right) \text{d}x = \int_{0}^{l} \left( j \hat{n} \right) \text{d}x,$$

where: $\hat{n}$ is the unit vector of the cathode (c) and anode (a) surface; $j = e\left( \Gamma_i - \Gamma_e \right)$ is the current density.

For calculation of parameters of the surface glow discharge in flat geometry all integral parameters (for example, the total current) should be related to length unit in AW section (see figure 1).

Boundary conditions are formulated in the following form:

At $y = 0$, $x \in [x_c, x_D]$ (surface of the cathode)

$$n_e = \gamma n_i \mu, \quad \frac{\partial n_e}{\partial y} = 0, \quad \varphi = 0; \quad (4)$$

at $y = 0$, $x \in [x_e, x_f]$ (surface of the anode)

$$n_i = 0, \quad \frac{\partial n_i}{\partial y} = 0, \quad \varphi = V; \quad (5)$$

at $y = 0$, $x \not\in [x_c, x_D]$, $x \not\in [x_e, x_f]$ (a surface of a dielectric)

$$n_e = n_i = n_0, \quad \frac{\partial \varphi}{\partial y} = 0; \quad (6)$$

$$y \to \infty: \quad \frac{\partial n_e}{\partial y} = \frac{\partial n_i}{\partial y} = \frac{\partial \varphi}{\partial y} = \frac{\partial T}{\partial y} = 0; \quad (7)$$

$$x = 0, \quad x_g = L: \quad \frac{\partial n_e}{\partial x} = \frac{\partial n_i}{\partial x} = \frac{\partial \varphi}{\partial x} = 0; \quad (8)$$
Here $n_0$ is the typical concentration of electrons on a surface of dielectric ($n_0$ is by several digits less, than in electro-discharge plasma above electrodes, for example, $n_0 \sim 10^3 \div 10^7$ cm$^{-3}$); $V$ is the potential of the anode relative to the cathode. Notice that electro-physical boundary conditions on the dielectric surface are substantially defined by its catalytic ability. Following coordinates of cathode and anode sections were used in the calculations: $x_c = 3.5$ cm, $x_d = 4.0$ cm, $x_e = 6.0$ cm, $x_p = 6.5$ cm.

Clouds of quasi-neutral plasma above the cathode and the anode were set as the initial conditions. The initial distribution of potential was obtained from the solution of Laplace equation under given boundary conditions (4) – (8).

3. Numerical simulation results of surface glow discharge

Configuration of the surface glow discharge is shown in figure 1. The following physical boundary conditions were used for numerical simulation: $p = 5$ Torr, $E = 700$ V, $R_0 = 300$ kOhm, $\gamma = 0.33$.

Figures 2, 3 show the distribution of the volume concentrations of electrons and ions in a surface glow discharge with different polarizations of the magnetic field induction with the absolute value $|B_z| = 0, +0.02$ T, $-0.02$ T. Attention is drawn to the very strong influence of the magnetic field on the configuration of the plasma cloud above the electrodes. With a positive induction, a plasma cloud is pressed against the surface on which the electrodes are located (see figure 2, b). In the case of a negative value, the opposite trend is observed, namely, pushing the plasma cloud from the surface (see figure 2, c). We note that the direction of the force acting on the plasma cloud is well confirmed by the empirical rule of the “right hand”.

From the presented figures it is clearly seen that the highest concentration of charged particles is observed near the electrodes. This is not surprising since, at the boundaries of the electrodes, there is always a local increase in the electric field strength. Figures 4 and 5 show the electric potential distribution and the lines of force of the effective electric field without and with regard to the magnetic field. In accordance with the given boundary conditions on the dielectric surface, the lines of the electric field strength are perpendicular to the surface. Figure 5 shows that near the electrodes the largest value of the electric field intensity is formed. Moreover, the vector lines of the effective electric field for different polarizations of the magnetic field are inclined in different directions with respect to the normal.

With a further increase in the magnetic field induction, the glow discharge behaves differently. When $B_z > 0$ a glow discharge continues to shrink to the surface. With an increase in the negative induction value of more than $B_z = -0.4$ T, the discharge goes out.

Thus, as a result of numerical experiments using the diffusion-drift model, a strong influence on the electrodynamic structure of the discharge of an external transverse magnetic field has been established. Moreover, an important factor in this effect is the polarization of the transverse glow discharge of the magnetic field. This confirms the results of numerical simulation of the force applied to a surface glow discharge, established in [2]. We emphasize that in [2], in contrast to this work, an ambipolar model of a glow discharge was used (without taking into account the space charge region near the electrodes).

Acknowledgments

The work was supported by the Russian Science Foundation grant # 16-11-10275 П.
Figure 2. Volume concentration of electrons \( N_e = n_e / 10^9 \text{ cm}^{-3} \) in surface glow discharge at \( p = 5 \text{ Torr, } \gamma = 0.33, E = 700 \text{ V} \) and different polarization of the magnetic field: (a) \( B_z = 0 \), (b) \( B_z = +0.02 \text{ T} \), (c) \( B_z = -0.02 \text{ T} \).
Figure 3. Volume concentration of ions ($N_i = n_i / 10^9 \text{ cm}^{-3}$) in surface glow discharge at $p=5 \text{ Torr}$, $\gamma=0.33$, $E = 700 \text{ V}$ and different polarization of the magnetic field: (a) $B_z = 0$, (b) $B_z = +0.02 \text{ T}$, (c) $B_z = -0.02 \text{ T}$. 
Figure 4. Electric potential \((Fi = \rho / V_{de})\) in surface glow discharge at \(p=5\) Torr, \(\gamma=0.33\), \(E = 700\) V and different polarization of the magnetic field:

(a) \(B_z = 0\), (b) \(B_z = +0.02\) T, (c) \(B_z = -0.02\) T.
Figure 5. The electric field strength and its lines of force in surface glow discharge at $p=5$ Torr, $\gamma=0.33$, $E=700$ V and different polarization of the magnetic field: (a) $B_z=0$, (b) $B_z=+0.02$ T, (c) $B_z=-0.02$ T.

4. References

[1] Shang J S and Surzhikov S T 2018 Plasma Dynamics for Aerospace Engineering (Cambridge: Cambridge University Press) 387 p

[2] Surzhikov S T, Shang J S 2005 Viscous interaction on a flat plate with a surface discharge in magnetic field High Temperature 43 (1) pp 19–30