The Radio-Frequency Capacitive Normal Glow Discharge in Transverse Magnetic Field

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Abstract. The problems of computer simulation of the two-dimensional structure of a radio-frequency capacitive (RFC) glow discharge are discussed. The diffusion-drift computational model of the discharge, burning in a quasi-stationary mode, was used to analyze the behavior of the RFC-discharge in a transverse magnetic field. The calculations were performed for a two-dimensional RFC-glow discharge at a pressure of 5–10 Torr and an emf of 520–1000 V power source with a frequency of 13.59 MHz. The magnetic field vector with induction $B = 0.2\ T$ is directed across the current column of the RFC-discharge.

1. Introduction
The possibility of using electromagnetic methods of modifying partially ionized gas flows in various aerospace technologies has been discussed in the literature for more than 60 years. One of the possible ways of such a modification is the use of glow gas discharge of continuous current and high-frequency discharges of induction and capacitive type, well known in physics. These types of discharges are characterized by relatively low energy costs and ease of organization.

An important feature of these types of discharges is that, when the pressure in gas flows is of the order of 1–10 Torr, they are fairly uniform, and the characteristic time of their formation is microseconds, which is noticeably less than the time of formation of the gas-dynamic structure.

In our previous works, a detailed theoretical and theoretical study of the structure of direct current glow discharges at pressures $p \sim 1$–20 Torr in the absence of a gas flow [1], in subsonic [2], supersonic [3], and hypersonic [4–7] gas flows were performed. It was shown that direct current discharges can be numerically described in the mode of normal current density [1], between electrodes on opposite surfaces [1-3] and on one [6] surface. These configurations can be promising for use in various aerospace applications. Moreover, the use of an external magnetic field of small induction can significantly enhance the effect of discharges on the gas-dynamic structure [5–8].
Figure 1. RFC-discharge schematic in an external magnetic field.

In this work, the studies started in [1–8] in the field of numerical simulation of glow discharges in rarefied flows are continued with respect to a radio-frequency capacitive (RFC) glow discharge burning in a quasi-stationary mode at a pressure of \( p = 5–10 \) Torr. The discharge circuit is shown in figure 1. The quasi-stationary mode of existence of a discharge is characterized by the fact that after its formation from some initial plasma cloud localized in the inter-electrode gap, which is used as initial calculation data (the process of forming the current column takes several microseconds), the RFC-glow discharge retains its configuration for a much longer period of time (more ~ 100 µs), evolving in gas discharge gap. As a rule, in calculations there is a slow expansion of the current column with preservation of the internal electrodynamic structure of the discharge with near-electrode regions of the space charge and a positive column.

As well as a direct current (DC) glow discharge, the RFC-glow discharge under investigation is characterized by a low degree of ionization of the rarefied gas, \( n_e/n_n \sim 10^{-5} \) (\( n_e, n_n \) are the numerical concentrations of ions and neutral particles), as well as a high degree of nonequilibrium at which the temperature of neutral particles and ions is close to room temperature, while the electrons are heated by an external electric field up to 20000–30000 K. In the normal current density mode, there is a balance between the ionization processes, recombination, and diffusion of the charged particles in the column of electrical discharge. The results of numerical studies of the one-dimensional structure of the RFC-discharge are published in [9]. The first two-dimensional calculation of the RFC-discharge (without a magnetic field) was performed in [10].

Note that the high-frequency electric field leads to the possibility of the existence of a greater variety of current structures than in the classical direct current glow discharge [9]. In particular, two forms of the RFC-glow discharge are observed in experiments [11], the so-called \( \alpha \)- and \( \gamma \)-forms of the discharge.

In this work, a quasi-stationary discharge forms are obtained by calculation, and the evolution of one of the discharge forms in a transverse magnetic field is investigated. We emphasize that this paper discusses the numerical solutions obtained for the quasi-stationary RFC-glow discharge at time intervals \( < 200 \mu s \).

2. Governing equations
A two-dimensional structure of a radio-frequency capacitive glow discharge in molecular nitrogen, which exists between two infinite flat electrodes, is considered (see figure 1). The problem is solved in
a rectangular Cartesian coordinate system so that the discharge structure is an infinite layer in the
direction of the $z$-axis.

The electrodynamic structure of the discharge is described by the continuity equations for the
volume density of electrons $n_e$ and ions $n_i$, together with the Poisson equation $\mathbf{E} = -\nabla \phi$ for the
electric field, as well as the heat equation for neutral particles. This system of equations is presented
herein a convenient form for numerical implementation in [7]:

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

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

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

\[
\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + q_j \tag{4}
\]

\[
\Gamma_e = n_e \mathbf{V} = -D_e \nabla n_e - n_e \mu_e (\mathbf{E} + \mathbf{V} \times \mathbf{B}) \tag{5}
\]

\[
\Gamma_i = n_i \mathbf{V} = -D_i \nabla n_i + n_i \mu_i (\mathbf{E} + \mathbf{V} \times \mathbf{B}) \tag{6}
\]

where: $D_e, D_i$ are the diffusion coefficients of electrons and ions; $p, T$ are the pressure and
temperature of neutral gas; $\phi, \mathbf{E}$ are the electric potential charge of an electron; $\Gamma_e, \Gamma_i$ are the density
of electron and ion fluxes; $|\Gamma_e| = \sqrt{\Gamma_{e,x}^2 + \Gamma_{e,y}^2}$; $\mathbf{B}$ is the vector of magnetic field induction (the
direction of this vector is shown in figure 1); $q_j = \eta (\mathbf{E})$; $\mathbf{j} = e (\Gamma_e - \Gamma_i)$; $\mathbf{V}$ is the gas velocity;
$\alpha(E), \beta$ are the ionization and recombination coefficients; $\mu_e, \mu_i$ are the mobility of electrons and
ions; $\eta$ is the part of Joule heating, which goes into heat (a significant part of the energy goes into the
excitation of the vibrational degrees of freedom of molecular nitrogen); $\mathbf{B} = (0,0,B_z)$ magnetic field
induction;

\[
b_e = \frac{\mu_e B_z}{c} = \frac{\omega_e}{v_e}, \quad b_i = \frac{\mu_i B_z}{c} = \frac{\omega_i}{v_i}, \tag{7}
\]

are the Hall parameters for electrons and ions; $\omega_e = \frac{e B_z}{m_e c}$, $\omega_i = \frac{e B_z}{m_i c}$ are the Larmor radii of
electrons and ions; $v_e, v_i$ are the collision frequencies of electrons and ions in a partially ionized gas;
$m_e, m_i$ are the mass of electrons and ions; $c$ is the speed of light.

Equations (1)–(4) are closed by the relation for the potential of the anode relative to the zero
potential of the cathode. In the calculations, it is possible to implement two modes of maintaining the
RFC-glow discharge. In the first case, to determine the potential of the anode with respect to the
potential of the cathode, the equation of the external current circuit is used [11]:

\[
\frac{E_{\text{anode}} - V(t)}{R_0} = \int_{-\frac{L_z}{2}}^{\frac{L_z}{2}} \int_{-\frac{L_z}{2}}^{\frac{L_z}{2}} (j_{x,y} - j_{y,x})_{y=\gamma_a} \mathbf{Z}_a dxdy = \frac{dQ}{dt}, \tag{8}
\]
\[ \varepsilon_0 Q(t) = \int_{\frac{1}{2}x_l}^{\frac{1}{2}x_r} \left( \frac{\partial \phi}{\partial y} \right)_{y=y_u} Z_u dx, \]  
(9)

\[ \varepsilon(t) = E_o \sin(2\pi ft), \]  
(10)

where \( \varepsilon_0 = 1.81 \times 10^{-6} \) B·cm, \( V(t) \) is the potential drop at the discharge gap, \( E_{\text{emf}} \) is the emf source; \( Q(t) \) is the amount of excess ions at the anode, due to the current imbalance in the electrical discharge gap and the external circuit; \( R_0 \) is the Ohmic resistance of an electrical circuit; \( Z_0 = 1 \) cm; \( f \) is the potential change frequency; \( t \) is the time.

In the second case, it is assumed that the potential of the anode varies according to a given law, for example

\[ V(t) = E_o \sin(2\pi ft), \]  
(11)

This paper presents examples of the implementation of the condition (11).

The boundary conditions for particle concentrations and for electric potential are given in the following form:

\[ y = 0, \quad \left. \frac{\partial \phi}{\partial y} \right|_{y=0} > 0: \quad \hat{\phi}_n, y = 0, \quad \Gamma_{y,e} = \rho \Gamma_{y,i}, \quad \phi = 0; \]  
(12)

\[ y = H, \quad \left. \frac{\partial \phi}{\partial y} \right|_{y=-H} > 0: \quad n_i = 0, \quad \hat{\phi}_n = 0, \quad \phi = E(t); \]  
(13)

\[ y = 0, \quad \left. \frac{\partial \phi}{\partial y} \right|_{y=0} < 0: \quad n_i = 0, \quad \hat{\phi}_n = 0, \quad \phi = 0 \]  
(14)

\[ y = H, \quad \left. \frac{\partial \phi}{\partial y} \right|_{y=-H} < 0: \quad \hat{\phi}_n = 0, \quad \Gamma_{y,e} = \rho \Gamma_{y,i}, \quad \phi = E(t); \]  
(15)

\[ x = 0: \quad \hat{\phi}_n = \frac{\partial n}{\partial x} = \frac{\partial \phi}{\partial x} = 0 \]  
(16)

\[ x = L: \quad \hat{\phi}_n = \frac{\partial n}{\partial x} = \frac{\partial \phi}{\partial x} = 0 \]  
(17)

In (12) and (15) \( y \) is the coefficient of secondary electronic emission.

It is assumed that the thermos-physical and transport electronic properties of the neutral particles of the discharge depending on temperature, therefore:

\[ \mu_e(p^*) = \frac{4.2 \times 10^5}{p^*}, \quad \text{cm}^2/(\text{V} \cdot \text{s}), \quad \mu_i(p^*) = \frac{1140}{p^*}, \quad \text{cm}^2/(\text{V} \cdot \text{s}), \]  

\[ p^* = p \frac{293}{T}, \quad \text{Torr}, \]  
(18)

\[ D_e = \mu_e(p^*) T_e, \quad D_i = \mu_i(p^*) T, \quad \text{cm}^2/\text{s}, \]  

\[ c_p = 8.314 \frac{7}{2} M_z, \quad \text{J/(g·K)}, \quad M_z = 28, \quad \text{g/mole}, \quad \rho = 1.58 \times 10^{-3} \frac{M_z p}{T}, \quad \text{g/cm}^3. \]
\[
\lambda = \frac{8.334 \cdot 10^{-4}}{\sigma \Omega^{22/3}} \sqrt{\frac{T}{M_\oplus}} \left(0.115 + 0.354 \frac{e/M_\oplus}{\bar{R}}\right), \text{W/(cm-K)},
\]

\[
\Omega^{22/3} = \frac{1.157}{(T^*/T)^{0.1472}}, \quad T^* = \frac{T}{(e/k)},
\]

\[(e/k) = 71.4 \text{K}, \quad \sigma = 3.68 \Omega, \quad \bar{R} = 8.314 \text{J/(K-mole)},
\]

\[p\] is the undisturbed pressure in the environment, \(N = 0.954 \times 10^{19} \frac{p}{T}, \text{cm}^3\) is the volume concentration of neutral particles. The recombination coefficient \(\beta\) is considered to be constant, \(\beta = 2 \times 10^{-7}, \text{cm}^3/\text{s}\).

The electron temperature \(T_e\) is calculated using the empirical relationship [12]:

\[
\frac{T_e}{T} = 29.96 \ln \left(\frac{E}{p}\right) + 24.64,
\]

where \(E/p\) is the reduced field (the discharge parameter), \(V/(\text{cm-Torr})\). Note that relation (19) is extrapolating for the cathode layer.

Ionization coefficient (the 1-st Townsend coefficient) is given in the form:

\[
\alpha(E) = p^* A \exp \left[-\frac{B}{(|E|/p^*)^n}\right], \text{1/(cm-Torr)},
\]

where \(A = 12, \text{1/(cm-Torr)}, B = 342, V/(\text{cm-Torr})\).

### 3. Results of numerical simulation

The electrodynamic structure of the RFC-glow discharge in molecular nitrogen at a pressure of \(p = 5 \div 10 \text{Torr}\) is studied using a numerical simulation method. The following parameters of the discharge were used: the amplitude values of the emf of power supply \(E_0 = 520 \div 1000 \text{V}\), the distance between the flat electrodes \(\text{cm}\) and the width of the gas discharge gap \(\text{cm}\) (see figure 1). The magnetic field induction vector is directed along the \(z\)-axis, and its modulus is \(B_z = 0.2 \text{T}\). The numerical simulation was performed per 1 cm of the length of the discharge gap in the direction of the \(z\)-axis. A non-uniform structured grid \(n_x \times n_y = 101 \times 51\) was used \((n_x, n_y)\) are the number of nodes of the computational grid along the \(x\) and \(y\)-axes).

The initial conditions in the inter-electrode gap were set in two stages. At first, a quasi-neutral plasma cloud of the spherical shape with the concentration of charged particles of \(n_0 = 10^{13} \text{cm}^{-3}\) was set at \(x_0 = 3 \text{cm}\) near the cathode. The formation of glow discharge of continuous current in the regime of normal current density in the absence of a magnetic field was observed for \(\sim 10 \mu\text{s}\). Developed numerical method ensured the symmetry of the numerical solution in the directions of the \(x\) and \(y\)-axes, which is important in simulating the RFC-discharge. At the second stage, the obtained numerical solution for a stationary glow discharge of direct current was used as the initial condition in simulating an RFC-discharge with similar parameters. We draw attention to an important fact: the initial condition for simulating an RFC-discharge is a normal glow discharge in the center of the computational domain far from the lateral boundaries.

The first series of calculations of the FRC-discharge was performed at \(p = 5\) Tor, \(E_0 = 520\) V without an external magnetic field. The two-dimensional electrodynamic structure of the RFC-discharge is shown in figures 2 and 3 for the two phases of the anode potential.
Phase A corresponds to the negative potential of the anode, and phase B to the positive potential. Figures 2, a and 3, a show the distribution of electric potential and figures 2 (b, c) and 3 (b, c) show electronic and ion concentrations. The configuration of the positive column of a quasineutral plasma is clearly visible, which in fact does not change during the anode polarity reversal. Electronic concentrations oscillate in the electric discharge gap in accordance with the oscillations of the electric potential. Significantly heavier ions remain almost immovable.

The second series of calculations gives an idea of the change in the structure of the RFC-discharge when the conditions change: at the pressure rises and the peak value of the voltage between the electrodes. Figures 4–7 show the results of numerical simulation of the RFC-discharge structure at a pressure of \( p = 10 \text{ Torr} \) and an amplitude of emf \( E_0 = 1000 \text{ V} \). As before, the magnetic field was not taken into account. Note that in this case, the amplitude value of the current is \( \sim 40 \text{ mA} \), which significantly exceeds this value in the previous calculation case (\( \sim 2 \text{ mA} \)). As before, the distribution of electrons in the gas-discharge gap oscillates in accordance with the electric potential between the electrodes. In the case under consideration, the thickness of the space charge regions (the cathode and anode layers) decreased significantly as compared with the previous case, and the concentration of ions in them increased markedly. Pronounced near-electrode layers were formed near the surfaces of the electrodes.

**Figure 2.** Electrodynamical structure of the RFC-discharge at \( p = 5 \text{ Torr}, E_0 = 520 \text{ V} \), \( f = 13.59 \text{ MHz} \) in phase A:
(a) electric potential \( \Phi = \varphi / E_0 \),
(b) \( N_e = n_e \cdot 10^{-9} \text{ cm}^{-3} \),
(c) \( N_i = n_i \cdot 10^{-9} \text{ cm}^{-3} \).

**Figure 3.** Electrodynamical structure of the RFC-discharge at \( p = 5 \text{ Torr}, E_0 = 520 \text{ V} \), \( f = 13.59 \text{ MHz} \) in phase B:
(a) electric potential \( \Phi = \varphi / E_0 \),
(b) \( N_e = n_e \cdot 10^{-9} \text{ cm}^{-3} \),
(c) \( N_i = n_i \cdot 10^{-9} \text{ cm}^{-3} \).

If we use a qualitative classification of the forms of existence of RFC-discharges [11], then the two categories considered can be conditionally attributed to \( \alpha \)- and \( \gamma \)-forms. In the latter case, of the two considered, the discharge exists in \( \gamma \)-form. The calculations did not reveal the evolution of the
electric current column, as in the first case. The discharge was simulated up to ~ 500 μs. This allows us to hope that a stationary configuration of an RFC-discharge of γ-form is obtained.

The inclusion of a transverse magnetic field noticeably changes the electrodynamic structure of a glow discharge. Figures 6, 7 show the results of numerical simulation under the following conditions: \( p = 5 \) Torr, \( E_0 = 520 \) V, \( B_0 = 0.2 \) T. The obtained calculated data show that the fields of electron and ion concentrations stabilize in space during the transition from phase A to phase B. From figures 6 and 7 it is seen that the maximum concentration of charged particles decreases as compared with the case of the absence of a magnetic field. An important consequence of the imposition of an external transverse magnetic field is the disappearance of the near-electrode layers of the space charge in the form in which they are shown in figures 2 and 3. As a result, the electric field intensity decreases in the near-electrode zone.

**Figure 4.** Electrodynamic structure of the RFC-discharge at \( p=10 \) Torr, \( E_0=1000 \) V, \( f=13.59 \) MHz in phase A: (a) electric potential \( \Phi = \varphi/E_0 \), (b) \( N_e = n_e \cdot 10^{-9} \) cm\(^3\), (c) \( N_i = n_i \cdot 10^{-9} \) cm\(^3\), (d) axial distributions of ions and electrons \( (N_{e,i} = n_{e,i} \cdot 10^{-9} \) cm\(^3\)), electric potential \( \varphi \) and electric field strength \( E = H \frac{\partial \varphi}{\partial y} E_0 \).

**Figure 5.** Electrodynamic structure of the RFC-discharge at \( p=10 \) Torr, \( E_0=1000 \) V, \( f=13.59 \) MHz in phase B: (a) electric potential \( \Phi = \varphi/E_0 \), (b) \( N_e = n_e \cdot 10^{-9} \) cm\(^3\), (c) \( N_i = n_i \cdot 10^{-9} \) cm\(^3\), (d) axial distributions of ions and electrons \( (N_{e,i} = n_{e,i} \cdot 10^{-9} \) cm\(^3\)), electric potential \( \varphi \) and electric field strength \( E = H \frac{\partial \varphi}{\partial y} E_0 \).
Figure 6. Electrodynamic structure of the RFC-discharge at \( p = 5 \) Torr, \( E_\alpha = 550 \) \( V \), \( f = 13.59 \) MHz, \( B_z = 0.2 \) T in phase A:
(a) electric potential \( \Phi = \varphi / E_\alpha \),
(b) \( N_e = n_e \cdot 10^{-9} \) \( \text{cm}^3 \),
(c) \( N_i = n_i \cdot 10^{-9} \) \( \text{cm}^3 \).

Figure 7. Electrodynamic structure of the RFC-discharge at \( p = 5 \) Torr, \( E_\alpha = 520 \) \( V \), \( f = 13.59 \) MHz, \( B_z = 0.2 \) T in phase B:
(a) electric potential \( \Phi = \varphi / E_\alpha \),
(b) \( N_e = n_e \cdot 10^{-9} \) \( \text{cm}^3 \),
(c) \( N_i = n_i \cdot 10^{-9} \) \( \text{cm}^3 \).

The plasma structure of the RFC-discharge with a magnetic field is long-lived, but evolving in the direction of forming a uniform electrical-discharge structure in the direction transverse to the electric current channel. In the time interval of \( \sim 200 \) \( \mu \text{s} \), the highest concentration in the positive column decreased by about five times.

Conclusion

The analysis of the results of numerical modeling of a two-dimensional structure of the RFC-discharge, existing between two flat electrodes in two forms, is performed. In the calculations, two burning modes of the RFC-discharge are identified. A quasi-stationary solution was obtained for an RFC-discharge of \( \alpha \)-modification that exists as a localized, slowly evolving plasma current column in the inter-electrode gap with parameters close to the normal glow discharge. The second solution was obtained for the RFC-discharge, which can be associated with the \( \gamma \)-form of the RFC-discharge. The structure of this form of the RFC-discharge remained unchanged for at least \( \sim 500 \) \( \mu \text{s} \).

An external transverse magnetic field with induction \( B_z = 0.2 \) T changes the current structure of the \( \gamma \)-form of RFC-discharge, leading to the disappearance of spatial charge regions in the near-electrode regions.

The experience of conducting numerical studies of the two-dimensional structure of the RFC-discharge in the presented formulation, as well as the numerical simulation results presented in the article, show that the electrodynamic structure of the RFC-discharge obtained in a numerical solution is very sensitive to such source data as pressure, amplitude values of the voltage on the
electrodes, between the electrodes. All this is in the correct qualitative agreement with experimental data and one-dimensional numerical calculations.

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4. References
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