Study of RF plasma flow at low pressure: electron temperature influence

A Yu Shemakhin, V S Zheltukhin, E Yu Shemakhin, I S Pryalukin

1Kazan Federal University, Kazan, Russia
2Kazan National Research Technological University, Kazan, Russia
3Saint Petersburg State University, Saint Petersburg, Russia

E-mail: shemakhin@gmail.com, vzheltukhin@gmail.com

Abstract. A mathematical model of low-pressure RF plasma flow taking into consideration electron temperature influence is presented. Results of calculations of carrier gas velocity, pressure and temperature as well as electron density and electron temperature in plasma flow are showed. Influence of electric field on electron temperature and plasma flow is analyzed.

1. Introduction
Plasma of RF discharges at low pressure ($p = 1.33 - 133$ Pa) is used for the modification of the different materials[1-6]. The plasma has the following characteristics: electron density $n_e$ from $10^{15}$ to $10^{19}$ m$^{-3}$, electron temperature $T_e$ is from 1 to 4 eV, ionization degree is from $10^{-7}$ to $10^{-4}$, temperature of atoms and ions $T_a$ is from $3 \cdot 10^3$ to $4 \cdot 10^3$ K in the plasma bunch while from $3.2 \cdot 10^2$ to $10^3$ K in the plasma stream[1]. Plasma flow is hybrid (both inductive and capacitive) coupled RF discharge [1]. The objective of the work is studying of undisturbed plasma flow in vacuum chamber in terms of electric field, electron temperature, and electron density.

2. Mathematical model
Mathematical model of RF plasma flow in vacuum chamber is constructed in non-local approximation in hypotheses of ambipolar diffusion. Motivation for correctness such approach is presented in [2-8]. The model is based on kinetic approach for carrier gas argon [9] and continuous approach for electron gas, electron temperature and electric field. The model is different from early works in hypotheses that equation coefficients depend on electron temperature.

The mathematical model includes the following equations with boundary and initial conditions:
1) The Boltzmann equation for neutral atoms
$$\frac{\partial f}{\partial t} + \mathbf{c} \cdot \nabla f + \mathbf{F} \cdot \nabla c = S(f), \quad \mathbf{F} = -\frac{1}{m_a} \nabla W_T,$$
(1)
$$f(c,r,0) = f_0(c,r).$$

2) The equation of gas continuity for electrons:
$$-\nabla \cdot (D_a \nabla n_e - \nabla n_e) = \nu_i n_e, \quad r \in \Omega,$$
$$n_e|_{\text{inlet}} = n_{e,0}, \quad n_e|_{\text{outlet}} = n_e|_{\text{walls}} = 0 \ ,$$
(2)

3) The equation of electrons heating:
The plasma carrier gas is argon, inlet pressure is 1000 K, the ionization degree \( \delta_i = 10^{-5} \), plasma density \( 1.208 \times 10^{22} \) m\(^{-3} \) which corresponds to gas pressure of 50 Pa, gas temperature \( T_a = 300 \) K. Coefficients of equations (2), (3) were calculated in range of electron temperature from 0.1 to 4 eV.

3. Method of calculation and results

Hybrid numerical method based on both modified Bird’s approach [10] for carrier gas and finite volume method for electron density, electron temperature as well as for curl part of electromagnetic field was constructed like presented in [8]. The program was coded by C++ using OpenFOAM [14] libraries.

Calculations of RF plasma flow for vacuum chamber of 0.065 m by radius, 0.12 m by length, and inlet hole of 0.02 m by radius was performed at different values of electric field. The plasma carrier gas is argon, inlet velocity \( V_{inlet} = 300 \) m/s, gas pressure \( P_{inlet} = 130 \) Pa, the carrier gas temperature \( T_{inlet} = 1000 \) K, the ionization degree \( \delta_i = 10^{-4} \).
Figure 1. Ambipolar diffusion coefficient $D_a$

Results of calculations of carrier gas velocity, pressure and temperature are showed on figure 2. The flow is laminar, at inlet velocity is 300 m/s and velocity (red line on the right side of fig. 2) is decreased to pumping velocity 50 m/s. The velocity modulus distribution in slice by central axis of the chamber is shown on the left side of figure 2. The gas pressure is decreased from 130 Pa in the inlet down to 50 Pa near the outlet (blue line on the fig. 2). Temperature of the carrier gas is decreased from 900 K in the inlet to 300 K in the chamber boundary direction.

Figure 2. Gradient field of spatial distribution of $|U|$ in axial direction of the chamber (a) and plots of $T$ (in K), $p$ (in Pa), $|U|$ (in m/s) versus distance along the chamber axis (b)
Calculation of electron temperature was performed at varying the electric field from 3000 V/m to 8000 V/m in two alternate version: 1) \( E^2 = |E_{cap}|^2 \) and 2) \( E^2 = |E_{cap}|^2 + |E_{Re}|^2 + |E_{Im}|^2 \). The electron temperature at \( |E_{full}| = |E_{cap}| = 7000 \) V/m as well as at \( |E_{full}| = |E_{curl} + E_{cap}| = 8000 \) V/m is showed on the figure 3a. For the second case the electron temperature at the discharge flow centre is approximately on 0.18 eV more than in the first case. It is mean that including curl electric field in the model allows us to determine plasma stream parameters more accurate.

The electron density is decreased from \( 5 \cdot 10^{18} \) on inlet to 0 on the chamber walls (Figure 3b). Results of calculations are showed that curl part of the electric field which is in range between 5 and 25% of curl electric field has essential influence on plasma flow parameters.

![Figure 3](image.png)

**Figure 3.** Electron temperature \( T_e \) on the central axis of chamber (a) and electron density \( n_e \) along the chamber axis (b).

4. **Acknowledgment**

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