Simulating glow discharge positive column parameters in neon

N A Demin* and A V Fedoseev

Institute of Thermophysics SB RAS, 1 Lavrentyev Ave., Novosibirsk 630090, Russia

*E-mail: demin@itp.nsc.ru

Abstract. The nonlocal self-consistent model for the low temperature plasma parameters in a glow discharge positive column is presented. The model implies relaxation method for the solving of the nonlocal Boltzmann equation for electron energy distribution function, continuity equation for ions distribution and Poisson equation for radial electric field. Calculations are provided for a cylindrical discharge tube used in the Plasma Kristall-4 experiments for neon as a plasma forming gas for the gas pressures of 30-70 Pa and discharge currents of 0.5-2.5 mA. Axial electric field strength, electron temperature and electron density are calculated as functions of the discharge current and the gas pressure. The results are in good agreement with the data provided by other authors.

1. Introduction

Glow discharge is in great demand among different discharge types for industry usages and fundamental investigations [1]. Several works in this field indicate that the electron energy distribution function (EEDF) in glow discharges substantially varies from the Maxwell distribution [2, 3]. The high-energy part of the EEDF is highly depleted because of losses in active elastic and inelastic electron collisions with neutral particles. Therefore, it is required to solve the Boltzmann equation for proper determination of the EEDF.

A complex, or dusty, plasma takes an important place in the low-temperature plasma physics. It is an electrically quasi-neutral medium containing microsized solid particles, along with electrons, ions and neutral gas. Dusty particles in complex plasma can form structures of different size and shape. Dusty plasma can exist in space (in planetary rings and magnetospheres, above spacecraft shell) and also in various plasma industrial plants for etching and thin film deposition [4]. Nowadays dusty plasma in positive glow discharge column is explored in the experiments of the Plasma Kristall-4 project (PK-4) onboard the International Space Station [5].

The type of gas that forms discharge plasma is one of the essential plasma characteristics, as it influences all important plasma parameters. Since the series of recent experiments of the PK-4 project has been performed in neon, this noble gas is of great interest for fundamental and applied research in complex and in pure plasma. In this work we present numerical calculations of the glow discharge plasma parameters with neon as a plasma-forming gas in the absence of dust particles for the discharge tube, similar to the PK-4 one, using a non-local self-consistent model.

2. Model

To calculate basic plasma parameters of the glow discharge positive column, we used nonlocal self-consistent model, that was presented in [6], for the case of pure plasma without dust particles. For the determination of the spatial and temporal evolution of plasma electrons of a positive column of the glow discharge, the nonlocal non-stationary Boltzmann equation for the velocity distribution function of electrons $f(t, \vec{r}, \vec{v})$ is used:
where $S^e(F)$ is the sum of all elastic collision channels of electrons, and $S^a(F)$ is the sum of all inelastic collision channels of electrons with excitation of the $k$-th state of an atom by electron impact. For neon six excited levels are taken into account including the 1-st excited level with energy of 16.62 eV and five levels higher, and ionization threshold of 21.56 eV [7]. We consider weak anisotropy of the discharge, so Boltzmann equation for the energy distribution of electrons function (EEDF) was used in the traditional "two-term" approximation for isotropic $f_0(t,r,v)$ and anisotropic $f_1(t,r,v)$ components. The transition from electron velocity $v$ to the full kinetic electron energy $e$ is also provided.

Electric radial field distribution $E(r,t)$ is obtained by the resolving of Poisson equation:

$$-\frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 \frac{\partial \phi(r,t)}{\partial r} \right] = 4\pi e \left[ n_i(r,t) - n_e(r,t) \right],$$

where $\phi(r,t)$ is the radial distribution of electric potential. The radial distribution of ions density $n_i(r,t)$ is calculated by non-stationary drift-diffusion equation:

$$\frac{\partial n_i(r,t)}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 \left( \mu_i n_i(r,t) E(r,t) - D_i \frac{\partial n_i(r,t)}{\partial r} \right) \right] = v_i(r,t) N_g,$$

where $\mu_i$ is the mobility coefficient for ions, $D_i$ is the ion diffusion coefficient, and $v_i(r,t)$ is the radial distribution of ionization frequency. This group of equations is solved with the help of relaxation method from some initial distribution functions for electrons and ions. It was verified that the form of the initial distribution function does not change the steady-state solution.

The radial distribution of electron density $n_e(r,t)$ is calculated by the integral of the isotropic part of EEDF $f_0(e,r,t)$ over full kinetic electron energy $e$:

$$n_e(r,t) = \int_0^{\infty} d\epsilon \epsilon^{3/2} f_0(e,r,t).$$

The radial distribution of electron temperature $T_e(r,t)$ is calculated as follows:

$$T_e(r,t) = \frac{2}{3} \frac{1}{n_e(r,t)} \int_0^{\infty} d\epsilon \epsilon^{3/2} f_0(e,r,t).$$

In the section 3 the values of $n_e(r,t)$ and $T_e(r,t)$ calculated at central axis of the discharge (at $r=0$), are presented.

The magnitude of axial electric field $E_z$ is calculated by a feedback of the discharge current $I_d$, which is defined for each calculation mode.

3. Results and discussion

Calculations of the positive column plasma parameters are provided for the discharge tube with diameter $d = 3$ cm for the range of pressures of plasma forming gas neon of 30-70 Pa and discharge currents of 0.5-2.5 mA. The axial electric field $E_z$ versus discharge current is shown in Figure 1a for different values of buffer gas pressures.

Figure 1a shows that electric field in the center of the discharge decreases with discharge current for the whole range of forming gas pressures, which is the characteristic property of low temperature plasma in positive column of glow discharges. The obtained dependences show good correlation with experimental and numerical data from works [5,8,9] for neon, and approximately coincide in absolute values in considered pressure range.
Figure 1. Electric field magnitude $E_z$ at the central discharge axis as a function of discharge current $I_d$ (a) and buffer gas pressure $p$ (b).

The pressure dependence of axial electric field for different discharge currents is presented in figure 1b. It is seen that the axial electric field strength changes non-monotonously with gas pressure, with minima at 40 Pa for discharge currents of 1.5-2.5 mA and 50 Pa for 1 mA. Such behavior of axial electric field is also observed in experiments [5], and similar behavior of axial electric field strength was observed for the helium based plasma [10].

Figure 2 presents the calculated electron temperature versus discharge current and gas pressure.

Figure 2. Electron temperature magnitude $T_e$ at the center of the discharge as a function of discharge current $I_d$ (a) and buffer gas pressure $p$ (b).

It is seen that electron temperature decreases substantially with increasing pressure for all values of discharge current, and slightly changes with varying discharge current, moreover at low pressure regimes the electron temperature increases more significantly than at high considered pressure values.
The obtained dependences are in good qualitative correspondence with experimental and numerical data from works [5,8].

Figure 3 presents electron density in the central axis of the discharge as a function of the discharge current (a) and plasma forming gas pressure (b).

![Figure 3](image)

**Figure 3.** Electron density magnitude $n_e$ at the center of the discharge as a function of discharge current $I_d$ (a) and buffer gas pressure $p$ (b).

In the Figure 3 the electron density at the center of the discharge is presented. For each gas pressure value it increases in linear way with increasing discharge current magnitude. With increasing buffer gas pressure at each discharge current magnitude the electron density at the center of the discharge also increases. Such behavior of the electron density in the glow discharges is a known characteristic for the positive column plasma of glow discharges. Calculated dependences of electron densities are in good agreement with data obtained in experiments [5] as well.

**Conclusions**

In this work we presented the nonlocal self-consistent model for modeling of the glow discharge positive column parameters. The calculations of plasma parameters in plasma forming gaseous neon are provided for the wide range of buffer gas pressures and discharge currents for the discharge cylindrical tube. The distributions of basic plasma parameters have been obtained, including electric field strength in the center of the discharge, electron temperature and electron density. Obtained results of all calculations are in a well correspondence with data from the experiments. An unusual dependence of the axial electric field on pressure was obtained. The calculated results are important for upcoming plasma investigations and simulations both in plasma with dust particles and in pure plasma in neon.

**Acknowledgments**

This work was carried out under state contract with IT SB RAS.

**References**

[1] Khrapak S A et al. 2005 *Physical Review E.* 72 016406
[2] Arndt S C, Uhrlandt D, Winkler R 2001 *Plasma Chemistry and Plasma Processing* 21 175–00
[3] Sigenefer F, Sukhinin G I, Winkler R 2000 *Plasma Chemistry and Plasma Processing* 20 87–110.
[4] Morfill G E and Ivlev A V 2009 *Reviews of Modern Physics* 81 1353–1404
[5] Pustylnik M et al. 2016 Review of Scientific Instruments 87 093505
[6] Fedoseev A, Sukhinin G, Doslobayev M and Ramazanov T 2015 Physical Review E 92 023106
[7] Pancheshnyi S et al 2012 Chemical Physics 398 148–53
[8] Fortov V et al. 2005 Plasma Phys Control. Fusion 47 537–49
[9] Behnkhe J, Golubovsky Y B, Nisimov S U, Porokhova I A 1996 Contrib. Plasma Phys. 1 75–91
[10] Demin N A, Fedoseev A V 2019 J. Phys.: Conf. Ser. 1382 012151