Determination of the plasma parameters of a glow discharge in long tubes

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Abstract. In this work experimental current-voltage characteristics of a glow discharge occurring in long tubes for a wide range of discharge conditions (pressure, diameter of the discharge tube, nature of the gas) were obtained. On the basis of the current-voltage characteristics was calculated the longitudinal potential gradient in the positive column. With the help of the developed computer program was calculated the electron temperature for discharge conditions corresponding to the experiment. The technique is based on the use of the balance equations of ionization in gas discharges occurring in long narrow tubes, and provides the possibility for calculation of the discharge plasma parameters, both in pure gases and in multicomponent mixtures. Based on the experimental values of the longitudinal potential gradient in the positive column and the calculated values of the electron temperature was calculated the dependence of accommodation coefficient for the electrons from the discharge conditions. The compliance between the experimental and reference data was obtained.

Determination of the plasma parameters of a glow discharge is an important task in the design and analysis of the gas discharge devices [1]. Of particular interest is the determination of the parameters of the discharge occurring in long tubes, for example, in gas discharge lasers. One of the main characteristics that defines the behavior of the discharge gap in the circuit is the current-voltage characteristic (CVC). The CVC allows judging the state of the active environment, in particular, the degree of leakage of the atmospheric gases [2]. In addition, the form of the CVC has a significant influence on the dynamic properties of the discharge [3, 4].

Discharge CVC determines the behavior of the longitudinal potential gradient. The longitudinal potential gradient $E_z$ in the positive column (PC) of a glow discharge is proportional to the square root of the accommodation coefficient $\chi$ of the electrons, which refers to the total energy of the electron $W_e$.

\[ E_z = \frac{1.5kT_e \sqrt{\chi}}{e\lambda_e}, \]

where $\lambda_e = \lambda_{el}/p$ – is the average free path length for electrons; $p$ – gas pressure.

Function $\chi = f(T_e)$ can be found taking into account shares of energy lost by electrons in elastic and inelastic collisions.
\[ \chi = \chi^* + \chi_a + \chi_w, \]  

where \( \chi^* = \frac{2m_e}{M} \) is the average fraction of the energy lost by electron in the elastic collision; \( \chi_a \) – average fraction of energy loss due to the excitation; \( \chi_w \) – share of energy losses at the walls.

Rigorous calculation of \( \chi \) for the conditions of discharges in long narrow tubes, realized in the gas discharge lasers, is difficult because of the diversity and complexity of the processes occurring in the plasma. In the literature there are experimental data about \( \chi \) relating to a number of pure gases [5, 6]. They reflect the dependence \( \chi = f(T_e) \) for a narrow range of the discharge conditions, so the use of the reference values in the calculation is difficult.

To increase the accuracy of calculations of the plasma parameters of a positive column in this work was taken an attempt to refine the values of the accommodation coefficient. The idea of refining \( \chi \) is based on the use of half experimental approach to the problem. Initially it was conducted a series of experiments to study the CVCs of the discharge gaps. In the experiments we used two models.

Layout 1 consisted of four discharge tubes with inner diameters of 1,1; 2; 3.4 and 5,2 mm, with movable anodes, transported by means of the magnetic actuators within the length of PC 0,1...0,25 m.

Layout 2 is a multianode tube with an inner diameter of 6,5 mm with the possible values of the active medium length 1,3; 1,12; 0,98; 0,78; 0,61; 0,47 and 0,35 m. In addition, layout 2 has an optical resonator and therefore the discharge gap can be used as the active medium of a He-Ne laser.

Layouts are connected with a vacuum pumping and filling system, which allows varying the gas content and operating pressure. In this work, were studied the characteristics of the discharge in pure helium and neon. The idea of refining \( \chi \) is based on a combination of theoretical and experimental approaches to the calculation of the plasma parameters. Initially, based on experimental CVCs was obtained information about the behavior of \( E_z \) in the wide range of the discharge conditions. Since \( T_e = T_e(pR) \) and \( \lambda_e \sim 1/p \), from (1) it follows that \( E_z/p = f(pR) \), the experimental values of the potential gradient are conveniently represented in this form (figure 1).

![Figure 1. Dependences \( E_z/p = f(pR) \) for helium and neon.](image-url)

Next, using the developed computer program was calculated the function of the temperature \( T_e \) for a range of changes in the discharge conditions: pressure \( p \); discharge channel diameter \( d \); composition of the gas mixture corresponding to the experimental conditions. The method of calculation of \( T_e \) is as follows. Since charged particles in the plasma are connected by the Coulomb forces of interaction, their diffusion has a specific nature. Electrons with greater energy and mobility compared to the ions ahead of the last participate in the diffusion process. The spatial charge of ions left behind tends to keep the electrons and accelerates the diffusion motion of the ions. Diffusion of charged particles of both signs can occur in plasma only in conjunction and is called ambipolar diffusion.

In the experiments, the plasma is enclosed in a cylindrical tube with internal radius \( R \). In such conditions, recombination in the volume is small, and neutralization of the charge mainly is due to the
ambipolar diffusion with the subsequent recombination on the walls. The condition of the balance of charges for such a cylindrical plasma column can uniquely associate the average ionization frequency with coefficient of the ambipolar diffusion. Taking into account the expression for the ambipolar diffusion, frequency of ionization is defined as

\[ \nu_i = \frac{b k (2.405)^2 T_e}{R^2 e} . \]

The average ionization rate can be written as

\[ \nu_i = n_a \int_0^\infty q_i(U) \nu(U) f(U) dU, \]

where \( n_a \) – is the concentration of atoms; \( q_i \) – ionization cross section; \( f(U) \) – Maxwell distribution function for electrons over energies. Approximations of the cross section of ionization for atoms and molecules were assumed linear. Thus, after integrating, was obtained an expression for the frequency of ionization:

\[ \nu_i = n_a \left( \frac{8 k T_e}{\pi m_e} \right)^{0.5} \cdot \alpha_i \exp \left( \frac{-e U}{k T_e} \right) \left( U_i + \frac{2 k T_e}{e} \right) . \]

The transcendental equation (4) is applicable for the single component active media of the gas discharge lasers. For multicomponent gas mixtures the sum of ionization frequencies of all gases within the mixture should be used:

\[ \sum_j \nu_i(j) = \frac{(2.405)^2 b k T_e}{R^2 e} = \frac{23.1 b k T_e}{e d^2} . \]

In these conditions, the average ion mobility of the gases can be calculated using the Blanc law.

The described above technique was used as the basis for the program to calculate \( T_e \). The program allows the choice of the laser type or the required gas mixture, and the display mode for the calculated information, definition of the constants and ranges of changes in the diameter of the discharge channel, the total and partial pressures of the gas components and gas temperature [7].

Based on the ratio (1) between the \( E_z \) and \( T_e \), can be obtained dependences \( \chi = f(pR) \) for each gas type (figures 2, 3). For the possibility of automated calculation of \( \chi \) and \( E_z \) taking into account equation (2) can be used approximation as the sum of \( \chi^* \) (does not depend on discharge conditions) and a falling function in the limit tending to zero.

![Figure 2](image-url)
Figure 3. Dependence $\chi = f(pR)$ for helium.

Form of the dependencies $\chi = f(pR)$ is falling in nature, which is consistent with the presentation of the accommodation coefficient, that is described by expression (1). For small values of $pR$ a significant share of the electron energy goes to heating of the walls. With the growth of $pR$ wall loss decreases, and the main losses of energy are due to the processes in the plasma volume. The validity of a half experimental approach to the assessment of $\chi$ is confirmed by the coincidence with an accuracy of $10...15\%$ of these results with the reference data from the literature [5].

In further studies we intend to extend the ranges of changes of the discharge conditions and gas mixtures, including typical for glow discharge lasers, such as He-Ne and CO$_2$ lasers [8].

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