CALCULATIONS FOR PARAMETERS OF A STATIONARY REFLEX DISCHARGE

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A variant of the stationary reflex discharge model based on the global (volume-averaged) model is under consideration. The calculation is carried out on the plasma electron density and temperature as a function of the adsorbed power in the reflex discharge, magnetic field value and initial gas pressure. The density of neutral atoms and cathode material ions coming into the discharge by the cathode sputtering mechanism is determined.

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INTRODUCTION

The reflex discharge, known as a Penning discharge was first proposed by Penning F.M. [1] for developing a vacuum manometer. During the many-year history a large number of various reflex discharge models were offered and investigated. A series of technical devices based on the reflex discharge has been developed and widely used for solving both physical and applied problems. The main fields of reflex discharge applications are: vacuum engineering, physics of atomic and electron collisions, physics of charged particle beams, plasma physics, applied plasma technologies etc. However, in spite of long-term and numerous investigations at present there is a lack of a sufficiently full physical model describing the reflex discharge. In particular, it is explained by the fact that the reflex discharge has several modes depending on the pressure and magnetic field values [2]. Moreover, in different modes the discharge and produced plasma parameters are different. The discharge modes were investigated theoretically and experimentally under low pressure $p \leq 1.33 \cdot 10^{-2}$ Pa e.g. in [2]. Under higher pressures and low plasma ionization level the reflex discharge is used most often for developing plasma sources based on this discharge. For this it is necessary to obtain an optimum relation between the plasma parameters and the energy contribution. Therefore it is of interest to consider the reflex discharge model under pressures $p > 1.33 \cdot 10^{-2}$ Pa.

In the present paper for the stationary case we consider a reflex discharge model based on the global (volume-averaged) model [3]. Weakly ionized nonisothermal plasma in a magnetic field and without magnetic field is studied.

1. CHARGED PARTICLE BALANCE IN THE PLASMA OF STATIONARY REFLEX DISCHARGE

The equation of charged particle balance in the plasma under condition, when the process of diffusion particle loss dominates over recombination, can be written in the following form [3, 4]:

$$N_e v_B A_{eff} = K_{iz} N_0 N_e V, \tag{1}$$

where V is the plasma-occupied volume m^3; K_{iz} – neutral particle ionization rate constant, m^3/s; N_0 – neutral particle density, m^{-3}; N_e – plasma electron density, $N_e = N_i$, m^{-3}; v_B – Bohm velocity, $v_B = \sqrt{qT_e/M_i}$, m/s; T_e – electron temperature, eV; q – electron charge, C; M_i – ion mass, kg ; A_{eff} – effective area of charged particle loss, m^2.

The effective area of charged particle loss is equal to $A_{eff} = A_L h_L + A_R h_R$, where A_L and A_R are, respectively, the base area and the cylinder lateral surface, m^2; h_L and h_R are the axial and radial relations of the plasma density at the plasma boundary to the plasma density in the center.

According to [5, 6] for the case of weakly nonisothermal plasma the values h_L and h_R are equal to:

$$h_L = 0.86\left(3 + \frac{L}{2\lambda_i}\right)^{-\frac{1}{2}}, \tag{2}$$

$$h_R = h_{R0}[1 + G + (G)^2]^{-\frac{1}{2}}, \tag{3}$$

where h_{R0} is the value of h_R for the case without magnetic field, $h_{R0} = 0.8\left(4 + \frac{R}{\lambda_i}\right)^{-\frac{1}{2}}$; λ_i – ion free path in gas $\lambda_i = 1/N_0\sigma_{mi}$, m; σ_{mi} – transport cross-section of ion scattering on the neutral particle, m^2. Upon the collision of ions with the proper gas neutrals $\sigma_{mi} = 2\,\sigma_{cx}$, where σ_{cx} is the charge exchange cross-section, m^2.

The parameter G is [6]:

$$G = 0.64\left(4 + \frac{R}{\lambda_i}\right)^{-\frac{1}{2}} \frac{R\lambda_e}{r_e r_i}, \tag{4}$$

where λ_e is the electron free path in gas, $\lambda_e = 1/N_0\sigma_{me}$, m; σ_{me} – transport cross-section of electron scattering on the neutral particle, m^2; $r_e = v_{Te}/\omega_{ce}$, $r_i = v_s/\omega_{ci}$, ω_{ce} and ω_{ci} – electron and ion cyclotron frequencies, respectively; B – magnetic induction, T; m_e – electron mass, kg; v_{Te} – electron thermal velocity, m/s; v_s – ion sound velocity, m/s.

Equation (1) can be reduced to the following form:

$$\frac{v_B}{K_{iz}} = \frac{N_0 V}{A_{eff}}. \tag{5}$$

By solving equation (5) the electron temperature T_e as a function of the neutral particle density can be determined.

2. POWER BALANCE IN THE PLASMA OF STATIONARY REFLEX DISCHARGE

The total power adsorbed in the discharge equals to:

$$P_{abs} = P_{Ve} + P_{le} + P_{li}, \tag{6}$$

where P_{Ve} is the power released in the volume due to the electron energy loss during collision with neutral particles, W; P_{le} – plasma power taken by electrons, W; P_{li} – plasma power taken by ions, W.

$$P_{Ve} = qN_eN_0V_p(K_{iz}\varepsilon_{iz} + \sum K_{ex}\varepsilon_{ex} + K_{el}\varepsilon_{el}), \quad (7)$$

where K_{ex} is the excitation rate constant, m^3/s; K_{el} – elastic collision rate constant, m^3/s; ε_{iz}, ε_{ex}, ε_{el} – energy being lost by electrons upon ionization, atomic excitation and elastic collisions.

The average energy for ion-electron pair formation or the ionization value is equal to:

$$K_{iz}E_{iz} = (K_{iz}\varepsilon_{iz} + \sum K_{ex}\varepsilon_{ex} + K_{el}\varepsilon_{el}). \quad (8)$$

Taking into account equations (1) and (2), equation (7) takes the following form:

$$P_{Ve} = qN_e v_B A_{eff} E_{iz}. \quad (9)$$

In the reflex discharge the most part of electrons go away in the radial direction to the anode, and ions are axially directed to the cathodes. The power taken by electrons and ions from the plasma can be written in the general form as:

$$P_{le} = qN_e v_B A_R h_R E_e, \quad (10)$$

$$P_{li} = qN_e v_B A_L h_L E_i, \quad (11)$$

where E_e is the average kinetic energy taken by electrons, in the Maxwell distribution assumption its value is $2T_e$; E_i – average kinetic energy taken by ions which equals to the sum of ion energies before coming into the layer and obtained in the layer, $E_i = (T_e/2)+V_s$, where V_s is the cathode potential drop approximately equal to the discharge voltage V_{dc}.

As a result, equation (6), with taking into account equations (9-11), takes the form:

$$P_{abs} = qN_e v_B\left(A_{eff}E_{iz} + A_R h_R E_e + A_L h_L E_i\right). \quad (12)$$

From equation (12) we can obtain the relationship connecting the density with the adsorbed power in the discharge that is equal to:

$$N_e = \frac{P_{abs}}{qv_B\left(A_{eff}E_{iz} + A_R h_R E_e + A_L h_L E_i\right)}. \quad (13)$$

3. CALCULATION OF THE DENSITY AND ELECTRON TEMPERATURE IN THE REFLEX DISCHARGE

Let us calculate the density and electron temperature in the reflex discharge and compare the calculation results with experimental data given in [7]. The initial conditions are as follows: plasma column radius R = 0.05 m; length L = 0.025 m; pressure *Ar* p = 4 Pa ($N_0 = 1.06\cdot10^{21}$ m^{-3}); plasma occupied volume $V = 1.963\cdot10^{-4} m^3$; $A_L = 0.016$ m^2, $A_R = 7.854\cdot10^{-4}$ m^2, B = 0 T. The charge exchange cross-section is calculated on the base of the asymptotic approach developed in [8] and for the ion thermal energies is σ_{cx} = $7.8\cdot10^{-19}$ m^2, and $\sigma_{mi} = 1.56\cdot10^{-18}$ m^2.

The values of the ionization rate, excitation and elastic collision constants, and the values of ε_{iz}, ε_{ex} are taken from [9]. The transport cross-section of electron scattering on the neutral particle is taken from [10].

By solving equation (5), with taking into account the initial conditions, the electron temperature T_e = 2.5 eV is obtained. The plasma density was calculated by formula (13) with taking into account the calculated electron temperature. The calculated curves of the plasma density as a function of the adsorbed power in the discharge in comparison with the experimental data of [7] are represented in Fig. 1.

By solving equation (5) with taking into account the initial conditions, the plasma electron temperature in a magnetic field and without magnetic field as a function of the pressure was obtained (shown in Fig. 2).

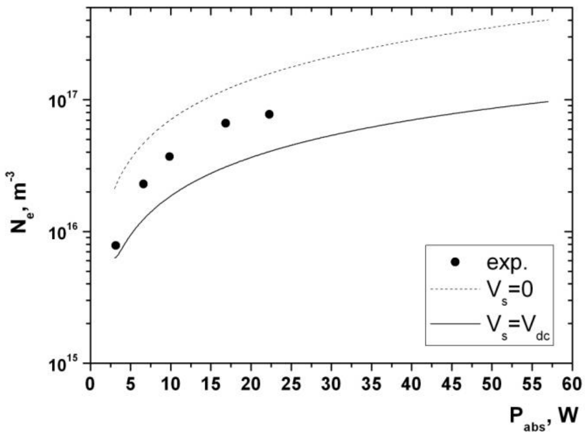

Fig. 1. Plasma density as a function of adsorbed power in the discharge

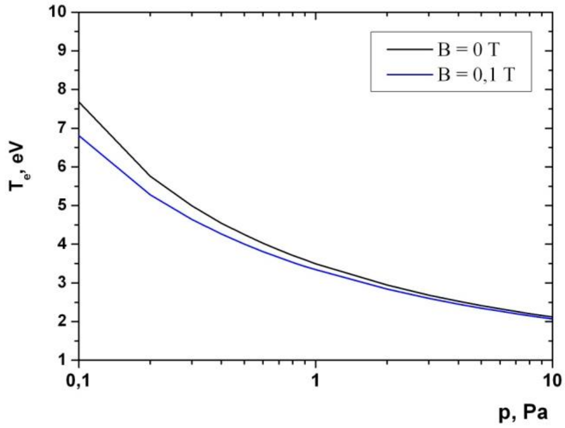

Fig. 2. Electron temperature as a function of pressure

The calculated curves of the plasma density as a function of the magnetic induction at the absorbed power in the discharge of 10 W (p = 4 Pa, V_s = 0) is presented in Fig. 3.

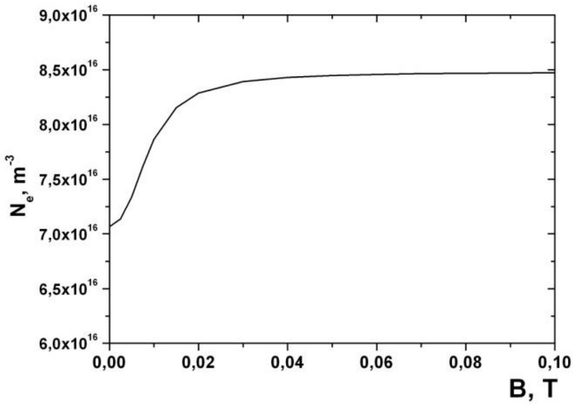

Fig. 3. Plasma density as a function of magnetic induction

4. CONSIDERATION OF THE NEUTRAL ATOMS PRODUCED BY THE CATHODE SPUTTERING WITH THEIR SUBSEQUENT IONIZATION IN THE REFLEX DISCHARGE

The flux of neutral atoms arriving into the discharge chamber volume as a result of cathode sputtering can be determined as:

$$\Gamma_m = YN_g^+ A_L h_L v_B, \quad (14)$$

where Y is the cathode material sputtering coefficient; N_g^+ is the gas ion density, m^{-3}.

The balance of neutral atoms coming into the reflex discharge due to the cathode sputtering, with taking into account equation (14), is written in the following form:

$$YN_g^+ A_L h_L v_B = \frac{N_m}{\tau_D} V + \frac{N_m}{\tau_i} V, \quad (15)$$

where N_m is the density of neutral atoms from the cathode material, m^{-3}; τ_D – particle diffusion characteristic time, $\tau_D = \frac{\Lambda^2}{D_m}$, where Λ is the characteristic diffusion length, m; D_m – diffusion coefficient of the atom scattered in gas, m^2/s; τ_i – neutral atomic ionization time, s.

By solving equation (15) the density of neutral metal atoms can be determined.

Taking into account that the ion of sputtered cathode material is formed by the electron impact ionization and gas ion charge exchange we can write the equation of metal ion balance in the following form:

$$N_m^+ = \frac{K_{iz} N_m N_e V + K_{CT} N_m N_g^+ V}{v_B^m A_{eff}}, \quad (16)$$

where N_m^+ is the metal ion density, m^{-3}; v_B^m – Bohm velocity of metal ion, m/s; K_{CT} – constant of gas ion charge exchange on the neutral metal atom, m^3/s.

To calculate the density of neutral atoms and cathode material ions let us taken the following initial conditions: energy of argon ions colliding with the cathode surface E_{Ar} = 360 eV; gas ion density $N_g^+ = 1.9\cdot10^{16}$ m^{-3} (calculated value for P_{abs} = 10 W, p = 4 Pa); electron temperature T_e = 2.5 eV (calculated value for p = 4 Pa); target material is stainless steel).

To calculate the sputtering ratio, the diffusion time of a neutral atom and the time of atomic ionization we use the model proposed in [11]. The values of constants for the iron atomic ionization rate by the electron impact and the velocity of charge exchange of gas ion on iron atom, taken from [12, 13], are $K_{iz} = 2\cdot10^{-15}$ m^3/s [12], $K_{CT} = 13.76\cdot10^{-15}$ m^3/s [13]. The calculated sputtering ratio in the case of normal ion incidence onto the target [14] for $Ar^+ \rightarrow Fe$ is 0.698 for $Fe^+ \rightarrow Fe$ = 0.677.

The calculated value τ_D of the particle diffusion time is $7.746\cdot10^{-6}$ s, the value of the ionization time is $\tau_i = 3.417\cdot10^{-3}$ s.

As $\tau_D < \tau_i$, a minor part of sputtered atoms will be ionized, and a major part will go onto the discharge chamber surface due to the diffusion.

By solving equation (15) we find the density value for iron neutral atoms $N_m = 3.5\cdot10^{15}$ m^{-3}, which is less by a factor of 10^5 than that of neutral argon particles. When the iron ion density is determined from (16) we obtain $N_m^+ = 2.8\cdot10^{13}$ m^{-3}, that is by ~3 order of magnitude less than the density of Ar ions. The metal atomic ionization level is $8\cdot10^{-3}$, for gas it is $1.8\cdot10^{-5}$. It should be noted that when the plasma density is << 10^{17} m^{-3} the Penning ionization can made a significant contribution into the metal atomic ionization level [15].

5. DISCUSSION OF CALCULATION RESULTS

The comparison of calculation results with experimental data [7] (see Fig.1) shows that they differ by a factor of ~2. May be this difference is related with some unaccounted factors in the model under consideration. In the above calculations it has been assumed that the electron energy distribution function (EEDF) is Maxwellian. In the plasma discharge several group of electrons with different energy can exist. For example, in [7] the EEDF bi-Maxwellian with a group of cold and hot electrons was observed. In [16] the calculations have been performed for a series of model EEDF's which were changing from the Maxwell function to the Druyvesteyn function and the EEDF influence on the calculated parameters T_e, N_e, E_{iz} was shown.

In the reflex discharge a group of fast primary electrons is produced as a result of the second emission from the cathode. These electrons are accelerated at the cathode voltage drop V_s being approximately equal to the discharge voltage V_{dc}.

Primary electrons, moving in a magnetic field, fall into a potential well between the cathodes and can oscillate between them. The primary electrons lose their energy during elastic and inelastic collisions with gas atoms. A part of the electron energy remains in the secondary electron knocked from the atom during ionization. The secondary electron energy is within the range from 0 to $E - \varepsilon_{iz}$, where E is the primary electron energy [17]. A part of knock-on (secondary) electrons, of an energy exceeding ε_{iz}, also participates in the ionization process. The average number of ions produced in the process is $\langle N_i \rangle = E/W_{iz}$, where W_{iz} is the average energy spent for ion-electron pair formation or the ionization value. Though W_{iz} and E_{iz} have a similar physical sense (see Eq.8), in the general case their values are not equal. The comparison carried out in [18] for the water molecule has shown that with $E > \varepsilon_{iz}$ the values of $W_{iz} > E_{iz}$, at $E = \varepsilon_{iz}$, are, consequently, $W_{iz} \rightarrow \infty$. It is related with different approaches to the determination of these values. According to [19] under pressure $p > 1.33\cdot10^{-2}$ Pa the flux of emitted electrons is proportional to the flow of ions falling onto the cathode. Hence the primary electron flux is equal to $\Gamma_{ep} = \gamma N_i A_L h_L v_B$, where γ is the ion-electron emission coefficient. So, the number of fast primary electrons being in the plasma volume can be determined as $N_{ep} = \gamma N_i A_L h_L v_B V^{-1} \left(\frac{\tau_D + \tau_E}{\tau_D \tau_E}\right)^{-1}$, where τ_D is the characteristic energy confinement time of fast electron diffusion to the anode and τ_E is the characteristic energy confinement time of the fast electron.

By calculating the reflex discharge parameters it is necessary to consider in the energy balance, besides the EEDF effect, the values of average kinetic energy taken with ions and, consequently, the cathode drop of potential V_s (see Fig. 1).

From the condition of self-maintained discharge stationarity, taken in [20], it follows that $\langle N_i \rangle \gamma = 1$,

consequently, $\frac{\gamma E}{W_{iz}} = \frac{\gamma q V_s}{W_{iz}} = 1$, and hence $V_{dc} \approx V_s = \frac{W_{iz}}{\gamma q}$. Using in calculations the experimentally measured values of V_{dc} [7] and taking $V_{dc} \approx V_s$, as well as, $V_s = 0$, we obtain the discrepancy between the calculation data and experimental results by a factor of ~ 2.

Analysis of the plasma density dependence on the magnetic induction (see Fig. 3) shows that the plasma density increases with magnetic field increasing and, consequently, the particle loss decreases across the magnetic filed. In the case under consideration a classic diffusion has been assumed and corresponding values h_L and h_R were taken [5, 6]. It should be noted that in the reflex discharge, after reaching some critical value of the magnetic field B_{cr} [21], an anomalous diffusion with the transverse diffusion coefficient, close to the Bohm diffusion coefficient, is observed [22].

CONCLUSIONS

Within the framework of the model under consideration the plasma electron density and temperature as a function of the adsorbed power in the reflex discharge, magnetic field value and initial gas pressure are calculated. The processes of cathode material sputtering with subsequent ionization of sputtered atoms in the plasma are investigated. The density of neutral particles and sputtered cathode material atomic ions is determined. The comparison between the calculation data and experimental results has been performed. The calculation data differ from the experimental results by a factor of ~2. Such accordance between the results is satisfactory for a sufficiently simple reflex discharge model under 4onsideration. Further development of the model can give more accurate coincidence between the experimental and calculation results.

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РАСЧЕТ ПАРАМЕТРОВ СТАЦИОНАРНОГО ОТРАЖАТЕЛЬНОГО РАЗРЯДА

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Рассмотрен вариант модели стационарного отражательного разряда на основе global (volume-averaged) модели. Проведен расчет зависимости плотности и температуры электронов плазмы от адсорбированной мощности в отражательном разряде, величины магнитного поля и начального давления газа. Определена плотность нейтральных атомов и ионов материала катода, поступающих в разряд за счет механизма катодного распыления.

РОЗРАХУНОК ПАРАМЕТРІВ СТАЦІОНАРНОГО ВІДБИВНОГО РОЗРЯДУ

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Розглянуто варіант моделі стаціонарного відбивного розряду на основі global (volume-averaged) моделі. Проведено розрахунок залежності густини та температури електронів плазми від адсорбованої потужності у відбивному розряді, величини магнітного поля і початкового тиску газу. Визначена густина нейтральних атомів та іонів матеріалу катода, що поступають у розряд за рахунок механізма катодного розпилення.