PLASMA PARAMETERS ESTIMATION IN THE NON-SELF-SUSTAINED GAS DISCHARGE WITH HOLLOW ANODE

I.O. Misiruk, O.I. Tymoshenko, V.S. Taran

National Science Center "Kharkov Institute of Physics and Technology", Institute of Plasma Physics, Kharkiv, Ukraine

E-mail: ivanmisiruk@gmail.com

A simple global model was built for estimation of the plasma properties in the non-self-sustained gas discharge with hollow anode [2, 4]. The calculated results are compared with experimental data of probe measurements. The applicability and limitations of the model are discussed.

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INTRODUCTION

Low temperature plasmas have a wide variety of applications [1, 2]. Understanding their properties is important for controlling of plasma based processes and technologies. Exact modeling of plasma behavior in the discharges with a complicated geometry by fluid equations or PIC-method has a large computational complexity. However, there is a possibility to build a simple model for estimation of plasma parameters without solving complicated equations.

Global modeling represents a numerical method of describing plasma discharges, based on fluid equations, that do not have spatial derivatives in order to enhance computational efficiency [3]. This numerical method gives a possibility for prediction of the volume averaged plasma parameters. Also it gives the relationships between main parameters and can be applied across a broad range of system properties.

1. GLOBAL MODEL

The model is based on particle and power balance equations. The zeroth moment of Boltzmann equation is the mass or particle balance equation and can be written [5]:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = G - L, \tag{1}$$

where G denotes the particles generation rate and L – the particles loss rate. We consider a single species neutral plasma with a low degree of ionization. For simplicity, only ionization processes and losses of charged particles at the walls of the vacuum chamber are taken into account. The ionization is assumed to be caused by only thermalized electrons of the plasma. Denoting K_i as ionization rate constant, the generation term can be expressed as $n_e n_0 K_{iz}$, where n_e, n_0 is an electron and neutral gas density, respectively. For the losses to the wall, a mean ion confinement time τ_i is defined by the loss of charged particles per unit volume and unit time. Considering stationary state case and neglecting spatial derivative (divergence), the ion balance equation can be rewritten as:

$$0 = n_e n_0 K_{iz} - \frac{n_i}{\tau_i}, \tag{2}$$

where

$$K_{iz} = \langle \sigma v (kT_e) \rangle_{iz} \tag{3}$$

is the ionization rate coefficient averaged over a Maxwellian distribution. Taking into account the quasi-neutrality of plasma $n_e = n_i$ equation (2) is simplified:

$$\tau_i = \frac{1}{n_0 K_{iz}}. \tag{4}$$

From this equation, the ion density has dropped out, demonstrating that the ion density is not determined by the ion balance. In low-pressure discharges a typical electron temperature is a few eV, so, only the high-energy Maxwellian tail contributes to ionization. Also, the volume recombination doesn't contribute to ion confinement time τ_i due to low electron – ion collision frequency. The volume integrated loss of density of ions has to be equal to the area integrated flux onto the walls. The ion flux at the sheath boundary and also to the walls is given by:

$$j_i = n_e v_B \exp\left(-\frac{1}{2}\right). \tag{5}$$

Quasi-neutral plasma is generated in the vacuum chamber with volume *V* and walls area *S*. With equation (5) we can write:

$$j_i S = n_i v_B \exp\left(-\frac{1}{2}\right) S = \frac{n_i}{\tau_i} V, \tag{6}$$

where

$$v_B = \sqrt{\frac{kT_e}{m_i}} \tag{7}$$

is the Bohm velocity [5].

From the equation (6) the ion confinement time becomes:

$$\tau_i = \frac{V}{S}\sqrt{\frac{m_i}{kT_e}} \exp\left(\frac{1}{2}\right) \tag{8}$$

and thus from equation (4):

$$n_0 K_{iz} \frac{V}{S} \exp\left(\frac{1}{2}\right) = \sqrt{\frac{kT_e}{m_i}}. \tag{9}$$

The left-hand side of the last equation varies much steeper with the electron temperature than the righthand side. Plasma adjusts the electron temperature so that equation (9) is fulfilled. The electron temperature decreases with increasing working gas pressure, but the dependence is rather weak. The electron temperature is determined by the geometry of the chamber for the certain pressure value. For calculation of the electron temperature we need some explicit expression for ionization rate versus temperature dependency. Such approximate expression, for the limited range of kT_e, can be given by [5]:

$$K_{iz} = K_{iz0} \exp\left(-\frac{U_{iz}}{kT_e}\right), \qquad (10)$$

where U_i is the ionization energy, K_{iz0} – constant. For Argon this constant is $K_{iz0} \approx 5\times10^{-14}$ m^3/s [5].

Electron temperature we determined from ion balance equation, so, for plasma density we should use the balance of power. The electrical power *P*, deposited into the discharge can be divided on two parts. The first part of it P_{iz} is consumed by the process of ionization. We assume that ionization is the main consumer and neglects the other processes. Then, the absorbed power is given by:

$$P_{iz} = n_e n_0 K_{iz} V U_{iz}\,. \qquad (11)$$

If P_{iz} is assumed to be constant, the plasma density results directly with the electron temperature defined by equation (9). The plasma density is proportional to the absorbed power, inversely proportional to the gas pressure and the ionization energy, and is strongly decreasing with increasing of electron temperature. The second part is associated with the ion acceleration in the sheath. The power consumed for ion acceleration is:

$$P_a = \varepsilon_i j_i S = \varepsilon_i n_i \sqrt{\frac{kT_e}{m_i}} \exp\left(-\frac{1}{2}\right) S\,, \qquad (12)$$

where ε_i is:

$$\varepsilon_i = e\Phi_{fl} = \frac{kT_e}{2}\left(1+\ln\left(\frac{m_i}{2\pi m_e}\right)\right). \qquad (13)$$

The floating potential Φ_{fl} is resulting from equation of electron and ion currents on the wall: $j_e + j_i = 0$. The total input power results as:

$$P = P_{iz} + P_a. \qquad (14)$$

With equations (11) and (12), the plasma density can be calculated as:

$$n_e = P\left(\begin{array}{l} n_0 K_{iz} V U_{iz} + \\ +\dfrac{S\left(kT_e\right)^{3/2}}{2\exp\left(\dfrac{1}{2}\right)\sqrt{m_i}}\left(1+\ln\left(\dfrac{m_i}{2\pi m_e}\right)\right)\end{array}\right)^{-1}. \qquad (15)$$

The process of global modeling can be divided into two main steps: first, we calculate the electron temperature by equation (9) and after that, we can determine plasma density.

2. RESULTS

Non-self-sustained gas discharge, in which the additional charge carriers are produced by a vacuum-arc plasma gun, is characterized by high-current electron and ion fluxes and high values degree of ionization [2, 4]. Such type of discharge may be easily excited in widely used vacuum-arc deposition setups. Due to enhanced plasma density and degree of ionization, the processes of surface treatment in such gas discharge are much more intense than it is in a self-sustained glow discharge.

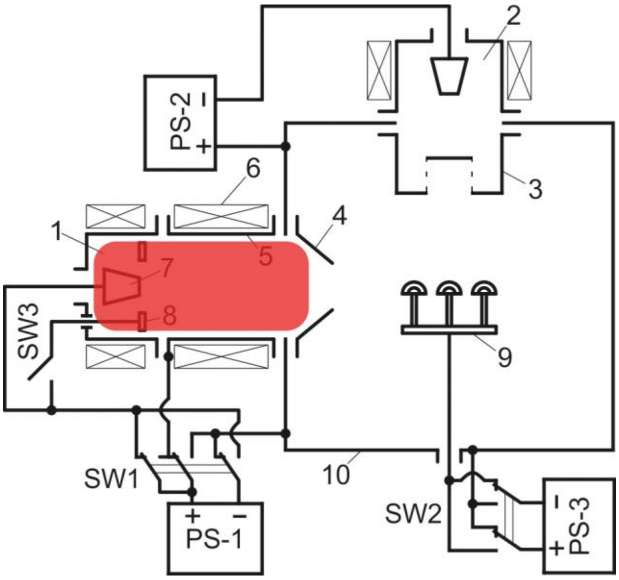

Fig. 1. Scheme of experimental set-up for non-self-sustained gas discharge excitation [2, 4]

The global model described in the previous paragraph was applied for plasma parameters estimation inside the hollow anode of the non-self-sustained gas discharge. The experimental set-up was discussed in [2, 4]. The region of interest is colored in red (Fig. 1). The region is axially symmetric and can be modeled as the cylinder with a radius of 0.1 m and height of 0.23 m.

The input parameters for the global model are presented in the Table:

Volume, m^3	7.22×10^{-3}
Surface area, m^2	2.07×10^{-1}
Input power, W	70
Ionization potential, eV	15.8

Langmuir probe measurements had been carried out for model validation. The probe was placed in the center of the chamber on the distance 10 cm from the hollow anode output. Data acquisition system based on Arduino Nano platform is used for Langmuir probe data recording [6]. The electron temperature in eV was calculated from the slope of I-V characteristics.

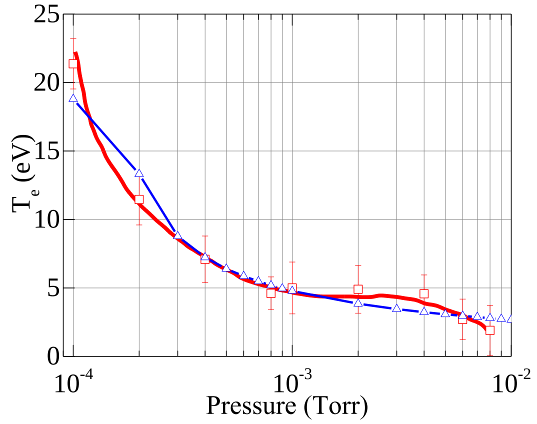

Fig. 2. Electron temperature versus pressure of Argon gas: experiment (red) and model (blue)

On the Fig. 2 we can see good correspondence between model and experimental data. The electron temperature is defined mainly by the discharge chamber geometry.

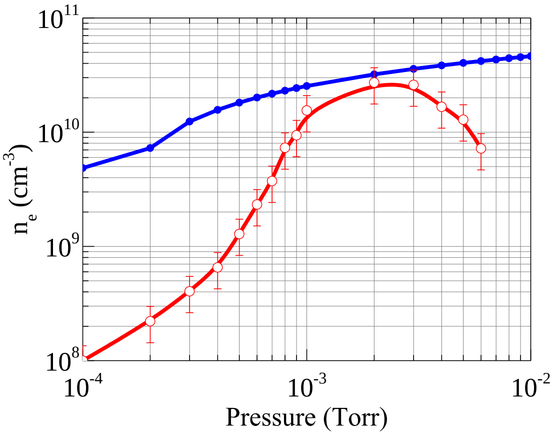

Fig. 3. Electron density versus pressure of Argon gas: experiment (red) and model (blue)

However, there is a big discrepancy between experimental and model data for plasma density (Fig. 3). This discrepancy can be explained by the presence of double layer at the output of the hollow anode.

CONCLUSIONS

A simple global model was built for estimation of the electron temperature and density in the plasma of non-self-sustained gas discharge [2, 4]. The calculations have been compared with a data of Langmuir probe measurements. The comparison shows a good agreement for electron temperature and a big discrepancy for electron density. The electron temperature is defined mainly by the discharge chamber geometry. The electron density coincides with experimental data only by the order of magnitude, in a narrow range of pressures. This behavior of density can be explained by the fact that in such simplified plasma model, the presence of a double layer of spatial charge is not taken into account. This results in the appearance of charged particles beams and the non-isotropic distribution of the current density on the surface of the electrodes of the discharge system. In a non-self-sustained gas discharge, such double layer is formed at the outlet of the hollow anode. The limitations of the model arise from the simplified assumptions that were made during it building. One of such assumptions was uniformity of plasma in the discharge volume. The second important assumption is neglecting of particles beams. Further improvements to the model developed here are needed for better parameters estimation.

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ОЦЕНКА ПАРАМЕТРОВ ПЛАЗМЫ В НЕСАМОСТОЯТЕЛЬНОМ ГАЗОВОМ РАЗРЯДЕ С ПОЛЫМ АНОДОМ

И.А. Мисирук, А.И. Тимошенко, В.С. Таран

Построена простая глобальная модель для оценки параметров плазмы в несамостоятельном газовом разряде с полым анодом. Результаты вычислений сравниваются с данными зондовых измерений. Обсуждается применимость и ограничения рассмотренной модели.

ОЦІНКА ПАРАМЕТРІВ ПЛАЗМИ В НЕСАМОСТІЙНОМУ ГАЗОВОМУ РОЗРЯДІ З ПОРОЖНИСТИМ АНОДОМ

І.О. Місірук, О.І. Тимошенко, В.С. Таран

Побудована проста глобальна модель для оцінки параметрів плазми в несамостійному газовому розряді з порожнистим анодом. Результати обчислень порівнюються з даними зондових вимірювань. Обговорюються застосовність та обмеження розглянутої моделі.