COMPUTER SIMULATION OF ABNORMAL GLOW DISCHARGE PROCESSES IN CROSSED ELECTRIC AND MAGNETIC FIELDS

A.V. Isakov, V.P. Kolesnik, A.M. Okhrimovskyy, N.P. Stepanushkin, A.A. Taran

National Aerospace University «KHAI», Kharkov, Ukraine

E-mail: lewka@3g.ua

A mathematical model for plasma parameters calculation in the abnormal glow discharge in crossed electric and magnetic fields is proposed. Numerical model made it possible to obtain the electric potential, electric field, electron density and temperature distributions in the interelectrode space working area. The application validating of the developed numerical model has proved to describe of the processes in the magnetron-type devices.

PACS: 669.187.58

INTRODUCTION

The main distinctive feature of the abnormal glow discharge in crossed magnetic and electric fields from the normal glow discharge is the presence of the transverse magnetic field. That leads to the absence of a steady leakage electron current to the anode. It allows obtaining high plasma densities at relatively low pressures.

In order to reduce the number of experiments for discharge parameters optimization it is necessary to understand clearly the basic processes in plasma. This can be achieved by developing the mathematical models for computational determination the investigated processes' parameters.

There is a variety of different mathematical models for determination of plasma parameters in crossed electric and magnetic fields, but no one of them considers systems of more than two electrodes.

1. RESEARCH OBJECTIVE DETERMINATION

There are many different approaches to the discharge plasma processes modelling, like fluid models, kinetic models, Monte Carlo method, hybrid models, etc. [1-3].

Based on the literature review in previous work [4], the fluid model is the most reasonable approach for modelling the abnormal glow discharge in crossed magnetic and electric fields at operating pressures of 0.1...0.8 Pa and magnetic field of 0.01...0.05 T.

Let us consider the spatial electrodes configuration, found on the Fig.1, where the magnetic field distribution in the interelectrode space, created by the magnetic system, are shown. The distribution of steady magnetic field in the discharge space was determined by means of PARDISO solver [5-7].

The anode (1) is under the positive potential 250...900 V. The cathode (3) potential is also positive, but lower than the anode potential (1). The cathode (4) and the polar tip (2) are under "zero" potential relatively to the anode.

2. MATHEMATICAL MODEL

Let us consider a fluid model presented in [8-15]. The fluid model is based on a system of differential equations in the form of partial derivatives, including the continuity equation (1) and the rate of change of the electron energy density equation (2). For heavy particles (neutral atom, metastable atom and ion) the continuity equation (3) is solved.

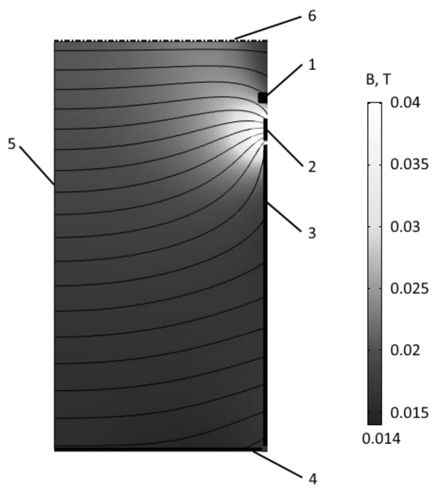

Fig. 1. The scheme of interelectrode space with crossed electric and magnetic fields: 1 – anode; 2 – polar tip; 3 – cathode; 4 – cathode; 5 – plane of symmetry; 6 – axis of symmetry

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{\Gamma}_e = S_e, \quad (1)$$

$$\frac{\partial \left(n_e T_e \right)}{\partial t} + \nabla \cdot \mathbf{\Gamma}_w + \mathbf{E} \cdot \mathbf{\Gamma}_e = S_w, \quad (2)$$

$$\frac{\partial n_k}{\partial t} + \nabla \cdot \mathbf{\Gamma}_k = S_k, \quad (3)$$

where n_e is electron number density, $\mathbf{\Gamma}_e$ is electron flux density, S_e is electron creation rate, T_e is electron temperature, $\mathbf{\Gamma}_w$ is electron energy flux density, $\mathbf{E}$ is electric field strength, S_w is a rate of electron energy density, n_k is the heavy particles number density, $\mathbf{\Gamma}_k$ is heavy particles flux density, S_k is rate of k-th particle creation.

Self-consistent electric field strength $\mathbf{E}$ and plasma potential φ are determined with help of the Poisson equation:

$$\Delta\varphi = -\frac{e}{\varepsilon_0}\left(n_i - n_e\right), \qquad \mathbf{E} = -\nabla\varphi,$$

where e is an elementary charge, ε_0 is a dielectric constant, n_i is ion density.

In the proposed model only the reactions, given in the table 1, are taken into account. The cross-sections of the correspondent collision processes were taken from the work [12].

Reactions in plasma

Scheme of reaction	Type of reaction
$e + Ar = e + Ar$	elastic collision
$e + Ar = e + Ar^*$	excitation
$e + Ar^* = e + Ar$	excitation dropping
$e + Ar = 2e + Ar^+$	direct ionization
$e + Ar^* = 2e + Ar^+$	stepwise ionization
$Ar^* + Ar^* = e + Ar + Ar^+$	Penning ionization
$Ar^* + Ar = Ar + Ar$	metastable quenching

The model have to take into account not only reactions in the bulk discharge but also those ones on the electrode surface, such as secondary electron emission, ion neutralization and excitation dropping of metastable atoms.

The main maintaining mechanism of discharge in the interelectrode space is the cathode secondary electron emission under ion bombardment. Secondary electron emission depends on the energy, ion mass and on cathode material. Secondary electrons are accelerated by the electric field in cathode dark space, where they gain enough energy to ionize argon molecules.

3. NUMERICAL SOLUTION

The solver PARDISO was applied to determine the plasma parameters distribution in the discharge space, which allows to solve the system of differential equations in the form of partial derivatives in one, two and three dimensional cases.

In order to simplify the numerical execution of fluid model, the influence of internal electromagnetic fields due to motion of charged particles upon the external steady electromagnetic fields caused by electromagnetic devices, was not considered [16].

A method, proposed in the works [5-7, 17, 18], for solving the differential equations was applied. The calculation program uses the affine invariant of Newton method [19].

The results depend on the initial approximation in a complicated manner. Therefore, to reduce the time and increase the accuracy of fluid model calculation, approximate value of variables at low computational accuracy are calculated at the beginning. These variables serve as initial conditions for the next step performed with higher accuracy.

It took from 2 to 6 hours to reach a steady state mode to solve the system of differential equations for the examined configuration on PC (Intel Core i7-4770K at 4.3 GHz, RAM 16 GB).

4. RESULTS OF MODELING

Solution of the system of differential equations is resulted in the electric potential, density and temperature of electrons distributions in the interelectrode space, which are presented in Figs. 2-4, correspondingly.

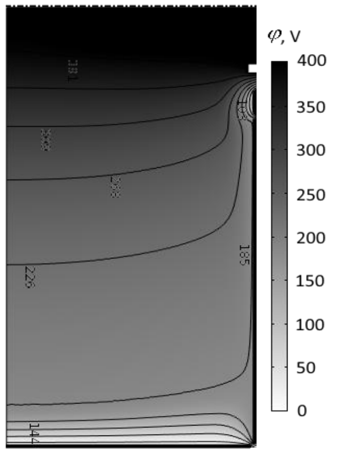

Fig. 2. Plasma potential distribution in the interelectrode space

The solutions were obtained under the following conditions: discharge voltage was up to 400 V, discharge current was up to 0.4 A, pressure in the vacuum chamber was of 0.2 Pa.

It's obvious from the Figs. 2, 3 that the numerical model give us an opportunity localize the main ionization area and describe the cathode region near the cathode (4) and polar tip (2) (see Fig. 1).

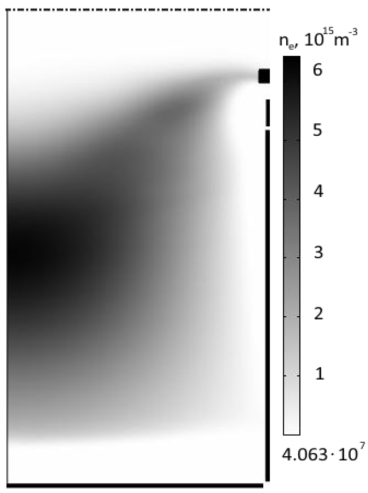

Fig. 3. Electron density distribution in the interelectrode space

From these distributions (see Figs. 2-4) we can conclude that the "magnetic trap" is formed between the polar tips. Trapped electron oscillates along the magnetic field lines and reflects in the polar tips area. Electron movement to the anode occurs by means of electrons shifting from one orbit to another due to the elastic and inelastic collisions. Emitted from the cathode surface (4), the electrons oscillate along the magnetic field lines and then reflect from the cathode (3) (see Fig. 1).

Low electron density in the discharge space is caused by run away of the part of electrons to the cathode (3), as it is under the positive potential, which is several times lower anode potential.

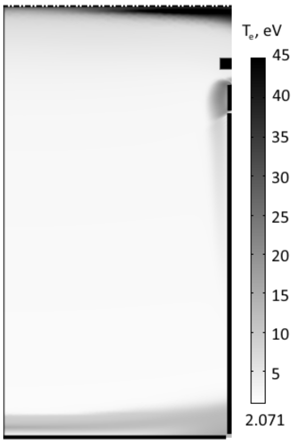

Fig. 4. Electron temperature distribution in the interelectrode space

From the electric field and magnetic field lines distribution (Fig. 5) one can conclude that the majority of ions (up to 45 %) moves to the cathode (4) and the other part of ions (30 %) moves to the cathode (3), while the remaining ions move to the polar tips (2).

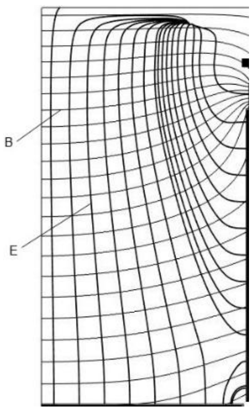

Fig. 5. Distribution of the electric field strength and magnetic field lines in the interelectrode space

5. MATHEMATICAL MODEL VERIFICATION

The experimental data of the discharge parameters in a cylindrical magnetron, shown in the work [20], were used in order to verify the proposed mathematical model. The abnormal glow discharge is initiated at the noble gas (argon) pressure of 3 Pa and discharge current of 0.2 A between two coaxial cylindrical electrodes, which are placed in a homogeneous longitudinal magnetic field of 0.02 T.

Figs. 6, 7 compares the results (distribution of the electric potential and electron density) in the midplane of the cylindrical magnetron obtained using the fluid model and the results are presented in work [20].

One can conclude from the Figs. 6, 7, that the numerical verification of the developed mathematical model has confirmed the qualitative and quantitative correspondence of the proposed fluid model, within the measurement error of the probe method [21], with the results of work [20].

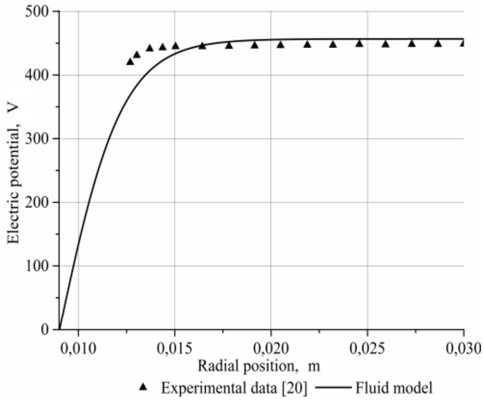

Fig. 6. Plasma potential distribution in the cylindrical magnetron midplane

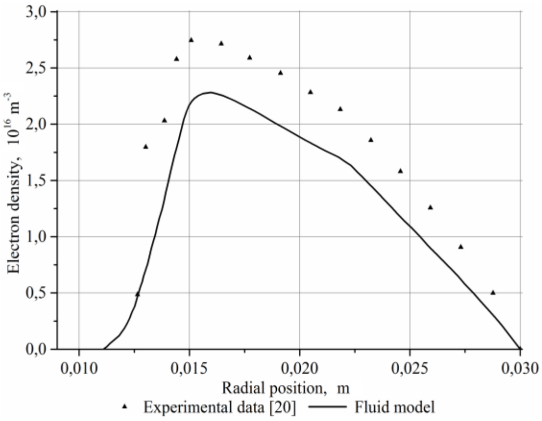

Fig. 7. Electron density distribution in the cylindrical magnetron midplane

CONCLUSIONS

The mathematical model makes it possible to undertake the numerical experiment for determination the discharge parameters in the examined interelectrode space under the operating pressures of 0.1...0.8 Pa and magnetic induction of 0.01...0.05 T. The solution of the differential equation system allow determine the distribution of the plasma potential, electron temperature and electron density in the abnormal glow discharge in crossed magnetic and electric fields.

The mathematical model reliability was validated by applying the proposed model for cylindrical magnetron calculation and by comparing the calculated data with the experimental ones. The results confirmed the qualitative and quantitative correspondence of the developed fluid model with results presented in the work [20].

It follows that the developed mathematical model allow us to specify the near-electrode areas and obtain the qualitative distribution of the plasma parameters at a short calculation time. Hence, it is possible to execute the optimization of magnetic field configuration and working area for examined spatial electrodes configurations.

REFERENCES

1. A. Bogaerts, E. Bultinck, I. Kolev, L. Schwaederle, K.V. Aeken, D. Depla. Computer modeling of magnetron discharges // *J. Phys. D: Appl. Phys.* 2009, v. 42, № 19, p. 194018. 1-12.

2 I. Kolev, A. Bogaerts. Detailed numerical investigation of a DC sputter magnetron // *IEEE Trans. Plasma Sci.* 2006, v. 34, № 3, p. 886-894.

3. J. E. Miranda, M. J. Goeckner, J. Goree, T. E. Sheridan. Monte Carlo simulation of ionization in a magnetron plasma // *J. Vac. Sci. Technol. A.* 1990, v. 8, № 3, p. 1627-1631.

4. A. V. Isakov, V. P. Kolesnik. The analysis of computer discharge modeling approaches in installations with radial plasma flows // *Sovremenie problemi raketno-kosmicheskoi tekhniki I tekhnologii.* 2013, p. 62-63 (in Russian).

5. O. Schenk, K. Gärtner. Solving Unsymmetric Sparse Systems of Linear Equations with PARDISO // *J. Future Generation Computer Systems*. 2004, v. 20, № 3, p. 475-487.

6. O. Schenk, K. Gärtner. On fast factorization pivoting methods for sparse symmetric indefinite systems // *Elec. Trans. Numer. Analysis.* 2006, v. 23, p. 158-179.

7. G. Karypis, V. Kumar. A Fast and High Quality Multilevel Scheme for Partitioning Irregular Graphs // *SIAM J. Sci. Computing.* 1998, v. 20, № 1, p. 359-392.

8. A. Bogaerts, A. Okhrimovskyy, N. Baguer, R. Gijbels. Hollow cathode discharges with gas flow: numerical modelling for the effect on the sputtered atoms and the deposition flux // *Plasma Sources Sci. Technol.* 2005, v. 14, p. 191-200.

9. G. J. M. Hagelaar, L.C. Pitchford. Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models // *Plasma Sources Sci. Technol.* 2005, v. 14, № 4, p. 722-733.

10. G.J.M. Hagelaar. *Modeling of Microdischarges for Display Technology* / Eindhoven: Technische Universiteit Eindhoven, 2000.

11. D. Graves, K. Jensen. A Continuum Model of DC and RF Discharges // *IEEE Trans. Plasma Sci.* 1986, v. 14, № 2, p. 78-91.

12. I. Rafatov, E.A. Bogdanov, A.A. Kudryavtsev. Account of nonlocal ionization by fast electrons in the fluid models of a direct current glow discharge // *Phys. Plasmas.* 2012, v. 19, p. 093503. 1-8.

13. R.J. Kee, M.E. Coltrin, P. Glarborg. *Chemically Reacting Flow: Theory and Practice* / 2nd Edition. New Jersey, A John Wiley & Sons, Inc. Publication, 2003.

14. R.B. Bird, W.E. Stewart, E.N. Lightfoot. *Transport Phenomena* / New Jersey, A John Wiley & Sons, Inc. Publication, 2002.

15. A.B. Laurence. *Transport Phenomena for Chemical Reactor Design* / New Jersey, A John Wiley & Sons, Inc. Publication, 2003.

16. S.M. Rossnagel, H.R. Kaufman. Induced drift currents in circular planar magnetrons // *J. Vac. Sci. & Technology A: Vacuum, Surfaces, and Films*. Maryland, 1987, v. 5, № 1, p. 88-91.

17. I.V. Tsvetkov. *Numerical methods application for the processes in plasma*. Moscow: MIFI, 2007.

18. B. Older, S. Frenbakh, M. Rotenberg. *Computational methods in plasma physics*. Moskow: "Mir", 1974.

19. P. A. Deuflhard. A modified Newton method for the solution of ill-conditioned systems of nonlinear equations with application to multiple shooting // *Numer. Math*. 1974, v. 22, № 4, p. 289-315.

20. I. A. Porokhova, Y. B. Golubovskii, J. F. Behnke. Anisotropy of the electron component in a cylindrical magnetron discharge. II. Application to real magnetron discharge // *Physical review E.* 2005, v. 71, p. 066407. 1-12.

21. V.A. Obukhov, V.G. Grigoryan, L.A. Latishev. Heavy ions sources // *Plazmenie uskoriteli i ionie inzhektori.* Moskow: "Nauka", 1984, p. 169-185 (in Russian).

Article received 18.09.2014

КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ В АНОМАЛЬНОМ ТЛЕЮЩЕМ РАЗРЯДЕ В СКРЕЩЕННЫХ ЭЛЕКТРИЧЕСКОМ И МАГНИТНОМ ПОЛЯХ

А. В. Исаков, В.П. Колесник, А.М. Охримовский, Н.П. Степанушкин, А.А. Таран

Предложена математическая модель расчета параметров плазмы в аномальном тлеющем разряде в скрещенных электрическом и магнитном полях. Численное решение системы уравнений позволило получить распределения потенциала, электрического поля, плотности и температуры электронов в рабочей зоне рассмотренного межэлектродного промежутка. Проведено обоснование применимости разработанной численной модели для описания процессов в устройствах магнетронного типа.

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ В АНОМАЛЬНОМУ ТЛІЮЧОМУ РОЗРЯДІ В СХРЕЩЕНИХ ЕЛЕКТРИЧНОМУ І МАГНІТНОМУ ПОЛЯХ

О.В. Ісаков, В.П. Колесник, А.М. Охримовський, М.П. Степанушкін, А.О. Таран

Запропонована математична модель розрахунку параметрів плазми в аномальному тліючому розряді в схрещених електричному і магнітному полях. Чисельне рішення системи рівнянь дозволило отримати розподіли потенціалу, електричного поля, густини і температури електронів у робочій зоні розглянутого міжелектродного проміжку. Проведено обґрунтування застосування розробленої чисельної моделі для опису процесів у пристроях магнетронного типу.