TRANSPORT PROCESSES IN THE LOW PRESSURE GAS DISCHARGE PLASMA

N.A. Azarenkov, A.A. Bizjukov, A.V. Gapon
Department of Physics and Technology, High-Technology Institute,
Kharkov National University, Kharkov, 61108, Kurchatov av., 31

Plasma technologies for the film deposition and etching based on the ion flows application are intensively elaborated and used now. Some of the most important requirements imposed on the ion flows are homogeneity and monoenergeticity, what necessitate the analysis of processes of particles flow formation in existing devices as well as under designing the new plasma technology devices [1-5]. On the base of the simple mathematical model the transport processes in the low pressure gas discharge are considered. It was assumed that the gas discharge is in steady state regime. For the nonmagnetized plasma free fall mode for ions and electrons is supposed and free fall mode is assumed only for ions if a constant external magnetic field is applied. Consideration is treated in the framework of 2D two liquid hydrodynamic plasma model.
PACS: 52.80.-s

1. STATEMENT OF THE PROBLEM

Geometry. Main subject of our investigation is shown in the fig.1 and represents the metal cylinder discharge chamber (1) filled with the plasma (2). The energy input is performed by electrodes (3), which are located between two glass disks (4) and powered from RF generator. The plasma produced leaves the chamber through the grid electrode (5). Driving electrode (6) is separated from the chamber wall by isolator (7) and serves for the particles flow control. An external magnetic field parallel to the axis can be applied. In this work we consider only problems with cylindrical symmetry.
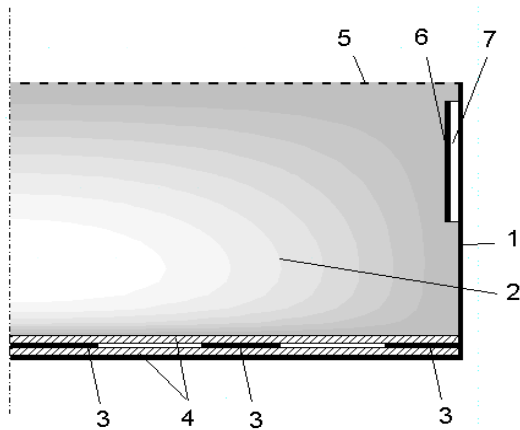

Fig.1

Processes considered. General scheme of our calculations consists of the successive consideration of more or less separate subproblems. They are: 1) ions movement in the field of ambipolar potential and in an external magnetic field, if one is present; 2) finding of the equilibrium space distribution of electron density and the ambipolar potential distribution; 3) balance of the total number of electrons; 4) heat transport; 5) HF electric field distribution. Let us consider each of these steps.

1.Ion movement is described by the set of equations

$$\frac{\partial n_i}{\partial t} + \nabla (n_i \vec{v}_i) = v^{\,i}(T) n_e \qquad (1.1)$$

$$\frac{\partial n_i v_i}{\partial t} + \nabla (n_i \vec{v}_i \otimes \vec{v}_i) = \frac{n_i e}{m_i}(-\nabla \Psi + \frac{v_i}{c} \times \vec{H}). \quad (1.2)$$

Here $n_{i,e}$ is the ion and electron fluids densities, v_i -ion fluid velocity, $v^{\,i}$ - ionization frequency dependent on the electron temperature T, e - elementary charge, m_i -ion mass, Ψ -ambipolar potential, c - light speed, H -the external magnetic field strength, $(v \otimes v)^{\alpha\beta} = v^{\alpha} v^{\beta}$, v^{α} is the α-th component of vector v. From elementary processes we took into account here only single ionization.

2. Electron density and ambipolar potential. The fact, that electrons relaxation time is more less than ion relaxation time, means that the time scale of transport processes is determined by ions, and gives the possibility of calculation of the electron density distribution for given ion one. Assuming that the electron gas is characterized by local equilibrium in the external force field at any moment of time, we can to use Boltzmann distribution

$$n_e = n_0 \exp(e\Psi / kT) \qquad (2.1)$$

with the normalization requirement

$$n_0 \int_V \exp(e\Psi / kT)\, dV = N_V, \qquad (2.2)$$

where k is Boltzmann constant, N_V is the total number of electrons in the volume under consideration. Let's note, that the distribution (2.1) is not valid in the Lorentz force field. Then, (2.1-2.2) is right in the absence of magnetic field or if we consider the distribution along its lines, if they are parallel. The set (2.1-2.2) is closed by the Poisson equation:

$$\Delta \Psi = 4\pi e(n_e - n_i) \qquad (2.3)$$

3. Balance of the total number of electrons in the volume V is subjected by the equation of continuity of the electron liquid:

$$\frac{dN_V}{dt} + \oint_{S_V} n_e \vec{v}_e d\vec{S} = \int_V n_e v^{\,i}(T)\, dV, \qquad (3.1)$$

where S_V is the boundary of the volume V. We needs of normal velocity components values $v_e|_S$ on the S_V. In

the case of free plasma we can expand V up to discharge chamber sizes and set $v_e|_S$ to ion sound velocity (Bohm condition [6]):

$$v_e|_S = \sqrt{T/m_i} \; . \qquad (3.2)$$

When the external magnetic field is applied, we must identify the volume V with the some small magnetic field tube and we can get $v_e|_S$ from the drift theory [6]:

$$v_e|_S = \frac{v_{coll}}{m_e \omega_c^2}\left(- e\nabla_\perp \Psi - T\frac{\nabla_\perp n}{n} \right) \qquad (3.3)$$

and use (3.2) on chamber walls. In (3.3) ω_c is the electron cyclotron frequency. Condition (3.2) in this case denotes longitudinal to magnetic field direction velocity component. Let's note, that the drift component of the velocity in the case of cylindrical symmetry magnetic field does not result in N_V changing. Secondly, as a rule we can neglect electrons transfer through the field tube walls if the tube is closed to the chamber wall.

4. Heat transport is realized mainly due to the electron heat conductivity and is described in the framework of the drift theory. Similar to electron density, electron heat flows steadies much faster then during the ion relaxation time, then we use the steady state heat conductivity equation:

$$\nabla q = 3/2\,\delta U/\delta t \; , \qquad (4)$$

$$\frac{\delta U}{\delta t} = n_e\left(-v^i U_i - \sum v^j U_j + \frac{2}{3}Q\right) + Tv^i n_e \; ,$$

$$q_\parallel = -\frac{5}{2}\frac{nT}{m_e v_{coll}}\nabla_\parallel T \; ,$$

$$q_\perp = -\frac{5}{2}\frac{v_{coll} nT}{m_e \omega_c}\nabla_\perp T \; ,$$

where U is the electron gas internal energy, $q_\parallel$ and $q_\perp$ are longitudinal and transverse heat flows densities, U_i is the energy of ionization, v^j and U_j are frequencies and energies of the j-th excited state of the working gas molecule, Q is the input power volume density. Boundary conditions for (4) can be obtained in the assumption that heat flow on the walls is convective and is determined by (3.1-3.2). The last remark in preceding subsection is also applicable to the heat flows.

5. HF electric field distribution. Electric field was calculated in linear potential approximation [7]. We use the fact that the electron temperature varies significantly slower, than any other the problem's variable. In the free plasma we have:

$$\nabla(\varepsilon\nabla\psi) + \frac{v_t^2}{\omega^2}\nabla^4\psi = 0 \; , \qquad (5.1)$$

where ψ is the RF electric field potential, $\varepsilon = 1 - \omega_p^2/\omega^2$ is the plasma permittivity, v_t -thermal electrons velocity, ω_p - the plasma frequency, ω - RF generator frequency. On the surfaces bounded the plasma we applied the "mirror reflection" condition [8], what leads to:

$$\vec{n}\nabla\left(\nabla^2\psi - \frac{\omega_p^2}{v_t^2}\psi\right)\Bigg|_S = 0 \; , \qquad (5.2)$$

where n -normal to the surface. Besades that, conditions of the total current continuity on dielectric surfaces [9]

$$n(\nabla\psi_p - \varepsilon_d\nabla\psi_d)|_S = 0 \; , \qquad (5.3)$$

where ψ_p, ψ_d is the HF potential in plasma and in dielectric and ε_d is the permittivity of the dielectric. The Dirichlet condition on RF electrodes and metal surfaces is used:

$$\psi|_S = \psi_0 \; . \qquad (5.4)$$

If the plasma is magnetized, (5.1) passes into

$$\nabla(\varepsilon\nabla\psi) + \frac{v_t^2}{\omega^2}\nabla(\hat{A}\nabla)\nabla\psi = 0 \; , \qquad (5.1')$$

where $\hat{\varepsilon}$ is the plasma permittivity tensor, $\hat{A} = \frac{\omega^2}{\omega_p^2}(1 - \hat{\varepsilon})$. The power resonantly absorbed (Q in (4)) can be evaluated as it shown in [10,7].

2. SOLUTION

The problem can be solved with the help of iterative solution of the set of subproblems enumerated above. In one's turn some of they are need of an iterative procedure. Subset of equations (1.1-1.2) is solved by the explicit MacCormac method [10]. We do one step of the solution of this subsystem with the time step $\tau \le c_s/L$, c_s - ion sound speed, L - problem's scale. Then we solve nonlinear subsystem (2.1-2.2) with the help of two iteration procedures, one is nested in other. External one is simply secant method for finding $n_0(N_V) = 0$ root (2.2); internal procedure is the Newton's method for solving (2.1,2.3) with n_0 fixed. Good accuracy can be reached by about 2-3 iteration of Newton's loop and about 10 iteration of secant loop. Subset (3) presents no difficulty, it is simply the algebraic equation. If magnetic field is present, we divide whole domain under calculation onto field tubes and find N_V for each of them. It should be noted, that in this case we have best convergence of subset (2) then in the case of free plasma. Heat conductivity equation (4) is solved similar to (2.1,2.3) by the Newton's method. Apparently, the best way to solve the subset (5) is to apply any direct method, it provides best accuracy, then standard iteration schemes, with comparable or less time needed (at least on the grids about 30x30 knots). This stage is the most durative.

3. RESULTS

Let's consider some examples of this technique. We considered transport processes in the planar plasma reactor described in [11]. An external magnetic field was not applied. RF feed was realized by the ring electrode situated at $r = 20cm$. The plasma was occupied the space with radial size $R=23cm$ and axial size $Z=3cm$ and it was enclosed between two glass disks. Total axial size of the discharge camera was $4cm$. Fig.2 shows the comparison of the experimental (points) and theoretical (line) plasma density values. Temperature is weakly dependent on radius and is equal to $3eV$ against $5eV$ in the experiment. It can be caused by an inaccuracy in ionization frequency value. Fig.3 shows the spatial distribution of the HF potential, normalized on its

maximal value. We also consider system shown at Fig.1 and had obtained some results about the influence of driving electrode and grid electrode potential values on the ion flow through the grid electrode in the absence of an external magnetic field. Sizes of the discharge camera is $R=22cm$ and axial size $Z=21cm$.
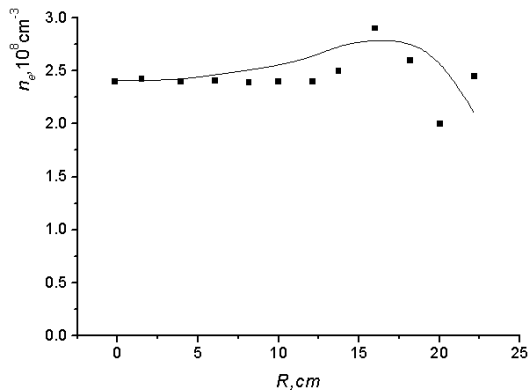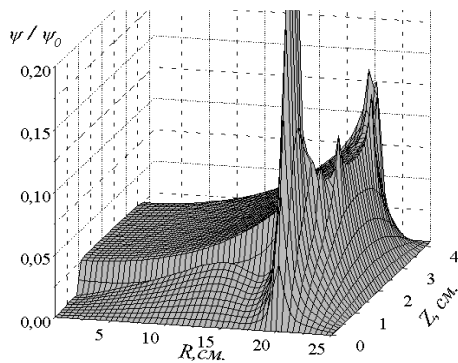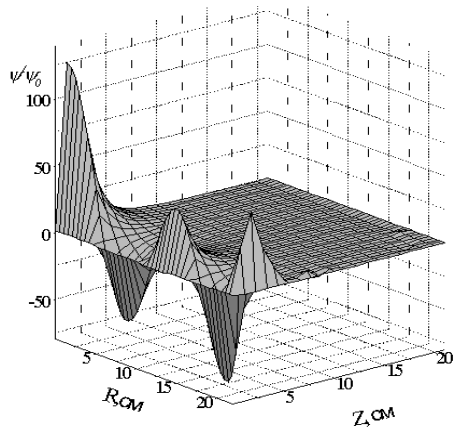

Fig.2

Fig.3

Fig.4

Fig.4 shows an example of HF potential distribution in the absence of magnetic field. Potential is normalized to one on the HF electrodes value. One can see, that HF power is localized near the RF electrodes and they distribution does not affect to the flow parameters. Following results are obtained with the assumption that the density of heat sources is uniformly distributed on the bottom base of discharge camera.

Fig. 5 reflects the influence of the grid electrode negative potential and the driving electrode positive potential to the radial distribution of the ion fluid density n^*

normalized to the average density value (*a*), ion velocity v^* normalized to the average ion sound speed (*b*), and angle α between the velocity and the camera axis (*c*). Solid lines correspond to the flow not perturbed. Dash lines correspond to the driving electrode positive potential (what is equal to the ambipolar potential maximum value), dot-dash lines correspond to the grid electrode negative potential (what module is equal to the two ambipolar potential maximum value).
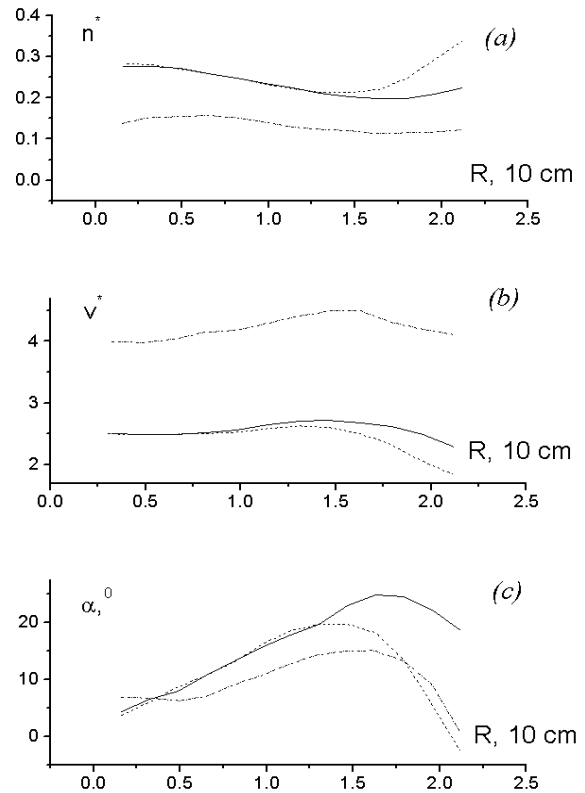

Fig. 5

REFERENCES

1. K. Suzuki, S. Okudaira, N. Sacudo and I. Kanomata// *J.Appl.Phys*. **16**, 1977, p. 1979
2. S. Matsuo and Y. Adachi.// *Jpn. J. Appl. Phys*. **21**, 1982, L4.
3. J. Asmussen// *J.Vac. Sci. Technol*., **A7**, (1989), p. 883.
4. F.F.Chen //*Plasma Phys. Control. Fusion*.**33**, 1991, p. 339.
5. Y.Yasaka, K. Ohnishi, T. Kikuchi, K. Tachibana and T. Itoh// *Jpn.J.Appl.Phys*. **36**, 1977, p.4572.
6. V.E. Golant, A.P. Zhilinskii and I.E.Sakharov Fundamentals of Plasma Physics. Wiley, New York, 1980.
7. A.N. Kondratenko. Surface and Bulk Waves in Bounded Plasmas./ Moscow: Energoatomizdat, 1985 (in Russian).
8. N.A.Krall, A.W.Trivelpiece. Principles of plasma physics./ McGr.H.Book Co.,1973
9. K.N. Stepanov// *J.Tech.Phys*., **35**, 1965, p.1002.
10. D.A.Anderson, J.C.Tannehill, R.H.Pletcher. Computational fluid mechanics and heat transfer. 1984, Hemisphere Publishing Corp., 1984.
11. N.A. Azarenkov, A.A.Bizjukov, A.V.Gapon, A.F. Tselujko, A.G. Chunadra.// *Proceedings of VIII conference on vacuum science and*

ПРОЦЕСИ ПЕРЕНЕСЕННЯ У ГАЗОРОЗРЯДНІЙ ПЛАЗМІ НИЗЬКОГО ТИСКУ

М.О. Азаренков, О.А. Бізюков, О.В. Гапон

Зараз інтенсивно розробляються та використовуються плазмові технології травлення та нанесення покриттів, що базуються на застосуванні потоків іонів. Одними з найбільш важливих вимог, що накладаються на потоки іонів, є їх однорідність за густиною та енергією, що тягне за собою необхідність аналізу процесів формування потоків частинок в існуючих пристроях та тих, що проектуються. На основі простої математичної моделі розглянуті процеси перенесення в газорозрядній плазмі низького тиску. Розглянуто стаціонарний режим розряду. Рух іонів та електронів у незамагніченій плазмі вважався беззіткненим, в замагніченій плазмі беззіткненим вважався тільки рух іонів. Задача розв`язувалася на основі двовимірної двохрідинної гідродинамічної моделі плазми.

ПРОЦЕССЫ ПЕРЕНОСА В ГАЗОРАЗРЯДНОЙ ПЛАЗМЕ НИЗКОГО ДАВЛЕНИЯ

Н.А. Азаренков, А.А. Бизюков, А.В. Гапон

В настоящее время интенсивно разрабатываются и используются плазменные технологии травления и нанесения покрытий, основанные на применении ионных потоков. Одним из наиболее важных требований, налагаемых на потоки ионов, является их однородность по плотности и по энергии, что влечет за собой необходимость анализа процессов формирования потоков частиц в существующих и проектируемых устройствах. На основе простой математической модели рассмотрены процессы переноса в газоразрядной плазме низкого давления. Рассматривается стационарный режим разряда. Движение ионов и электронов в незамагниченной плазме считалось бесстолкновительным, в замагниченной плазме бесстолкновительным считалось только движение ионов. Рассмотрение проведено на основе двумерной двухжидкостной гидродинамической модели плазмы.