Complex numeric analysis of gas-discharge chamber parameters

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Abstract

In last few decades one can see an increasing interest for accelerated ions sources. They can be used as ion thrusters for satellites, as technological sources for surface treatment and creation of thin films on it, as injectors for fusion facilities. Gas-discharge chamber (GDC) is the essential part of all such ion sources. It specifies several parameters such as power efficiency, propellant utilisation efficiency, uniformity of ion beam distribution etc. Often GDC should meet very stringent requirements, especially for satellite's ion thrusters.

Attempts of numeric analyses of GDC processes have been started in 60-s (in MAI also). However, as far as available computers capacity was not enough they can not regard all basic influencing factors at the same time. So, they have qualitative results only. Now high-capacity personal computers become available and authors attempt to carry out the software for GDC investigations and develop simplifying, which regard complex of basic processes.

Nomenclature

B - magnetic field induction
E_{ion} - effective ionisation energy
k - Boltzman constant
m - electron mass
M - ion, atom mass
n_o - neutral atoms concentration
n_i - ions concentration
n_e - slow electrons concentration
n_{es} - fast electrons concentration
N - fast electrons number, needed for one ionisation act
T_e - temperature of slow electrons
T_{es} - temperature of fast electrons
v_o - neutral atoms velocity
v_i - ions velocity
v_e - slow electrons velocity
v_{es} - fast electrons velocity
W_e - full energy of slow electrons
W_{es} - full energy of fast electrons
ΔW - energy of fast electrons, which goes to slow electrons after ionisation act
φ - plasma potential
$\langle\sigma v\rangle$ - rate factor for ionisation by slow electrons
$\langle\sigma_s v_s\rangle$ - rate factor for ionisation by fast electrons
$\langle\sigma_e v_e\rangle$ - rate factor for slow-fast electrons collisions
$\langle\sigma_o v_o\rangle$ - rate factor for slow electrons-atoms elastic collisions
$\langle\sigma_{os} v_{os}\rangle$ - rate factor for fast electrons-atoms elastic collisions
$\langle\sigma_i v_i\rangle$ - rate factor for slow electrons-ions elastic collisions
$\langle\sigma_{is} v_{is}\rangle$ - rate factor for fast electrons-ions elastic collisions

Introduction

To reduce costs of research and development of gas-discharge devices a closed numeric model of a chamber is desired. It should regards basic GDC processes: propellant ionisation by electrons, ions recombination on the chamber's walls, electric and magnetic fields influence on the charged particles etc. Two electrons groups ("slow" and "fast") should be used for more precise description of electrons distribution by energies. Propellant parameters (ionisation energy, ionisation and collision cross section dependence on electrons energy), chamber geometry, magnetic field, propellant mass flow, ion acceleration system transparency for ions and neutral atoms, walls potentials have to be set as model input data. One can find such models in works[5, 7]. However, several assumptions of them are rather oversimplified. For example, atoms concentration, slow electrons temperature and fast electrons energy was assumed as constants values. In this report authors tried to account these uncertainty.

Simulation model

In this report stationary case is considered, plasma waving is not taken into account. Proceeding form works[1, 2, 4], simulation model based on following assumptions:

- mean free path of atoms and ions is higher than chamber length;
- Larmor radius of ions is mach higher than chamber length;
- Larmor radius of electrons is mach higher than Debye length;
- magnetic field induction, created by discharge current, is mach less than induction from external sources;
- ionisation by collisions (radiate losses are taken into account);
- energy is income to plasma only with electrons, emitted from cathode;
- ions recombine at chamber walls only, recharging is not took into account;
- double-charged ions concentration is ignored.

Concentration and velocity vector for every particles group, temperature of electrons and plasma potential are considered. As shown in work[1], Poisson's equation can be displaced to quasi-neutral condition for all chamber value, except near-electrode layer Width of the laer can be ignored.

Following parameters should be set:

- chamber geometry
- geometry and induction of magnetic field
- walls potentials
- walls transparency for ions and for atoms
- mass inflow
- neutral atoms temperature
- fast electrons emission.

Boundary conditions are as follows:

- no mass flow through walls (or propellant inflow is given),
- wall-normal ions velocity at plasma-layer boundary is equal to Bohm's velocity,
- condition for electrons wall normal speed at plasma-layer boundary.

Software allows to change boundary condition set easily in any point, it gives the possibility to change simulating chamber parameters easily.

Calculation technique includes solving of following equations:

$$
\begin{cases}
\operatorname{div}(n_e \mathbf{v}_e) = n_o (n_e < \sigma v > + \\
\quad +(N+1) n_{es} < \sigma_s v_s >) + n_e n_{es} < \sigma_e v_e > \\
\operatorname{div}(n_{es} \mathbf{v}_{es}) = -N n_o n_{es} < \sigma_s v_s > - n_e n_{es} < \sigma_e v_e > \\
\operatorname{div}(n_o \mathbf{v}_o) = -n_o (n_e < \sigma v > + n_{es} < \sigma_s v_s >) \\
\operatorname{div}(n_i \mathbf{v}_i) = n_o (n_e < \sigma v > + n_{es} < \sigma_s v_s >) \\
\nabla m n_e \mathbf{v}_e^2 = e n_e (\nabla \varphi + [\mathbf{v}_e, \mathbf{B}]) - \\
\quad - \nabla (n_e k T_e) + n_e n_{es} < \sigma_e v_e > m \mathbf{v}_{es} - \\
\quad - n_e \mathbf{v}_e (n_o < \sigma_o v_o > + n_i < \sigma_i v_i >) \\
\nabla m n_{es} \mathbf{v}_{es}^2 = e n_{es} (\nabla \varphi + [\mathbf{v}_{es}, \mathbf{B}]) - \\
\quad - \nabla (n_{es} k T_{es}) - n_{es} (n_e < \sigma_e v_e > + \\
\quad + n_o < \sigma_s v_s >) m \mathbf{v}_{es} - \\
\quad - n_{es} \mathbf{v}_{es} (n_o < \sigma_{os} v_{os} > + n_i < \sigma_{is} v_{is} >) \\
\nabla M n_i \mathbf{v}_i^2 = -e n_i \nabla \varphi - \\
\quad - n_o (n_e < \sigma v > + n_{es} < \sigma_s v_s >) M \mathbf{v}_o \\
\nabla M n_o \mathbf{v}_o^2 = n_o (n_e < \sigma v > + \\
\quad + n_{es} < \sigma_s v_s >) M \mathbf{v}_o \\
\operatorname{div}(n_e \mathbf{v}_e W_e) = n_e (-n_o < \sigma v > E_{ion} + \\
\quad + n_{es} < \sigma_s v_s > W_{es}) - \\
\quad - n_e k T_e \operatorname{div} \mathbf{v}_e + e n_e (\mathbf{v}_e \nabla \varphi) + \\
\quad + n_o n_{es} < \sigma_s v_s > \Delta W \\
W_{es} - e\varphi = const \\
n_e + n_{es} = n_i
\end{cases}
$$

Square residual sum minimisation method is used for equation system solving.

Describing method carries out following distributions on chamber space: densities and velocities of all particles groups, temperatures of electrons, electric potential. So, it can evaluate parameters of real gas-discharge devices (for example at designing period).

Results

50mm diameter ion thruster[6] designed in MAI and Keldysh Centre have been chosen for tests. Thruster has divergence magnetic field and ion-accelerating system based on perforated disks. It scheme is shown in fig.1.

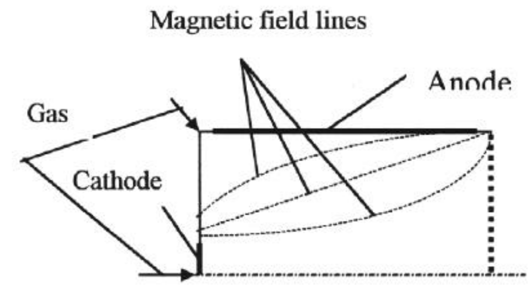

Fig. 1.

Simulation results in comparison with experimental data are given in table 1.

Table 1.

Parameter	Simulation	Experiment
Discharge current, A	0.57	0.57
Ion beam current, A	0.058	0.07
Propellant utilisation	0.58	0.7
Ion cost, W/A	394	343

Figure 2 shows the electric potential distribution in chamber space.

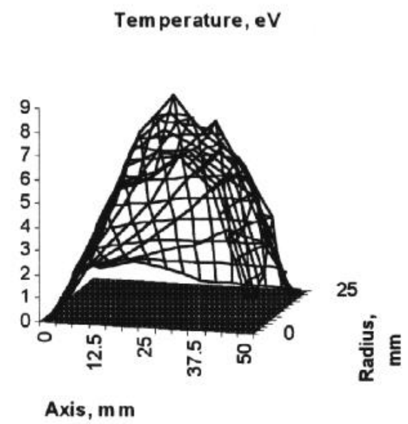

Fig. 2

A set of calculations for several design features has bean carried out. For example, fig. 3 and fig. 4 shows dependencies of discharge current and coefficient of propellant utilisation on magnetic polepiece radius. Dependencies of the same parameters from anode length are presented in fig. 5 and fig. 6. So, model allows to simulate design changes and to forecast it influence on ion thruster characteristics.

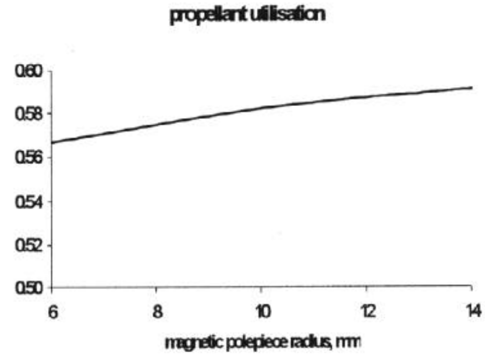

Fig. 3

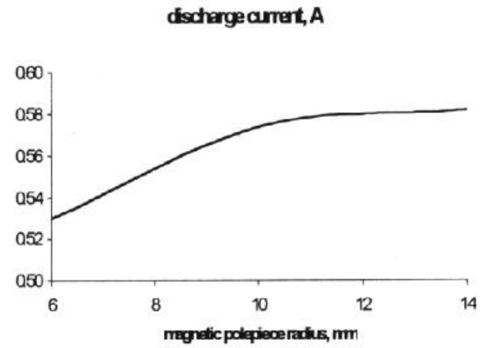

Fig. 4

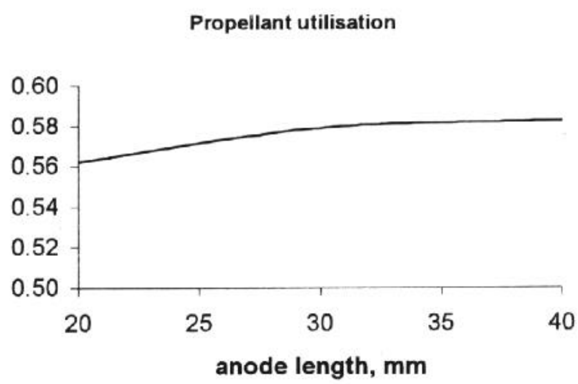

Fig. 5

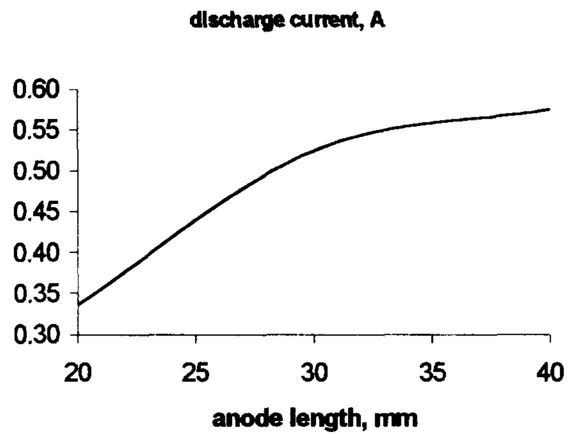

Fig. 6

Conclusion

1. Simulation model of ion thruster GDC plasma parameters has been created.
2. Computer code, based on this model, has been developed and tested.
3. GDC plasma simulation has been carried out for several modes. Numeric results match experimental data well.

Reference

1. Морозов А.И. Объемные электростатические поля в плазме // Плазменные инжекторы и ионные ускорители. Под ред. Козлова Н.П., Морозова А.И. сс. 82-106 М. Наука. 1984
2. Морозов А.И. Физические основы космических электроракетных двигателей. Т.1: Элементы динамики потоков в ЭРД. М. Атомиздат, 1978. 328 с.
3. Обухов В.А., Григорьян В.Г., Латышев Л.А. Источники тяжелых ионов // Плазменные инжекторы и ионные ускорители. Под ред. Козлова Н.П., Морозова А.И. сс. 82-106 М. Наука. 1984
4. Протасов Ю.С., Чувашев С.Н. Физическая электроника газоразрядных устройств. Плазменная электроника. Т 1, 2. М. Высшая школа. 1993. 496 с.
5. Y. Arakawa, K. Ishihara. A Numerical Code for Cusped Ion Thrusters. IEPC-91-118. Viareggio. Italy, October 1991.
6. Gorskov O.A., Grigorian V.G., Kanev S.V., Minakov V.I., Muravlev V.A. An Ion Engine For Small Satellites. IEPC-95-94. Moscow, 24th International Electric Propulsion Conference. 1995
7. M. Hirakawa, Y. Arakawa. Plasma Particle Simulation in Cusped Ion Thrusters. IEPC-93-242.