A study of some physical processes in Hall Thruster, operated in the discharge voltage up to 1000 V

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Abstract: To find a ways of Hall thruster (HT) modernization (by extension of a discharge voltage range) some key problems have been allocated and studied. Periodic azimuthal heterogeneous luminescence of plasma, which exist in area the cathode - an edge of discharge chamber (DC) and reflect azimuthal heterogeneity of plasma potential have experimentally registered and influence of these heterogeneity on electron movement have been studied by method of numerical modeling. Experiments were carried out with HT type of SPT M-70 in a nominal mode. Three-dimensional mathematical model of processes have developed based of Monte-Carlo method for numerical experiments. The basic features of electron movement in area the cathode – an edge of DC have determined. One-dimensional hydrodynamic mathematical model of processes in HT discharge interval have developed and potential drop on separate sites of this interval have determined while a discharge voltage vary up to 1000 V. HT efficiency and a specific impulse have determined. Some reasons of HT efficiency reducing at increasing of a discharge voltage were analyzed.

Nomenclature

B	=	magnetic induction
E	=	electric field strength
e	=	elementary charge
I	=	current
I_{sp}	=	specific impulse
F_T	=	thrust
M, m	=	ion and electron mass
n	=	concentration
U	=	discharge voltage
V	=	velocity
σ	=	cross-section of some process
ε	=	energy
φ	=	potential of electric field
η_T	=	thrust efficiency

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I. Introduction

Within many decades, researches are carried out to expand a range of a Hall thruster (HT) discharge voltage up to 1000 V. 700V firing tests of SPT-100 executed in the middle of 90s had demonstrated absent of thrust efficiency increase in spite of voltage increase[1]. Next tests[2, 3] have shown that thrust efficiency decrease with increasing of discharge voltage up to 800…1000V. One of key questions of HT perfection is a problem of potential drop determining in a discharge interval and influence of plasma fluctuations (especially in an azimuthal direction) on HT characteristics. As is shown, the considerable part of ionized and accelerated processes is concentrated outside discharge chamber[4, 5]. It is clear potential distribution depends on such spatial location. However, the basic regularities of potential distribution were not investigated enough. In addition, reasons determining the occurrence of potential heterogeneity in an azimuthal direction of HT plasma flow and influencing on conductivity of electrons are not investigated enough.

II. Research areas of the discharge interval

The following research areas are determined in HT discharge interval (Fig. 1). They are: 1) an experimental researches of azimuthal plasma heterogeneity in zone the cathode-neutralizer (CN or cathode) - edge of discharge chamber (DC); 2) study of electron movement regularity in the cathode - edge of DC zone taken into account an electric field azimuthal component; 3) the calculation of potential drop in various zones of the discharge interval between anode and cathode.

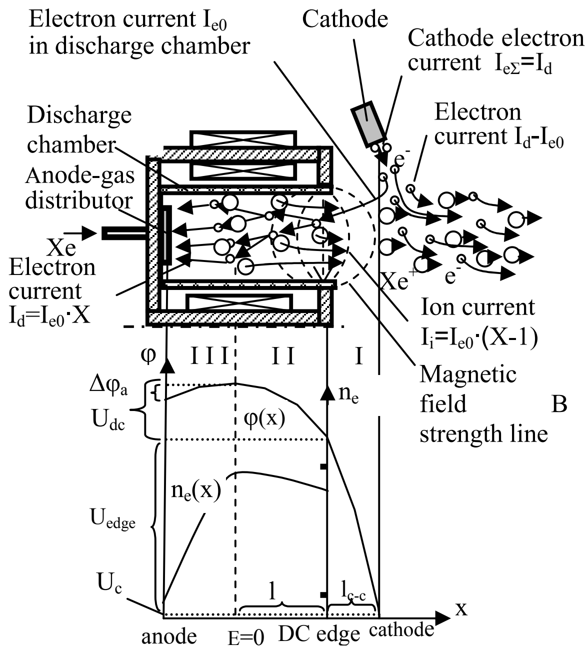

Figure 1. HT scheme. Electron flow distribution. Distribution of potential drop in zone (I, II, III) of the discharge interval.

A. An experimental research of an azimuthal plasma heterogeneity in zone I

It was experimentally established existence (Fig. 2) of azimuthal heterogeneity in plasma flow[6]. The azimuthal extension of these areas is estimated as $L \sim 10^{-2}$ m. It is clear this heterogeneity can increase electron conductivity in a plasma flow. It should be taken into account for determination of intra thruster regularities.

To determine possible "mechanisms" of electrons conductivity the plasma fluctuations close to the DC edge were investigated on HT M-70 type operated in a nominal mode (on voltage and mass flow rate). It was observed, that the plasma zone extended along HT axis with non-uniform brightness of a luminescence as is shown in Fig. 2.

Due to the existence of areas of charges heterogeneities in an azimuthal direction (Fig. 2.) an occurrence of opposite azimuthal components of an electric field E_y is possible. The extent of areas, in which charges concentration of electrons and ions is increased, is estimated as visual distance of $L \sim 10^{-2}$ m, amplitude of potential drop $\varphi_{max} \sim \varepsilon_e$ – electron energy, the intensity of the induced electric field in an azimuthal direction is $E_y \approx \varphi_{max}/L$. The picture of charges distribution, as well as the scheme of prospective process, is shown in Fig. 3, where there is a field $E_Y \sim 10^3$ V/m in an azimuthal direction, that make electron drift along E_X field in discharge chamber. Analyzing of possible mechanism of electrons conductivity, these fluctuations should be taken into account as the additional factor, which increase electron conductivity longwise discharge interval due to drift V_{drX}.

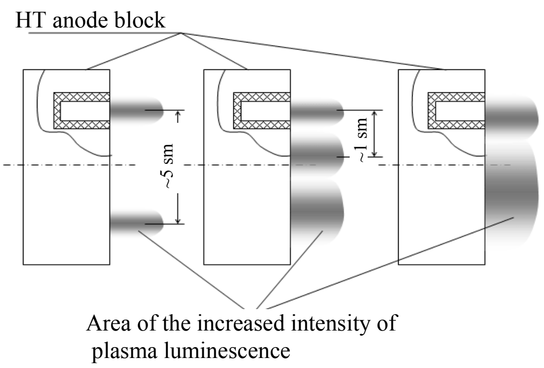

Figure 2. Azimuthal heterogeneous luminescence of plasma

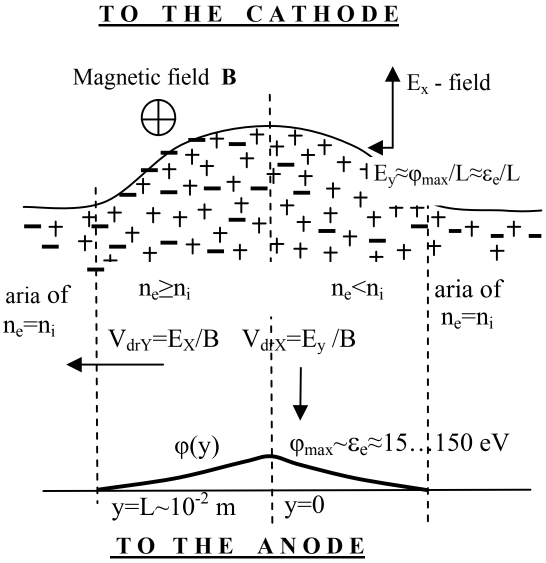

Figure 3. Possible polarization of plasma charges in the area of non-uniform concentration – seen as area of the increased intensity of plasma luminescence.

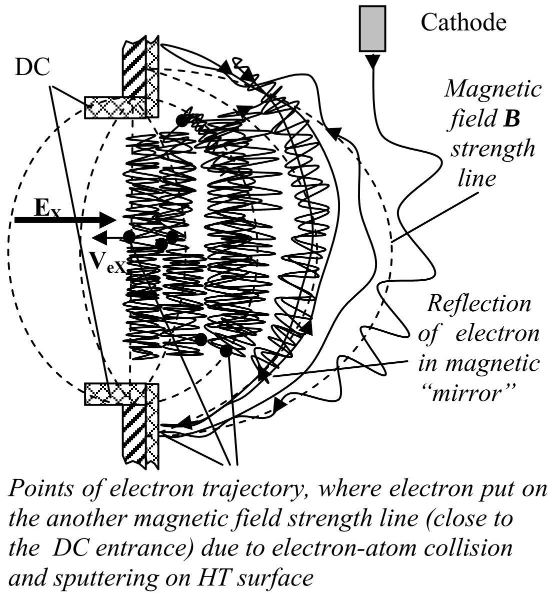

Figure 4. Features of electron drift movement in the cathode – edge of discharge chamber area.

B. Research of processes in zone I

The features of an electron movement in zone I (Fig. 4) was studied by Monte-Carlo method modeling.

The following boundary conditions were taken: potential drop in modeled area U_{dc}, cathode - $\dot{m}_c$ and anode - $\dot{m}_a$ mass flow rate, temperature - T_e of electrons emitted by the cathode. Forms of the distribution of magnetic and electric fields were taken according to the experimental researches[6], but the value of potential drop was calculated.

Analysis of calculated results specifies the following: 1) distributions of electron concentration and energy at the DC edge is non-uniform with increasing (more than twice) to the DC centerline; 2) the mechanism of electron conductivity, caused by a periodic azimuthal electric field (Fig. 2) can increase conductivity of zone I up to 5 %.

III. Hydrodynamic model for HT local and integral characteristics calculation (HMT)

A. Assumptions and the simplifications of the modeling

1) The one-dimensional model of processes in HT discharge interval is assumed.

2) The following parts of potential drop presented in Fig. 1 and 5 are included in HT discharge interval. (1) Magnetic system with potential drop U_{MS}; (2) A HT discharge interval with potential drop U_d; (3) Area of plasma from CN up to DC edge with potential drop U_{en}; (4) Potential drop U_c on CN; (5) Area inside DC - from DC edge up to the anode-gas distributor. The last part is in turn divided into two sites: a) a zone of ionization and acceleration (ZIA) - from DC edge up to section in which intensity of an electric field is reduced up to zero, with potential drop U_{zia}; b) area close to the anode - from the anode-gas distributor prior to the beginning of ZIA with negative potential drop $\Delta\varphi_a$.

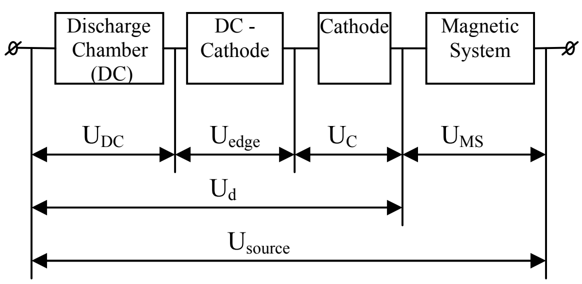

Figure 5. Potential drop on HT discharge interval.

3) Among non-elastic processes electron-atom ionization collisions are taken into account only, and expenses of energy for excitation are taken into account by constant.

4) Neglect influence of fluctuations in plasma on processes of atom ionization and acceleration of ions.

In Fig. 6 the schema of distributions of fields and atom concentration $n_a(x)$ is resulted. The characteristic kind (form) of these distributions is set, but absolute values of electric E and magnetic B fields are determined by value of potential drop on a corresponding site and by value of a discharge current (for a magnetic field in a case if the magnetic coil is included in a circuit of the discharge).

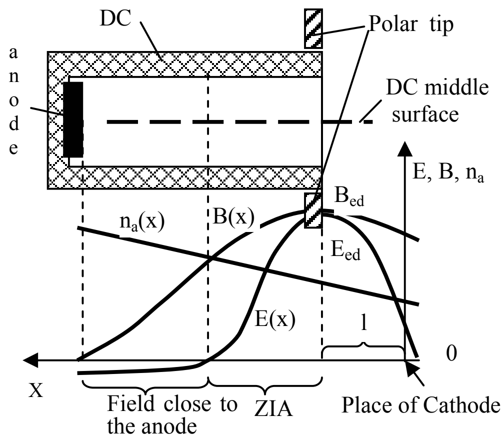

Figure 6. Characteristic distribution of electric E and magnetic B fields, n_a - atom concentration (before discharge) in HT discharge interval.

B. Research of processes in zone I

A study of electron movement features carried out on the previous stage of researches has shown that electron drift movement in an azimuthal direction have significant thermal component of velocity. This component of velocity (along a magnetic field force line) is got because of dispersion on small corners at Coulomb collisions. Displacement into direction of a DC input can be caused by at transition of an electron to other magnetic field force line after dispersion on DC surface. As approaching DC entrance electrons collect energy in an electric field and can be reflected in magnetic “mirror” of a magnetic tip with preservation of “magnetic moment”. Such reflection can occur without collision with DC wall. Thus, "transition" of an electron to other force line is probable after dispersion in the big corner caused by Coulomb collision that is improbable, or after dispersion caused by collision with a molecule of gas.

By development of model it was assume, that the electrons emitted by CN and have reached DC, pass area CN - DC edge (Fig. 1) mainly due to elastic atom collisions - being displaced at each collision to DC edge on size $h_c=2\cdot R_l$ (height of a cycloid equal to twice Larmor radius) with probability $P_c\approx0.5\text{-}0.8$.

Then the resulted probability P, that electron emitted cathode have reached DC (due to elastic collisions with atoms)

$$P=(P_c)^{N_{min}}, \tag{1}$$

where: $P_c=f(\varepsilon_e)$ - probability that electron (ε_e - energy) was displaced on a height of a cycloid $h_c=2\cdot R_l$ to an DC entrance due to collision with atom; N_{min} - a minimum quantity of electron-atom collisions, necessary to reach DC at the $l_{c\text{-}c}$ distance from cathode

$$N_{min}=\int_0^{lc\text{-}c}\frac{dx}{h_c},\quad N_{min}\approx\frac{l_{c-c}\cdot\overline{B_{en}}\cdot\sqrt{e}}{2\cdot\sqrt{2\cdot m\cdot U_{en}}}, \tag{2}$$

where U_{en}, $\overline{B_{en}}$ are potential drop and average magnetic induction between CN and DC entrance.

Azimuthal drift velocity $V_{dr.en}$ on the DC entrance is determined by the electron kinetic energy, assuming that electrons reache DC mainly due to elastic collisions

$$V_{dr.en}=\sqrt{U_{en}\cdot 2\cdot e/m}\cdot \tag{3}$$

Choosing the stream of electrons reached DC I_{e0}/e from total electron stream I_d/e the following expression can be obtained.

$$I_{e0}=I_d\cdot(P_c)^{N_{min}}. \tag{4}$$

Axial electron velocity V_{eXen} at DC entrance was determined as follow.

$$V_{eXen}=V_{dr.en}\cdot\sigma_\Sigma\cdot n_{a.en}\cdot h_{c.en}\cdot P_c, \tag{5}$$

where $V_{dr.en}$ - drift velocity; σ_Σ - total collision cross-section; $n_{a.en}=n_{DC.en}+n_{cathode.en}$ - atom concentration and $\dot{m}_c$ - cathode and $\dot{m}_a$ - anode mass flow rate respectively.

To calculate atom concentration $n_{DC.en}$ on DC edge next processes and regularities were taken into account: "burning out" of atoms owing to ionization in DC; $\dot{m}_a$ /M/S - atom stream through the DC area of cross-section S; $V_{a.en}\sim(k\cdot T_{DC}/2/M)^{1/2}$ - longitudinal velocity of atom movement to the DC exit ($T_a\approx700\ldots1000$ K); (I_d/e - I_{e0}/e) - stream of ions on DC edge.

$$n_{DC.en}=\frac{\dot{m}_a/M-(I_d-I_{e0})/e}{V_{a.en}\cdot S}. \tag{6}$$

C. Modelling of processes in zone I I - atom ionization and ion acceleration zone (ZIA)

The coordinate system is located so, that on DC edge x=0, and electric field strength E=0 at the x=l.

The anode discharge current I_d represents the electron current I_{e0} at DC edge abruptly increased in ZIA.

$$I_d=I_{e0}\cdot X,\quad X=\exp\left(\int_o^l\alpha(x)\cdot dx\right), \tag{7}$$

where $\alpha(x)$ - number of ionization collisions per unit of length lengthways an axis X

$$\alpha(x)=n_a(x)\cdot\sigma_i\cdot\frac{V_{dr}(x)}{V_{eX}(x)}. \tag{8}$$

where: σ_i - ionization cross-section; $V_{dr}(x)=\sqrt{2\cdot e\cdot\varepsilon_e(x)/m}$ - drift and $V_{eX}(x)$ - axial electron velocities (energy $\varepsilon_e(x)$) on distance x from an DC edge, $V_{eX}(x)$ was determined likely Eq. (5).

Concentration $n_a(x)$ in any section at distance x was calculated as

$$n_a(x)=\frac{\dot{m}_a}{M\cdot V_a(x)\cdot S}-\frac{I_d-I_{e0}\cdot\exp\left(\int_0^x\alpha(x)\cdot dx\right)}{M\cdot V_a(x)\cdot S}, \tag{9}$$

Energy of an electron $\varepsilon_e(x)$ in running site on distance x from DC edge was determined by balance

$$\partial(q_e\cdot\varepsilon_e(x))/\partial x=q_e\cdot E(x)-Q_{i.e.}(x), \tag{10}$$

where: $q_e\cdot E(x)=V_e\cdot n_e\cdot E(x)$ – energy flux collected by electrons during their movement in an electric field E(x); $Q_{i.e}(x)$ – energy flux spent for atom ionization and excitation.

Electron - $n_{e.en}$ and ion - $n_{i.en}$ concentrations are equal and are determined at DC entrance (edge)

$$n_{i.en}=\frac{I_i}{V_{i.en}\cdot e\cdot S}=\frac{I_{e0}\cdot(X-1)}{V_{i.en}\cdot e\cdot S}=n_{e.en}=\frac{I_{e0}}{V_{eXen}\cdot e\cdot S}, \tag{11}$$

where $V_{i.en}$ - ion velocity at DC edge and V_{eXen} - axial electron velocity.

Balance of the HA discharge interval voltage

$$U_d=U_c+U_{en}+U_{dc}-\Delta\varphi_a. \tag{12}$$

Processes in the cathode was not studied separately and cathode potential drop U_c was set as

$$U_c=20+(I_d-4)^2. \tag{13}$$

D. Modeling of processes in zone I I I (close to the anode)

It is admitted an invariance of streams (Fig. 7)

$$n_{ia}\cdot V_{ia}=n_{i0}\cdot V_{i0},\ n_{ea}\cdot V_{ea}=n_{e0}\cdot V_{e0}, \tag{14}$$

where $n_{ia,0}$, $n_{ea,0}$, $V_{ia,0}$, $V_{ea,0}$ – ion and electron concentrations and velocities as shown in Fig.7.
In view $\Delta\varphi_a >> \varepsilon_{a.gener}$ – initial ion energy (equal to atom energy)

$$\frac{V_{i0}}{V_{ia}} = \sqrt{\frac{\varepsilon_{a.gener}}{\Delta\varphi_a}}, \quad \frac{V_{ea}}{V_{e0}} = \frac{n_{e0}}{n_{ea}} = \frac{n_{i0}}{n_{ia}} = \sqrt{\frac{\Delta\varphi_a}{\varepsilon_{a.gener}}}, \tag{15}$$

Where $\Delta\varphi_a$ – potential drop in field close to the anode.

Diffusion electron movement to the anode in an electric field, which interferes with their moving (Fig. 6), is determined by collisions with DC walls. Axial electron velocity is determined

$$V_{e0} = \frac{j_{e0}}{n_{e0}} = D_{e0} \cdot \frac{dn_{e0}}{dx} \cdot \frac{1}{n_{e0}}, \quad D_{e0} \sim l_{free} \cdot V_h \tag{16}$$

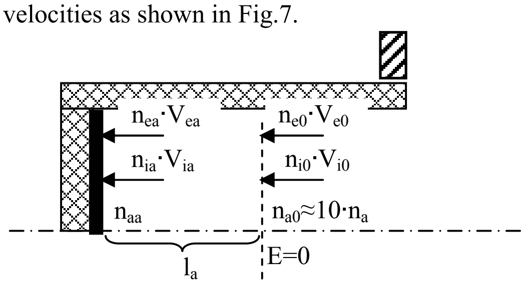

Figure 7. Electron and ion streams close to the anode area. Potential and concentration distribution in this zone are shown in Fig. 6

Where j_{e0} – diffusion electron stream to the anode due to electrons dispersion on DC walls; $l_{free}=h_c=2R_l$ – electron run length between dispersion; $V_h=h_c/\tau_{collis0}$ – equivalent of chaotic velocity, taking $\tau_{collis0}=b_к/V_{dr0}$ and $b_к$ – DC channel width. Estimating a ratio $dn_{e0}/(dx \cdot n_{e0}) \approx l_a/2\text{-}l_a$ (Fig.1), axial $V_{e0,a}$ and drift V_{dr0}, V_{dra} electron velocities determined by electron energy ε_e were calculated as

$$V_{e0,a} = \frac{V_{dr0,a}{}^3}{e \cdot 2 \cdot b_k} \cdot \left(\frac{m}{e \cdot B_{0,a}}\right)^2, \quad V_{dr0} \approx \sqrt{\frac{\varepsilon_{e0}}{3} \cdot \frac{2 \cdot e}{m}}, \quad V_{dra} = \left(V_{dr0}{}^2 - \frac{\Delta\varphi_a \cdot 2 \cdot e}{m}\right)^{1/2}. \tag{17}$$

Value $\Delta\varphi_a$, necessary for balance of discharge voltage Eq. (12), was calculated by

$$\frac{\left(V_{dr0}{}^2 - \frac{\Delta\varphi_a \cdot 2 \cdot e}{m}\right)^{3/2}}{V_{dr0}{}^3} \cdot \left(\frac{B_0}{B_a}\right)^2 = \sqrt{\frac{\Delta\varphi_a}{\varepsilon_{a.gener}}}, \tag{18}$$

where $B_{0,a}$ – magnetic induction in aria as shown in Fig. 6 with subscripts as shown in Fig. 7.

IV. Calculation of HT integral characteristics

Volt-ampere characteristic of HT is determined by calculation of Eqs. (2 - 18). Among them as the final solution take those, for which the value of a discharge current is maximal

Thrust F_T was determined as

$$F_T = \int_0^l \left(\sqrt{\left(\int_0^x E(y) \cdot dy + U_{en}\right) \cdot \frac{2 \cdot e}{M}} \right) \times \left\{ \exp\left(\int_0^{x+dx} \alpha(y) \cdot dy\right) - \exp\left(\int_0^x \alpha(y) \cdot dy\right) \right\} \cdot \frac{I_{e0}}{e} \cdot dx / l \tag{19}$$

Where l – length of zone of ionization and acceleration as was shown in Fig. 1, U_{en} – potential drop between cathode and DC edge,

Specific impulse I_{sp} and thrust efficiency η_T was calculated by

$$I_{sp} = \frac{F_T}{\dot{m}_c + \dot{m}_a}, \quad \eta_T = \frac{F_T{}^2}{2 \cdot U_d \cdot I_d \cdot (\dot{m}_c + \dot{m}_a)}. \tag{20}$$

As a test, HT integral characteristics (Fig. 8 and Fig. 9) of model M-70 have been calculated at the nominal parameters of the discharge mode: the Xe mass flow rate through cathode-neutralizer - 0.3 mg/s; through the anode-gas distributor - 2.5 mg/s. Cathode-neutralizer is located on the distance of 7 mm from a DC edge. Magnetic coils are included in a discharge circuit. To estimate accuracy of modeling, in the same figures experimental HT (SPT M-70) integral characteristics are resulted. The deviation of settlement and experimental dependences of a discharge current (Fig. 9) reflect inexact determination of the mechanism of electron conductivity in a site cathode-neutralizer - an input in the HT discharge chamber.

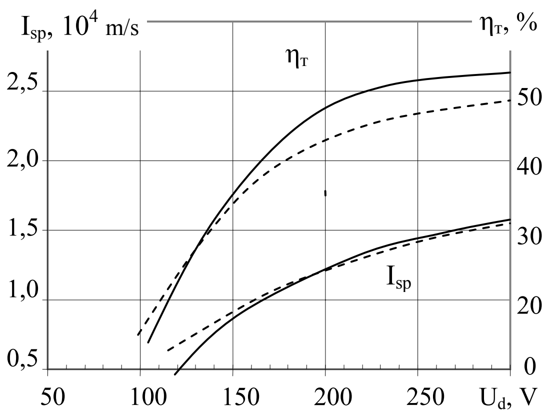

Figure 8. Specific impulse I_{sp}, total thrust efficiency η_T of SPT M-70 at stationary mode depended on discharge voltage U_d.
—— Calculation on HMT.
- - - - Experiment.

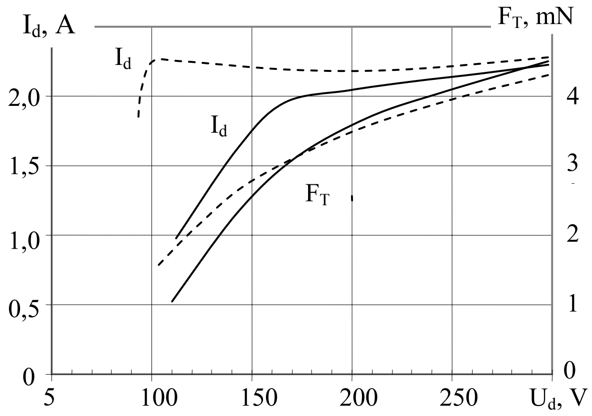

Figure 9. Volt-Ampere characteristic and thrust F_T of SPT M-70 type at stationary mode.
—— Calculation on HMT.
- - - - Experiment.

Calculation of HT integral characteristics over the range of discharge voltage up to 1000 V has been carried out under the same conditions, as for testing. To find out the reasons of change of HT efficiency, the potential drop on two sites have been calculated: from CN up to DC edge and within DC (Fig. 10).

The relation of an ion current to an electron current emitted by CN and penetrated in DC have been calculated and drawn by bold continuous line in Fig. 11, were experimental data have been drawn by interrupted line. The analysis of results of calculation (Fig. 10, 11, 12) allows to results that at increasing of discharge voltage U_d the potential drop on site CN – DC edge increases that lead to Larmor electron radius increasing and, so, cause the increasing of conductivity of site CN – DC edge and to the significant increasing of an electron current into DC. Thus, electric capacity increases (that is not compensated by thrust increasing) and overall HT performance is reduced. The increasing of an electron current in DC can be limited by increasing of a magnetic field radial component in discharge interval of HT.

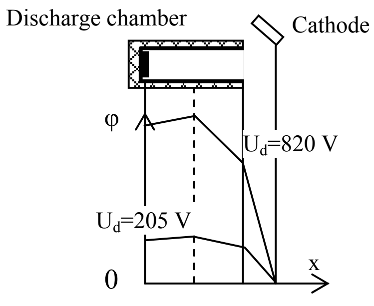

Figure 10. Distribution of potential drop in various zone of SPT M-70 discharge interval.

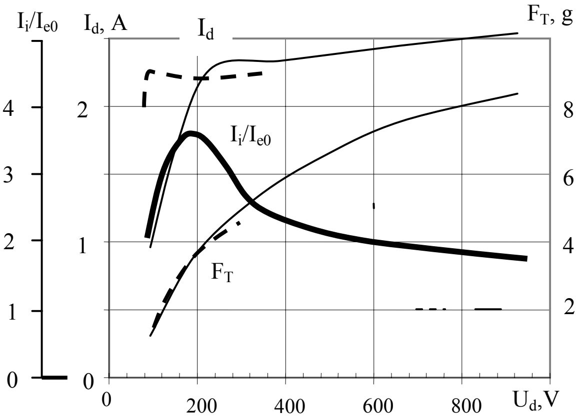

Figure 11. V-A characteristic, thrust F_T, I_i/I_{e0} relationship between ion I_i and electron I_{e0} current of SPT M-70 depended on discharge voltage U_d.

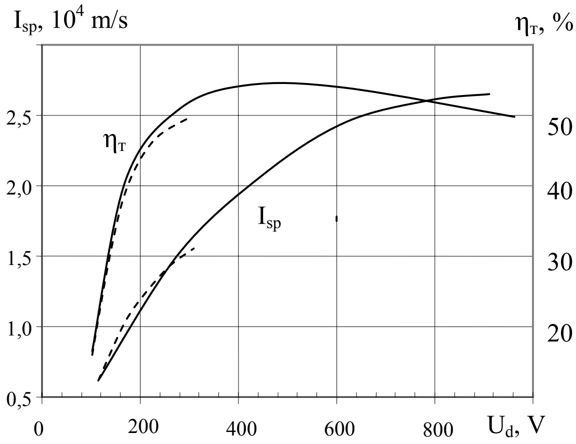

Figure 12. Specific impulse I_{sp} and thrust efficiency η_T of SPT M-70 vs. discharge voltage U_d.

— Calculated data

- - - Experimental data

V. Conclusion

Periodic azimuthal heterogeneous luminescence of plasma has been experimentally registered in area the cathode – the edge of discharge chamber. Such effect demonstrates heterogeneity of potential in azimuthal direction. It was resulted on the base of numerical modeling that electron reaches discharge chamber entrance mainly due to elastic electron-atom collision. Electron dispersion on HT surfaces close to the discharge chamber entrance can affect electron mobility cross magnetic field. Periodic azimuthal component $E_y \sim 10^3$ V/m can affect electron mobility cross magnetic field and increases conductivity up to 5 %. It was calculated that largest part of the discharge voltage could be concentrated outside of HT discharge chamber. Thrust efficiency decrease since 500 V over the analyzed range of input parameters owing to increasing of an electron current from cathode-neutralizer through a discharge interval. Some increase of thrust[3] cannot compensate such negative process.

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