INVESTIGATION OF NEAR-CATHODE AREA OF 5-CM ION THRUSTER: A CURRENT STATE OF WORK

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Abstract

Ion thrusters as electric propulsion with a maximum specific impulse provide the greatest economy in fuel, resulting in opening up opportunities for their effective application on the small spacecraft. The investigation of physical processes, taking place in near-cathode area of these thrusters, and subsequent optimisation of its geometry, would give the possibility to increase thruster propellant utilisation efficiency and to decrease the discharge voltage – one of the critical operation parameters. This paper presents some integral characteristics and results of calculation and measurement of magnetic field of 5-cm ion thruster when varying the geometry of near-cathode area. Preliminary work to realise the system of probe measurement in coupling plasma is also described.

Introduction

One of the leading tendencies of up-to-date space activity in the world is a sharp expansion of activities on creation and use of the small spacecraft with a mass less than 1000 kg. Low-power electric propulsion may find its application on small communication and remote sensing spacecraft for countering of outside disturbances, orbit correction, maintenance of orbital structure of satellite constellations, etc. Thrusters with accelerating in electric field are considered to be the most perspective for these tasks realisation. There are some problems that face the designers and investigators of mentioned thrusters. Among the problems concerning optimisation of working processes is the electron transition to the main discharge. Transition is occurred in so-called near-cathode area that is the subject of present research. As an investigation object the 5-cm ion thruster was chosen.

It was investigated at the working range of power between 50...150 W. Thruster output parameters for this power range without taking into account the power and mass losses in cathode-neutraliser are: specific impulse 3100...3700 s, thrust 1...5 mN, efficiency 0.5...0.6.

Thruster description

Conventional Kaufman-type ion thruster with anode diameter of 52 mm† was used in this work. Thruster principal schematic is shown in Fig. 1. Backplate 1, cylindrical shell 2 and electrode holder 3, on which the screen grid 4 is fixed, form thruster discharge chamber. The cathode unit 5 and ring-shaped collector-gas distributor 6 are fixed to the backplate. The main discharge is set up between the axial hollow cathode 7 and the cylindrical anode, fixed on the shell with three insulators 9. The propellant – xenon – is supplied to the discharge chamber by two channels: through hollow cathode and collector 6. To prevent the primary electrons from travelling directly to the anode, the discharge chamber is put to the axial divergent magnetic field. It is generated by six solenoids 10, situated around the shell, and concentrated by cathode 11 and anode 12 polepieces. The magnetic circuit is formed by backplate of discharge chamber and electrode holder of screen grid. Plasma generated during ionisation in discharge chamber, flows to the ion extraction system, which for triple-grid design consists of screen 4, accelerator 14 and decel grids (decel grid is made together with thruster plasma shield and is not shown in Fig. 1). Here positively charged ions are extracted and accelerated to velocities of about 30-50 km/s by electric fields, applied between the grids. Positive space charge of extracted ions is neutralised by electrons, drawn to the beam from cathode-neutraliser that has the same design as the main cathode.

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Experiment and results

Ion thruster degree of perfection depends on perfection and effective operation of its main units: cathode unit, ion extraction system, discharge system and cathode-neutraliser. One of the promising ways to improve the laboratory model of 5-cm ion thruster can be the optimisation of its near-cathode area. This area strongly influences the diffusion of primary (fast) electrons, its distribution in volume of discharge chamber and, therefore, the effective ion production. The investigation of physical processes, taking place in near-cathode area, and subsequent optimisation of its geometry, would give the possibility to increase thruster propellant utilisation efficiency and to decrease the discharge voltage — one of the critical operation parameters.

The near-cathode area of ion thruster can be defined as area limited by cathode position and baffle disc or edge of polepiece if baffle is absent. In this laboratory model the cathode polepiece forms not only the geometrical dimensions of near-cathode area but also the configuration of magnetic field in the main volume of discharge chamber. Thus, it exerts complex influence on electrons input from the hollow cathode and its following diffusion to anode in discharge chamber volume. Beside cathode polepiece, its length and external and internal diameters, cathode position and dimensions of cathode baffle disc form the geometry of near-cathode area.

In this investigated laboratory model baffle was not used.

All experiments were carried out in Keldysh Research Center. The volume of vacuum chamber was 1.2 m$^3$, residual gas pressure — not worse than 2·10^{-5} torr (by air).

Near-cathode area geometry and volume variation

In conducted experimental series the variation of some integral characteristics of 5-cm ion thruster as functions from volume and geometry of near-cathode area were investigated. To realise it the variations of cathode position relative to cathode polepiece edge and dimensions of polepiece were carried out. Cathode position variation was realised by moving the whole cathode unit, thus the geometry of space between cathode and keeper remained invariable. The measurements were conducted at constant propellant flow rates. The experiments with cathode position variation were conducted using ion extraction system made from flat perforated plates and experiments with cathode polepiece dimensions variation — using slit-type ion extraction system. During the first part of series the potentials of screen and accelerator grids remained invariable and were 1200 V and —800 V. In the second part the potential of screen grid was kept constant (900 V) and potential of accelerator grid was varied to provide the minimal current on it.

The following distances between cathode and cathode polepiece edge were chosen: 10 mm, 15 mm, 20 mm and 25 mm. The dimensions of used cathode polepiece were: full length - 18 mm, operation length - 16 mm, internal diameter - 21,5 mm, external - 23,5 mm. In Fig. 2-4 the ion production cost as a function of propellant utilisation efficiency is shown for four cathode positions and currents in electric magnet coils equal to 2 A, 3 A, 4 A. (The values of ion production cost are in arbitrary units because ion extraction system used in this series was unconventional. They are qualitative and comparative in character.) From these plots it is seen that the most ineffective distance between cathode and polepiece edge is 10 mm. Therefore, further decrease of this distance would not have sense. Other three positions give approximate results, which are within measurement error zone, though 20-mm distance looks preferable. Besides, it is evident that the best results were achieved at magnet current equal to 4 A (this fact was confirmed by previous investigations, during which it was also obtained that further increase of magnet current led to excessive heating of coils). Magnet current decrease resulted both in characteristic deterioration and in insignificant difference between the plots, obtained for various cathode-polepiece edge distances. Such a difference also disappeared for plots obtained at various magnet currents if the mentioned distance is 15 mm or 10 mm.

After that the experiments with two different cathode polepieces were conducted. In this case molybdenum hollow cathode was substituted on niobium one and perforated ion extraction system — on slit-type system. The dimensions of cathode polepieces correspondingly were: first — full length 18 mm, operation length 16 mm, internal diameter 21.5 mm, external — 23.5 mm; second — full length 12 mm, operation length 10 mm, internal diameter 21 mm, external — 24 mm. For the first case the distance between cathode and polepiece edge was 20 mm, for the second — 14 mm. Therefore, in accordance with results of first part of experimental series such decrease in near-cathode area volume should not have a vital importance for integral characteristics, specifically for ion production cost - propellant utilisation efficiency relation. On the other hand, cathode position relative to discharge chamber elements remained invariable. Changes occurred only in magnetic circuit of the thruster.

In Fig. 5 the plots of ion production cost as a function of propellant utilisation efficiency are presented for these two cases. From its comparison it is seen that first cathode polepiece use led to considerably better thruster performance than for "short" polepiece case. Such a situation existed within the whole range of
total mass flow rate (70...110 eq.mA). Cathode flow rate was 30 eq.mA since it has been obtained that it is optimal value for this cathode. Magnet current was equal to 4 A.

Therefore, it can be preliminary concluded that there is a noticeable change of thruster integral parameters with variation of volume and geometry of near-cathode area and, probably, magnetic field in thruster volume. The last circumstance concerns not only magnet current variation that has been obtained previously but also change of magnetic system configuration.

**Magnetic field modeling**

So far as it was mentioned that cathode polepiece forms not only the geometrical dimensions of near-cathode area but magnetic field configuration then the next stage of investigation was obtaining the magnetic field map in discharge chamber of ion thruster. This map would probably give the possibility to estimate field influence on thruster parameters.

For this work software “MAGNET” was used\(^2\). The distribution of magnetic field lines and change of magnetic induction in thruster volume were calculated for three values of magnet current (2A, 3A, 4 A) and two cathode polepieces used. In Fig. 6, 7 the distributions of magnetic field lines for two cathode polepieces at magnet current equal to 4 A are shown. Calculated data were compared with measured ones\(^3\), \(^4\). Its similarity allowed concluding that these calculations might be applied to analysis of magnetic field distribution in discharge chamber of 5-cm ion thruster.

The calculations indicated that field lines were distributed in near-cathode area in such a way that the value of transversal component of magnetic induction vector was 100-120 Gauss in the vicinity of cathode polepiece edge, i.e. in the place where baffle has previously been mounted. Taking into account that estimated value of electron cyclotron radius for this range of magnetic induction is less than 1 mm, then some failures with baffle installation on previous stages of work might be explained by blocking up the part of electrons by magnetic field in baffle annulus. Therefore, the selection of baffle dimensions and its positioning should be coordinated with existing magnetic field. It can be also noted, that there is some difference in field lines distribution at cathode polepiece substitution. The value of magnetic induction in the case of longer polepiece was average 15-20 % higher than for “short” one at the same distances from cathode polepiece edge and at the same magnet currents. As a whole this value did not exceed 200 Gauss with the exception of narrow layers (~ 2.5 mm width) around the poles of magnetic system where field was strong but it did not considerably influence the travelling of plasma electrons. From obtained data it is still difficult to understand how changes in magnetic field led to improvement of thruster parameters.

**Probe measurements**

Based on described experimental results the investigation of plasma parameters in near-cathode area and discharge chamber was recognised as expedient. As a basic method of investigation it is considered to use probes method of diagnostics, which gives the possibility to obtain sufficiently accurate idea about distribution of electron concentration and energy and about distribution of potentials in plasma.

According to existing data and engineering estimations the single cylindrical Langmuir probes with tip diameter of 0.5 mm and length of 5 mm are chosen. The probes are made from tungsten wire, packed in ceramic isolation. For effective measurements it is proposed to make a comb of probes and to conduct the parallel measuring in 3-4 points. To realise it, the unit for probe motion with positioning accuracy of 0.1 mm and high level of motion smoothness was designed and manufactured. Measuring duration was estimated according to calculation of probe heat condition. In this calculation it was required that emission current from probe should not exceed 10 % from current on probe. Actually it meant that the temperature of operation part of probe material should not exceed its melting point. In this calculation the probe was assumed as half-bounded body at \( T_o \), which bounding surface was heating by constant flux \( q_e = \text{const} \). Then:

\[
\frac{\partial}{\partial \tau} T(x, \tau) = a \frac{\partial^2}{\partial x^2} T(x, \tau),
\]

\((\tau>0; 0<x<\infty);\) \hspace{1cm} (1)

\(T(x,0)=T_0=\text{const};\) \hspace{1cm} (2)

\(\lambda \frac{\partial}{\partial x} T(0, \tau) + q_e = 0 ;\) \hspace{1cm} (3)

\(T(\infty,\tau)=T_\infty \frac{\partial}{\partial x} T(\infty, \tau) = 0.\) \hspace{1cm} (4)

Further this problem amounted to the heat conduction problem with known boundary condition. Variable \( T \) was changed on new one \( q \) (heat flux density), which was specified by equation

\(q(x, \tau) = -\lambda \frac{\partial}{\partial x} T(x, \tau).\) \hspace{1cm} (5)

Differentiating (1) by \( x \) and substituting (5), it was obtained

\[\frac{\partial q(x, \tau)}{\partial \tau} = a \frac{\partial^2 q(x, \tau)}{\partial x^2}.\]
q(x,0)=0; \tag{7}
q(0,t)=q_c=\text{const}; \tag{8}
q(\infty,t)=0. \tag{9}

The solution of equation (6) at conditions (7)-(9) was

\[ q(x,t) = \frac{q_c \text{erfc} \frac{x}{2\sqrt{\lambda t}}}{2\sqrt{\lambda t}}. \tag{10} \]

Substituting q(x,t) on (10) in (5) and integrating it between x and \( \infty \), the following final equation was found:

\[ T(x,t)-T_0 = \frac{q_c}{\lambda} \text{erfc} \left( \frac{x}{2\sqrt{\lambda t}} \right) \left( \frac{2\sqrt{\lambda t}}{\lambda} \right) \text{erfc} \left( \frac{x}{2\sqrt{\lambda t}} \right), \tag{11} \]

where \( x \) - current value of probe length (m), \( \lambda \) - thermal conductivity of probe material (W/m-K), \( \nu \) - temperature conductivity (m²/s), \( \tau \) - time (s).

Depending on measuring points, heat flux \( q_c \) in which were taken from MAI data, the duration (\( \tau \)) of volt-ampere characteristic obtaining varies between tens of seconds and several minutes, that makes it possible to conduct as manual as automatic measurements.

The value of magnetic induction vector does not exceed 200 Gauss, as it was mentioned above. In this case the relation of electron cyclotron radius to \( (r_c=mv/eB) \) to probe radius is much more than 1. Then, the magnetic field should not influence the form of probe curve.

Presently the work on probe system assembly is carrying out. Measured and processed data will be described in the next papers.

\section*{References}


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\section*{Conclusions}

The following conclusions can be made according to the investigation results.

1. There is a noticeable change of thruster integral parameters with variation of volume and geometry of near-cathode area and, probably, magnetic field in thruster volume. The last circumstance concerns not only magnet current variation that has been obtained previously but also change of magnetic system configuration.

2. The best results are achieved at magnet current equal to 4 A. Magnet current decrease results both in characteristic deterioration and in insignificant difference between the plots, obtained for various cathode-polepiece edge distances.

3. The selection of baffle dimensions and its positioning should be coordinated with existing magnetic field.

4. There is some difference in field lines distribution at cathode polepiece substitution. The value of magnetic induction in the case of longer polepiece was average 15-20 % higher than for "short" one at the same distances from cathode polepiece edge and at the same magnet currents.
Figure 1. 5-cm ion thruster principal schematic

Figure 2. Ion production cost as a function of propellant utilisation efficiency. $l_m=4\,\text{A}$ and $l_{\text{fp}}=16\,\text{mm}$.

Figure 3. Ion production cost as a function of propellant utilisation efficiency. $l_m=3\,\text{A}$ and $l_{\text{fp}}=16\,\text{mm}$.
Figure 4. Ion production cost as a function of propellant utilisation efficiency. $I_m=2\,\text{A}$ and $l_q=16\,\text{mm}$

Figure 5. Ion production cost as a function of propellant utilisation efficiency at various values of total flow and cathode polepiece dimensions.

$m_c=30\,\text{eq.mA}; I_m=4\,\text{A}$.

- * $\dot{m}_c=70\,\text{eq.mA}$; + $\dot{m}_c=90\,\text{eq.mA}$; # $\dot{m}_c=110\,\text{eq.mA}$ at $l_q=16\,\text{mm}$;
- * $\dot{m}_c=70\,\text{eq.mA}$; % $\dot{m}_c=90\,\text{eq.mA}$; $\$ $\dot{m}_c=110\,\text{eq.mA}$ at $l_q=10\,\text{mm}$.

**The exact values of ion production cost are not put into plots because ion extraction system used in this series was unconventional. They are qualitative and comparative in character.
Figure 6. Distribution of magnetic field lines in 5-cm ion thruster at magnet current equal to 4 A. Cathode polepiece operation length is 16 mm, external diameter – 23.5 mm, internal – 21.5 mm.

Figure 7. Distribution of magnetic field lines in 5-cm ion thruster at magnet current equal to 4 A. Cathode polepiece operation length is 10 mm, external diameter – 24 mm, internal – 21 mm.