Middle power Hall Effect Thrusters with centrally located cathode

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Abstract: the work is dedicated to investigation of middle-power SPT (M70 and M100 type) with centrally located cathode-neutralizer. The main advantages and limitations of this cathode position scheme are analyzed. Experiments shown that central cathode leads to improvement of output characteristics of SPT, total efficiency of SPT M70 type was 2-5 % greater than with cathode located externally to the thruster. It is shown that for reduction of energy costs for electron transportation from cathode to plasma beam it is necessary to shift central cathode downstream along the thruster axis.

Nomenclature

B_r = radial component of magnetic field, mTl
$\mathrm{B}_{\mathrm{SAT}}$ = saturation induction, mTl
$\mathrm{D}_{\mathrm{INN\ CORE}}$ = outer diameter of inner core, mm
$\mathrm{d}_{\mathrm{INN\ CORE}}$ = inner diameter of inner core, mm
I_D = discharge current, A
I_{SP} = specific impulse, s
$\dot{\mathrm{M}}_{\mathrm{A}}$ = anode mass flow rate, mg/s
$\dot{\mathrm{M}}_{\mathrm{K}}$ = cathode mass flow rate, mg/s
T = thrust, mN
U_{CG} = cathode-ground potential, V
U_D = discharge voltage, V
η_T = thrust efficiency

I. Introduction

Stationary Plasma Thrusters (SPT) are well known to be widely used as a propulsion for satellites. Both orientation and maneuvering tasks are successfully solved using propulsion systems based on SPT.

In spite of the fact that first SPT was in space in 1971 [1], researches carry out very intensive works for its investigation and improvement until now. The most noteworthy is that the works are fulfilled not only by 3-5 organizations, as it was during USSR times [2], but by many scientific organizations from all the world.

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SPT is a complex system, efficiency of which depends on many factors, and seeming simplicity of SPT design does not solve this problem. Investigation of SPT is still complicated by absence of reliable information on some factors influence, which can act either individually or in common with other factors.

In general SPT consists of two parts: anode block (a source of accelerated ions) and cathode-neutralizer (a source of electrons). There are a lot of factors which determine efficiency of SPT operation; particularly, position of cathode relative to anode block does not have the last place in it. Cathode position has influence on the following:

- Life time of SPT. The cathode is one of the main SPT's elements which undergoes erosion. The reason of cathode scattering is ion flow escaping the discharge chamber (DCh) under high angles. Thus, position of cathode relative to anode block and leaving it ion beam will define the life time of the cathode and correspondingly of the SPT [3].
- Reliability of thruster firing.
- Performance of SPT (see in detail paragraph II).

There exist two scheme of cathode position relative to anode block: when a cathode is placed on one side of the anode block, at its periphery (external cathode), and when a cathode is located on the axis of SPT (internally-mounted cathode). In the last case inner core of the thruster is hollow and cathode is placed inside of the hole.

Scheme with external cathode is «traditional» and has the greatest spreading. In all space applications of SPT exactly this scheme is implemented. However, the scheme with central cathode has a variety of weighty advantages. [4, 5, 6, 7]:

1. increased performance characteristics up to 5%;
2. absence of thrust vector deviation in the side of operating cathode;
3. absence of cathode erosion by ions escaping the DCh at high angles;
4. uniform erosion of DCh walls;
5. lower angle of ion beam and as a result lower negative influence upon satellite elements;
6. increased vibration strength and resistance;
7. lower mass and higher compactness of SPT;
8. more simple positioning of SPT on satellites.

Then we have logical question: "why not use scheme with central cathode in all cases?" The fact of the matter is that only organizations who have high-power SPT (more than 5 kW of consumable power) could afford to use this scheme. They are Busek (thruster BHT-8000, 8 kW [5]), Snecma (thruster PPS-20k, 20 kW, Fig. 1), ODB «Fakel» (7 kW SPT-140 and 30 kW SPT-290) and others. In the first instance this is connected with fact that in low and middle power SPT it is physically impossible to mount a cathode in the center because of large size cathodes from one side, and from another side because of relatively small sizes of the thrusters.

Due to developed in KhAI miniature selfheated cathodes (Fig. 2) there was realized a possibility to implement the scheme with central cathode in middle power SPT such as M70 and M100 type (0.7 and 1.5 kW correspondingly) and even in lower ones.

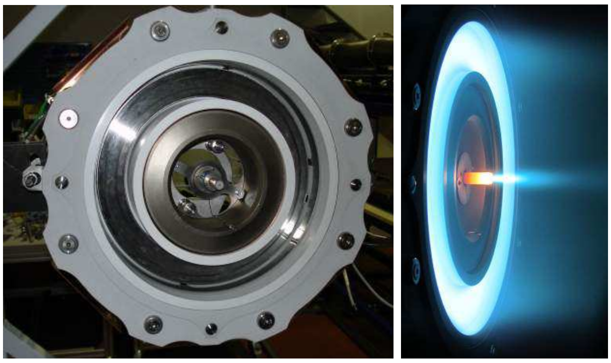


Figure 1. Snecma's high-power HET PPS-20k ML with KhAI's cathode [8].

Figure 2. KhAI's miniature selfheated cathodes: from left to the right:
SHC-0.3A for SPT-20M; SHC-2A.6 for M70
SHC-2A.10 for M70; SHC-5A for 100M.

II. Criterions for choice of cathode location

As a rule, exact place of external cathode position for each thruster is determined experimentally, however the main trends and criterions are well seen.

From the point of view of total SPT efficiency the main criterion is minimal cathode-to-ground potential U_{CG} at maximal thrust T. There are two places near the anode block where we can achieve it. In the first case the cathode (hereinafter we mean an orifice from which electrons are ejected) should be near the DCh exit section in the place where magnetic field lines are closed between pole tips. In the second case the cathode should be significantly moved off from the anode block [5], but this case is not acceptable because of well-known reasons. Cathode location in first case can also be critical, since cathode approaching to DCh exit means its approaching to the flow of accelerated ions. That is why the final choice of external cathode location should be determined with account of these factors.

When cathode is located in the place where magnetic force lines (MFL) are not closed on tips (region of magnetic field leakage) U_{CG} increases because of increased energy losses for electron transportation from the cathode to plasma beam. Electron transportation becomes hampered. At the beginning electrons drift azimuthally in magnetic field with negative gradient with slowdown. This takes place in the region of magnetic field leakage. When electrons reach the region where MFL are closed on tips they are forced to change direction of azimuthal drift to the opposite and to move in the magnetic field with positive gradient with acceleration. All this leads to increasing of energy losses in SPT [9].

It is possible to decrease U_{CG} without cathode approaching to DCh exit using some special methods and solutions, for example, extending of outer magnetic pole [10], and using additional solenoids [11] for shifting of separatrix line which divides two regions with different magnetic field behavior, or using additional channels with “0” magnetic field [12].

Scheme with central cathode is deprived of this drawback, since the place of electron ejection is located in the right place initially. U_{CG} is found to be really lower than in all external cathode positions [6].

If to talk about SPT efficiency, central cathode lets increase η_T up to 3-7 % [6, 13]. However during tests of BHT-1500 it was noticed efficiency decreasing up to 7 % for central cathode [14]. Probably the reason was that the thruster operated on not nominal regime 0.7 kW instead of 1.5 kW.

During tests of low-power SPT [15] in front of central core there was discovered a region with lower electric field. Involved in it ions led to decreasing of thrust and erosion of inner magnetic pole tip. Probably application of central cathode will solve this problem by increasing a pressure from cathode gas flow and redistribution of electric field profile.

Using of central cathode leads to better focusing of ion beam [5]. Divergence angle is at least 8 % lower in comparison with external cathode. Authors suppose that the effect could be due to decreasing of radial pressure gradient in near axis region, which tries to pull ions to the axis, thus worsening beam focusing.

All this confirms the reasonability of using the scheme with centrally located cathode.

III. Cathode mounting in the central core of SPT

Installation of cathode in the center of SPT is possibly only if outer diameter of inner core $D_{INN\ CORE}$ is bigger than outer diameter of cathode. However, even under fulfillment of this condition there can be problems. The hole in the core decreases cross-section of the magnetic conductor and this can cause its saturation and shift thruster operation in anomalous mode.

Let’s analyze a possibility of cathode installation in the center of middle power SPT M70 and M100 type, which have inner cores with outer diameters 18 mm and 26 mm correspondingly.

Analysis of hole size influence on magnetic field distribution in DCh was carried out in software package Ansoft Maxwell 14.0. Figure 3 presents the dependence of Brmax along DCh midline on cross-section of magnetic core. Decreasing of the cross-section lower than critical value causes saturation of the core (in this case it was made of permendur with c B_{SAT}=2,35 Tl [16]) and magnetic field profile deviates from optimal configuration (Fig. 4–5).

Critical diameters of the holes in inner cores of M100 and M70 types are 13 mm and 18 mm. With such sizes we can

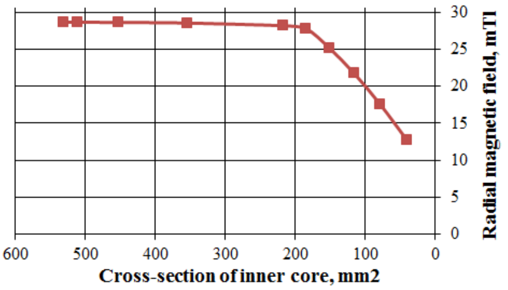
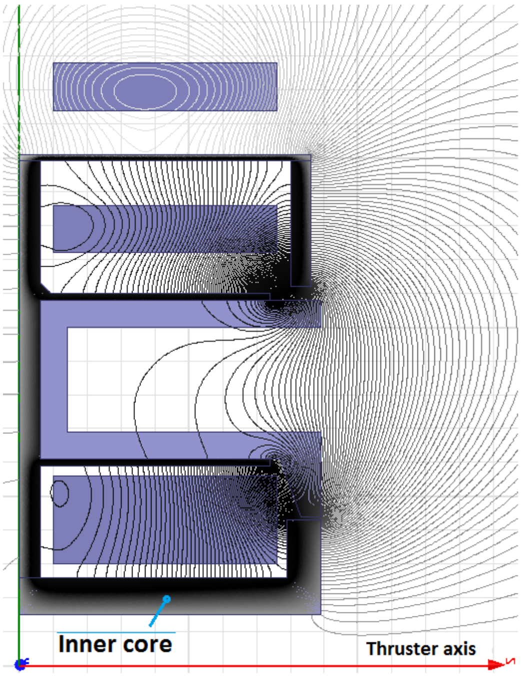


Figure 3. Cross-section of inner core of M100 versus Brmax along midline of DCh. ($D_{INNER\ CORE}$ = 26mm, parameters of magnetic system are taken from [17]).

neglect changes in magnetic field in view of their insignificance.



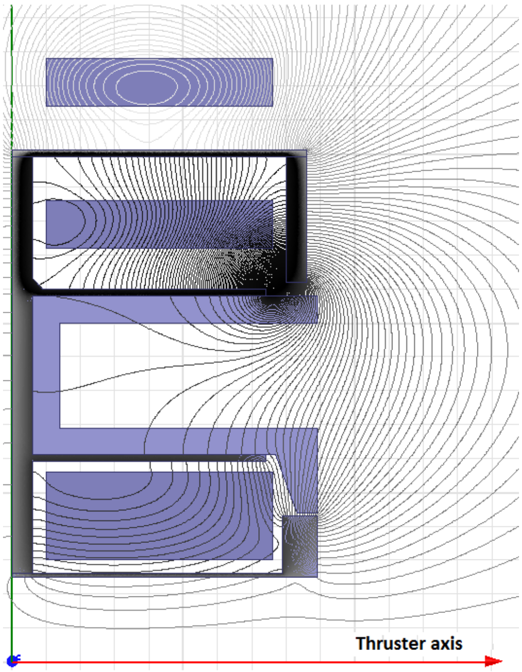


Figure 4. Normal MFL profile, when inner core is out of saturation.

Figure 5. Degradation of magnetic field as a result of inner core saturation.

On the basis of what was said, maximal dimensions of cathodes (with account of gaps between the cathode and inner surface of the core) are 11 mm for SPT M70 type and 18 mm for SPT M100 type. Analysis of flying models of cathode-neutralizers (for example, from ODB "Fakel" [18]) shows that none of the cathodes in its original scheme can be used as a central cathode because of their big dimensions. If to apply laboratory model of cathodes as it was in works [5, 14] it becomes possible, but only for M100 type, not for M70.

During magnetic system calculations we noticed that $D_{INNER\ CORE}$, has low influence on magnetic field in DCh (sure for $D_{INNER\ CORE}$=20–28 mm). The principal is to keep cross-section of the core constant. So in fact it is possible to increase a little diameter of the hole sacrificing the place intended to inner solenoid. However it will be necessary to increase current density in the solenoid to keep ampere-turns constant.

Developed in KhAI parametric series of selfheated cathodes (Table 1) can give several standard size cathodes for SPT M70 and M100 types. Notably, that dimensions of cathode SHC-5A let us insert two cathodes in M100 (fig. 7) and thus increase the total reliability.

Table 1. Parametric series of selfheated cathodes of new generation in "KhAI"

Cathode type / Parameter	SHC-0.3A	SHC-2A.6	SHC-2A.10	SHC-5A	SHC-20A	SHC-50A	SHC-200A
Current, A	0,2 – 1	1 – 2.5	1 – 3	2 – 7	10 – 30	10-70	25-200
Life time, hours	17000	20000	20000	20000	20000	27000	30000
Mass, g	7	10	15	30	41	77	180
Dimensions DxL, mm	8x40	8x40	10x48	10x48	16x50	25x66	29x110

IV. Tests of SPT M70 type with centrally located cathode

A. Vacuum facility

Experiments were carried out in the vacuum chamber in electric propulsion laboratory of National Aerospace University "KhAI". The chamber is stainless, 2 m diameter and 3.5 m long. It is equipped with two oil-diffusion pump which can provide pumping speed of 40000 l/s. Ultimate background pressure is 1.0×10^{-5} Torr (at air) and during experiments with Xenon flow rate of 2.5 mg/s it was 1.5×10^{-4} Torr.

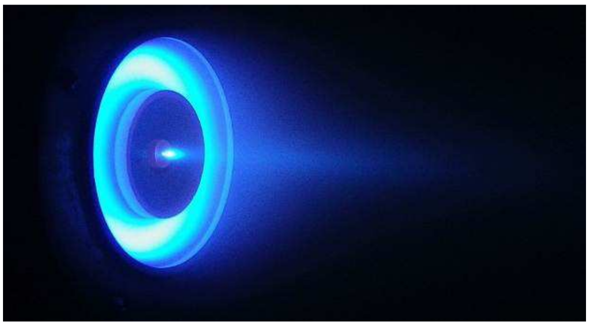


Figure 6. Operation of KhAI's SPT-M70.CHC with centrally located cathode SHC-2A.10.

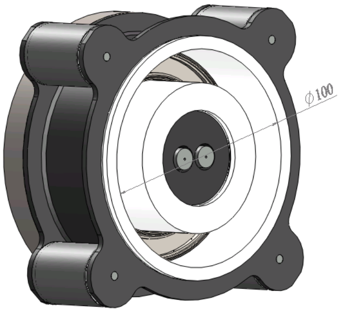


Figure 7. SPT-M100.CHC with 2 cathodes in the center.

B. Supporting systems

Specially developed two-channel system of gas supply and storage was used. The system provides flow rates with 3% accuracy (verified using gas flow controllers Bronkhorst F-201CV).

SPT thrust was measured using torsion balance with laser pointer. Mistake was less than 1.4 mN.

Thruster was electrically supplied with standard laboratory power supply unit 600V10A. For cathode ignition it was used the power supply 1kV200mA. Main power supply was protected from oscillations in discharge circuit by LC-filter 40 mH, 200 μF.

Coils of magnetic system were electrically supplied by current stabilizer PS30V15A.

Electric parameters were registered using digital oscilloscope Tektronix DPO 3052 and appropriate probes: Tektronix P5200 High Voltage Differential Probe and TCPA3000 AC/DC Current probe.

C. Thruster and cathode

Thruster SPT-M70.CHC was specially designed and manufactured for realization of two schemes of cathode position. Nominal power of the thruster is 600 W at 300 V and 1.9 A. On the nominal regime (Fig. 6) it produces thrust of 38 mN and specific impulse of 1650 s. Total thrust efficiency is 54%. Thruster operates in 250W-1100W with specific impulse 1100–2200 s and thrust 20–60 mN.

Cathodes for internal and external schemes are the same type SHC-2A.10. Those selfheated cathodes [19, 20, 21, 22] provide fast start (20–25 ms after giving ignition voltage to the cathode [19]) and reach stationary thermal condition after 1 min. At all tests cathode flow rate was 0.13 mg/s.

D. Tests description

After firing the thruster operated during one hour before reaching stable thermal condition and stable parameters. Also after each change of operating regime the thruster operated 20 minutes before following data registering. Currents in solenoids were chosen to provide the minimal discharge current.

There were conducted two separate experiments:

In the first experiment the influence of cathode position along the thruster axis was defined. Cathode was moved along thruster centerline by motion system. The operating regime was nominal. Thruster was not installed on the torsion balance, so only electric parameters were registered.

Figure 8 presents binding of cathode to elements of anode block. Zero position was matching of cathode diaphragm and outer surface of inner magnetic pole tip in one plane. Cathode motion was ± 7 mm from zero position.

During the second experiment both schemes of cathode position we investigated. Cathodes were switching without opening the vacuum chamber however with turning the thruster off. Thruster was installed on torsion balance. Regimes with anode mass flow rates lower than nominal were investigated.

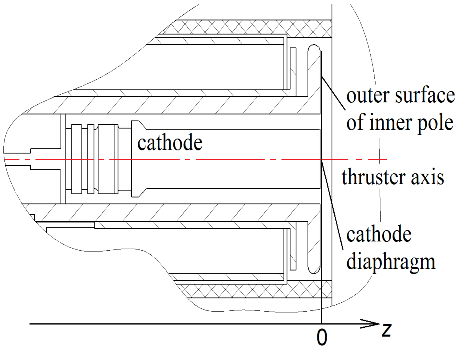


Figure 8. Cathode binding to anode block elements.

E. Test results

1) Influence of cathode position along thruster axis.

Figure 9 presents dependence of U_{CG} on cathode position along thruster axis. Notwithstanding cathode moving at small distances, it is clear tracked that moving-out the cathode downstream leads to decreasing of U_{CG}, so energy losses for electron transportation are also decreasing.

2) Internal cathode versus external one.

At all operating points for central cathode we observed increasing in performance characteristics. Figures 10–13 shows obtained characteristics for both schemes of cathode position at $\dot{M}_A$=2.0 mg/s.

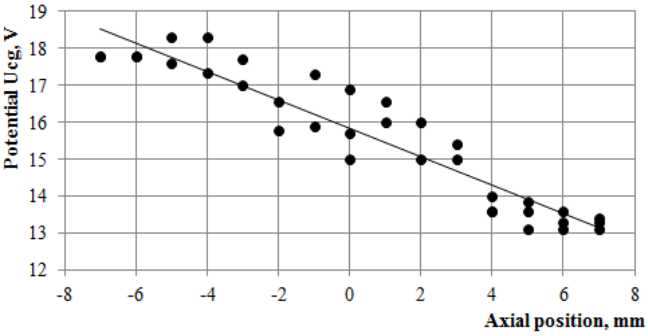


Figure 9. U_{CG} versus cathode position along thruster axis.

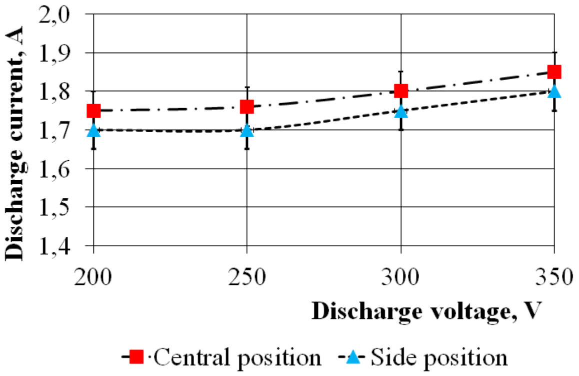


Figure 10. V-A characteristics of SPT-M70.CHC with central and external cathodes

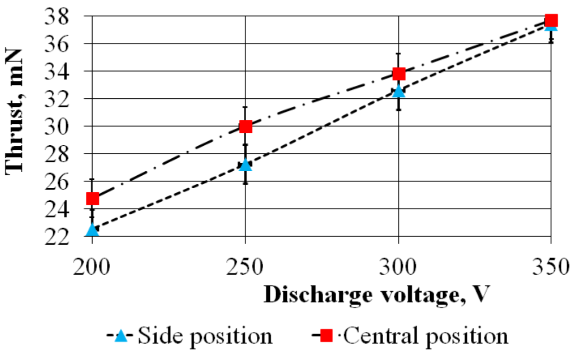


Figure 11. Thrust versus discharge voltage

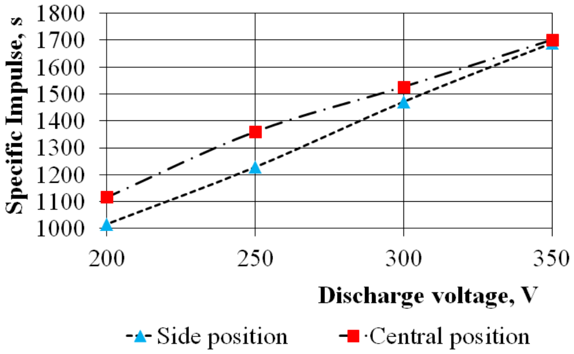


Figure 12. Specific impulse versus discharge voltage

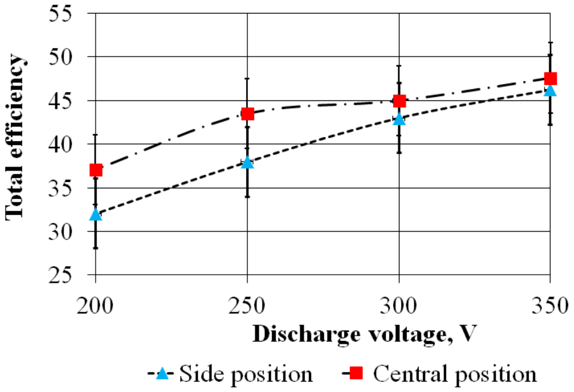


Figure 13. Total efficiency versus discharge voltage

As it can be noticed thruster with central cathode has higher at 3.5 % discharge current at the same gas flow rate through cathode and anode. Positive increment in thrust and specific impulse were obtained with centrally located cathode. Total efficiency was 2–5 % also higher. Interestingly enough that positive effect of central cathode declines with increasing of discharge voltage and parameters get become equal. Difference between parameter for both schemes is in error borders of measurement or very close to it, thus for precise determination of influence of cathode position scheme it will be necessary to increase measurement precision.

Figure 14 shows behavior of U_{CG} for both schemes. At all operating points U_{CG} is 6–8 V lower for central cathode.

The same behavior of thruster characteristics was observed for $\dot{M}_A$= 1.7 mg/s.

V. Conclusion and future works

Initial tests of middle power SPT-M70.CHC have shown:

1. The minimal loses of electron transportation from cathode to plasma beam are received when cathode is located on the thruster axis and shifted along this axis downstream.
2. Scheme with centrally located cathode provides better performance characteristics than the scheme when cathode is at periphery.

Presented results are the first step in investigation of middle power SPT with centrally located cathode. In the period ahead we plan to fulfill full-featured tests with using of far-field and near-field diagnostics. All this is necessary for further optimization and improvement of Stationary Plasma Thrusters.

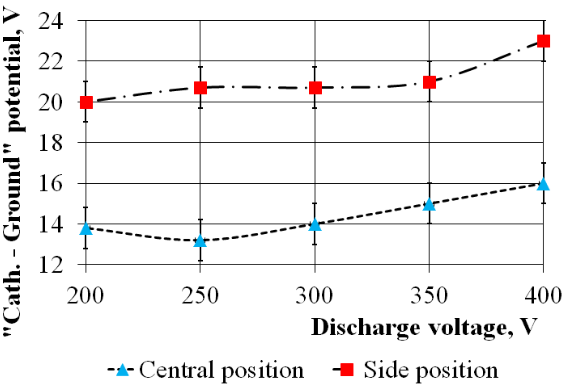


Figure 14. U_{CG} versus discharge voltage

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