ABSTRACT

The results of the analysis and investigation of the thruster element dimension, the working gas properties and operating mode parameters influence on thruster efficiency and lifetime are presented in the report. Existence of the optimum topology and magnetic field intensity in the accelerating channel of the thruster as well as the possibility to control the position and thickness of the magnetic field distribution in the accelerating channel are shown. The possibility to use the geometrical similarity in the thrusters of different dimensions and to increase the thruster lifetime by positioning the accelerating layer at the outer of the accelerating channel and outside of the magnetic system counter is indicated. Last solution is realized in the accelerators with the so-carried out accelerating layer, for example in the SPT-100. It allows so obtain the lifetime over 7000 hours demonstrated already in thr tests.

So, design solutions developed and checked many times up to now in a flight qualified thrusters allow to create effective modern SPT's with high enough life time, for wide range of output parameters.

INTRODUCTION

As it is well known [1,2], stationary plasma thrusters (SPT) already many years are successfully used in the Russia Space Technology and in the nearest future they shall be used in the Western spacecrafts. This is the result of large volume of investigation and development works, fulfilled in the several Russian Organizations during previous years. In this paper the results of applied researches, obtained during 1970s - 1990s by Moscow Aviation Institute (MAI), Research Institute of Applied Mechanics and Electrodynamics of MAI (RIAME MAI) and Design Bureau (DB) Fakel are represented.

MAIN FACTORS DETERMINING THE THRUSTER PERFORMANCES.

Principal SPT diagram in Russia was proposed by professor Alexey Morosov, under his leadership in the Kurchatov Institute of atomic energy the complex of fundamental researches was fulfilled and as a result the first SPT laboratory models were developed having acceptable level of performance and some possible ways to improve the performance was developed. the first experimental propulsion system (PS) successfully tested on 1972 was
developed and created. The success of the flight test pushed the beginning of the further physical and applied investigations to create effective enough SPT meeting all requirements to the thruster for space applications i.e. to reach high level of thrust efficiency, lifetime, and dynamic characteristics, structural and thermal resistivity etc. In MAI jointly with DB Fakel beginning from the 1969 the main efforts were concentrated to reach high SPT thrust efficiency and large lifetime. Dynamic characteristics and thermal problems were studied also. The most important results will be considered below.

1. SPT DESIGN DIAGRAM

SPT Design diagram could be characterised by the following features:
- existence in the thruster of special ionization chamber,
- existence of more than one stage of acceleration stages,
- existence of special heaters to ensure the successful thruster work on condensed substances under normal conditions,
- type of working substance distribution system in the discharge chamber,
- number and position of electrodes to organize discharge in the working chamber,
- type of magnetic system,
- mechanical (structural) diagram,
- thermal diagram.

It is not so complicated to recognize that there are a lot of options to develop the thruster design and in the several organizations of Russia the investigations were fulfilled to choose base SPT design diagram. Some of the most important results will be considered below more detaily.

1.1 As a result of analysis, based on the investigation fulfilled in the different organization the single stage SPT principal diagram was chosen, when the ionization of working substance and acceleration of ions are realised in the same working volume. This choice is causing high enough spread of ions on energies, but efficiency losses due to the nonideal ion energy distribution are not exceeding 10%. Then single stage SPT has big plume divergence, but energy losses due to this factor are not exceeding 10% also. It is necessary to underline that according to our experience usage of special ionization chamber gave higher losses than they was in the single stage SPT than they was in the single stage SPT chamber.

The single stage SPT gives us very low energetical cost of ionization. So the total energetical ion cost in the discharge is \(~(6-8)\) \(\varepsilon\varphi_i\) per ion where \(\varphi_i\) is ionization potential and only significant energy losses in the acceleration are causing the reduction of thruster efficiency.

Taking into account presented data and simplicity of the design it was chosen the single stage diagram for the modern SPT.

Let's add that in the most important for the modern space technology range of specific impulse \(I_{sp}=(1000-3000)\)s single stage diagram is giving acceptable level of the acceleration efficiency.
1.2 In MAI there were tested the SPT models on different working substances (Xe, Kr, Ar, Cs, Li, Na-K mixture) and it was found that SPT design could be accommodated to the condensed under normal conditions substances by application only heater for the feeding line, including distribution inside of accelerating channel. So, the task to operate on such substances are simple enough. Considering the thruster performance it is possible to conclude that additionally to Xe, the most interesting for the nearest future are the Kr, Cs or Kr and Na-K mixture.

Thruster operating on these substances has high enough level of efficiency [3,4]. Besides Kr is approximately by an order of magnitude cheaper than Xe and industry for its production is powerful enough.

Thrusters on Cs and Na-K mixture could operate satisfactorily under low discharge voltages (~50 V and higher) and thrusters on Cs is giving thrust efficiency 50% under $U_d=100$ (Fig.1). Correspondingly it's possible to receive low value of energetical cost of thrust (less than 10 kW/N). Na-K mixture with low temperature of melting is more simple to store and allows to extent the $I_{sp}$ range under moderate discharge voltage (Fig.2) and both options don't require the changes in design excluding insertion of the heaters. So SPT has additional capabilities, could be useful in the future.

1.3 There were investigated the different types of the working gas distribution systems (Fig.3) inside of the discharge chamber (DC). The main result of these investigations excluding evident one (the necessity of having high enough level of uniformity of the gas distribution) could be summarized as necessity to obtain low longitudinal atom velocity component, especially under low values of the mass flow rates $m$ through the accelerating channel (AC). This result could be explained using expression for the free path of atoms before their ionization: $\lambda_i = v_{az} / \langle \sigma_i v_z \rangle n_e$, where $\langle \sigma_i v_z \rangle$ - ionization rate factor, $n_e$ - mean value of plasma concentration in the channel, proportional under field conditions to $m$. So reducing $v_{az}$ we are interesting the probability of the atom ionization in the AC.

Let is add that deflectors reducing the $v_{az}$ could effectively protect the output channels for gas distribution from contamination and such solution is protected as invention by patents [5].

1.4 There are different possibilities to organize discharge in the AC of the SPT. For example, it is possible to distribute discharge current between several electrodes (anodes) having different potentials or organize additional discharge in the AC (Fig.4). Evidently we have not studied all possibilities, but one of the important result was that its possible to obtain effective enough organization of discharge having only one electrode, fulfilling the function of gas distributor. And such decision is used in the modern SPTs.

1.5 The possibilities to ensure high SPT dynamic characteristic were studied also namely: the conditions of resiable discharge ignition, the possibility to start up quickly enough etc. It was shown that it's possible to reach operation mode close to the steady state in a some ms if cathode is ready to work and gas is getting cathode, and in a ~ 0.15 it we are switching on only gas feeding.
1.6 The stationary and transition thermal fields were studied also. They allowed to
determine thermal stresses in the structural elements, to determine optimal thruster thermal
diagram. In particular it was shown that to reduce the temperature level of the magnetic
system it's useful to organize additional thermal bridges to avoid excessive heat flows through
magnetic system elements.

So, the complex of such applied investigation allowed to develop reliable design of
modern SPT's.

2. MAGNETIC SYSTEM OF THE MODERN SPT'S

2.1 Magnetic field influence on the SPT performances.

Magnetic field intensity and topology is one of the main factors, determining the
thruster efficiency and life time. And the problem was to ensure high level of both
parameters. Therefore the magnetic field influence on the complex of output parameters
were investigated.

It is necessary to underline, that key role of magnetic field as to suppress electron
mobility across to the magnetic field. There are different understanding of real mechanism of
electron mobility in the SPT channel. In this connection it is necessary to remember that
from the measurements of the Hall current inside of the AC mode first time in the Institute of
atomic energy [6] and measurements of longitudinal component of electron current it was
found that for the SPT effective value the Hall parameter is 200-300. That means, that at
least in the part of AC the electron mobility is determined by classical mechanism (drifting in
the azimuthal direction electrons are scattering by neutral atoms, ions and walls).
Estimations show that the most significant role could play the collisions with DC walls, and
then with neutral atoms, (concentration of atoms in the AC more than by an order of
magnitude exceeding the concentration of ions). Experimental measurements show also that
accelerating layer is located in the part of acceleration channel with magnetic induction value
close to the maximal one. So, roughly speaking, AL is located in the space with maximal
resistance of plasma (Fig.5) and changing the magnetic field distribution it's possible to
control the AL. This possibility was checked using not only probe measurements but
longitudinal size of erosion traces on the walls. Obtained results (Fig.6) show that boundary
of AL at anode side is located approximately near the cross-section where the magnetic
induction magnitude at mid surface is ~0.8 Br_{max} (Br_{max} is the maximum value of Br at the
same surface). So, changing the distribution Br(z) of the radial component of magnetic
induction at mid surface under quasissymmetric geometry of magnetic field lines focusing the
ion flow it is possible to control the position and longitudinal size (thickens) of AL. The
magnetic layer thickness could characterized by width of Br(z) distribution (for example by
l_h=0.8Br_{max}, see Fig.6) or by l_h'=1/\nabla z Br(z), where \nabla z Br(z) is mean value of Br(z) gradient at
mid surface of the AC. And influence of this parameter on thruster performance was studied.
Obtained results (Fig.7) showed that there is optimal value of \( I_b \) or \( V_{zB} \), when thrust efficiency is reaching the maximum value, mainly due to the high enough value of ratio \( I/I_d \), where \( I_i \) - ion current at the exit of the AC and \( I_d \) - discharge current. It was found also that under fixed other conditions too high value of \( V_{zB}(z) \) are causing oscillation intensity increase. This fact and data on influence of AC geometry on the thruster performance is confirming the significant role of plasma interaction with the walls to maintain the discharge stability. And it is possible to explain such tendency by significant role of the near wall electron conductivity and role of neutrals on the longitudinal current formation.

2.2 Choice of magnetic system diagram.

To control the magnetic field characteristics it was necessary to develop corresponding magnetic systems (MS). To obtain the focusing geometry MS has to create the magnetic field with lines of force similar to lens. Such kind of magnetic field could be produced by system with two poles (Fig.8). But our investigation shows that they have limited capability to produce necessary gradients of magnetic field. More wide capabilities has system with four magnetic poles (so-called double lens magnetic system). But this MS requires higher magnetomotive force due to the additional gap on the magnetic circuit. Therefore it was proposed to use MS with so-called screens (fig.9) having increased capability in comparison with the general 2-pole MS. And mentioned above results were received using last type of MS. Let's underline additional features of MS with screens:

- The magnetic field lines configuration at anode side is forming mainly by configuration of the screens. Therefore we have slow restriction on the gap between the pole and can increase this gap without significant change of the magnetic field in anode side lens.

- The MS with screens allows to increase the size of magnetic coils without to reduce the losses in the coils by reduction of the current density in the wires.

The first feature allows to create magnetic lens outside of the MS counter (Fig.10) and to obtain additional space to use this space for discharge chamber walls. Simple option is to use this space to increase the wall thickness and thruster lifetime. The same action is giving the reduction of the coil temperature. Taking into account all mentioned circumstances the MS with screens have been chosen as a basic one for the modern SPT's. And it is realised for example, in the SPT-100 design. So, in the SPT-100 is realised the idea to fix AL out of MS counter, and to increase significantly DC wall thickness to increase the lifetime. And nowadays the lifetime more than 7000 hours is confirmed by tests [7].

Optimisation of the magnetic field distribution for SPT's of different size showed also that characteristic width of magnetic layer is proportional to the AC width \( b_c \). That means that SPT's of different sizes could be designed using the similarity condition for main their sizes. Therefore the procedure of development could be significantly simplified. And by now the family of such thrusters are developed and tested.

Thus the thrusters with MS with screens have some advantages and protected by patents [8].
CONCLUSION

Results presented above allows to state that complex of investigations made in MAI, RIAME and DB Fakel together with the results of other Russian institutes have created the base for the successful modern SPT development.

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Fig. 1. SPT characteristics on Cs.  
Fig. 2. SPT characteristics on Na-K mixture.
Fig. 3. Gas distribution diagrams.

Fig. 4. Diagrams of drain recession.

Fig. 5. Distribution of the magnetic and electric fields along the accelerating channel.

Fig. 6. Correlation between magnetic induction distribution and longitudinal size of erosion area.
Fig. 7. Thrust efficiency versus $V_e Br$.

Fig. 8. Magnetic system with two poles.

Fig. 9. Magnetic system with the screens.

Fig. 10. Topology of magnetic field obtained by magnetic system with screens.