MODERN TRENDS OF ELECTRIC PROPULSION ACTIVITY IN RUSSIA

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Abstract

The Russian electric propulsion thrusters (EPT) are in use in space already more than 25 years. By now:

- SPT-100 propulsion subsystems (PS) operate on board of four geostationary satellites (GEOsats) of GALS and EXPRESS type;
- Resistojet PS operates on board of Electro GEOsat;
- TAL operates on board of american STEX satellite according to RHEFTT program.

This year the GEOsats SESAT and Yamal are to be launched having SPT-100 and SPT-70 based PS for their orbit correction. The new generation of GEOsats of EXPRESS and Yamal type with SPT based propulsion subsystem (PS) are under development and will be launched soon. PS based on the SPT-100 and French/Russian SPT of PPS-1350 type is under development and qualification for the European "Stentor" and Astra-1K GEOsats scheduled for the launch in 2000, SPT-100 based propulsion subsystem is designed for the commercial "Telstar-8" US satellite to be launched in 2001.

There are some studies of EPT applications for the orbit raising and for Far Space missions. One of them is the Fobos sample return mission with launch in 2005 or 2007. Preliminary investigation shows that this mission could be realized using Soyuz type launcher with the combined chemical and electric upper stages. For the electric stage the SPT-140 based PS could be used with the initial PS power (7-10) kW and specific impulse value ~2200 s.

R&D works to improve EPT performance level are continued also, namely the development of:

- Teflon pulse plasma thruster (PPT) engineering models for the small spacecraft orbit control, having thrust efficiency ~ (12÷÷20)% under mean power N≈(20÷100)W and specific impulse I_{sp} ≈(1000÷1400) s;
- Xenon ion thrusters (IT) laboratory models with beam diameter 5 cm and 10 cm and power level from 50 W till 500 W;
- Stationary plasma thrusters (SPT) laboratory and engineering models with the external accelerating channel diameter from 2 cm till 300 cm at least, operating under powers from 100 W till 30 kW, including SPT-140 flight model for the operation power ranges (3-5) kW.
- Laboratory and engineering models of thrusters with anode layer (TAL) with the mean accelerating channel diameter from ~2,0 cm till ~200 cm, operating under powers from ~400 W till ~50 kW;
- Lithium magnetoplasmadynamic thruster (MPT) laboratory model with applied magnetic field, operating till powers ~200 kW;

Significant part of these R&D works are conducted according to International programs.

Introduction

As it is well known [1,2] the development of the electric propulsion thrusters (EPT) in Russia was started at the end of 50-th and there were investigated the EPT of all types known by now. The most significant progress was achieved in the development of the so-called Hall thrusters due to the fruitful

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activity of the scientific schools in the former USSR worked under leadership of professor Alexei I. Morozov and Askold V. Zharinov, as well as due to the intensive works of engineers and designers of several Russian institutes and design bureau Fakel. These efforts allowed to develop and to poductise the stationary plasma thrusters (SPT) and to develop prospective thrusters with anode layer (TAL) both having unic performance level in the range of specific impulses I_{sp}=(1000-3000)s for the single stage option and in the range of I_{sp}=(3000-8000)s for the double stage option. By now SPT has very impressive flight heritage, because already more than 100 thrusters successfully operated on board of spacecraft's.

It is necessary to add that the new impulse to the Hall thruster development was done by the international cooperation. As a result the Russian SPT-100 thruster module was qualified by International Space Technology, Inc. (ISTI)joint venture for the application on board of western spacecraft's, there was developed and qualified the power processing unit (PPU) for the propulsion subsystems (PS) by Space Systems/Loral, the SPT of PPS-1350 type jointly developed by Societe Europeenne de propulsion (SEP, France) and design bureau Fakel (Russia) and European PPU developed by ETCA are under qualification for the commercial Customers. The series of prospective Russian Hall thrusters were tested at the best american and european facilities and these tests have added significant part of information on the thruster performance and on their integration issues. Nowadays there is going the 1-st TAL flight test on board of the American STEX satellite.

The T-160 SPT modification designed by the Keldysh RC is under preparation for the flight test on the Russian EXPRESS spacecraft (S/C). The preparation of the D-38 TAL modification is also under preparation for the test on a small S/C to be integrated and launched from the International Space Station.

But not only Hall thrusters are developed in Russia. There are some R&D works related to the pulse plasma thruster (PPT), low power ion thruster (IT) and powerful magnetoplasmadynamic (MPD) thruster development. They will be considered in this paper also.

1. Status of the Russian electric propulsion application

As it was mentioned above the stationary plasma thrusters, developed and produced by design bureau Fakel are systematically used in a Russian space technology already more than 25 years. The new feature of their application in Russia is that now they are introduced into S/C design by several Russian enterprises (Table 1) and companies (besides NPO PM these are Lavochkin NPO, RSC "Energiya" and there are known the projects of Hall thruster usage by other Russian space companies).

It is known also that within years 2000-2001 there will be launched the French technological satellite "Stentor", the European commercial satellites "Astra-1K" designed by Alcatel and american "Telstar-8" of Space Systems/Loral (see Table 1). They will be equipped by the Fakel's SPT-100 ("Stentor" sat will consist of the SPT-100 and PPS-1350).

Table 1

Program title, number of S/C	Prime-contractor	Number of thrusters per S/C and thruster type	Thruster power, kW	Specific impulse, s	In use or launch date
1	*2*	*3*	*4*	*5*	*6*
GALS 2 S/C	NPO PM	8 SPT-100	1,35	1500	In use
EXPRESS 2 S/C	NPO PM	8 SPT-100	1,35	1500	In use
Yamal-100	RSC Energiya	8 SPT-70	0,7	1400	1999
SESAT	NPO PM	8 SPT-100	1,35	1500	1999
EXPRESS A 3 S/C	NPO PM	8 SPT-100	1,35	1500	since 1999
BANKIR	Lavochkin NPO	4 SPT-70	0,7	1400	2000
STENTOR	Alcatel	2 SPT-100 2 PPS-1350	1,35 1,5	1500 1600	2000
ASTRA-1K	Alcatel	4 SPT-100	1,35	1500	2000
Yamal-2000	RSC Energiya	8 SPT-70	0,7	1400	2001
Telstar-8	SS/L	4 SPT-100	0,7	1500	2001

As one can see the application area and scales of the Russian or jointly developed Hall thrusters is extended now significantly.

Besides programs indicated in the Table 1 there are some another ones under consideration. One of them is the Skybridge constellation where SPT or TAL could be used. Realization of this program will drastically change the scales of Hall thruster application. In addition one can note that there are at least several potential missions are under consideration where Hall thruster could be used. They are as follows:

- Combined chemical and electric propulsion insertion of satellite into GEO and its station keeping. Hall thruster for this mission has to operate with power at level of several kW and specific impulse within the range (1500-2500)s.
- International Space Station drag compensation where the TAL of D-100 type or SPT-140 are applicable with specific impulse within the range(1500-3000) s.
- Sample return mission to Fobos, where SPT-140 or D-100 could be used with specific impulse within the range (1500-2500)s.
- Teledesic/Celestri constellation where Hall thruster with power (1,5-3,5)kW and I_{sp} within the range (1500-2500)s could be used for the S/C orbit raising, orbit keeping and control and S/C deorbiting.
- Missions to small bodies in a Deep Space where TAL or SPT with power of single thruster unit from 1 kW till 10 kW could be used. To compete with ion thrusters it is necessary to have Hall thrusters with specific impulses I_{sp} = (3000-5000) s.
- Mars mission of heavy spacecraft's where TAL or SPT could be used with power of single thruster unit till 50 kW and higher and specific impulse I_{sp}=(3000-5000)s depending on the payload mass and mission specifics.

Considering the Electric Propulsion application area it is necessary also to take into account the growing scales of small spacecraft usage, allowing to reduce the total mission cost due to the possibility to use smaller and cheaper launchers. Analysis shows that existing Hall thrusters of SPT-50, SPT-70 and SPT-100 as well as the prospective TAL models could be effectively used for the S/C orbit raising, insertion into GEO and S/C orbit transfer and keeping. But to compete successfully with the other types of electric thrusters it is necessary to improve the Hall thruster and the respective propulsion subsystem performance.

Summarizing the presented data it is possible to conclude that in spite of the great progress in a real Hall thruster application it is still actual to improve their design and performance as well as to continue the studies of their compatibility with other S/C subsystems and integration issues. Therefore there are continued the R&D works on the prospective Hall thruster development and their investigation.

2. Main directions of the Electric Propulsion Investigation and Development

As it was stated above there are some new missions where Hall and other types of electric propulsion thrusters (EPT) could be used as well as there is the necessity to improve performance level of the existing thrusters and to increase effectiveness of their usage. Therefore there are continued the electric propulsion R&D works in Russia. These works are directed to solve the following tasks:

- To develop the EPT effectively operating under lows powers (less than 100 W) and designed for the small spacecraft's (S/C).
- To develop the effective enough thrusters for the small spacecraft's able to operate under powers ~(100-500)W and different specific impulses in the range ~(1000-5000)s.
- To develop more effective Hall thrusters covering range of power (0,5-5,0) kW and specific impulse range I_{sp}=(1500-5000) s.
- To develop the thruster models designed to operate under increased powers N=(5-10)kW, N=(10-25)kW, N≈50kW and higher and specific impulses (2000-5000)s.
- To develop the powerful MPD thrusters for the future heavy spacecraft transportation in space.

For the level of powers less than 100W there are developed at Research Institute of Applied Mechanics and Electrodynamics (RIAME) the pulse plasma thruster (PPT) engineering models of erosive type (Fig. 1) using teflon as a propellant. Achieved thrust efficiency for these models is (12-20)% under energy release per single discharge (40-100) Joules and specific impulse $I_{sp} \approx$(1000-1400) s, mean powers from some Watts till ~100W depending on the firing frequency. Propulsion subsystem (PS) on base of these models are designed for the total firing number $\sim 2\cdot 10^7$. It is considered that these thrusters are competitive with other EPT's till total thrust pulses $I_\Sigma = 1\cdot 10^5$ Ns. The main advantages of such PS are the simplicity of PS design and thrust pulse control. The used design solutions were checked many times in flight conditions when plasma injectors on base of PPT were tested on board of sounding rockets and space station "Mir". One of such injectors developed and produced by RIAME operates on board of "Mir" station already more than 11 years.

For the range of powers N=(100-500)W there are developed SPT and thrusters with anode layer (TAL). For SPT models developed at RIAME there is achieved the accelerator thrust efficiency η_a (calculated without cathode losses) ~25% under specific impulse I_{sp}=800s and power consumption ~100W. For the ranges of powers N=(200-300)W it is possible to obtain η_a values at the level of 0,35-0,4 under specific impulses (1000-1500)s. Such level of efficiency is demonstrated by SPT models developed by RIAME, Fakel, Keldysh Research Center (KeRC) jointly with MAI [3, 4, 5]. These models have the external accelerating channel diameter from 25 mm till 50 mm. So, for the power range N =(100-500) W it is possible to develop competitive SPT's and SPT based subsystems. And Russian scientists and engineers have to-day laboratory and engineering models of such SPT's and great enough data base for their further development. Choice of concrete thruster size and operation mode is to be done taking into account the full requirements to PS.

It is necessary to note that there is not developed the cathode for the small SPT's operating under modes with discharge currents $I_d \leq 1,5$ A. But such cathodes were developed in USA (by NASA LeRc) and in Europe (by PROEL). So, if necessary SPT could be equipped by cathodes using the International cooperation.

For the considered range of power there is developed also the ion thrusters (IT) by Keldysh RC [6]. So, the Hall thrusters have to compete with IT. Achieved Russian low power ion thruster performance level is traditional for this type of EPT (thrust efficiency $\eta_T \geq 0,5$ under specific impulses $I_{sp} \geq 2500$s) at the level of engineering models. There is also the problem of neutralizer development for the small ion beam currents.

As it was shown in a part I of this paper for the power range N=(0,5-1,5) kW there are serial versions of SPT-70 and SPT-100 having great flight heritage. Nevertheless there are continued the R&D efforts to improve the Hall thruster effectiveness, to increase their lifetime and to reduce plume divergence. And some obtained results are hopeful and were represented at different scientific conferences and meetings. These results were obtained at RIAME, design bureau Fakel and MIREA. But the problem is to realize the qualification of new thruster what is very expensive task. Therefore the mentioned preliminary results are still only scientific ones demonstrating the possibility to improve thruster design and its performance level. So, probably the competition will give the chance to realize qualification of new designs. In this connection it is necessary to note that such attempts are made by the KeRC with its foreign partners. But published performance data for their SPT versions still have no remarkable difference in comparison with the flight qualified and proven SPT designs.

More hopeful situation is with the TAL development because this thruster promise some additional advantages: lower overall scales, reduction of the eroded material release. TAL development had made the significant step due to the success of RHEFTT program, while there was created and now is tested in flight the TsNIIMASH TAL design. But there are still a lot of works to be done to qualify TAL design for such serious missions like commercial application on board of GEOsats or LEO/GEO orbit transfer etc. But it seems that the world competition will allow to qualify the KeRC SPT and TsNIIMASH TAL. It seems also more probable that such qualification will be realized for thrusters with output parameters significantly different from the SPT-70, SPT-100 and PPS-1350 output parameters. One of such new SPT's is the T-160 type thruster developed by KeRC and TsNIIMASH TAL of D-100 (or TAL-110) type able to operate under powers (1-5)kW. And as it is known [2], there is in preparation the flight test of T-160 on board of Express spacecraft, while two samples of TAL-110 went through the 1000-hour lifetime tests in Russia and USA (Fig. 2, [6]).

Design bureau Fakel developed with support of RIAME the SPT-140 (Fig. 3) flight prototype in the frames of the International Space Technology, Inc. (ISTI) R&D and Airforce IHPRPT programs [2]. The SPT-140 development successfully went through the CDR and one of SPT-140 sample was tested during more than 1200 hours at Fakel. Some results of the SPT-140 development will be presented at this conference.

It is necessary to note that there was some indications that for the constellations it is necessary to have thruster able to operate under at least two modes with power N_1 in the range (1,5-1,7) kW and with power N_2 in the range (2,3-3,5) kW having increased relative to SPT-100 specific impulse and total thrust pulse $I_\Sigma \sim 3 \cdot 10^6$ Ns. These requirements exceed the possibilities of SPT-100, but SPT-140 or D-100 are a little bit large for this mission. Therefore it was interesting to develop SPT having intermediate sizes between SPT-100 and SPT-140. Laboratory model of such thruster SPT-115 was developed at RIAME and tested [7]. It was shown that such thruster could meet all requirements indicated above. This model was tested also till discharge voltages 1100V and it was obtained the accelerator specific impulse (without cathode losses) ~3500s under moderate discharge power value $N \approx 2,5$kW acceptable for the long SPT-115 operation.

Thus one can expect that in a 2-3 years there will be flight qualified designs of SPT-140, D-100 (TAL-110) or SPT of T-160 type. These thrusters will have an increased efficiency (55-60)% at BOL and operation power in the range (3-5)kW as well as will be designed for at least two modes of operation.

The expected performance data of SPT-140 and TAL-110 are represented in the Table 2.

Table 2

Thruster type	Power, kW	BOL performance			
		Thrust, mN	Thrust efficie-ncy	Specific impulse, s	Life time, hours
SPT-140	3	190	≥ 0,55	≥1700	≥7000
	4,5	300	≥ 0,58	≥1750	≥4500
TAL-110	3	177	≥ 0,58	≥2000	≥3000

Propulsion subsystems on base of these thrusters could have operation power till at least 20kW and will allow to solve the serious tasks on the orbit raising, orbit transfer, interplanetary missions. For example, in a mission to Fobos being now under study in Russia usage of PS on base of SPT-140 of TAL of D-110 type gives significant mass gain and allow to realize sample return by spacecraft launched from Baikonur by "Soyuz" type rocket. Analysis shows also that such kind of PS are able to fulfil the final part of S/C insertion to GEO. Thus development and qualification of the mentioned mean power Hall thrusters will allow to extend the EPT application area and its scales.

Last years there was repaired the interest to the more powerful EPT's. Therefore some R&D works on such thrusters are continued in Russia:

- There was developed and tested in Russia and in USA the TAL of TM-50 type designed by TsNIIMASH for the operation till 50kW.
- Many years ago there was developed and tested by Fakel the SPT-290 till powers N=35kW and specific impulses till 3000 s. Now according to the NASA Glenn Center request sample of this thruster model is repaired and prepared for the tests in USA.
- Already several years RIAME and MAI develop and test the so-called end Hall lithium MPD thrusters with external magnetic field according to the contracts with JPL. And finally there was developed the thruster model operating stationary under power N≈190kW (Fig. 4) and demonstrating the thrust efficiency $\eta_T \approx 0{,}45\text{-}0{,}5$ under specific impulse $I_{sp} \approx 4500$s.

Surely all the mentioned developmental works are supported by the physical and applied investigations. They are concerned with the specifics of small SPT operation study, investigations of the SPT and PPU joint operation, study of the transient thermal processes impact on SPT performance and low power ion thruster operation particularities. Some of their results will be presented at this conference.

Conclusion

Presented data shows that electric propulsion activity in Russia still have wide enough scales and gives results interesting for international community.

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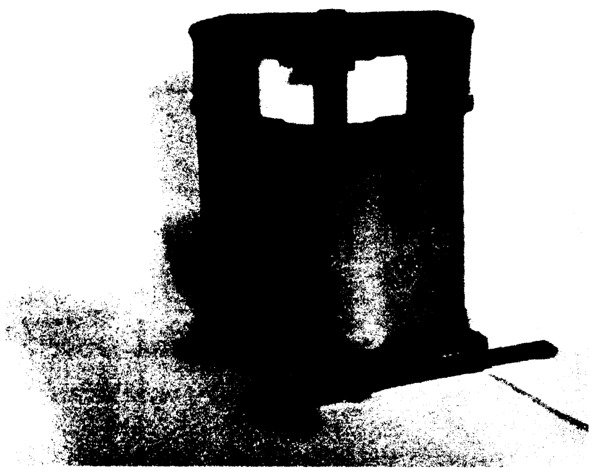

Fig.1 General appearance of the erosive PPT engineering model.

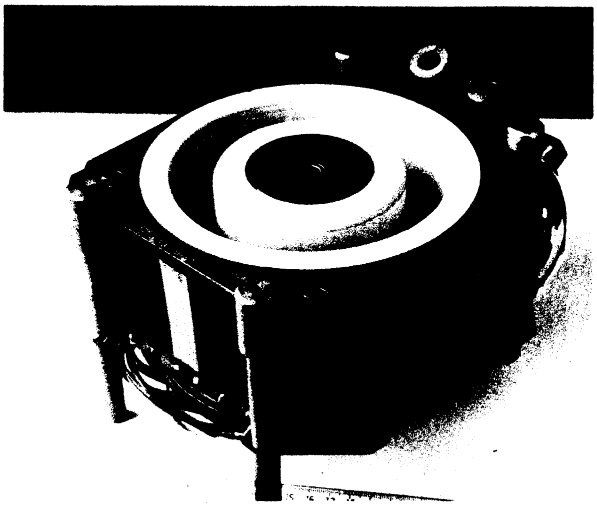

Fig.3 SPT-140 demo model.

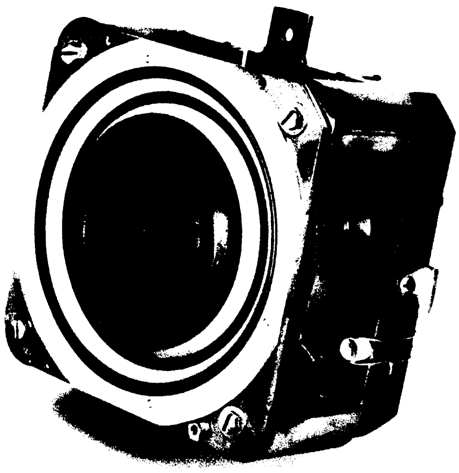

Fig.2 TAL-110 engineering model.

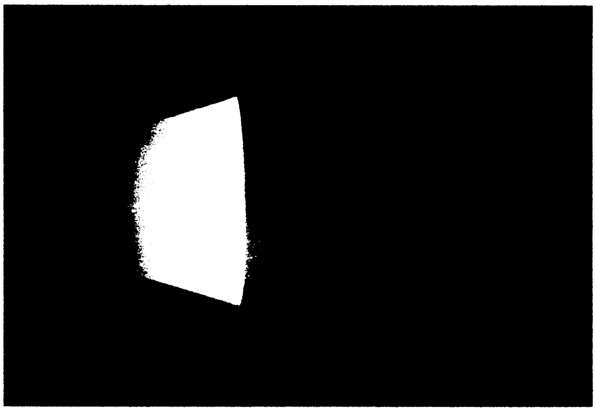

Fig.4 General appearance of the operating MPD thruster.