STATE OF THE ART AND PROSPECTS OF ELECTRIC PROPULSION IN RUSSIA*†

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Abstract

The state of development and application of stationary plasma thrusters (SPTs), thrusters with anode layer (TALs), ion thrusters (ITs), magnet-plasma-dynamic thrusters (MPDTs) and pulse plasma thrusters (PPTs) in Russia are considered in this paper. The main results of the electric propulsion (EP) activity are as follows:

- application of series of SPT-70 and SPT-100 thrusters on board Russian geostationary satellites and delivery of these Fakel thrusters for Western spacecraft has been continuing; EDB Fakel is continuing to develop propulsion systems for small spacecraft. The T-120 thruster is now under flight qualification aboard the Express-A No. 4 spacecraft;
- a series of works to improve the design of the SPT-140 qualification model to be used in a propulsion system for the Fobos spacecraft has been performed by Experimental Design Bureau Fakel. A PPT-based propulsion system for a small Vulkan-type spacecraft is being developed by RIAME MAI and Institute of Electromechanics;
- a series of research works including the erosion tests to study SPT high specific impulse operation modes has been performed at Keldysh Research Center and RIAME MAI according to the Russian internal program and in cooperation with Orleans university; it has been shown that it is possible to develop an SPT with total thrust efficiency over 50% at discharge voltages of ~1,000 V and specific impulse of ~3,000 s, as well as to develop a dual mode SPT capable of operating effectively enough in a mode with high thrust and moderate specific impulse and in a mode with high specific impulse;
- investigations of the double stage TAL have been continued and it has been shown that such a thruster can operate effectively enough as a single stage thruster in operation modes with high thrust and moderate specific impulse and in a double-stage mode when it is necessary to provide high specific impulse (2,500-3,000 s);
- studies of SPT plume and its interaction with spacecraft structural elements have been continued; in particular it has been shown that the SPT-70 plume has characteristics similar to those of the SPT-100 plume;
- SPT studies have been continuing at Moscow Institute of Radio Electronics and Automatics (MIREA), Moscow Aviation Institute (MAI) and Kurchatov Institute; MPDT studies have been continuing at RIAME MAI and MAI in co-operation with Centrospazio (Italy).

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INTRODUCTION

A full review of development history and state of the art as of year 2002, as well as prospects of electric propulsion (EP) in Russia are given in paper [1] presented by leading Russian experts in the field of EP at the 38th AIAA/ASME/SAE/ASEE international conference on July 7-10, 2002 in Indianapolis, USA. A summary of this review that contains the renewed data as of February 2003 and takes into account materials of the review paper [2] on Russian electric propulsion systems presented at the 27th international conference in Pasadena, California, on October 14-19, 2001 is given below. The order of materials presented hereafter corresponds to the list of main results of electric propulsion activity in Russia stated in the above abstract.

1. FLIGHT OPERATION AND PROSPECTS OF SPT THRUSTERS APPLICATION

The flight operation data and prospects of application are systemized in accordance with the following Russian companies – developers of spacecraft with EP systems: NPO PM, RSC Energia, Khrunichev State Research and Production Space Center (SR&PSC), NPO Mashinostroyeniya.

1.1. NPO PM (Scientific and Production Association of Applied Mechanics)

Eight NPO PM's Gals-, Express-, Express-A-, and SESAT-type spacecraft equipped with SPT-100 and SPT-100B thrusters have been launched within a period from 1994 to 2003.
The main results of NPO PM's activity in the field of electric propulsion systems application as part of NPO PM-developed spacecraft are presented in papers [3, 4].

During the passed period since 2000 the new results of EP systems application as part of NPO PM's spacecraft as compared to previously published materials are:

1.1.1. An Express-A No. 4 spacecraft with the electric propulsion system similar to that used on previous spacecraft of this series has been launched and is successfully operating in orbit. Thus, a summary table of launches of the NPO PM's spacecraft with electric propulsion systems on board is as follows Table 1:

Table 1 - Launches of the NPO PM's spacecraft with electric propulsion systems on board

Spacecraft	Orbit	Thruster type (quantity)	Date of launch
Kosmos-1366 (Potok №1)	GEO	M-70 (4)	18.05.1982
Kosmos-1540 (Potok №2)	GEO	M-70 (4)	02.03.1984
Kosmos-1700 (Luch №1)	GEO	M-70 (4)	25.10.1985
Kosmos-1738 (Potok №3)	GEO	M-70 (4)	04.04.1986
Kosmos-1888 (Potok №5)	GEO	M-70 (4)	01.10.1987
Kosmos-1897 (Luch №2)	GEO	M-70 (4)	26.11.1987
Kosmos-1961 (Potok №6)	GEO	M-70 (4)	02.08.1988
Kosmos-2054 (Luch №4)	GEO	M-70 (4)	27.12.1989
Kosmos-2085 (Potok №7)	GEO	M-70 (4)	19.07.1990
Kosmos-2172 (Potok №8)	GEO	M-70 (4)	22.11.1991
Gals №1	GEO	M-100 (8)	20.01.1994
Kosmos-2291 (Potok №9)	GEO	M-70 (4)	21.09.1994
Express №1	GEO	M-100 (8)	13.10.1994
Luch №3	GEO	M-70 (4)	16.12.1994
Gals №2	GEO	M-100 (8)	17.11.1995
Kosmos-2319 (Potok №10)	GEO	M-70 (4)	30.08.1995
Luch-1	GEO	M-70 (4)	11.10.1995
Express №2	GEO	M-100 (8)	26.09.1996
Express-A №2	GEO	M-100 (8)	12.03.2000
SESAT	GEO	M-100 (8)	18.04.2000
Potok №11	GEO	M-70 (4)	05.07.2000
Express-A №3	GEO	M-100 (8)	24.06.2000
Express–A №4	GEO	M-100 (8) T-120 (1)	10.06.2002

1.1.2. An additional propulsion system based on the T-120 thruster developed by the Keldysh Research Center has been installed on Express-A No. 4 spacecraft in addition to the electric propulsion system based on M-100 thrusters developed by EDB Fakel.

The purpose of this additional EPS is to qualify the T-120 thruster in flight. Simultaneously with the flight test this thruster is planned to be used to perform standard orbit inclination corrections.

Trial firings showed that the additional propulsion system was normally functioning. Based on flight test results of the T-120 thruster a decision will be made regarding the use of this thruster on other NPO PM-developed spacecraft.

1.1.3. For prospective GEO satellites with a long-term life (15 years and more) NPO PM plans to use newly developed thrusters with an increased specific impulse and newly developed elements of propellant storage and supply systems. On a small-class Express-1000 platform it is suggested to use Hall thrusters with a specific impulse of no less than 2,000 s developed by Keldysh Research Center. For this very platform a xenon storage and supply unit with a mass that is significantly lesser than that of the existing models used in propulsion systems on board NPO PM's spacecraft is now being developed.

Thrusters with a specific impulse increased up to 2,500-3,000 s are planned to be used on Express-2000 platform. Experimental models of such thrusters are available at the Keldysh Research Center, EDB Fakel and TsNIIMASH.

1.2. RSC Energia

As of January 31, 2003 the total time of SPT operation aboard the Yamal-100 spacecraft manufactured according to the order from Gazkom JSC was **2,277** hours and **6** minutes at 4,083 firings.

RSC Energia is now developing new spacecraft equipped with electric propulsion systems.

In 1989 – 1990 they started experimental development works to create EPS for a heavy Universal Space Platform communications satellite (with a mass of ~ 17 tons). Last years these works have been given another impulse of development. At present time all the key technical problems to realize such an EPS have practically been solved.

In 2000, RSC Energia performed design development works on a EPS-based booster with a power of 10…15 kW for transferring a communications spacecraft from a high-elliptical start orbit to GEO. It has been shown that such a buster (without a power plant) will have mass about 700 kg. The use of such a booster in an Aurora-type rocket space complex being launched from the Baikonur Cosmodrome will allow spacecraft weighing up to 2,300 kg to be put into GEO at a transfer duration of 210 to 140 days and at a power plant's power of 10 and 15 kW respectively.

RSC Energia has also developed a project of a Yamal-type satellite to be placed into GEO-transfer orbit by using the existing Soyuz launch vehicle with a Fregat booster followed by a transfer from the GEO-transfer orbit to GEO using the on-board electric propulsion system.

1.3. Khrunichev State Research and Production Space Center

Yahta-D33 spacecraft – under qualification test. The spacecraft is intended for Earth remote sensing. The propulsion system consists of two SPT-100-type thrusters used for spacecraft orbit correction and attitude control. The total impulse is $4 \cdot 10^5$ N·s.

Yahta-GEO spacecraft – at a stage of Technical Assignment coordination. This is a communications satellite. The propulsion system consists of four SPT-100-type thrusters to be used for LEO-to-GEO transfer, orbit correction and attitude control. This spacecraft will be the first to be transferred from a transfer orbit to GEO by using an electric propulsion system with a total impulse of $1.35 \cdot 10^6$ N·s, including $0.5 \cdot 10^6$ N·s of total impulse for orbit correction and attitude control.

RAMOS spacecraft - at a stage of EP schematic coordination. The spacecraft is intended for optical and electronic observation of Earth surface.

1.4. Lavochkin NPO (Scientific and Production Association)

Fobos-Grunt spacecraft –draft design has been completed.

1.5. NPO Mashinostroyeniya (Scientific and Production Association)

Ruslan-MM spacecraft – at draft design stage. This spacecraft is planned to be transferred from a transfer orbit to GEO by using an electric propulsion system with a total impulse of $2 \cdot 10^6$ N·s, including $1.8 \cdot 10^5$ N·s of total impulse for orbit correction.

2. DEVELOPMENT OF ELECTRIC PROPULSION SYSTEMS FOR SMALL SPACECRAFT.

Improvement of overall performances of spacecraft imposes higher requirements to control actuators used for orientation, station keeping and attitude control concerning mass-dimensional and specific parameters of thrusters, and to the expansion of their functionality [5]:

- expanded thrust operating range of thrusters used;

- the possibility to adjust the thruster thrust vector at any moment, also in automatic control systems by each of spacecraft control channels [6];
- change of thrust vector direction both at the expense of thruster capabilities and at the expense of use of an actuator's external movable gimbal or the propulsion system as a whole;
- admissibility of thruster operation using additional propellants (for example, in a hydrazine propulsion system, the use of propellant tank pressurization gases at the final stage of spacecraft life, or the use of gaseous propellant in the spacecraft integrated propulsion system [7].

The calculation analysis of the application of different thrusters in propulsion systems of small spacecraft weighing 100-500 kg shows that the use of Hall thrusters is preferable at a propulsion system total impulse of more than $1.5\cdot10^4$ N·s for thrusters with a power of 100 W, and at a total impulse of $8\cdot10^4$ N·s and more for thrusters with a power of 500 W

The following Russian geostationary spacecraft can be attributed to that class: Exoress-1000, Gnom (NPO PM), Yahta (Khrunichev SR&PSC), Ruslan-MM (NPO Mashinostroyeniya) etc. The spacecraft mass is 400-900 kg, and active life is more than 10 years.

These requirements are of special importance for small spacecraft that are limited in energy, and development of which is now widely discussed.

Taking into account the above mentioned requirements Fakel has developed a number of propulsion systems which (or some of their elements) can be used in orientation, stabilization and attitude control systems of small spacecraft. First of all, these are electric propulsion systems on the basis of xenon stationary plasma thrusters (SPTs) and hydrazine propulsion systems based on different modifications of thrusters: thermal catalytic thrusters (TCTs), electric heating thrusters (EHTs), and arcjet thrusters (AJTs). These PS include propellant storage and management assemblies, for xenon and hydrazine respectively, actuators, as well as connecting pipes and electric cables. Calculations show that low-power SPTs are especially effective for such spacecraft. One of those thrusters – SPT-50 – is shown in Photo 2.

Table 2 contains the results of comparative analysis of use of different types of thrusters (EHTs, AJTs, SPTs) to solve the task of maintaining a standing point of geostationary spacecraft that weigh 600-1,000 kg and use EHTs in their propulsion systems. As follows from Table 1, the use of SPTs on a 1,000-kilogram satellite provides an EPS mass saving of about 370 kg and 180 kg as compared to the use of EHT-based or AJT-based propulsion systems respectively.

Table 2 - – EPS mass distribution on geostationary communications spacecraft

Thruster type		EHT	AJT	SPT
Specific impulse, m/s		3000	5000	13500
Spacecraft mass - 600 kg	Propellant mass, kg	134.8	84.3	34.8
	Propellant mass change, kg	0	50.5	100
	PS mass , kg	184.2	125	64,7
	PS mass change , kg	0	58.9	119.9
	Total spacecraft mass change, kg		120.4	219.9
1000 kg	Propellant mass, kg	224.4	140,3	58.0
	Propellant mass change, kg	0	84.1	166.4
	PS mass , kg	293	197	91.6
	PS mass change , kg	0	96	201
	Total spacecraft mass change, kg	0	180.1	367.4

While designing the PS configuration, the modular principle is generally used. It means that the propulsion system consists of separate units. Nomenclature and quantity of the units depends on particular requirements imposed by spacecraft no the propulsion system. However a monounit configuration of the propulsion system or its thruster units (TUs) is not excluded. For example, when an external movable gimbal is used on a spacecraft to change the thrust vector direction. An example of Fakel-developed thruster unit is shown in Photo 1.

The TU consists of:

- an SPT module that includes a discharge chamber, two cathode-compensators (main and redundant), structural elements that ensure thermal conditions of the thruster;
- a propellant storage system based on two high-pressure tanks with filling elements;
- a propellant flow controller consisting of small-size valves, a set of restrictors, pressure transducers, and a receiver.

The TU nomenclature and structure can vary depending on tasks to be solved by this thruster unit. In particular, other low power SPTs (being developed or qualified) can be used instead of the SPT-70 thruster. The main technical characteristics of the SPT-70-based thruster unit are presented in Table 3.

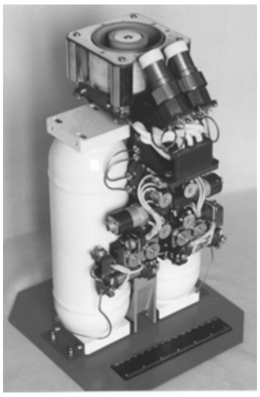

Photo 1 – Xenon TU (general view)

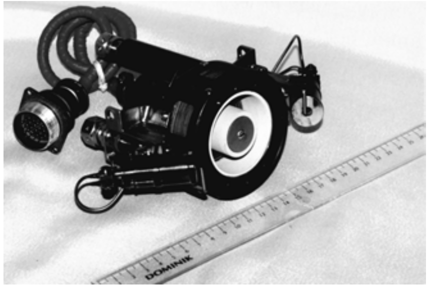

Photo 2 - SPT-50 (general view)

Table 3– Technical data of the xenon TU with SPT-70

Total impuls, kN·s	100
Thruster thrust, mN	40
Number of thruster actuations	1100
Minimal duration of one actuation, s	20
Pressure in propellant tanks, MPa:	
- BOL	12
- EOL	0.3
Overall dimensions L×B×H, mm	375×168×210
TU mass with propellant, kg	10.8

Three dimension-types of low power thrusters (KM-37, KM-45 и KM-60) were also developed at the Keldysh Research Center. The thrusters are intended for a power range of 100-600 W. The main parameters of these thrusters are shown in Table 4.

Table 4 – Parameters of KM-37, KM-45 and KM-60 thrusters

Thruster	Power, W	Thrust, mN	Specific impulse, s
KM-37	**90-320**	**5 – 19**	**800 – 1700**
KM-45	**180-420**	**10 – 26**	**1100 – 1600**
KM-60	**450-900**	**23 – 44**	**1700 – 2200**

3. PRE-QUALIFICATION WORKS ON SPT-140, DEVELOPMENT OF PROPULSION SYSTEM FOR FOBOS SPACECRAFT

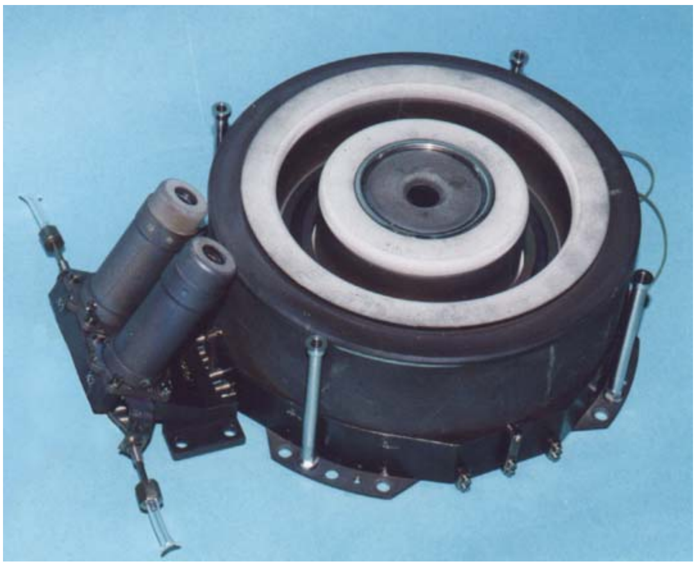

Photo 3 – SPT-140 model (general view)

3.1 Energy-and-ballistic analysis of present-day missions concerning interorbital transportation and orbit correction of heavy-weight geostationary satellite platforms demonstrates that these purposes require to build up a Hall thruster with a power of 3-6 kW in one modular block. Keldysh Research Center, EDB Fakel and TsNIIMASH are involved in creation of such thrusters. One of such thrusters - the EDB Fakel's SPT-140 - is shown in **Photo 3**. The works to prepare the SPT-140 for qualification test were also continuing in 2002. During this period a series of tests were carried out to study characteristics of this thruster at powers of 2 to 6 kW.

The thruster characteristics confirmed by the tests of the DM4 development model with a predicted life of 4,000…5,000 hours are presented in Table 5.

Table 5 - SPT-140 characteristics

U	I	N	F	M_Σ	Total Isp	Total Eff
V	A	W	mN	mg/s	s	
250	15	3750	256	14.5	1766	0.58
300	15	4500	287	14.5	1979	0.61
350	15	5250	311	14.5	2145	0.61
400	15	6000	331	14.5	2283	0.61
450	15	6750	350	14.5	2414	0.60
250	10.5	2625	190	11.2	1696	0.59
300	10.5	3150	212	11.2	1893	0.61
350	10.5	3675	220.8	11.2	1971	0.57
400	10.5	4200	240.8	11.2	2150	0.59
450	10.5	4725	255	11.2	2277	0.59
300	6.7	2010	134.6	7.7	1748	0.56
350	6.7	2345	144	7.7	1870	0.55
400	6.7	2680	150	7.7	1948	0.52
450	6.7	3015	161.2	7.7	2094	0.54

Mass, kg - 8
Overall dimensions, mm - 280×190×110
Predicted life, hour - 7200

3.2 Development of the thruster unit for the Fobos spacecraft.

In the framework of the Russian Federal Space Program a new project Fobos-Grunt is being developed. It is intended to be realized within 2007-2010. The scientific tasks of this project are:

- Landing on Fobos, taking soil samples and delivery of the lander with Fobos soil samples to the Earth;
- Studies of the Fobos physical and chemical characteristics, analysis of its internal texture, orbital and its own motion;
- studies of interaction between solar wind and Fobos;
- Remote studying of the Martian atmosphere and surface;
- Analysis of the Fobos soil samples delivered to the Earth.

The implementation of the project implies the application of the Soyuz medium-lift launch vehicle. To transport the spacecraft developed by Lavotchkin NPO from the Earth orbit to the Martian orbit, a three-stage rocket system should be used. It has to include a liquid-propellant engine of the Fregat booster, an EPS with solar power plant, and a liquid-propellant engine of the return launch vehicle with 50-kg thrust which is used also for spacecraft deceleration in a near-Mars orbit.

The use of solar-powered EPS nearly doubles the mass efficiency of the orbital injection in comparison with the application of chemical jet propulsion only. And this allows finally to use a relatively inexpensive Soyuz launch instead an expensive heavy-lift Proton launch vehicle.

The ballistic calculations impose the initial requirements towards EPS: necessity to create a thrust of $P=30 - 33$ *g* at the beginning of the trajectory of the flight to Mars at a power of 6.5 kW and a specific impulse of $I_{sp}=2,100$ *s*.

The EPS is based on three SPT-140s. During the flight the power consumption will vary in the range of 6.5 – 2.8 kW. One SPT-140 must provide required thrust and power levels at all stages of the flight while forcing it on discharge voltage. As far as flight goes on, at first, the first thruster should pass its life period which corresponds to the thrust impulse calculated value of 4.5 MN/s, then the second thruster should cover the remaining 3.5 MN/s at a reduced power consumption. The third thruster is in cold reserve condition and should be fired in case of failure of any of the two previous ones.

4. INVESTIGATION EFFORTS TO STUDY OPERATING MODES OF SPTs WITH HIGH SPECIFIC IMPULSE, AND TO STUDY THE POSSIBILITY TO USE SPTs IN TWO MODES

4.1. The list of spacecraft on which Russian manufacturers intend to use EPSs constantly expands. And spacecraft customers require increasing the spacecraft active life.

In Russia a traditionally important consideration is given to a research and design of Hall EPSs. During last years a few relatively latest options of such investigations have been formed, and these aim at the satisfaction of growing needs of the market for satellites with various power availability level and at the building of multifunctional EPSs.

One of these options is the activity on making Hall thrusters with the increased specific impulse and so-called multimode thrusters. The use of such thrusters will allow to extend effectiveness of EPS use while solving the task of LEO-to-GEO transfer and stabilization of geo-stationary earth artificial satellites in standing point and solving other problems.

Taking into account the tendency of extending the spacecraft flight operation duration the Russian spacecraft manufacturers consider the possibility to switch to more effective thrusters with a specific impulse of 2,000-3,000 s. Experimental models of thrusters with such performances have been built at EDB Fakel, Keldysh Research Center and TsNIIMASH.

Table 6 presents the characteristics of SPT-1 developed at EDB Fakel

Table 6- Characteristics of SPT-1 developed at EDB Fakel

Parameter	Value
Thrust, mN	98
Power, kW	2.3
Specific impulse, s	2,500 … 3,000
Thrust efficiency, %	0.65
Life, h	7,000
Mass, kg	3.5
Status	Laboratory model

4.2. Studies of a double-stage TAL

A wide-range possibility in adjusting the specific impulse in one thruster can be achieved using a scheme of a double-stage thruster with anode layer (TAL), models of which were studied at TsNIIMASH in different years. Works are currently continuing there to study a multi-mode double-stage D-80 thruster that is similar to the models previously created by TsNIIMASH in the framework of joint efforts with Boeing and NASA. The experiments are aimed at investigation of the ways to further increase thruster efficiency at moderate and low flow rates and at high accelerating voltages.

EDB Fakel is currently testing a prototype of the D-X0 thruster developed by TsNIIMASH in order to determine optimal modes of its operation for top range of @Bus platform. Qualification environmental tests and a 1000-hour life test of such a thruster manufactured by EDB Fakel are scheduled to be completed by 2006.

4.3. Efforts to create double-stage SPTs.

Examining the development of high specific impulse SPTs, it can be noted that flight SPTs had specific impulse values that did not exceed 1,600 s [8]. New SPTs, such as PPS-1350 [9] and SPT-140 [8], that have specific impulses of ~1,700 s and ~1,800 s, respectively, are under qualification now. In connection with new requirements to SPTs with respect to their power and/or specific impulse, and taking into account the widening of their application, it would be reasonable to investigate the possibility of creating SPTs capable of operating effectively at higher specific impulses (~3,000 s) and even more in order to estimate the ability of high power (4-6 kW) thrusters to operate effectively at least in two operating modes:

- in mode 1 with sufficiently high thrust and at a moderate specific impulse;
- in mode 2 with high specific impulse allowing mass saving for long-term missions.

Such dual-mode SPTs would clearly be of interest for geostationary satellites when using the mode 1 for contribution to orbit-to-orbit transfer, and when using the mode 2 for station keeping.

The SPT-140 laboratory model had design scheme traditional for modern SPTs. Its performances and plume parameters were registered at discharge voltages of Ud=200-1,000 V [10].

The obtained data are presented Table 7, Figure 1 and Figure 2.

Table 7 - The performances SPT-140 laboratory model

	M_a=3.0, mg/s		M_a=3.5, mg/s	
U,V	Isp, s	Eff	Isp, s	Eff
300	1550	0.43	1600	0.49
400	1950	050	2000	054
500	2250	0.53	2400	055
600	2500	0.55	2550	0.56
700	2750	0.57	2800	0.56
800	2800	0.57	3100	0.56
900	3150	0.58	3400	0.56
1000	3400	0.58	3550	0.56

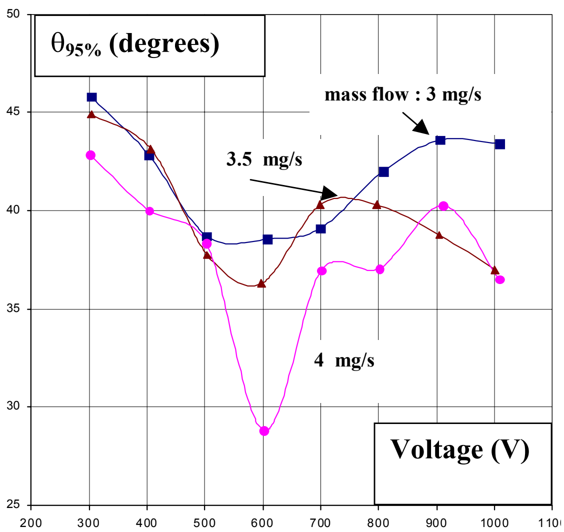

Figure 1– Angular distribution of mass flow as a function discharge voltage for three mass flows

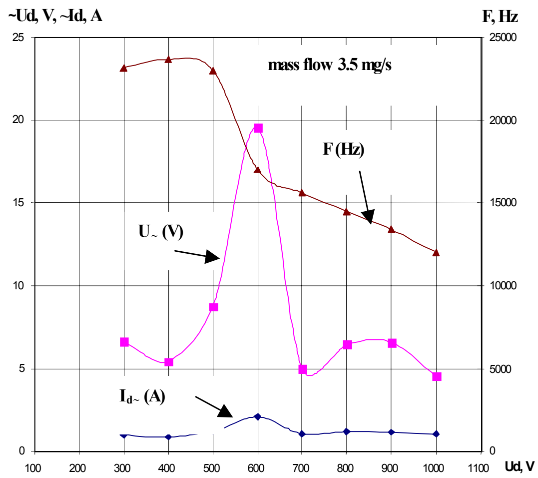

Figure 2– An example of oscillations evolution as a function of discharge voltage

The obtained data (Table 7, Figure 1, and Figure 2) show that:

- it is possible to achieve thrust efficiency η_a >0.55 and specific impulse Ispa >3,400 s (the values are calculated without taking into account the cathode mass flow) at a mass flow rate of (3-3.5) mg/s and at a discharge voltage of Ud~1,000 V, what means that it is realistic to obtain the total thrust efficiency of ~50% and total specific impulse over 3,000 s at powers of (3.5-4) kW;
- taking into account the fact that SPT-140 models have already demonstrated high performance level at moderate discharge voltages, one can conclude that on the basis of the SPT-140 thruster it is possible to develop sufficiently effective dual-mode SPT with an operating power of, at least, more than 3.5-4 kW;
- some operating modes of the SPT-140 laboratory model were found when the plume divergence (Figure 1) was significantly reduced, therefore it is interesting to study such operating modes more carefully.

5 INVESTIGATIONS OF SPT PLUME, PLUME INTERACTION WITH SPACECRAFT STRUCTURE ELEMENTS

At a number of Russian space-industry enterprises, theoretical and experimental methods are successfully used to estimate the influence of EP plasma plumes on:

- properties of spacecraft external coatings;
- interference for radio frequency and optical communications channels;
- changes in spacecraft orbital movements that became apparent in thrust losses and origination of torques;
- satellite electrization and current passing along its structure.

5.1. Computer-simulated and experimental studies of problems related to the influence of EPS operation on spacecraft systems

Software has been developed at TsNIIMASH to compute the impact of plasma plumes on geostationary satellites and their on-board systems. The software complex allows computing: parameters of both primary and secondary plasma plume of any electric propulsion thruster without any limitation of calculated area dimensions; plasma force influence; as well as plasma plume impact on optical sensors and radio communications. Mathematical models of artificial plasma formations (APF), which take into account the influence of plasma's own electric fields, external geomagnetic field [11, 12], secondary plasma, and spacecraft's own external atmosphere [13] on the APF characteristics, have also been developed there. These factors have significant effect on ion flow distribution in the electric thruster plumes. These models have been confirmed not only by test bench measurements but also by several independent methods [14] in space plasma experiments under EPICUR program.

In RIAME MAI, works are now being carried out to create a multipurpose software complex that will allow them to model various processes of EPS interaction with spacecraft: electrization, EPS's own electromagnetic radiation. MAI is continuing to develop application software dealing with practically all the above mentioned issues, namely: force influence, erosion influence, contamination, interaction with spacecraft's own external atmosphere, and interaction with solar arrays.

5.2. In-orbit studies of problems related to the influence of EPS operation on spacecraft systems

Investigations of plasma plume parameters are now being carried out on NPO PM's Express-type geostationary satellites.[15]

NPO PM places high emphasis on and systematically studies, under in-orbit conditions, the influence of SPT operation on spacecraft systems. Practically on all the spacecraft, disturbing moments that originate due to interaction between SPT plumes and spacecraft structure, and, first of all, solar arrays, are measured. The large body of information obtained allowed specifying more exactly the methods used to calculate the effects of thruster plumes interaction with spacecraft structure.

Onboard the Express-A No. 2 and No. 3 spacecraft launched in 2000 special scientific equipment was installed to study parameters of plasma thrusters' plumes. Sensors installed in different points of spacecraft allow determining ion current energy and density. Two motionless sensors are installed in the area where the payload (transponders) is located. Another two sensors are installed on the rotating wings of solar arrays, at different distances with respect to SPT. During their flight operation SPTs operate at different angular positions of sensors with respect to the thrusters. A set of data obtained allows plotting the ion current density and plume energy distribution as a function of angular and linear distance from the thruster. Of course, the very topical task is to compare flight measurements with similar ones taken under ground test-bench conditions.

Besides measurements of plume parameters, electric field intensity is measured in different points of spacecraft onboard the Express-A No. 2 and No. 3 spacecraft with both operating and non-operating SPTs. Onboard the Express-A No. 4 spacecraft launched in 2nd quarter of 2002, NPO PM plans to continue the study of SPT operation influence on spacecraft systems. Electric field intensity sensors as well as sensors to measure ripples in the transponders' and PPU's power supply circuits are installed on this spacecraft. In addition to these measurements, microatmosphere pressure in different points of spacecraft is supposed to be measured.

CONCLUSION

The high technical level of Russian Hall-thruster-based EPSs, confirmed by positive results of their long-term operation as part of NPO PM's and RSC Energia's spacecraft, shows that Hall thrusters are undoubtedly prospective for use on long-living spacecraft that have adequate power supply.

The dual-mode Hall thruster that allows using a high-thrust mode for contribution to an orbit-to-orbit transfer, and using a high-specific-impulse mode for station keeping is of certain interest to spacecraft developers.

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