ELECTRIC PROPULSION SYSTEMS OF THE SPACECRAFT: THE STATE-OF-THE ART IN DEVELOPMENT AND OUTLOOKS FOR PROGRESS

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1. Introduction

Sophistication of the tasks solved in space requires increasing the fraction of payload in a spacecraft structure and growth of active operation lifetime (AOL). Propellant reserve required for solving long tasks substantially decreases a fraction of payload, so the main direction in updating of SC thrusters is a rise in specific impulse.

Traditional liquid rocket engines of low thrust (LT LRE) provide the specific impulse no higher than 300 s with no reserve for increasing. With a rise of AOL from 10 to 15 years for a geostationary SC with a mass of 2 tons, the propulsion system (PS) mass fraction increases from 25…30% up to 40…45%. So, about a half of mass of a geostationary spacecraft with LT LRE, having a 15 year AOL, will fall to the share of the PS.

The situation changes radically at using electric propulsion. In that case it is possible to realize propellant efflux velocity up to 30,000 m/s and higher and, consequently, to make too high-economic engines. Use of electric propulsion systems (EPS) providing a specific impulse from 1500 to 3000 s in the structure of PS for orbit correction of a geostationary SC with AOL of 10 to 15 years substantially decreases the required propellant reserves. Mass saving in case of transition from LT LRE to EP will be hundreds of kg for a long-life SC.

The required specific impulse for most of the up-to-date applications having a practical value is 1000…3000 s. Among all the known engine types – resistojets, arcjets, pulsed plasma, magnetoplasmadynamic, Hall-type with closed electron drift (stationary plasma thrusters (SPT) and thrusters with anode layer) and ion thrusters (IT), the mostly favorable for this range of specific impulse are Hall-type and ion thrusters. Therefore the current state and prospective spacecraft applications of the Xenon utilizing Hall-type and ion thrusters are discussed bellow.

The analysis of efficiency of EPS application incorporated in the motion control systems of the orbital SC reveals that the most reasonable fields of EPS application are as follows:

- drag compensation of low-orbit SC;
- transfer from low reference orbit to high reference orbit;
- orbit raising and placement of satellites into orbital positions specified for the given constellation;
- compensation for disturbances of orbital parameters, stipulated by gravitational forces, solar pressure etc;
- SC removal from the orbit in case of a failure or spent service life.

Besides, at the present time, Hall-type and ion thrusters start to be used as cruise engines for fulfillment of transport operations both in near-Earth space and on interplanetary missions.

A brief review of state-of-the-art in development and application of Hall-type and ion thrusters in Russia and the rest of the world is given in the second section of the article. The lines of further development for thrusters of the noted types are presented in the third section. KeRC activities on high specific impulse EP are considered in the fourth section.

2. State-of-the-art in application of EP in Russia and the world

Active researches of EP were started in Russia more than 40 years ago by many organizations. The greatest success was achieved in development and practical use of stationary plasma thrusters.

The EPS based on SPT-class thrusters found a practical use on Russian SC. The first flight tests of the SPT in Russia still took place in the seventies. A standard usage of SPT-type serial thrusters started in 1982, when the thrusters SPT-70 with nominal power of 660 W and thrust of 40 mN were used for orbit correction in longitude (in the direction “East-West”) of the geostationary SC “Potok”. Later SPT-70 thrusters were also used as part of EPS for the SC “Luch”, “Luch-2”, “Kupon”, “Yamal-100”, “Yamal-200” [1].

Since 1994, SPT-100 with the nominal power of 1.35 kW and thrust of 85 mN have been used as a part of EPS of the geostationary SCs “Gals”, ”Express”, “Express-A”, “SESAT” and “Express-AM” for correction of both longitude and inclination (in the direction “North-South”) [1].

The SPT-70 and SPT-100 thrusters were developed by EDB “Fakel”. Besides, in the recent time a Hall thruster KM-5 developed by KeRC is undergoing flight tests aboard the geostationary SC “Express-A” #4 developed by NPO PM. The thruster is designed to operate at nominal power of 2 kW (thrust – 115 mN, specific impulse – 1850 s) and is capable to function at augmented power of 2.5 kW and de-rated power of 1.35 kW. The spacecraft with the KM-5 thruster onboard was launched in June 2002 with a “Proton” rocket.

At the present time, leading space states in the wake of Russia proceed to the practical application of Russian Hall thrusters in their SC. So, in 2002 it was made an attempt to place two geostationary SCs “STENTOR” (French Space Agency) [2] and “ASTRA-1K” (Alcatel Space) with the SPT-100 aboard to an orbit. Both spacecrafts were lost because of a launch vehicle failure.

In 2003, the European Space Agency launched the spacecraft SMART-1 towards Moon. A Hall thruster PPS-1350 with nominal thrust of 68 mN is used as a cruise engine of the spacecraft. Development of this thruster is a result of combined efforts of EDB “Fakel” and SNECMA (France).

Several Western SC with Russian SPT-100 thrusters onboard were launched within the year 2004. Among them two geostationary SC – IntelSat-10-2 (Eurostar 3000 platform developed by EADS Astrium) and Telstar-18 (LS-1300 platform developed by Space

Systems Loral), both launched in June 2004. Another one is Amazonas (Eurostar 3000 platform, EADS Astrium), launched in August. A spacecraft AMC-12/WorldSat-2 (Spacebus 4000C3 platform, Alcatel Space) was launched in February 2005. Another spacecraft, Inmarsat-4/F1 (Eurostar 3000 platform, EADS Astrium) was launched in March 2005.

Practical use of ion thrusters was initiated in 1997, when USA launched PAS-5 and Galaxy-8i communication spacecrafts, based on the platform BSS-601HP by Boeing Satellite Systems Company with ion thrusters XIPS-13. In 2000, the Galaxy-11 satellite on the platform BSS-702 equipped with the second-generation IT XIPS-25 with 4.5 kW of power was launched, where for the first time a PS with IT was aimed not only for orbit correction, but also for carrying out interorbital transfers during SC orbit placement. A spacecraft Deep Space-1 intended for exploration of 19P/Borrelly comet was launched in 1998 by the USA. A 30-cm xenon ion thruster XIPS-30 with 2.3 kW of power and 92 mN of nominal thrust, whose development was conducted at the Lewis Center, later - at Hughes and JPL companies, had operated as a cruise engine during 16,265 hours [3].

In Europe an EPS named RITA was used in 1992 aboard a low-orbit research platform EURECA for a flight test of RIT-10 IT with radiofrequency ionization, developed in Germany. In the year 2001 RIT-10 (EADS Astrium, Germany) and UK-10 IT with electron bombardment (EADS Astrium, Great Britain) were launched to an orbit together within an EPS of an experimental geostationary communication SC Artemis [4].

Ion thrusters developed and made in Japan successfully operated on experimental geostationary SCs ETS-3, ETS-4 and COMETS, launched in 1982, 1994 and 1998 respectively. In 2003 an interplanetary SC MUSES-C was launched where the 10-cm microwave IT IES developed by the Institute of Space and Astronautical Science (ISAS) at 0.4 kW of power is used [5].

Thus, widening the field of application of electric propulsion on spacecrafts is one of the leading and regular tendencies on the present stage of space activities in the world.

3. The main lines of prospective Hall and Ion thrusters development

Further improvements of Hall thrusters are associate with modern trends in SC development, such as the growth of power-to-weight ratio and increase of AOL, urge towards enlargement of payload fraction in a spacecraft structure, widening of SC mass range, including low weight-size SC and heavy satellite platforms, rise of EPS task complexity, growth of demands on efficiency, reliability and SC system compatibility. All the aforementioned stimulates development of new generation Hall thrusters, having the following main features:

- increased specific impulse (up to 2500…3000 s);
- capability to operate efficiently in a wide range of consumed power magnitudes, from low (50 or less…100 W) to high (up to 50 kW and above per unit thruster);
- increased service life of continuous operation (for some applications it is to be up to the values in range of 8000… 10000 hours and above);
- decreased angular divergence of a plume that’s important to reduce the influence on SC members;

The following key problems are to be solved while developing new generation hall thrusters:

- to find out the main regularities of acceleration channel and magnetic system profiling that would allow to reach high efficiency and extended lifetime for a thruster operating in a range of discharge voltage values up to 1000 V;

- to increase the performance of low-power thrusters;
- to determine the conditions of high-performance functioning for the same thruster at different power and discharge voltage levels with lifetime retaining;
- to develop the trustworthy methods for accelerated life tests, that is useful for cost and time reduction;
- to search for wearproof structural materials, maintaining prolonged operation with a high level of performance.

As for the prospective ion thrusters, that are mainly considered as a solution to be used for interplanetary mission, one can mention the following lines of development:

- rise of the specific unit power up to 50 kW and above;
- rise of active operation time that can amount to tens of thousand hours;
- search for cheaper than Xenon propellants, sustaining high thruster performance.

The main EP developers in Russia and abroad are recently solving the aforementioned problems.

4. KeRC activities in the field of EP

Today, the active works on the subject of EP are underway at KeRC. The activities include research and development (R&D) as well as the creation of thruster flight models. The emphasis is made on development of Hall thrusters.

4.1. Hall thrusters

Main purpose of the new generation Hall thruster development program is to solve the key problems marked in the chapter 3.

Two laboratory hall thrusters with high specific impulse are developed at KeRC in the course of high specific impulse Hall thruster magnetic optimization activities. These thrusters operate at nominal power of 900 W and 2000 W, respectively. The operation voltage can be up to 1000 V. Both thrusters have an enhanced capability for magnetic field topology transformation. Design of the thrusters includes four coaxial magnetic coils and a set of coaxial magnetic screens. The magnetic system allows changing the axial and radial position of plasma lens and the shape of magnetic field lines by varying current ratio in the coils during an experiment. To investigate the influence of magnetic lens topology on the structure and position of the accelerating layer the thruster is equipped with a set of near-wall Langmuir probes. The probes are placed in the external ceramic wall of discharge chamber. The recent experiments are performed on the 900 W model. The purpose of the experiments is to study the influence of magnetic field parameters onto the thrust, specific impulse, efficiency, propellant utilization coefficient, ion to electron current ratio, average ion energy, length and position of the acceleration layer. Two variants of magnetic field topology that differ in the inclination of magnetic field lines with respect the thruster axis are shown in figure 1.

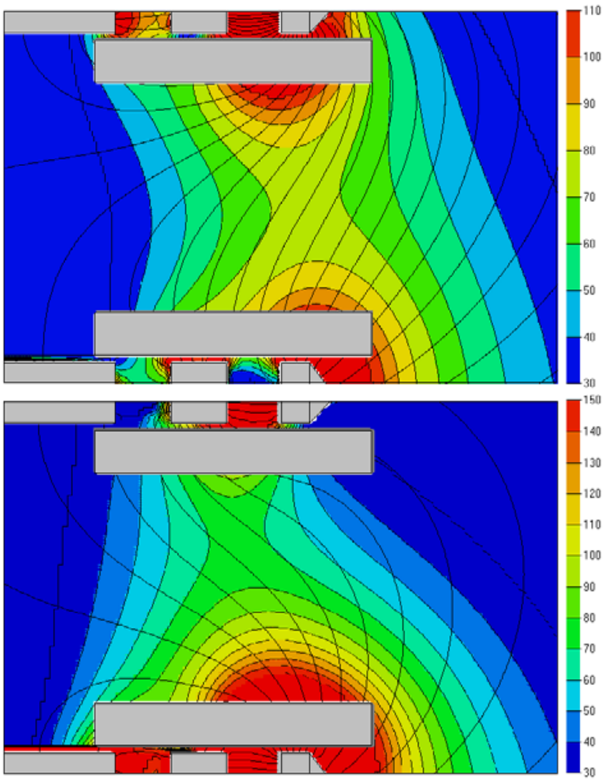

Fig.1

Another field of research is associated with searching for the optimal design of a high voltage HET channel.

For this purpose studies of performance and local parameters in the channel of a laboratory Hall thruster with nominal power of 700 W are carried out on different designs of the discharge channel exit part. The studies are performed at various voltages in range of 300…600 V. The classical design of the discharge chamber with cylindrical ceramic walls is compared with the hybrid design in which the basic part of the discharge chamber is made of metal, and the exit zone is equipped with ceramic rings. Design variations with different height of discharge chamber metal part and length of ceramic rings are investigated.

A fully kinetic numerical model aimed for better understanding of processes in a Hall thruster discharge is under development. The model is two-dimensional in space and three-dimensional in velocities and treats electrons, ions and neutrals as particles. Coulomb collisions, elastic and ionization electron-neutral collisions, electron-neutrals excitation, charge-exchange and ion-wall recombination are accounted for. Electric filed is defined from Poisson's equation. Using the model there were obtained distributions of plasma parameters for several operational modes of low power HETs developed at KeRC. An example of results of HET plasma density calculation is presented in figure 2.

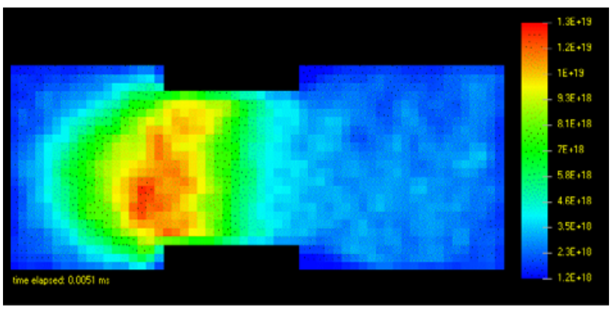

Fig. 2

In the recent time main efforts are made to decrease the computation time and to improve the accuracy of boundary-condition modeling and collisions simulation. It is planned to represent the results of the noted studies on the International Electric Propulsion Conference that is to take place in USA, in autumn 2005.

A software package for modeling of interaction between a plasma plume and a spacecraft is being developed for solving the problems appearing in the course of electric thrusters integration within a spacecraft (see fig. 3). The computations can provide data on thrust loss, misalignment angular velocity, spacecraft units overheating, changes of mechanical and optical properties of spacecraft external surfaces and solar panels.

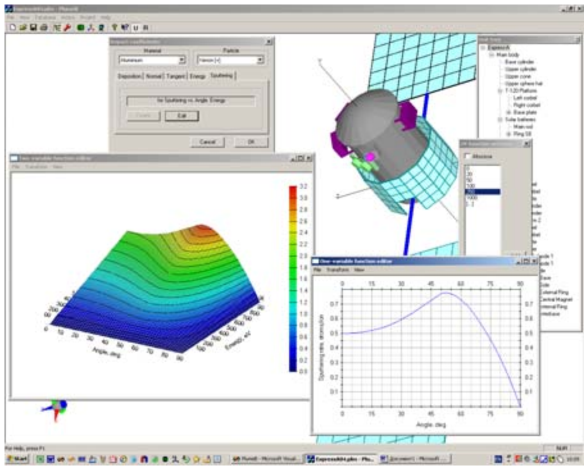

Fig. 3

Methods of optical spectral emission diagnostics of Hall thruster plume are developing rapidly. Studies intended to measure erosion rate of Hall thruster accelerating channel using spectral methods are performed during both long-term firing life tests and working mode optimization firing tests. The experiments allowed to detect spectral emissions of thruster ceramic wall atoms and to observe a good correlation between the lines intensity and the erosion rate measured by a direct method (see fig. 4). The method of non-contact optical diagnostics may become a part of an accelerated life tests procedure. The latter can be very important for life test time and cost reduction.

Thrusters of different types and sizes with a power from 50 W to 6 kW have been made with a use of the mentioned research data. These are the thrusters of low power (up to 1 kW) – KM-37, KM-45 [6], KM-60, the mean-power thrusters (1 to 2.5 kW) – KM-4, KM-5, KM-100 and the thrusters of high power – KM-6, KM-7. The Hall-type thrusters KM-5, KM-7 and KM-45 have been successfully subjected to qualification tests.

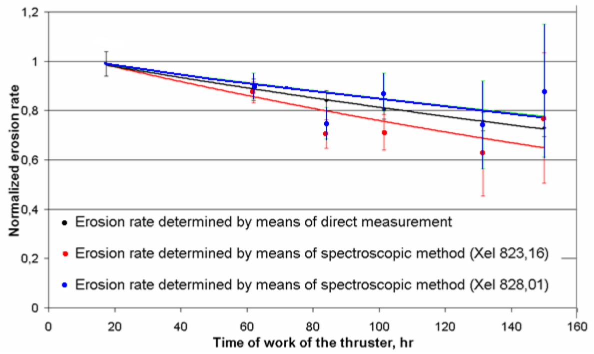

Fig. 4

Nowadays the KM-5 Hall thruster is undergoing flight tests aboard the geostationary "Express-A" SC developed by NPO PM.

The Hall thruster KM-45 (fig. 5), with nominal thrust of 18 mN at power 350 W is designed for small spacecraft (mass up to 500 kg), e.g. "Gnom" SC.

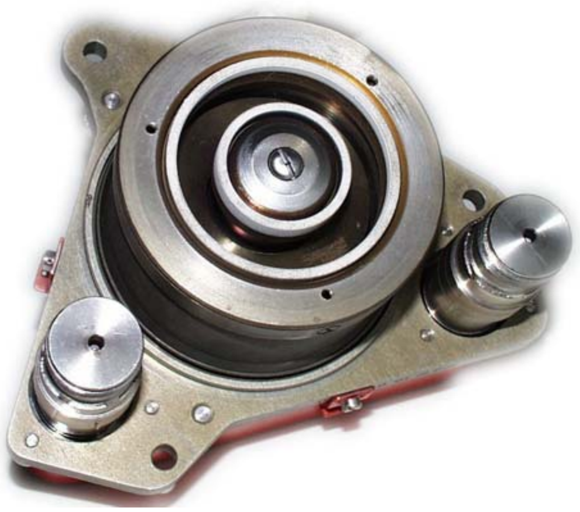

Fig. 5

A high power thruster KM-7 (3.5…6 kW, 200…450 mN) is designed for orbit correction of heavy GEO SC (e.g @Bus platform developed by Alcatel Space and EADS Astrium). This thruster can also be fitted on a European space tug ConeXpress that is aimed for sustaining operability of GEO satellites with exhausted lifetime or for rescue of spacecrafts with improper orbital placement.

A 10 kW thruster KM-10 based on a design of T-220 thruster is being developed. It is designed for inter-orbital transport systems.

Following the tendency of optimal specific impulse increase, KeRC develops KM-60 and KM-100 thrusters with enhanced specific impulse. KM-60 thruster is to be used on prospective geostationary light-weight platform. Its specific impulse at 900 W of power is about 2000 s in the beginning of lifetime. The development is now at the engineering model stage. The environmental resistance tests are recently performed as well as the integrated firing life tests with a xenon flow control unit. Two cathodes have already passed the autonomous cycling life test. Each cathode successfully operated in course of about 20000 On-off cycles.

The development of KM-100 thruster with a high specific impulse for an advanced geostationary mid-weight platform has been started. A laboratory model of the thruster is capable to operate at power of 1.5…2.5 kW with a specific impulse of 2500…3000 s.

4.2. Ion thrusters

The works in field of IT development are performed in cooperation with Moscow Aviation Institute. Recently the main efforts are concentrated on studies of IT using alternative propellants for interplanetary spacecraft propulsion. A 30-cm IT is used as a prototype of such thrusters. Comparative tests of the thruster were performed on Xenon, Krypton and Argon at power of 5 kW.

4.3. Experimental and production basis

KeRC has created an experimental and production basis for HET laboratory research and development, as well as for flight models manufacturing.

Up-to-date test base allows research and update of thrusters with a power up to 10 kW. More than 10 experimental installations have been actuated for testing of EP, EPS and their members.

The cryovacuum facility CVF-35 is intended for performing firing tests, including life tests of thrusters with a power of up to 6 kW. The vacuum chamber of the facility has the volume of 35 m^3 and the diameter of 3 m. The total capacity of the vacuum system is 42 m^3/s for xenon.

Considering the experience gained during operating the CVF-35 facility, the new big cryogenic vacuum stand CVF-90 has been put into operation for tests of high-power EP with a vacuum chamber of 90 m^3 volume. The total pumping rate after installation of all cryogenic pumps will reach 200,000 l/s (by xenon) [7]. The facility allows to perform high power electric thruster life tests, as well as all types of limited firing tests and parameterization. The test stand is equipped with the plume diagnostics system that allows measurement of plasma plume on operation of Hall thruster.

As of the moment the stand makes it possible to conduct firing tests of Hall thrusters with a power up to 10 kW. The total capacity of pumping comprises 71,000 l/s.

5. Conclusion

1. The EP differ beneficially from LT LRE by the higher value of specific impulse which results in that the total mass of EP becomes less than that of chemical PS at comparable values of the total impulse. A gain due to the application of EPS grows with increasing total impulse.

2. At the present time EP are actively used both in Russia and in the world. Development of advanced SC makes creation of next-generation EP actual.

3. Today, the active works on the subject of EP are underway at KeRC. The activities R&D as well as the creation of thruster flight models. A family of Hall thrusters designed for operation in the range of power from 50 W to 6 kW, including flight models of thrusters, has been developed.

4. KeRC has its own modern test and production base allowing the manufacturing of flight thrusters.

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