Stationary Plasma Thrusters in Russia: Problems and Perspectives

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Abstract

The state of the Stationary Plasma Thruster (SPT) development in Russia and directions of their further development are considered in this paper. It is shown that development of thrusters of different power is reasonable nowadays including development of the medium power SPT with increased specific impulse and life time. The problems appearing in the different directions of development are considered also.

Keywords

stationary plasma thruster (SPT); spacecraft (S/C)

Introduction

As it is known [1], SPT's had started to operate in space in 1972 and since that time they are regularly used for the spacecrafts (S/C) orbit correction. The main developer and producer of the flight SPT versions in Russia is Experimental Design Bureau (EDB) Fakel and by now over 300 thrusters produced by this EDB were operating or are operating in space. Thus, SPT had become the really operating example of the space technology. Therefore it is interesting to consider perspectives of the further SPT development and problems to be solved during such development.

1. Characterization of the Modern State of the SPT Development and Its Perspectives

As was noted SPT's successfully operate in space and scales of their application are growing. The SPT-70 and the SPT-100 type thrusters developed by EDB Fakel were used onboard many spacecrafts (Figure 1, Table 1, [2]). Nowadays the medium power SPT-140 with specific impulse ~1770 s, the SPT-100D and SPT-140D thrusters able to operate with increased till 2750 s specific impulses are developed at Fakel (Table 2, [2]). Flight SPT versions including that ones with increased specific impulse are also developed by experts of the Keldysh Research Center (Table 3, [2]). Therefore one can expect that in the nearest future thrusters represented in the Tables 2 and 3 will be regularly used in space too. First they will be used to solve the traditional for SPT task of the geostationary satellites final positioning and station keeping, their repositioning and deleting to the storage orbit after finishing of the satellite operation. It is reasonable to add that with help of SPT the Smart-1 spacecraft from the near the Earth to the near the Moon orbit transfer was realized by European Space Agency (ESA) [3] and in USA the final orbit transfer of the AEHF-1 spacecraft with help of BPT 4000 thruster was realized also [4]. Thus, solving of new tasks with help of SPT had been started. More over, if one takes into account that very impressive asteroid sample return mission Hayabusa was successfully realized by Japan with help of ion thruster having not very high mean specific impulse and thrust efficiency [5] and some mission analysis including development of the «Fobos-Soil» mission ballistics [6] one can conclude that at least SPT-140 and SPT -140D thrusters with performance data represented in the Table 2 but with increased life time could be used for realization of some interplanetary and deep space missions.

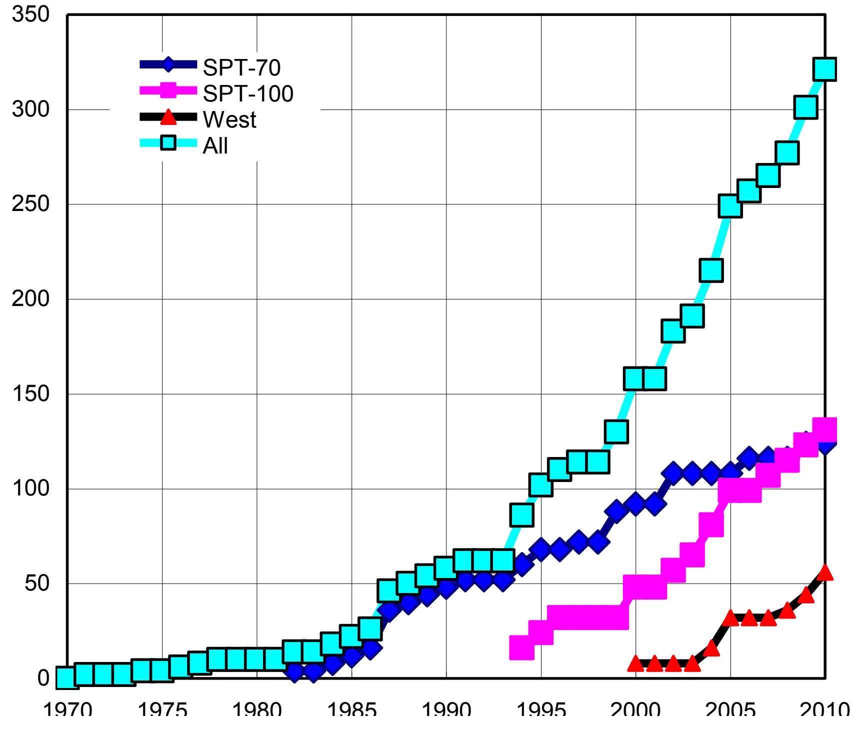

Figure 1 - Number of the SPT was Operating or Still Operating in Space Versus Years

Table 1

Fakel's Flight SPT Performances

Performance	SPT-50	SPT-70	SPT-100
Nominal Power, W	~500	700	1350
Discharge Current, A	2.65	2.17	4.5
Discharge Voltage, V	190	300	300
Thrust, mN	30	40	83
Specific Impulse, s	1300	1500	1600
Lifetime, hours	2500	3100	7500(9100)

Table 2

Performance of the Fakel's Flight SPT Versions under Qualification

Performance	SPT-140	SPT-100D	SPT-140D
Power Range, W	3000-5000	600-2100	3000-5000
Nominal Power, W	4500	2100	4500/4800
Discharge Voltage, V	300	800	300/800
Thrust, mN	290	75	290/180
Specific Impulse, s	1770	up to 2750	1770/2750
Lifetime, hours	11000 (qual.)	7000 (qual.)	15000 (qual.)

Table 3

Performance of the Keldysh's Research Center Flight SPT and SPT Versions under Qualification

Performance	KM-5	KM-45	KM-60	KM-88	KM-7
Power Range, W	1350-2500	200-450	450-1100	1000-2500	3500-6000
Thrust, mN	80-140	10-28	30-50	50-105	200-380
Specific Impulse, s	1600-2100	1250-1500	1200-2200	2000-3000	1700-2650
Status	Flight version	qualified		Under qualification	qualified
Lifetime, hours	More than 2000 in flight	No published data	More than 4000	No published data	

Thus, the SPT application area is extended and to realize new missions it is necessary to improve thruster operation organization and design first of all to increase thruster specific impulse and life time. Particularly, even for modern geostationary satellites station keeping the optimum specific impulse is ~3000 s and for many deep space missions it is better to have even higher specific impulse and life time exceeding 15000 hours. Taking the mentioned into account according to European space program the T-6 ion thruster was developed and qualified able to operate with powers till 6 kW and specific impulse till 4500 s [7]. In USA the NEXT multimode ion thruster with power till 7 kW and specific impulse till 4500 s was developed too [8]. Therefore besides finishing of the SPT-100D and SPT-140D development with increased specific impulse and increase of their life time it seems reasonable to develop the medium power SPT with specific impulse over 3000 s and life time exceeding 15000 hours which will be able to solve the tasks similar to that ones to be solved by the mentioned ion thrusters.

It is necessary to note also that nowadays the spacecrafts masses are extended in direction of their reduction as well as in direction of their increase. For SPT it is interesting to consider small spacecrafts with masses from 50 kg till 500 kg. If one assumes that these spacecrafts will be able to provide power with rate ~1 W/kg to the electric propulsion system (EPS), then it is necessary to have thrusters able to effectively enough operate with powers 50…500 W. For the power range 200…500 W the already existing flight version of the SPT-50 could be used. So, for Russia it is interesting to develop SPT for the power range 50…200 W. Development of such SPT's been and are made in many countries and institutions [9]. As it will be shown in the part 2 of this paper the main problem of the effective low power SPT development is difficulty to create optimum magnetic field topology within the accelerating channel. Therefore the final result depends on skills of the persons developing thruster. Particularly, it was shown by RIAME experts during 1998-2000 that acceptable thruster performance under discharge powers ~100 W could be obtained with usage of the simplest single coil magnetic system (Fig.2) for thrusters with external accelerating channel diameter 20…25 mm [10]. Further development and improvement of thruster models with such design by Kharkov Aviation Institute (KhAI) experts had allowed obtaining of high enough performance and large enough life time even under powers less than 100 W [11]. Another design options are considered by other experts. For example, in Italy the low power SPT with permanent magnet is developed having some advantages in the magnetic field creation [12]. Fakel's experts are developing new low power SPT version [13]. Thus, by now some solutions of the low power SPT were elaborated and in the nearest future one can expect appearance of the low power SPT flight versions onboard small spacecrafts.

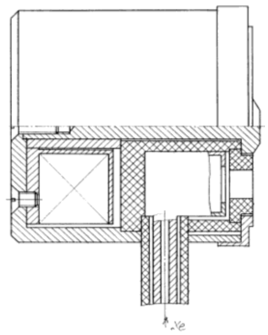

Figure 2 – Design of the SPT-20 with External Accelerating Channel Diameter 20 mm

Figure 3 – Laboratory Model of the SPT-100 (in the Left) and SPT-25, SPT-20 (in the Right)

Concerning SPT of increased and large power one can note that possibility to create effective enough thrusters with operating power till 35 kW was shown already in USSR many years ago [9]. At the beginning of 2000^{th} the laboratory model of powerful SPT was created and tested in USA under powers till 95 kW effectively enough operating with Xenon and Krypton and able to operate with specific impulses till 4500 s [14]. Taking into account that in the nearest 20…30 years the power plants with the solar batteries will be dominating in space one can estimate that upper level of the spacecraft power will be limited by ~100 kW. Therefore for the mentioned period of time it seems sufficient to have flight versions of SPT with nominal power 15…20 kW including versions of such thrusters with increased specific impulse and large life time. On base of such thrusters it will be possible to develop propulsion systems and transport modules with power till 100 kW. In connection with development of the megawatt nuclear space power plant started nowadays in Russia it is interesting also to develop not only powerful ion thruster [15], but also the flight SPT versions with power 50…100 kW able to operate effectively enough with specific impulses 2000…4000 s at least and having large lifetime. EPS of megawatt-class on base of such thruster and corresponding transport modules can solve wide enough range of tasks in space such as the Moon cargo and manned missions etc.

So, for the nearest 20-30 years one can consider as the challenging the following directions of the SPT development:

- development and creation of the low power SPT flight versions able to effectively and stationary operate under powers ~100 W and less;
- development and qualification of the multimode SPT with power 5…7 kW, maximum specific impulse over 3000 s and life time exceeding 15000 hours;
- development of SPT with nominal power 15…20 kW able to effectively operate with specific impulses 2000…3500 s and SPT with power within the range of 50…100 kW able to effectively operate with specific impulses 2000….4000 s with Xenon and alternative propellants for the powerful propulsion systems.

2. Problems to be solved under further SPT development

As was noted above the main problem of the effective low power stationary operating SPT is creation of the optimum magnetic field topology within thruster accelerating channel. This difficulty is caused by the necessity to reduce the mass flow rate through the accelerating channel to reduce discharge power because the discharge current in SPT in the first approximation is proportional to the mentioned mass flow rate. As result under reduction of the mass flow rate it is necessary to reduce the accelerating channel cross-section area that is to reduce its mean diameter d and width b_{ch} in order to ensure great enough plasma concentration n and small enough free pass $\lambda_i = V_a / \langle \sigma_i V_e \rangle n$ of atoms before their ionization by electrons, where $\langle \sigma_i V_e \rangle$ is the ionization rate factor averaged through the electrons distribution function in velocities. This free pass is to be significantly less than the accelerating channel length to ensure high probability of atoms ionization within the accelerating channel. But under reduction of the accelerating channel sizes it is necessary to reduce sizes of the magnetic system elements and gaps in between them to get optimum magnetic field topology. At the same time with reduction of thruster scale it is necessary to increase magnetic induction B_r in the working gap of magnetic system and respectively in the magnetic core because according to the SPT scaling laws [16-17]

$$B_r b_{ch} \approx const. \tag{1}$$

This means that it is impossible to optimize the magnetic field topology due to saturation of the magnetic core elements under accelerating channel diameters less than 40…50 mm. So, for the low power SPT it is necessary to use the nontraditional magnetic systems and as was shown above some solutions of the low power SPT were already developed.

As was shown above, one of the important directions of the further SPT development is an increase of specific impulse. And one of the main problems for high specific impulse SPT development is elaboration of solutions allowing obtaining of large SPT lifetime. The most evident and simplest way to increase SPT specific impulse is an increase of the discharge voltage but the higher discharge voltage the more complicated is the mentioned problem. Indeed, with increase of the discharge voltage it is necessary to reduce the mass flow rate through the accelerating channel in order to maintain moderate level of the power density and moderate power release on thruster elements. Under fixed power the highest specific impulse is achieved with lowest mass flow rate through the accelerating channel (Figure 4, [9, 18]). But with reduction of the mentioned mass flow rate the efficiency of the propellant ionization and thrust efficiency are reduced due to reduction of plasma concentration within the accelerating channel [18]. Moreover reduction of the mass flow rate below definite level causes extension into anode direction of the ionization and accelerating layer where the main potential drop is realized. This extension causes an increase of ions and power losses on walls and increase of the wall erosion rate more significant than increase of the discharge voltage (Figure 5, [19]).

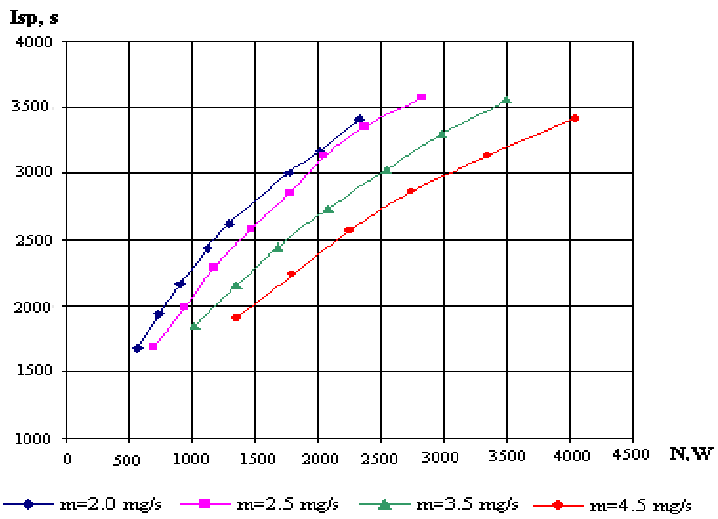

Figure 4 – Specific Impulse of the SPT-100 Laboratory Model versus Discharge Power under Different Mass Flow Rates

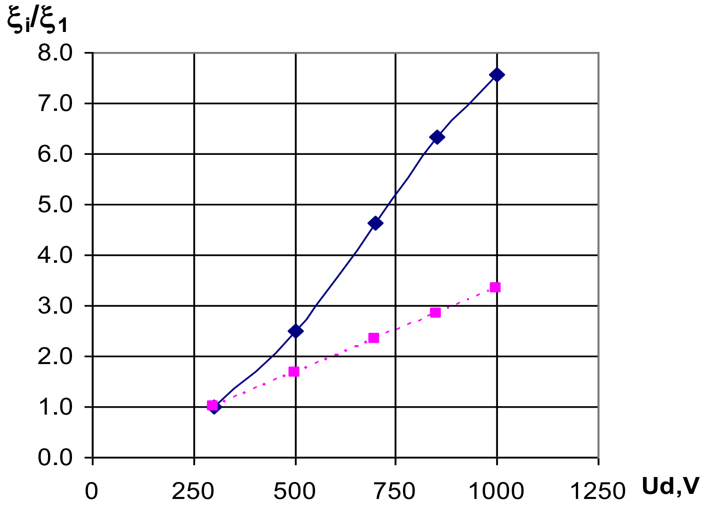

Figure 5 – Relative Increase of the Discharge Voltage (Lower Curve) and of the Discharge Chamber Erosion Rate Related to the Unit of the Mass Flow Rate for the SPT-100 Laboratory Model

Thus, the problem of the life time increase for thrusters with increased specific impulse is complicated enough and to solve this problem it is necessary to use complex of solutions including improvement of thruster operation and design, rational choice of operation mode and material of the discharge chamber, etc.

It is important to note that solving of this problem is simplified with increase of thruster scale. Indeed, results of investigations show that with increase of the thruster sizes one can maintain rough similarity of the magnetic system elements geometrical configuration, surrounding an accelerating channel, and as the main scaling parameter one can use the accelerating channel width [16, 17]. Besides, for optimized thrusters with geometrical similarity of the mentioned magnetic system elements and of the accelerating channel cross-section configuration one can obtain that comparable conditions for the propellant atoms ionization are achieved, if the ratio of the mass flow rate $\dot{m}_a$ through the accelerating channel and accelerating channel diameter satisfies the following condition [16, 17]:

$$\frac{\dot{m}_a}{d} \approx const. \tag{2}$$

As result the required mass flow rate to obtain comparable ionization efficiency is increased with increase of thruster sizes proportionally to its characteristic diameter but not proportionally to the accelerating channel cross-section. Therefore in thrusters with increased sizes according to relationship (2) one can obtain acceptable ionization efficiency under reduced mass flow rate density $\dot{m}_a / \pi d b_{ch} \sim 1/b_{ch}$ and increased discharge voltage what means that the same power density one can obtain under operation mode with increased discharge voltage and specific impulse [16, 17]. Moreover, for such thrusters under comparable power densities in the first approximation thruster life time is proportional to the accelerating channel width or thrusters scale [16, 17]. These conclusions were partially confirmed by development and tests at RIAME under operation modes with high specific impulse of the SPT-140 scale laboratory model having external accelerating channel diameter 140mm and its width 20 mm. Parametric and 100-hours erosion tests of this model had shown that [19]:

- thrust efficiency ~0.55 calculated not accounting for cathode mass flow rate could be obtained under discharge voltages till 1000 V, mass flow rate through the accelerating channel ~4 mg/s and power close to nominal one for the SPT-140;
- under discharge voltage 950 V ensuring the possibility to get total thruster specific impulse 3000 s and power ~4.2 kW the obtained erosion rate allow prediction of the thrusters lifetime not less than 10000 hours.

Estimations with usage of the scaling laws show also that for the SPT-500 with accelerating channel external diameter 500 mm and accelerating channel width 60mm under operation mode with discharge voltage ~2 kV and mass flow rate ~25 mg/s one can expect thrust efficiency not less than ~0.6, specific impulse not less than 4000 s and life time not less than ~30000 hours. These estimations show that powerful SPT is able to provide high enough thrust efficiency and life time under operation modes with specific impulses till at least 4000 s. Naturally to develop powerful SPT it is necessary to solve the problem of the large scale discharge chamber manufacturing and to create facilities for their ground testing. Particularly, it is necessary to create vacuum chambers of large sizes with great pumping speed for their evacuation. For example, for the ground tests of the SPT-500 operating with power 50 kW and mass flow rate ~100 mg/s (specific impulse ~2000 s) it is necessary to have pumping speed over ~1500 m^3/s, if the acceptable pressure inside vacuum chamber during tests is $\sim 1\times10^{-5}$ Torr. Estimations show also that vacuum chamber diameter for the SPT-500 tests preferably is to be larger than 5 m.

It is necessary to add that development and qualification of electric propulsion thruster (EPT) with lifetime 5…10 thousand hours within more or less general programs takes 5…10 years. Therefore development of EPT with large life time is to be started significantly earlier of its possible application time. So, it is right time to start development of the mentioned above SPT's with increased power, specific impulse and lifetime.

Conclusion

As it follows from the abovementioned SPT was successfully implemented into space technology and there are some directions of its further development which will allow extension of their application. The problems to be solved to realize these opportunities were considered in the given paper.

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