Development of Next Generation APPT at RIAME

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Abstract: The known APPT advantages, its simplicity, efficiency, low production and operation cost, capability for normal operation at the power consumption from units to hundreds of W being among them, allow it to meet requirements imposed on the thrusters of low-orbit mini and micro spacecraft (MSC) flight control systems to the maximum extent. But under the conditions of growing competition from the side of other electric propulsions characterized by low thrust and power, low thrust efficiency of "typical" APPT limits possibilities for its technologically and economically justified application substantially. The APPT efficiency jump within the mentioned power range that was reached in recent years makes it advisable to equip low orbit MSC designed for different purposes with such reliable and inexpensive electric propulsion systems.

Efforts aimed at the development of highly efficient APPT were concentrated at RIAME ten years ago, and at the turn of centuries results were obtained, which allow speaking about the development of a thruster of next generation.

Brief analysis is presented for the publications containing results of work, which made, in the author's judgment, real contribution to the development of highly efficient ablative pulsed plasma thrusters.

Besides, a number of characteristics is presented, which demonstrate differences between the next generation thruster and APPT with low efficiency of operation process most clearly.

I. Introduction

It is 10 years in 2007 since [1] was published, in which in very general form there were presented ideas on the ways to solve the problem of increasing extremely low efficiency of the operation process of APPT with the discharge channel of rail type and Teflon as propellant. It became a bench mark for the beginning of large-scale developments at RIAME, which were aimed at obtaining considerable growth in the thrust efficiency of the thruster. Some results of work oriented at the APPT efficiency increase and development of highly efficient thruster models that was conducted at RIAME during the past 10 years are presented hereafter. Such APPTs can be widely used to control mini and micro spacecraft within the entire mass range practically that is typical for the spacecraft of such classes.

Low thrust efficiency of "typical" APPTs developed earlier, which in many parameters were nearly ideal thrusters for the low-orbit MSC control, does not allow to secure their competitiveness for the problems that may also be solved by the thrusters of other designs. Assessments made during that period of time showed that wide enough application of APPT may be secured if its thrust efficiency is increased 1.5…2 times at least within the stored energy range of 20…150 J. At that, design, technologic and functional simplicity, reliability and low cost, which are inherent to this thruster and are the important components of its advantages over the electric propulsions of other types, should not be sacrificed to efficiency.

II. Analysis for the Results of Studies Aimed at Increasing the APPT Operation Process Efficiency

From the historical point of view, works in the APPT field might be divided into two stages. Development of the thruster concept, selection of design and technological solutions for its basic elements and studies for the APPT operation process formed the content of the first stage (60-ies, 70-ies). At that stage, APPTs with solid dielectric as propellant, coaxial and "rail" discharge channels were selected from a large number of options for practical realization. Those thrusters were distinguished by design and technologic simplicity and low production cost. With respect to operation, the "rail" APPT had important advantage over the coaxial thruster, because it allowed simple and convenient store for considerable amounts of propellant and its feed to the discharge channel. Schematic diagram of the "rail" APPT with the side feed of propellant (Teflon) is presented in Figure 1. Thruster comprises: energy store, plane electrodes (anode and cathode), two Teflon bars (propellant), and discharge initiation unit (igniter).

Thruster operates in the following way. Source of electric energy charges energy store, operating voltage of which is applied to the thruster electrodes. Pulsed discharge (with average duration of ~15 μs) between the cathode and anode follows the low energy discharge initiated by a high-voltage igniter, and the so-called initial plasma closing the discharge gap is formed.

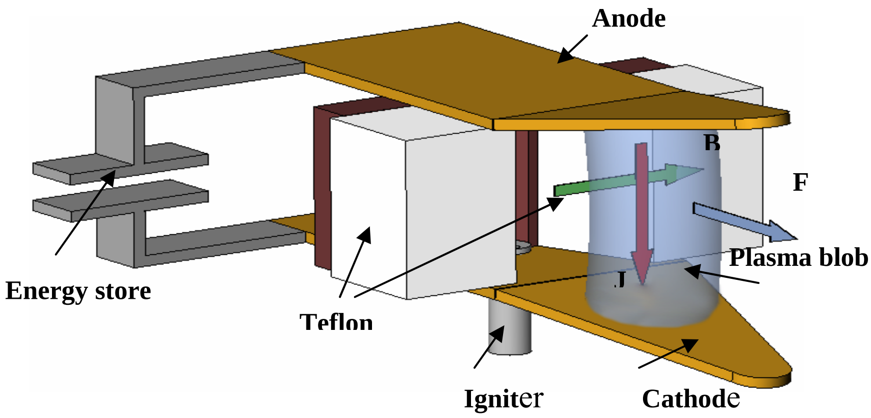


Figure 1 – APPT Schematic Diagram

Plasma formed as a result of evaporation of Teflon surfaces facing discharge is accelerated by gasdynamic and electromagnetic forces. The process is further repeated in the same sequence. Propellant, with its consumption, is fed into the discharge channel by the simplest spring mechanism. The highest efficiency of acceleration process is achieved when the electromagnetic accelerating force is dominating.

Tendency to the reduction of the SC overall dimensions and mass outlined by the end of 80-ies – beginning of 90-ies, appearance of the first small SC, which were developed with the motto: "Faster, better, cheaper", put on an agenda the issue of designing and developing *simple and* cheap highly efficient plasma thrusters capable to control MSC at the power consumption of ~100 W and substantially lower. APPT with the discharge channel of rail geometry appeared to be the most simple and cheap thruster of such class (as was noted above) that was furthermore successfully tested under flight conditions many times [2]. But low efficiency of the APPT operation process did not allow to realize its advantages. That is why the second stage of work in the APPT field was aimed at solving the problem of considerable increase for the efficiency of its operation process.

In Russia works under the "rail" APPT were started in the beginning of 90-ies, and the first report on the development of such thruster with the discharge energy of ~100 J [3] was prepared soon. To a certain extent that was a bid for the development of highly efficient thruster of low power, because analysis for the tasks of MSC orbital control [4] showed that even control for relatively light spacecraft with the mass of 100…250 kg requires the use of APPT with the thrust efficiency of not lower than 15…25 % at the stored energy of 30…70 J. There were no such thrusters at that time. But there was an understanding that APPT with low efficiency of operation process had a few chances only in the competitive activity.

In the APPT contemporary history the issue of increasing efficiency of its operation process became to be the basic one. In the 90-ies, not less than 50% of all works were aimed at solving that problem in this or that form. A number of them are discussed hereafter.

Results of data procession for the magnetic-probe measurements in the channel and in the APPT plume are presented in [1]. Distribution of the discharge current in the thruster channel in the discharge time are presented, which allowed to reveal the fact that appeared to be very important for achieving final success, namely that the current concentration area and plasma are moving in the discharge channel at high velocity under the action of electromagnetic force during the first half-period of discharge only. During the further 3-4 half-periods of discharge (which are characteristic for the discharge process of "typical" APPT), to which over 50% of the stored energy are applied, the current area remains to be non-mobile and localized near the end insulator, facilitating stronger evaporation of propellant that moves at the heat velocities and propagates after the channel exit plane within the solid angle of up to 180°. Hence a conclusion was made on the necessity of transition to an aperiodic discharge in the APPT with the duration close to the duration of current processes in the channel (about 10…15 μs). But at that period of time the authors of that report did not have clear enough understanding for the physical processes of plasma flow in the thruster channel and, correspondingly, did not make definite proposals on the realization of aperiodic discharge in the APPT. More over, experience of work with the forming lines from the very beginning allowed to exclude possibility for their use as having no prospects from the point of view of thruster efficiency increase.

Publication [5] is rather informative and useful for understanding phenomena causing substantial loss of APPT efficiency. A model was discussed in that publication that connected efficiency of processes in the thruster with the development of decaying oscillations of discharge current, with due account for the influence of difference in the impedances of the outer and inner parts of electric circuit on the efficiency. Impedance assessments presented in that publication are an important indicator for the way to increase efficiency of the APPT operation process substantially that is associated with the optimization of parameters of its electric circuit.

It is necessary to mention publication [6] also that was devoted to the experimental study for one of the basic problems of ablative APPT that condition its low thrust efficiency – excessive propellant consumption. Dependencies of propellant consumption on the propellant bar temperature were defined, according to which reduction of the bar surface temperature, due to the reduction of the energy store discharge frequency for example, might lead to the evident consumption reduction and substantial (up to 25%) growth in the thrust efficiency of the thruster. It was shown also that at the temperature increase of up to 80°C for those areas of Teflon bar, which are close to the working surface, the excessive Teflon consumption might have considerable influence on the APPT performance, thus operation modes of the thruster should be chosen in view of this circumstance. Along with this, it is necessary to understand that the APPT operation modes with the power level close to the maximum one are required for solving majority of real tasks on the MSC control.

Fairly connecting many APPT problems with its propellant, authors of [7] studied possibility to increase efficiency of the thruster operation process by modifying Teflon. Results are presented in this publication for the experimental refinement of APPT, in which Teflon with carbon additives was used as propellant, as well as porous, nominal and high-density Teflon. The best results were obtained when Teflon with carbon additives was used. It was determined that at the introduction of about 2.5% of carbon into the propellant, the APPT thrust efficiency grew by 6…10%. This result should be taken into account when solving the problem of increasing thrust efficiency of pulsed plasma thrusters.

Experimental studies presented in [8] became a noticeable step towards the practical realization of ideas on the APPT thrust efficiency increase. Influence of discharge capacitance on the efficiency of discharge processes was purposefully studied on the basis of calculation assessments. Capacitance was varied from 10 μF to 200 μF. The capacitance influence on the current curve was noted, but the thruster efficiency growth with the capacitance variation appeared to be insubstantial and did not exceed several percent in the best case. In spite of the modest results (as became evident later, mainly caused by the underestimation of the role of the electric circuit inductance), studies in this direction were continued. And noticeable increase in the thrust impulse bit, specific pulse and thrust efficiency of APPT was obtained in a year already.

III. Development of Highly Efficient APPT

Obvious advancement in the direction of substantial increase for the APPT operation process efficiency that was achieved in 1999 is described in [9]. Considerable redistribution of linear current density in the discharge channel of the thruster with the discharge energy of ~100 J (APPT-100) that resulted in the formation of discharge close an aperiodic one was detected for the first time by a magnetic probe at the variation of the circuit C and L and obtaining of their combination close to an optimum. Thrust efficiency of the thruster grew from 12% up to 22% with this. (Further studies for the APPT-100 operation process allowed to increase its thrust efficiency up to 35%). Variations in the operation process are demonstrated in the best way by the curves of discharge current (Figure 2, 3), which are typical for the APPT-50 with low and high efficiency, as well as by the curves of discharge current linear density distribution in the time of discharge in the channels of mentioned thrusters (Figure 4, 5), which were obtained with the help of magnetic probe. The following substantial differences are obvious:

- Transition from oscillatory to quasi-stationary discharge process;
- Absence of considerable currents in the non-mobile areas, which are formed near the end insulator at the secondary discharge of the energy store in the case of the highly efficient thruster that resulted in the excessive Teflon consumption earlier;
- Absence of the pronounced current bridge, and more uniform current distribution in the discharge channel volume associated with it;
- Appearance of considerable “carry-over” currents that results in the reduction of excessive propellant consumption also, as well as in the substantially better focusing of the plasma flow.

It is shown in [10, 11] that not current distribution only, but distribution of the charged plasma component in the discharge channel of highly efficient APPT and after it exit plane also differs substantially from the density distribution in the channel of low efficient thruster. At that, density maximum, as well as the current maximum, is carried out of the channel zone limited by the bars towards the exit plane of the electrodes, and this is accompanied by considerable reduction in the excessive consumption of Teflon.

According to the results of study for the operation processes of APPT with the stored energy of 30 J and less, there are certain difficulties in the obtaining of so considerable effect while optimizing circuit

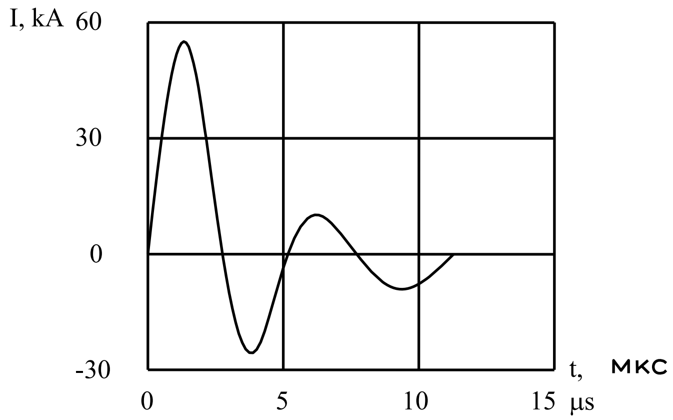


Figure 2 – Discharge current of the typical APPT

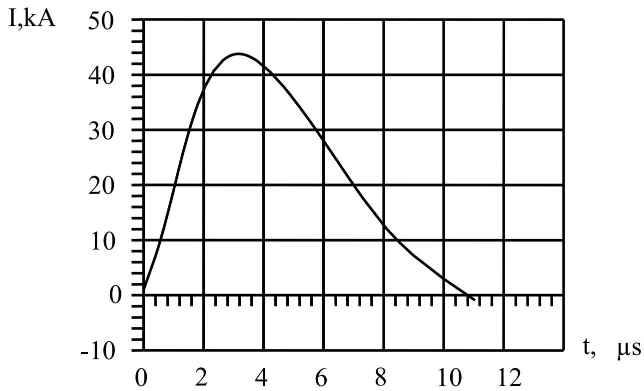


Figure 3 – Discharge current of the highly efficient APPT

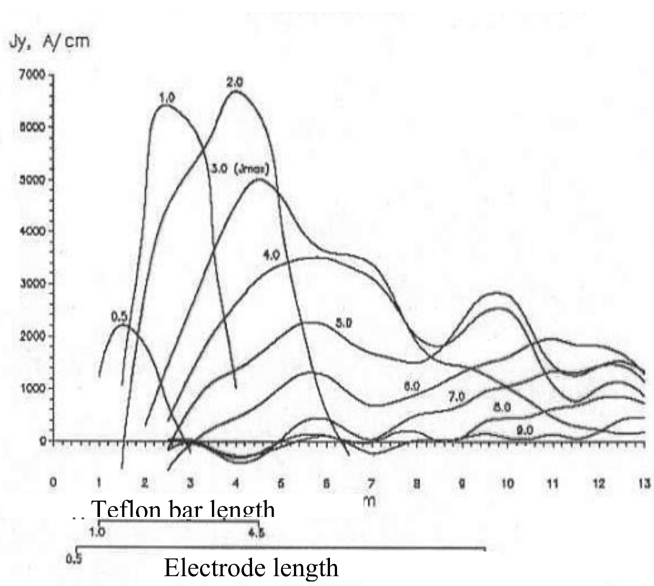


Figure 4. – Current density distribution in a typical APPT

elements of the low energy thrusters, because not all engineering solutions that were used in the highly efficient APPT with the energy of 40 J and higher may be used in this case. First of all, it is a question of difficulties in securing optimum ratio of L and C parameters of the power supply circuit. At that, there are no problems of principal nature here, but substantial relative growth of the overall dimensions and mass of the energy store with the reduction of the APPT discharge energy rather quickly poses a limit for the search of optimum values for the mentioned circuit elements. Nevertheless, thrust efficiency increase by (50-60)% in the flight prototypes of the low energy thrusters was reached. Distributions for the discharge current density in the APPT-20 channel are presented in Fig. 6. It is obvious that the nature of curves in the first half-period is close to the nature of curves presented in Figure 5.

Generalized test results for the APPTs with different energies are presented in Fig. 7. On the basis of this data it is possible to form an approximate picture of expected values for the appropriate parameters for any energy of the considered range. But an important reservation should be made here. Dependencies presented in Fig. 7 were obtained, when the energy store on the basis of capacitors with the capacitance of 20 μF was used. Energy store with such capacitors is not optimum for the thrusters with the discharge energy of less than 50 J. Thus, test results reflecting characteristics of such thrusters are underestimated slightly. Characteristics corresponding to the modern level of APPT development are presented in [12], for example. Some characteristics are presented in the Table.

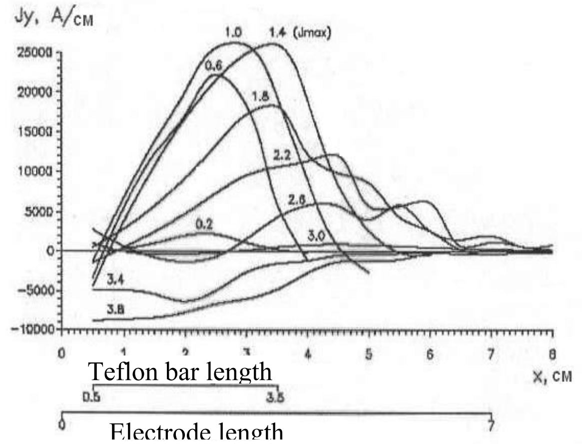


Figure 5 – Current density distribution in a highly efficient APPT

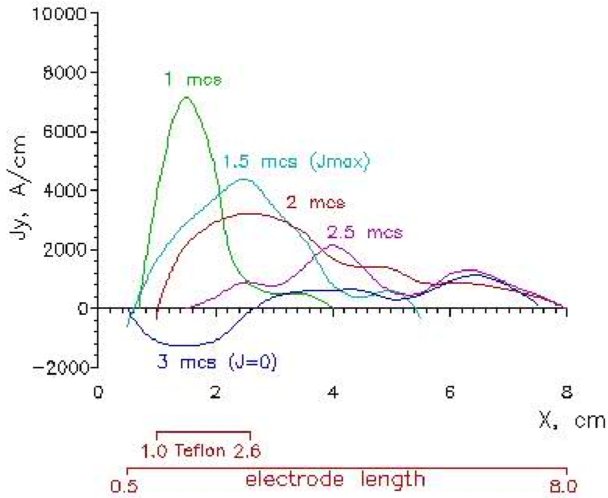
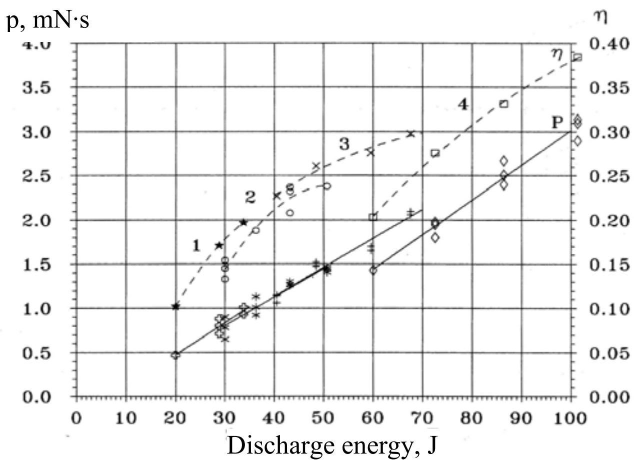


Figure 6 – Distribution of linear current density along the discharge channel (1st half-period)



1,2,3,4 – number of capacitors forming the energy store (capacitance of one capacitor is: C= 20 μF).

Figure 7 – APPT power impulse and thrust efficiency as functions of the discharge energy

Table

Characteristics	APPT-20	APPT-50	APPT-100	APPT-150
Discharge energy, J	20	50	100	150
Thrust impulse bit, mN·s	0.5	1.4	2.8	4.5
Thrust efficiency	0.14	0.23	0.30	0.40

IV. Conclusion

Studies conducted at RIAME allowed to develop models of competitive APPT capable of securing efficient flight control for the MSC with the mass of (50-350) kg.

Russia is currently realizing transition from the development of MSC with the mass of (50-350) kg to their production. Application of propulsion systems based on the APPT of next generation is envisaged in a number of MSC projects, namely as parts of their flight control systems. (It should be noted that in view of the necessity to meet additional requirements associated with the lifetime securing and reduction of overall dimensions and mass of the propulsion system flight models, their thrust efficiency appears to be (5-10)% lower than that of the laboratory analogs, as a rule. This difference appears to be higher, the lower is the energy stored in the store. This problem may be solved with the development of flight models of energy stores with high specific energy reaching the following values: g= (30-40) J/kg). Currently, g values for the laboratory models of energy stores used by RIAME are about 15 J/kg.

Flight model of the APPT-50 (discharge energy of 50 J) based propulsion system developed at RIAME is presented in Fig. 8. It has passed complete cycle of ground developmental tests and is designed for the orbit control of MSC with the mass of (200-350) kg.

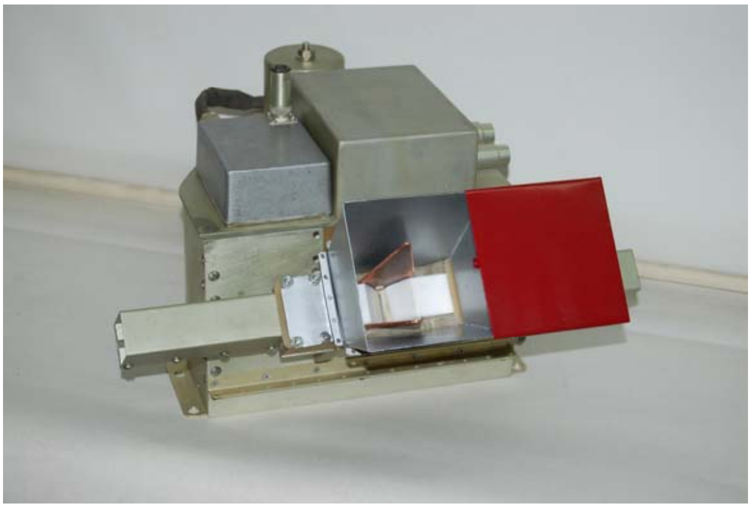


Figure 8 – Flight model of the APPT-50 based propulsion system

Fig. 9 shows flight model of the APPT-35 based propulsion system that is being developed at RIAME for providing control of MSC with the mass of (50-250) kg. This propulsion system differs by the presence of two discharge channels and discharge initiation units that allows to increase reliability of propulsion system substantially and to reduce overall dimensions of the propellant store and feed unit simultaneously that being especially important at the propulsion system arrangement on board small spacecraft.

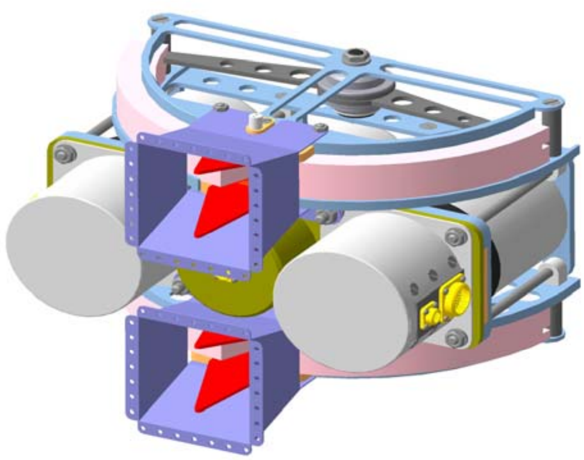


Figure 9 – Flight model of propulsion system based on two thrusters of APPT-35 type

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