High Thrust APPTs for Spacecraft Orbit Control

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Abstract: Ablative Pulsed Plasma Thruster (APPT) are simple, low mass, flexible power level, high I_{sp} and low cost device. Last years developments of APPT have resulted to appearance the thrusters in energy range 30 J -150 J with thrust efficiency from 15 to 40%. Developed thrusters provide total impulse up to 50 kNs with specific impulse up to 2500 s. Paper presents the estimation of high trust APPT capabilities for spacecraft insertion to working orbit and its keeping on subpolar circular orbits in a strip ± (5 – 10) km. Spacecrafts with masses of 350 kg and 1750 kg, placed in subpolar circular orbits H=550 km, =81º and H=900 km, φ = 82º are considered. Analysis has shown that considered missions can be satisfied with PS based on high power APPT-95. Thruster design elements and propellant heating study presented. Working modes of operation have been determined. Produced thermal APPT-95 tests confirmed the possibilities of its space applications.

I. Introduction

ABLATIVE Pulsed Plasma Thrusters (APPTs) are attractive electric propulsion devices for attitude and orbit control tasks, including translation propulsion, momentum management, drag make-up, orbit raising and de-orbiting applications. APPT are simple, low mass, flexible power level, high I_{sp} and low cost device[1,2].

Low power APPT cover (2- 10) J bank energy range and work with operation frequency up to 20 s^{-1}. Main characteristics of these APPT and LEO applications for micro-satellite with orbits from 400 km to 800 km and with mass 20-100 kg are considered in[3,4]. It is shown that it is possible to develop APPT with the power consumption from 10 W to 50 W and specific characteristics acceptable for space activities. Produced total impulse up to 3 kNs meet the requirements of orbits maintenance for a number of micro satellite LEO missions planned in Russia having mass 20- 100 kg. However decreasing of impulse bit in low bank energy APPT usually coupled with decreasing of specific impulse and, correspondingly, mass saving.

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Developments of APPT have resulted to appearance the thrusters in energy range 20 J -150 J with thrust efficiency from 15 to 40%. Developed thrusters provide total impulse up to 50 kNs with specific impulse up to 2500 s[5,6]. These thrusters meet the requirements a number of LEO missions[6,7]. Quite a number of LEO applications, having SSC mass from 100 to 1000 kg are now under consideration and development in Russia. Application field of SSC is wide enough and includes communication, navigation, meteorology, Earth observing and environmental control etc. High power APPTs, working in 100 J bank energy range have an electrodynamic mode of operation and high specific impulse together with high total impulse. So, noticeable mass saving takes place. Its applications ranged from control propulsion for larger satellites to primary propulsion for small satellites[8,9,10].

Family of APPT developed in RIAME is given in Fig.1. These cover total impulse range up to 50 kNs with input power up to 150 W.

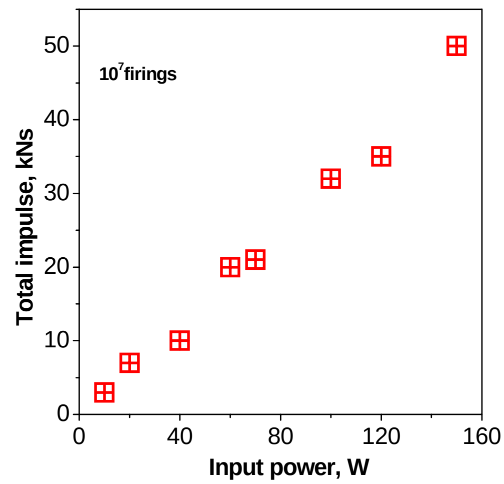

Figure 1. Total impulse – Input power dependence (referred to 10^7 firings, room temperature). RIAME developed APPTs.

Paper presents the results of workout of temperature operating modes for APPT-95 design elements. These cover 100 J bank energy range and operation frequency up to 3 s^{-1}. Main characteristics of these APPTs are presented. LEO applications for two reference missions with circular orbits 550 km and 800 km having masses 350 kg and1750 kg, correspondingly, are considered. High trust APPT capabilities for spacecraft insertion to working orbit and keeping this on subpolar circular orbits in a strip ± (5 – 10) km are estimated.

II. Missions Description

Mission characteristics (#1 and #2) together with some others planned in Russia are shown in Table 1. Spacecrafts with masses of 350 kg and 1750 kg, placed in subpolar circular orbits H=550 km, φ =81° and H=900 km, φ = 82° were considered. APPT PS task is to provide initial SC orbit correction for appointed area and then to support the orbit in a strip of 5-10 km width. The calculations of correcting impulses to form a working orbit and maintenance of a swath width accuracy of (5-10) km for two SC variants and working orbits (H=350 km and 900 km) have been produced. Operation lifetime was accepted equal 7 years. The increment of characteristic velocity has made accordingly 75.6 m/s, 29.7 m/s. Total impulse of 27 kNs and 53 kNs are necessary consequently to complete these missions for a planned service life. These total impulses are in APPT application area.

Table 1. Mission requirements

Mission	#1	#2	Kanopus-V	Gonets-M	Monitor-E	Victoria
SSC mass, kg	350	1750	400	280	750	750
Orbit	Circular H=550 km, 81^O	Circular H=900 km, 82^O	Circular SSO 97.5^O	Circular Near polar H=1450 km, 82.5	Circular SSO H=540 km, 97.5^O	Circular SSO H=510 km, 97^O
Orbit displacement, km (strip width)	5-10	5-10				
On-board power source, W	200	200	570	200	1200	490
Mission duration, years	7	7	5	5	5	5
Impulse bit, Ns	$1{\cdot}10^{-3}$	$4{\cdot}10^{-3}$				
Total impulse, kNs	27	53	40	23	400	120

III. Laboratory High Power Thruster APPT-95

In Figure 2, two channel APPT-95 assembly, installed on 134 μF capacitor banks is shown. This assembly serves also as the base for 4 channel APPT PS development. Appearance of APPT-95 prototype is given in Fig. 3.

A. Workout of temperature operating modes of APPT-95 design elements

High sensitivity of the important elements of APPT design (first of all Teflon bars and capacitors) to a temperature mode is the feature of APPT determining its efficiency and reliability in the solving of real tasks of SSC control. It is known, that even rather small overheat of Teflon bars leads to increasing of a propellant flow rate and consequently to appreciable decrease in specific thrust of APPT. The service life of capacitors can significantly decrease as a result of excess of the maximum permissible temperature making, near 80ºC. Both factors action can lead to the default of a task due to decrease in a total impulse or refusal of the engine because of breakdown in the capacitor. For these reasons thermal workout of APPT flight prototypes presents very important.

For thermal tests APPT-95 prototype has been assembled in a nominal variant - with two blocks of discharge initiation, central cover and screens. By means of special duralumin fixing arms the model has been installed on face flange of the vacuum chamber. Power of the thruster varied by the change of firing frequency. One of temperature gauges was placed inside of a propellant bar. Operation mode of APPT was defined by appearance of an equilibrium temperature. Propellant bar temperature in dependence on duration of APPT work at various frequencies is displayed in Fig. 4. It is visible, that with increase in frequency and, accordingly, power together with growth of T_{prop} , derivative of temperature in initial stages of APPT performance increases.

Thermal operating modes of following elements of the thruster have also been studied:

- cathode and anode - in an area of propellant bars,
- minus lead terminal of the capacitor,
- an medial part of capacitor,

Obtained results of temperature measurements of cathode, anode, propellant, minus lead terminal of the capacitor and its lateral surface in dependence of working time for frequencies of 4 Hz and 2 Hz are presented in Fig. 5, 6 consequently.

It is seen, that electrodes temperature increases sharply during first minutes of work, which then replaced by its slow increase. Propellant heating is a little different

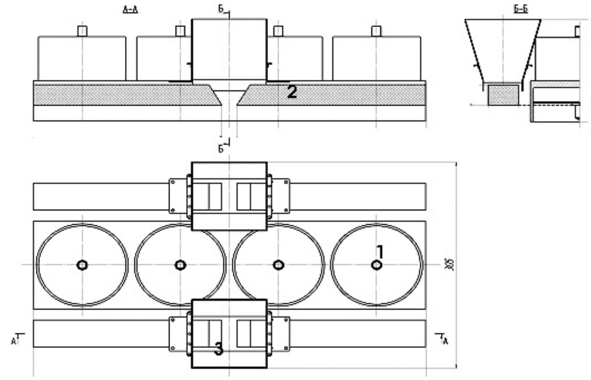

Figure 2. APPT-95 assembly, 1 – capacitors, 2 – propellant bar, 3 – acceleration channel.

Figure 3. Appearance of APPT-95 prototype

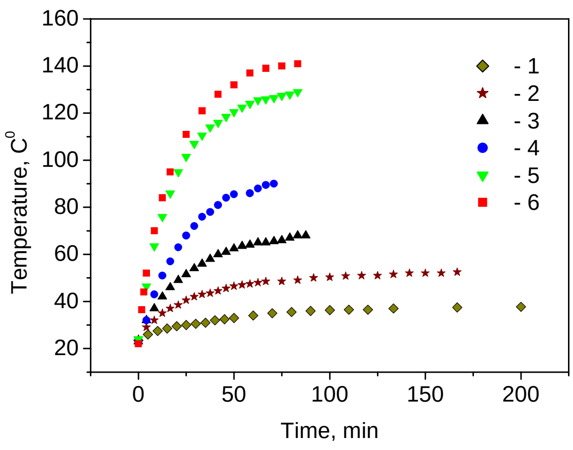

Figure 4. Propellant bar temperatures in dependence on duration of APPT work at various frequencies. 1 - f=0.2 Hz, m=0.07 mg; 2 - f=0.5 Hz, m=0.074 mg; 3- f=1 Hz, m=0.078 mg; 4- - f=2 Hz, m=0.084 mg; 5 - f=3 Hz, m=0.087 mg; 6 - f=3 Hz, m=0.092 mg.

achieving some low temperature. Heating of the capacitor volume to equilibrium temperature takes place with other characteristic time. This occurs relatively slow thanks to big mass of the capacitor and its heat contact with an aluminum platform of the assembly.

Cathode temperatures are a little bit greater, than anode values. It is caused by features of an assembly design, namely worst conditions for effective cooling, compare with anode. APPT capacitors have a big current loading. In this case a heat release in one of its weakest places, namely in a current feeder, starts to be significant.

Current feeder heating is due to Ohmic resistance of lead terminal of the capacitor and Ohmic resistance of contacts. Additional heating takes place from electrodes. Possibly, the temperature of lead terminal could grow up to melting temperature of solder and cause the destruction of capacitor connection. It is seen in Fig. 5, 6, that temperature level of lead terminal exceeds temperature of the capacitor lateral surface, and also the top limit of a working interval of temperatures of the capacitor (+85^{0}C). Such a way, temperature of lead terminals is the important parameter determining an opportunity of long work of the thruster. So, at frequency of 4 Hz the temperature of lead terminals almost twice exceeds temperature of a lateral surface. Moreover, possibly there is main limiting factor of effective APPT performance. Therefore its control is necessary element of thermal monitoring system of APPT working in conditions of increased power level.

One of the factors determining thermal condition of energy store, consisting of several capacitors is their non-uniform heating. Thus the temperature of the central capacitors can exceed acceptable, and peripheral ones can have temperature close to room. Maintenance of the best heat transfer between capacitors allows to decrease lead terminal temperature of central capacitors on 20ºC and to provide comfortable operating conditions of energy store.

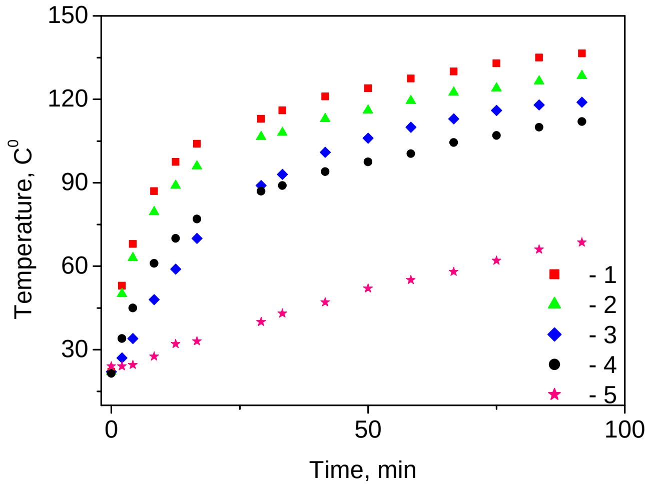

Figure 5 - Temperature of APPT elements vs duration of work at 4 Hz frequency. 1 -cathode, 2 -anode, 3- -propellant, 4- lead terminal of the capacitor, 5- lateral surface of the capacitor

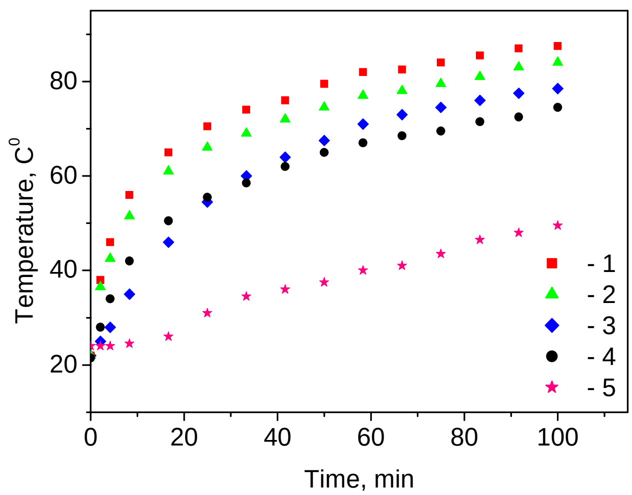

Figure 6. Temperature of APPT elements vs duration of work at 2 Hz frequency. 1 -cathode, 2 -anode, 3- -propellant, 4- lead terminal of the capacitor, 5- lateral surface of the capacitor

IV. EPS Based on APPT-95

Mass-size mock-up of EPS based on APPT-95, giving the general representation about its design features is presented in Fig. 7. Top and bottom heads of EPS Skeletons contain spring systems for propellant feeding, propellant bars and accelerating channels. They produced in the form of cylinders and formed everyone by two structurally similar fixing elements. Cylindrical form of a head allows creating the maximal mass of propellant in minimal dimensions. Presence of two alternately working accelerating channels enables to increase reliability of the EPS and to reduce temperature of propellant bars. Duplicated discharge initiation units located in a front part of EPS between accelerating channels are served also for reliability increase.

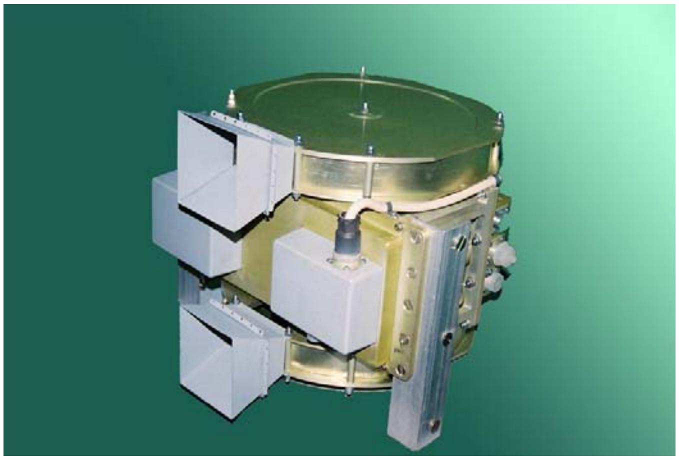

Figure 7. Mass-size mock-up of EPS based on APPT-95.

Two blocks of power supply and control system are placed in a back part of EPS. In case of failure of one of the listed blocks remained can ensure the performance of any accelerating channel. Basic force element of the EPS construction fastening all blocks is the rectangular skeleton. Capacitors together with current feeding bars are placed inside a skeleton.

Protective screen having the form of truncated pyramid installed in accelerating channels serves for protection of spacecraft elements against impact of peripherical flows. A significant part of the Carbon formed at decomposition of Teflon is deposited on the screen.

Table 2. EPS Estimates

Bank energy, J	**35**	**50**	**95**
Working frequency	3	3	2
Thrust, mN	3	4.5	6
Total impulse, kNs max (1,5 10^7 firings)	15	21.3	45
Propellant (Teflon) mass per thruster, kg	1	1.5	2
Impulse bit, mNs	1.1	1.4	2.6
Specific impulse, s	1100	1400	1900
Propulsion system dry mass, kg	4.9	6.5	12

Parameters of EPS based on APPT-95, having one accelerating channel is given in Table 2 together with 35 J and 50 J EPS. Analysis has shown that considered missions can be satisfied with PS based on high power APPTs. Mission # 1 can be solved with single APPT-95, having 134 µF capacitor banks. This device produces 30 kNs with $1.5{\cdot}10^7$ firings and 2 kg propellant consumption.

Maximal working frequency is 2.1 Hz, needed power - 200 W. Such a way APPT-95 can solve the task # 1.

Spacecraft of 1750 kg needs in 2 channel APPT-95 to complete Mission #2. Thrusters are mounted on the same as previous capacitor bank. Total number of firings is $2.0{\cdot}10^7$, number of firings for separate channel is$\cdot 10^7$, working frequency- 2.1 Hz, needed power is 200 W. Total propellant consumption is 3 kg. Total EPS estimated mass is 15 kg.

V. Conclusion

Developed and tested APPT-95 is capable to provide total impulse up to 45 kNs with thrust efficiency up to 25%.

Thermal tests of APPT-95 confirm the possibilities of its space applications. Thermal limitations on APPT performance were studied. Working modes of operation have been determined.

Two LEO Earth missions with circular orbits, 500 km and 900 km altitude were considered with spacecraft mass 350 kg and 1750 kg correspondingly. APPT-95 based EPSs meet the requirements for spacecraft insertion to working orbit and keeping this on sub polar circular orbits in a strip ± (5 – 10) km during its service life.

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