Low Bank Energy APPT for Micro Satellites

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Abstract: **Paper presents the estimation of low bank energy APPT for micro satellite applications. These APPTs are the side-fed propellant models and have rail electrodes. Low discharge energy and high frequency of operation will allow expanding APPT applications variety to smaller mass SC. Evaluation of applications is made on the base of APPT models studied in RIAME within last year. These cover (2- 10) J bank energy range and work with operation frequency up to 20 s^{-1}. Developed laboratory thruster models have thrust efficiency at the level of 3% and maximal thrust near 1mN. Main characteristics of these APPT are presented. Application of such APPTs for LEO orbits from 400 km to 800 km and for satellites with mass 20-100 kg is considered.**

Nomenclature

C_t = power-to-thrust ratio
F = average thrust of the thruster
f = pulse repetition frequency
J = discharge current
m = propellant consumption per a pulse
N = – power consumption, N=W·f

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P_{bit} = impulse bit, P_{bit}=F/f
Uo = capacitor voltage
W = capacitor bank energy
η = thrust efficiency

I. Introduction

ABLATIVE Pulsed Plasma Thrusters (APPT) is attractive electric propulsion device for Small Spacecrafts (SSC) due to its simplicity, low mass, appropriate power level, high I_{sp} and low cost[1]. APPT provides small, controlled impulse bits at high specific impulse in a self-contained package with storable solid propellant and a simple spacecraft interface. 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%.[2,3.] Developed thrusters provide total impulse up to 50 kNs with specific impulse up to 2500 s. It is capable to produce translation maneuvers, orbit maintenance and positioning LEO and GEO small satellites (50-500) kg in mass. SSC constellations exhibit great interest due to rather low cost their development and manufacturing, as well as price reduction of orbital injection. Quite a number of small satellite LEO constellations (Volcano 1" and "Volcano 2, Compass etc.) having SSC mass from 70 to 500 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.

Last decade a renewed interest has developed for employing micro-satellites in the scientific and commercial market, as technology has permitted sophisticated payloads to be developed into smaller volumes[4,]. So, miniaturization of space hardware proposes application of acceptable thrusters to satisfy mission requirements. Typical needed total impulses are at the level of several kilo Newton-seconds. Basically APPT can provide such impulses. However decreasing of impulse bit in low bank energy APPT thruster usually coupled with decreasing of specific impulse. On the other hand thruster is capable to operate with higher frequency.

Paper presents the results of APPT tests studied in RIAME within last year. These cover (2- 10) J bank energy range and work with operation frequency up to 20 s^{-1}. Main characteristics of these APPT are presented. LEO applications for micro-satellite with orbits from 400 to 800 km and with mass 20-100 kg are considered.

II. Laboratory Micro Thruster

There were sequentially designed and produced three laboratory models: APPT-8, APPT-5 and APPT-5 (3 capacitors) allowing determination for the expected performance of pulsed micro thrusters. Capacitors of new type with substantially lower Joule losses were used as the energy storage units. Capacitors capable of storing energy from 2 J up to 8.5 J were used for different models, and an option with parallel connection of capacitors was considered for the latter model. These models allowed variation for the discharge channel configuration and sizes within the broad limits that being necessary for determining optimal geometric dimensions.

The laboratory model APPT-8 is presented in Fig. 1. Fig. 2 shows the firing of the thruster model. From the design point of view the models are railotrons with plane electrodes and side feed of a propellant. The models differ by the absence of the thruster body, and the body of capacitor is used as the basic force element of the structure. This allows considerable reduction for the mass of the thruster as a whole. The frame, on which discharge channel and propellant feed mechanism are mounted, is installed on the capacitor body directly.

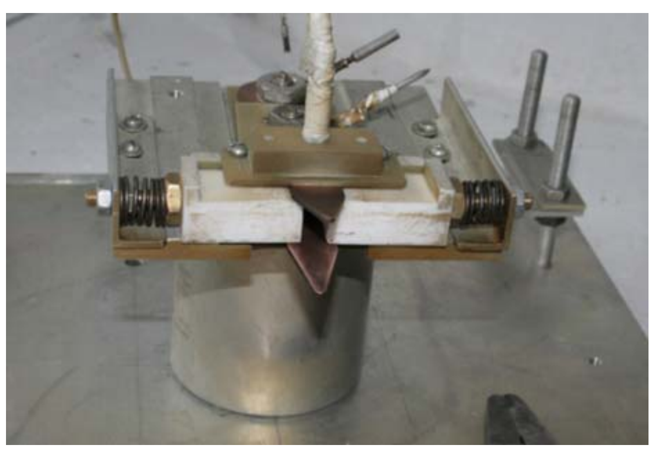

Figure 1. Appearance of the laboratory APPT

Discharge channel is formed by the electrode system, end ceramic insulator, and operating surface of bars of the plasma-forming substance (propellant). To reduce Joule losses the electrodes are connected to the capacitor contacts directly. Discharge circuit is designed on the base to have minimum resistance and inductance of the discharge circuit. Discharge is ignited by the plug (igniter) mounted near the cathode surface and powered by the high-voltage discharge initiation unit. Bars of plasma-forming propellant are fed into the discharge channel by a spring mechanism according to the Teflon consumption. In the model

APPT-5 (3 capacitors) the bars shifting into the discharge channel is limited by the prismatic stop fixed on the anode.

A number of tests for the considered low-thrust APPT laboratory models were made to determine operational capability of the thrusters of such type under the conditions of low power. Carbonization of discharge channel and propellant bars have allowed excluding some operation modes as non-working and determining optimal sizes for the between electrodes and for the propellant bars.

The following parameters were measured during tests: average thrust of the thruster F, propellant consumption per a pulse m, discharge current J, pulse repetition frequency f, and capacitor voltage, Uo. The following characteristics were calculated based on the measurement results: P_{bit}=F/f – impulse bit; W=½CUo^2 – capacitor bank energy; N=W·f – power consumption; $\eta_t = \frac{P_{bit}^2}{2mW}$ - thrust efficiency; $\langle V \rangle = \frac{P_{bit}}{m}$ - mean-mass velocity of the plasma blob (specific impulse); $C_t = \frac{W}{P_{bit}}$ - power-to-thrust ratio.

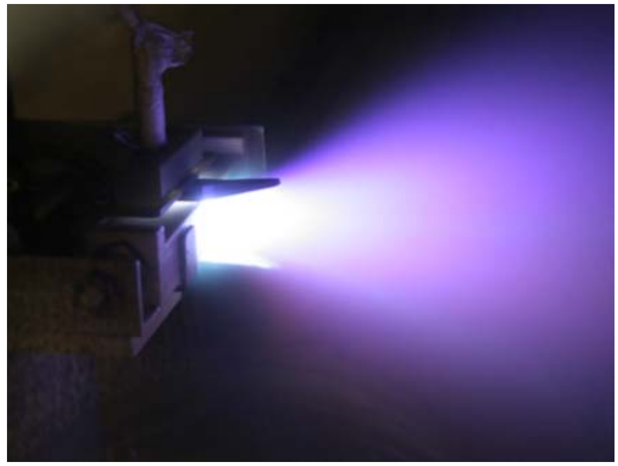

Figure 2. APPT-8 discharge

Measured characteristics, as well as the calculated on the basis of the measurement results, are presented in Tables 1, 2 and Figs. 5-8. Thrusts of the low-power APPTs are so low that additional difficulties in their measuring emerge. With the thruster mounted on the sting thrust-meter, the thrust measurement error is from –5% to +10%. The thrust-meter is a platform suspended by strings, deflection of which is proportional to thrust and registered by inductive sensor. Based on this, it is possible to suppose that thrust of the thruster of this type is possibly a little bit higher than the thrust determined by test. Satisfactory results were obtained as a result of a series of experiments for the model APPT-8 with the stored energy from 5 to 8 J. Some carbonization of bars at the voltage of up to 1300 V was observed near the inlet part of the discharge channel in the anode region only. At the higher voltage the Teflon bars remained to be clear, as may be seen in the photo (Fig. 3). The discharge current oscillogram is typical for APPT and has four half periods. Impulse bit as a function of stored energy is shown for this model in Fig. 4.

These results made it possible to start development and fabrication of the model APPT-5 with the capability to store energy from 1.5 J to 4.5 J at the thruster mass reduction due to the use of capacitors with lower capacitance.

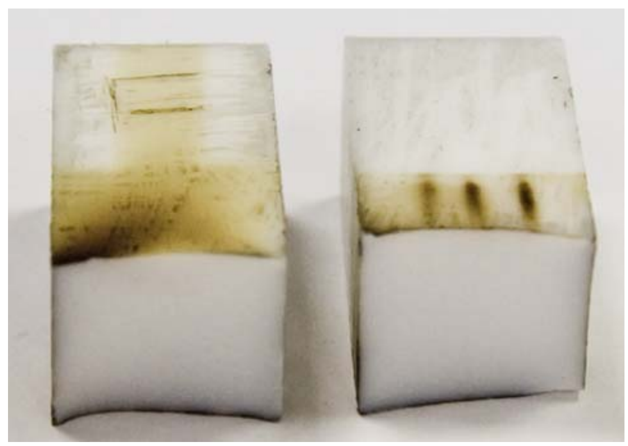

Figure 3. Propellant bars for the model APPT-8

One of the tasks for this model was the capability to operate at high frequencies of about 20 Hz. Carbonization of propellant bars was observed starting from 5 Hz up to 10 Hz at the capacitor voltage of 1300 V. Voltage increase up to 1500 V might change this situation, but high temperature is an important limitation for the operational capability of this model. Tests were performed for defining limits of the operational capability of this model with the thermal sensor connected directly to the capacitor contacts, because this place appeared to be the most vulnerable for the model APPT-5. Results of thermal tests allowed to determine the maximum permissible power for APPT-5 that appeared to be 25 W. After that it became possible to continue experiments and increase frequency up to 20 Hz having reduced capacitor voltage correspondingly.

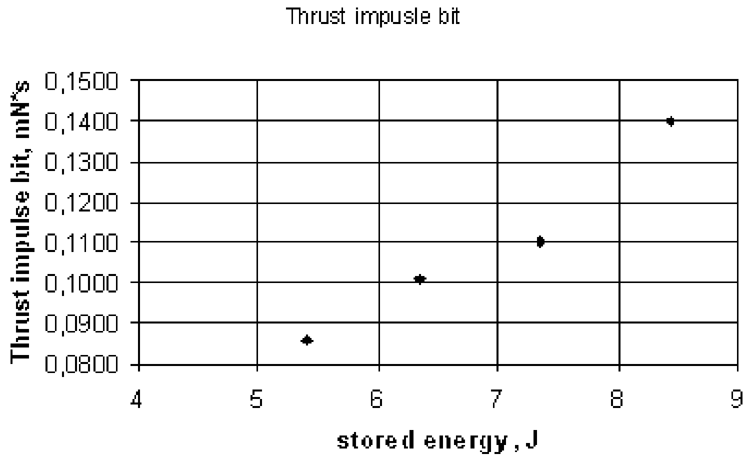

Figure 4. Thrust impulse bit as a function of stored energy for the model APPT-8

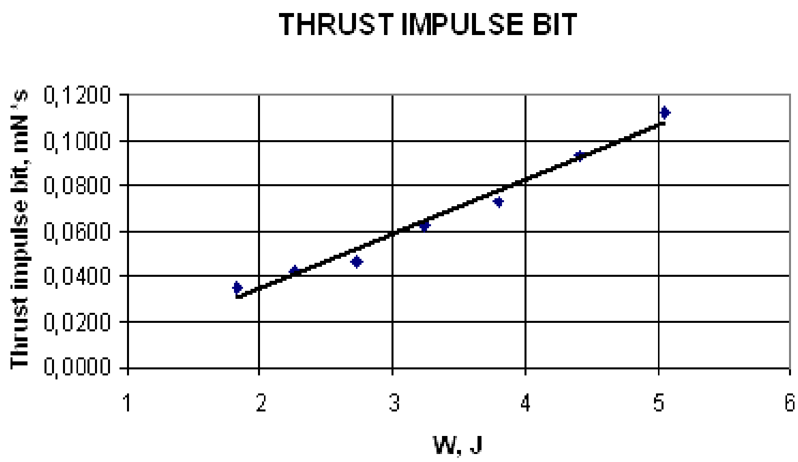

Figure 5. Thrust impulse bit as a function of stored energy for the model APPT-5-3b

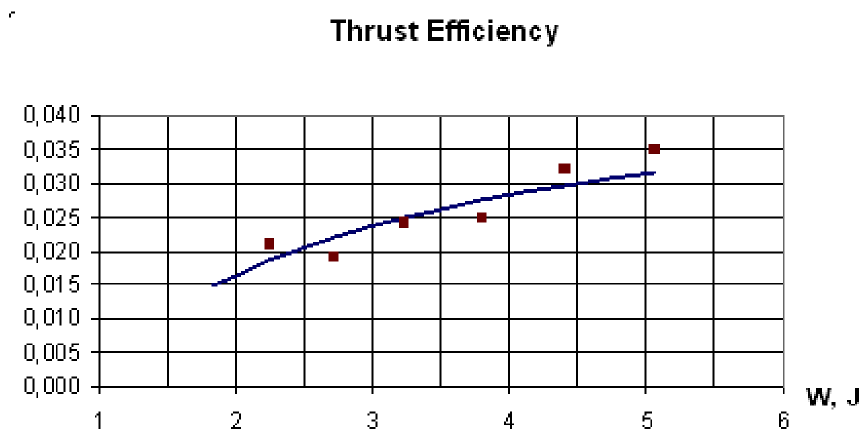

Figure 6. Efficiency as a function of stored energy for the model APPT-5-3b

To increase specific characteristics of the thruster, it was decided to test another model with the capacitor bank consisting of 3 capacitors connected in parallel (model APPT–5–3b). Circuit inductance of the model is $22 \cdot 10^{-9}$ H that being twice less comparing to the previous model ($45 \cdot 10^{-9}$ H), while by its initial characteristics it does not yield to it.

Purpose of the first tests for the model APPT-5-3b was to demonstrate operational capability of this model within the required range of stored energy. At the capacitor voltage reduction down to 1000 V and pulse repetition frequency of 5 Hz, the bars were consumed without carbonization. Typical curves for the thrust impulse bit and efficiency dependence on the stored energy are presented in Fig. 5 and Fig. 6.

Table 1. APPT-5-3b Performance

Capacitance, μF	Voltage, V	Frequency, Hz	Consumption per pulse, g	Thrust impulse bit, mN*s	Energy, J	Power W,	Efficiency
4.5	1500	5	3.53E-05	0.1120	5.0625	25.3125	0.035
4.5	1400	5	3.09E-05	0.0932	4.41	22.05	0.032
4.5	1300	5	2.75E-05	0.0730	3.8025	19.0125	0.025
4.5	1200	5	2.47E-05	0.0620	3.24	16.2	0.024
4.5	1100	5	2.11E-05	0.0466	2.7225	13.6125	0.019
4.5	1000	5	1.92E-05	0.0426	2.25	11.25	0.021

Distance between the propellant bars is an important factor determining the efficient ablation of Teflon in the discharge channel. According to test results, the longer the distance - the higher the efficiency, but carbonization of discharge channel takes place after some number of shots. Optimal distance between the Teflon bars was determined by tests, thus it was advisable to make subsequent tests with the fixed sizes of the channel.
The measurements were performed at continuous monitoring of temperature for the capacitor contacts that should not exceed the permitted value. According to measurements, with all variants the temperature became stable during the test, and all values were lower than the threshold value for this model.

Propellant bars of the micro APPT models were consumed with the formation of the barrel shape, and this differs from the high-voltage ablative pulsed plasma thrusters designed by RIAME earlier. Such consumption of bars caused anxiety that with the increase in the total number of pulses further consumption of the "middle" of the barrel-like shape of the bars would be intensified and thus limit lifetime of the micro APPTs. Rational location of stop in the channel might either eliminate such a problem, or minimize it. However, according to the tests, after some

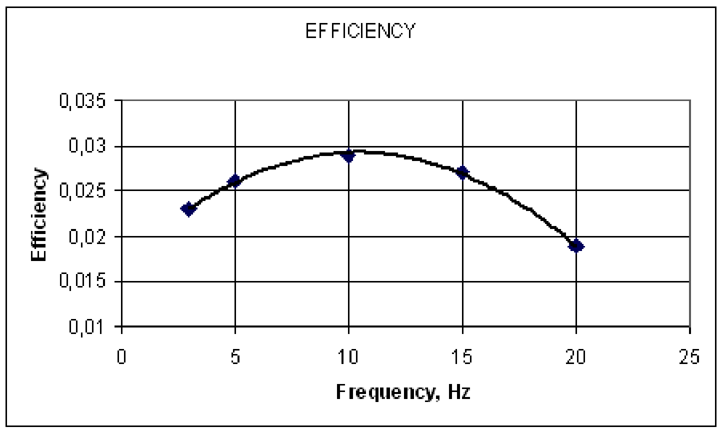

Figure 8. Efficiency as a function of pulse repetition frequency for the model APPT-5-3b

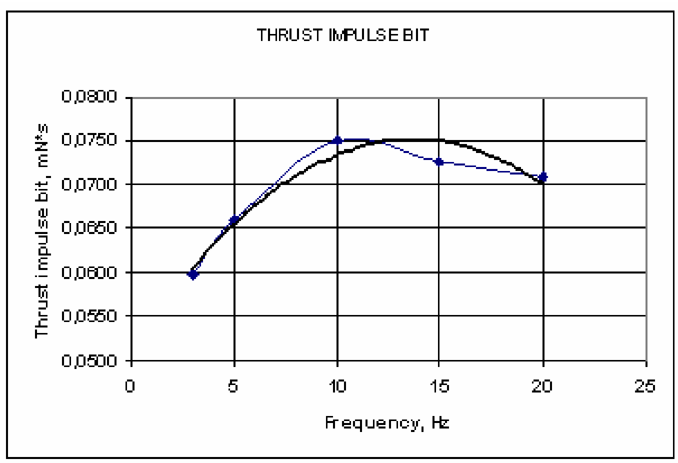

Figure 9. Thrust impulse bit as a function of frequency

number of pulses the steady barrel shape was not changed during test.

Installation of stop on the anode caused carbonization of bar corners being in contact with this stop. That is why design of the model was modified, and dimensions of the igniter were reduced. It became possible to mount the stop on the cathode. After that the bars were consumed without carbonization during the test again. Efficiency and thrust impulse bit as functions of the pulse repetition frequency are presented in Fig. 8, and Fig. 9.

Tests for the APPT model verified its operational capability at different ranges of energy stored in the capacitor bank and pulse repetition frequency variation from 3 Hz to 15 Hz (up to 20 Hz for the model APPT-5-3b). Thus, it is possible to develop APPT with the power consumption from 10 to 50 W and specific characteristics acceptable for space activities.

Table 2. Micro APPT parameters for 3 – 15 Hz repetition frequency.

Capacitance, μF	Voltage, V	Frequency, Hz	Consumption per pulse, g	Thrust impulse bit, mN*s	Energy, J	Power, W	Efficiency
4.5	1300	3	2.07E-05	0.0598	3.8025	11.4075	0.023
4.5	1300	5	2.17E-05	0.0660	3.8025	19.0125	0.026
4.5	1300	10	2.57E-05	0.0751	3.8025	38.025	0.029
4.5	1300	15	2.63E-05	0.0727	3.8025	57.0375	0.027

Naturally working temperature is increased with frequency increase[5]. Maximal achievable frequency in the test was 20 Hz.

III. Micro Satellite Missions

The proposed propulsion technology has smaller impulse bits which allow finer control of satellite positioning and power advantages over the high energy APPT technology, which make it better suited to the proposed micro satellites. For today, there are a few programs in Russia aimed to the development of SSC with mass (20- 90) kg, having on-board power at the level of (20 – 50) W. Mission requirements are shown in Table 3. Accounts of total impulse, propulsion system mass and propellant consumption for producing orbit maintenance for SC, having (1 – 3) year's service life, are presented.

Table 3. Mission requirements

Mission	Colibri	Chibis	Baumanets	Compass	Compass 2
SSC mass, kg	20,5	40	92	70	86
Orbit	Circular H=380 km	Circular H=480 km	Circular H=650 km-800 km	Circular H=400 km	Circular H=450 km
On-board power source, W	20	50	35	20	25
Mission duration	1	1	3	1-3	3
Total impulse, kNs	1.5	1.3	1-1.35	2.5	3.5

The possibility to use APPT EPS is considered on the base of tested thrusters with (3-10) J bank energy. Characteristics of these APPT are given in Table 4. It is seen that orbit maintenance for considered SC can be provided with single APPT, having bank energy more or equal 5 J. 10 J thrusters[6] has the advantage for such application. Electrodynamic mode of operation in the performance of this thruster is more significant, so this can provide noticeable mass saving. Estimated EPS mass is on the level of 1.5 kg for 10 J thruster.

Table 4. APPT parameters for bank energy 1.6 J, 5 J, 10J

Bank energy, J	1.6	5	10
Working frequency, s^{-1}	5-20	5-10	5
Total impulse, kNs (max $1.3\ 10^7$)	0.26	1.4	3.25
Impulse bit, mNs	0.02	0.11	0.25
Propellant mass, kg	0.01	0.045	0.08
Mass bit, kg	$7.5\ 10^{-9}$	$3.5\ 10^{-8}$	$6\ 10^{-8}$
EPS mass, kg	1	1	1.5

IV. Conclusion

Low thrust side-fed micro APPTs with bank energy 2- 10 J have been developed and tested. It is shown that it is possible to develop APPT with the power consumption from 10 to 50 W and specific characteristics acceptable for space activities. Produced total impulse meet the requirements of orbits maintenance for a number of micro satellite LEO missions planned in Russia having mass 20- 90 kg.

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