Influence of the discharge circuit inductance on the ablative pulsed plasma thruster performance

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Abstract. The most promising option for motion control of small spacecrafts with weight less than 50 kg is a pulsed plasma thruster with an energy of less than 20 J (micro-PPT), which has such advantages as low weight, structure simplicity, precise pulse control, sufficiently long life time, constant operational readiness and low inertia. It was believed that PPT with low discharge energy (less than 20 J) needed reduction of the initial inductance, despite the fact that the low capacity of the capacitor bank would not allow to achieve the optimal C/Lo ratio. However, the results of calculations and experiments show that a slight increase in the initial inductance of the discharge circuit, contrary to the assumptions, has a positive effect on the micro-PPT characteristics, reducing the propellant consumption and mainly increasing the specific impulse without significant reduction of the thrust impulse (unit impulse). This feature of the discharge circuit of the PPT with a low discharge energy allows us to discover new solutions in micro-PPT designing and improve the thruster specific characteristics.

1. Introduction
Currently, there has been a steady increase in the number of small spacecrafts with masses of up to several tens of kilograms. Russia and other countries consider the use of spacecraft in orbital groups consisting of up to several hundred units. To control the spacecraft motion, it is necessary to develop a highly efficient small-sized thruster for correcting and maintaining orbits. In this regard, the ablative pulsed plasma thruster (APPT) is seen as the most promising option among the wide range of spacecraft thrusters. Its advantages are precise pulse control, sufficiently long lifetime, constant operational readiness, low inertia and low cost. The area of use of these thrusters is expanding, so it is necessary to increase their specific characteristics, in particular specific impulse.

The ablative pulsed plasma thrusters (APPTs) continue to be developed in Russia and abroad. These thrusters are intended mainly for small spacecraft with limited power supply system capacity [1-6]. Figure 1 demonstrates the schematic diagram of the APPT discharge circuit with the electromagnetic mechanism of plasma acceleration. The main characteristics of the APPT discharge circuit are the constant capacitance Co, resistance Ro and inductance with the constant Lo and the variable component ΔL [7].
The electrodynamic efficiency is largely determined by the ratio of the constant capacitance to the initial inductance of the discharge circuit. Therefore, in order to increase the electrodynamic efficiency for APPT with discharge energy of more than 50 J the initial inductance $L_0$ has to be reduced [8-10]. It was believed that the same approach was necessary for APPT with small discharge energy (less than 20 J), despite the fact that the bank capacity is much lower and thus the optimal $C_0/L_0$ ratio for such thrusters could not be achieved.

This being said, the search for the optimal ratio is a necessary, but not sufficient condition for obtaining high specific characteristics. A significant part of the mass of the plasma-forming substance enters the channel after the discharge is almost over. This part of the low ionization plasma flow is accelerated only to thermal speeds, which leads to a decrease in both specific impulse and propulsion efficiency of the thruster. In order to improve the coordination of input of energy and mass into the channel it is necessary to study how inductance affects the propulsion and specific characteristics of the thruster.

To conduct experiments on the influence of the discharge circuit inductance on the characteristics of the APPT, we took the previously studied laboratory model of rail geometry with side feed of the propellant with energy of 6.6 J (figure 2) [11]. During the vacuum bench tests, the initial voltage $U_n$ on the capacitor bank and oscillograms of discharge current of the thruster were registered, its average thrust was periodically measured, and the amount of discharge pulses were recorded. The discharge current and the thrust were measured using a dual-traced digital storage oscilloscope, one input of which was reading the signal transmitted via an RC integrator from the Rogowski belt located on the cathode bus of the model, while the other was receiving the signal from the inductive sensor of the thrust-measuring device.

To measure the average thrust of the APPT, we used a direct string pendulum thrust-measuring device fitted with an inductive displacement sensor and a calibration system with low-friction joints. Figure 3 displays the device diagram.
Figure 2. Principle diagram of the pulsed plasma thruster discharge channel [9, 11].

Figure 3. Diagram of the thrust measuring device.

Measurement of the flow rate of the propellant during the operation of the APPT was carried out by weighing the Teflon bars on highly sensitive analytical balances before and after a series of \((3...8)\cdot10^3\) pulses, the results of which also determined its flow rate per pulse. With a total number of pulses of \(~5\cdot10^3\), the relative error in the mass of the bars did not exceed \(\pm0.5\%\).

The integral characteristics of the APPT prototype were determined based on the measured APPT thrust and average flow rate of the propellant per pulse. The errors did not exceed \(\pm5\%\) for thrust and \(\pm1\%\) for discharge voltage.
2. Materials and research methods

2.1. Physical-and-mathematical modeling of plasma acceleration processes in APPT with low discharge energy

A physical-and-mathematical model of the plasma acceleration process in the APPT discharge channel was previously developed [11] in order to study the impact of the initial inductance of the discharge circuit on the characteristics. The model is a system of ordinary differential equations and one integral equation. Plasma blob on the one hand is considered as a material point (it has zero dimension) and on the other hand is described as an extended object that changes its shape and characteristics. In this model, we used the ordinary differential equations of motion of the center of mass of the PB and equations describing the evolution of the plasma blob averaged characteristics, such as temperature and pressure. The plasma blobs accelerate in the channel mainly as the result of electromagnetic forces, with their mass replenishing due to the Teflon bars ablation. For simplicity, it is stated that all the radiation energy originates from the blob center and falls on the surface of the Teflon bars that are facing the acceleration channel. The absorption of energy by the bars results in ablation of the propellant entering the channel. A moving PB absorbs the propellant that ablated inside the PB, and “scoops” the ablated propellant in the channel in front of it. The propellant entering the channel behind the PB is lost for this particular PB, but the next one can pick it up. The propellant ablated behind the last blob is completely lost. The proposed scheme is simplified, but at the same time, it describes all the basic processes occurring in the discharge channel. The model contains correction factors that are chosen in accordance with the condition of the best match of the calculated current curve and the physical experiment.

Despite the fact that the model mainly describes the motion of the center of mass of a plasma blob, we used in it the two-dimensional spatial models of plasma radiation, radiation transport and energy absorption by the channel walls. This allows us to describe adequately these processes in the model.

In APPT with energy up to 20 J there is an oscillatory discharge with a significant number (4...6) of half-periods of the discharge current oscillations, leading to wave-like generation and acceleration of the plasma. This quasi-one-dimensional physical-and-mathematical model takes these features into account. The periodicity of the plasma generation process is modeled by the formation of several plasma blobs moving one after the other in the acceleration channel. The dynamics of all plasma blobs is calculated similarly to the first blob, while the density and pressure are determined by the amount of propellant that has ablated by this time.

The initial inductance of the discharge circuit $L_o$ varied during the calculations. The results are summarized in table 1.

| Initial inductance, nH | 33  | 40  | 46  | 50  | 52  |
|-----------------------|-----|-----|-----|-----|-----|
| Discharge energy, J   | 6.62| 6.62| 6.62| 6.62| 6.62|
| Mass flow rate, µg per pulse | 23.7 | 20.8 | 17.5 | 15.8 | 14.9 |
| Single thrust impulse, mN·s | 0.112 | 0.118 | 0.134 | 0.150 | 0.154 |
| Specific thrust impulse, m/s | 4741 | 5648 | 7672 | 9436 | 10346 |

The above calculation results let us conclude that an increase in the initial inductance of discharge circuit for an APPT with the low discharge energy positively affects the characteristics of the APPT, contrary to the generally accepted principles. It reduces the flow of the propellant and increases the thrust specific impulse, due to better coordination of energy and mass input in the discharge channel.
2.2. Experimental study of the impact of the discharge circuit initial inductance on the characteristics of APPT with low discharge energy

In order to verify the results of the calculation by the physical-and-mathematical model, we conducted experimental studies of the impact of the discharge circuit inductance on the characteristics of APPT with low discharge energy. For this purpose, we made a laboratory model of APPT with energy of 6.6 J, which consisted of the following main elements: a discharge channel, a capacitor bank consisting of two capacitors, and a system for feeding the propellant (figure 4). The discharge channel was formed by two flat copper electrodes (cathode and anode), two Teflon bars installed on the sides between them and an end insulator. High-voltage igniter was inserted into the hole in the cathode electrode.

![Figure 4. The laboratory model of the APPT.](image)

We installed additional flexible copper conductors between the capacitor block and the discharge channel in order to vary the inductance in the APPT (figure 5). It was possible to achieve different values of the initial inductance of the discharge circuit by changing the distance between these conductors.

![Figure 5. Modification of the laboratory model of APPT in order to increase the initial inductance of the discharge circuit: a) before the change, b) with additional conductors.](image)
Figure 6 shows the oscillograms of the discharge current at different Lo values.

![Oscillograms of discharge current](image)

**Figure 6.** The oscillograms of the current at different values of APPT discharge circuit inductance.

To determine the value of the initial inductance, a current oscillogram was taken at the short circuit of the electrodes at the very beginning of the discharge channel. Then the value of the discharge circuit initial inductance \( L_0 \) was calculated by the following formula:

\[
L_0 = \frac{T^2}{\pi^2 \cdot C},
\]

where \( C \) is the bank capacity and \( T \) is the duration of the half period of discharge current.

During the tests, we measured the average thrust and flow rate of the propellant as well as the discharge circuit initial inductance. In addition, we calculated the characteristics of the test sample, such as discharge energy, power consumption, thrust impulse and mean – mass plasma flow rate (specific thrust impulse). The results of tests of APPT with energy of 6.6 J with various inductance values are given in table 2. Comparison of the experimental data with the calculated data is shown in table 3 and figure 7.

**Table 2.** Test results for a 6.6 J APPT at different initial inductance.

| Characteristics         | \( L_0=33 \) | \( L_0=41 \) | \( L_0=50 \) |
|-------------------------|-------------|-------------|-------------|
| Discharge energy, J     | 6.6         | 6.6         | 6.6         |
| Power consumption, W    | 13.2        | 13.2        | 13.2        |
| Single thrust impulse, mN·s | 0.11      | 0.109       | 0.095       |
| Mass flow rate, µg per pulse | 21.4     | 18.9        | 13.5        |
Table 3. Comparison of experimental and calculated data.

| Inductance, nH | Specific thrust impulse, m/s | Inductance, nH | Specific thrust impulse, m/s |
|---------------|----------------------------|---------------|----------------------------|
| 33            | 4966                       | 33            | 4741                       |
| 36            | 5070                       | 36            | 5142                       |
| 41            | 5777                       | 41            | 6074                       |
| 46            | 6850                       | 46            | 7672                       |
| 50            | 7058                       | 50            | 9436                       |
| 51            | 6976                       | -             | -                          |
| 103           | 7797                       | -             | -                          |

Figure 7. Dependence of the specific impulse on the initial inductance of the discharge circuit.

It is evident that the tendency of specific impulse growth with an increase in the initial inductance of the thruster discharge circuit coincides well with the preliminary calculations. At the same time, the experiments have shown that with a significant increase in inductance the duration of the discharge increases so much that it is carried beyond the discharge channel. This leads to a decrease in the energy inside the APPT channel, which in turn results in such a negative phenomenon as Teflon bar carbonization. It also happens due to the low degree of ionization of the propellant that evaporated at that moment, which settles on the surface of the discharge channel. The calculation model does not take into account the carbonization and reduction of the working surface area of the Teflon bars. This explains the observed discrepancy between theoretical and experimental results when the inductance exceeds 45 nH.
3. Results and discussion

3.1. Modernization of the sample propulsion system PPT-120 experimental model

The results of computational, theoretical and experimental studies have allowed us to finalize the PPT-120 propulsion system (PS PPT-120) in order to improve its specific characteristics. The PS PPT-120 experimental model has been developed on demand of the Space Systems Research and Development Institute (NII KS) and is intended to maintain and correct the orbit of a small low-orbit spacecraft weighing less than 100 kg. The PPT-120 propulsion system is shown in figure 8.

![Figure 8. PPT-120 propulsion system.](image)

The PPT-120 propulsion system is made as a monoblock comprising an energy storage unit (ESU) (1) with an electrodes system forming a discharge channel, a discharge initiation unit (DIU) (2), a power propulsion unit (PPU) (3) and a screen shield (4) intended to protect the thruster elements and adjacent spacecraft systems from the effects of peripheral flows of the thruster plasma jet (figure 8).

Capacitors located in the energy storage unit are connected to the electrodes of the discharge channel by means of flexible conductors. A series of conductors of different lengths was designed to change the initial inductance of the discharge circuit. After installing each set of the conductors, we measured the inductance of the model and conducted the experiment. Figures 9-11 show the experimental dependences of the specific thrust impulse, the mass flow rate per pulse and the single thrust impulse on the initial inductance of the discharge circuit.
Figure 9. Dependence of the specific thrust pulse of PPT-120 on the initial inductance of the discharge circuit.

Figure 10. Dependence of the mass flow rate in PPT-120 per pulse on the initial inductance of the discharge circuit.

Figure 11. Dependence of a single thrust pulse on the initial inductance of the discharge circuit of PPT-120.
The graphs demonstrate that the increase in the initial inductance of the electric circuit in the range of \(~35 \ldots 60\) nH leads to a significant increase in the specific impulse (20%), from 7125 m/s to \(~8500\) m/s. This happens due to a decrease in the mass flow rate per pulse (25%) with a significantly smaller decrease in the thrust single impulse (10%). The characteristics of the original and upgraded propulsion system are given in Table 4.

**Table 4.** Characteristics of the original and upgraded PPT-120 propulsion system.

| Characteristics                        | PS PPT-120 with Lo=37 nH | PS PPT-120 with Lo=59 nH |
|----------------------------------------|---------------------------|---------------------------|
| Discharge energy, J                    | 20                        | 20                        |
| Single thrust impulse, mN·s             | 0.34                      | 0.31                      |
| Mass flow rate, µg per pulse           | 48                        | 36                        |
| Specific thrust impulse, km/s           | 7.1                       | 8.5                       |
| The operating frequency of the impulses, Hz | 2.65                      | 2.65                      |
| Power consumption, W                   | 53                        | 53                        |
| Average thrust, mN                     | 1.1                       | 0.82                      |
| Propellant                             | Teflon                    | Teflon                    |
| Propellant store, kg                   | 0.12                      | 0.12                      |
| Number of pulses (cycle life)          | \(2\cdot10^6\)            | \(3\cdot10^6\)            |
| Total thrust impulse, kN·s              | 0.8                       | 0.95                      |
| PPT total mass, kg                     | 3.5                       | 3.5                       |

The table shows that the specific and total thrust impulses of the thruster after its completion significantly increased by 20% and 19%, respectively. At the same time, there is a decrease in the single thrust impulse and, consequently, the average thrust, which can easily be compensated by increasing the frequency of the propulsion system pulses.

A reduction in consumption and, consequently, an increase of the specific thrust impulse are affected by a decrease in the effect of propellant bar post-streaming after completion of the process of main Teflon mass acceleration. With the increase of the inductance, this happens due to an increase in the discharge duration and a decrease in the peak value of current, which in turn leads to a corresponding decrease of the plasma radiation energy and the positioning of the radiating plasma blob at a greater distance from the Teflon bars.

The efficiency of the PPT-120 propulsion system was verified by long-term tests, which resulted in the absence of carbonization traces on the Teflon bar working surfaces. Figure 12 shows the state of the discharge channel after long tests.

**Figure 12.** The PS PPT-120 discharge channel after longer tests.
4. Conclusion
The calculations by the above-mentioned physical-and-mathematical model allow us to understand the reasons for the increase in the specific impulse of the thrust with an increase in the initial inductance of the discharge circuit. Figure 13 displays graphs of ablated mass in the discharge channel as a function of time under different initial inductance of discharge circuit, taken from the calculation model. There are also graphs of the square of the discharge current as a function of time, characterizing the power released in the discharge channel in the first two half-cycles.

Figure 13. Calculated curves of ablated mass and square of discharge current as a function of time.

The figure shows that the duration of the discharge increases with an increase in the initial inductance of the discharge circuit, while the value of the evaporated mass fed into the channel decreases. At the same time, the mass flow of the plasma-forming substance stops at the end of the second half-period, while at a lower inductance it goes on. If the ablation mass decreases with increasing Lo, this leads to an assumption that the flux of radiant energy hitting the ablating surface decreases, both due to the fact that the discharge burns farther from the surface of the Teflon bars and
due to a decrease in the current amplitude inversely proportional to the root of $L_0$. That is, with $L_0$ increasing, the so-called after-evaporation effect is reduced when the ablated mass is not accelerated efficiently in the discharge channel. However, with a further increase, the positive effect of increasing the inductance $L_0$ is lost. Also, the optimal $L_0$ inductance value can be different for each APPT model.

The results of the experiments allowed discovering the nature of the influence of the discharge circuit $L_0$ inductance on the characteristics of a low-energy APPT.

We can therefore say that with an increase in the initial inductance of the circuit, the APPT with low discharge energy sees improvement in the coordination of the input of energy and mass into the acceleration channel.

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