Thrust characteristics of compact high-voltage pulsed plasma thruster utilizing liquid propellant

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Abstract. In this work, we present the results on thrust performance of 0.5 kg sub-joule pulsed plasma thruster prototype based on a high-voltage transformer with magnetic storage capable of work at frequency of 400 Hz. The discharge unit is made of ferroelectric ceramics with an option for utilizing liquid propellant. In case of vacuum oil as a propellant, we obtained values of thrust of ~ 80 nN·s per discharge and 33 μN·s for 400 pulses in 1 second.

1. Introduction

Recently, many programs on development of small satellites having mass from 1 kg (i.e., CubeSats) to tens of kilograms have been initiated all over the world [1–3]. Such small satellites require comparably small thrusters for orientation and orbit correction. The thruster should meet the requirements of compactness, low weight, high thrust efficiency and high propellant efficiency. The requirements of compactness and low weight are due to the size of the satellite and due to general economical reasons concerning launch of the load to the orbit. The requirement of thrust efficiency arises because as the thruster becomes smaller and the pulse bit becomes weaker, it is important not to lose it’s controllability in order to change the orientation of the spacecraft in reasonable time. Propellant efficiency is of great importance because the propellant is limited on the orbit, whereas the source of energy for propulsion of this propellant is practically unlimited (solar radiation). The last requirement stimulate to focus on devices which accelerate mass at as high velocity as possible. From this point of view, the favorable choice is pulsed plasma thrusters (PPT) based on a phenomenon of surface vacuum flashover, which provide maximum velocity of plasma ejection of ~ 100 km/s and higher [4].

By now, among low-thrust PPTs, the most developed systems are based on capacitors storing ~ 5-10 J of energy, which are able to operate at frequency ~ 1-2 Hz and discharge current of ~ 10 kA [5]. Such working parameters limit the minimal mass of the capacitor (not less than 0.5 kg), making it one of the heaviest parts of the entire thruster assembly. Some solutions concerning decrease of the weight [6] imply shortening of the discharge gap, decrease in value of stored energy with corresponding decrease in the voltage and reduction in the discharge surface [7]. Unfortunately, this leads to the considerable extension of propellant rods and problems with their supply. Moreover, decrease in mass of the energy storage unit by the expense of its capacity down to sub-joule values
without changes in design of the thruster inevitably leads to poorer thrust performance. However, lower energy capacity may be compensated either by the higher operating rate, or higher impulse in order to keep the thrust-to-weight ratio constant. Higher operating frequency may be obtained by the using of magnetic energy storage, whereas higher impulse may be obtained by higher velocity of propellant ejection. The latter approach both provides necessary level of thrust and enables to decrease the mass of the thruster considerably. Earlier, we researched low-joule (~2 J) PPT prototypes and demonstrated that it is possible to obtain particle beams having average mass velocity of ~10 km/s and thrust of ~3-5 μN·s per discharge [8].

2. Thruster design
Following the above-mentioned approach, we proposed a pulsed thruster prototype based on a high-voltage generator with an inductive storage working in high-repetition rate mode [9]. The generator alternately charges two 3-nF capacitors by pulses of voltage of ~10 kV. Discharge of these capacitors in self-breakdown mode provides high-frequency current of up to 100 A during 1 μs. The thruster has a mechanical system for smearing of the liquid propellant on a ceramic substrate. This system provides homogeneous supply of the propellant and formation of thin liquid layer on the surface of the dielectric in the linear discharge gap. However, the complexity of the unit for propellant distribution leads to overweight and unreliability.

The improved low-weight prototype also is based on the generator with the inductive storage and ceramic substrate. The main difference is in electrode configuration (coaxial scheme) and propellant distribution unit (valve). Figure 1 shows the photograph of the thruster prototype assembly. It consists of a high-voltage transformer (energy storage) (1), discharge unit with a liquid propellant supply system (2) with an additional capacitor (3), and a power unit (4). The assembly is mounted on a rotating platform (5). The weight of the pulsed transformer with the discharge unit accounts for ~450 g.

The discharge unit of the thruster (see figure 2) consists of a disk cathode (diameter 15 mm) with a central rod (diameter 4 mm, length 30 mm), outer tube-shaped anode (diameter 29 mm, height 15 mm), polyamide housing, and ceramic substrate with a dispenser for liquid propellant. The anode tube and cathode rod represent an effective capacitor (~120 pF). We used an additional capacitor (470 pF) in parallel to the discharge gap to change the working mode of the pulsed transformer.

The ceramic substrate was cut out of a commercially produced (Sr,Bi)TiO₃-based ceramic capacitor ($\varepsilon \approx 900$). This material was chosen to maximize the share of ions generated at the initial
stage of the flashover process, because bias current, which is proportional to permittivity of the sample, dominate over conduction current at this stage of the discharge. For comparison with the literature, we use PTFE. As liquid propellants, vacuum and castor oil were chosen due to their low pressures of saturated vapor.

High-voltage transformer produces pulses of high voltage at frequency of 400 Hz (programmed) being powered by 28 V onboard power supply unit. In no-load mode (2-MΩ resistor), voltage is \( \sim 25 \) kV. When the generator is loaded on the discharge unit and an additional parallel capacitor (entire capacity of the load - 600 pF), we obtain voltage of \( \sim 2 \) kV at the discharge current of 0.1 A during 600 \( \mu \)s and the peak voltage of 5 kV after current cut-off.

Power unit consists of a stack of electrical batteries (total voltage of 28 V) and a circuit board put into a sealed metal cylinder with a transparent window. The thruster turns on by irradiating of IR-receiver on a circuit board by an IR-LED. Controller is programmed to initiate a train of 400 1-ms pulses within 1 second.

3. Electrical parameters

Electrical parameters of the thruster were measured in three cases: 1) Resistive load; 2) PTFE sample as load; 3) Dry ceramic substrate as load. Figure 3 shows the waveforms of voltage as the generator is loaded on 40 kΩ and 90 kΩ resistors. Using these waveforms, we calculate impedance of the generator and electromotive force, which are 120 kΩ and 25 kV, respectively. By integration of waveforms of voltage and current we estimate full energy stored in magnetic storage as \( \sim 60 \) mJ.

![Figure 3. Voltage across the discharge gap in case of the resistive load: 40 kΩ (solid line) and 90 kΩ (dashed line).](image)

The waveforms of voltage across the discharge gap and current during flashover of PTFE and ferroelectric ceramics are presented in figure 4. During the flashover of the PTFE, voltage across the
additional capacitor at the moment of the flashover initiation accounts for ~ 4 kV; the current accounts for ~ 0.1 A. The energy introduced into the discharge is estimated as 14 mJ.

Total duration of the discharge in case of flashover of dry ferroelectric ceramics is ~ 500 μs (see figure 4). The entire discharge process consists of several discharges of the capacitor connected in parallel to the discharge gap (about 6 discharges at capacity of 120 pF). Connection of the additional capacitor in parallel reduces the number of these discharges, but increases the duration of each of them. A possible explanation of this is as follows. The gap of ~ 6-8 mm with ferroelectric ceramic in this electrode configuration can withstand voltage of ~ 3-5 kV. Since the generator provided maximum current of ~ 1 A, the additional capacitor (470 pF) may be charged not less than within 2–3 μs. These parameters determine the process in the gap as a consequence of several discharges within a single charge cycle (30 μs).

4. Thrust measurements
The measurements of thrust have been carried out in a vacuum chamber at pressure of < 10⁻⁴ mm Hg. The platform with the thruster assembly is hanged on a thin metal thread in the chamber. Moment of inertia of the assembly is 0.09 kg·cm²; period of oscillations is 175 s. The thrust is calculated from the rotation angle of the platform, which is measured by deflection of a laser beam. This measuring technique provides relatively high sensitivity (~ 0.5 μN·s per a series of pulses) and immunity to electromagnetic noise.

In case of PTFE, thrust in one second is 28 μN·s, whereas thrust per one discharge is 70 nN·s. Being normalized to unit of energy introduced into the discharge channel, these values, obtained for a series of relatively long pulses (30 μs), demonstrate good agreement with the values obtained for single nanosecond pulses also using PTFE (~ 4-6 μN·s/J) [8].

| Thrust | PTFE | Dry ceramics | Ceramics + vacuum oil | Ceramics + castor oil |
|--------|------|--------------|-----------------------|-----------------------|
| In 1 second (μN·s) | 18   | 30           | 33                    | 38                    |
| Per 1 discharge (nN·s) | 45   | 75           | 83                    | 95                    |
| Per 1 joule (μN·s/J) | 3.2  | 1.5          | 1.7                   | 1.9                   |

In case of dry ferroelectric ceramics, thrust in one second accounts for 20 μN·s and thrust per one discharge is ~ 50 nN·s. Liquid propellants (vacuum oil and castor oils) were tested being smeared on the ceramic surface of the discharge unit before the chamber being vacuumed. This thin layer of oil provides considerable increase in thrust to be compared to dry ceramics (33 μN·s and 38 μN·s for vacuum oil and castor oils, respectively). The results on thrust for all the cases are in table 1.

5. Conclusion
The offered approach allows to obtain satisfactory thrust characteristics (~ 3 μN·s/J) at relatively low stored energy by compact low-weight (~ 0.5 kg) thruster. The results show that ferroelectric ceramic demonstrate better thrust performance than PTFE. Promising results on oils at high-repetition rate for sub-joule thruster open the way to future experiments with water as a liquid propellant.

Acknowledgements
This work was supported in part by the Russian Foundation for Basic Research; project 18-08-000185.

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