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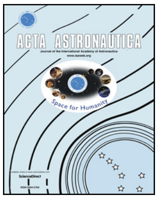

# Continuous discharge in micro ablative pulsed plasma thrusters

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ABSTRACT

The mechanism of continuous discharge in micro ablative pulsed plasma thrusters has always been ignored. A series of experiments on discharge completion rate were conducted, and theoretical analyses were performed to understand the results. These results showed that as initial voltage decreased to a certain value, a portion of energy was not released in a short time, which caused overall efficiency to greatly decrease. As the initial voltage decreased sequentially, this phenomenon occurred more frequently. This study provides a reference for high-frequency micro ablative pulsed plasma thrusters.

## 1. Introduction

As satellite development progresses toward increasing miniaturization, the electric propulsion thrusters including micro ablative pulsed plasma thrusters (μAPPTs), which have high specific impulses and simple structures, have become increasingly popular [1–3]. In current space missions, μAPPTs are mainly used in micro-spacecraft (especially satellites with a mass of less than 100 kg) for flight attitude control and as the main thrusters of nanosatellites [4]. Given these thrusters' high ignition frequency, high reliability, high overall efficiency and low power, prospects for μAPPTs have expanded as thrust accuracy has increased [5,6]. However, the low energy conversion efficiency of APPTs has always been criticized. Certain studies have suggested that the main reason for this poor efficiency is low propellant utilization efficiency, but these investigations have almost completely ignored another important factor, discharge completion rate (which indicates whether energy was not released during μAPPT discharge), especially for low-power ($< 2$ W) and high-frequency ($> 100$ Hz) APPTs.

In the initial process, the large current near the surface of the propellant ablates the solid propellant (usually uses Polytetrafluoroethylene, PTFE) to form neutral gas. This gas is then broken down into plasma using high voltage and accelerated by electromagnetic and thermal forces; in other words, the plasma is at a higher velocity than the gas (Figs. 1 and 2) [7]. As the discharge continues, the conductive path (plasma) is ejected. If the neutral gas does not break down, the circuit is broken, and the electrode voltage does not decrease to zero but instead maintains its value (Fig. 3); as a result, a subset of energy is wasted. For high-frequency μAPPTs, this wasted energy accounts for a larger proportion of total energy. In addition, the electrode voltage is essential for ionizing the propellant [8]; if discharge is not incomplete, propellant utilization efficiency loss is greatly increased. Therefore, a series of experiments on discharge completion rate were conducted, and theoretical analyses were performed to understand the results.

## 2. Experimental setup

The experimental system included a μAPPT prototype, an electrical power supply, a vacuum system (with a vacuum degree of $5 \times 10^{-3}$ Pa), an oscilloscope, a high-voltage probe and a Rogowski coil. Since the power of the PPU in microsatellites or nanosatellites is always less than 10 W, the mass of the electrical power supply accounts for a large fraction of the total mass of the μAPPT system and is related to the charged voltage. Therefore, we refer to LES-series PPTs [4]. The discharge energy was selected to be less than 1 J, and the capacitance of the main capacitor was selected to be 2.1 μF. Other parameters are listed in Table 1.

As shown in Fig. 4, voltages across the electrodes were measured using a high-voltage probe. Discharge time histories were observed using an oscilloscope to obtain discharge completion rates. Additionally, we wiped the surfaces of the spark plug, the electrodes and the propellant before each test to reduce the effects of deposition. Working conditions and parameters are listed in Table 2.

## 3. Results and discussion

The APPT discharge process is similar to arc discharge. In particular, APPT discharge must satisfy Thompson's condition for self-sustainment:

$$\gamma\left(e^{\alpha d} - 1\right) = 1 \tag{1}$$

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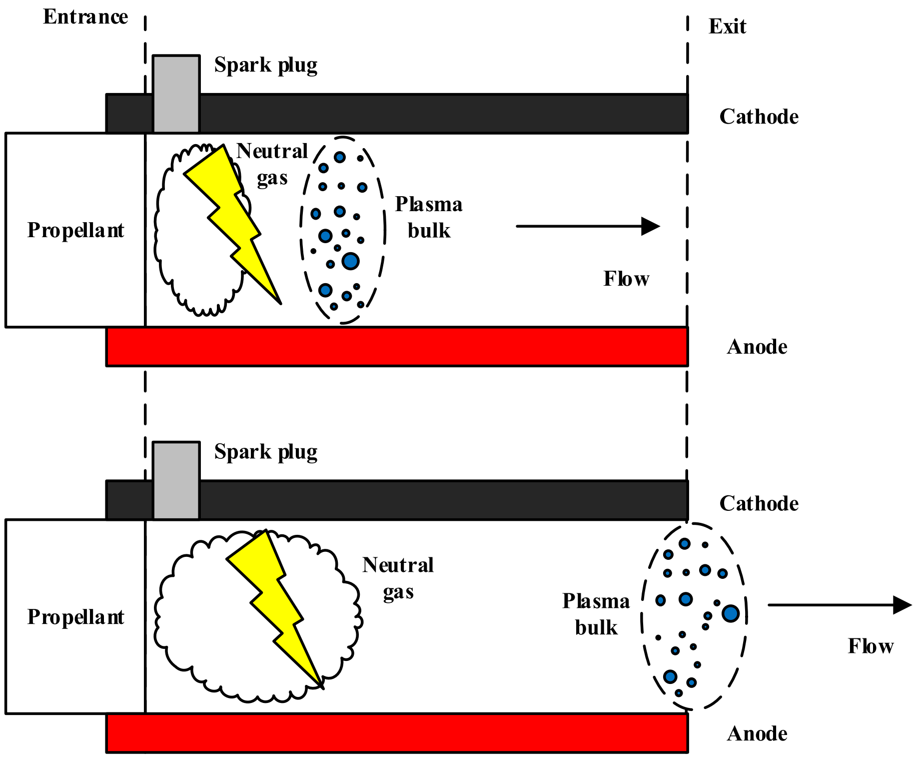
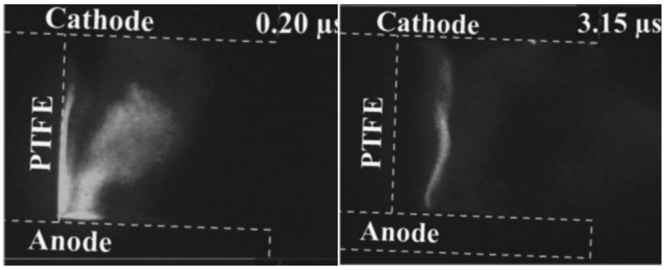


**Fig. 1.** Discharge principle for a μAPPT.



(a) (b)

**Fig. 2.** Plasma flow in μAPPT discharges [7], the propellant was Polytetrafluoroethylene (PTFE).

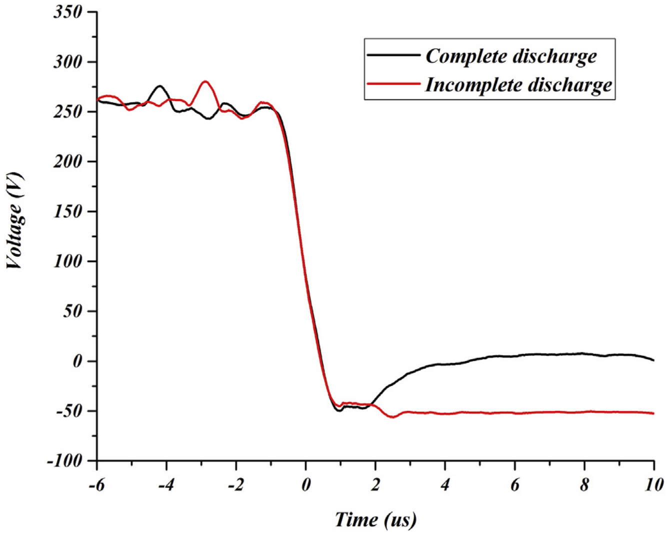


**Fig. 3.** The discharge waveforms of μAPPTs.

**Table 1**
Parameters of the experimental APPT.

| Parameter | Value |
|---|---|
| Length of electrodes | 25 mm |
| Width of electrodes | 12 mm |
| Thickness of electrodes | 4 mm |
| Electrode gap | 25 mm |
| Maximum diameter of spark plug | 10 mm |

where $d$ is the electrode gap, the coefficients $\alpha$ and $\gamma$ are functions of $E$, the electric intensity between the electrodes. Considering the electromagnetic radiation between the electrodes, the electric field is not uniform between the electrodes [9]. Since the distance between the electrodes is small, the electric field is assumed to be uniform in the discharge process. When the thruster's geometry and electrode gap $d$ are constant, $\alpha$ and $\gamma$ are functions of the electrode voltage $U$. That is, $\alpha$ and $\gamma$ vary directly with $U$ when other parameters remain unchanged. In the self-sustaining condition, there is a critical voltage of self-sustaining discharge (i.e., the minimum voltage required to completely maintain μAPPT discharge) [10].

$$U_{\lim} = \frac{B(pd)}{C + \ln(pd)}, \quad C = \ln\frac{A}{\ln(1 + 1/\gamma)} \tag{2}$$

where $p$ is the pressure of neutral gas ablated from the solid propellant and $A$ and $B$ are constants, with $A = k\sigma/T$ and $B = AU_i$.

Assuming that the neutral gas bulk acts as an ideal gas,

$$pd = nkRd \tag{3}$$

where $n$ is the particle density, and

$$n = N_A m/M_{gas} \tag{4}$$

where $M_{gas}$ is the molar mass of neutral gas ablated from Polytetrafluoroethylene (PTFE), $N_A$ is Avogadro's number, and $T$ is the temperature of the neutral gas bulk.