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Discharge reliability in ablative pulsed plasma thrusters

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ABSTRACT

Discharge reliability is typically neglected in low-ignition-cycle ablative pulsed plasma thrusters (APPTs). In this study, the discharge reliability of an APPT is assessed analytically and experimentally. The goals of this study are to better understand the ignition characteristics and to assess the accuracy of the analytical method. For each of six sets of operating conditions, 500 tests of a parallel-plate APPT with a coaxial semiconductor spark plug are conducted. The discharge voltage and current are measured with a high-voltage probe and a Rogowski coil, respectively, to determine whether the discharge is successful. Generally, the discharge success rate increases as the discharge voltage increases, and it decreases as the electrode gap and the number of ignitions increases. The theoretical analysis and the experimental results are reasonably consistent. This approach provides a reference for designing APPTs and improving their stability.

1. Introduction

Pulsed plasma thrusters (PPTs) are spacecraft propulsion devices that use plasma accelerated by an electromagnetic field created by a pulsed electrical discharge [1]. The most common PPTs use a solid polymer, usually polytetrafluoroethylene (PTFE), as the propellant. These PPTs are called ablative pulsed plasma thrusters (APPTs). Fig. 1 shows a schematic of a parallel-plate APPT. APPTs are reliable, relatively simple to design, inexpensive, and provide a high specific impulse. These devices require low power (< 10 W) and are useful for applications such as altitude control for larger satellites and propulsion for microsatellites [2]. APPTs remain an important propulsion device for space missions [3].

Ignition is an important process in APPTs. The present study is motivated by a desire to improve the performance of pulsed electromagnetic accelerators in the context of plasma propulsion. The analysis presented in this study is relevant to improving the reliability of the discharge in APPTs.

2. Review of the problem

2.1. Definition of the problem

Discharge reliability is crucial for the operation of APPTs. In many ignition experiments, discharge reliability has been a problem. Ignitors, or spark plugs, generate the initial charged particles, but breakdown (i.e., the flow of current) between the electrodes may not occur until the next ignition. As shown in Fig. 2(a), the spark plug (red line) discharges, but the main capacitor (blue line) does not. In this case, the APPT does not successfully discharge. Fig. 2(b) shows the time histories of the voltages for a proper discharge. To quantify the discharge reliability, we define the discharge success rate (*ds*) as

$$ds = \frac{N_{ds}}{N_t} \tag{1}$$

where N_{ds} is the number of successful discharges, and N_t is the total number of ignitions.

2.2. Review of previous research

Early APPT studies investigated the physics of APPTs via experiments [4,5] and numerical simulations [6,7]. Several of the most significant studies on spark plug ignition in APPTs are described in the following:

Aston and Pless [8] studied ignitor plug deposition and erosion and the design of the electrical circuit. Their results indicated that inductive rather than resistive coupling to the thruster cathode and the use of a high-current, short-pulse-length plug trigger circuit significantly improved ignitor plug longevity.

Feng and Wu [9] investigated a spark plug that was used in the MDT thruster series and detailed the selection of the type of spark plug, the design requirements for the plug, the performance, and test results.

Hou [10] studied the ignition system in pulsed plasma thrusters. A discharge initiation circuit and three different electrode structures for the spark plug were discussed. The investigators found that spark plug with a parallel electrode provided the best ignition.

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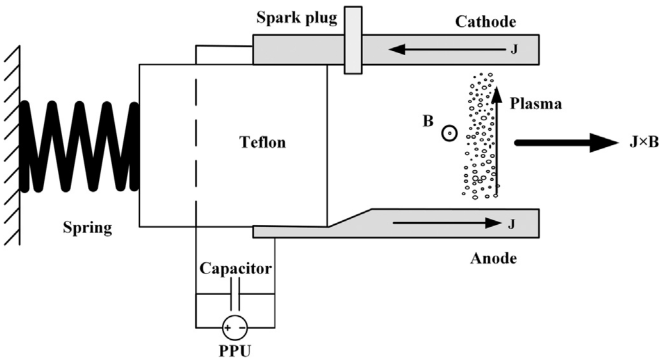

Fig. 1. Diagram of a parallel-plate APPT.

Brady [11] studied a semiconductor spark gap ignitor plug to initiate the discharge in PPTs. In that study, the dynamic plug impedance, the energy utilization efficiency, the plug erosion characteristics and the velocity of the ignitor plug plasma plume were analysed.

Huang [12] studied the breakdown process during APPT ignition and found a time delay (ranging from < 1 μs to 10 μs) between the spark plug discharge and the capacitor discharge. The time delay affected the performance of high-pulse-rate (> 10 kHz) and double-discharge APPTs.

Most studies of PPTs have focused on the durability [8] and the reliability of the spark plug and the associated electrical circuit [9,11]. Furthermore, typical APPT experiments have mostly focused on only one ignition process [9–11], and discharge reliability has not been addressed [9–12]. Space missions may last many years, so discharge reliability is a concern. Discharge failures occur under many conditions, but a detailed analysis of the subject is lacking.

Recently, a newer and more efficient type of APPT [13–15], the double-discharge APPT, was introduced, and the discharge success rate of this type remains to be evaluated. In this design, the energy is stored in two capacitors that discharge at different times [13] or locations [14,15]. The plasma is accelerated in two stages, and thus, the plasma is accelerated over a longer period of time than in previous designs. The performance of the thrusters would be significantly higher if the discharge success rates were 100%. The motivation for this study was to improve the discharge success rate of double-discharge APPTs.

2.3. Outline of the study

We first investigated the APPT ignition behaviour and measured the discharge reliability. Then, we measured the discharge voltage and current of an APPT to obtain the discharge success rate. By analysing the results, we characterised the relation between the discharge success rate and various factors. We then examined how these factors affect the ignition performance. Finally, we investigated the ignition mechanism by performing a theoretical analysis. Suggestions for improving the performance of APPTs were provided.

3. Experimental method

3.1. Hardware

The experimental system included two parts, namely, the propulsion system and the measurement system. The propulsion system included the APPT and the electrical power supply. The measurement system included a vacuum chamber, an oscilloscope, two high-voltage probes and a Rogowski coil.

An actual thruster was not used for the experiments. Rather, a simplified parallel-plate accelerator that facilitates the observation of discharges was used. The experimental APPT was composed of rectangular copper electrodes, a capacitor, a spark plug, a rubber band (or a constant force spring), and a block of polytetrafluoroethylene (PTFE) propellant. The initial plasma was generated by a coaxial semiconductor spark plug that was mounted on the cathode of the APPT. Table 1 lists the main parameters for the experimental APPT and their values.

The electric power supply had three functions, charging the APPT energy storage capacitor, energizing the spark plug and controlling the ignition process. The electric power supply also provided circuit protection.

The vacuum chamber was cylindrical, and the vacuum was maintained by two rotary vane pumps, one Roots pump and one diffusion pump. The chamber and the thruster cathode were grounded. Table 2 presents the main parameters of the electrical and vacuum systems and their values.

3.2. Procedures

In our experiments, the APPT was ignited in the pulsed mode. To reduce the effects of deposition, we wiped the surfaces of the spark plug, the electrodes and the propellant before each test.

As shown in Fig. 3, the voltages across the spark plug and electrodes were measured using high-voltage probes, and the discharge current was measured using a Rogowski coil. The discharge time histories were observed using an oscilloscope to obtain the discharge success rate.

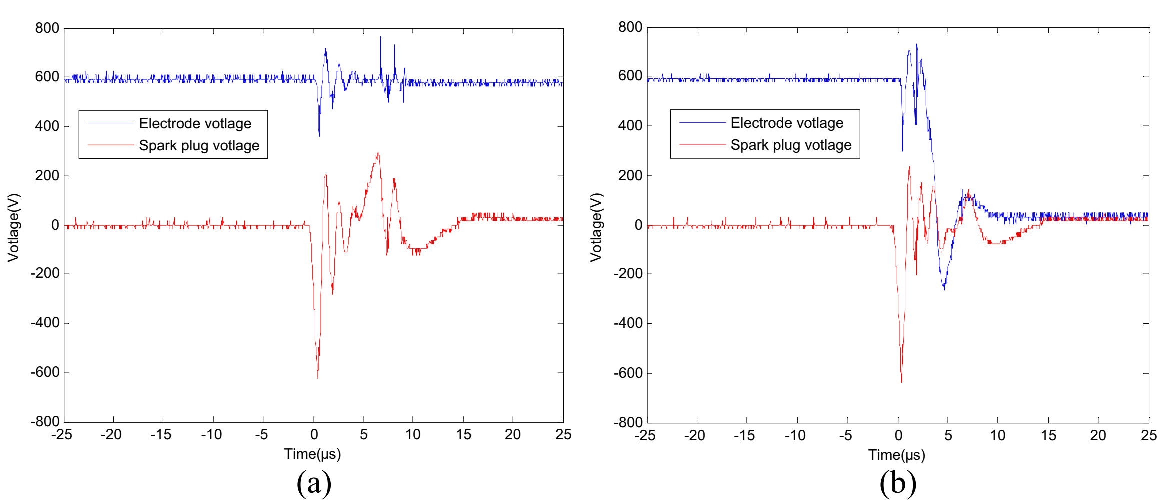

Fig. 2. Time histories of voltages measured across the electrodes and the spark plug (600 V, 25 mm) (a) unsuccessful discharge (b) successful discharge.