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Ignition mechanism in ablative pulsed plasma thrusters with coaxial semiconductor spark plugs

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ABSTRACT

Ignition process, as the initiation of the entire discharge, plays an important role in ablative pulsed plasma thrusters. While spark plug exactly how initiate discharge is achieved is still under review. This study did some experiments with two kinds of propellant surfaces (normal or inclined) and without propellant to explain the ignition process. The experimental results showed: when the thruster discharge without propellant, it is essentially a surface flashover process on ceramics; when the propellant was loaded, the main discharge occurs after the initial conductive path composed of electrons emitted by spark plug forming. This study provides a reference for the high performance pulsed plasma thrusters.

1. Introduction

Ablative pulsed plasma thrusters (APPTs), use polytetrafluoroethylene (PTFE) as the propellant, are spacecraft propulsion devices that utilize plasma accelerated by electromagnetic field created by pulsed electrical discharge [1,2]. APPTs are reliable, relatively simple to design, inexpensive, and provide a high specific impulse. In addition, they require low power (<10 W) and are used for attitude controlling for larger satellites and propulsion for microsatellites [3], that is, they remain an important propulsion device for space missions [4]. Ignition process using spark plug, as the initiation of the entire discharge, plays an important role in ablative pulsed plasma thrusters (APPTs). Some early APPT studies measured the ignited characteristics [5,6] and investigated the physics via experiments [7,8] and numerical simulations [9]. However, spark plug exactly how initiate discharge is achieved is still under review.

Nowadays, two possible theories have been proposed: the first [7,8] is that the spark plug begins to ignite and provides the initial plasma for the multiplication process of secondary electrons, when the number and distribution of charged particles (ions, electrons) meet the circuit requirements, a plasma channel forms between electrodes and the main capacitor starts to discharge. The second involves field emission [10]. In the presence of strong electric fields, a potential barrier forms at the surface of the solid (such as electrodes), as shown in Fig. 1. If the electric field is strong enough and the potential barrier suitably thin, the electrons would tunnel quantum mechanically through the barrier and escape into the vacuum (the discharge channel). That is, the electrons would be emitted, the augment the electric field creating a conductive path, the main discharge then occurs.

Above all, the initial conductive path how to be formed were in divergent. While solid propellant must be ablated by the arc (conductive path) in APPT, that is, the surface characteristic of the propellant becomes a characterization in these two assumptions. In this study, a series of APPT discharge experiments with two kinds of propellant surfaces (normal, inclined surface) are operated to analyze the ignition process using spark plug how to initiate the main discharge and the parameters are shown in Fig. 2. For ensuring the discharge completion rate [11], the charged voltage in these experiments was set at 1130, 1430 V, respectively, and the ignition frequency was 0.5 Hz. In addition, APPT was ignited without propellant to verify the ignition mechanism.

2. Experimental steps

The experimental system included an APPT prototype, an electrical power supply, a vacuum system, an oscilloscope, a high-voltage probe and a Rogowski coil. In each experiment, the experimental vacuum chamber had a pressure of 5×10^{-3} Pa. The voltages in the APPT discharge circuits were measured using a high-voltage probe, and the currents in the circuits were measured using a Rogowski coil. The total ablated mass after operations was determined using a high-precision balance under different working conditions (i.e., to calculate the mass shot). And the parameters of the experimental APPT are shown in Table 1, the coaxial semiconductor spark plugs using in experiments is shown in Fig. 3.

Since the surface characteristic of the electrodes, propellant, even

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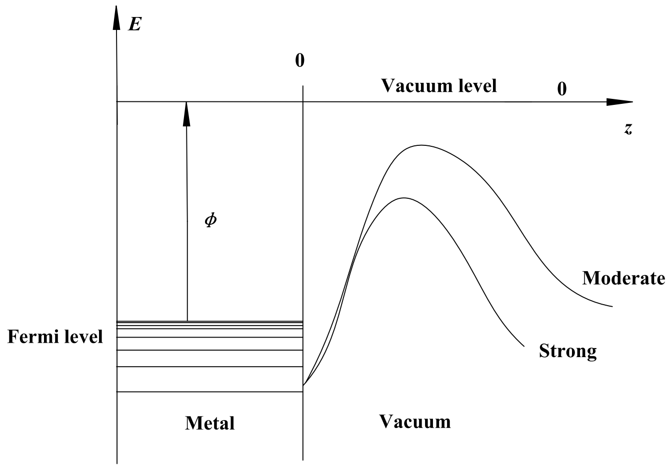


Fig. 1. Schematic of the electron escaped condition.

the spark plug may affect the experimental results, the surfaces of the spark plug, the electrodes and the propellant were wiped before each test. To eliminate external interference, operational errors or wrong data, multiple sets of data were retained. In addition, the "Propellant A, Propellant B, No Propellant" represents the condition when the APPT was loaded with normal propellant, inclined propellant, no propellant, respectively.

3. Results and discussion

Figs. 4 and 5 show the discharge voltage and current waveforms when the propellant was loaded or unloaded. The APPT was capable of discharging even if no propellant was loaded, the total discharge time was similar, and the difference between the discharge voltages, currents with propellant A, B and with no propellant wasn't obvious, which is consistent with the secondary theory. However, when the propellant wasn't loaded, the discharge light (as shown in Fig. 6) was framed and only attached to the inner wall of the starting section of the accelerated channel.

Since the light-emitting area was obtained by the discharge in the vacuum, which needed to be carried out along the surface of the medium. In this condition, the surfaces of the two side insulating ceramics at the beginning of the acceleration channel would be supplied with the medium, while the middle region (propellant location) between the ceramic didn't be lighted in the actual work lack of media required for the discharge. Above all, ignition process, when the propellant wasn't loaded, is explained as follows:

(1) Similarly to the secondary theory [10], the initial electrons are generated by ablating and ionizing by the electrodes in the case of high voltage (or strong electric field), while the light shows that the insulating ceramic is used as a medium. The discharge process is essentially a surface flashover process on ceramics.

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

Fig. 3. Coaxial semiconductor spark plugs using in experiments.

(2) The voltage waveform of spark plug was measured (as shown in Fig. 7). The duration time of the spark plug voltage is nearly 15 μs, which is much longer than the duration time of the APPT discharge process (~5.5 μs). Therefore, the electrons emitted by spark plug to maintain the discharge.

The ignition experiments were operated two times with two kinds of propellant surfaces, respectively. The waveforms of voltage and current were shown in Figs. 8 and 9.

According to the above waveforms, ignition processes in these conditions (with propellant) are explained as follow:

(1) After spark plug igniting, the electrode voltage fluctuated at the beginning of discharge, which indicated the initial conductive path formed. And the total resistance of the circuit (~10 mΩ) was so little that the initial current (~500 A) generated enough thermal energy. With thermal energy in initial conductive path, some neutral gas could be ablated.
(2) With the high voltage, the initial neutral gas was ionized to plasma quickly (~0.5 μs): according to ionized model [12], the initial voltage provided electron emitted by spark plug with the enough energy to ionize the little amount of neutral gas. Additionally, considering the electromagnetic radiation between the electrodes, the electric field is not uniform between the electrodes [13]. Since the distance between the electrodes is small, the electric field is assumed to be uniform in the discharge process. The energy that accelerated electron obtained is

$$E_v = q\lambda E = q\lambda U/d \tag{1}$$

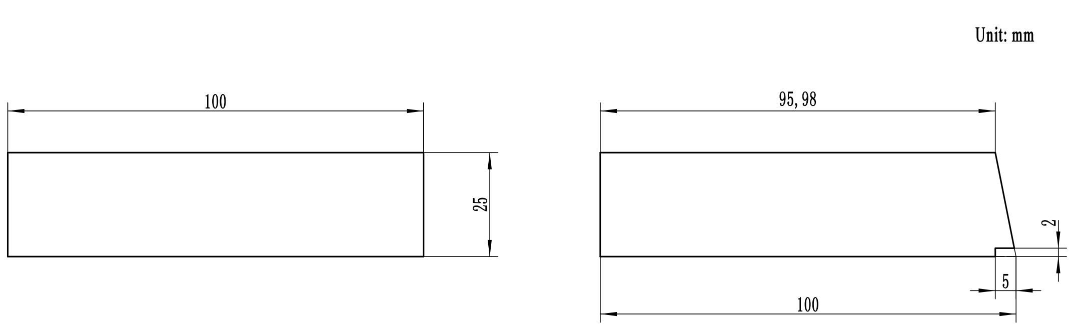
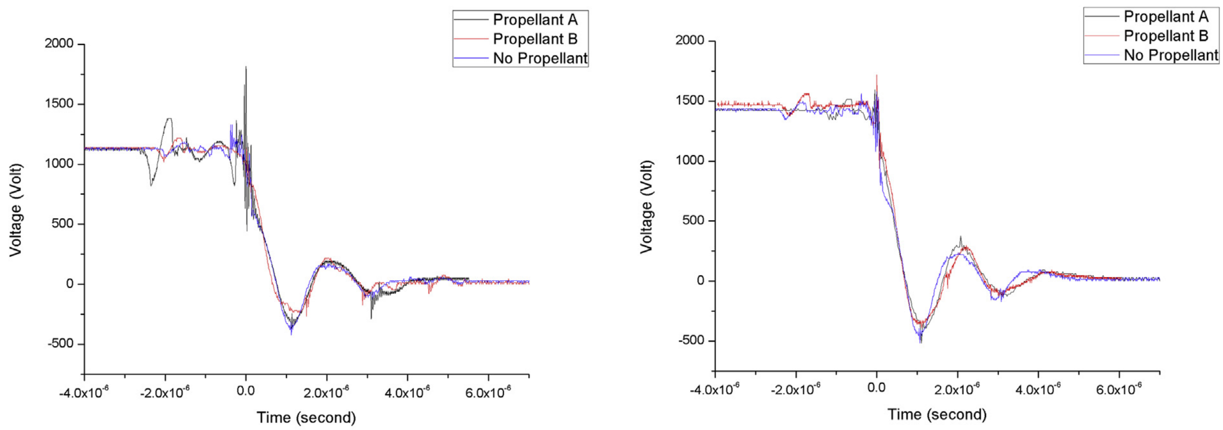
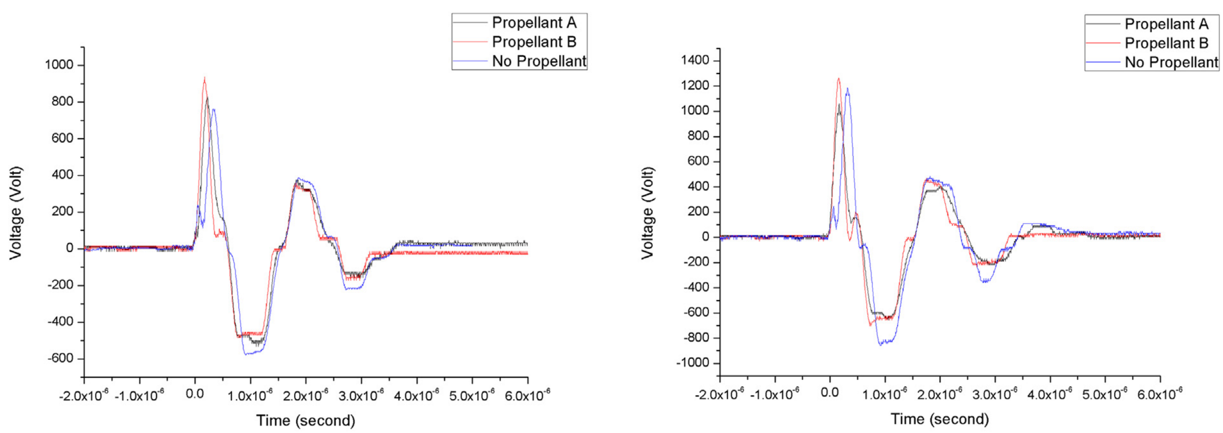


Fig. 2. Two kinds of propellant surfaces.



(a)1130V (b)1430V

Fig. 4. Voltage waveforms of APPT discharge when the propellant was loaded or unloaded.



(a)1130V (b)1430V

Fig. 5. Voltage waveforms of Rogowski coil when the propellant was loaded or unloaded.

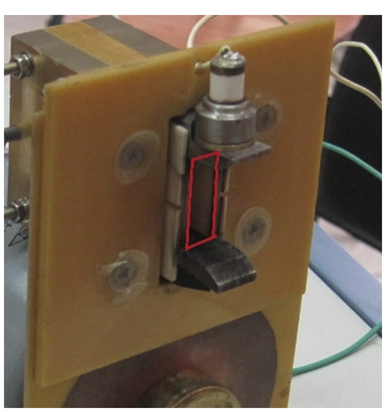


Fig. 6. The light-emitting area (red rectangle) when the propellant wasn't loaded. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

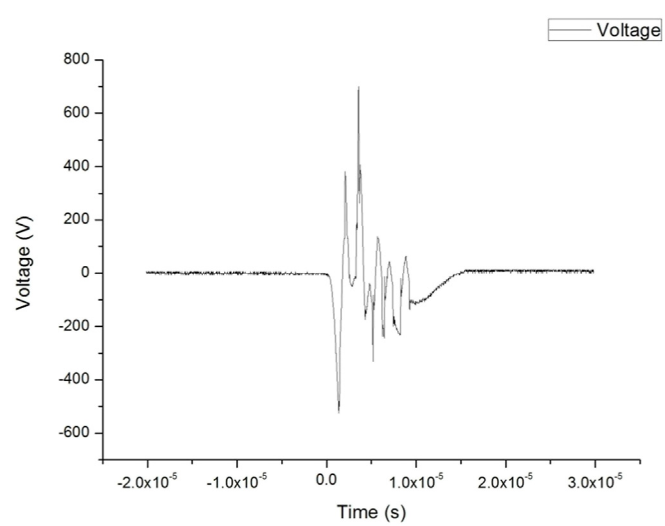
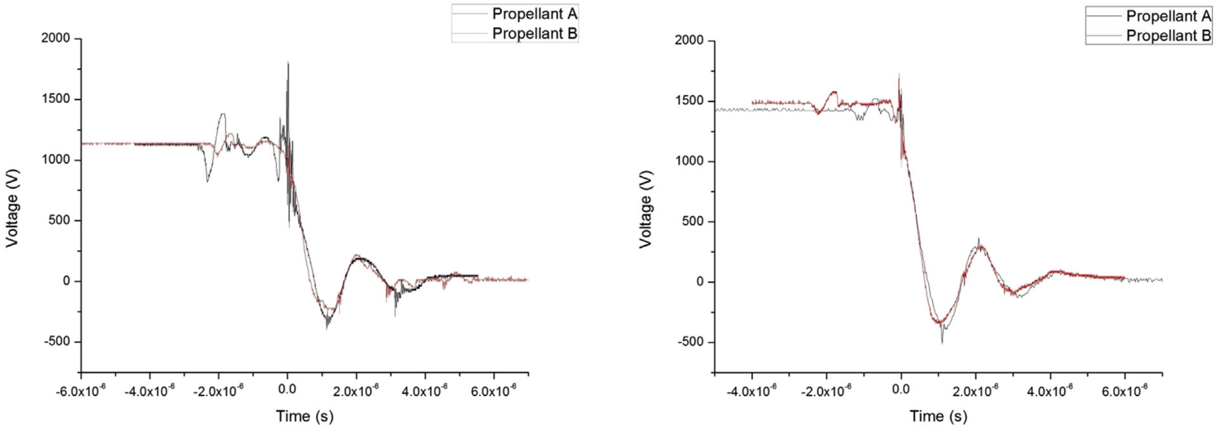


Fig. 7. Voltage waveforms of spark plug.

where q is the charge of an electron; U is electrode voltage; d is electrode gap; λ is the average distance between electron and neutral gas atoms;

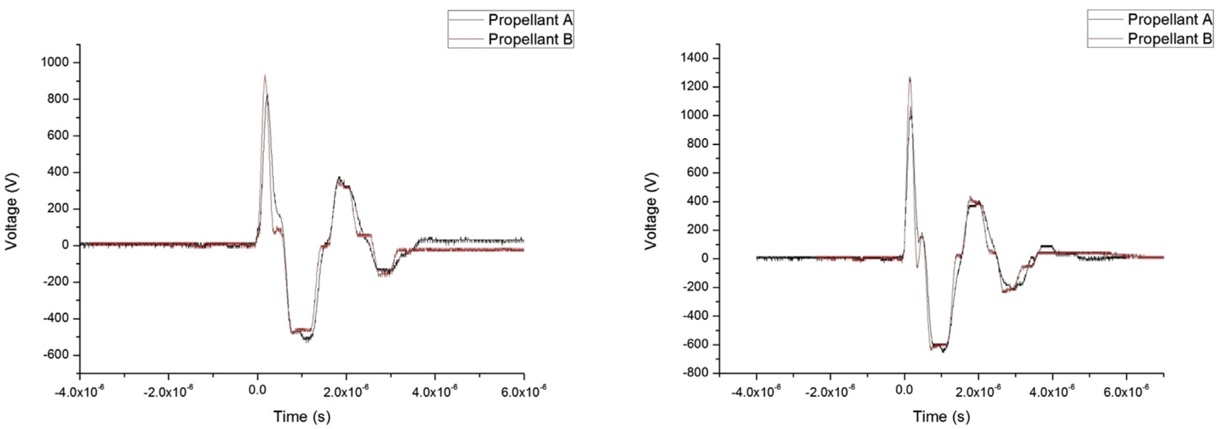
$$\lambda = 1/n(1/3\pi r_C^2 + 2/3\pi r_F^2) \quad (2)$$

where n is the atom density of neutral gas; r_C, r_F is the radius of C and F atoms, respectively. According to measured results in experiments, we assumed the initial mass of neutral gas is about 5% of mass shot per discharge, that is, the atom density is obtained.



(a)1130V (b)1430V

Fig. 8. Voltage waveforms at different conditions when two kinds of surfaces of propellants were loaded.



(a)1130V (b)1430V

Fig. 9. Voltage waveforms of Rogowski coil at different conditions when two kinds of surfaces of propellants were loaded.

Table 2
Discharge characteristics in two kinds of different surfaces of propellant.

Surface of propellant	Ignition number	Mass shot/ μg	Discharge success rate/ %
Normal	1500	4.23	99
Normal	2000	3.99	98
Inclined 2/25	1500	3.50	83
Inclined 2/25	2000	3.31	81
Inclined 5/25	1500	3.01	72
Inclined 5/25	2000	2.88	70

Note: Discharge voltages were all 1430 V.

$$m \propto \int I^2 dt \quad (3)$$

$$n = N_A m/(hdlM) \quad (4)$$

where M is the molar mass of the gas, h is electrode width, l is length of initial gas. If the energy that accelerated electron obtained is enough to ionize the gas ($Ev > E$, $E = 1/3E_C + 2/3E_F$), the conductive path would be continued. According to the above equations, the minimum discharge voltage is about 468 V. To verify this idea, the experiments with different discharge voltages (450, 500, 550, 600 V) were operated, and the discharge success rate (the total ignition number was 2000 times) when the initial discharge voltage is 450 V decreased quickly from 85% (the initial discharge voltage is 600 V) to 39%, which is consistent with the analysis.

(3) The ionized plasma is introduced into the discharge channel and augments the electric field creating a continuous conducting path, which the main discharge then occurs. Or, the ionized condition doesn't meet, the initial conductive would be cut, the voltage only fluctuated at the beginning of discharge, then keeps a constant value.

To verify this idea, the discharge reliability (spark plug ignited, while the electrode didn't discharge) was measured, which showed that it became worse in APPT experiments with the inclined propellant (shown in Table 2). Since the inclined propellant covered more area of anode than normal propellant, it decreased the possibility of initial electron reaching the anode, the initial conductive path wouldn't be formed. Thus, the inclined angle was enlarged from 2/25 to 5/25, the discharge success rate decreased from about 80% to 70%, which was consistent with our expectations. In addition, as the number of ignition increased, the pollution that harming spark plug increased, resulted that the energy of initial electron would be decreased, the ionized possibility of neutral gas would be decreased, the discharge success rate would be decreased, it is consistent with the experimental results, too.

4. Conclusions

Ignition process, as the initiation of the whole discharge, plays an important role in ablative pulsed plasma thrusters (APPTs). While spark plug exactly how initiate discharge is achieved is still under review. A series of experiments with two kinds of surfaces of propellant (normal or inclined) and without propellant to explain the ignition process. The experimental results showed:

(1) When the APPT discharge without propellant, the electron emitting by spark plug mainly maintains the entire discharge, and it is essentially a surface flashover process on ceramics.
(2) When the propellant was loaded, after the initial conductive path composed of electrons emitted by spark plug forming, the main discharge occurs. Some suggestions on increasing the possibility of the spark plug emitting rate are recommended.
(3) The main discharge success rate also depends on the ablated mass during the ignition process, some methods on controlling the ablated mass can be suggested.

This study provides a reference for the high performance pulsed plasma thrusters.

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