Experimental Study on Ignition Reliability of Pulsed Plasma Thrusters

IEPC-2019-321

Presented at the 36th International Electric Propulsion Conference
The University of Vienna • Vienna • Austria
September 15-20, 2019

Xiangyang Liu[1], Yiman Ding[2], William Y.L. Ling[3], Kan Xie, Zhiwen Wu, Ningfei Wang
Beijing Institute of Technology, Beijing, 100081, China

Abstract: Pulsed plasma thrusters (PPTs) are electric propulsion devices based on plasma electromagnetic acceleration. They have the characteristics of high TRL, high reliability and simple structure, etc and are thus suitable for many propulsion tasks of micro-satellites. To support the life study of PPT, this paper carried out PPT reliability test with traditional PTFE. By analyzing discharge delay time, a new insight for PPT ignition reliability research, ignition reliabilities of PPT with different charging voltages and ignition numbers were obtained. The results show that the evolution law of PPT discharge delay time with ignition number is significantly different at different charging voltages. The carbon deposition of propellant is the main reason of the evolution of discharge delay time during PPT test. Discharge delay time changes nonlinearly with the increment of ignition failure rate. As a criterion for PPT failure, discharge delay threshold changes nonlinearly with charging voltage.

I.Introduction

Pulsed Plasma Thrusters (PPTs) have been developed for more than fifty years. With many advantages such as high TRL (Technical Ready Level), high reliability, simple structure and reasonable price, they have been listed in the important candidates for many propulsion tasks of micro-satellites, such as orbit maintenance, resistance compensation and attitude control[1]. PPT researches are still active for their potential application in some space missions[2,3].

Total impulse has a significant role in the performance evaluation of PPT. PPT is a sort of micro-propulsion devices. For micro-propulsion, total impulse is more important than specific impulse since the propellant mass is only a small ratio of total mass of the entire propulsion system. Moreover, higher total impulse of PPT could increase the economic cost-effectiveness of low-cost micro-satellites and extend the application range of micro-propulsion.

Ignition reliability is a core issue for PPT life. For the pulse working mode, higher total impulse means long life and larger ignition shots. Ignition failure is a usual failure phenomenon of PPT. Ignition reliability research could clarify the ignition failure mechanism and the extended life of PPT prototype is thus expected. Moreover, the life experiment of PPT needs long-time occupation of PPT experimental devices and accelerated life test method is thus required. A new accelerated life test method could be proposed with the new understanding of ignition reliability.

Previous Researches show that the surface status of propellant, discharge energy and ignition energy could have significant influence on the ignition reliability of PPT. Vondra and Thomassen found that the carbon deposition of propellant would hinder the longtime usage of PPT[4]. Palumbo pointed out that the electrode and spark plug would have heavy erosion during the large discharge energy of PPT [5], the conclusion that too large discharge energy had an disadvantage for the ignition reliability of PPT had thus been drawn. An S-M et al. discovered that ignition energy should not be lower than a special threshold value. If so, the uneven ignition of main discharge would appear and arouse the un-even ablation of propellant[6]. Pottinger et al. found that low ignition energy could cause the carbon

[1] Associate Professor, School of Aerospace Engineering, liuxy@bit.edu.cn, the corresponding author.
[2] Master student, School of Aerospace Engineering, amlboy@126.com.
[3] Associate Professor, School of Aerospace Engineering, william.yl.ling@gmail.com, the corresponding author.

deposition of propellant and increasing ignition energy could erase such phenomenon[7]. Keidar et al. proved that low discharge energy would also arouse the carbon deposition[8]. Kumagai's research showed that the carbon deposition of propellant could be solved by increasing discharge energy[9].

Recently, there are some researches about the representation of ignition reliability and the influence law. Huang T. et al. proposed discharge delay time as a new representative parameter of ignition reliability and experimentally researched the variation of discharge delay time[10]. It is shown by test that discharge delay time increases with the increment of ignition shots and decreases with the increment of charging voltage. Wu Z. et al. tested PPT at 750V, 1000V and 1500V charging voltage and found that ignition success rate increase with charging voltage while it decreases with the ignition shots[11].

Previous researches have investigated discharge delay time and ignition failure rate separately, but ignored the connection between both parameters and how carbon deposition effects on discharge delay time. To investigate ignition reliability mechanism of PPT, an ignition reliability test was done. Experimental setup is described in Section II. The experimental result is then presented and discussed in Section III. The conclusions are drawn in Section IV finally.

II.Experimental setup

The principle of PPT is described as follows. A solid propellant bar, usually PTFE (also called Teflon), fills the gap between two electrodes connected to a charged capacitor in vacuum. Once the ignition signal is sent, the spark plug starts to work and produces the initial plasma, triggering an electrical arc across the exposed surface of the propellant, which is then accelerated by electromagnetic and pressure forces[1].

Traditional PTFE was chosen as the propellant of PPT for the reliability experiment. High vacuum environment is necessary for it. Two parameters representing the ignition reliability of PPT, ignition failure rate and discharge delay time, were measured. Here, the former was obtained by counting ignition success number and the latter was gotten from the waveform of discharge voltage.

A. PPT prototype

As shown in Figure1, the prototype tested is a rectangular breech-fed PPT. It consists of electrodes, propellant, spark plug, feeding mechanism, energy-stored capacitor and transmitting line. Here, electrodes are made of stainless steel. Spark plug uses a coaxial semiconductor type with an outer diameter of 10 mm. Feeding mechanism is accomplished by a rubber band. The capacitor adopts a coaxial type capacitor made of oil-immersed papers. In order to diminish inductance and resistance caused by transmitting line, it was made of copper plane and designed to have minimum area of current loop. The details of working parameters of PPT prototype were shown in Table 1.

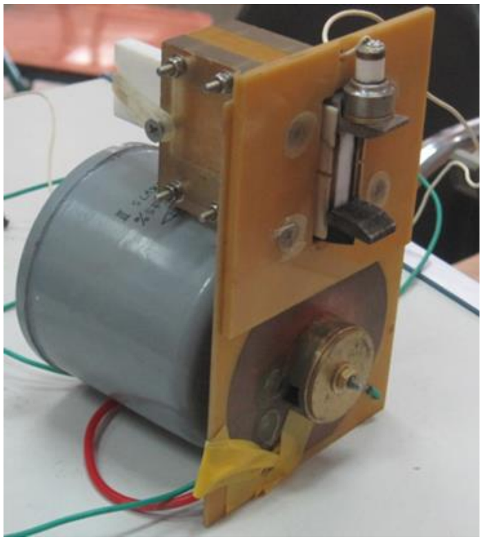

Figure 1. PPT prototype

Table 1 Parameters of PPT prototype

Parameters	Value
Capacitance /μF	2±5%
Electrode length /mm	14
Electrode width /mm	12
Electrode thickness /mm	4
Electrode gap/mm	25

B. Vacuum system

The vacuum system consists of vacuum chamber, vacuum pump unit and electrical control cabinet. The vacuum chamber is cylindrical and placed horizontally with an inner diameter of 1.8 m and a length of 3 m. The vacuum pump unit consists of 2 mechanical pumps, 1 Roots pump and 1 oil diffusion pump, which can pump the cabin environment from the atmosphere to the required high vacuum. The electrical control cabinet adopts PLC programming components to control the vacuum pump unit and vacuum pumping process, and has an alarm function for operation errors. The ultimate vacuum degree that the vacuum system can achieve is 5×10^{-4} Pa, and the working vacuum degree is 5×10^{-3} Pa, meeting the requirements of PPT reliability test.

C. Voltage acquisition system

Discharge delay time is an important parameter to characterize the ignition reliability of PPT and can be obtained by measuring discharge voltage curve [10].As shown in Figure 2, discharge delay time is defined as:

$$t_R = t_2 - t_1 \tag{1}$$

Where, t_2 is the discharging moment of capacitor, and t_1 is the igniting moment of spark plug. During PPT discharge work, spark plug first emits charged particles, and causes an oscillation in PPT discharge voltage curve. The charged particles then break down the gap between both electrodes to start the discharge and discharge voltage curve decline. Therefore, discharge delay time represents the difficult degree of PPT discharge. Through analysis of discharge delay time, the ignition reliability state of PPT can be obtained in advance before ignition failure occurs.

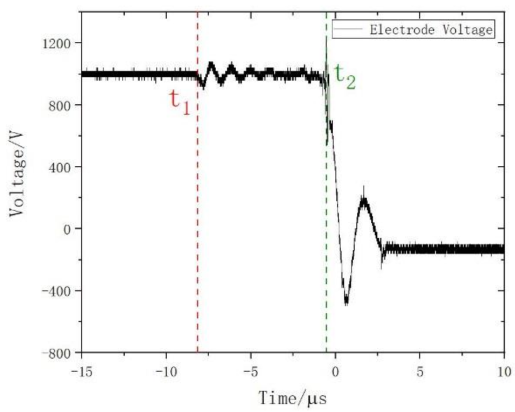

Figure 2 Definition of discharge delay time

The voltage acquisition system, which was used to measure discharge voltage curve, is mainly composed of a voltage probe and a data acquisition equipment. Considering the high voltage, THDP0100 differential high voltage probe from Tektronix Company was used. Its specific parameters are shown in Table 2. MDO3014 oscilloscope of Tektronix Company was selected as the data acquisition equipment. Its specific parameters are shown in Table 3.In view of the μs order of PPT discharge delay time, in order to ensure the measurement accuracy of discharge delay time, the sampling rate set in the test was 500MSa/s, and the corresponding time resolution was 1ns.

Table 2 Technical parameters of high pressure probe

Parameters	Value
Attenuation	100X/1000X
Differential voltage	1000X: 6,000 V 100X: 600 V
Common mode voltage	6,000 V
Maximum input to ground voltage	2,300 V CAT Ⅰ 1,000 V CATⅢ
Bandwidth	100 MHz
Cable length	1.5 m

Table 3 Technical parameters of Oscilloscope

Parameters	Value
Bandwidth	100 MHz
Analog channel	4
RF channel	1
Sampling rate	2.5 GS/s
Record length	10 M
RF frequency range	9 kHz ~100 MHz

D. Experimental condition

PPT reliability test requires setting charging voltage and ignition numbers. The set voltages in this study were 750V, 1000V, 1250V and 1500V. The principle of voltage selection is selecting the same interval voltage within the normal working voltage range of the PPT prototype. The ignition shot was set to 5000.

III.Results and Discussion

A. Evolution of discharge delay time and ignition failure rate

Table 4 shows the ignition failure rate at 750V and 1000V. Since PPT at 1250V and 1500V voltages did not show any ignition failure during the test, so they were not listed in the Table. It is clear that ignition failure rate decreases with the increment of charging voltage while it has an increasing trend with the increment of ignition.

Table 4 Ignition failure rate of different charging voltage (%)

Ignition number	750V	1000V
1-500	70	1.6
501-1000	91.6	2.6
1001-1500	--	15.6
1501-2000	--	5.4
2001-2500	--	31.6
2501-3000	--	9.8
3001-3500	--	20.4
3501-4000	--	39
4001-4500	--	41.8
4501-5000	--	46.6

Considering that ignition failure rate changes significantly at 1000V voltage, the relationship between ignition failure rate and discharge delay time was explored here on behalf of 1000V. Figure 3 shows the evolution of ignition failure rate and discharge delay time with ignition number. The data shown in the figure are the averaged value based on 500 fires. The evolution trend and fluctuation rule of discharge delay time are nearly consistent with ignition failure rate. It indicates that there is a strong correlation between discharge delay time and ignition failure rate.

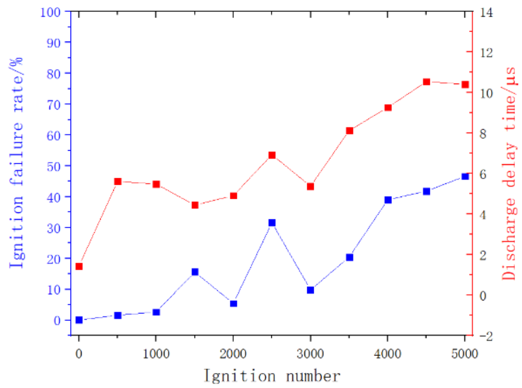

Figure 3 Evolution of ignition failure rate and discharge delay time

Figure 4 and Figure 5 respectively show the evolution rule of ignition delay time with ignition number at three different voltages except 750V. Different from Figure 3, the data is obtained by averaging the data of 50 firings.

Figure 4 is the comparison of discharge delay time of three voltages during 5000 ignition. Discharge delay time fluctuates within 1 to 5 μs at 1250V and 1500V while it fluctuates within 1 to 15 μs at 1000V. The results show that the evolution of ignition delay time follows different laws at different energy levels.

Figure 5 compares the discharge delay times at three voltages during the first 500 firings. Discharge delay time at 1000V increase significantly within 1 to 7 μs with the increment of ignition numbers while it at the other two voltages varies within 2 to 3 μs. When PPT ignition starts to fail at 1000V, discharge delay time suddenly increases, but then remains within a range of fluctuations. However, discharge delay time at 1250V and 1500V does not change much. This is consistent with the conclusion obtained by Wu Z [11].

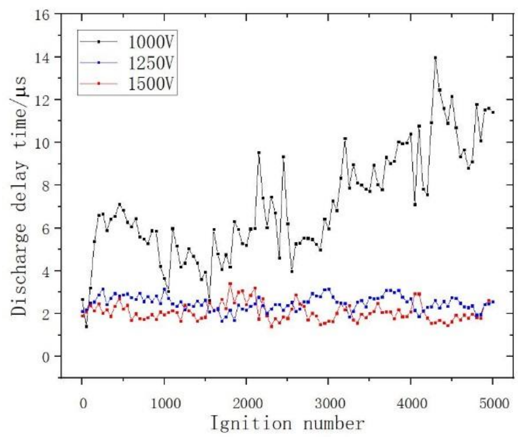

Figure 4 Evolution of discharge delay time at 5000 shots

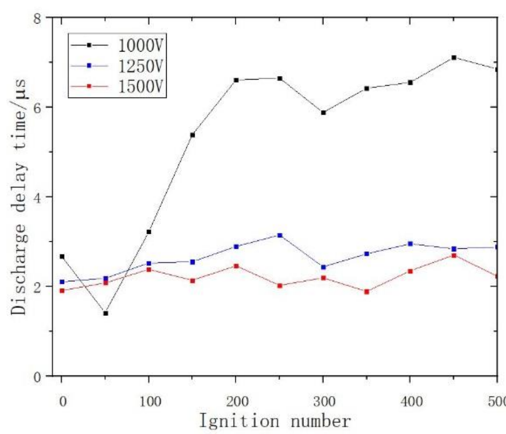

Figure 5 Evolution of discharge delay time at first 500 shots

B. Effect of carbon deposition

According to the working principle of PPT, spark plug ignite PPT firstly to generate an arc discharge, propellant is then ablated to generate plasma in the surface of propellant, the plasma eject finally outward under the function of Lorenz force. As the result of pulse discharge, some particles do not reach enough speed to eject outside the discharge channel of PPT. Since carbon has higher molting and vaporing point than Fluorine, solid carbon particles are easier to be attached to the surface of PPT. Carbon deposition thus occurs in some components of PPT, such as electrodes and propellant. Since PPT discharge depends on propellant ablation to generate plasma to maintain, carbon deposition will hinder the formation of discharge and is the internal cause of the increment of discharge delay time and ignition failure.

Figure 6 shows the carbon deposition of propellant and anode after the test. The carbon depositions are reduced with the increment of charging voltage and discharge energy. It could be explained by the fact that higher discharge energy is easier to vapor solid carbon particles and have more power to accelerate them.

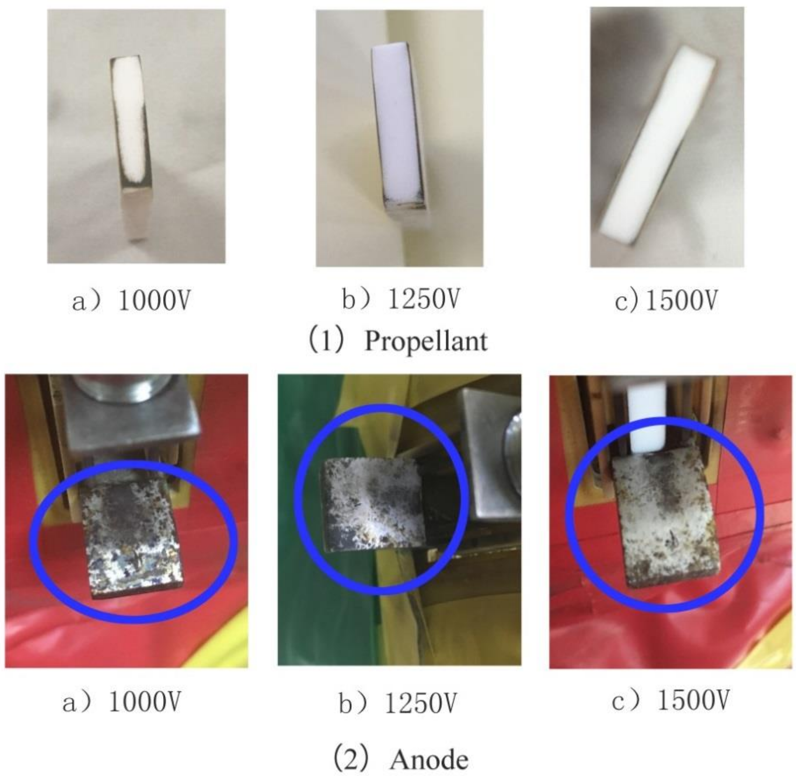

Figure 6 Carbon depositions of Anode and propellant

To investigate the effect of carbon deposition on ignition reliability, some comparative experiments were done to clarify the contribution of the carbon deposition of electrode and propellant to discharge delay time. Both of the components with and without carbon deposition were installed respectively into the PPT prototype and some ignition experiments were done at different charging voltages, discharge delay time was obtained based on the average of 10 fires.

Figure 7 shows the experiment results. Here, Curve 1 represents the carbon deposition status after the test, curve 2 represents the status of the propellant without carbon deposition, and curve 3 represent the status of the electrodes without carbon deposition based on the status of curve 2. It is clear that the carbon deposition of propellant has a significant influence on discharge delay time at all tested voltages. It causes the obviously increasing of discharge delay time and thus has a disadvantage on ignition reliability. Compared with propellant, the carbon depositions of electrodes have a similar influence on discharge delay time but the intensity is weaker. So it could be drawn that the evolution of discharge delay time is mainly caused by the carbon deposition of propellant.

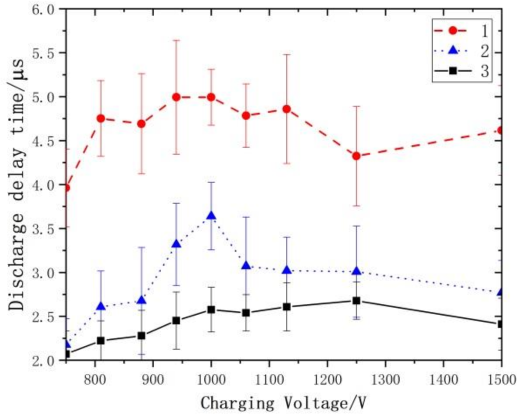

Figure 7 Discharge delay time of the propellant and electrodes with/without carbon deposition

C. Discharge delay threshold

Figure 8 shows the relationship between discharge delay time and ignition failure rate. Discharge delay time has a strong correlation with ignition failure rate, which changes in a non-linear pattern with ignition failure rate. With the increment of ignition failure rate, discharge delay time increases rapidly in the initial stage, and is then in the stable state of increasing slowly.

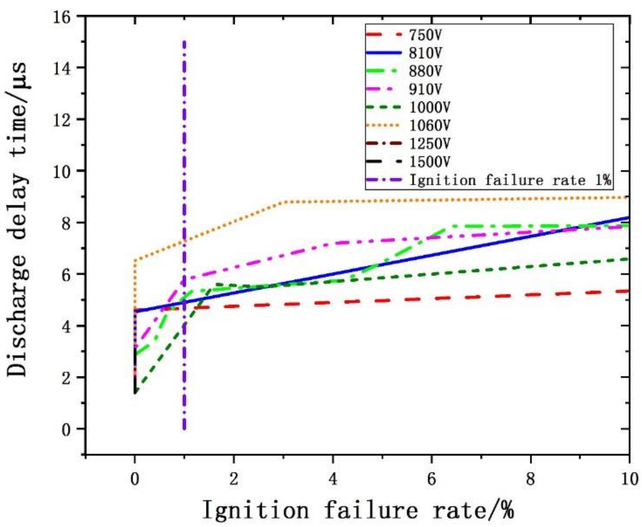

Figure 8 Discharge delay time vs ignition failure rate

To facilitate the use of discharge delay time to analyze ignition reliability, the concept of discharge delay threshold is proposed in this paper. It is defined as the value of PPT discharge delay time when ignition failure rate is 1%. The criterion for PPT failure is that discharge delay time is greater than the value of discharge delay threshold. As shown in Figure 8, discharge delay threshold is the intersection points of vertical lines and curves. It is in the abrupt stage of discharge delay time. When discharge delay time is greater than this value, ignition failure rate will increase significantly, and PPT ignition reliability will decline rapidly. Therefore, from the point of view of mechanism, it is correct to use the discharge delay threshold in the abrupt stage to characterize the failure of PPT. Furthermore, the ignition failure rate of 1% is acceptable from the perspective of engineering application. So the definition of discharge delay threshold is reasonable.

Figure 9 shows the change of discharge delay threshold between 750V and 1060V charging voltage. Since there are not any ignition fault in 5000 ignition numbers at the charging voltage of 1250V and 1500V, so the corresponding discharge delay threshold could not be obtained. The change law of discharge delay threshold with charging voltage is relatively obvious and shows an nonlinear law.

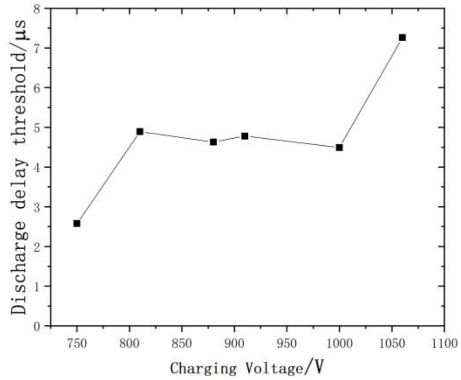

Figure 9 Discharge delay threshold vs Charging voltage

IV.Conclusion

PPT ignition reliability has been experimentally investigated. Discharge delay time has been chosen as a representative parameter of ignition reliability to evaluate PPT life. The effect of carbon deposition on it has been also analyzed. The conclusions are as follows.

(1) There is a significant difference law of discharge delay time for different charging voltages. For low charging voltages, discharge delay time increases dramatically in the initial stage and then increases smoothly with small fluctuation along with the occurrence of ignition failure. For high charging voltages, discharge delay time varies with periodically oscillation without any ignition failure.
(2) The increasing trend of discharge delay time with ignition number is mainly caused by the carbon deposition of propellant.
(3) Discharge delay time has a strong relation with ignition failure rate and varies with it nonlinearly.
(4) Discharge delay threshold is defined to represent the failure of PPT and has a nonlinear relation with charging voltage.

Acknowledgments

This research was supported by Chinese National Natural Science Foundation (51576018).

References

[1] Burton R L ,Turchi P J . "Pulsed Plasma Thruster". *Journal of Propulsion and Power,* 1998, 14(5):716--735.

[2] Antropov N. N., Kazeev M. N., Khodnenko V. P. ,et al. "IONOSFERE Satellite with APPT Based EPS" In *the 33rd International Electric Propulsion Conference, Washington,*2013.

[3]Ciaralli S, Coletti M, Gabriel S B. "Performance and Lifetime Testing of a Pulsed Plasma Thruster for Cubesat Applications". *Aerospace Science & Technology*, 2015, 47:291-298.

[4]Vondra R J, Thomassen K I. "Performance Improvement in Solid Fuel Microthrusters". *Journal of Spacecraft and Rockets*, 1972, 9(10):738-742.

[5]Palumbo D J. "Solid Propellant Pulsed Propulsion Development for N-S Station Keeping". *AIAA* 79-2097, 1979.

[6]An S-M. "The Effect of Ignition Energy on Main Discharge Process" In *19th International Electric Propulsion Conference, Colorado Springs,*1987.

[7]Pottinger S J, Scharlemann C A. "Micro Pulsed Plasma Thruster Development" In *30th International Electric Propulsion Conference, Florence,*2007.

[8]Keidar M, Boyd I D, Antonsen E L, et al. “Optimization Issues for a Micropulsed Plasma Thruster”. *Journal of Propulsion and Power*, 2006, 22(1):48-55.
[9]Kumagai N, Sato K, Tamura K, et al. “Research and Development Status of Low Power Pulsed Plasma Thruster System for μ-Lab Sat II” In *28th International Electric Propulsion Conference, Toulouse*,2003.
[10] Huang T, Wu Z, Liu X, et al. “Study of Breakdown in an Ablative Pulsed Plasma Thruster”. *Physics of Plasmas*, 2015, 22(10):103511.
[11] Wu Z, Sun G, Yuan S, et al. “Discharge Reliability in Ablative Pulsed Plasma Thrusters”. *Acta Astronautica*, 2017, 137:8-14.