5 w Ablative Pulsed Plasma Thruster for12-Unit Cubesat Propulsion Experimental Results

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Abstract: A 5w ablative pulsed plasma thruster (APPT) which is designed to provide attitude and orbit control for 12-Unit Cubesat platforms is shown. The qualification model presented in this paper has been developed by Science and Technology on vacuum Technilogy and physics Laboratory of LanZhou Institute of Physics in China, to qualify the unit for space flight. Experimental results which include 1,000,000 lifetime test results, vibration tests, thermal vacuum characterization are shown in this paper. In addition, APPT is characterized by an averaged specific impulse of 600 ± 24s and a deliverable total impulse of 40.2 ± 3.4Ns. Finally, it has been found that the results fulfill to the12-unit Cubesat space flight mission.

Nomenclature

APPT	=	ablative pulsed plasma thruster
C	=	capacitance
E	=	capacitance initial energy
g_0	=	gravitational acceleration
f	=	frequency of the main discharge
I	=	discharge current
V	=	discharge voltage
m_{bit}	=	mass bit consumption
η_{th}	=	overall efficiency
$I_{bi}t$	=	impulse bit
I_{sp}	=	specific impulse
PPU	=	power-processing unit
HVDP	=	high voltage differential probe

I. Introduction

In recent years, the small satellite[1] (10~100 kg), especially cubesats[2,3],has become an important part in the field of space due to its low cost, flexible means of launch quickly, formation flying for different constellation in the future. However, the lifetime of the small satellite generally operated in low orbit is severely restricted because of the lack of propulsion for orbit transfers and attitude control.

A pulsed plasma thruster (PPT) is expected to be used as a thruster for a small satellite due to its features[4-6] superior to other kinds of electric propulsion. It has simple structure , low power consumption, small impulse bit level and high reliability. These benefits make the PPT an attractive and reliable on-board propulsion alternative for orbit maintenance[7,8], orbit raising and de-orbiting of small satellites[9].

In this paper, a 5w ablative pulsed plasma thruster (APPT) qualification model which is designed to provide attitude and orbit control for 12-Unit Cubesat platforms and developed by Science and Technology on vacuum Technilogy and physics Laboratory of LanZhou Institute of Physics in China is presented. Experimental results of the thruster, including performance test ,mechanical test and thermal vacuum test ,are shown. In addition, APPT is characterized by an averaged specific impulse of 600 ± 24s and a deliverable total impulse of 40.2±3.4Ns. The test results show that the design of thruster can meet the requirements of environment, at the same time, the life of the thruster and parameters such as specific impulse, thrust, ect， meets the demand for space propulsion task.

II. Experiment Apparatus

A. Pulsed plasma thruster

The thruster used in this experiment is a 5w parallel breech-fed ablative pulsed plasma thruster[10](APPT) qualification model using solid Teflon as propellant which contains three discharge chambers(thruster heads). A solid bar of Teflon propellant with a cross section of 8cm×25cm is spring fed to the electrodes. The APPT is equipped with 2.15μF±5% capacity bank which consists of two parallel arrangements of 12 ceramic capacitors . The thruster has the input voltage of 1600V, discharge time of 10μs. The thruster can be used to perform orbit changes and attitude control.

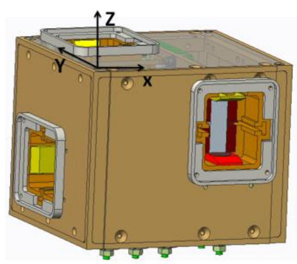

Figure 1. PPT qualification model

B. Test Facility

In addition to thermal vacuum test, most of the experiments were carried out TS-5A vacuum system, developed by the Science and Technology on vacuum Technilogy and physics Laboratory of Lan Zhou Institute of Physics, which includes the vacuum chamber, pumps, control system and other auxiliary systems . The vacuum chamber is an cylindrical shaped chamber with 0.4 m in inner diameter and about 0.5m in length. It is pumped by an rotary cryopump and a Leybold Turbovac Mag W1300C turbo pump the facility pumping speed is 1,100 l/s on N_2, with a base pressure of 5×10^{-5}Pa. The operating pressure in the vacuum chamber can maintain at 5.0×10^{-3} Pa during the experiment.

III. Test campaign

A. Thruster basic performance test

Two high voltage differential probes(HVDP) have been employed as well to measure the capacitor bank voltage and spark plug voltage, whereas a Rogowski coil[11,12] directly connected to spark plug has been used to monitor the current and the data is acquired by a Tektronix oscilloscope. Impulse bit measurements on the 5 w ablative pulsed plasma thruster qualification model was conducted at the State Key Laboratory of Laser Propulsion &Application Equipment Academy ,China, on a torsional micro-thrust stand, This balance provides reliable I_{bit} measurements in a range between 1 and 1000 μNs with the resolution 1μNs.A more detailed description of the balance can be found in the literature[13,14] .The thruster has been fired at its nominal initial voltage of 1600V with firing frequency of 1 Hz. The thrust of three discharge chambers (heads) were measured. The PPT electrical test setup is reported in Figure 2.

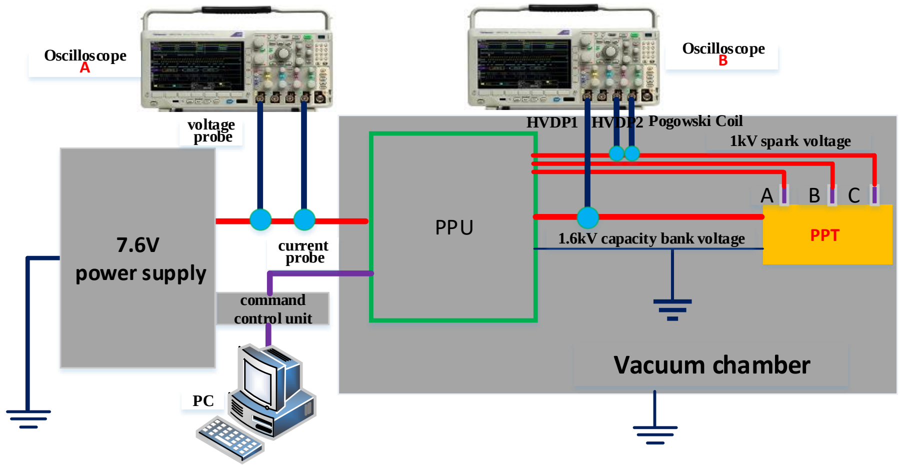

Figure 2. PPT Electrical test setup

The specific impulse (I_{sp}) and the overall efficiency (η_{th}) can be calculated using equations 1 ,once I_{bit} and m_{bit} have been measured.

$$I_{sp} = \frac{I_{bit}}{m_{bit} g_0} \qquad \eta_{th} = \frac{I_{bit}^{\ 2}}{2 \cdot m_{bit} \cdot E} \tag{1}$$

Where g_0 is the standard gravitational acceleration, g_0= 9.81 m/s^2, m_{bit} is the thruster mass consumption for single pulse. The mass bit consumption (m_{bit}) has been measured using a high precision balance with the range of 120 g and an accuracy of ± 10μg.

B. Lifetime

The testing of a single discharge chamber(thruster head) with the same design as the thruster qualification model used in the life test was conducted with the TS-5A vacuum chamber. Life[2,15-18] time measurements using the test procedure were performed at intervals of 24 h, or approximately 86,000 ignitions. The ablative mass of the propellant is measured after one cycle with high-precision balance. The voltage discharge curves were measured using two high voltage probes and the discharge current curves were measured using a Rogowski coil. The data has been acquired by a Tektronix oscilloscope.

C. vibration tests

As shown in Figure 3, a shaker table was used to the vibration[17] and random test for the APPT on which two sensor were placed to monitor the response of the thruster . Acceleration test and shock experiment for the APPT qualification model were conducted using a three axis acceleration test device and shock test stand.

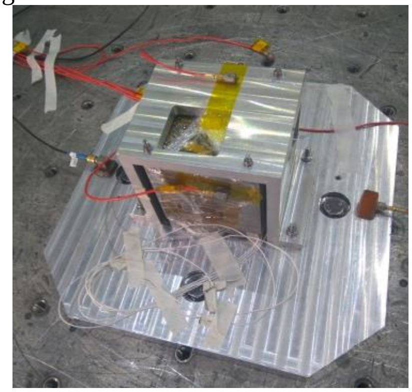

Figure 3. PPT Mechanical test setup

D. thermal vacuum

The vacuum chamber, shown in Figure 4, can be provided high and low temperature environment for the 5 w ablative pulsed plasma thruster qualification model. The PPT thruster temperature was measured using three K-type thermocouples: one was located on the upper surface of the thruster as a temperature control point whereas the others were placed the surface of the thruster without the chamber(thruster head) as temperature monitor points and gathered by the control software automatically. The PPT thruster was mounted on the base plat and was cooled through the liquid nitrogen flowing through the bottom plate in the way heat conduction and heat sink in the mean of thermal radiation whereas high temperature environment was created by heating the resistance wire.

Figure 4. PPT Thermal test setup

IV. Experimental results

A. Thruster basic performance test

The basic performance test of μ-PPT electric propulsion system performance test for the thruster head was conducted at intervals of 5min, or approximately 300 ignitions. The pressure was maintained by the pumping system between 5.0×10^{-3} Pa and 7.5×10^{-4} Pa throughout the basic performance tests. Figs. 5 shows the discharge voltage and ignition voltage curves for three thruster heads, obtained averaging the data of three different shots and the initial charged voltage of the thruster is 1.6 kV, the peak value of the ignition voltage is about 1000v and the discharge time of the PPT is about 10 μs.

The entire thruster module was mounted on the torsional micro-thrust stand and fired at 1Hz to simulate CubeSat operational conditions with an average power consumption of less than 5 W. APPT is characterized by an averaged specific impulse of 600 ± 24s together with mass bit experimental results， a deliverable total impulse of 40.2 ± 3.4Ns and the efficiency of thruster is about 37%.

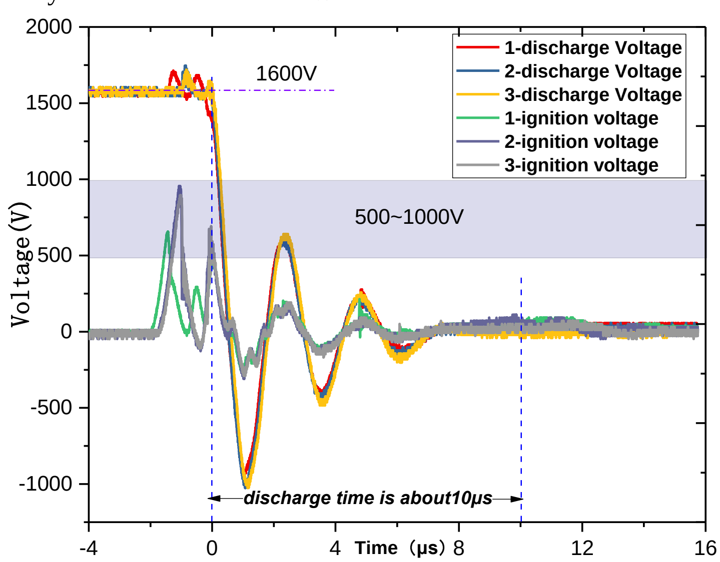

Figure 5. discharge voltage and ignition voltage curves

B. Lifetime

Life time tests have been performed using μ-PPT electric propulsion system for one thruster head. Life time measurements using the test procedure described before were conducted at intervals of 24 h, or approximately

86,000 ignitions. The APPT operated in a vacuum chamber under a pressure of 5×10^{-3}Pa at an ignition frequency of 1 Hz during the whole life test. The discharge current waveforms at different period were shown in Figure 7 during the entire life test. All weight measurements for Teflon propellant bar have been conducted after storage of the propellant under vacuum conditions for 24 h to account for atmospheric humidity intake. The discharge for the thruster head reached over 1.0×10^{6}. Long duration mass bit（averaged over the number of discharges of the determination interval.）measurement was performed over the test duration of 1.0×10^{6} ignitions and the resulting value is about 6.6 μg ~7.2 μg . The propellant bars is shown in figure 6 after 1.0×10^{6} ignitions.

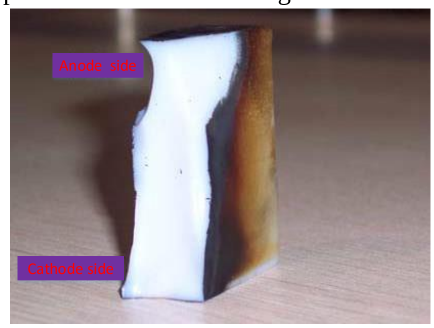

Figure 6. PPT propellant bars

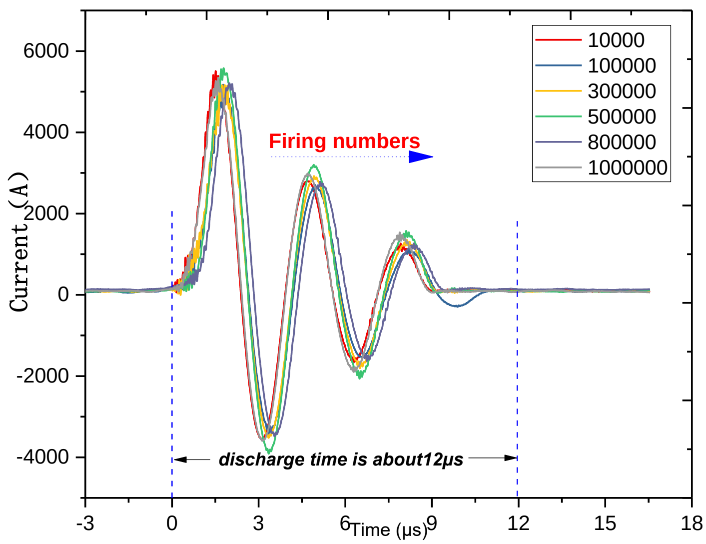

Figure 7. discharge current curve

C. vibration tests

The PPT qualification model has successfully passed flight qualification shock and vibration tests. The tests included random vibration about three orthogonal axes defined in Figure 1 respectively to apply a quasi-static load to the thruster and shock pulses up to 3000 g. A low sine sweep test from 5 to 2000 Hz at 0.5g along three orthogonal axes was conducted to assess the natural frequency of the PPT qualification model at the beginning and in the end of the sine burst and the random vibration and the sine burst was performed from 5 to 100 Hz at 3.6g. The random vibration test condition is summarized in Table 2 and Figure 5 respectively.

Table 1 Random vibration test parameters

Frequency, Hz	Power spectral density, g^2/Hz
20～150	6 dB/oct
150～560	0.1125
560～768	0.5625
768～800	0.1125
800～2000	－6 dB/oct

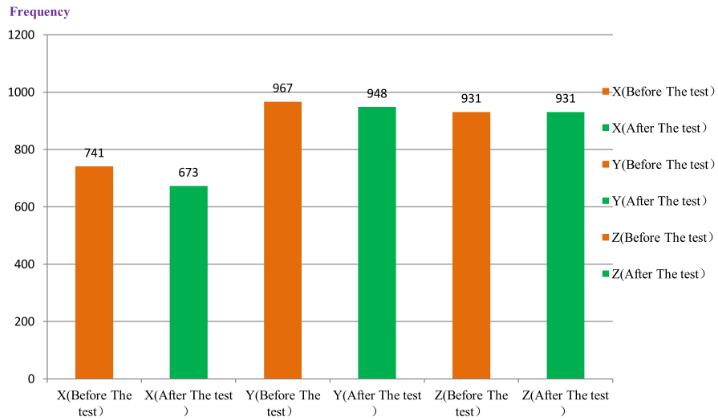

Figure 8. **Low sine sweep test results**

There were no damage or failures during the vibration testing. The natural frequency of the PPT qualification model is summarized in Figure 8. no significant frequency changes were observed before and after the test and the max value of frequency changed was about 9.1% along the x-axis. Before and after the vibration tests, a basic performance test was carried out to assess PPT qualification model. A comparison of the discharge voltage curves are reported in Figure 9. The discharge voltage curves, obtained averaging the data of three different shots in each test case, are very similar and show that the main discharge lasts about 7 μs.

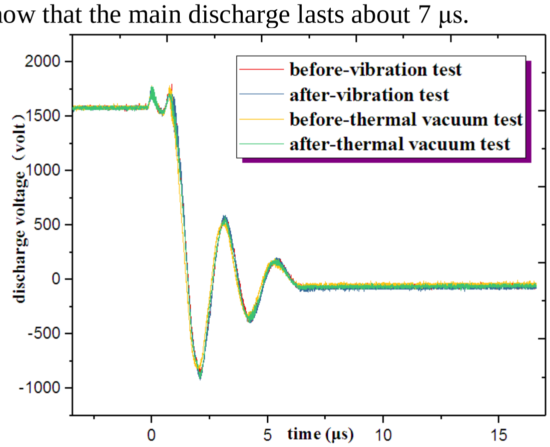

Figure 9. **Low sine sweep test results**

D. thermal vacuum

The aim of this thermal vacuum was to verify that the PPT qualification model can work normally in the range of the operating temperatures, going from - 50°C to + 50°C for four cycles. The PPT qualification model underwent a 1 hour discharge test at the temperature of + 50°C and - 50°C and repeated the cycle in the operative temperature range four times. The base pressure in the vacuum chamber can maintain at about 5×10^{-4} Pa during the thermal vacuum experiment. A comparison of the discharge voltage curves were reported in Figure 9 before and after the thermal vacuum test. The discharge voltage curves, obtained averaging the data of three different shots in each test case, are very similar and show that the main discharge lasts about 7 μs. It also shows that the thruster can withstand the thermal vacuum environment and meet the needs of the space environment.

V. Conclusion

In this paper, a 5w ablative pulsed plasma thruster (APPT) qualification model which is designed to provide attitude and orbit control for 12-Unit Cubesat platforms and developed by Science and Technology on vacuum Technilogy and physics Laboratory of LanZhou Institute of Physics in China is presented.

The entire thruster module was mounted on the torsional micro-thrust stand and fired at 1Hz to simulate CubeSat operational conditions with an average power consumption of less than 5W. APPT is characterized by an averaged specific impulse of 600 ± 24s together with mass bit experimental results，a deliverable total impulse of 40.2 ± 3.4Ns and the efficiency of thruster is about 37%. Long duration mass bit（averaged over the number of discharges of the determination interval.）measurement was performed over the test duration of 1.0×10^6 ignitions and the resulting value is about 6.6 μg ~7.2 μg .The discharge voltage curves, obtained averaging the data of three different shots in each test case, are very similar and show that the main discharge lasts about 7 μs. It also shows that the thruster can withstand the thermal vacuum and vibration environment and meet the needs of the Cubesat space flight mission.

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