Experimental Investigation on the Ablation Mechanism of HTPB Propellant PPT

IEPC-2017-322

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

Yang Zhou[1] and Xiangyang Liu[2]*
Beijing Institute of Technology, Beijing, 100081, China

Xuning Zhang
Jiangmen Polytechnic, Jiangmen Guangdong, 529090, China

Zhiwen Wu, Kan Xie, Ningfei Wang
Beijing Institute of Technology, Beijing, 100081, China

Abstract: Pulsed plasma thrusters (PPTs) are attractive microthrusters for its advantages such as compactness and lightweight compared to other electric propulsion systems. Accordingly, PPTs have been used in station keeping, drag make-up, and attitude control for small satellites. Combustible solid chemicals have been used to enhance the thrust performance of PPT instead of the most common PPT propellant, Teflon (Polytetrafluoroethylene: PTFE) and experiments have been conducted to test the performance of combustible solid chemicals. However, little research has been down on the ablation mechanism of combustible solid chemicals. In that case, operation tests of rectangular breech-fed PPT have been conducted with HTPB propellant. The mass bit, the discharge parameters and the emission spectra are measured. Calculations are done to help investigate the ablation mechanism of HTPB propellant. The results show that the mass bit with HTPB propellant used in this work is only about 50% of that with PTFE propellant. The electrothermal energy was calculated which shows almost no differences. The results of spectrum experiments show that the electron temperature is 0.18eV lower with HTPB propellant than that with PTFE propellant. The electron density with HTPB propellant is 2.7*17cm^{-3} while the electron density with PTFE propellant is 1.7*17cm^{-3}. It turns out that the energy distribution mechanisms of HTPB propellant and PTFE propellant are not the same. The HTPB propellant releases energy during ablation while PTFE propellant absorbs energy, and HTPB propellant consumes more energy in ionization than PTFE propellant. The ablation of HTPB propellant is a complex of the energy released in the combustion process and the plasma radiation after the attenuation of the barrier layer.

Nomenclature

V	=	discharge voltage
I	=	discharge current
Q	=	electric charge
L_0	=	mean inductance
R_0	=	mean resistance
C	=	capacitance

[1] Ph. D. candidate, School of Aerospace Engineering, 3120150062@bit.edu.cn
[2] Professor, corresponding author, School of Aerospace Engineering, liuxy@bit.edu.cn.

T_e = electron temperature

N_e = electron density

I.Introduction

ALONG with the development of micro satellite technology in many areas of civil spaceflight fields, people have put forward the strict requirements of light weight, low power consumption and precise control for its propulsion system. Pulsed plasma thruster (PPT) has high technical maturity and meets the requirement of micro satellite to propulsion system. However, PPT has been criticized for its low efficiency, so the development of high-specific impulse PPT is very important for improving the life and payload of small satellites[1]. In the development of high-specific impulse PPT, the choice of propellant plays a particularly important role. Several kinds of propellant have been tested but the results of these experiments are not much good[2-4].

To enhance the thrust performance of PPT, Hideto Mashidori proposed to use solid chemical propellant instead of the most common PPT propellant, Teflon (Polytetrafluoroethylene: PTFE). The performance tests of coaxial pulsed plasma thruster have been done and the results showed that the thrust power ratio was increased with the help of the chemical energy of the propellants[5]. Also, polymers showed superior performance in efficiency for laser-based microthrusters[6]. However, the investigation on the ablation mechanism with combustible solid chemicals has attracted few attentions so far.

Mechanism experiments are conducted with HTPB propellant (for short, HTPB) in order to measure the ablation parameters including mass shots, discharge voltage and current. Also, the spectroscopic emission measurements have been conducted. The ablation mechanism of HTPB propellant is preliminary explained with some calculations related.

II.Experimental Setup

The HTPB propellant used for experiments consists of 11% HTPB (hydroxylterminated polybutadiene), 68% AP (ammonium perchlorate), 17% Al (aluminum) and 4% others. The thruster used for experiments is rectangular breech-fed PPT (Fig. 1) which consists of a pair of copper electrodes connected to one capacitor with 2 uF. A semiconductor spark plug is used as igniter. The vacuum chamber used for experiments is shown in Fig. 2. The parameters of the PPT and the vacuum chamber are shown in Tab. 1.

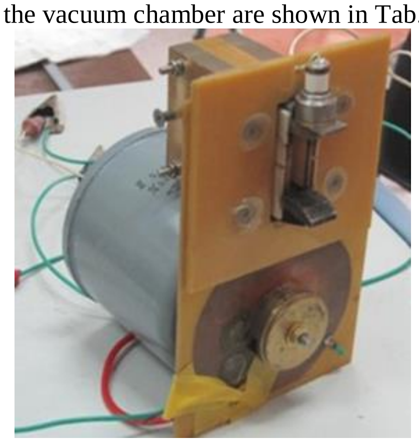


Figure 1. PPT used in this paper

Figure 2. Vacuum chamber

Table 1. Experimental conditions

Parameters	Value
Capacitance	2uF±5%
Electrode length / width / thickness	14mm/12mm/4mm
Electrode gap	25mm
Vacuum chamber diameter / length	Φ1.8m/3m
vacuum pressure	5×10-3Pa

The voltage was measured by an oscilloscope, and the discharge current was measured by a Rogowski coil, as shown in Fig. 3.

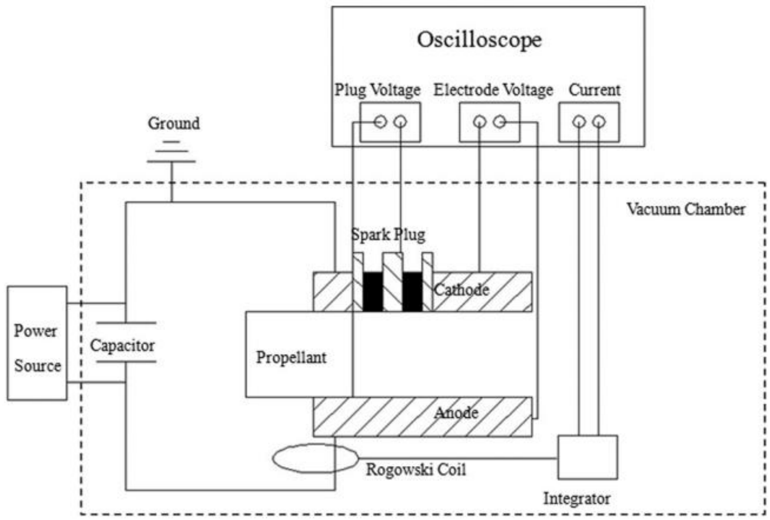


Figure 3. Block diagram of the experiment setup.

Experimental system for spectroscopic emission is shown in Fi. 4. Outside the vacuum chamber is spectrometer, photomultiplier, filter wheel, high voltage power supply, high speed data acquisition system, PC control host and controller device (Fig. 5a). Inside the vacuum chamber is optical fiber, lens, stepper motor, positioning laser, calibration light source and other devices (Fig. 5b).

The spectral signal of the measuring position of PPT is focused on the optical fiber through lens during the PPT ignition, then through the filter where multi spectrum is eliminated into the spectrometer (wavelength width of 0.27nm) and eventually reach photomultiplier. The light signals change for electrical signals recorded by the data acquisition system.

The spectral signals at the wavelengths of C Ⅱ with high intensity are measured and the Ocean Optical HL-2000-CAL calibration light source is used as calibration system shown in Fig 4. The laser is used to fix position.

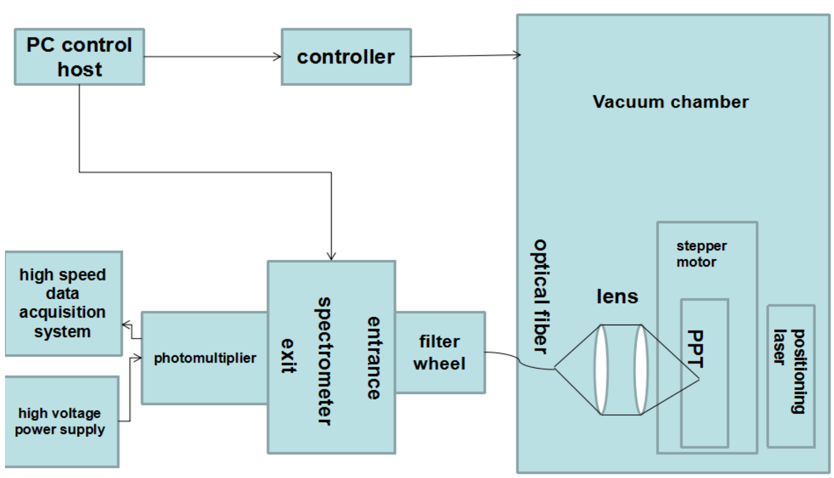


Figure 4. Structure diagram of experiment system

(a) Spectroscopic emission experiment system outside the vacuum chamber

(b) Spectroscopic emission experiment system inside the vacuum chamber (positioning laser and calibration light source on the right)

Figure 5. Picture of spectroscopic emission experiment system

III.Experiment Results

A. Mass bit

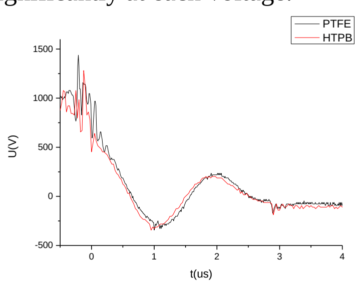
The mass bit with HTPB as well as PTFE are measured at three different voltages of 1000 V, 1200 V, 1500 V. To measure the propellant mass consumption per shot, the propellant was weighed before and after over 500 thruster firings. The average mass bit was calculated by dividing the weight difference by the number of firings. The mass bit for each propellant are shown in Tab. 2. Conclusion can be drawn from the results that the mass bit with HTPB used in this work was approximately 50% of that with PTFE while discharge voltages changed from 1000V to 1500V.

Table 2. Mass shots(ug)

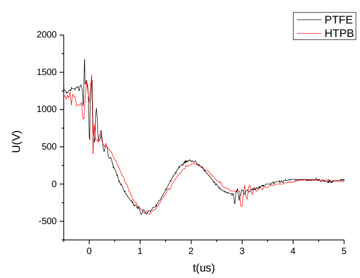
	1000V	1200V	1500V
HTPB	1.6	2.4	3.4
PTFE	3.0	6.5	8.2

B. Discharge Voltage and Current

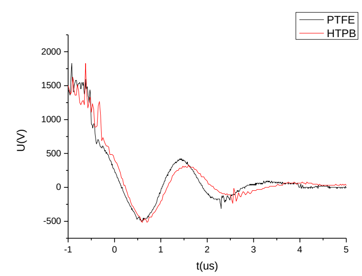
The discharge voltage and current waveforms were measured respectively. The comparisons of discharge voltages waveforms using different propellant at different voltages are processed and shown in Fig. 6 and comparisons of discharge currents in Fig. 7. It can be seen in the figures that discharge voltage and current waveforms do not differ significantly at each voltage.



(a)1000V

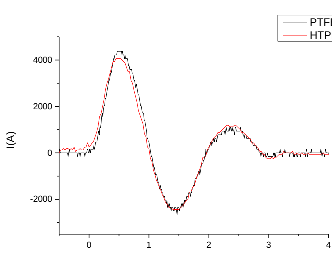


(b)1200V

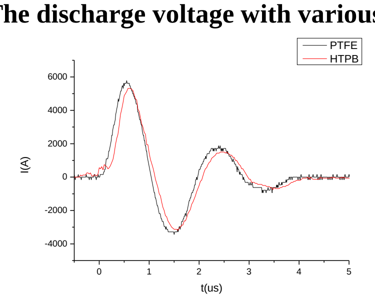


(c)1500V

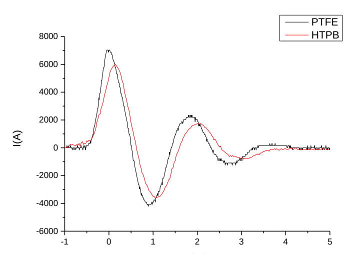
Figure 6. The discharge voltage with various propellants



(a)1000V



(b)1200V



(c)1500V

Figure 7. The discharge current with various propellants

C. Spectrum Experiment

The spectral signals at the center of propellant surface were measured to evaluate the ablation condition of the two different propellant. All spectrums of elements with the two propellants were measured.

The spectral signals transmitted through the lens during measurements. Then multi spectrums were eliminated into the spectrometer (wavelength width of 0.27nm) after they passed through the filter and eventually they reached the photomultiplier. At last the light signals were changed into electrical signals and recorded by the data acquisition system.

All the signal of H+, C+, N+, O+, Cl+, Al+, were detected with HTPB. The electron temperature and electron density were calculated with the signals of CII**Error! Reference source not found.**. The calculation method is consistent with that in the conference[7]. The results are shown in Tab. 3. Conclusion can be drawn that the electron temperature using HTPB propellant is lower than that using PTFE propellant, the electron density using HTPB propellant is larger than that using PTFE propellant.

Table 3. Mass shots(ug)

	T_e (eV)	N_e (cm^{-3})
HTPB	0.92	$2.7*10^{17}$
PTFE	1.10	$1.7*10^{17}$

IV. Analysis and Discussion

A. Mass Bit

The mass bit of HTPB propellant used in this work was approximately 50% of that of PTFE propellant while discharge voltages changed from 1000V to 1500V. In Hideto Mashidori's work[5], the results of mass bit show a certain regularity that is shown in Fig. 8. Due to the differences in PPT type, it is meaningless to compare the mass shots directly, so the ratio of $m_{\mathrm{HTPB}}/m_{\mathrm{PTFE}}$ is used in comparison.

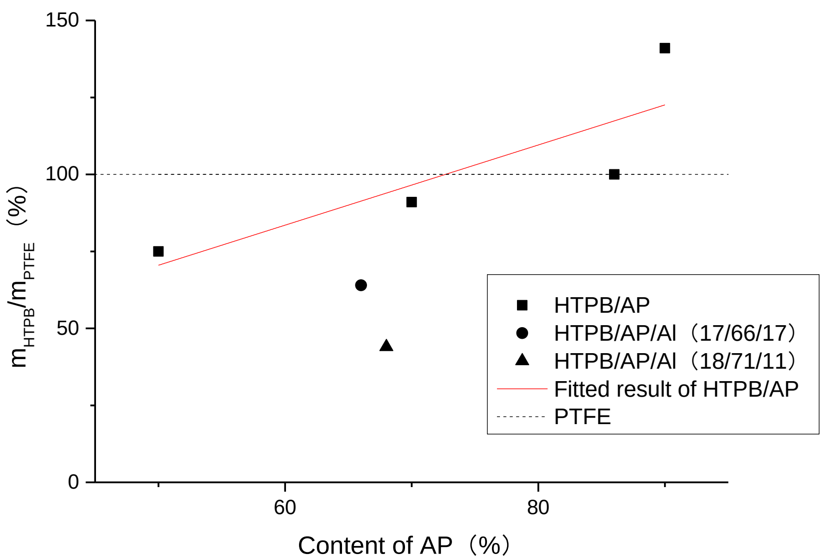


Figure 8. Comparison of the mass shots in different works

As shown, the mass bit with HTPB/AP is obviously effected by the content of AP. Also, the mass bit with HTPB/AP/Al turn out to be apparently less than that with PTFE propellant.

B. Electrothermal Energy

In order to investigate the ablation mechanism of HTPB propellant, it is important to calculate the electrothermal energy.

The electrothermal energy can be calculated according to the equation (1):

$$E = \int I^2 \cdot Rdt \qquad (1)$$

Where R is the resistance, I is the discharge current. Obviously, the resistances are essential to the calculation of electrical-heat energy.

The resistances can be calculated by formula fitting method which is according to an equation in voltage U[7].

$$U = \frac{U_0}{\omega\sqrt{L_0 C}} e^{-\frac{R_0}{2L_0}t} \sin(\omega t + \delta) \qquad (2)$$

Where,

$$\omega = \left(\frac{1}{L_0 C} - \frac{R_0^2}{4L_0^2} \right)^{\frac{1}{2}} \qquad (3)$$

$$\delta = \tan^{-1}\left(\frac{4L_0}{R_0^2 C} - 1 \right)^{\frac{1}{2}} \qquad (4)$$

L_0 is the mean inductance, R_0 is the mean resistance and C is the capacitance.

The experimental data of voltage is fitted using a curve fitting method so that we can calculate the resistance by relation. The results are shown in Tab. 5.

Table 5. Resistance(mΩ)

	1000V	1200V	1500V
HTPB	28	28	28
PTFE	28	24	21

The results of electrothermal energy are shown in Tab. 6. Therefore, it would be concluded that the electrothermal energy are about the same. The percentages represent their shares of total energy stored in the capacitor.

Table 6. electrothermal energy (J)

	HTPB	PTFE
1000V	0.66(66%)	0.69(69%)
1200V	1.03(72%)	1.16(81%)
1500V	1.41(63%)	1.54(68%)

The mass shots are apparently different while the electrical-heat energy do not differ significantly at each voltage, that is to say, there must be some other factors that influence the total of the mass shots.

C. Chemical Reaction

As is known to all, the energy allocation mechanism with HTPB and that with PTFE are not the same. Calculations have been done to investigate the differences between the energy allocation mechanism with HTPB used in this work and that with PTFE. The result turns out that the energy allocation mechanisms of HTPB propellant and that of PTFE propellant are not the same. The result is shown in Fig. 9 which shows that HTPB releases energy during ablation while PTFE absorbs energy, and HTPB consumes more energy in ionization than PTFE. The calculations are according to chemical reaction principle of HTPB[9,10].

Each kinds of the ions contained in the ionization products have been detected in the spectroscopic emission measurements. Also, both the results of experiments and the results of calculation turn out that the electron density with HTPB is larger than that of PTFE.

Obviously, the biggest difference in the ablation process between the two propellants is that the chemical reaction occurs after the ablation using HTPB propellant. The existence of chemical reaction products hinders the conduction of electrical-heat energy. That is likely to be the main factor that causes the difference in mass shots.

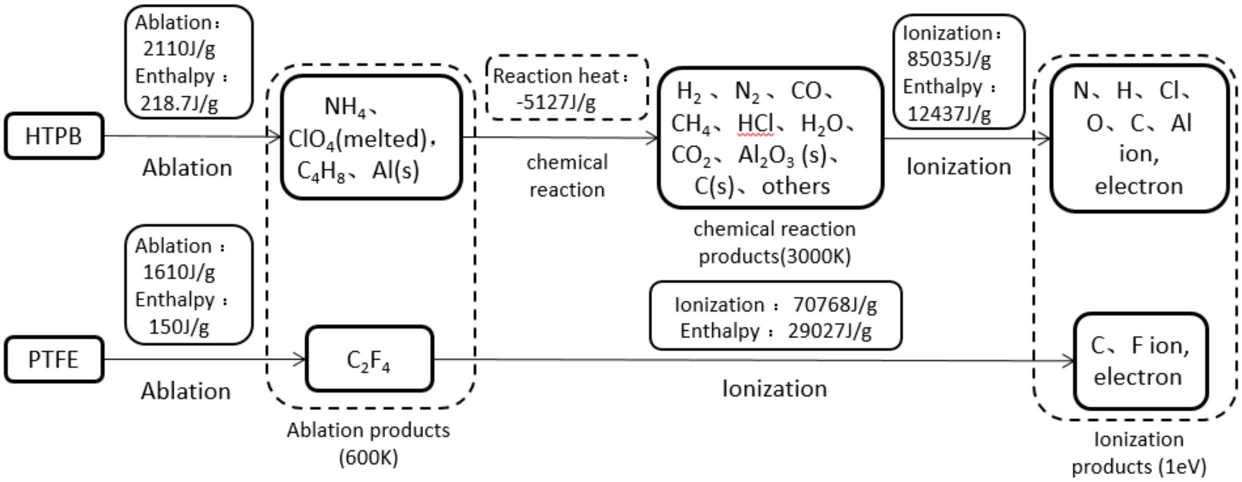


Figure 9. Energy distribution mechanism of HTPB and PTFE

Calculations are done to investigate how the existence of chemical reaction products hinders the conduction of electrothermal energy. 1 g PTFE is considered to product 0.01 mole gas in ablation. The products in ablation using HTPB is calculated by CEA, and the results is shown in Tab. 7.

Table 7. products in chemical reaction with HTPB

Products	Mole fractions(%)	Products	Mole fractions(%)
CH_4	4.3	H_2O	17.6
CO	0.4	N_2	8.0
CO_2	9.4	Al_2O_3	10.0
HCl	16.7	C	10.2
H_2	23.0	Others	0.4

The results show that 1 g HTPB produces 0.023 mole gas which is much larger than that using PTFE. For convenience of calculation, plasma between electrodes is usually considered to be optically thin. However, it seems that the assumption is not appreciate in the energy transfer, and the main factor of the difference of the mass shots is the gas production.

The energy required for ablation of ordinary PTFE is derived from the radiation heat of the plasma. When HTPB is used, the chemical reaction of the ablated product occurs. Although some chemical energy is injected, it also forms a unique barrier layer formed by the combustion products. This layer effectively blocks the radiation energy transferred from the plasma, and the heat that the ablation wall gets is obviously reduced. In that case, the mass produced in the 'late-time' ablation is obviously decreased. As a results, the mass bit with HTPB are greatly reduced compared with the mass bit with PTFE.

In addition, there are a large part reducing products in the calculation of the products with HTPB used in this work. That means the chemical reaction will take place more completely when the content of AP is increased. In that case , more energy is released that adds to the 'late-time' ablation while the quantities of gas productions almost do not change. That is the reason that the mass bit changes with the content of AP as shown in Fig. 8.

In a words, the ablation of HTPB is a complex of the energy released in the combustion process and the plasma radiation after the attenuation of the barrier layer, which causes the difference of the mass bit between HTPB and PTFE.

V.Conclusion

Conclusions can be drawn from the experiments and calculations related:

(1) The mass bit with HTPB used in this work are about 50% of that with PTFE at different discharge voltages.
(2) The results of electrothermal energy do not differ significantly with the two different propellants at each voltage.
(3) It produces more gas in ablation when HTPB is used in comparison with that with PTFE.
(4) The ablation of HTPB is a complex of the energy in the combustion process and the plasma radiation after the attenuation of the barrier layer that causes the difference of the mass shots between the HTPB and PTFE.

For further works, it is necessary to detect the existence of the different kinds of gas produced in chemical reaction with HTPB. Also, it is meaningful to evaluate the performance of the shielding effectiveness of the barrier layer formed by the combustion products.

Acknowledgments

This work was supported by National Natural Science Foundation of China (No. 51576018).

References

[1] Palumbo D. J., "Continuing Development of the Short-Pulsed Ablative Space Propulsion System," *AIAA Journal*, Vol. 10, No. 6, 2514. pp. 1154.

[2] Leiweke, R. J., "Experiments with Multi-Material Propellants in Ablation-Fed Pulsed Plasma Thrusters," *AIAA Journal* Vol. 10, No. 6, 2514. pp. 2916.

[3] Pencil E. J, "Evaluation of Alternate Propellant for Pulsed Plasma Thruster," 27th.International Electric Propulsion Conference. Pasadena, 2001.

[4] Tony S., "Influence of Propellant in the Discharge Process of PPT," *AIAA Journal*, Vol.10, No. 6, 2514. pp. 4278.

[5] Hideto M, "A Coaxial Pulsed Plasma Thruster Using Chemical Propellants," *Vacuum*, Vol.80, No.11,12. pp. 1229, 1233.

[6] Urech, L., "Polymers as Fuel for Laser-based Microthrusters: Investigation of Thrust, Material, Plasma and Shockwave Properties," *Applied Surface Science*, Vol.19, No. 253. pp. 7646, 7650.

[7] Zuo G. Y., Liu X. Y., "Study on the Evolutionary Process of Characteristics of Plasma Properties in Pulsed Plasma Thruster," 6th Russian-German Conference on Electric Propulsion and Their Application, 2016.

[8] Jahn, R. G., Lyman, F. A., *Physics of Electric Propulsion*, McGraw-Hill , America, 1968, Chaps. 36 (3).

[9] CHEN J. K., BRILL Z. B., "Chemistry and Kinetics of Hydroxyl-terminated Polybutadiene (HTPB) and Diisocyanate-HTPB Polymers during Slow Decomposition and Combustion-like Conditions," *Combustion and Flame*, Vol. 87, 1991, pp. 217-232.

[10] Lu Y. C., Kuo K. K., "Thermal decomposition study of hydroxyl-terminated polybutadiene (HTPB) solid fuel," *Thermochimica Acta*, Vol. 275, No. 2, 1996, pp. 181-191.