The study on the lifetime of the micro cathode arc thruster

IEPC-2019-A-536

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

Jinyue Geng[1] , Yu Qin[2], Jun Long[3], Xuhui Liu[4], Yan Shen[5]
Beijing Institute of Control Engineering, China

Abstract: The influence of discharge parameters on the thrust, specific impulse and lifetime of the micro-cathode arc thruster was studied. The results show that the peak discharge current increases, the cathode ablation increases, and the thrust increases; compared with the lower peak discharge current (10A), the higher peak discharge current (40A) can extend the working life of the thruster.

I. Introduction

The Micro-Cathode Arc Thruster is a kind of pulsed micro-electric thruster based on vacuum arc ablation[1]. Coaxial μCAT thruster, as shown in Figure 1, is mainly composed of coaxial electrodes (anode, cathode), insulating medium, spring, shell and electromagnetic coil [2].

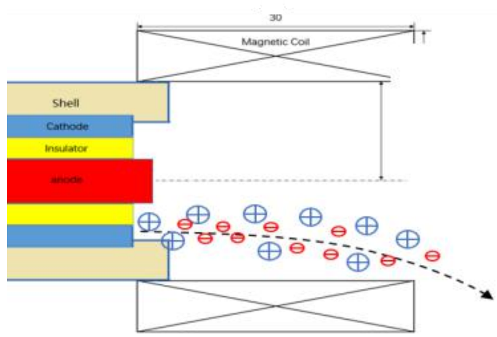

Fig.1 Schematic diagram of the Co-axial μCAT

"Vacuum arc" should accurately be "metal vapor arc in vacuum environment". The biggest difference between vacuum arc and traditional arc is that the conducting working substance is metal vapor produced by metal electrode ablation, while the conducting working substance of traditional arc is mostly provided by external supply (commonly argon, hydrogen, nitrogen, helium and the mixtures). Therefore, the conventional arc thruster can directly control the propellant flow rate by adjusting the external flow-meters, while the propellant supply in the μCAT is generated by the discharge ablation of the vacuum arc, and the propellant supply is coupled with the arc discharge process. This will lead to a certain difference between the discharge process of vacuum arc and traditional arc discharge, that is, discharge parameters will affect thrust and other performance through propellant supply in addition to controlling input energy.

[1] Senior Engineer, Beijing Institute of Control Engneering, jinyuegeng@163.com.
[2] Engineer, Beijing Institute of Control Engneering, qinyu@bit.edu.cn.
[3] Senior Engineer, Beijing Institute of Control Engneering, longjun306066044@163.com.
[4] Senior Engineer, Beijing Institute of Control Engneering, liuxh99@163.com.
[5] Professor, Beijing Institute of Control Engneering, shenyan7806@163.com.

A lot of studies has been done on the physical processes such as vacuum arc ignition, cathode spot ablation and plasma acceleration[3-15]. However, there are few studies on the influence of discharge parameters on the performance and life of the thruster. This paper will mainly focus on this aspect.

II. Experimental Setup

A. The micro cathode arc thruster

The output pulse is controlled by the software and the input voltage is 28V. The peak discharge current can be adjusted by the time of inductance charging as shown in Table 2 (Section III).

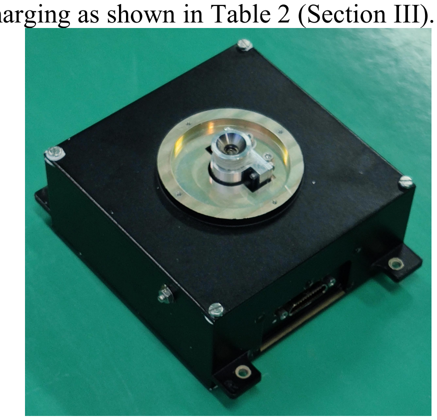

Fig. 2 μCAT module

B. Measuring devices

Voltage Probe: Model P4100, Passive High Voltage Differential Probe, 100MHz bandwidth, attenuation ratio 100, measurement range 0-2000V, finished products purchased, compensation range: 10pF-35pF, accuracy in the range of 1%;

Current probe: Model CP8150A, suitable for high current applications; It can measure continuous current of 150A and peak current of 300A, providing a 12 MHz bandwidth; The probe has two ranges of 150A (accuracy: +1%) and 30A (accuracy: +1%) which can be selected. The 30A range is used for small current measurement with a resolution of up to 10mA.

Oscilloscope: Model TDS3014, 500MHz bandwidth, 4-channel data acquisition, sampling rate up to 5GS/s.

Fig. 3 Voltage probe and current probe

III. Results and discussion

A. The influence of discharge parameters on thruster performance

The discharge parameters of the μCAT thruster will affect the performance of the thruster by affecting the cathode spot ablation during vacuum discharge, that is, the propellant consumption process. In practice, the inductance of the inductance coil and the charging and discharging timing can be adjusted.

The discharge of the thruster in vacuum is shown in Fig. 4. The pressure in the vacuum chamber is 8×10^{-4} Pa. The parameters of discharge current and voltage are shown in Fig. 5. The maximum breakdown voltage is 800V, the discharge voltage is tens of volts and the discharge time is hundreds of microseconds.

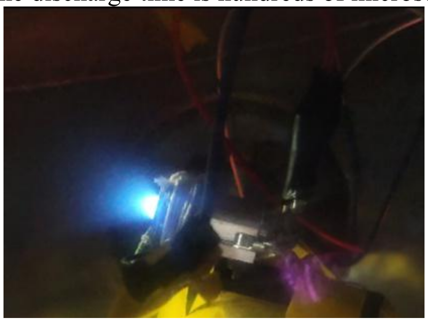

Fig. 4 Thruster working in the vacuum chamber

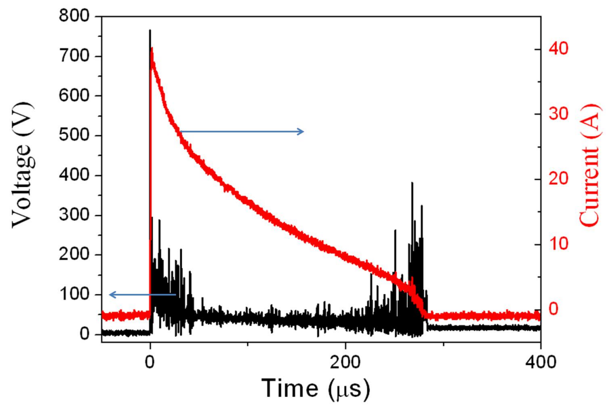

Fig. 5 Discharge current and voltage

The inductance coils of 0.1mH and 0.2mH are used respectively, the average impulse (without external magnetic field) of the pulse is obtained under different charging time lengths as shown in Fig. 6. For both inductance coils, the impulse increases with the increase of charging time. This is because with the increase of charging time, the charging current in inductance coil increases (as shown in Table 2), which makes the discharge current of cathode spot increase at breakdown instant. Single discharge can ablate more cathode materials (weighing after tens of thousands of ignition pulses and calculating the ablation mass at a single time, as shown in Table 3), which is equivalent to the flow rate of propellant. The increase of impulse leads to the increase of thrust, but for the inductance coils of 0.1mH and 0.2mH, the increase of impulse is small under the same discharge current, which indicates that the current value of charge and discharge plays a leading role in the process.

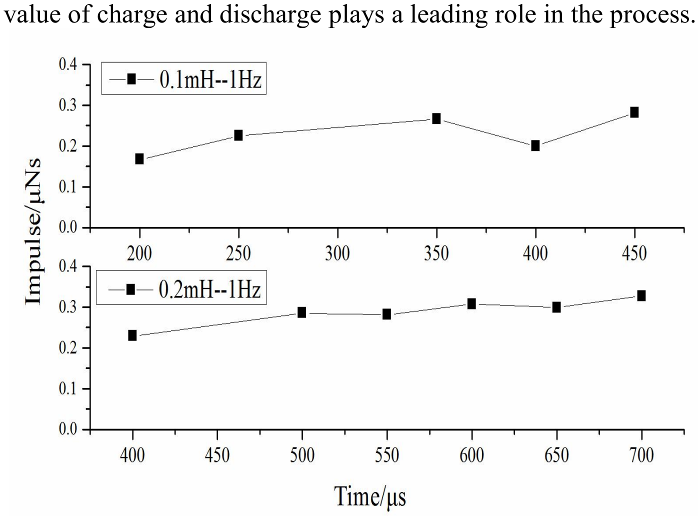

Fig. 6 Impulse under different discharge parameters

Table 2 The relationship between discharge current and charging time

No	0.1mH		0.2mH	
	Chargin g time μs	Peak current A	Charging time μs	Peak current A
1	200	42	300	34
2	300	65	400	48.5
3	350	74	500	63
4	400	77	550	62
5	450	77	600	65

Table 3 Mass loss of the cathode

No	Total mass loss (mg)	Working times ($\times 10^4$)	Erosion rate (μg/pulse)	Peak current (A)
1	4.1	10	0.041	42
2	2.2	5	0.042	42
3	1.4	2.2	0.064	74

From the above results, it can be seen that the influence of discharge parameters on thrust is mainly caused by the change of discharge current (current density) at the cathode spot during vacuum arc operation, which changes the ablation consumption of cathode material, i.e. the propellant supply flow rate, thus affecting the thrust of the thruster.

B. the influence of lifetime using triggerless method

In this study, the trigger ignition process adopts the "triggerless" ignition as shown in Ref. [9] and [10]. According to the voltage and current curve of the discharge in Fig. 5, under the suitable working conditions, the "triggerless" ignition with breakdown voltage not exceeding 800V has been achieved. Two different discharge parameters were used to test the lifetime.

Fig. 7 shows the current curve of low discharge current (10A). Fig. 8 shows the corresponding breakdown voltage and peak current signals obtained in the discharge life test of "triggerless" ignition under 10A discharge current. It can be found that both voltage and current signals are relatively stable at the beginning of life, but at the end of life. There is a sudden change in the discharge current signal.

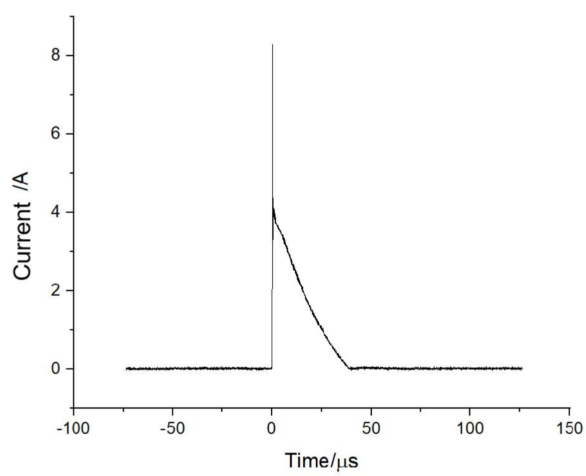

Fig. 7 Discharge current under low peak current condition (peak current=10A)

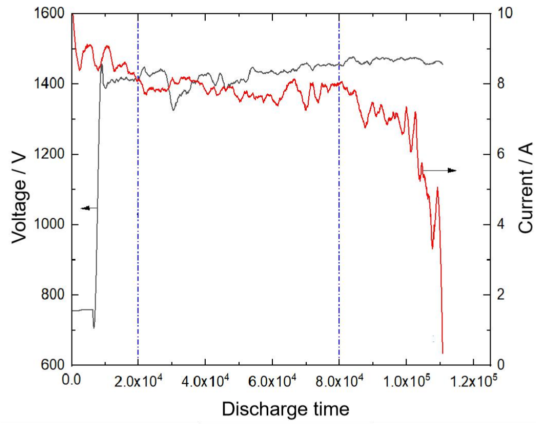

Fig. 8 Discharge voltage and peak current(peak current=10A)

Fig. 9 shows the variation of the corresponding resistance during the test verification of Fig. 8. At the beginning of life, the change is slow, but at the end of life, the resistance changes abruptly, which leads to the failure of non-triggered breakdown ignition. From the variation process of resistance value in Fig. 9, it can be seen that resistance value can also be used as an important reference index for evaluating the ignition life of arc initiation without triggering.

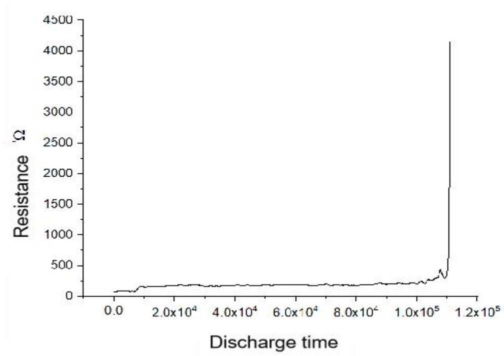

Fig. 9 The resistance variation (peak current=10A)

When the discharge parameters are adjusted to the typical discharge conditions shown in Fig. 4 (peak discharge current is 40A), the resistance changes during ignition without triggering arc are shown in Fig. 10. From Figure 10, it can be seen that the load resistance of thruster is relatively stable and still in a normal working state in the more than 300,000 life tests that have been completed. The suitable discharge parameters greatly prolong the ignition life of the thruster without trigger.

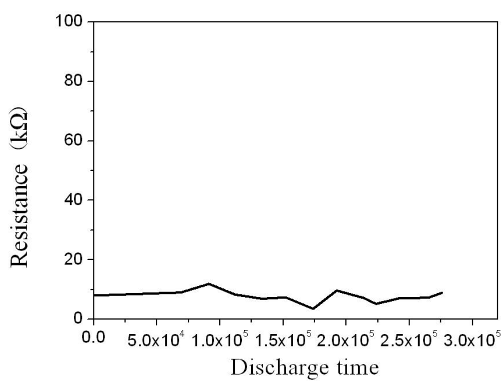

Fig. 10 The resistance variation(peak current=40A in Fig. 4)

Under the condition of lower discharge current, the discharge time is shorter, and the discharge area is mostly concentrated in a special position, which makes the ablation serious and can't be uniformly ablated on the whole cathode surface, too small discharge current (10A) will greatly shorten the life of thruster, while under the condition of 40A peak discharge current, with the cathode spot. Rotation can ablate the whole cathode surface and prolong its life greatly.

In addition, in the process of thruster operation, the breakdown discharge will consume the conductive film instantaneously, and the subsequent cathode ablation products will adhere to the surface of the conductive film to repair it, so that it can achieve dynamic equilibrium in a certain time. This phenomenon is called "self-repairing phenomenon". In this case, the phenomenon of self-repairing is more significant under the peak discharge current of 40A.

IV. Conclusion

In this paper, the main factors affecting the performance of micro cathode arc thruster are analyzed by means of experimental research.

(1) The discharge current affects the thrust through the cathode spot ablation. The discharge current increases, the cathode loss increases, and the thrust/impulse increases.

(2) The magnitude of discharge current will affect the life of thruster. Compared with low current (10A) discharge, the life of thruster is longer under high current discharge.

Acknowledgments

The Author thanks the financial support of the National Natural Science Foundation of China (No: 11702021) and the Defense Industrial Technology Development Program.

References

[1]Zhuang T, Shashurin A, Denz T, et al. Performance characteristics of micro-cathode arc thruster [J]. Journal of Propulsion and Power, 2014, 30(1): 29–34.

[2]Keidar M, Zhuang T, Shashurin A, et al. Electric propulsion for small satellites [J]. Plasma Physics and Controlled Fusion, 2015, 57(1): 14005-14014.

[3]Plyutto A A, Ryzhdov V N, Kapin A T. High speed plasma streams in vacuum arcs[J]. Soviet Physics JETP， 1965， 20（2）：328-337.

[4]Gilmour A S. Concerning the feasibility of a vacuum arc thruster[C]. 5th Electric Propulsion Conference. San Diego，California：AIAA，1966.

[5]Gilmour A S, Clark R J, Veron H. Pulsed vacuum-arc microthrustors[C]. AIAA Electric Propulsion and Plasma Dynamics Conference. Colorado：AIAA，1967.

[6]Jüttner B. Cathode spots of electric arcs[J]. Journal of Physics D: Applied Physics, 2001, 34(17): 103-123.

[7]Dorodnov A M. Technical applications of plasma accelerators[J]. Soviet Physics Technical Physics, 1978, 23(9): 1858-1870.

[8]Zhuang T. Micro-Cathode Arc Thruster System for Cube Satellite [D]. The George Washington University, 2012.

[9]Anders A, MacGill R A, McVeigh T A. Efficient， compact power supply for repetitively pulse，‘triggerless’ cathodic arcs[J]. Review of Scientific Instruments, 1999, 70(12): 4532-4535.

[10]Anders A, Schein J, Qi N. Pulsed vacuum-arc ion source operated with a ‘triggerless’ arc initiation method[J]. Review of Scientific Instruments, 2000, 71(2): 827-829.

[11]Beilis I. State of the theory of vacuum arcs[J]. IEEE Transactions on Plasma Science, 2001, 29(5): 657-670.

[12]Beilis I. Vacuum Arc Cathode Spot Theory . History and Evolution of the Mechanisms[C]. 28th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), 2018.

[13]Burkhard Jüttner. The dynamics of arc cathode spots in vacuum: New measurements[J]. Journal of Physics D Applied Physics, 1997, 30(2): 221-229.

[14]Gashkov M A, Zubarev N M, Mesyats G A, et al. The mechanism of liquid metal jet formation in the cathode spot of vacuum arc discharge[J]. Technical Physics Letters, 2016, 42(8): 852-855.

[15]Zhuang T, Shashurin A, et al. Ion velocities in a micro-cathode arc thruster [J]. Physics of Plasma. 2012, 19, 063501.