

ORIGINAL RESEARCH

Double-ejection micro-cathode arc thruster applied to micro-satellite

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Abstract

An innovative double-ejection micro-cathode arc thruster (AC_d-μCAT), which consists of a cylindrical inner anode, a cylindrical outer cathode and two insulating sleeves (an inner insulating sleeve and an outer insulating sleeve), was proposed. The differences in electrical characteristics, plasma parameters and propulsion performance between the newly proposed AC_d-μCAT and a traditional μCAT were examined. Study results showed that compared to the traditional μCAT structure, by using the AC_d-μCAT, the peak value of produced thrust was increased 9.3 times, while the amplitude of the ion current and the ion-to-arc ratio were increased 5.4 and 5.9 times (from 1.2% to 7.1%), respectively. In addition, data from Langmuir probe experiments indicated that peak values of the directional propagation speed and density of plasma plume were increased 3.1 times and 4.2 times, respectively. Moreover, plasma plume directional ejection performance was also significantly improved. This study result will provide support for the development of a new-generation μCAT.

1 | INTRODUCTION

The micro-cathode arc thruster (μCAT) is an electromagnetic device that produces thrust by a directionally ejected plasma jet generated by ablating the metal cathode material, which is suitable to serve as a propeller for micro-satellites [1, 2]. However, practical applications of μCAT are limited due to its insufficient thrust, resulting from limited metal plasma production.

It is recognized that the maximum thrust provided by a μCAT mainly depends on the ejection performance of the metal ions generated during operation, which is determined by the metal ion production and its directional propagation energy. Other particles, including electrons and macro-particles, only have a negligible contribution to the thrust. The traditional typical μCAT was coaxial, which was constituted by a cylindrical inner cathode, an inner insulating sleeve (IIS) and a cylindrical outer anode [3, 4], and is denoted as CA_s-μCAT, where the foot mark 's' indicates a single insulating sleeve, in

this research work. To improve the propulsion performance of a μCAT, some research works have already been conducted [5–7]. However, almost all of the current μCAT structures provided thrust by mainly using the directional ejected plasma jet formed near the cathode during operation, where the anode just acted as a collector of charged particles from the cathode.

In our previous study focussing on the propulsion performance of a μCAT, we found that double clearly visible plasma jets (ejections), one generated near the cathode and the other one near the anode, were produced in a single shot by adopting the structure using an Ethylene Vinyl Acetate (EVA) micropore [8]. The propulsion performance of a μCAT could be improved by using double ejections [9, 10]. But it is inferred that the operation stability and propulsion performance will be declined after long duration work due to the EVA material whose melting point is low.

Accordingly, in this study, we propose a novel double-ejection micro-cathode arc thruster using two insulating

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sleeves (marked as AC_d-μCAT where the foot mark 'd' indicates double insulating sleeves) without insulating materials having a low melting point. To clearly present the performance of the AC_d-μCAT, we comparatively investigated differences in electrical parameters and propulsion performance among the AC_d-μCAT, AC_s-μCAT and the traditional CA_s-μCAT, by measuring discharge voltage, discharge current, directional propagation speed of plasma plume, ion current, ion-to-arc ratio and thrust produced in a single shot.

2 | EXPERIMENTAL SETUP

2.1 | Design of μCAT and its circuitry

In this study, all experiments were performed in a grounded stainless steel vacuum chamber, which has been described in detail in the previous work [9], with a pressure of 10^{-4} Pa.

A schematic representation of the three different μCAT types examined is shown in Figure 1. Figure 1a shows the traditional μCAT structure, which consists of a cylindrical inner cathode, an IIS and a cylindrical outer anode, and is denoted as CA_s-μCAT as previously mentioned. In this case, the diameter of the cathode was 1 mm. The IIS with an outer diameter of 3 mm was arranged on the outer surface of the cathode, and its nozzle extended out of the discharge end of the cathode by 2 mm. An outer anode having a diameter of 5 mm was sleeved on the insulating sleeve, and its nozzle was set at the discharge end of the cathode. The axes of the cathode, the insulating sleeve and the anode coincided with each other. Figure 1b shows another μCAT structure, the AC_s-μCAT, which was regarded as a comparative structure. In this case, the positions of the cathode and the anode were opposite compared to the traditional CA_s-μCAT, but the corresponding parameters were kept the same. The newly proposed μCAT structure using two insulating sleeves is shown in Figure 1c and is denoted as AC_d-μCAT, as mentioned in the introduction. In this case, compared with the AC_s-μCAT, the outer surface of the cathode was also sleeved by a cylindrical outer insulating sleeve (OIS), which had an outer diameter of 6 mm and extended out of the discharge end of the cathode by 6 mm. In the design of the AC_d-μCAT, the double insulating sleeves were used to hinder the radial diffusion of plasma near the cathode and anode and to allow more particles being ejected out in the axial direction of the μCAT to produce a thrust. For the three μCAT structures described above, the metal cathodes and anodes were all composed of lead (Pb). Additionally, because part of the plasma that was emitted from the cathode flowed to and was absorbed by the grounded vacuum chamber wall during μCAT operation, the chamber also acted as an anode, collecting charged particles [8].

A simplified single-pulse discharge circuit, which was described in detail in our previous work [11], was used to generate the discharge and is schematically presented in Figure 1 for all μCAT structures under study. The cathode was electrically connected to the negative high voltage terminal of the discharge circuit, and the anode was grounded. Discharge

voltage ($V(t)$) was directly measured by a Tektronix P6015A high-voltage probe, while the discharge current flowing through the cathode (cathode current, $I_C(t)$) and through the anode (anode current, $I_A(t)$) were simultaneously measured by using Rogowski coils. The current flowing to vacuum chamber (chamber current, $I_{\text{chamber}}(t)$) was determined by $I_{\text{chamber}}(t) = I_C(t) - I_A(t)$. Plasma density and directional propagation speed were measured by using an improved Langmuir probe measurement method [8–11].

2.2 | Ion current measurement system

A semispherical measurement system, which has been already used in a pulsed discharge diagnostic [8, 12], was applied to monitor the ion current, I_i , generated in a single shot for the different μCAT structures under study, and is schematically presented in Figure 2.

To collect the ions ejected from the axial direction of the μCAT, a semispherical stainless steel collector having a radius of 80 mm, which was arranged 80 mm away from the discharge end of the cathode, was used. Due to in a pulse mode measurement, before starting the μCAT operation, the ion current measurement system was placed downstream of the plasma plume, and a voltage of -100 V was applied to the semispherical collector. Then, the ion current was recorded by monitoring the voltage on a 5Ω measurement resistor using a Tektronix TBS 1154 oscilloscope. The measured data at a fixed applied voltage on the capacitor bank were averaged from 10 shots to improve the accuracy. In order to evaluate the production efficiency of metal ions produced by different μCAT structures, a parameter, ion-to-arc ratio (G_r), which was defined as the ratio of the peak ion current I_i to the peak arc current (I_{arc}) [8], is adopted,

$$G_r = \frac{I_i}{I_{\text{arc}}} \quad (1)$$

From this definition, it is clear that a larger G_r value signifies a higher metal ion production efficiency, which is desirable for a better propulsion performance of a μCAT.

3 | RESULTS

3.1 | Visual appearance of the discharge phenomenon

Long-duration discharge phenomenon between the electrodes helps understand the differences in discharge characteristics and plasma propagation characteristics for the different μCAT structures and was therefore examined first. Capturing of the discharge phenomena was conducted using a Nikon D7100 camera with an ISO of 400 and an exposure time of 0.5 s, which was far greater than the single-pulse duration ($\sim 10 \mu\text{s}$) and using more than 500 shots for each of the three μCAT structures. When the voltage applied to the capacitor bank was

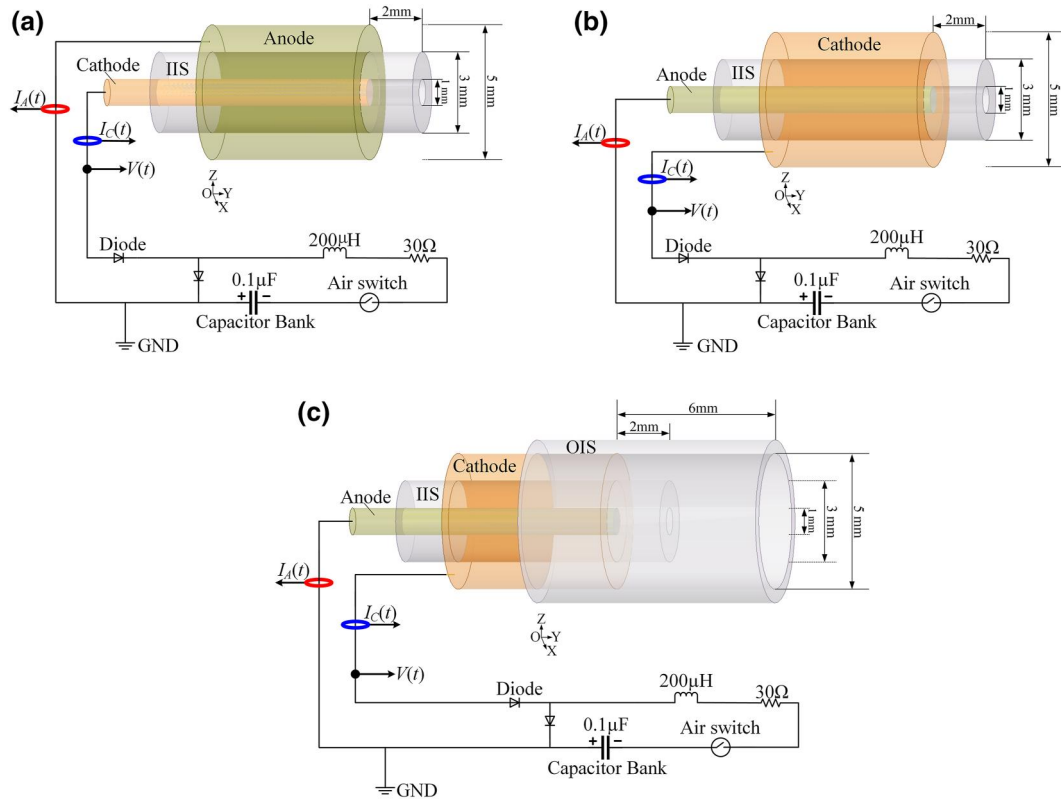


FIGURE 1 A schematic representation of (a) the CA_s-μCAT, (b) the AC_s-μCAT and (c) the AC_d-μCAT and their circuitry, where the footmark 's' denotes a single insulating sleeve and 'd' denotes double insulating sleeves

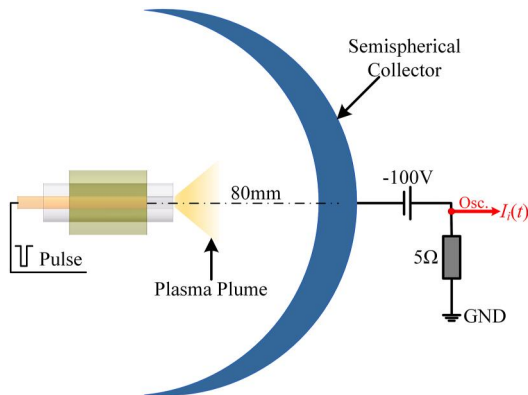


FIGURE 2 A schematic of the semispherical ion current measurement system

8.0 kV (3.2 J), the typical long-exposure side-view discharge images are shown in Figure 3.

It is seen from Figure 3a that for the CA_s-μCAT, a clearly visible plasma jet was generated at the nozzle of the IIS. In addition, there was also a visible luminescence region on the anode outer surface, which constantly moved around the side surface close to the anode nozzle during different shots. Figure 3b shows that in the case of the AC_s-μCAT, whose positions of cathode and anode were opposite compared to the CA_s-μCAT. There was an area with strong light intensity on the cathode outer surface, and notably, a clearly visible

plasma jet which was ejected from the nozzle of the IIS was also produced. Finally, Figure 3c reveals that by using the AC_d-μCAT, a visible plasma jet was generated at the nozzle of the outer insulating sleeve (some of the discharge light was blocked by the OIS). Due to the shielding by the OIS, the discharge phenomenon near the anode cannot be shown, but it was clear that the plasma generation and propagation processes were similar to those in the case of the AC_s-μCAT. In addition, the ejection length of the plasma jet was significantly increased compared to those of the CA_s-μCAT and the AC_s-μCAT.

To quantitatively evaluate the directional ejection length of the plasma jet ejected from the insulating sleeve nozzle and produced by the different μCAT structures, light intensity distributions of the discharge images shown in Figure 3 were calculated using the simulation software of MATLAB [8]. As an example, for the AC_s-μCAT structure, the calculated result based on Figure 3b is shown in Figure 4, where values of light intensity in the colour bar were dimensionless normalised data. Point 0 on the abscissa corresponds to the position of the discharge end surface of the cathode. In this study, we defined that the length of the region having a light intensity greater than 100 along the axial direction of the insulating sleeve as the ejection length of the plasma jet.

According to the calculated results, for the three different μCAT structures (CA_s-μCAT, AC_s-μCAT and AC_d-μCAT), the corresponding directional ejection lengths of the plasma jets were 4 mm, 5 mm and 11 mm, respectively, and repeatability

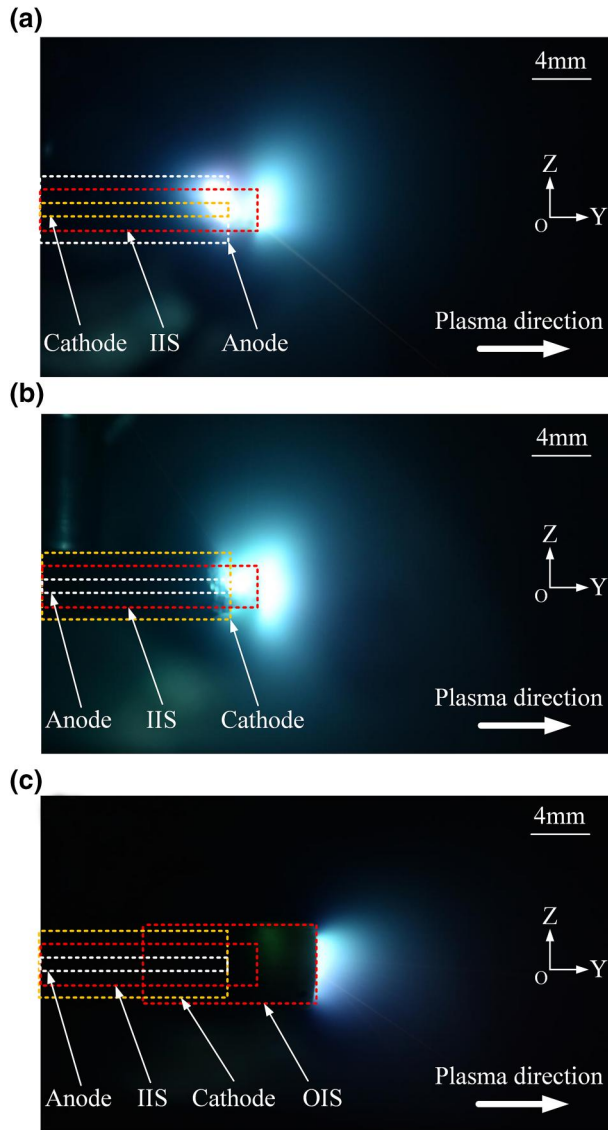


FIGURE 3 Typical long-exposure side-view images of (a) the CA_s - μ CAT, (b) the AC_s - μ CAT and (c) the AC_d - μ CAT

error was less than 8% for each μ CAT structure. So, compared to the traditional CA_s - μ CAT structure, the directional ejection length of the plasma jet produced by the AC_d - μ CAT was increased 2.7 times.

3.2 | Plasma parameters

By using the improved double Langmuir probes measurement method where both probes were arranged at axis and downstream of the plasma plume with an interval of 35 mm, the directional propagation speed and propagation direction of plasma in the exit plumes which were produced by different μ CAT structures were determined [8]. For the AC_s - μ CAT, when the applied voltage on both probes was 12 V, the typical measured electron current waveforms flowing through both probes are shown in Figure 5.

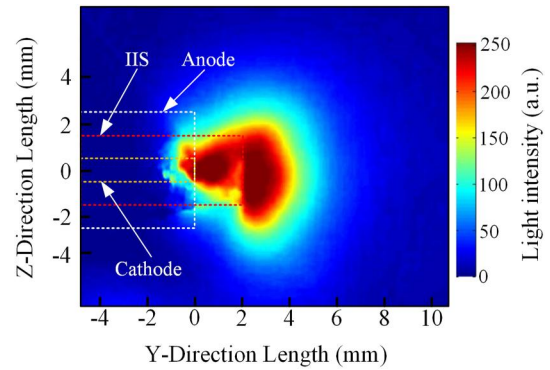


FIGURE 4 Light intensity distribution of the discharge image shown in Figure 3b for the AC_s - μ CAT

According to Figure 5, the electron current on probe 1 reached a peak value of 77 mA at 21.2 μ s, while the electron current on probe 2 reached its peak value of 27 mA at 23.4 μ s. Accordingly, it was clear that for the AC_s - μ CAT structure, the plasma generated at the IIS nozzle first propagated to the nearer probe (probe 1) and then got to the farther probe (probe 2), which suggested that the plasma jet was axially ejected out of the IIS nozzle. Due to the diffusion of the plasma plume, there was a decrease in electron current amplitude at probe 2 compared to probe 1. Moreover, using the distance between the two probes and the time interval (Δt) between the electron current peaks shown in Figure 5, the directional propagation speed of the plasma at the double probe measurement position was calculated to be 1.59×10^4 m/s. By using the same method at the same measurement position, waveforms of electron currents in the cases of the CA_s - μ CAT and AC_d - μ CAT structures were also measured. Results showed that the electron current waveforms were similar to those in the case of the AC_s - μ CAT shown in Figure 5, and the corresponding directional propagation speeds of plasma were calculated to be 1.02×10^4 m/s and 3.18×10^4 m/s for the CA_s - μ CAT and AC_d - μ CAT structures, respectively. The accuracy was improved by using the average of 10 shots for each μ CAT structure (repeatability error was less than 5%). According to the data above, compared to traditional CA_s - μ CAT, the peak value of the directional propagation speed of the plasma plume produced by the AC_d - μ CAT was increased approximately 3.1 times.

Additionally, by using the improved single Langmuir probe measurement method where the probe was arranged 170 mm away from the discharge end of cathode, plasma density distribution of the three different μ CAT structures, at different spatial angles ranging from -90° to $+90^\circ$ with an interval of 15° , were measured [9, 10], and the results are shown in Figure 6.

According to Figure 6, spatial distributions of plasma densities of the three μ CAT structures under study are all almost axisymmetric, and peak values of plasma densities all lie in the angle of 0° . Among the three different μ CAT structures, the peak density of plasma produced by the

AC_d-μCAT structure was the largest. Compared to the AC_s-μCAT and the traditional CA_s-μCAT, the peak plasma density of the AC_d-μCAT was increased 3.1 times and 4.2 times, respectively. Additionally, to evaluate the directional ejection performance of plasma plume, a parameter R_{45} was adopted [9]. Using the data shown in Figure 6, the R_{45} values for the three μCAT structures were calculated and were found to be 76%, 66% and 15% for the CA_s-μCAT, AC_s-μCAT and AC_d-μCAT, respectively. Accordingly, among the three different μCAT structures, the directional ejection performance of plasma plume produced by the AC_d-μCAT was the best. According to the literature [13], plasma plume contamination caused by the plasma diffusion was adverse to the service life of plasma thrusters, it can thus be concluded that, compared to the traditional CA_s-μCAT, the plasma ejection performance can be significantly improved by using the proposed AC_d-μCAT structure as the latter shows a higher plasma density, a larger directional propagation speed and a better directional ejection performance of the plasma plume.

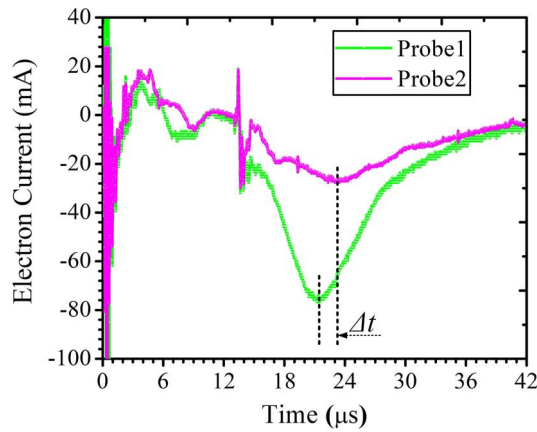


FIGURE 5 Typical waveforms of electron currents flowing through the double probes at a bias voltage of 12 V for the AC_s-μCAT

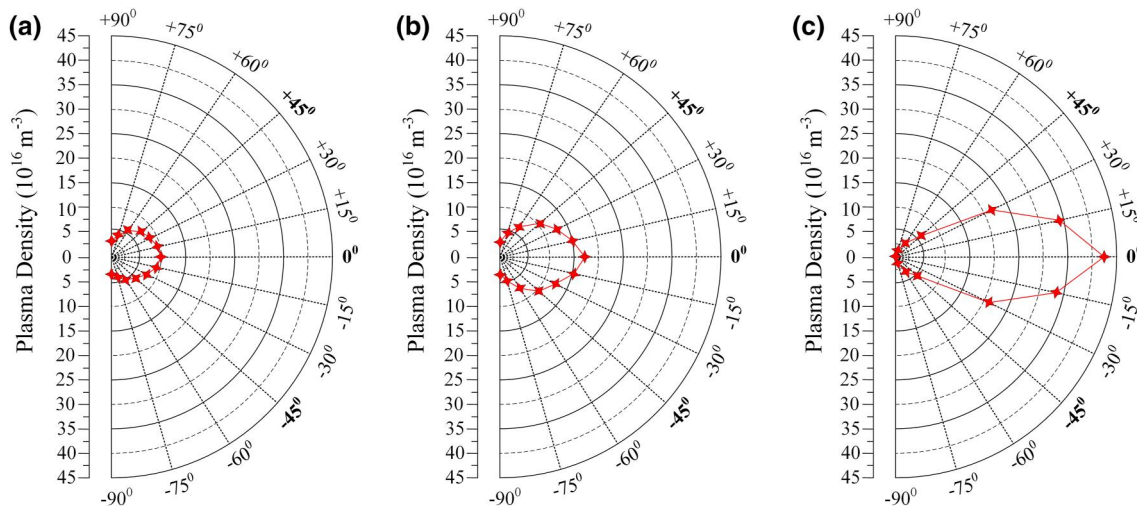


FIGURE 6 Spatial distributions of the plasma densities in the exit plume of (a) CA_s-μCAT, (b) AC_s-μCAT and (c) AC_d-μCAT

3.3 | Electrical parameters

During experiments, discharge voltage and currents were also recorded for the three different μCAT structures shown in Figure 1. Figure 7 shows the measured typical waveforms of discharge voltage and discharge currents when applied voltage on the capacitor bank were 8 kV (3.2 J). Specific discharge parameters obtained from Figure 7 are also shown in Table 1.

According to the data shown in Figure 7 and Table 1, for the CA_s-μCAT, the breakdown voltage was 5.6 kV. The amplitudes of cathode current and anode current were approximately 176 and 143 A, so the anode current amplitude was 81% of that of the cathode current. For the AC_s-μCAT structure, the breakdown voltage was increased by 10% compared to the CA_s-μCAT. In this case, the cathode current was approximately 163 A, which was only 58% of the cathode current. In the case of the AC_d-μCAT structure, the breakdown voltage was 5.2 kV, which was a decrease of 7% compared to CA_s-μCAT. The cathode current was 176 A, and the anode current amplitude accounted for 56% of the cathode current. Analysis showed that the remaining part of the current passed through the grounded vacuum chamber.

According to the previous work [1], to produce a high thrust, a large output chamber current is thus desirable. Based on the data shown in Figure 7, it was calculated that, for the CA_s-μCAT, AC_s-μCAT and AC_d-μCAT, the corresponding integrals of the chamber currents were 0.27×10^{-3} , 0.53×10^{-3} and 0.73×10^{-3} C, respectively. According to these data, it is inferred that more charged particles will be ejected from the μCAT, producing a larger thrust, if a AC_d-μCAT structure is adopted instead of a traditional CA_s-μCAT.

3.4 | Ion current and ion-to-arc ratio

By using the semispherical ion current measurement system shown in Figure 2, the peak ion current (I_i) and the corresponding G_r values produced in a single shot, at different

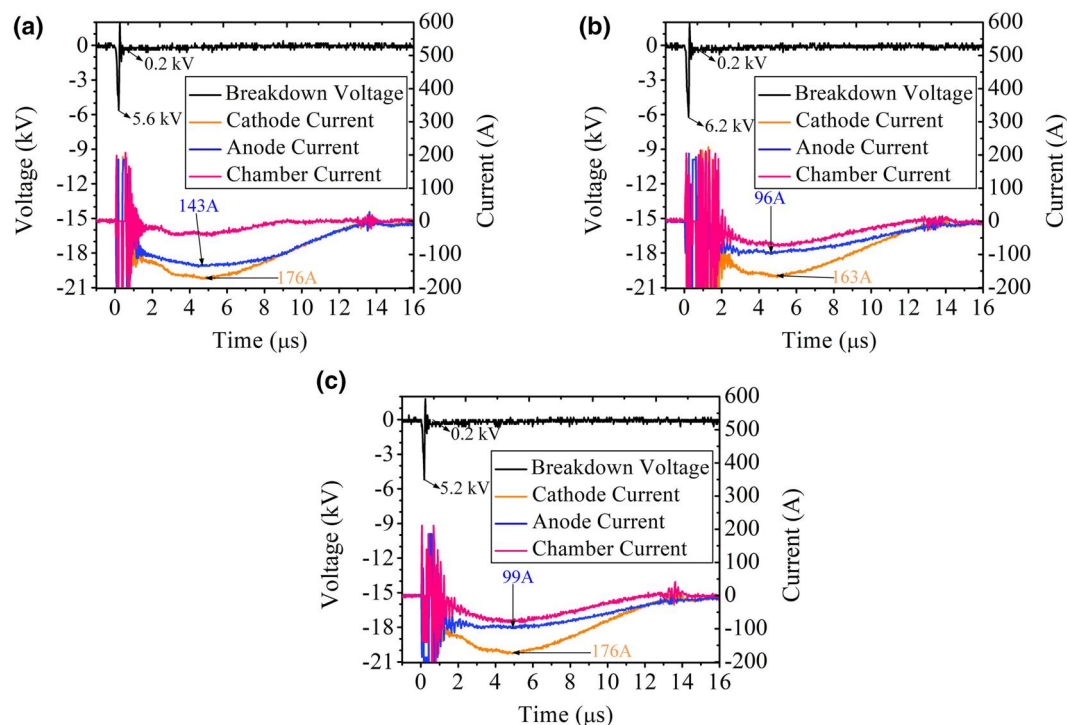


FIGURE 7 Measured waveforms of the discharge voltage and discharge currents using (a) the CA_s - μ CAT, (b) the AC_s - μ CAT and (c) the AC_d - μ CAT at an applied voltage on the capacitor bank of 8 kV (3.2 J) in all cases

TABLE 1 Electrical parameters of the different μ CAT structures

μ CAT structure	Breakdown voltage (kV)	Amplitude of the cathode current (A)	Amplitude of the anode current (A)
CA_s - μ CAT	5.6	176	143
AC_s - μ CAT	6.2	163	96
AC_d - μ CAT	5.2	176	99

capacitor energies, E (3, 4, 5, 6, 7 and 8 J), were measured. $E = 1/2 CU^2$, where C denotes the capacitance and U denotes the applied voltage of the capacitor bank [8].

Figure 8 shows the measurement results of I_i as a function of capacitor energy for different μ CAT structures.

According to Figure 8, with an increase in the capacitor energy, the peak values of I_i produced by the three different μ CAT structures all gradually increased. At a fixed capacitor energy level, I_i comparisons followed the order $I_{iAC(d)-\mu CAT} > I_{iAC(s)-\mu CAT} > I_{iCA(s)-\mu CAT}$. The increase in I_i with capacitor energy also followed the same order. For the traditional CA_s - μ CAT, the generated I_i was increased from 1.2 A at a capacitor energy of 3 J to 2.6 A at a capacitor energy of 8 J. In the case of the AC_s - μ CAT, the I_i was increased from 1.3 A at a capacitor energy of 3 J to 3.4 A at an energy of 8 J. In contrast, the I_i produced by the AC_d - μ CAT was increased from 3.8 to 14.2 A under the same conditions. So, at the fixed capacitor energy of 8 J, compared to the traditional CA_s - μ CAT, the peak I_i generated by the AC_d - μ CAT was increased 5.4 times. Accordingly, I_i produced by a μ CAT could be effectively increased by replacing the traditional CA_s - μ CAT with the AC_d - μ CAT structure proposed in this study.

Figure 9 shows the calculated G_r values as a function of capacitor energy for the three different μ CAT structures.

According to Figure 9, among the capacitor energy levels examined in this study, the G_r values among the μ CAT structures followed the order: $G_{rAC(d)-\mu CAT} > G_{rAC(s)-\mu CAT} > G_{rCA(s)-\mu CAT}$. Moreover, with an increasing capacitor energy, the values of $G_{rCA(s)-\mu CAT}$, $G_{rAC(s)-\mu CAT}$ and $G_{rAC(d)-\mu CAT}$, were all increased. For the traditional CA_s - μ CAT, the G_r value was increased from 0.78% at a capacitor energy of 3 J to 1.2% at a capacitor energy of 8 J. In contrast, the G_r value of the AC_d - μ CAT was increased from 2.5% to 7.1% under the same conditions. So, when the capacitor energy was 8 J, compared to the traditional CA_s - μ CAT, the G_r value generated by the AC_d - μ CAT in a single shot was increased 5.9 times, which was a significant improvement.

Based on the data presented in this section, it was concluded that the ion production and the corresponding G_r values were significantly increased by using the AC_d - μ CAT structure instead of the traditional CA_s - μ CAT. It was previously recognized in literature that the maximum thrust that a μ CAT can produce is determined by the metal ions generated during operation [14]. Therefore, it was inferred that the

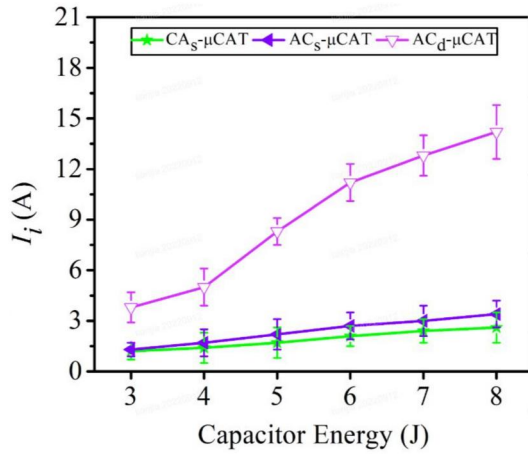


FIGURE 8 Peak values of ion current (I_i) varied with the capacitor energy. Error bars indicate the maximum deviations from the average values

propulsion performance can be effectively improved by using the AC_d-μCAT. To confirm this assumption, the propulsion performance has been examined as well and the results will be given below.

3.5 | Propulsion performance

In this section, the thrust (T) produced by the three different μCAT structures was measured. For this purpose, a thrust measurement platform based on a piezoelectric film sensor, which has already been used in thrust measurement for pulsed plasma thruster, was adopted [9, 15–17], and a detailed description of the platform was previously given [9]. In this study, the thrust was measured in a single shot, at different capacitor energies (3–8 J) and the results are shown in Figure 10. The accuracy was improved by averaging 15 shots at a fixed capacitor energy in Figure 10.

Figure 10 shows that with increasing capacitor energy, the peak values of the thrust produced by the three different μCAT structures were all gradually increasing. At a fixed capacitor energy level, the thrust comparisons followed the order, $T_{AC(d)-μCAT} > T_{AC(s)-μCAT} > T_{CA(s)-μCAT}$. The increase in thrust with capacitor energy also followed the same order. For the traditional CA_s-μCAT, the generated thrust was increased from 2 μN at a capacitor energy of 3 J to 4.5 μN at a capacitor energy of 8 J. For the AC_s-μCAT, the generated thrust was increased from 2.2 μN at an energy of 3 J to 5.9 μN at 8 J. In contrast, in the case of the AC_d-μCAT, the produced thrust was increased from 4.7 to 42.2 μN under the same conditions. So, when the capacitor energy was 8 J, compared to the traditional CA_s-μCAT, the peak thrust produced by the AC_d-μCAT was increased 9.3 times.

Based on the discussions above, it is concluded that in the design of a μCAT, using the AC_d-μCAT structure instead of the conventional CA_s-μCAT structure can effectively improve propulsion performance of a μCAT. Moreover, there are no insulating materials with low melting

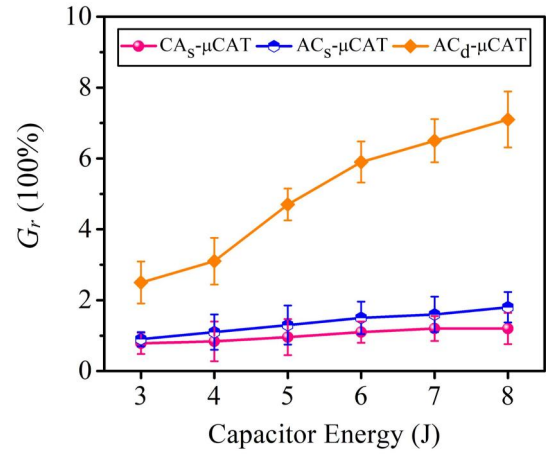


FIGURE 9 G_r values varied with the capacitor energy. Error bars indicate the maximum deviations from the average values

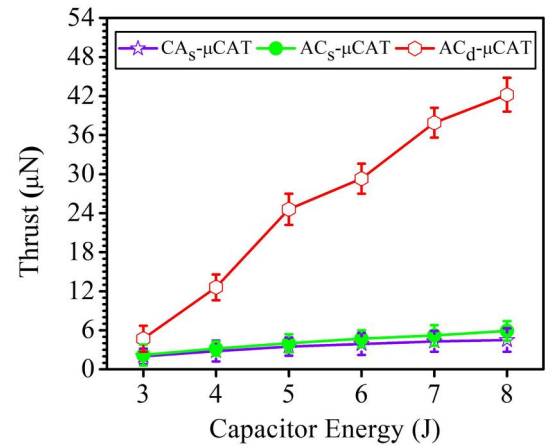


FIGURE 10 Thrusts varied with the capacitor energy. Error bars indicate the maximum deviations from the average values

points, so it is inferred that the operation stability of the μCAT will be improved compared with the existing structures [9].

4 | OPERATION MECHANISM OF THE AC_d-μCAT

During the experiments, when using the three μCAT structures shown in Figure 1, after 200 shots, the surfaces of the cathodes, the insulating sleeves and the anodes were carefully examined. The results showed that the discharge end surfaces of the cathodes were all obviously ablated for all μCAT structures, but there were no visible ablations on the walls of the insulating sleeves and anode surfaces. So, it was concluded that for the AC_s-μCAT, the plasma jet (as shown in Figure 3b) generated at the nozzle of the IIS was formed by the plasma generated from the cathode.

Taking into account the discussion above, the electron field emission [18, 19] and Hump theory [20], and our previously obtained results [8], a simplified circuit diagram of the charged

particles, mainly including the ion and electron flow for the AC_d-μCAT operation, is proposed and presented in Figure 11.

As shown in Figure 11, it was concluded that the operation mechanism of the AC_d-μCAT was as follows [8]. First, when a high voltage was applied on the μCAT, a strong electric field E_c formed on its cathode surface. Under the action of field emission, electrons were emitted from cathode spots. These electrons collided with metal vapours, which were generated from the cathode, producing metal ions f_{i1} and more electrons f_{e1} . Then, electrons moved towards the anode, while ions accumulated near the cathode due to its much lower movement speed compared with the electrons, forming a positive spatial potential Hump_C near the cathode, U_c . Under the joint action of the U_c and the Coulomb force between electrons and ions, part of the charged particles (f_{e2} and f_{i2}) were ejected from the interval between IIS and OIS to form the first plasma ejection, and others (f_{e3} and f_{i3}) moved in the direction of the anode. Subsequently, when part of plasma (f_{e3} and f_{i3}) arrived near the anode, some of the electrons f_{e4} entered the anode, forming the anode current. On the other hand, the ions accumulated near the anode, also forming a positive spatial potential Hump_A near the anode surface, U_a . Under the action of U_a , charged particles near the anode (f_{e5} and f_{i5}) were ejected out, forming the second plasma ejection. Finally, all the particles (f_{e2} , f_{i2} , f_{e5} and f_{i5}) were ejected from the AC_d-μCAT to produce a thrust.

According to the analysis above and the experimental data shown in Sections 3.1–3.5, it can be concluded that compared to the traditional CA_s-μCAT, the AC_s-μCAT results in a higher ion density near the cathode, due to a smaller exposed anode surface, resulting a higher U_a . Under the action of this higher U_a , electrons were hindered to enter the anode, resulting in a smaller anode current. However, on the other hand, the plasma arriving near the anode was accelerated to form a visible plasma jet. But, in this case, because the space near the cathode spot was increased, the ion density near the cathode was decreased, leading to a smaller U_c . Under the action of this smaller U_c , the plasma production was decreased (it was seen from Figure 7 that the amplitude of the cathode current was decreased compared to the CA_s-μCAT structure). In contrast, for the AC_d-μCAT, due to the existence of the double insulating sleeves, IIS and OIS, both a high Hump_C and Hump_A were generated. Accordingly, among the three different μCAT structures, the amount of plasma ejected from the AC_d-μCAT structure was the largest, thereby leading to the largest thrust.

5 | CONCLUSION

In the study on the design and propulsion performance of a μCAT, a novel double-ejection micro-cathode arc thruster using two insulating sleeves, AC_d-μCAT, is proposed. This paper presents the latest research results of this innovative μCAT. In a single shot, the AC_d-μCAT produced thrust by using two directionally ejected plasma jets, one formed near the cathode and the other one formed near the anode. It is firstly

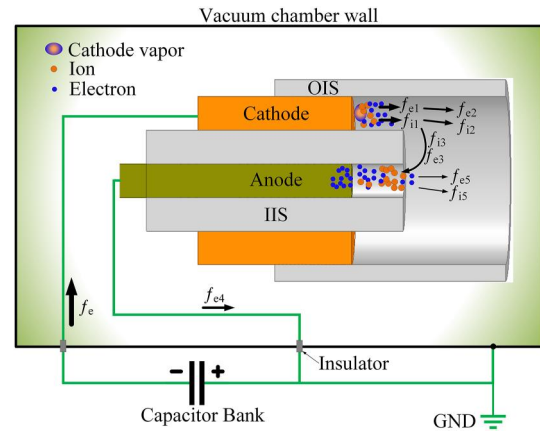


FIGURE 11 A simplified circuit diagram of the charged particles for the AC_d-μCAT system

experimentally demonstrated that by using the novel AC_d-μCAT instead of the traditional CA_s-μCAT structure, productions of ion current and the ion-to-arc ratio, were significantly increased, accordingly effectively increasing the thrust for a μCAT. The study results showed that compared to the traditional μCAT structure, the peak value of the produced thrust was increased 9.3 times by using the new AC_d-μCAT structure. As the AC_d-μCAT design can be easily implemented, it is a simple and effective approach for improving the propulsion performance of a μCAT.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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