Analyses of Ignition Processes of an Applied-Field Magnetoplasmadynamic Thruster

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A steady-state radiation-cooled applied-field magnetoplasmadynamic thruster was investigated experimentally to analyze its ignition processes and clarify the influences of applied magnetic field strength, discharge current value, and propellant type on these processes. The range of the applied magnetic field strength utilized is 0-0.25T whereas that of the discharge current is 130-190A. Besides, either argon or nitrogen was adopted in each test. It was found that applied magnetic field and high discharge current can contribute to the breakdown of neutral gas and the establishment of arcs. Moreover, durations of arc transition under different magnetic field strengths, discharge currents and propellant types were obtained, and two opposite effects of applied magnetic field on arc transition were found. Furthermore, the duration of arc transition does not show strong dependence on discharge current when nitrogen is used as the propellant under given operation conditions. In the end, discharge voltages after stabilization of each test were displayed. It is shown that discharge voltage generally increases with increasing applied magnetic field strength, whereas displays no dependence on discharge current when nitrogen is adopted as the propellant under given operation conditions.

I. Introduction

Magnetoplasmadynamic (MPD) thrusters have demonstrated the capability to operate at high power levels with a simple, robust design and are attractive candidates for Earth-orbit, planetary robotic, and manned missions.¹² However, serious shortcomings, for example, the limited lifetime of thruster components have precluded the applications of MPD thrusters in actual missions.¹³⁻⁵ Previous studies have proven that cathode erosion is the major life-limiter of MPD thrusters operating below a critical current,⁶⁻⁸ and a number of theoretical and experimental studies have been done to gain some insights into the cathode and discharge phenomena occur in MPD thrusters under pulsed or steady-state operation mode.⁸⁻¹⁴ It is suggested that cathode erosion rate may depend strongly on thruster geometry and operating conditions.¹³⁻⁸

What’s more, as a process characterized by a cold cathode and a highly unstable, spotty arc attachment, the ignition or start-up phase generally exhibits an erosion rate that is several orders of magnitude higher than that of the steady operation state.¹⁹⁻¹²,¹³⁻¹⁵,¹⁶ Though the duration of ignition phase is much shorter than that of continuous operation in a steady-state MPD thruster, effects of start-up on cathode erosion are still evident especially when it comes to actual missions or pulsed devices which may involve hundreds of start-ups, thus making it crucial to investigate the fundamental processes underlying the ignition phase. Unfortunately, despite of previous studies involving the ignition processes of self-field MPD (SF-MPD) thrusters¹⁷,¹⁸ investigations on the ignition phase of applied-field MPD (AF-MPD) thrusters have been quite limited so far and effects of operating conditions on ignition processes have not been fully understood yet.³

The purpose of this paper is to investigate the ignition processes of an AF-MPD thruster and the influences of applied magnetic field strength, discharge current value, and propellant type on these processes. Besides, suggestions on the selection of ignition operation conditions are proposed to attain more reliable start-ups and reduce cathode erosion during the ignition phase. Furthermore, instead of weighting cathode mass loss or analyzing

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surface features, this work mainly focuses on analyzing the voltage and current transition procedures during the ignition phase under different operation conditions.

II. Experimental Setup

The steady-state radiation-cooled AF-MPD thruster used in this study has a central hollow cathode made of tungsten (99.95%) and a coaxial convergent-divergent anode made of molybdenum (99.95%). The schematic diagram of the thruster is illustrated in Fig.1. The cathode, which has an inner diameter of 4mm and outer diameter of 6mm, is connected to cathode connection components made of copper to allow for easy replacement and axial adjustment. Besides, the cathode is isolated against the anode by an insulator made of boron nitride, and the overall length of the thruster is about 352 mm. Propellant is injected into the chamber via the hollow cathode and the ring channel surrounded by the insulator and one anode connection component, and propellant mass flow though each channel is named as the “cathode mass flow” or “anode mass flow” correspondingly for convenience. Two kinds of propellants, i.e., argon and nitrogen were applied in this study, and the cathode and anode mass flow rate of each propellant were controlled and measured by two mass flow controllers (Seven Star Instruments, model D07-7B) respectively.

The slowly divergent applied magnetic field in the discharge region is produced by external coils surrounding the thruster with one end 20 mm away from the thruster’s exit plane. Besides, the magnetic field strength at the magnet coil center can reach a maximum of 0.25 T with 150 A through the solenoid.

The vacuum chamber in which the AF-MPD thruster and magnet coil are placed is 1.8 m in diameter and 3 m in length, and the tank pressure was maintained around 0.03 Torr during tests at mass flow rate up to 65 mg/s.

The thruster power was provided by a current-regulated power supply, which consists of a main circuit, control circuit, safety circuit, and high-frequency starter circuit. The starter circuit could output 10 kV pulse at a frequency range of 40 kHz-1 MHz to initiate the arc, and the open-circuit voltage of the power supply is about 340 V. Besides, the maximum current output of the power supply is 350 A while the maximum voltage is 100 V.

A GEN2i sixteen-channel data acquisition system manufactured by HBM was used in this study to collect discharge voltage, discharge current, and propellant mass flow rate data during the tests, and the sampling rates were set to 1 kHz in all the tests.

III. Results and Discussion

A. Durations of Arc Transition

Similar to that in an arcjet,19,20 the ignition phase of an MPD thruster can also be characterized by three basic steps, i.e., arc initiation, arc transition, and arc stabilization. During the arc initiation step, which is featured by a sudden decrease in voltage together with an increase in current, initial localized tiny spots are formed on the cathode with high-frequency pulse exerted between the cathode and anode, and the propellant injected into the chamber is drastically ionized by electrons emitted from these spots. During the arc transition step, whose duration may be associated with discharge current value, propellant type and applied magnetic field strength, highly unstable arc spots remain on the cathode surface, accompanied by fluctuations of discharge voltage and current. These
fluctuations tend to disappear when the cathode becomes hot enough for thermionic emission to support current conduction, which indicates the establishment of a stable diffuse arc attachment and the end of the start-up phase.

To clarify the ignition processes of AF-MPD thrusters and the influences of applied magnetic field strength, discharge current value, and propellant type on these procedures, a series of ignition tests have been carried out. The applied magnetic field strength involved is in the range of 0.25 T, whereas the discharge current is 130-190 A. Specifically, the applied magnetic field strength utilized in each test is 0, 0.03 T, 0.075 T, 0.125 T, 0.155 T, 0.2 T or 0.25 T, whereas the discharge current is 130 A, 145 A, 175 A or 190 A. Besides, either argon or nitrogen was adopted in the test, and the mass flow rate for argon is 65 mg/s while that for nitrogen is 32 mg/s. Moreover, the thruster was allowed to cool down to the environmental temperature before next ignition in all the tests to exclude the interference of electrode temperature.

Fig. 2 depicts typical discharge voltage and current transition curves during the ignition phase of the AF-MPD thruster used. It can be seen that the arc did undergo a quite severe fluctuation and transition process before it stabilized. Besides, the successfullness of each ignition test was recorded and is displayed in Fig. 3. It is shown that the thruster cannot be ignited successfully under low discharge currents when the applied magnetic field strength is zero and argon is used as the propellant. However, successful ignitions can be achieved when external magnetic field is applied or the discharge current is increased, which indicates that applied magnetic field and high discharge current can contribute to the breakdown of neutral gas and the establishment of arcs. Moreover, successful ignitions were obtained in all the tests with nitrogen under given operation conditions. A possible explanation is that the mass flow rate of nitrogen used in these tests is smaller than that of argon, thus leading to a declining need for energy to ionize neutral gas and establish arcs.

Durations of arc transition under different magnetic field strengths, discharge currents and propellant types are shown in Fig. 4. As for tests with argon, the duration of arc transition fluctuates with applied magnetic field strength, which indicates two opposite effects of applied magnetic field on arc transition. On one hand, the application of magnetic field can accelerate arc transition process by increasing input power, speeding up the heating of cathode,
and causing more regular movement of cathode spots;\textsuperscript{21,22} on the other hand, however, magnetic field may obstruct arc transition by confining plasmas and leading to the starvation of current carrying particles near the anode. The interactions of these two opposite effects lead to the fluctuations of arc transition duration.

As for tests with nitrogen, however, the duration of arc transition generally decreases with increasing applied magnetic field strength instead of fluctuating. This is because the mobility of nitrogen ions is better than that of argon ions owing to the difference of mass, thus making it harder for the magnetic field to confine nitrogen ions. That is to say, applied magnetic field strengths utilized in current tests are still not high enough to exert effective confinement of nitrogen ions, and the positive effects of applied field on arc transition overweight its negative effects under given operation conditions.

Moreover, the duration of arc transition does not show strong dependence on discharge current when nitrogen is used as the propellant under given operation conditions.

B. Discharge Voltages after Stabilization

To better understand the effects of operation parameters on ignition processes, discharge voltages after stabilization of each test were also recorded, as depicted in Fig.5. We can see that the discharge voltage generally increases with increasing applied magnetic field strength, which indicates that more energy is input into the thruster with larger magnetic field strength. This will speed up the heating of electrodes and accelerate the arc transition process, which validates the discussions about arc transition durations above.

![Figure 4. Duration of arc transition under different operation conditions.](image1)

![Figure 5. Discharge voltage under different operation conditions.](image2)
IV. Conclusion

Experimental investigations were carried out to analyze the ignition processes of a steady-state radiation-cooled AF-MPD thruster, and to clarify the influences of applied magnetic field strength, discharge current value, and propellant type on these processes. The applied magnetic field strength involved is in the range of 0-0.25 T, whereas the discharge current is 130-190 A. Besides, either argon or nitrogen was adopted in each test, and the mass flow rate for argon is 65 mg/s whereas that for nitrogen is 32 mg/s.

It was found that the thruster cannot be started successfully under low discharge currents when the applied magnetic field strength is zero and argon is used as the propellant. However, successful ignitions can be achieved when external magnetic field is applied or the discharge current is increased, which indicates that applied magnetic field and high discharge current can contribute to the breakdown of neutral gas and the establishment of arcs. Moreover, successful ignitions were obtained in all the tests with nitrogen under given operation conditions.

Durations of arc transition under different magnetic field strengths, discharge currents and propellant types were recorded and compared. As for tests with argon, the duration of arc transition fluctuates with applied magnetic field strength, which indicates two opposite effects of applied magnetic field on arc transition. As for tests with nitrogen, however, the duration of arc transition generally decreases with increasing applied magnetic field strength instead of fluctuating. Moreover, the arc transition duration does not show strong dependence on discharge current when nitrogen is adopted as the propellant under given operation conditions.

In the end, discharge voltages after stabilization of each test were displayed. It is shown that discharge voltage generally increases with increasing applied magnetic field strength, which indicates that more energy is input into the thruster with larger magnetic field strength.

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