

Video Article

A 100 KW Class Applied-field Magnetoplasmdynamic Thruster

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Abstract

Applied-field magnetoplasmdynamic thrusters (AF-MPD thrusters) are hybrid accelerators in which electromagnetic and gas dynamic processes accelerate plasma to high speed; they have considerable potential for future space applications with the significant advantages of high specific impulse and thrust density. In this paper, we present a series of protocols for designing and manufacturing a 100 kW class of AF-MPD thruster with water-cooling structures, a 130 V maximum discharge voltage, a 800 A maximum discharge current, and a 0.25 T maximum strength of magnetic field. A hollow tantalum tungsten cathode acts as the only propellant inlet to inhibit the radial discharge, and it is positioned axially at the rear of the anode in order to relieve anode starvation. A cylindrical divergent copper anode is employed to decrease anode power deposition, where the length has been reduced to decrease the wall-plasma connecting area. Experiments utilized a vacuum system that can achieve a working vacuum of 0.01 Pa for a total propellant mass flow rate lower than 40 mg/s and a target thrust stand. The thruster tests were carried out to measure the effects of the working parameters such as propellant flow rates, the discharge current, and the strength of applied magnetic field on the performance and to allow appropriate analysis. The thruster could be operated continuously for significant periods of time with little erosion on the hollow cathode surface. The maximum power of the thruster is 100 kW, and the performance of this water-cooled configuration is comparable with that of thrusters reported in the literature.

Video Link

The video component of this article can be found at <https://www.jove.com/video/58510/>

Introduction

MPD thrusters are well known for a relatively high thrust density and a high specific impulse^{1,2,3}. However, the typical thrust efficiency¹ of MPD thrusters is relatively low, especially with propellants of noble gases^{4,5,6}. For most MPD thrusters, a part of the propellant flow is injected into the discharge chamber from a slit between anode and cathode^{7,8}, with the result that a radial component is a significant proportion of the total discharge. However, in order to generate thrust, radial kinetic effects need to be converted into axial kinetic motion with a physical nozzle or a magnetic nozzle. Accordingly, a key feature of the new design MPD thruster is that all propellant is supplied through the cathode, which can act to inhibit radial discharge; in this way, the proportion of axial energy can be increased. There is an added effect in that the Hall parameter in the plasma around the anode can be increased by the decrease of the number density around the anode, which can strengthen the Hall acceleration component⁹. Since the propellant is close to the inner surface of the cathode where large quantities of initial electrons are emitted in this mode of injection, the propellant ionization rate can be increased greatly. Furthermore, the anode length has been minimized to decrease the wall-plasma connecting area and reduce anode power deposition^{10,11}. As a divergent anode is applied, this will decrease the angle between the anode and magnetic field lines and decrease anode power deposition further^{12,13}.

Despite the advantages noted above to improve performance, complete propellant supply by cathode injection can increase the risk of anode starvation which can result in "onset" phenomena¹⁴. To inhibit this behavior, we have retracted the cathode back to the base of anode. The electrons can then diffuse sufficiently in the radial direction before leaving the anode exit, which will act to relieve anode starvation. Further, a multichannel hollow cathode is adopted; compared to the single channel hollow cathode, a multichannel hollow cathode can increase the electron emission area and make the distribution of the propellant more uniform. With this modification, both the lifetime and stability of the thruster can be increased^{15,16,17}.

The designed power of the thruster is 100 kW and a cooling structure is necessary with steady state operation. In the present laboratory experiments, an efficient water-cooling structure is employed. However, to evaluate the performance of the MPD thruster design, it is critical to obtain the thrust. With the application of a high-pressure water system to transfer heat, there will be strong vibration during the operation of such

cooling, which can create significant interference if we used traditional thrust measurements. Accordingly, a target thrust stand is employed to measure the thrust.

MPD Thruster

As shown in **Figure 1**, the MPD thruster consists of anode, cathode and insulator. The anode is made of copper with a cylindrical divergent nozzle, the minimum inner diameter of which is 60 mm. There is an S-shaped cooling channel around the inner wall of the anode. The inlet and outlet of the channel are on the top of the anode, which are separated by a baffle. A slender copper block is employed to connect the anode and electric cable. The junction is on the outer surface of the anode.

The cathode material is tantalum tungsten, with nine propellant channels. The outer diameter of the cathode is 16 mm. The cooling of the cathode is achieved with a water-cooling holder around the cathode base. There is a ring-shaped channel inside the holder. The cold water is injected into the holder from the bottom and flows out from the top. There is a hollow cathode connector on the left side of the cathode. The propellant flows through the center of the connector and into the hollow cathode chamber; there is a large cavity inside the cathode base connecting with nine narrow cylindrical channels. The cavity acts as a buffer to increase the uniformity of the propellant distribution in nine channels. The cathode is connected to the electric cable with an annular copper block, which is installed around the cathode connector.

In addition to the main body of the thruster, an external magnetic coil is also necessary to generate fields for the mechanisms in the AF-MPD thruster; magnetic fields provide a convergent-divergent magnetic field to accelerate the plasma together with the electric field. The field coil consists of 288 turns of circular copper pipes, which act as the passage for both electric current and cooling water. The inner diameter of the coil is 150 mm, while the outer diameter is 500 mm. The highest field strength in the center is 0.25 T with current of 230 A.

Experiment System

The experiment system includes six subsystems. The schematic diagram of the overall layout of the experimental system is shown in **Figure 2**; the layout of the thruster inside the vacuum chamber is shown in **Figure 3**.

First, the vacuum system, which provides the necessary vacuum environment for the thruster operation, consists of one vacuum chamber, two mechanical pumps, one molecular pump and four cryogenic pumps. The diameter of the chamber is 3 m, and the length is 5 m. The environment pressure can be maintained under 0.01 Pa when the flow rate of (argon) propellant is no more than 40 mg/s.

Second, this source system provides a high voltage pulse to ignite the thruster, provides power for the thruster to accelerate the plasma, and provides power for the magnetic field coil to sustain the external magnetic field. The power source system consists of an ignition power source, a thruster power source, a coil power source and cables. The ignition power source can provide 8 kV or 15 kV discharge voltage. The thruster power source provides a direct current up to 1000 A. The coil power source provides a direct current up to 240 A.

Third, the propellant supply system feeds gas propellant for thrusters. The system mainly includes the gas source, the mass flow rate controller and gas supply pipelines.

The fourth sub-system is the water-cooling system, which provides cool high-pressure water to exchange the heat of the thruster, magnetic coil and power sources. As shown in **Figure 4**, the system consists of pumps group, water tank, refrigerator, water supply pipelines and pumps controllers. The non-conducting pipes inside the vacuum chamber provide a cooling water terminal for the thruster and magnetic coil, and ensures that electrical insulation among the anode, the cathode, and the ground.

The acquisition and control system can record the signals measuring thruster operation conditions and control operation of other systems. It is composed of three computers and corresponding software, data acquisition card and cables.

As shown in **Figure 5**, the target thrust stand consists of plate target, slender beam, displacement sensor, support frame, axial moveable platform and radial moveable platform. The target can intercept the plasma which pushes the target. The displacement of the target can be measured by a sensor placed behind the target, in this way enabling evaluation of the thrust¹⁸.

Protocol

1. Preparation for experiment

1. Install the thruster.
 1. Wipe the components of the thruster with non-dust cloth, soaked with anhydrous alcohol, in a clean room.
 2. Assemble the anode with the insulator.
 3. Bring together the cathode, cathode holder and cathode connector.
 4. Add the cathode part to the anode part.
 5. Install the middle connector into the assemblage and fix them with screws (hexagon socket head screw, M5×16).
 6. Establish the coil seat on experiment platform with forklift.
 7. Place the experiment platform on guide rail of the vacuum chamber.
 8. Install the thruster on the coil.
 9. Link the anode and cathode with corresponding electric cables.
 10. Link the magnetic coil with the coil power source.
 11. Join up the water-cooling pipes and propellant supply pipe with the thruster.
 12. Join up the water-cooling pipes with the coil.
 13. Install the moveable platform inside the chamber and fix the main body of thrust stand on it.

14. Adjust the position of the radial moveable platform to make the control lines of the thruster and the target coincide with each other.
2. Calibrate the thrust stand.
 1. Load different weights (10 g, 50 g, 100 g, 200 g), one by one, on the calibration device and record the corresponding output of the thrust stand.
 2. Unload the weights one by one.
 3. Repeat the process for three times at least.
 4. Calculate the elastic coefficient of the thrust stand according to the calibration data.
3. Evacuate the vacuum chamber.
 1. Close the door of the chamber.
 2. Start the mechanical pumps.
 3. Start the molecular pumps when the background pressure in the chamber is lower than 5 Pa.
 4. Start the cryogenic pumps when the background pressure in the chamber is lower than 0.05 Pa.
 5. Wait for the pressure to reach 1×10^{-4} Pa.

2. Ignition and Thrust Measurement Experiment

1. Preheat the thruster if it has been exposed to the air.
 1. Start recording the signal.
 2. Set the propellant mass flow rate at 40 mg/s and keep supplying for at least 20 minutes
 3. Turn on the cooling water supply.
 4. Set the working frequency of cooling water pumps at 10 Hz.
 5. Move the thrust stand to the position far from the thruster.
 6. Switch on the coil power source with the coil current of 90 A.
 7. Switch on the thruster power source with the discharge current of 240 A.
 8. Switch on the ignition power source.
 9. Keep the thruster working for at least 5 minutes.
 10. Switch off the thruster power source and propellant supply.
 11. Stop the recording.
2. Thrust measurement
 1. Move the thrust stand to the position 550 mm from the thruster.
 2. Start recording the signal.
 3. Start the propellant supply.
 4. Ignite the thruster with 90 A coil current and 240 A discharge current.
 5. Increase the coil current to 150 A.
 6. Increase the discharge current to 800 A.
 7. Increase the coil current to 230 A.
 8. Switch off the thruster when the output of thrust stand becomes stable.
 9. Stop the propellant supply.
 10. Stop the recording.

Representative Results

In the experiment, we control discharge current (I_d), propellant mass flow rate ($\dot{m}$) and applied magnetic field (B_a). In operation, we measure the value of discharge voltage (V_d) and thrust (T), from which base we can get other performance parameters like power (P), specific impulse (I_{sp}) and thrust efficiency (η)¹.

A typical signal of discharge voltage is shown in **Figure 6**. Upon initiation of the power source, there will be an open-circuit voltage between the anode and cathode, the value of which is about 230 V. This open-circuit voltage is not high enough to break down the neutral propellant in the discharge chamber; we need to apply a high frequency discharge voltage to ignite the thruster. After ignition, the voltage will decrease rapidly; then the voltage trends to a constant value after a period of oscillation.

A typical thrust measurement result is shown in **Figure 7**. We start recording the signal of the thrust stand before initiating supply of the propellant, which is treated as zero-thrust point. There will be a weak thrust after beginning supply of the propellant. After thruster ignition, there will be a large signal with oscillations, after which the thrust trends to steady value. Then we turn off the thruster. There will be a zero-drift due to the thermal deformation of the target; the error caused by this effect will be no more than 1%.

Figure 8 shows the Influence of discharge current, applied field and propellant mass flow rate on thrust for arc power up to 25 kW. We choose: $I_d = 200$ A, $B_a = 100$ mT, $\dot{m} = 40$ mg/s, as a basic operation condition; a series of experiments are conducted to compare with the basic data. Only one operation parameter will be changed in each contrast experiment: the discharge current can be varied from 160 A to 360 A; the applied field strength can be varied from 34 mT to 258 mT; the propellant mass flow rate can be varied from 20 mg/s to 80 mg/s. For the convenience of comparison, we normalize these three operation parameters, as shown in the bottom x-axis in **Figure 8**. When normalized operation parameters are 1.0, it means the operation conditions are the same as the basic one. Along with the bottom x-axis, there are three more x-axes on the top, which correspond to the original values of the three parameters, respectively.

Figure 9 shows the discharge characteristics during a half-hour of continuous operation. It can be seen that the thruster trends to a steady state rapidly after ignition, and the voltage is stable during this period.

Figure 10 presents photographs of the tantalum tungsten cathode before and after tests. The total runtime of the tests was 10 h, including one half-hour continuous operation and short time testing for more than 90 starts. It can be seen that the erosion is slight and distributed uniformly on the outer surface of the cathode. According to this result, the thruster has the potential to operate for a long time.

Following the continuous operation tests, we explored the performance of the thruster in the power range of 50-100 kW. The thrust was measured with the target thrust stand, and the measurement results are shown in **Figure 11**. The best performance is obtained at 99.5 kW, where the thrust is 3052 mN, specific impulse is 4359 s and thrust efficiency is 67%. In addition, a theoretical thrust value was calculated, as in Eq. 1 (Mikellides¹²), to compare with measured thrust values; the largest difference between them was 11.6%.

$$T = \frac{25}{A^{0.25}} \sqrt{\frac{a}{\bar{\phi}}} \frac{R(R+1)\sqrt{R-1}}{\sqrt{R^{3.8}-1}} \sqrt{\dot{m}IB} \quad (1)$$

(a is cathode radius to electrode length ratio; R is electrode radius ratio; A is atomic weight in atomic mass unit and $\bar{\phi}$ is the ionization factor¹².)

Effect of thruster optimization

The resulting values of thrust in response to variation of system parameters is shown in **Figure 8**, where it can be seen that the influence of propellant mass flow rate on the thrust is similar to that of applied field. As gas dynamic acceleration¹⁹ is sensitive to $\dot{m}$, it can be concluded that the gas dynamic acceleration component is enhanced in our thruster. Moreover, the discharge current and applied field affect the electromagnetic acceleration in several different mechanisms and their influence should be evident¹. In our experiments, the thrust is significantly more sensitive to an increase of discharge current as compared with that of the applied field, as shown in **Figure 8**. One aspect of this behavior may be due to strengthening gas dynamic effects from increasing axial discharge current owing to the specific propellant supply mode through the cathode. Further, as shown in **Figure 11**, the MPD thruster reaches a highest thrust efficiency of 67%, which is comparable to the superior efficiency of MPD thrusters with propellant of alkali metal²⁰. Thus, the effects of the design changes are seen to improve the performance of MPD thruster significantly.

Additionally, despite the fact that there is no anode region propellant supply, our thruster had stable operation at a discharge current of 800 A and propellant supply rate of 70 mg/s. By comparison, the MPD thruster SX3²¹ with partial propellant supply from the anode, reached an onset regime at a discharge current of 500 A and propellant supply rate of 60 mg/s. Based on the stability of an MPD thruster with critical value $I^2/\dot{m}$ ²², the present thruster is slightly superior to SX3.

Target thrust measurement errors

With the target thrust measurement, it is necessary to avoid overestimation of the thrust at the highest performance operation. Here we assume that the collision between the target and the heavy particles in the plasma is perfectly elastic. Thus, the half of measured thrust is taken as the true thrust. Moreover, in the flow of propellant to the target, we assume that the plasma is completely constrained by the magnetic field. We chose the magnetic field lines that pass through the outer range of the anode as the boundary of magnetic nozzle. Assuming that the plasma particles are distributed uniformly in the nozzle, as shown in **Figure 12**, we can get the range of the plasma at the target plane, which is 704 mm in diameter. Then the relationship between the measured thrust and true thrust can be expressed as:

$$T = \frac{F}{2} \cdot \left(\frac{704}{600}\right)^2 = 0.69F \quad (2)$$

where F is the measured thrust by the target and T is the true thrust.

Further, due to the barrier behavior of the target, propellant particles may flow back into the discharge chamber. Assuming that all particles are released from the center of the target, as shown in **Figure 13**, and that the distributions of back-flow particles obey the cosine law²³, then the proportion of reentry particles can be evaluated with Eq. 3. If the back-flow particles distribute uniformly in all directions of space, the proportion will be expressed with Eq. 4. The variations of the proportions with the target-thruster distance z , under two distribution assumptions, are listed in **Figure 14**. In the thrust measurement, the target-thruster distance was 550mm; thus, the proportion of reentry particles was calculated to be no more than 0.3%.

The background pressure can also influence the measured thrust performance. When the thruster reaches the highest performance, the background pressure in the system can be maintained at 0.2 Pa with the mass flow rate of 70 mg/s. However, the measured thrust may be higher than the actual value because of the influence of this high background pressure^{20,24,25}. To eliminate this possible influence the pump speed of the vacuum system should be increased, and this is a planned upgrade.

The target is made of electric conductive material, and it is insulated from the ground during thrust measurement. However, there is an outflow current in the plume that may interact with the target and influence the behavior for the MPD thruster measurement¹⁵. This can be a factor influencing the magnitude of thrust efficiency and is worthy of further consideration.

$$P_{Cos} = \frac{R_a^2}{z^2 + R_a^2} \quad (3)$$

$$p_{U_{\text{fil}}} = 1 - \frac{z}{\sqrt{z^2 + R_d^2}} \quad (4)$$

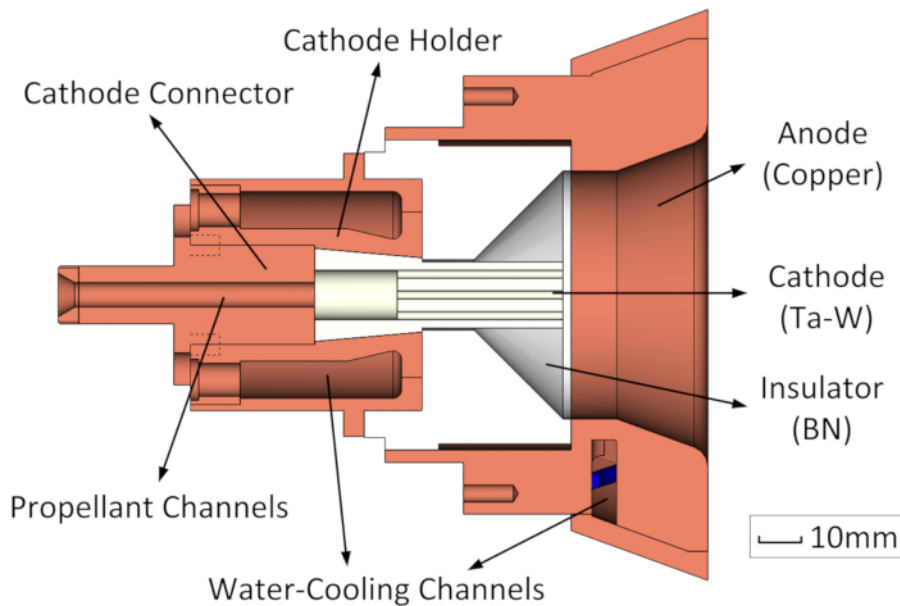


Figure 1. Schematic diagram of the AF-MPD thruster

The main body of the MPD thruster includes anode (copper), cathode (tantalum tungsten), insulator (boron nitride), cathode holder (copper) and cathode connector (copper). [Please click here to view a larger version of this figure.](#)

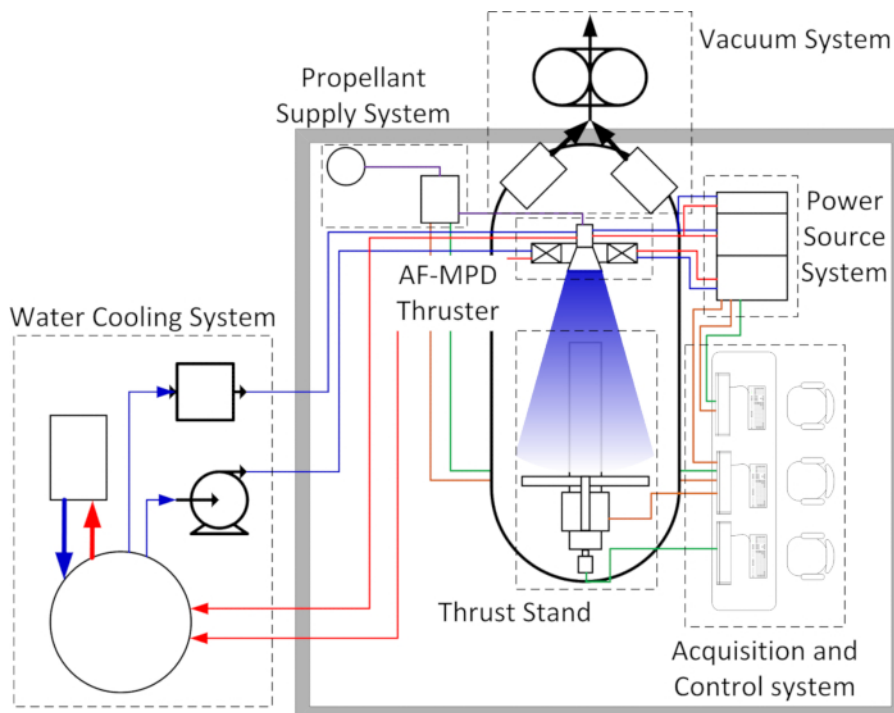


Figure 2. Schematic diagram of experiment system

Blue lines in water cooling system: high pressure cold water; red lines in water cooling system: heated water. Green lines in acquisition and control system: signals of operation parameters; brown lines in acquisition and control system: signals of control instructions. Blue lines in power source system: wires connecting to the anode of thruster and magnetic coil; red line in power source system: wires connecting to the cathode of thruster and magnetic coil. Blue trapezoid in the middle: beam of the thruster. [Please click here to view a larger version of this figure.](#)

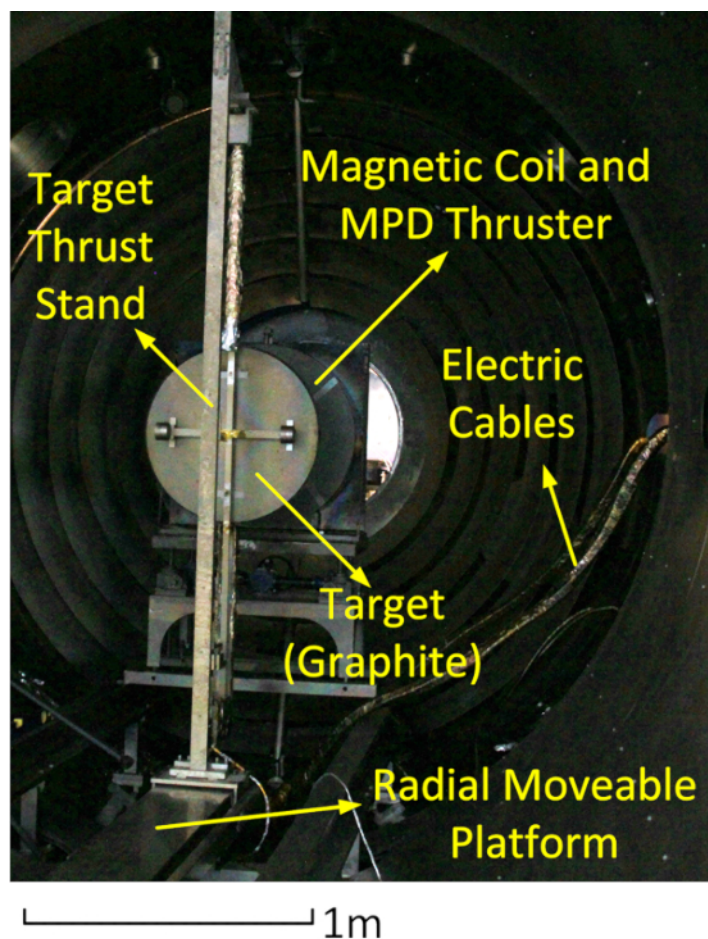


Figure 3. Experiment layout inside the vacuum chamber

The thruster is positioned inside the magnetic field coil. The coil is behind the target thrust stand; thus, the thruster view is obstructed by the target from the visual angle in the figure. [Please click here to view a larger version of this figure.](#)

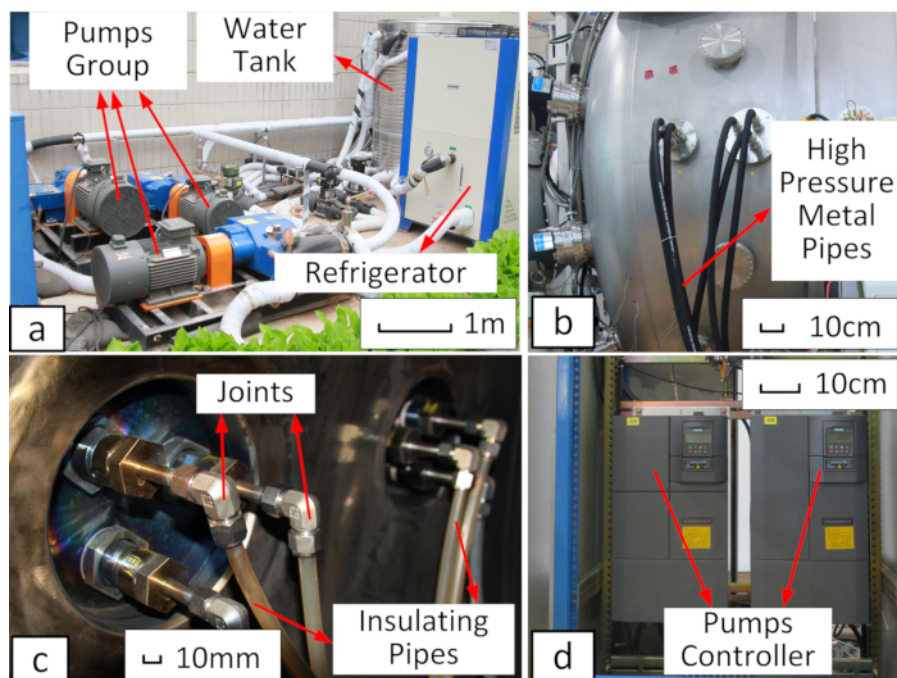


Figure 4. Water cooling system

(a) Pumps group, water tank and refrigerator (placed outside the laboratory). (b) High pressure metal pipes supplying the cooling water (outside the vacuum chamber). (c) Joints and insulating pipes supplying cooling water for electrodes and magnetic coil (inside the vacuum chamber). (d) Pumps controllers set the flow rate of the water pumps. [Please click here to view a larger version of this figure.](#)

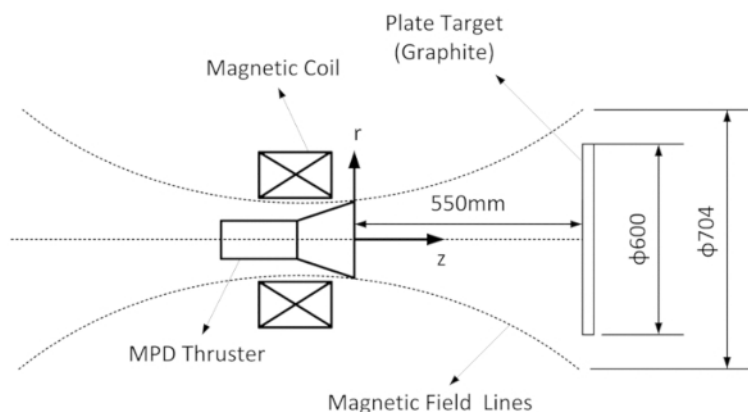


Figure 5. Target method thrust stand

The central line of the thruster and the target are coincident with each other. The axial position of the target can be adjusted with the moveable platform. [Please click here to view a larger version of this figure.](#)

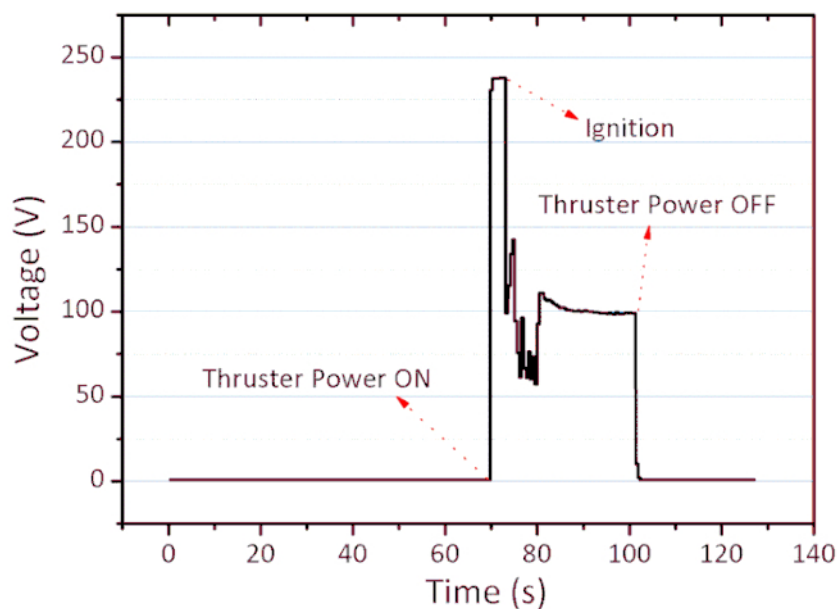


Figure 6. Typical discharge voltage for the thruster

Discharge current of 240 A, applied field of 258 mT, propellant mass flow rate of 40 mg/s. [Please click here to view a larger version of this figure.](#)

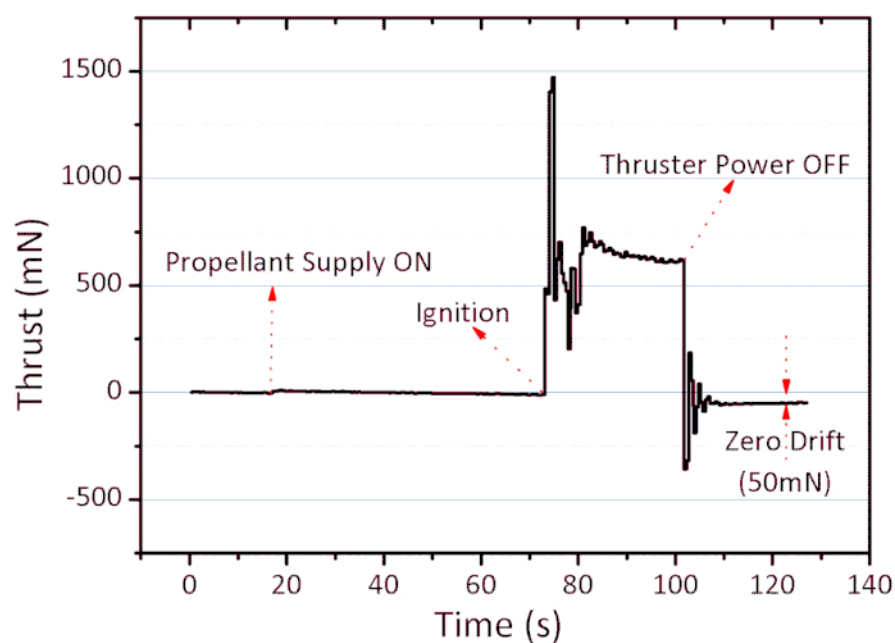


Figure 7. Typical thrust measurement signal

Discharge current of 240 A, applied field of 258 mT, propellant mass flow rate of 40 mg/s. [Please click here to view a larger version of this figure.](#)

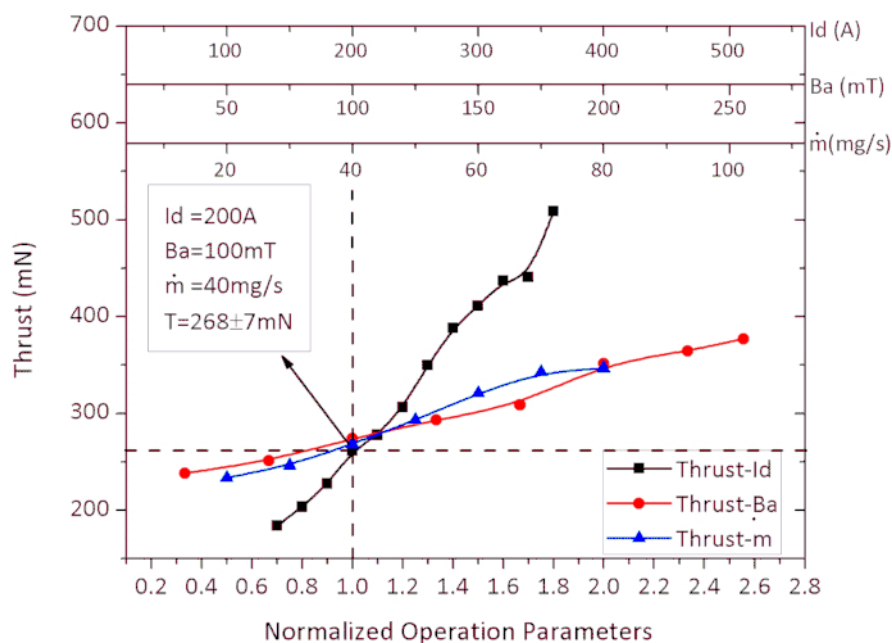


Figure 8. Influence of discharge current, applied field and propellant mass flow rate on thrust, with arc power up to 25 kW. Abscissa at the bottom represents the normalized operation parameters including: I_d (discharge current), B_a (applied magnetic field strength) and $\dot{m}$ (propellant mass flow rate) with $I_d = 200$ A, $B_a = 100$ mT, $\dot{m} = 40$ mg/s selected as basic operation conditions, corresponding to the value of 1 on the bottom abscissa. Abscissas on the top correspond to the original values of the three parameters. [Please click here to view a larger version of this figure.](#)

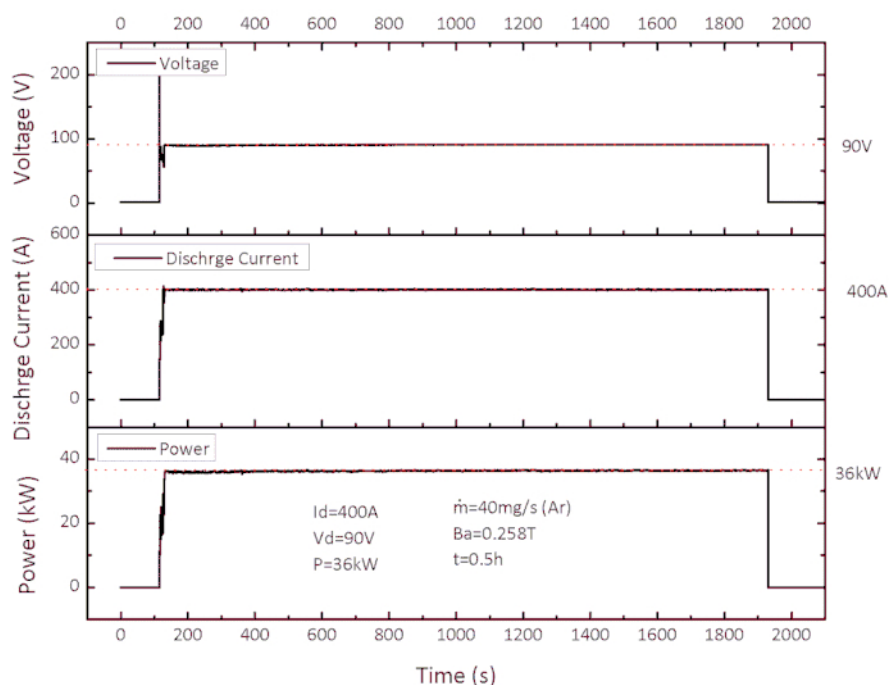


Figure 9. Continuous operation current and voltage for arc power of 36 kW Three solid lines are output signals for discharge voltage, discharge current and calculated arc power, respectively. [Please click here to view a larger version of this figure.](#)



16mm

Initial Cathode After Working of Total 10 Hours

Figure 10. Initial cathode appearance and cathode after operation for total 10 hours.

The left side of the figure shows the image of tantalum tungsten hollow cathode before undergoing discharge; the right side shows the cathode after a total of 10 hours under discharge. [Please click here to view a larger version of this figure.](#)

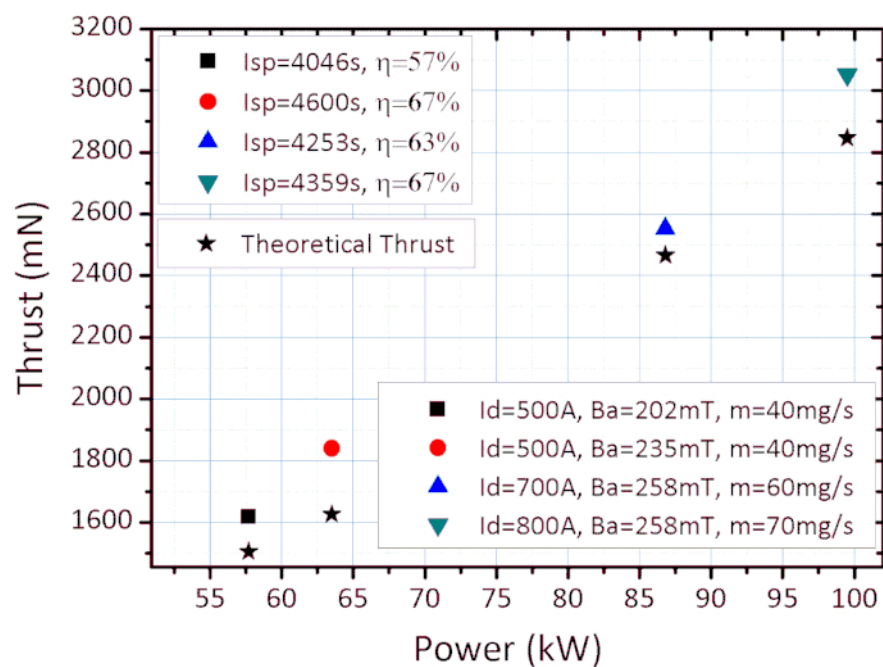


Figure 11. Performance of the thruster in the power range of 50-100 kW

Points with star symbols are values of thrust calculated by thrust formula¹². Other symbols are values of thrust measured with the target thrust stand. [Please click here to view a larger version of this figure.](#)

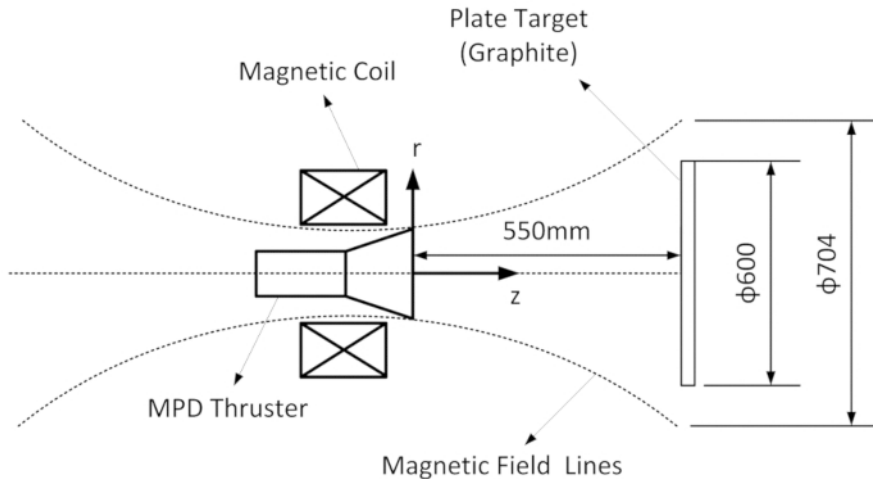


Figure 12. Schematic of size of the target compared to the geometry of the magnetic field

The dotted lines represent magnetic field lines through the outer range of the anode. The magnetic field within the dotted lines can form a slender magnetic nozzle in the space. The diameter of the nozzle is 704 mm at the target plane, which is 550 mm from the thruster in the experiment. [Please click here to view a larger version of this figure.](#)

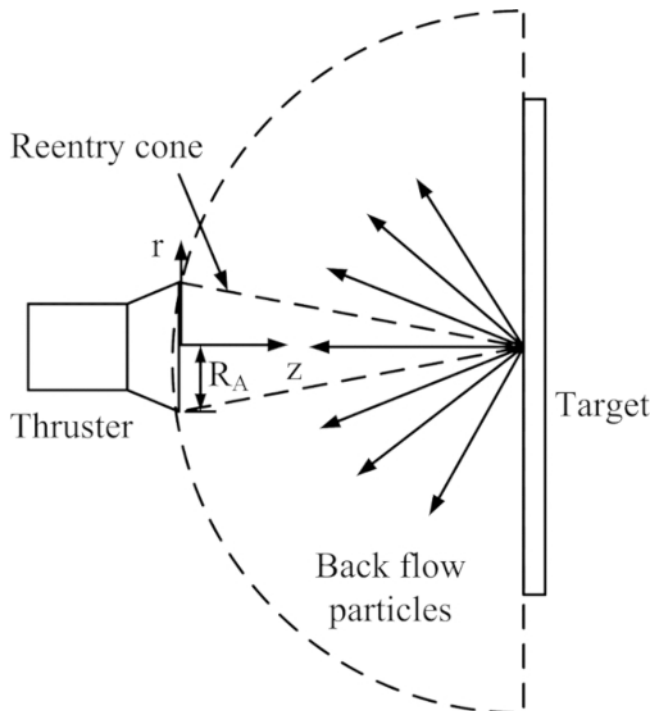


Figure 13. Schematic of back flow particle dynamics

The radiated arrows from the target represent rebound particles from the center of the target. Here we assume that all particles rebound from the central point of the target. This assumption will overestimate the calculation of the proportion of reentry particles. [Please click here to view a larger version of this figure.](#)

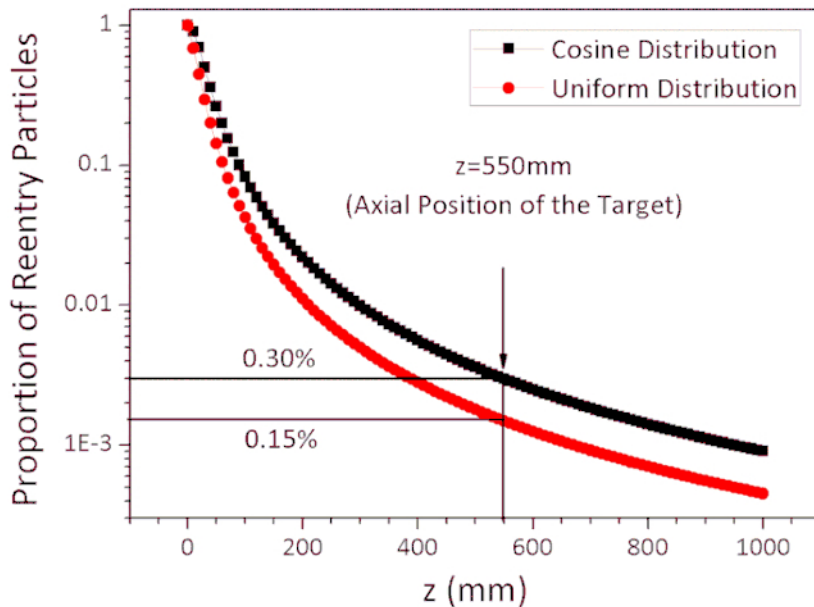


Figure 14. Percentage of backflow propellant into the discharge chamber

The line with symbols of squares represents the proportion of reentry particles based on the assumption that the backflow particles obey a cosine distribution. The line with diamond symbols represents that from a uniform distribution. The abscissa is the distance between the target and the anode exit. [Please click here to view a larger version of this figure.](#)

Discussion

This protocol describes the processes of ignition, operation, and thrust measurement of a 100 kW class applied field MPD thruster. The key point in designing an MPD thruster for optimum performance is choosing the proper configuration according to the specific objective. MPD thrusters with convergent-divergent anode can function steady-state in a large operation range. However, the performance may be lower than the thruster with divergent anode. The hollow cathode, especially the multichannel hollow cathode, is superior to a traditional rod cathode in most aspects. Application of the hollow cathode is beneficial for improving thruster performance, and it provides choices for propellant supply modes. Manufacturing cost of a hollow cathode is relatively high compared with a solid cathode.

A fluid circuit cooling structure is necessary for operation of the thruster if it is designed to work for more than 10 minutes. Alternatively, radiation cooling is another choice²⁶, which can avoid complex coolant piping. However, this may cause a large radial size of the thruster. Furthermore, a heat pipe can be another choice when employed in actual space mission.

An external magnetic field is indispensable for the AF-MPD thruster. The field can be provided by a traditional solenoid coil, as described in the protocol, or a permanent magnet. In addition, superconductivity is a potential candidate, which can provide much stronger magnetic field than traditional coil and the mass of which is also less than the traditional solenoid coil.

To hold the thrust measurement experiment, the background pressure should be lower than $0.013\text{--}0.13\text{ Pa}^1$. Otherwise, the operation of the thruster may be influenced. In addition, according to research²⁷, there are outflow currents in the plumes of MPD thrusters and the furthest current can reach the position 90 cm from the thruster in axial direction. Thus, increasing the size of the chamber is beneficial for decreasing the influence of the facility on the thruster.

Disclosures

The authors have nothing to disclose.

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