Performance Characteristics of a DME Propellant Arcjet Thruster

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This paper describes the influence of cathode configuration on performance of an arcjet thruster using dimethyl ether (DME) propellant. DME, an ether compound, has suitable characteristics for a space propulsion system; DME is storable in a liquid state without being kept under a high pressure, and requires no sophisticated temperature management such as a cryogenic device. DME can be gasified and liquefied simply by adjusting temperature whereas hydrazine, a conventional propellant, requires an iridium-based particulate catalyst for its gasification. In this study, thrust of a 1-kW class DME arcjet thruster is measured at a discharge current of 13 A, DME mass flow rates ranging 15 to 60 mg/s under three cathode configurations: flat-tip rods of 2 and 4 mm in diam. and 4-mm-diam. rod having a cavity of 2 mm in diameter. Thrust measurements show that thrust is increased with propellant mass flow rate. Among the tested cathodes, the flat-tip rod of 4 mm in diam. with 55 mg/s DME flow rate yielded the highest performance: specific impulse of 330 s, thrust of 0.18 N, discharge power of 1400 W and specific power of 25 MJ/kg.

Key Words: Electric Propulsion, Arcjet Thruster, Dimethyl Ether, Cathode, Thrust Measurement

Nomenclature

- \( d_c \) : outer diameter of cathode
- \( I_d \) : discharge current
- \( P_c \) : plenum chamber pressure
- \( T \) : thrust
- \( V_d \) : discharge voltage

1. Introduction

Among electric propulsion devices, arcjet thrusters have higher thrust-to-power ratios and specific impulses than chemical thrusters. Arcjets have been applied in various missions including North-South station keeping1-3); Telstar-401 with 1.8 kW class arcjets launched in 19934); Kodama, a Japanese data-transmitting satellite launched in 2002, had arcjet thrusters5). Currently, hydrazine is mainly used as a propellant because it can be shared with chemical thrusters. The propellant can be decomposed into gases such as ammonia, nitrogen, and hydrogen using iridium-based particulate catalyst. Because the decomposed gas has a relatively low molecular weight, a hydrazine arcjet thruster provides a comparatively high specific impulse. MR-510, a thruster of this type manufactured by Aerojet, yielded a specific impulse of 580 s with a discharge power of 2.2 kW6). Hydrazine can be stored in a liquid state without cryogenic device.

On the other hand, hydrazine has a freezing point of 1 °C and hence requires temperature management. Materials for tanks and tubes should be compatible with this propellant due to its strong reactivity. Gas treatment systems are required for ground tests because of its strong toxicity. Increased temperature would deteriorate iridium-based particulate catalysts.

Diverse propellants such as ammonia, and hydrogen were utilized for arcjet thrusters. Hydrogen not only requires complex storage systems such as cryogenic device but also embrittles materials including metals and rubbers, although the lowest atomic weight can yield the highest specific impulse. Ammonia, a hydrogen-rich molecule, can yield a comparatively high specific impulse. On the other hand, it has a pungent odor and is reactive to most metals because of its alkalinity.

The authors propose to use dimethyl ether (DME) as a propellant for arcjet thrusters7). DME, an ether compound, has the molecular formula CH₃-O-CH₃; it has a structure where two carbon atoms are bonded through an oxygen atom, permitting relatively low-cost materials such as stainless steel or Teflon®. The 6-atm vapor pressure, enabling self-pressurization in tanks, allows us to make tanks, storage and delivery devices with low soot production in chemical reactions. Its freezing and boiling points are -154 and -54 °C at 1 atm, respectively, and a vapor pressure is 6 atm at room temperature8). These features enable not only gasification simply by adjusting temperature without a catalyst but also liquid-form storage in satellites without complex temperature management.

DME, which has relatively low toxicity and reactivity, requires no exhaust gas treatment system for ground testing, and allows us to make tanks, storage and delivery devices with relatively low-cost materials such as stainless steel or Teflon®. The 6-atm vapor pressure, enabling self-pressurization in tanks, eliminates not only a pressurant such as nitrogen or helium, but also its storage devices. At present, DME is more readily available because many studies and development activities related to its synthesis, storage, and transportation have enhanced the efficiency of its production and distribution, reducing its cost. This ether is now applied to industrial uses as diesel fuel and coolant. From this viewpoint, DME has various characteristics preferred for an arcjet thruster propellant.

Our research shows that a designed 1-kW class DME arcjet thruster successfully produced arc plasmas at mass flow rates and discharge currents that are comparable to those of...
conventional arcjet thrusters\textsuperscript{7}. Discharge voltage, power, and plenum chamber pressure for DME are higher than those for nitrogen at each mass flow rate or discharge current. The DME arcjet thruster also exhibits both high- and low-voltage modes. Thrust was measured with a vertical thrust stand using a torsional spring to evaluate discharge power, thrust, specific impulse, and thruster efficiency\textsuperscript{9,10}. In this study, a prototype 1-kW class DME arcjet thruster was tested to clarify the correlation between performance and cathode configuration at a discharge current of 13 A.

2. Experimental Apparatus

2.1. Designed thruster

Figure 1 and Table 1 show a schematic diagram of a prototype 1-kW class arcjet thruster and its configuration, respectively. Gaseous propellant, supplied from a DME port, goes through a gap between a feeder and a cylindrical ceramic insulator into a plenum chamber of 6 mm in diameter. Then, the propellant gas enters a tungsten nozzle having convergent and divergent angles of 15 and 45 deg with an expansion ratio of 100. The gap between the flat-tip cathode and the anode was kept at 1.0 mm in the present study. Afterwards, the plasma is expanded and expelled from the thruster.

2.2. Cathode configuration

Three types of cathode were tested in the current study. Figure 1 and Table 2 present cathode schematics and configuration, respectively. All types of cathode had a flat tip, whereas most arcjet thrusters have a conical cathode to enhance resistive heating in the neighboring arc plasma. Our previous study shows that conical cathodes reduce the reproducibility of experimental results for DME propellant\textsuperscript{7}; in some tests, stable arc plasmas were successfully produced for more than 60 s; whereas, in other tests plenum chamber pressure rose repeatedly and dropped even under the same experimental conditions. In the worst cases, arc discharge was autonomously interrupted within 5 s following ignition because of a sudden increment of plenum chamber pressure. In contrast, a flat tip cathode exhibited better reproducibility of experimental results compared to conical tip cathodes. Hence, in the study, flat tip cathodes were used to sustain stable arc discharge.

Flat 2- and flat 4-type cathodes have flat-tip thoriated tungsten rods of 2 and 4 mm in diameter. In a past study, a thruster using a flat 2-type cathode was tested to evaluate performance\textsuperscript{9,10}. Flat 4-type cathode was also used to investigate dependence on cathode diameter. A cavity-type cathode, with a 4-mm outer diameter thoriated tungsten rod having a 5-mm-depth 2-mm-diam. hole, was designed to prevent the constrictor from being choked by soot. Such a hollow-type cathode using a methane propellant was tested to reduce soot accumulation in the inter-electrode region\textsuperscript{11}.

2.3. Experimental setup

The designed arcjet thruster was tested in a cubic vacuum chamber with a 300 mm side. The vacuum chamber had vertical and horizontal cylindrical extensions. The vertical cylindrical extension holding a thrust stand increased the length of a thrust stand arm to improve measurement resolution and sensitivity. More detailed information on the thrust stand is given in the next section.

![Schematics of designed thrusters.](image-url)
In the current study, discharge current was fixed at 13 A. Discharge current was supplied with a current-stabilized regulator, suppressing its pressure to 4 atm, and then was fed to the horizontal extension cylinder, cooled with water, absorbed plume heat.

The vacuum chamber was evacuated by a rotary pump with an exhaust rate of 240-L/min. In the tests, back pressures of the vacuum chamber were kept below 2 kPa.

DME was stored in a pressure vessel in a vapor-liquid equilibrium state. Gaseous DME was supplied to a pressure regulator, suppressing its pressure to 4 atm, and then was fed to a mass flow controller (Kofloc, 3665) to maintain the required mass flow rates. Mass flow rate tested in the experiments are summarized in Table 3.

Discharge current was provided by the arcjet thruster. The high-temperature plume from the thruster negatively affects thrust measurement accuracy because additional heat causes thermal deformation of the vacuum chamber and the thrust stand. As a result, it gives a bias to the displacement of the thrust stand arm. During tests, the horizontal extension cylinder, cooled with water, absorbed plume heat.

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Discharge current was supplied with a current-stabilized power supply at a rated voltage and current of 120 V and 35 A. In the current study, discharge current was fixed at 13 A. Discharge voltage and current were measured using a resistive voltage divider and a Hall effect current sensor. The power supply provided a train of 10-kV peak voltage pulses for arc discharge ignition.

An RTAI/Linux personal computer with an analog interface board (Interface, PCI-3521) stored the displacement-sensor output for the thrust chamber arm, discharge current, voltage, plenum chamber pressure, and back pressure of the vacuum chamber at a sampling rate of 100 Hz. All the sensor outputs were smoothed using a resistive-capacitive low-pass filter with a cut-off frequency of 1000 Hz.

3. Results and Discussion

3.1. Time history

Figures 2 to 4 show time histories of discharge current, voltage, plenum chamber pressure, and thrust for flat2-, flat4-, and cavitary-type cathodes. Time origin \( t=0 \) represents the moment when arc discharge is initiated. Focusing on Fig. 2, at \( t=-9 \) s, plenum chamber pressure is increased soon after DME supply started. At \( t=0 \) s, an arc discharge is initiated by a train of high voltage pulses. Shortly after ignition, the thruster yields relatively intense fluctuations of discharge voltage, which subsequently become small. Whereas thrust and plenum chamber pressure exhibit variations accompanied by discharge voltage fluctuations, the arc discharge is successfully maintained without autonomous extinguishment. At \( t=40 \) s, the plenum chamber pressure rises due to the adhesion of agglomerated carbon to the electrodes. At \( t=62 \) s, thrust and plenum chamber pressure are decayed by interrupting the discharge current.

In the case of the flat 4-type cathode, the thruster exhibits a similar time history with an exception, as depicted in Fig. 3; for the first 5 s following ignition, the thruster showed a low-voltage mode, thereafter it maintained a high-voltage mode. Compared to the flat 2-type, the flat 4-type yields large-amplitude low-frequency ripples of discharge voltage. Thrust and plenum chamber pressure also vary with time in accordance with the variation of discharge voltage.

As illustrated in Fig. 4, the cavitary-type cathode, showing a low-voltage mode for the initial five seconds of arc discharge, finally yielded a high-voltage mode after gradually increasing discharge voltage. Although the high-voltage mode is
3.2. Dependence of discharge voltage and power on mass flow rate

Figure 5 illustrates the dependence of discharge voltage and power on mass flow rate. Plotted symbols express the average values, and error bars exhibit the standard deviations. The values are evaluated in the period between the start of high voltage mode and discharge-current interruption. For both the flat 2- and flat 4-type cathodes, discharge voltage was discontinuously increased with mass flow rate in the vicinity of 30 mg/s. At flow rates of 30 mg/s or more, the thruster showed higher discharge voltage and yielded the plume downstream from the nozzle exit. Below 30 mg/s, it exhibited a low discharge voltage and generated no plume outside. Hence, the flat 4-type cathode also shows high- and low-voltage modes, which are dependent on flow rate. The cavity-type cathode would also have the low-voltage mode in a low-flow rate range, although it was not tested below 25 mg/s to prevent the low voltage mode operation, which can sometimes melt the cathode due to plasma confinement inside the thruster.

At a given mass flow rate, the flat 4-type cathode exhibited the highest discharge voltage and resultant power among the tested cathodes, and the flat 2 and cavity-type cathodes showed almost the same values.

3.3. Dependence of thrust and specific impulse on mass flow rate

As depicted in Fig. 6, mass flow rate influences thrust and specific impulse. Thrust and specific impulse also spike at 30 mg/s, then increase with flow rate in the same way as discharge voltage and power. The flat 4-type cathode showed maximum thrust and specific impulse among the tested cathodes, while the flat 2 and cavity-type cathodes produced almost the same values. In the current study, the flat 4-type cathode yielded a specific impulse of 330 s, a thrust of 0.18 N at a discharge power of 1400 W, and a specific power of 25 MJ/kg.

The dependence of thrust and specific impulse on cathode configuration is partially ascribed to augmented discharge voltage and resultant power for the flat 4-type cathode at a given mass flow rate. As mentioned in the following sections, the flat 4-type yielded the highest specific impulse at a given specific power.

3.4. Dependence of thruster efficiency on specific power

Figures 7 and 8 illustrate the dependence of thrust, specific impulse, and thrust efficiency on specific power. At a given mass flow rate, the flat 4-type cathode shows a maximum
specific impulse of 330 s at 55 mg/s and a thruster efficiency of 0.23 at 60 mg/s among the tested cathodes. The flat-2 and cavitary types yielded almost the same specific impulse and thrust efficiency at a given specific power.

3.5. Soot adhesion to cathode

Under all of the cathode configurations tested, soot accumulated on the tips of cathodes and convergent sections of anode nozzles. The soot was a brittle cratered rod with a relatively sharp edge, as shown in Figs. 9 and 10, and was easily removed from the cathode by hand.

The soot for the flat-4-type had almost the same shape with the exception of its diameter. The concave soot rod has diameters of 2, 1, and 0.6 mm for the flat-4, flat-2-, and cavitary-type cathode, respectively. With regard to the cavitary-type cathode, the concave soot rod on the cathode tip extended its length especially toward the anode nozzle rather than toward the cavity. Hence, the cavitary-type cathode had a slight influence on the period for which the accumulated soot choked the constrictor. In all the cathodes tested, the top of the concave soot rod was closer to the anode nozzle than the cathode tips; hence, the concave soot rod would behave like a virtual cathode during arc discharge.

3.6. Influence of cathode configuration

As shown in Figs. 4 to 9, thrust measurements showed that the flat-4-type cathode had advantages in terms of performance among the tested cathode configurations both at a given mass flow rate and a specific power. This is ascribed to enhanced heat exchange between arc plasma and its surrounding DME gas. As mentioned in the previous section, soot accumulated more on the flat-4-type cathode than the other cathodes. With this cathode, heat from the arc plasma is most intensely exchanged between the arc plasma and the gaseous neutral DME.

On the other hand, the flat-2-type and cavitary-type had almost the same diameter of accumulated soot. Accordingly, the heat exchange intensity is identical for these cathode types. Enhanced heat exchange contributes not only to accelerating exhaust velocity but also to producing lighter molecules in exhaust gas. In a high-temperature environment, DME is readily decomposed into lighter weight molecules such as methane, hydrogen, and carbon monoxide. Moreover, DME requires 67 MJ/kg for completely dissociating into atoms, whereas specific power ranged from 10 to 40 MJ/kg. Hence, DME dissociation is not completed in the current experiments, and thermal decomposition helps reduce the molecular weight of the exhaust gas.

4. Summary

We proposed applying DME as an arcjet thruster propellant, and evaluated the performance of a DME arcjet thruster to clarify the influence of cathode configuration at DME mass flow rates ranging 15 to 60 mg/s. The following is a summary of the current paper.

1. Three types of cathode were tested at a discharge current of 13 A: the flat-2 and 4 types are rods having a flat tip of 2 and 4 mm in diameter, respectively; and the cavitary-type cathode is a 4-mm circular cathode having a 2-mm-diam. cavity.

2. At high mass flow rates, all cathode types tested showed a high-voltage mode where thrusters yield higher performance.

3. At a given flow rate, the flat-4 type yielded the highest thrust and specific impulse among the cathodes tested. The other types of cathode showed almost identical performance. At a specific power, the flat-4 type exhibited the best specific impulse and thruster efficiency among the tested cathodes.

4. For all cathodes tested here, soot adhered to the cathode tip, forming rods having a crater with a sharp edge. The concave soot rod had outer diameters of 2, 1, and 0.6 mm for the flat-4, flat-2, and cavitary-types, respectively.

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References


