Thrust Evaluation of an Arcjet Thruster Using Dimethyl Ether as a Propellant*

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This paper describes the performance of an arcjet thruster using dimethyl ether (DME) as a propellant. DME, an ether compound, has adequate characteristics for space propulsion systems; DME is storable in a liquid state without a high pressure or cryogenic device and requires no sophisticated temperature management. DME is 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 the designed kW-class DME arcjet thruster is measured with a torsional thrust stand. Thrust measurements show that thrust is increased with propellant mass flow rate, and that thrust using DME propellant is higher than when using nitrogen. The prototype DME arcjet thruster yields a specific impulse of 330 s, a thruster efficiency of 0.14, and a thrust of 0.19 N at 60-mg/s DME mass flow rate at 25-A discharge current. The corresponding discharge power and specific power are 2.3 kW and 39 MJ/kg.

Key Words: Electric Propulsion, Arcjet Thruster, Dimethyl Ether

1. Introduction

Arcjet thrusters, which show higher specific impulses than chemical thrusters, and yield higher thrust-to-power ratios among electric propulsion devices, have been applied to many missions such as North-South station keeping.1–3) Telstar-401, launched in 1993, had 1.8-kW class arcjet thrusters,4) and Kodama, a Japanese data transmitting satellite launched in 2002, had arcjet thrusters.5) At present, hydrazine is commonly used as a propellant because it can be shared by chemical thrusters used in reaction control systems. Hydrazine is storable in liquid form without being kept under a high pressure and requires no cryogenic devices. Hydrazine can be decomposed into gases such as ammonia, nitrogen and hydrogen using an iridium-based particulate catalyst. Since the decomposed gas has a relatively low molecular weight, a hydrazine arcjet thruster provides a comparatively high specific impulse. MR-510, a hydrazine arcjet thruster manufactured by Aerojet, yielded a specific impulse of 580 s with a discharge power of 2.2 kW.6) On the other hand, hydrazine has a freezing point of 154°C and 54°C at 1 atm, respectively, and a vapor pressure of 6 atm at room temperature.8) These features enable liquid-form storage in satellites without complex temperature management. DME can be gasified simply by adjusting temperature without a particulate catalyst. The molecular structure where two carbon atoms are bonded through an oxygen atom permits low soot production in chemical reactions. DME, having no toxicity and less reactivity, requires no exhaust gas treatment systems for ground testing, and allows manufacture of tanks and tubes from relatively low-cost materials such as stainless steel and Teflon®. The 6-atm vapor pressure of DME, which enables self-pressurization in tanks, eliminates not only pressurants such as nitrogen or helium, but also valves. At present, DME is more readily available because many studies and developments related to its synthesis, storage and transportation have enhanced efficiency in production and distribution, and as a result have reduced its cost. DME is applied to industrial uses as diesel fuel and coolant. From this viewpoint, DME has various preferred characteristics as an arcjet thruster propellant.

Our previous research shows that a designed 1-kW class DME arcjet thruster successfully produced arc plasmas at
mass flow rates and discharge currents that were comparable to those of conventional arcjet thrusters. Discharge voltage, power and plenum chamber pressure of DME was higher than for nitrogen at each mass flow rate or discharge current. The DME arcjet thruster also exhibited both high- and low-voltage modes. For a discharge current of 12 A, the thrust of a 1-kW class DME arcjet thruster was measured with a vertical thrust stand using a torsional spring to evaluate discharge power, thrust, specific impulse and thruster efficiency. In this study, a prototype kW-class DME arcjet thruster was tested to clarify performance under various cathode configurations at a discharge current of 13 A, and investigate the correlation between cathode geometry and performance.

2. Experimental Apparatus

2.1. Designed thruster

Figure 1 and Table 1 show a schematic diagram of a prototype kW-class arcjet thruster and its configuration, respectively. The cathode, made of 2-mm diam. thoriated tungsten rod, has a flat tip, whereas most arcjet thrusters have a conical cathode to enhance resistive heating in neighboring arc plasma. Our previous study shows that conical cathodes reduce the reproducibility of experimental results for DME propellant; 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 condition. 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, the flat-tip cathode exhibited enhanced reproducibility of experimental results in comparison with conical-tip cathodes. Hence, in the study, flat-tip cathodes were tentatively used for stable sustenance of arc discharge.

Gaseous propellant, supplied from a propellant inlet, went through a gap between a feed-through and a cylindrical ceramic insulator into a plenum chamber 6 mm in diameter. Then, the propellant entered 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 was expanded and expelled from the thruster. Nitrogen was also used as a propellant for comparing the performance of the prototype arcjet thruster with those of conventional thrusters. Table 2 shows mass flow rate and discharge current in the experiment.

2.2. 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 regarding the thrust stand is described in the next section.

The horizontal cylindrical extension was utilized to reduce thrust-measurement errors originating from the intense heat provided by the arcjet thruster. The high-temperature plume from the arcjet thruster negatively affected thrust measurement accuracy because heat addition causes thermal deformation of the vacuum chamber and the thrust stand, and as a result gives a bias to the displacement of the thrust stand arm. During the tests, the horizontal extension cylinder, which was cooled with water, absorbed the plume heat.

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

DME was stored in a pressurized vessel in a vapor-liquid equilibrium state. Gaseous DME was supplied to a pressure regulator, which suppressed DME pressure to 4 atm, and then was fed to a mass flow controller (Kofloc, 3665) to maintain the required mass flow rates.

Discharge current was supplied with a current-stabilized power supply at a rated voltage and current of 120 V and 35 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 displacement sensor output for the thrust chamber arm, discharge current, voltage, plenum chamber pressure and back pressure of the vacuum chamber.
vacuum chamber at a sampling rate of 100 Hz. All the sensor outputs were smoothed using a resistive-capacitive low-pass filter 1000 Hz in cut-off frequency.

2.3. Thrust stand

Thrust of the prototype thruster was measured with the thrust stand held by the vertical cylindrical extension. The thrust stand had flexible hinges with two circular cylinders connected through flat springs. The flexible hinges produced restoring torque without friction or hysteresis. Deflection of the thrust stand arm caused by thrust was measured using a 10-µm resolution LED displacement sensor (Omron Z4W-V). A silicon-oil damper was designed so that the thrust stand arm oscillated in a critically damped manner. The critically damped system was adopted because it can eliminate self-induced oscillations that represent no thrust variation with the minimum deterioration of responsivity to varying thrust. The thrust stand, which had a natural frequency of 6 Hz, can measure time history of thrust up to 1 Hz. Due to the previously-mentioned vertical cylindrical extension, the thrust stand yielded approximately 1-mm displacement of the arm for 0.1-N thrust.

In calibration, aluminium disks were connected to the thruster with a string, and the corresponding displacement of the thrust stand arm was measured using the displacement sensor. Nine reference forces, produced by the combination of the aluminum weights, ranged from 0.036 to 0.16 N. To evaluate null-position drift caused by hysteresis or friction of flexible hinges, tubes and electrical wires, arm displacement was measured during each calibration routine; measurements started before the reference force was exerted to the thrust stand and continued until its removal was completed. The calibration routines were iterated three times for each reference force. The thrust stand never showed null-position drift after each calibration routine. Calibration exhibited the linearity between reference force and displacement sensor output with a typical coefficient of determination $R^2$ of 0.9916. From the results, the error originating from calibration was approximately 1.8%.

3. Experimental Results

3.1. Time variation in discharge voltage, current, plenum chamber pressure and thrust

Figure 2 illustrates the time history of discharge current $I_d$, voltage $V_d$ and plenum chamber pressure $P_c$ and thrust $T$ for 60-mg/s DME flow and 13-A discharge current. At $t = 0$, s, when arc discharge was ignited, discharge voltage reached 100 V, and the plume was ejected from the nozzle exit. Until $t = 80$, s, when the discharge current was manually interrupted, arc discharge was maintained with relatively small variations of discharge voltage, plenum chamber pressure and thrust. The arcjet thruster yielded a thrust of 0.15 N, a specific impulse of 270 s, and a thrust power ratio of 120 mN/kW with a time-averaged discharge power of 1300 W and a specific power of 21 MJ/kg. Hence, the DME arcjet thruster is comparable to a conventional one in performance, as well as discharge voltage and power.

Fig. 2. Time history of discharge current $I_d$, voltage $V_d$, plenum chamber pressure $P_c$, and thrust $T$ for DME at mass flow rate of 60 mg/s at discharge current of 13 A.

On the other hand, at $t = 65$, s, plenum chamber pressure increased with time. This was caused by adhesion of soot to the constrictor. After the test, a fragile black material adhered to the constrictor and reduced the area of propellant flow passage. X-ray diffraction (XRD) analysis in our previous study shows this black material comprises 97% carbon and 3% tungsten.7) Although the experiments for Ref. 7) differed from those of the present study in terms of thruster configurations, mass flow rate and discharge current, the black material had almost the same composition as that determined by the XRD analysis.

The arcjet thruster using DME propellant produced a more unstable arc discharge than when using nitrogen. As depicted in Fig. 2, discharge voltage fluctuated in the neighborhood of 90 V. The plume expanded and shrank repeatedly and changed direction, accompanied by variations of discharge voltage. Variations of thrust also coincided with that in discharge voltage. In contrast, as shown in Fig. 3, nitrogen displayed less fluctuation than DME; plume length and direction were kept constant during arc discharge. Under some experimental conditions, at the other mass flow rates, especially at higher rates, DME exhibited fluctuations of discharge voltage and variations of plume size and direction.

Fig. 3. Time history of discharge current $I_d$, voltage $V_d$, plenum chamber pressure $P_c$, and thrust $T$ for nitrogen at mass flow rate of 60 mg/s at discharge current of 13 A.
3.2 Voltage modes

Mass flow rate affected discharge voltage, plume volume and thrust. Figure 4 depicts the time history of discharge current, voltage, plenum chamber pressure and thrust at 13-A regulated discharge current with 15 mg/s DME flow. The arcjet thruster using 15 mg/s provided a lower time-averaged discharge voltage of 33 V and power of 430 W with smaller fluctuations than when using 60 mg/s as illustrated in Fig. 2. No plume was found downstream of the nozzle exit, and arc discharge always remained inside the plenum chamber. Although exhibiting a higher specific power of 29 MJ/kg at 15 mg/s, the arcjet thruster yielded poorer performance: 0.015-N thrust, 0.018-MPa plenum chamber pressure, 99-s specific impulse and 34-mN/kW thrust power ratio.

From these results, it is evident that the DME arcjet thruster has the same voltage mode as conventional thrusters. Many studies have shown that discharge voltage and power are larger in high-voltage mode than in low-voltage mode.1,2,11,12) In high-voltage mode, which is usually found at augmented mass flow rates, the plume is found outside the nozzle, whereas the arc plasma stays inside the plenum chamber in the low-voltage mode. Specific impulse and thrust are generally enhanced in the high-voltage mode. Hence, the DME arcjet thruster has the same characteristics for voltage modes as conventional thrusters.

On the other hand, the DME arcjet thruster has another mode. As shown in Fig. 5, discharge voltage varies repeatedly in the range between values for low-voltage mode and for high-voltage mode. Time variations of plenum chamber pressure and thrust are accompanied by changes of discharge voltage. Expansion and shrinkage of the plume also coincided with changes of discharge voltage; whereas the arc plasma was confined inside the thruster when the discharge voltage dropped to the level for low-voltage mode, the plume appeared downstream from the nozzle when the discharge voltage rose to the high-voltage mode level. Nitrogen never showed such a repeated altering of voltage modes, although in some cases the voltage mode suddenly switched from low to high as shown in Fig. 3.

Table 3 shows the dependence of voltage mode on mass flow rate and discharge current. Marks ◆ and ▲ express high- and low-voltage modes, respectively; the triangle mark ▲ indicates the voltage mode in which the characteristics of arc discharge repeatedly change from those for high-voltage mode to those for low-voltage mode. As shown.

Table 3. Dependence of voltage mode on mass flow rate and discharge current.

<table>
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<th>Prop.</th>
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<th>Mass flow rate, mg/s</th>
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$I_d$: discharge current, ◆: high-voltage mode, ◆: low-voltage mode, ▲: alternating discharge mode where discharge mode is repeatedly switched from high to low.
in Table 3, for both DME and nitrogen propellant, the thruster yielded low-voltage mode at mass flow rates below approximately 20 mg/s, and high-voltage mode for values above 25–30 mg/s.

Only for DME propellant did voltage mode repeatedly change from high to low in the intermediate mass flow rate region ranging from 20 to 30 mg/s. This could be because DME arc discharge was relatively unstable in the high-voltage mode, and the intermediate mass flow rates were in the neighborhood of the threshold determining voltage mode. If discharge voltage dropped due to some disturbances in the high-voltage mode, plenum chamber pressure decreased. Accordingly, the voltage switched to low mode. Nevertheless, because the mass flow rate was sufficient to sustain the high-voltage mode, the thruster showed high-voltage mode again. This process was repeated during arc discharge for DME at intermediate mass flow rates, and resulted in altering voltage mode.

### 3.3 Dependence of discharge voltage and power on mass flow rate

Figures 6 and 7 show the dependence of discharge voltage and power on mass flow rate for DME and nitrogen, respectively. All values are time-averaged because discharge voltage varied with time as shown in Figs. 2 and 5.

For both DME and nitrogen propellants, discharge voltage and power were increased with mass flow rate. For nitrogen, as illustrated in Fig. 7, discharge voltage and power expanded discontinuously in the vicinity of the intermediate mass flow region ranging from 20 to 30 mg/s. In contrast, for DME propellant, as shown in Fig. 6, discharge voltage and power were increased continuously in the intermediate mass flow region. The exception was the experimental results for 13 A, at which discharge voltage and power jumped in the same way as for nitrogen. Consecutive increases of discharge voltage for DME are attributable to unstable arc discharge in the intermediate mass flow rate region, in which the voltage mode was switched from high to low, repeatedly. Due to the alternation of voltage mode at mass flow rates, time-averaged discharge voltage and power remained at intermediate values and resulted in a continuous increase with mass flow rate.

From Figs. 6 and 7, at each mass flow rate and discharge current, the arcjet thruster with DME propellant yielded a higher discharge voltage and therefore power than nitrogen. This is partially ascribed to a discrepancy in dissociation enthalpy and ionization energy. For DME, dissociation enthalpy and the sum of ionization energy are 67 and 250 MJ/kg, respectively, whereas for nitrogen they are 34 and 100 MJ/kg. Hence, DME requires augmented energies for dissociation and ionization, and subsequently, the discharge voltage for DME is higher than for nitrogen.

### 3.4 Influence of mass flow rate on thrust and specific impulse

Thrust and specific impulse are increased with mass flow rate for both propellants, as shown in Figs. 8 and 9. From Fig. 8 and Table 3, the arcjet thruster using DME propellant yielded better performance in high-voltage mode than in low-voltage mode as in the case of conventional arcjet thrusters. As depicted in Figs. 8 and 9, DME propellant exhibits higher thrust and specific impulse than nitrogen at a given mass flow rate and discharge current. This is partially because the arcjet thruster with DME showed higher discharge voltage and power. As mentioned in the next section, DME also provides higher performance than nitrogen at a specific power. Hence, DME has some advantages in terms of performance compared to nitrogen.

As shown in Figs. 6 and 8, variations of thrust and specific impulse on mass flow rate are very similar to those of discharge voltage and power. The arcjet thruster using nitrogen propellant displayed discontinuous increases of thrust and specific impulse in the intermediate mass flow region, ranging from 20 to 30 mg/s. In contrast, for DME, both thrust and specific impulse increased continuously even in the intermediate mass flow regime, with the only exception of 13 A. The continuous increments in thrust and specific impulse for DME are also attributable to the unstable arc discharge, where the voltage mode repeatedly switched from high to low. Under unstable arc
discharge, thrust changed from high to low values according to discharge voltage, and as a result time-averaged thrust has a mean value.

3.5. Dependence of performance on specific power

At each mass flow rate and discharge current, the arcjet thruster using DME displayed higher discharge voltage and power. Then, to evaluate the influence of propellant on performance, Figs. 10 and 11 illustrate the correlation between specific power and performance. From Figs. 10 and 11, both thrust and specific impulse increase with specific power at each mass flow rate. DME propellant displayed enhanced thrust and specific impulse compared to nitrogen. This could be attributable to a disparity in average atomic or molecular weight of the plume. In the case that DME, which has nine atoms and a molecular weight of 46, is completely dissociated, average molecular weight becomes 5.1. For nitrogen propellant, average molecular weight becomes 14 in fully-dissociated plumes. Moreover, DME is relatively easily degraded to lighter-weight molecules such as carbon monoxide and hydrogen in a high-temperature environment. Hence, DME propellant would provide plumes containing lighter molecules than nitrogen. The resultant lighter molecules augmented the specific impulse for the DME arcjet thruster.

Figure 12 shows the dependence of thruster efficiency on specific power. Thruster efficiency tends to attenuate with specific power. Since at a constant specific power, thruster efficiency theoretically increases with specific impulse, i.e., exhaust velocity, DME exhibited enhanced thruster efficiency in comparison to nitrogen.
In the experimental results presented here, the thruster exhibited a maximum specific impulse of 330 s and corresponding thruster efficiency of 0.14 with a specific power of 39 MJ/kg at 60 mg/s.

4. Summary

We propose that DME, which is storable in tanks in liquid form, is applied to arcjet thrusters. The thrust of the DME arcjet thruster was measured using a thrust stand. The following is a summary of this paper.

1. For the prototype DME arcjet thruster, discharge voltage and therefore power increased with mass flow rate as is the case with conventional arcjet thrusters.
2. The DME arcjet thruster provided high- and low-voltage modes. High-voltage mode was found at an enhanced mass flow rate as is the case with conventional thrusters.
3. In the intermediate mass flow rate region ranging from 20 to 30 mg/s, the DME arcjet thruster provided another voltage mode in which the characteristics of arc discharge repeatedly changed from those for high-voltage mode to those for low-voltage mode.
4. The DME arcjet thruster showed a high-voltage mode at almost the same discharge current and mass flow rate as when using nitrogen propellant. High-voltage mode was obtained at mass flow rates above approximately 30 mg/s.
5. DME exhibited a relatively unstable arc discharge compared to using nitrogen; discharge voltage and plenum chamber pressure had fluctuations in high-voltage mode.
6. Thrust measurements showed that the DME arcjet thruster yielded thrust at the mass flow rate and discharge current comparable to those of nitrogen.
7. At a discharge current, increasing mass flow rate developed thrust for DME as in the case of conventional propellants. DME propellant exhibited high thrust and specific impulse compared to nitrogen.
8. At a specific power, the arcjet thruster using DME generated more thrust and specific impulse than when using nitrogen.
9. Under the experimental conditions and thruster configuration, the DME arcjet thruster yielded a maximum specific impulse of 330 s and thrust of 0.15 N at 60 mg/s at 25 A. The corresponding specific power was 39 MJ/kg, which is comparable to those of conventional thrusters.

References