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Application of dimethyl ether to arcjet thruster as propellant

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ABSTRACT

We proposed applying dimethyl ether (DME) to arcjet thrusters and conducted experiments to demonstrate the operation, since DME has good storage properties. DME has a freezing point of −143 °C and a boiling point of −54 °C, and it liquefies at 6 atm under room temperature. Thus, DME is stored in liquid without any complex temperature management device such as cryogenic devices. DME also has little toxicity and is chemically stable. Its molecular structure contains no direct binding between carbon atoms; instead, the carbon atoms bind with an oxygen atom in between, and it is expected that soot generation is lower. We have shown that a DME arcjet thruster produced arc plasma with a discharge power ranging from 1000 to 1600 W with a resulting specific power from 20 to 40 MJ/kg. Furthermore, the plenum chamber pressure reached 160 kPa. We have thus confirmed that our DME arcjet thruster is capable of operating under almost equivalent conditions to conventional arcjet thrusters.

1. Introduction

Arcjet thrusters are one of the space propulsion devices and have high thrust power ratio among electric propulsion and high specific impulse compared to chemical propulsion [1,2]. Hence, the arcjet thrusters have been used for North–South station-keeping in satellites. Hydrogen, helium, and hydrazine have been used as propellant. Although a high specific impulse can be obtained using gases such as hydrogen and helium as propellant, cryogenic cooling is unavoidable when storing these gases, and the storage system becomes complex. In comparison, hydrazine has the advantages of storage as a liquid and sharing the propellant supply system with the chemical thruster used in reaction control system [3,4]. Nevertheless, hydrazine has a high freezing point of 274 K, and temperature control is required for its storage. In addition, hydrazine has high reactivity, which limits tank materials, and its high toxicity requires an exhaust treatment system for experiments on the ground, leading to high costs until the thruster is manufactured [2].

In this study, we propose using dimethyl ether (DME) as the propellant for arcjet thrusters. DME is an ether compound with the molecular structural formula CH3–O–CH3, freezing point of −143 °C, boiling point of −54 °C, and vapor pressure at room temperature of 6 atm [5]. It is thus possible to store it as a liquid under a relatively low storage pressure. Conversely, it is easy to gasify by adjusting temperature. Furthermore, it has little toxicity and reactivity, which leads to good storage properties. Its two carbon atoms are bound by an oxygen atom, and DME generates little soot. At present DME is also readily available because it is used frequently in industrial applications, and research and development are being actively conducted on its synthesis [6].

2. Experimental apparatus

2.1. Prototyped arcjet thruster

Fig. 1 shows the prototype of the DME arcjet thruster. Both anode and cathode have coaxial shapes with an electrode gap of 0.3 mm. The cathode is a thoriated tungsten rod 2 mm in diameter and 20° in half-conical. The nozzle also acts as the anode, and its convergent section and constrictor are made of copper tungsten. The constrictor length is 1.0 mm and diameters are 0.8, 1.0, and 1.2 mm. Its divergent section is made of copper with a 15° semi-vertical angle and a 10.5 mm outlet diameter. The propellant is introduced from the supply inlet on the left in Fig. 1 and is supplied to the plenum chamber through a space between the discharge current feed line that fixes the cathode and the cylindrical ceramic insulator.

2.2. Overall experiment system

We tested the prototype under a vacuum environment by attaching the nozzle tip of the prototyped arcjet thruster to the aluminum flange of a vacuum chamber. This vacuum chamber, which was made of acrylic and was 100 mm in inner diameter and 500 mm in length, was evacuated by a vacuum pump with a 120 l/min exhaust velocity. DME, which was stored in a compressed cylinder, was supplied to the thruster via the mass flow meter and flow rate adjustment valve after decompression by a pressure regulator. A constant-current stabilized power supply with 120 V

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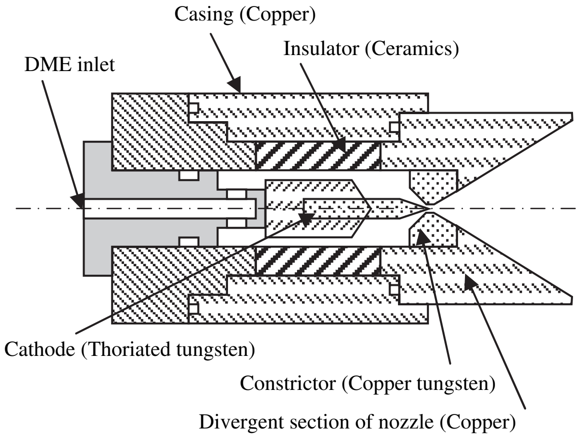

Fig. 1. Designed DME arcjet thruster.

rated output voltage and 35 A rated current was used as the discharge power supply. In the beginning, this power supply generates a high pulsed voltage and induces a spark discharge between the anode and the cathode to begin discharge. Discharge voltage is measured by the probe, and the discharge current is measured using a hall element-type current sensor with electrical insulation.

3. Results and discussion

3.1. Ignition test

The DME arcjet thruster successfully produced arc plasma with a 1.2-mm constrictor diameter, while varying the DME flow rate in the range of 38–47 mg/s and discharge current in the range of 12–20 A. Fig. 2 shows changes in discharge current, discharge voltage, and plenum chamber pressure over time with 38 mg/s DME flow rate and 16 A discharge current. The discharge voltage fluctuated cyclically and was unstable as shown in Fig. 2. Although the plasma attached to the nozzle's divergent section and the plume was visible downstream from the nozzle, it was unstable in a similar fashion to the discharge voltage, and the plume length sometimes decreased and become invisible outside the nozzle. However, the plenum chamber pressure was nearly stable and the system continued operating without discharge being halted by soot besides the unstable discharge.

Fig. 3 shows discharge voltage and current characteristics. The expressed discharge voltage values are average values because it periodically fluctuated as described earlier. As shown in Fig. 3, the discharge voltage decreased slightly as the discharge current increased, and it was shown that the prototype was operating at an equivalent level to the conventional arcjet with a discharge power of 1000–1600 W and a specific power of 20–40 MJ/kg. Fig. 4 shows the relationship between the discharge power and the plenum chamber pressure. Plenum chamber pressure increased as discharge power increased, and it was nearly at the same level as that of the conventional arcjet thrusters. Based on the above, we confirmed that the DME arcjet thruster operated at discharge power, specific power, and plenum chamber pressure equivalent to those of conventional arcjet thrusters.

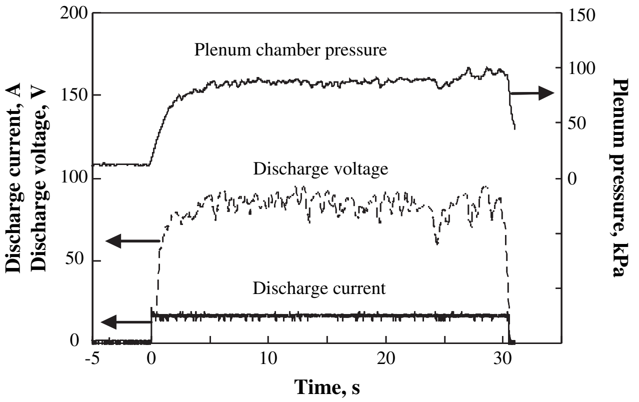

Fig. 2. Time history of discharge current, voltage, and plenum chamber pressure. DME mass flow rate: 38 mg/s; discharge current: 16 A; constrictor diameter: 1.2 mm.

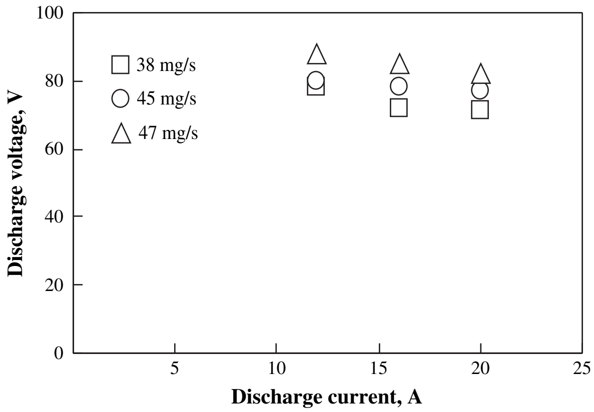

Fig. 3. Discharge current and discharge voltage using 1.2-mm constrictor diameter.

3.2. Dependence of discharge mode on DME flow rate

Although we confirmed operation of the DME arcjet thruster under all conditions when we conducted an experiment using a constrictor 1.0 mm in diameter, while varying the DME flow rate in the range of 15–47 mg/s and the discharge current in the range of 12–20 A, there were fluctuations in the discharge voltage and plume conditions depending on the DME flow rate even under the same discharge current. Fig. 5 shows changes in discharge current, discharge voltage, and plenum pressure over time when discharge current was 12 A, DME flow rate was 25 mg/s, and constrictor diameter was 1.0 mm. As shown in Fig. 5, the plenum pressure increased gradually once discharge began, and ultimately reached an almost stable value. The discharge voltage was almost stable at approximately 53 V. However, the plasma stayed continuously

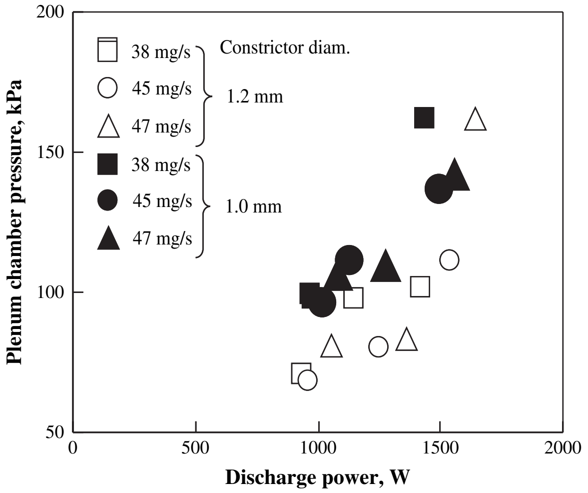

Fig. 4. Discharge power and plenum chamber pressure.