Technical Notes

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Current Distributions in a Quasisteady Magnetoplasmadynamic Arcjet

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Introduction

THE quasisteady multimegawatt magnetoplasmadynamic (MPD) arcjet thruster, characterized by high specific impulse and large thrust density, is a propulsion device suitable for orbital transfers of large space structures and interplanetary missions. Experimental and theoretical research[1-4] on MPD thrusters has been conducted to improve the thrust performance for practical use. One of the important subjects in MPD thruster development is to enhance the thrust efficiency by increasing the discharge current for a given mass flow rate. In previous experiments[3,4] for various propellants, it was inferred that preferred propellants were molecular gases like hydrogen and ammonia; a preferred operating current for a given propellant and mass flow rate was identified at a current just below a limiting current, which was determined experimentally from the waveform of the discharge voltage. In operating conditions above the limiting current, the arc becomes unstable; severe electrode erosion is likely to occur at the cathode tip and the surface of the anode end due to local concentration of current. Therefore, the previous research has been focused on achieving the higher limiting current and on decreasing electrode erosion. The unstable limiting phenomenon is related closely with physical properties in the discharge chamber. It is important to understand interior physical processes for that purpose.

In this Note, current distributions in an arc chamber of a self-field MPD arcjet were investigated to understand the discharge mechanisms. Current patterns were measured with a $\dot{B}_\theta$ probe using various gases. From experimental results, the influence of propellant species and discharge current levels on the patterns of current conduction in the MPD arcjet chamber are examined.

Experimental Apparatus

The MPD arcjet used in this study is provided with a straight anode 50 mm in diameter × 75-mm deep. The anode is made of copper. A cylindrical cathode, 9.5 mm in diameter × 45-mm long, is made of thoriated tungsten (Th-W).

This arcjet is provided with two auxiliary electrodes at floating potential and two slits for propellant injection (anode and cathode slits). The floating electrodes are useful in relaxing current concentration near the anode and cathode bases at the initial state of the discharge.

Propellants were injected into the discharge chamber through a fast acting valve (FAV) fed from a high-pressure reservoir. The rise time and width of the gas pulse, measured with a fast ionization gauge, are 0.5–1.0 ms and 6 ms, respectively. The mass flow rates were controlled by adjusting the reservoir pressure and the orifice diameter of the FAV.

A pulse forming network (PFN) delivered a single nonreversing quasisteady current with a pulse width of 0.6 ms. A vacuum tank, 0.6 m in diameter × 5.75 m in length, where the arcjet was fired, was evacuated to some 10^{-3} Pa prior to each discharge by diffusion and rotary pumps.

Discharge currents were measured by a Rogowski coil calibrated with a known shunt resistance. Voltage measurements were performed with a current probe, which detected the small current bled through a known resistor (10 kΩ) between the electrodes.

Current patterns were measured with a $\dot{B}_\theta$ probe. The probe signal was integrated passively. An axial current distribution can be inferred, because the recorded self-induced magnetic field B_θ is proportional to the enclosed current within the radius of the probe position. With the assumption of axial symmetry of the discharge current, the $\dot{B}_\theta$ probe was used to measure a local current distribution in the discharge chamber and near the electrodes. The $\dot{B}_\theta$ probe is wound 70 turns with a wire 100 μm in diameter on a 1-mm epoxy core. The coil is encased in the quartz glass tube of 2-mm o.d. and 1.7-mm i.d., and the space between the coil and quartz tube is filled with a ceramic material. The probe was mounted on a movable probe stand. Probing was performed at intervals of 3 mm along the arcjet axis and 2 mm in the radial direction. The $\dot{B}_\theta$ probe was calibrated by measuring the far magnetic field induced by a known current through a long conductor rod of 0.5 m, located on the arcjet axis; the current was supplied by the PFN. It is very important that the probe is accurately aligned in the meridian plane of the arcjet by adjustment of the probe stand.

Experimental Results and Discussion

The present experiments were conducted with five propellant gases (helium, argon, hydrogen, nitrogen, and ammonia) at discharge currents of about 5, 10, and 14–15 kA. The mass flow rate for each gas was setup at a corresponding critical current of about 10 kA, which was derived theoretically from the rule of minimum input power or Alfvén's critical ionization velocity.[5,6] All measurements were performed several times to verify repeatability. Typical variation in the integrated output signals was less than 5% at a same probing position and discharge current.

The typical enclosed current contours for helium and ammonia at the low (5 kA) and high (14–15 kA) currents are drawn in Figs. 1 and 2, respectively, where the numbers on the contours indicate the ratios of the current downstream of the given line to the discharge current. The measured limiting

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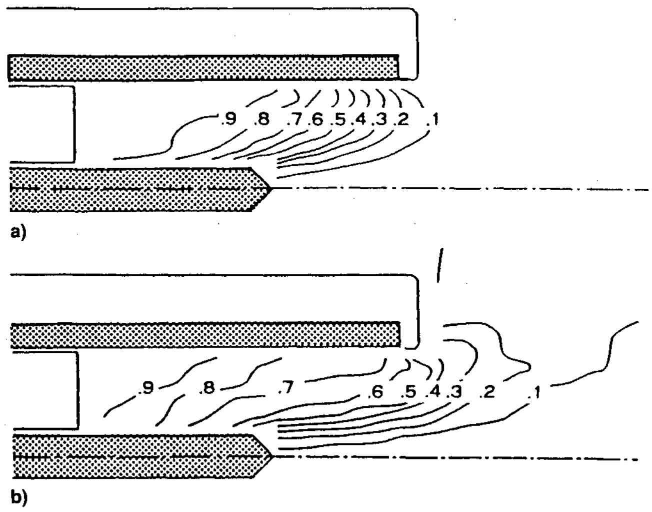

Fig. 1 Enclosed current contour for helium at: a) 5.1 kA and b) 14.5 kA, both having 0.52 g/s with straight anode.

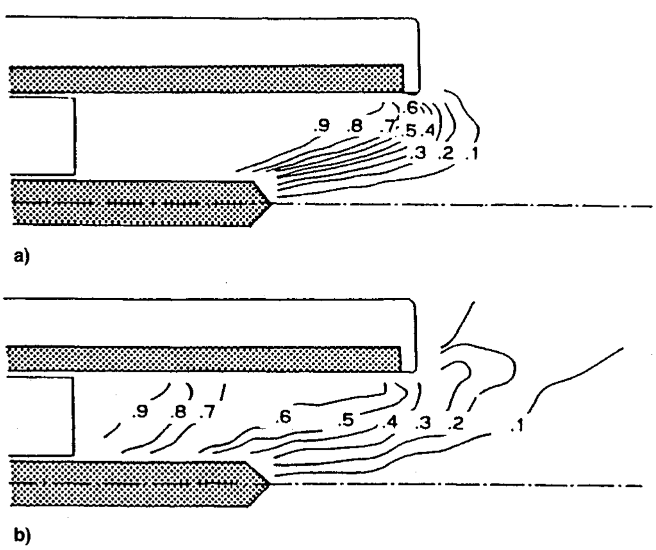

Fig. 2 Enclosed current contour for ammonia at: a) 5.0 kA and b) 14.0 kA, both having 0.71 g/s with straight anode.

current was 13.5 kA for He and 10.8 kA for NH_3.[3,4] The current patterns are found to depend strongly on the gas species and the discharge current levels. Particularly, it is interesting that the current patterns are divided into two classes at the low current. For the rare gases such as He and Ar, the discharge occurs mainly inside the discharge chamber, and the current flows almost uniformly over the side surface of the cathode as shown in Fig. 1a. For the molecular gases such as NH_3, H_2, and N_2, the contours move downstream, and most of the discharge current enters the cathode tip and the end surface of the anode as shown in Fig. 2a. These features of the current patterns are explained as follows.[7] The ionization process of molecular gases is slower than that of rare ones, owing to a time lag due to dissociation process at the low current level. The ionization process of molecular gases starts near the arcjet exit. At the high current level, the current patterns for the molecular gases are similar to those for the rare gases. The zones of current conduction spread widely from the inside of the arcjet chamber to the downstream region as shown in Figs. 1b and 2b.

In front of the cathode tip on the axis, the axial current densities for all gases become larger as the discharge current increases. Hence, the heated plasmas are expected to be compressed radially by the stronger pumping force and to be expanded into vacuum as the cathode jets.

For all propellants, a considerable fraction of the discharge current flows widely downstream from the front surface of the insulator, which is called to the diverging current, as the discharge current is raised from 5 kA to about 15 kA. The Lorentz force generated by the diverging current does not contribute to thrust at all, and the consumed power cannot be converted to axial kinetic energy, because the direction of the force is in the positive radial direction. The existence of the ineffective force prevents the increase of thrust efficiency at high current levels. Furthermore, the diverging current seems to flow along the insulator and to concentrate near the anode end. Therefore, the current pattern with the straight anode tends to form local anode spots at the anode end and to bring about erosion, resulting from relatively large heat transfers to the anode. The generation of anode spots, which may be responsible for the noisy voltage waveform observed at high discharge currents, is likely to be a significant signal of the limiting phenomenon.[3,4]

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Performance Characteristics of a Medium Power Hydrogen Arcjet

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Introduction

WITH the availability of sufficient electric power for propulsion purposes, recent years have seen an increased interest in the application of thermal arcjet concepts for satellites.[1,2] In a thermal arcjet an electric arc discharge increases the enthalpy of the propellant flow through a supersonic nozzle. The thruster consists of a coaxial electrode system, which

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