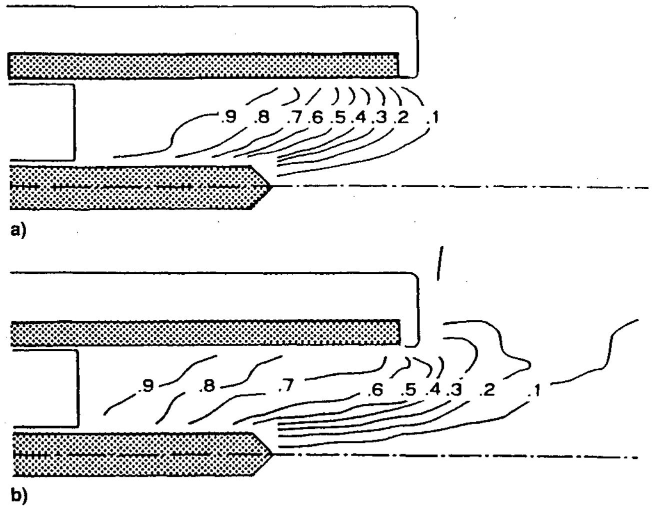

Fig. 1 Enclosed current contour for helium at: a) 5.1 kA and b) 14.5 kA, both having 0.52 g/s with straight anode.

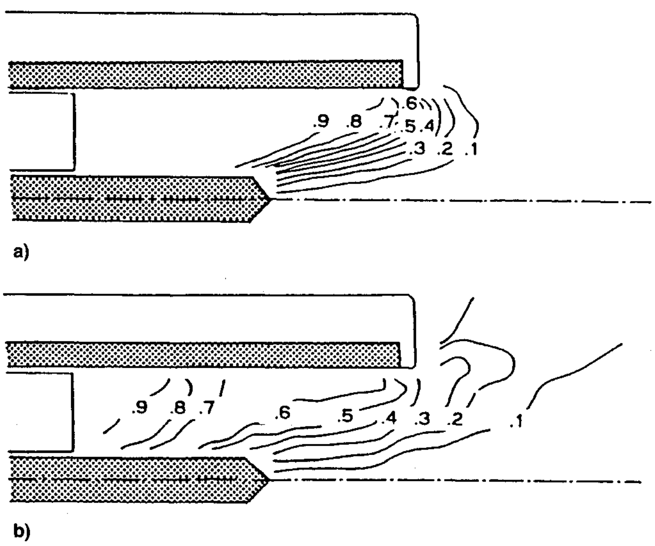

Fig. 2 Enclosed current contour for ammonia at: a) 5.0 kA and b) 14.0 kA, both having 0.71 g/s with straight anode.

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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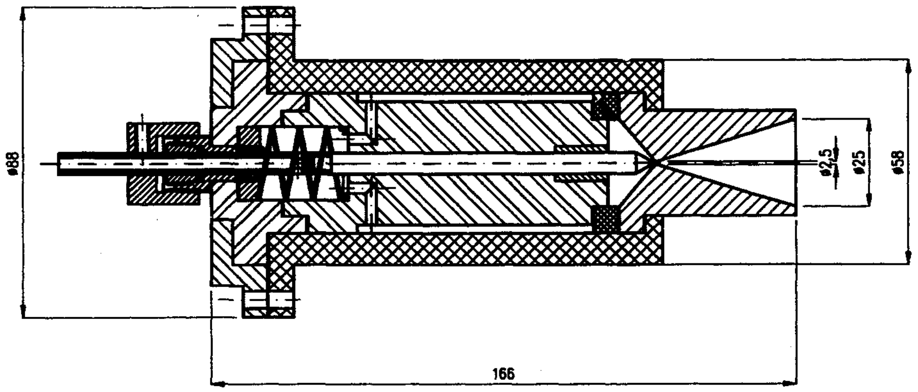

Fig. 1 Schematic of the radiation cooled hydrogen arcjet.

supports an electric discharge within an axial gaseous propellant stream. The gas is heated by an arc, and a plasma is created, which is accelerated in a thermal expansion. Within the nozzle the thermal energy is converted into directed kinetic energy, and thereby produces thrust. Therefore, it is possible to achieve specific impulses which are higher by a factor of 2 compared to conventional chemical thrusters.

Based on the experience with a water-cooled 15-kW laboratory thruster,[3] a 5–20-kW radiation cooled arcjet thruster was developed and tested with hydrogen, simulated hydrazine, and ammonia as propellants.[3] Operation characteristic with the two latter propellants are well known. However, the highest specific impulse can be achieved with pure hydrogen, because the molecular weight and the frozen flow losses are the lowest with pure hydrogen. In the sixties, with this propellant with a 30-kW thruster, specific impulses of more than 1200 s at thrust efficiencies of more than 40% were achieved.[4] In the 10-kW range, only few experimental results with pure hydrogen are known.[5] This Note will give an impression of the specific impulse levels and of the thrust efficiencies expected with an hydrogen arcjet.

Thruster

A schematic of the radiation-cooled thruster (MARC) is shown in Fig. 1. The nozzle geometry and the electrode configuration are the same as in a previously investigated water-cooled version[3] so that the characteristics of these two devices with different cooling systems could be compared. The constrictor is 2.5 mm in diameter and has a length of 5 mm. The contour is conical with an expansion half-angle of 17.5 deg, and the expansion ratio is 1:100. The design concept allows an easy exchange of the critical components and the investigation of other nozzle geometries by changing only one single part. The radiation-cooled anode is machined from 2% thoriated tungsten and is located in a molybdenum housing. Between the cathode and the housing there is a boron nitride insulator. The cathode is machined from 2% thoriated tungsten, has a 30-deg half-angle, and is 6 mm in diameter. It is press-fitted into a stainless steel cathode feed tube. The propellant is fed in at the rear of the thruster through the cathode feed tube, cooling the rear side of the cathode. This tube measures 6 mm in diameter with a 3-mm bore hole. The propellant is fed into a ring channel between the housing and the boron nitride insulator, and into the injector ring, cooling the housing and the boron nitride insulator. The propellant is finally injected tangentially into the plenum chamber through four holes 0.5 mm in diameter.

Test Facility

The thruster is mounted on a thrust balance described elsewhere.[3] The thruster and the balance are integrated in a stainless steel tank with a diameter of 1.25 m and a length of 4 m, which is connected to a roots pump vacuum plant with a pumping speed of more than 200,000 m^3/h at 10^{-2} mbar. The

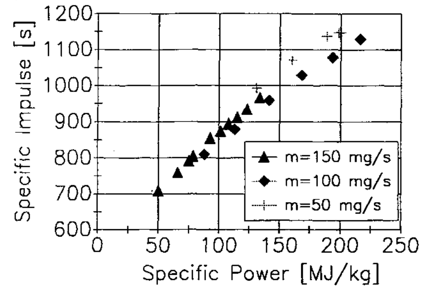

Fig. 2 Specific impulse vs specific power.

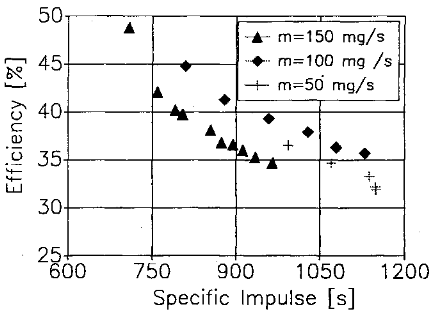

Fig. 3 Thrust efficiency vs specific impulse.

power is supplied by a current regulated dc power unit with a maximum voltage of 1000 V and a maximum current setting of 1000 A. The gas supply system and the starting procedure are described in more detail.[3] It is possible to measure voltage, thrust, current, mass flow, and pressure in the feed line of the propellant close to the thruster under computer control.

Experimental Results with Hydrogen as Propellant

Test runs were conducted with 50, 100, and 150 mg/s pure hydrogen as propellant. The most important measurement results are shown in Figs. 2 and 3. The thruster was started at a power level of 10 kW and operated until thermal equilibrium was reached. Then a new current level was set and again kept constant until equilibrium. The depicted points are the points at thermal equilibrium.

The specific impulse with hydrogen was higher than 1000 s at a specific power of more than 150 MJ/kg (Fig. 3). It reaches 1150 s at 11 kW with a mass flow rate of 50 mg/s. The thruster was operated from 6 kW up to 11 kW for 50 mg/s, up to 17 kW for 100 mg/s, and up to 20 kW with 150 mg/s. Thus, for the lower mass flows more than 200 MJ/kg specific power was achieved without operational problems, consequently, it will be possible to achieve higher specific impulses at higher specific power than the investigated ones.

The thrust efficiency ranges from about 35% for the higher power levels to 45% for the lower power levels. The efficiency is calculated relating the thrust power to the electric input power.

As mentioned above, the arcjet geometry of radiation-cooled thruster was the same as that of a previously investigated water-cooled thruster. A comparison of the results shows that the thrust efficiency with the radiation-cooled thruster is about 20% higher, and the specific impulse is about 320-s higher at the same power level.[7] This can be explained by a regenerative cooling effect. The incoming gas is heated to about 900°C in the radiation-cooled device and a greater part of the heat is regained than in the water-cooled thruster. Although the operating characteristics of water-cooled and radiation-cooled devices are quite different, data obtained from water-cooled thrusters are useful for determining general operating conditions and performance trends, and they give a theoretical insight into the physics of the system.[6]

Conclusions

In this Note it is shown that with hydrogen as propellant, specific impulses of more than 1100 s with efficiencies of 35–40% can be achieved. This high specific impulse makes hydrogen arcjets very interesting for orbit transfer applications of larger satellites. Although the highest specific impulses can be achieved with hydrogen, new storage systems have to be developed if this thruster is to be used for orbit transfer vehicles.

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Applied-Field MPD Thruster Performance with Hydrogen and Argon Propellants

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Introduction

MAGNETOPLASMADYNAMIC (MPD) thrusters have demonstrated performance levels and power handling capabilities approaching those required for Earth orbit, robotic planetary, cargo, and piloted missions.[1,2] These thrusters employ electromagnetic body forces generated by the interaction of a discharge current passing through the propellant and either the self-induced or externally applied magnetic field to accelerate a propellant to velocities between 10–50 km/s.[2] Self-field MPD thrusters using argon or nitrogen propellant have been operated continuously at power levels over 500 kW at 20% power-to-thrust conversion efficiency and 1200-s specific impulse, or pulsed at power levels of several megawatts with efficiencies of up to 40% and 5000-s specific impulse.[2] However, the performance of self-field thrusters decreases rapidly as the thruster power is decreased, and the highest power spacecraft currently planned is the SP-100 space nuclear reactor, which will deliver 100 kWe.[1] This power limitation has forced a more detailed evaluation of applied magnetic fields, thruster geometries, and propellants, in the expectation that a high performance thruster design can be established at power levels of interest.

Previous reports have presented results for 12 applied-field MPD thruster geometries operating on argon propellant at power levels between 20–150 kW.[3,4] Thruster performance increased monotonically with the applied magnetic field strength, reaching 23% efficiency at 2300-s specific impulse. The specific impulse increased with decreasing flow rate, but the efficiency decreased. While the applied-field clearly improved thruster performance, the best performance with argon propellant was not high enough to satisfy mission requirements. Work in the 1960s in the U.S., and more recently in Japan, indicated that using hydrogen propellant substantially increased both thruster specific impulse and efficiency.[5,6] However, both those efforts were conducted in facilities with ambient pressures that have been shown to affect thruster performance,[3,7] and neither one provided a quantitative comparison of performance with argon and hydrogen. This report presents results of a study in which a single thruster geometry was tested with argon and hydrogen propellants across the same range of operating conditions. Following a brief description of the thruster design and test facility, the performance results are presented and their implications for power deposition and thruster loss mechanisms are discussed. Finally, a summary of the study conclusions is given.

Experimental Apparatus

Thruster Design

The thruster, shown in Fig. 1, consisted of a 5.0-cm-i.d. copper anode with a coaxial, 1.2-cm-diam, 2% thoriated tungsten cathode. Both electrodes were 7.6-cm long. The thruster was water-cooled, the anode through passages in its wall, the cathode by conduction through a water-cooled cathode clamp. A boron nitride backplate was used to inject half the propellant flow through an annulus around the cathode base and half through 24 holes at a radius of 1.6 cm. The MPD thruster was mounted inside a 15.3-cm-i.d., 15.3-cm-long coil consisting of 36 turns of 1.3-cm-diam copper tubing. The thruster was mounted such that the anode exit plane was flush with the end of the solenoid. Calibrations of the axial field strength at the centerline of the magnet exit plane as a function of coil current yielded strengths of 1.66×10^{-4} T/A.

Test Facility and Diagnostics

The thruster test stand was mounted in a 3-m-diam test chamber separated from the main 7.6-m-diam, 21-m-long tank by a 3-m-diam gate valve. The main tank was pumped by 20 0.9-m oil diffusion pumps backed by three roots blowers and two roughing pumps. The facility pressure was below 0.07 Pa (5×10^{-4} Torr) during all tests.[3]

The thruster power supply consisted of a series-parallel network of six 65-kW arc welding supplies. This network, which was electrically isolated from ground, could supply up to 3000 A at 130 V to the thruster. The applied-field magnet

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