MPD Thruster Performance with Various Propellants

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The thrust performance of a quasisteady MPD arcjet is studied with different propellant species. It is found that the thrust obtained with molecular gases is larger than that with monoatomic gases, and that the voltage increase with current is steeper for the monoatomic gases. These differences are attributed to the larger contribution of aerodynamic thrust by the molecular gases. The specific impulse ranged from 2000 to 6000 s by changing gas species. Selection criteria of gas species are discussed from the viewpoint of the thruster system.

Nomenclature

e = electron charge
g = standard acceleration of gravity
I_{sp} = specific impulse
J = discharge current
k = rate coefficeint
K.E. = kinetic energy
M = third particle in three-body recombination
$\dot{m}$ = mass flow rate
R = effective radius of current attachment
T = thrust
T/P = thrust-to-power ratio
V = discharge voltage
α = constant in Eq. (1)
η = thrust efficiency
μ = permeability of free space

Subscripts

a = anode
c = cathode

Introduction

THE study of the magnetoplasmadynamic (MPD) thruster has been made with Ar gas as the primary propellant. For practical implementation of the MPD thruster, however, the selection of propellant species should be made not only by the thrust performance but also by its ease of storage and supply and its impact on the spacecraft environment. The thrust performance will have to be assessed in terms of the thrust, thrust efficiency, and electrode erosion. From the viewpoint of storage and supply, such gases (generally molecular) as H_2O, CO_2, CO, and NH_3 are favorable. In addition, these gases could be wastes of manned and unmanned spacecraft. It was for those reasons that 11 atomic and molecular gases, H_2, He, CH_4, NH_3, Ne, N_2, CO, O_2, Ar, CO_2, and Xe, were studied.

From research conducted on the MPD arcjet, it is well known that for a given propellant flow rate, the discharge current must be kept below a limiting value in normal operation to present excessive electrode erosion. This critical current, which corresponds to the upper limit of specific impulse attainable for the propellant species, increases with decreasing atomic mass.[1] In this regard, several propellants may be selectively used to achieve good thruster performance over a wide range of specific impulses. The present report deals with the thrust characteristics, electrode erosion, and the ranges of specific impulse determined for the 11 different propellants mentioned above. Also, the criteria for propellant selection from the viewpoint of thruster system applicability are discussed.

Experimental Apparatus

The configuration of the discharge chamber used in this experiment is described in Fig. 1. It is the same design as the KOMABA III arcjet that has been used in previous studies,[2] except for the anode front shape. One of the key features of the KOMABA III is its floating electrode design. These electrodes are effective for buffering current concentration at the cathode root. The annular copper anode, uninsulated to the environment, consists of a cylindrical part, a diverging cone, and a front plate (20 cm in diameter), and is coaxially aligned with the cylindrical thoriated tungsten cathode. An anode shape such as this may be favorable for radiation cooling of a practical high-power MPD thruster. These anodes and cathodes are insulated from each other by a flat backplate of boron nitride lined with the two floating electrodes. Also the

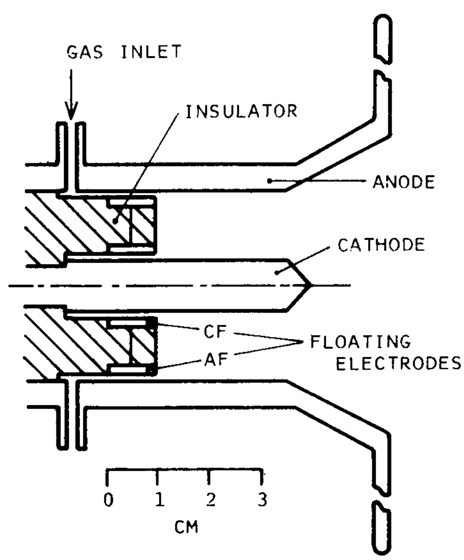

Fig. 1 Configuration of discharge chamber.

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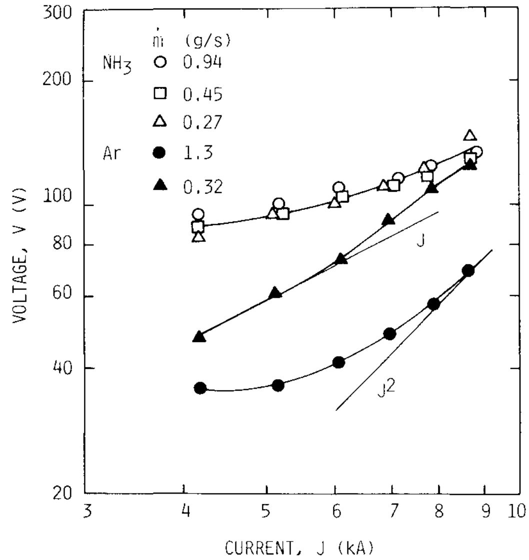

Fig. 2 Voltage-current characteristics.

discharge chamber may be readily disassembled into a few components so that the weight loss of each component can be accurately measured after a number of discharges.

The pulse-forming network (PFN) supplying the electrical power and the vacuum system in which the arcjet was fired were also the same as those used in the previous studies.[2] The PFN delivers a discharge current up to 10 kA with a pulse width of 1 ms. The tank pressure before the discharge is less than 10^{-3} Pa. Voltage measurements are made with a current probe which monitors the current in a high-impedance shunt resistor between the electrodes. The discharge currents are measured by a Rogowski coil.

The propellant gas was injected into the discharge chamber from the fast acting valve (FAV) developed previously.[3] The gas pulse showed a risetime of 500 μs and a variable steady-state time of 1.5 ms or more was obtained with H_2 gas as measured by a fast ionization gage (FIG) near the cathode tip. The mass flow rate was varied from about 0.2 to 1.5 g/s with a choking orifice in the FAV for all of the test gases. This flow rate has been confirmed using the rectangular pulse shape determined using the FIG and the measured reduction of the reservoir pressure. The thrust measurement was made using the pendulum method. Namely, the MPD arcjet device, consisting of a discharge chamber and an FAV, was suspended by a steel wire from the top of the vacuum tank. Just after the discharge, the backward displacement was detected by a linear differential transformer. Thrust was then obtained from the displacements calibrated with known impulses.

Experimental Results and Discussion

Thrust and Voltage Measurements

As verified in the previous studies with the KOMABA III arcjet,[2] the gas injection along the anode surface reduces the anode fall voltage at high power, hence, improving the thrust efficiency. Therefore, in this experiment, anode side gas injection was used for all of the test gases. After the thrust due solely to cold gas flow was measured at a given mass flow, the arc discharge was affected, and the arcjet-induced thrust was obtained by subtracting the cold gas flow thrust. The terminal voltage was determined at the same time by varying the discharge current. For hydrogenous gases, in particular, characteristic high-frequency fluctuations were observed in the voltage signal. In these cases, filter passing frequencies below about 40 kHz were used to obtain a reasonable mean voltage profile.

In general, the results could be classified according to whether the gas was monoatomic, molecular, or hydrogeneous molecular. As a typical result, the voltage-current characteristics of Ar and NH_3 are presented in Fig. 2, wherein there are several features to be noted: the monoatomic gas (Ar) shows a voltage increase proportional to the square of the current, especially at large values of current J. This voltage-current curve is also strongly dependent on the mass flow for argon, whereas in the case of the hydrogenous gas (NH_3) the voltage is relatively insensitive to the current and mass flow. It should be noted, however, that at low currents the arc impedance for NH_3 is higher than that for Ar. This may be an indication that for the lighter gas, due to its greater number of particles for a given mass flow rate, the dissociation and ionization effected by the electron impact require higher voltage.

Table 1 Cathode erosion with several gas species (7.8 kA)

Working gas	Specific impulse, s	Mass loss μg/C	Mass loss μg/kJ
H_2	6100	11.0	67
NH_3	4700	6.4	44
O_2	2050	3.5	38
Ar	3100	3.4	31

The thrust-current characteristics are shown in Fig. 3. Here the solid lines marked "MAX" and "MIN" represent the theoretical prediction of electromagnetic acceleration given by

$$T=(\mu/4\pi)J^2[\ell n(R_a/R_c)+\alpha] \tag{1}$$

The quantity α, a function of current fraction on the conical cathode tip, corresponds to ¾ for the MAX curve and zero for the MIN curve. Results obtained with argon exhibit a transitional dependence of thrust on the current from J to J^2 at a mass flow of 1.3 g/s. At smaller mass flow rates, the thrust is noticeably J^2 dependent and, moreover, is insensitive to the mass flow—a typical feature of the electromagnetic acceleration. In the case of ammonia, on the other hand, different thrust characteristics are observed in Fig. 3. First, the measured thrust is greater than the predicted one, and second, it is linearly proportional to the current at large mass flow rates. From these features, the contribution of intense aerodynamic acceleration to the high-thrust generation observed at large mass flow rates may be inferred. Of course, with decreasing mass flow, situations such as in the case of argon would be attained.

Other gases such as oxygen or nitrogen show either one of these two characteristic behaviors depending upon the values of $J^2/\dot{m}$. When the voltage characteristics are compared with those of thrust (Fig. 2 vs Fig. 3) it may be noticed that the low rate of increase and the weak flow rate dependence of discharge voltage are related to the aerodynamic acceleration, whereas the steep rise and the strong mass flow rate dependence of discharge voltage are related to the electromagnetic effect of thrust.

Thrust Efficiency

The measured discharge voltage and thrust were used together with the discharge current and mass flow rate to obtain the specific impulse and thrust efficiency,

$$I_{sp}=T/\dot{m}g \tag{2}$$

$$\eta=\frac{T^2}{2\dot{m}VJ}=\frac{gI_{sp}}{2}\left(\frac{T}{P}\right) \tag{3}$$

$$\frac{T}{P}=\frac{T}{VJ} \tag{4}$$

The results of $\eta - I_{sp}$ characteristics are summarized for several gases in Figs. 4 and 5, where the heavy solid lines represent constant thrust-to-power ratios.

From these and the results of other gases not shown here, it may be concluded that the thrust efficiency generally exhibits a monotonic increase with specific impulse, hence, with discharge current. The efficiency is observed to level off at large values of specific impulse. In the case of ammonia this departure from linearity occurs near an I_{sp} of 6000 s. The same behavior was observed with many gases, although the "critical" I_{sp} corresponding to leveling off is smaller for heavier gas. When the aerodynamic effect is dominant in the thrust, the thrust-to-power ratio may conceivably be nearly constant. In the case of intense electromagnetic acceleration on the other hand, the thrust efficiency should tend to reach a saturation level as indicated by Eq. (3) for the case where the thrust and voltage are proportional to J^2 and J^3, respectively. However, hydrogen which is the lightest gas, shows no apperance of this feature even above a specific impulse of 6000 s.

Above an I_{sp} of 2000 s, which is of a practical interest for high-power MPD thrusters, the thrust performance is better with hydrogenous gases rather than with monoatomic gases.

In Fig. 5 maximum efficiencies attained in the present investigation with various gases are shown. On the whole, the efficiency has a nearly square-root dependence on I_{sp}. Other gases such as nitrogen and oxygen showed the intermediate η-I_{sp} characteristics between those of hydrogenous and monoatomic gases. Xenon was found to be the worst performer. As the I_{sp} increases with decreased mass flow rate, the experimental data for the hydrogenous gases fall approximately on a single curve, while for the monoatomic gases the data are on separate curves depending on the mass flow rate (Fig. 4). This feature seems to correspond to the strong mass flow rate dependence of voltage mentioned earlier.

Aerodynamic Thrust

The theory of electromagnetic acceleration predicts the thrust depends upon neither the gases nor their mass flow rate. However, the results of the present study show that the thrust levels higher than those predicted can be obtained, particularly with hydrogenous gases. In this regard, although some effect due to the variation of α could be suggested by Eq. (1), it is reasonable to infer a contribution of aerodynamic thrust described in the following paragraphs.

First, the relationships between the gas species and the thrust characteristics are as shown in Fig. 6, where the thrust, voltage, and efficiency at the same current of 7.8 kA and mass flow rate of about 0.3 g/s are replotted against the number of atoms contained in a given gas flow as normalized by that of H_2, which is taken to be unity. In this arrangement, gases with the smaller mean mass of their component atoms will find themselves on the right-hand side. It is interesting to note that lighter gases would enhance the thrust efficiency of the MPD arcjets that are the subject of this report. The discharge voltage and thrust decrease as the number of atoms decreases, but the former turns upward at about 0.05 with the latter kept at 9.7 N which is determined mainly by the eletromagnetic effect. This implies that the discharge with argon is "starved," while those with oxygen and hydrogen are in the "matched" and "overfed" conditions, respectively, with respect to carriers of current.[4] The dominant particles in the last case are neutral atomic hydrogen and the degree of ionization is only 5%. In such a plasma the electron motion is strongly affected by the elastic collision with the atoms[5] and the high-discharge voltage is required to maintain the discharge with Joule heating. Moreover, assuming the number density of atomic hydrogen to be 1×10^{16} cm^{-3}, and using the cross section of 1×10^{-15} cm^2 for collisions among them, the electron mean

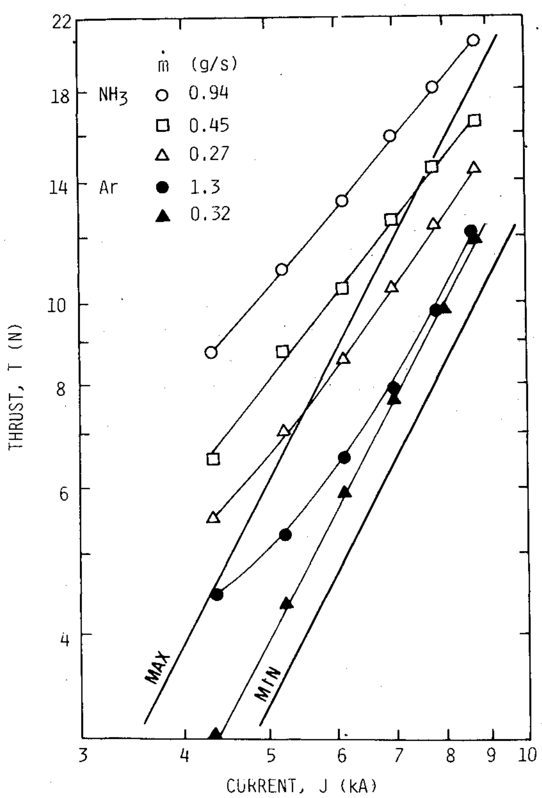

Fig. 3 Thrust-current characteristics.

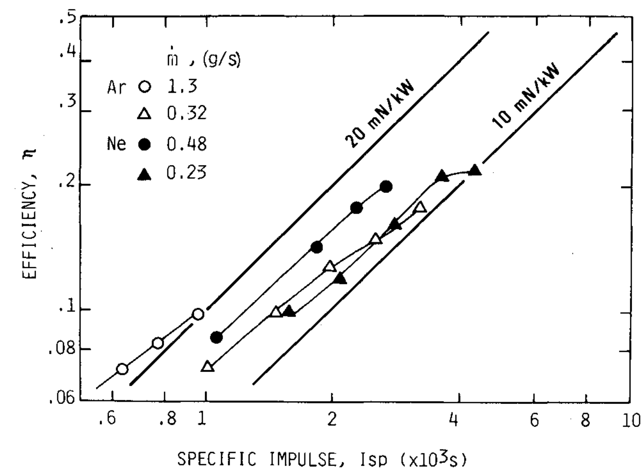

Fig. 4 Thrust efficiency vs specific impulse.

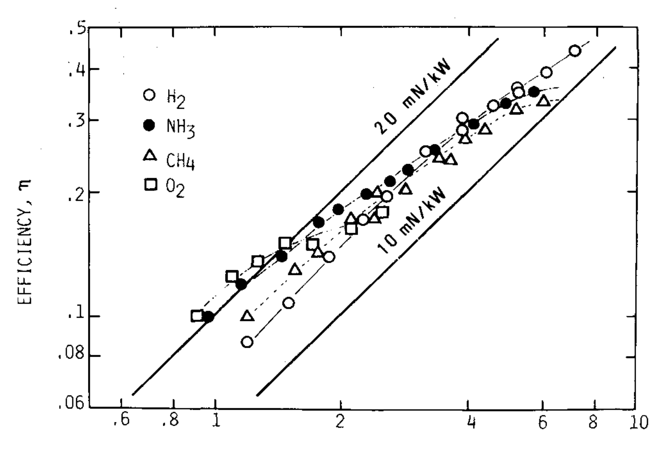

Fig. 5 Thrust efficiency vs specific impulse.

free path is estimated to be 0.05 cm, which is smaller than the typical chamber dimension. In such a situation, where there is a high gas enthalpy due to a large particle density accompanied by a large heat input and where particle collisions are sufficiently frequent to effect thermalization, an aerodynamic effect for thrust generation can be reasonably inferred. The above consideration also aids in the understanding of the exceptionally poor performance exhibited by helium, as shown in Fig. 6. The helium plasma may be ineffective in utilizing Joule heating energy for the aerodynamic thrust because its elastic-collision cross section is small compared with the case of hydrogenous gases.[5,6]

Second, molecular gases such as oxygen and ammonia have large thrust-to-power ratios at relatively low I_{sp}. Two reasons may be suggested for this behavior. One is the low ionization potential for molecular ions, i.e., 10.2 eV for NH_3 and 12.2 eV for O_2. The other is the reversion of their ionization energy to kinetic energy through the three-body recombination or the dissociative recombination.

$$O_2^+ + e + M \rightarrow O_2 + M + \mathrm{K.E.} \tag{5}$$

$$O_2^+ + e \rightarrow O + O + \mathrm{K.E.} \tag{6}$$

where M represents the third particle required for energy/momentum conservation. The rate equation of the latter reaction is

$$\frac{\mathrm{d}[O_2^+]}{\mathrm{d}t} = -k[O_2^+][e] \tag{7}$$

where k is the rate coefficient, $\sim 10^{-7}$ cm^3 s^{-1} (Ref. 7), and brackets denote the number density. With electron number

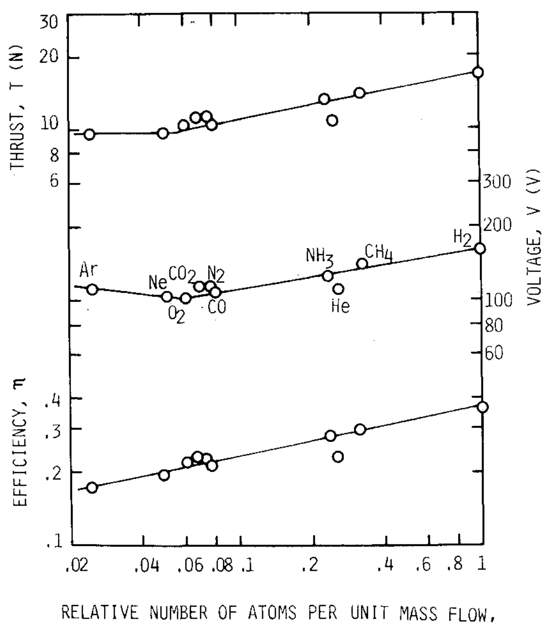

Fig. 6 Gas species comparison of thrust, voltage, and thrust efficiency (7.8 kA, 0.3 g/s).

density estimated to be about 10^{15} cm^{-3} in the discharge region, the characteristic time of reaction is $1/k[e] \simeq 10^{-8}$ s. As the flight time of ions across the chamber is about 10^{-6} s or more, the energy reversion may well be affected.

Thus, it is concluded that use of certain species of molecular gas in MPD arcjet enhances the thrust generation beyond what may be predicted by theory of electromagnetic acceleration due to the aerodynamic effect.

Erosion Test

Table 1 summarizes, for several gases, the cathode weight loss after the discharge of 100 to 200 shots at 7.8 kA. The mass flow rates were adjusted to the appropriate "critical" values of interest in the η-I_{sp} characteristics (Figs. 4 and 5). The minimum weight increment that could be measured was 0.1 mg. During this test, the anode erosion was not measured because the damage was not as severe as that for the cathode. Significant mass losses of the floating electrode and the inside surface of the insulator (Fig. 1) could not be detected.

From Table 1, it will be found that:

1) The mass loss for oxygen propellant is comparable with that for argon. Although the oxidation was expected to enhance the erosion, this observation suggests that the chemical effects are not dominant in the strongly ionized plasma.

2) Thus far, the erosion is known to be proportional to the discharge current.[8] If the mass loss per unit electrical charge is plotted against the maximum atomic mass found in the propellant molecule, the former clearly decreases with the latter increased. This fact may be attributable to the cathode bombardment by the atom of higher mass which facilitates electron emission so that localized heating is thereby avoided.

3) The voltage fluctuation, which is often thought to be a feature of hydrogen gas operation, may be related to the electrode erosion.

With respect to item 3 above, the cathode surface after the test in hydrogen gas showed especially severe and irregular cracks. The cracks are thought to be formed by the thermal stress due to the cathode spots and repeated discharges. Once cracks are formed, interruption of the heat transfer from the arc spot to its surroundings increases the erosion. These phenomena occur under the cold condition of the electrode[9] as in this test. Although a new cathode was used for each gas in this test, some uncertainty remains concerning the absolute value of the mass loss, because the 100 to 200 shots might not have been sufficient to make the effects of differences in the initial condition of the cathode surface insignificant.

Selection Criteria

In the selection of a propellant for MPD thrusters to be used in space, the following factors should be considered.

1) Superiority in thrust performance. For specific impulses more than 2000 s, the hydrogenous gases are advantageous.

2) Resistivity against the electrode erosion. Contrary to the above results, molecular gases containing hydrogen atoms are disadvantageous.

3) Minimal risk of space environment pollution. In the future MPD arcjets would be used as the main thruster with a large amount of exhaust plasma to transport such large space structures as SPS (Solar Power Satellites). For this service

Table 2 Characteristics[a] of propellants

Item[b]	H_2	He	CH_4	NH_3	Ne	N_2	CO	O_2	Ar	CO_2	Xe	H_2O
Thrust performance	1	2	1	1	2	2	2	1	2	2	3	1
Electrode erosion	3	2	2	2	2	2	2	1	1	2	1	2
Impact on environment	1	1	1	1	2	1	1	1	3	1	3	1
Storability as liquid	3	3	1	1	3	2	2	3	3	1	3	1
Cost	1	3	1	1	3	1	1	1	1	1	3	1

[a]1: good, 2: acceptable, 3: poor. [b]Items such as EMI and spacecraft contamination should be assessed.

heavy particles are not desirable because they may cause such special disturbances as an increase of radiation dosage in the Van Allen belt and severe distortion of the particle distribution in ionosphere or magnetosphere.[10] Therefore, the working gas should consist of atoms which already exist in the space, for example, nitrogen, oxygen, hydrogen, etc.

4) Storability in the liquid state. Here, methane, ammonia, etc., are advantageous. The water, although not actually tested in the present study, appears promising by analogy to the present experimental results.

5) Low cost. The use of a large quantity of xenon and helium would be prohibitively costly.

6) Low level of EMI (electromagnetic interference). As far as judged from the voltage fluctuation, the noisiest will be hydrogen. It will be necessary to investigate whether this noise results in electromagnetic radiation or conduction.

7) Minimum contamination of spacecraft, satellites, and solar panels. A systematic investigation of this topic is necessary in the future.

Table 2 summarizes the above as assessed by the data obtained in the present study and by literature survey.

Summary and Conclusion

In the testing of an MPD arcjet with various propellants, the following results were obtained:

1) Molecular gases used as MPD arcjet propellant showed high-thrust efficiencies over a wide range of specific impulses.

2) Aerodynamic acceleration made a significant contribution to the thrust when molecular gas propellants were used.

3) Except for hydrogen, molecular gas propellants caused only modest erosion on the cathode.

4) When the oxygen is used, contrary to expectation, the cathode erosion was held to the same level as that obtained with argon.

5) When assessed from such other aspects as cost, ease of storage, and liability to space polution, methane and ammonia were found to be desirable propellants for MPD arcjets.

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