Optimization of Current Distribution in an Applied-Field MPD Thruster

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Abstract

Steady-state, applied-field MPD thrusters have been constructed. Varying propellant type, strength and pattern of applied magnetic field, discharge current and mass flow rate, thruster performance tests were conducted. Thrust efficiencies of more than 20% were obtained for hydrogen, helium and argon. On the other hand, the performance of nitrogen was low. Thruster performance was found to be closely related to the discharge current distribution. When it is distributed downstream, electromagnetic thrust is produced by interaction with the applied field. Current distribution was found to be determined mainly by propellant type and operating mode. Using a segmented-anode MPD thruster, positive control of current distribution was attained suggesting the feasibility of thruster performance enhancement.

Nomenclature

B =magnetic field
B₀ =applied magnetic field strength
e =charge of electron
e₀ =applied magnetic field strength at cathode tip
E =electric field
I =discharge current
I₁ =discharge current of anode 1 (upstream discharge)
I₂ =discharge current of anode 2 (downstream discharge)
J =current density
k =Boltzmann's constant
n =plasma number density
P =electron pressure
r₁ =effective anode radius
R =effective anode radius
Rₐ =effective cathode radius
r, θ, z =cylindrical coordinate (the exit plane of the downstream coil is defined as z=0)
T =thrust
Te =thrust due to conversion of rotational motion
Tₑ =electron temperature
U =velocity
u₀ =velocity defined by Eq. (2)
uᵩ =velocity defined by Eq. (3)
V₁ =discharge voltage of anode 1 (upstream discharge)
V₂ =discharge voltage of anode 2 (downstream discharge)
Vₑ =electrical conductivity
e₁ =electron Hall parameter
nₑ =electron number density

Introduction

Potential advantages of a steady-state MPD thruster for application to future space mission have been recognized as being its high thrust density, structural simplicity and high power capability etc. However, many problems exist before a practical thruster can be realized. Further work should be focused upon enhancing thruster performance without paying a 'painful' price. In order to improve thruster performance and operating stability, most steady-state MPD thrusters have been designed with externally-applied magnetic fields. However, application of a strong magnetic field is not necessarily the best way of increasing performance since it can cause such operating instabilities as current spokes and can necessitate an moderate increase in weight and electrical power requirements of a thruster system.

A permanent magnet MPD thruster was investigated in our previous study. For hydrogen, a thrust efficiency of 25% at a specific impulse of 7700 sec was obtained, though it gave a low thrust/power ratio. On the other hand, heavier propellants such as argon provided higher thrust/power ratio, but at very low thrust efficiencies. The difference in performance between the propellants was found to be closely related to the current distribution in the discharge region. For hydrogen the discharge current was distributed downstream and a large azimuthal Hall current was induced, implying considerable electromagnetic acceleration caused by the applied field occurred. On the contrary, much of the current was distributed in the upstream region for argon.

The purpose of the present investigation is to obtain higher thruster performance in a wider operating range. The key seems to lie in better understanding of the acceleration mechanism in which the differences between the propellants originate. It also lies in developing a method of obtaining an optimum current distribution.

Steady-state MPD thrusters using solenoidal coils have been constructed. Four species, hydrogen, helium, nitrogen and argon, were used as a propellant. Utilizing a newly designed thrust stand, thruster performance was investigated with the intention of obtaining the optimum operation for each propellant. Furthermore, various methods were tried in order to obtain a current distribution favorable towards electromagnetic acceleration.
Experimental Apparatus

Two types of steady-state operating MPD thruster were constructed in this study. The thruster shown in Fig. 1 is characterized by two solenoidal coils to which coil currents can be supplied separately. The cathode is made of 2% thoriated tungsten and has a diameter of 8 mm with a conical tip. The anode, made of copper, has a throat diameter of 8 mm, a throat length of 5 mm and a nozzle exit diameter of 44 mm. The anode, cathode and solenoidal coils are water-cooled. The insulator between the electrodes is made of boron nitride. It is enclosed with a newly developed ceramic spacer, which was found to be durable in thruster operation of more than 10 kW. The propellant is tangentially injected upstream of the electrodes.

A segmented-anode MPD thruster is illustrated in Fig. 2. The anode is separated into two electrically isolated sections at the nozzle throat. A boron nitride spacer (1mm-thick) and a mica sheet are inserted between the two anode sections. The anode throat section has a diameter of 8 mm and a length of 10 mm, while the anode exit diameter is 58 mm. Each section is water-cooled, and connected to a separate power supply. The cathode section is identical to that of the former thruster.

Each thruster is mounted on a newly-designed (based on the ISAS model), pendulum type thrust stand (Fig. 3). Special attention has been devoted to eliminate the effects of emitted heat from the exhaust plume and of thrust stand friction on thrust measurement. It is composed of a vacuum bellows and two radial bearings. The vertical position of the fulcrum is adjustable, thereby allowing atmospheric pressure and the weight of the stand itself to be supported by the bellows. Hence, no radial load is exerted on the bearings. Resolution of the thrust measurement, which is mainly determined by the friction of feed lines, was 2 mN. Discharge current, coil current, cooling water and propellant are fed through seven 8mm-diam. copper tubes which go through the stand arm. Filling the inner space of the stand arm with insulating silicone oil, the stand itself is sufficiently cooled. In order to minimize the drift of the zero point caused by heat flux from the plasma, the thrust stand and the vacuum chamber wall are shielded from plasma radiation with water-cooled copper plates. Thrust was calibrated with a pulley and weight arrangement in air. And sensitivity of the stand was checked during thruster operation in vacuum.
forms a diverging magnetic field in the discharge region. The C2S-type represents the field produced by two coils connected in series; in this case, coil currents are supplied in the same direction. Its field divergence is smaller and field strength in the downstream region larger than that of the C1-type. Supplying the coil currents in opposite directions, a cusp field is formed in the vicinity of the thruster nozzle exit. This pattern was tested in the expectation that discharge current would be distributed on the cusp location.

The experiments were performed in a 0.8-m-diam., 2.5-m-long stainless steel vacuum tank. It was evacuated by a 22-inch-diam. oil diffusion pump backed by a mechanical booster and rotary pumps. A tank pressure of 6x10⁻⁷ Torr was maintained at an argon mass flow rate of 9 mg/s.

Results and Discussion

Operating conditions are summarized in Table 1. For hydrogen and helium, applied field strength is small; higher field strength resulted in operating instability and decreased performance (see the section on Hall current). However, due to relatively high discharge voltages, thruster power was high for these propellants.

Effect of Applied Field Pattern

A comparison of thruster performance was made among the three applied field patterns shown in Fig. 4. The C1-type represents the magnetic field pattern produced by a single solenoidal coil. It forms a diverging magnetic field in the discharge region. The C2S-type represents the field produced by two coils connected in series; in this case, coil currents are supplied in the same direction. Its field divergence is smaller and field strength in the downstream region larger than that of the C1-type. Supplying the coil currents in opposite directions, a cusp field is formed in the vicinity of the thruster nozzle exit. This pattern was tested in the expectation that discharge current would be distributed on the cusp location.

Fig. 5 shows thrust efficiency vs. discharge current for these three field patterns. Although the values of attainable field strength are different, a comparison was made at a field of 0.15 T at the cathode tip, which was the largest value obtainable by the C20-type. In spite of the expectation mentioned above, the performance of the C20-type (cusp field) was much lower than those of the diverging fields. In the vicinity of the cathode, the applied field's contour and strength are almost the same for each field pattern. Hence, when a propellant

Table 1: Operating condition

<table>
<thead>
<tr>
<th>Propellant</th>
<th>( \dot{m} ), mg/s</th>
<th>( B ), T</th>
<th>( I_d ), A</th>
<th>( I_d V_d ), kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2 )</td>
<td>0.9 - 1.2</td>
<td>0.05</td>
<td>150-400</td>
<td>5.5 - 15.9</td>
</tr>
<tr>
<td>( He )</td>
<td>1.8 - 2.4</td>
<td>0.025</td>
<td>70-400</td>
<td>3.5 - 14.8</td>
</tr>
<tr>
<td>( N_2 )</td>
<td>8.4 - 12.6</td>
<td>0.05</td>
<td>70-400</td>
<td>2.2 - 8.3</td>
</tr>
<tr>
<td>( Ar )</td>
<td>9.0 - 15.0</td>
<td>0.05</td>
<td>70-400</td>
<td>2.4 - 7.9</td>
</tr>
</tbody>
</table>

Fig. 4: Applied magnetic field pattern.

Fig. 5 Effect of applied magnetic field pattern on thruster performance.
in which discharge current tends to
distribute upstream is used, discharge
current is not greatly affected by the
downstream field pattern.

Better performance was obtained with
the C2S-type than with the C1-type. It is
thought to result from larger field strength
in the downstream region, which is effective
in confining the plasma there. Such a field
pattern was favorable to performance at
low field strengths. In fact, an increase in
field strength made the difference smaller.

Thruster Performance

Thruster performance of the 2 coil
thruster with the C2S-type field pattern is
summarized in Fig. 6. Thrust efficiency of
more than 20 % was obtained for hydrogen,
helium and argon. For hydrogen and helium,
however, the thrust/power ratio obtained
was low; at most 7.2 mN/kW for hydrogen and
15.2 mN/kW for helium, respectively. On the
contrary, large thrust/power ratio, more
than 40 mN/kW, was obtained for argon. High
performance for argon was obtained in a
characteristic operating mode to be
discussed later. When nitrogen was used as a
propellant, performance obtained was
relatively low.

It has been pointed out that
electromagnetic thrust produced in an
applied-field MPD thruster increases
proportionally to the approximate product of
discharge current, \( I_d \), and applied field
strength, \( B \). However, in this study,
thrusts obtained at the same product of \( I_d B \)
but for different propellants or at a
different mass flow rate, \( \dot{m} \), are
considerably different. And yet, a close
correlation was obtained by including the
effect of \( \dot{m} \):

Fradkin et al.\(^{11} \) gave a formula for the
thrust due to conversion of rotational
to axial motion of plasma, \( T_r \), such that,

\[
T_r = \frac{1}{2} I_d B R_a \left[ 1 - \frac{3}{2} \left( \frac{R_c}{R_a} \right)^2 \right] \quad (1)
\]

where \( I_d \) is discharge current, \( B \) is applied
field strength, and \( R_c \) and \( R_a \) are the
effective radii of the anode and cathode,
respectively. Through the measurement of
plasma density by a Langmuir probe, the half
value width of plasma density was found to
be almost as large as \( R_a \) near the exit of
the thruster nozzle. Hence, the maximum
velocity obtained by this mechanism, \( U_{br} \),
can be estimated by the following equation,

\[
U_{br} = \frac{1}{2} \frac{I_d B R_a}{\dot{m}} \quad (2)
\]

And exhaust velocity of the plasma is
estimated by,

\[
U_{ex} = \frac{T}{\dot{m}} \quad (3)
\]

Fig. 6 Thruster performance of 2 coil
MPD thruster (C2S-type).

Fig. 7 shows the relationship between
\( T/\dot{m} = U_{ex} \) and \( I_d BR_a / \dot{m} \). Equation \( U_{ex} = U_{br} \)
is also plotted. As shown in this figure, these
data are categorized into two groups. The
upper group contains data for hydrogen and
helium. Relatively high performance was
obtained in this group. The lower one
contains mainly that for nitrogen. Data for
argon is distributed in both groups
depending on the operating mode. This will
discussed later.

Fig. 7 T/\dot{m} vs \( I_d BR_a / \dot{m} \) (equation \( U_{ex} = U_{br} \)
is also plotted).
As $U_0$ is estimated assuming that $R/R_0 < 1$, and substituting the value at the cathode tip into $B$, $U_0$ may be an overestimation. Yet, $U_x$ exceeds or is almost the same as $U_0$ in the upper group. This phenomenon cannot be accounted for by the above mentioned acceleration mechanism alone.

**Hall Current**

Using a solid-state, Hall-effect sensor, azimuthal current density in the exhaust plume was measured. Large current density was measured for hydrogen and helium. On the contrary, no azimuthal current was detected for nitrogen and argon. Figure 8 shows radial distribution of azimuthal current density near the exit of the thruster.

**Generalized Ohm’s law in a fully ionized plasma is,**

$$J = \sigma_0 \left( E + U \times B - \frac{J \times B}{ne} + \frac{\nabla P_e}{ne} \right)$$  \hspace{1cm} (4)

Here, major components of azimuthal current are $\sigma_0 U_B$ and $(\sigma_0/ne) J_B$. The former term is current induced by motional electromotive force and the latter term which is approximately given by $(\omega \tau_e) J_B$ is Hall current. These two terms have opposite signs. Measured azimuthal current, $j_\theta^e$, is then

$$j_\theta^e = (\omega \tau_e) J_B - |\sigma_0 U_B|$$ \hspace{1cm} (5)

Fig. 8  Radial distribution of azimuthal current density ($z = 8$ mm).

**Fig. 8**  Radial distribution of azimuthal current density ($z = 8$ mm).
where the direction in which the applied magnetic field is cancelled is defined to be positive. Using typical values, \( n = 1.1 \times 10^7 \) m\(^{-2}\), \( kT = 4.8 \text{ eV} \), \( B = 2.4 \times 10^4 \text{ T} \), \( u = 4.7 \times 10^4 \text{ m/sec} \) (estimated by \( T/m \)) and \( B/B_0 = 0.05 \) (H, \( B = 0.075 \text{ T} \), \( I = 260 \text{ A} \), \( z = 8 \text{ mm} \), \( r = 5 \text{ mm} \), the Electron Hall parameter is calculated to be 150. And the second term of Eq. (5) is estimated to be 60 A/cm\(^2\). Its absolute value is comparable to that of measured current density but in the opposite direction. Under the operating conditions shown in Fig. 8, Hall current is greater than the second term.

**Dependence of current density on the applied field strength** is different for each propellant. For hydrogen, current density is relatively high and almost independant of the field strength. On the other hand, current density is a strong function of field strength for helium. Field strengths larger than 0.075 T made thruster operation unstable and the sign of the Hall-effect sensor output reverse and/or nonaxisymmetric at a helium mass flow rate of 1.8 mg/sec (see Fig. 9-(2)). This implies that the Hall current becomes smaller than the other component and/or the discharge current pattern is not axisymmetric. Moreover, at high field strengths, thrust was observed to decrease and thruster operation became unstable, resulting in unreproducible thrust data.

**Fig. 10** shows thrust as a function of applied field strength. For hydrogen, thrust is approximately a linear function of applied field, \( B \). On the other hand, thrust increases almost in proportion to \( B^2 \) for helium. Electromagnetic forces, \( j_\theta B_\theta \) and \( j_\phi B_\phi \), are produced by interaction between the azimuthal current and the applied field. The \( j_\theta B_\theta \) term is an electromagnetic force directed axially, which acts exactly the same as the 'blooding force' in a self-field MPD thruster. The \( j_\phi B_\phi \) term is a radial force. It confines the plasma toward the axis. This component is balanced by the radial gas pressure gradient and the centrifugal force of the rotating plasma. The solid body of the thruster undergoes gas pressure pumped up by the radial force; thereby producing a thrust component ('pumping force'). Thrust related to both components scale with \( j_\phi B_\phi \). The variation of the azimuthal current density and applied field strength for both propellants.

**Fig. 10** Variation of thrust with applied magnetic field strength for hydrogen and helium.

As stated in the section on thruster performance, for the two species of heavier atomic weight, high performance was obtained only for argon. Thruster operating...
characteristics of these propellants are shown in Fig. 11. For argon at low discharge currents, operation at high voltage with large thrust, which in this paper will be referred to as 'high voltage mode' was observed. In this operating mode, both thrust and discharge voltage increase with increasing discharge current. This operating mode is obtained only with a strong field. High thruster performance was obtained in this mode. However, increasing the discharge current past a certain point resulted in a transition from high voltage mode to 'low voltage mode' with lower thruster performance. The transition also occurred in the opposite direction with decreasing current. The value of discharge current at which the transition occurred ranged from 110 A to 125 A in each operation. From visual observation, the exhaust plume in high voltage mode was brighter than that in low voltage mode even though the input power in the former mode is almost the same as or less than that in the latter mode.

When nitrogen was used as a propellant, operation mode transition was not observed. The discharge voltage decreases and thrust increases with increasing discharge current. When both discharge current and applied field are low, discharge voltage becomes high. It is thought to be caused by a sharp decrease in electrical conductivity of the plasma.

Some observations that a thruster can operate in more than one voltage mode have been reported. Condition of the cathode and position of electrodes etc. have been suggested as causes. However, as of yet, this phenomenon is not fully understood. In this paper, a qualitative explanation of this phenomenon is made.
Two independent discharge modes are assumed here. One will be referred to as 'upstream discharge' mode, in which arc discharge occurs in the upstream interelectrode region (Fig. 12-(1)-1) and voltage-current characteristics are governed by the ionization process of the propellant. For this mode it is thought that the discharge voltage will fall with increasing arc current much the same as a 'static voltage-current characteristic' (Fig. 12-(2)-1). Another one is 'downstream discharge' mode (Fig. 12-(1)-2). In this mode, electromagnetic acceleration occurs by the interaction with the applied magnetic field. Thus discharge voltage can be assumed to increase with increasing discharge current (Fig. 12-(2)-2). Although the discharge characteristics of the latter are affected by those of the former, they are assumed to be independent of each other in the present discussion.

Thruster operating point is determined by a matching up of these discharge characteristics. For example, in Fig. 12-(3)-3, the width of the graph represents total discharge current, and the distances from the left side and the right side of the graph are currents of the upstream and downstream discharge, respectively. Discharge voltage and current ratio are determined at the intersection point. At a lower discharge current, however, two intersection points exist (Fig. 12-(3)-1,2). If the higher discharge voltages (points a, b) are chosen as an operating point, discharge characteristics become such that discharge voltage and the ratio I_d/1 both increase with increasing discharge current. Fig. 12-(4) shows discharge voltage-current characteristics obtained through the process explained above. Tracing points a,b,c results in a voltage-current characteristic similar to that obtained for argon in the experiment.

According to this explanation, it may be concluded that a large portion of

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Fig. 12 Explanation of voltage mode.

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**Figures**

1. upstream discharge
2. downstream discharge

(1) discharge mode

1. upstream discharge
2. downstream discharge

(2) voltage-current characteristics of individual discharge mode

(3) determination of operating point

(4) discharge voltage-current characteristics
discharge current is distributed downstream and a considerable electromagnetic acceleration occurs in the high voltage mode. At this stage, what factors result in the high voltage mode has not been made clear. A quantitative analysis in order to clarify the difference between the propellants is to be conducted.

**Segmented-Anode MPD Thruster**

Kuriki et al. 16 have obtained an azimuthally uniform arc discharge with the anode segmented in that direction. In this study, an MPD thruster with an axially segmented anode was employed for the purpose of enhancing thruster performance with argon or nitrogen by electromagnetic acceleration (see Fig. 2). If a thruster has a single anode, thruster operation is determined at a single point (for example point c in Fig. 12-(j)-3). However, the thruster used here has two electrically isolated anodes (hereafter the upstream and downstream anode section will be referred to as anode 1 and anode 2, respectively), each of which is connected to a separate power supply. Hence, in an ideal operation, this thruster can be run with any current ratio as an operating point. By supplying a current larger than that of point c to anode 2, higher performance operation is expected.

![Fig. 13 Variation of discharge voltage, thrust and thrust efficiency with current ratio, I_2/I_4.](image)

A typical result is shown in Fig. 13. As predicted in the previous section, the discharge voltage of anode 2, V_2, increased with increasing I_2, whereas V_1 varied little. Thrust and thrust efficiency also rose with increasing the current ratio I_2/I_4. The operating point at which V_1 equals V_2 can be considered to be equivalent to the shift obtained with both anodes electrically connected to a single power supply ('single anode point'). As seen from this figure, thruster performance was enhanced by supplying to anode 2 a current larger than that of this point.

There are two factors which limit current ratio and thruster performance. One is considerable erosion of anode 2 at the juncture for large value of I. To solve this problem, anode cooling methods should be improved. Another factor is that there is an optimum current ratio above which thrust efficiency decreases even though it is not accompanied by severe anode erosion.

In spite of these problems, the result obtained in this experiment agrees with the presumption about the relationship between current distribution and thruster performance discussed above.

**Conclusion**

Thruster performance was proved to be closely related to the current distribution in an applied-field MPD thruster. When discharge current is distributed in the downstream region of the discharge chamber, large electromagnetic acceleration by the interaction with the applied magnetic field occurs resulting in high thruster performance. Current distribution was found to be determined mainly by the propellant type and operation mode. Some efforts towards positive control of current distribution were made in this study. The results of the segmented-anode MPD thruster suggest the feasibility of thruster performance enhancement by controlling the current distribution.

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