OPTIMIZATION OF CHANNEL CONFIGURATION OF HALL THRUSTERS

Kenji MIKAMI,* Kimiya KOMURASAKI,* and Toshi FUJIIWARA††

Abstract

The length of the acceleration channel is an important design parameter for Hall-type plasma accelerators. The effect of the channel length on the thrust efficiency and on the plume divergence has been examined experimentally and theoretically in this study. As a result, it was found that the optimum channel length is determined from the characteristic length for ionization and for ion-loss. The beam divergence angle of the exhaust plume is decreased with the increase in channel length. This is thought due to the beam-collimation effect of the acceleration channel itself.

1. Introduction

A Hall thruster is one of the electrostatic accelerators. It consists of axisymmetric electrodes and an acceleration channel in which radial magnetic fields are applied as schematically shown in Fig. 1. The radial magnetic fields reduce the electron conductivity and permits the plasma to sustain a large electric field between an anode and an external cathode. Since the electrons drift in the azimuthal direction by the interaction between the axial electric field and the radial magnetic field, their trajectories are closed in the annular channel. The trapped-electrons diffuse in the upstream direction in the channel and ionize the propellant gas. On the other hand, the ions are electrostatically accelerated in the downstream direction without collisions and are exhausted as beam ions. Since the channel is filled with quasi-neutral plasma, there is no space-charge limited current. Therefore, they can produce higher thrust density than conventional electrostatic thrusters. Furthermore, they are capable of operating in the wide Isp range by choosing proper discharge current, acceleration voltage and propellant gas. Because of these advantages, Hall thrusters are thought useful for applications to near earth missions [1,2].

They, however, still have three major problems to be overcome. The first is their low thrust efficiency compared with the conventional electrostatic thrusters. The second is the insulator erosion due to the ion sputtering which determines their life-time. [3,4,5] The third is the large exhaust-beam divergence which can cause the communication interference of the satellite. Several studies have been made on Hall thruster configurations to improve the thruster performance [6,7], and then the channel length was found to be one of the most important parameters that is related to both the ionization and the wall loss. The optimum channel length for high thrust efficiency would exist where the ion-production rate and the ion-loss rate are well balanced. The objective of this research is to get the information about the design-criteria of the channel length for good thruster performance by measuring the acceleration efficiency and the exhaust beam profiles.

Department of Aerospace Engineering, Nagoya University, Chikusaku, Nagoya 464-01, Japan.

* Graduate Student
†† Assistant Professor, Member AIAA
††† Professor, Member AIAA
2. Experimental apparatus and methods

Hall Thruster

A variable channel-length Hall thruster is shown in Fig. 2. It has an acceleration channel insulated with two ceramic cylinders. An anode is located at the upstream end of the channel and has twenty small apertures to uniformly feed the propellant gas into the channel. The channel length is variable by changing the anode-rings (1.5 - 10 mm wide). Magnetic pole pieces are made of iron and a solenoidal coil is set around the center pole of the thruster to apply the radial magnetic fields in the channel. The magnetic fields are uniformly aligned in the radial direction and the field strength is constant in the channel. Argon, Krypton and Xenon gases are used as a propellant, and their mass flow rate is regulated using a thermal valve mass-flow controller. The filament cathode, which supplies electrons to sustain the discharge and to neutralize the electrons, is set in front of the thruster exit instead of a hollow cathode for operation convenience. The filament is made of 2% thoriated tungsten wires coated with the double-carbonate powder to emit electrons easily. The discharge can be sustained without the external filament heating after the ignition. The distance between the cathode and the thruster exit is variable from 5 mm to 40 mm.

Equipments

The experiments are done in a vacuum chamber (φ1.0 m x 1.6 m) evacuated by two diffusion pumps rated at 5000 l/s and backed by a roots blower rated at 400 l/s and a rotary pump. The back-pressure is measured using an ionization gauge. The pressure was maintained in the order of 10⁻³ Torr during operation.

Three power supplies (for Main discharge, Magnetic coil and Cathode filament) are used for this thruster operating. In order to stabilize the discharge, 20 Ω resistor is added to the main discharge circuit. It takes a few minutes for discharge current to become steady state.

For the plume diagnostics, seven ion-collectors are arranged on three arcs at radii of 20, 30, 40 cm from the thruster as shown in Fig. 3. The collectors are all pointed at the center of thruster-exit. Each collector consists of a copper plate (2 cm x 5 cm) biased to -30 V.

Thruster performance evaluation

The thrust efficiency \( \eta_t \) can be expressed in a convenient form using several important parameters. [8]

\[
\eta_t = \frac{F^2}{2mV_dI_d} = \frac{IM_b V_m}{em V_d} = \eta_s \cdot \eta_a \cdot \eta_e \quad (1)
\]
where, $F$ is thrust, $I_b$ is the total beam-ion current at the thruster exit, $V_d$ and $I_d$ are the discharge voltage and current, respectively, $V_a$ is the average beam-ion energy, $\dot{m}$ and $M$ are the propellant mass flow rate and molecular weight, respectively. The acceleration efficiency $\eta_a$ is the ratio of the beam-ion current to the discharge current, and the propellant utilization efficiency $\eta_u$ is defined as the ratio of the exhausted beam-ion current to the equivalent propellant flow rate (A-eq.). $\eta_E$ is called the ion-energy efficiency defined as the ratio of the average beam-ion energy to the discharge voltage. Since $\eta_E$ is almost constant (0.6 - 0.8) in many of the thrusters and for various operating conditions, $I_b$ is the most important parameter to be measured for evaluating $\eta_a$.

**Total beam-ion current measurement**

Precise measurement of the total beam-ion current is necessary for evaluating the thruster performance. The total beam-ion current, $I_b(r)$, is obtained by means of the hemispherical integration of an angular beam-current distribution $f(\theta)$ (as shown in Fig. 4), which is obtained by using ion-collectors surrounding the thruster at radius $r$.

$$I_b(r) = \int_0^\pi f(\theta) r^2 \sin \theta d\theta d\phi$$  \hspace{1cm} (2)

The angular beam-current distribution was interpolated in the form of a polynomial function

$$f(\theta) = a_0 + a_1 \theta + a_2 \theta^2 + \cdots + a_n \theta^n = \sum_{i=0}^{n} a_i \theta^i$$  \hspace{1cm} (3)

$I_b(r)$ is calculated by summing the products of the coefficient $a_i$ and integral weight $w_i$.

$$I_b(r) = \sum_{i=1}^{n} a_i w_i, \quad w_i = \int_0^\pi r^2 \sin \theta d\theta d\phi$$  \hspace{1cm} (4)

$I_b(r)$ is plotted in Fig. 5. The beam-current is decreased with the increase in distance between the ion-collector and thruster exit. This is due to the resonant charge-exchange collisions between ions and neutral particles [9-12]. This reaction can be expressed for argon propellant as

$$Ar^+ + X \rightarrow Ar + X^+, \quad X^+ + e^- \rightarrow X$$  \hspace{1cm} (5)

where, $X$ stands for the neutral particles, and boldfaced characters represent high energetic particles.

Solid lines in Fig. 5 show exponential fitting for the measured beam current data. The lines indicate that the characteristic length for the beam-decrease is approximately 300 mm despite that the magnetic field strength ranges from 200 G to 600 G. Theoretically, the total beam-ion current, $I_b(r)$ can be expressed in the form.
where, the characteristic length for the charge exchange, \( L_{\text{ce}} \), is identical to \( l_{\text{nuc}} \alpha_{\text{ce}} \) (\( \alpha_{\text{ce}} \) and \( n_{\text{n}} \) are the resonant charge-exchange cross section and the neutral density, respectively). \( I_{b0} \) is the total beam current at the thruster exit \( (r = 0) \). \( L_{\text{ce}} \) obtained from the experiments are listed in Table 1 along with the theoretically calculated ones. It shows a good agreement between them. Therefore, \( I_{b0} \) can be precisely estimated from Eq. (6) when the back pressure and the collector location are known.

### Table 1 Characteristic length for the charge-exchange reaction

<table>
<thead>
<tr>
<th>Experimental</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>325 mm (200 Gauss)</td>
<td>320 ~ 480 mm</td>
</tr>
<tr>
<td>305 mm (600 Gauss)</td>
<td>(( T_i = 50 ~ 400 \text{ eV} ))</td>
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3. Results and discussions

**Acceleration efficiency**

Figure 6 shows the relationship between the channel length and the acceleration efficiency. In the case of Ar propellant, the maximum efficiency is marked at the channel length \( L = 4 \text{ mm} \), whereas with Kr or Xe propellant, their efficiencies decrease monotonically with the increase in the channel length, and their peak seems to shift toward the shorter channel length. Since both the ion-production rate and the ion-loss rate are expected to change with the channel length, the optimum condition is thought to be obtained where the ion production and loss are balanced.

The ion-loss to the insulator walls is mainly caused by the radial component of the distorted electric field. The electric field distortion is induced due to the curvature of the magnetic field lines \([5,6]\) and due to the presheath made on the insulator surface by thermal electrons as schematically shown in Fig. 7. In a practical thruster design, the fringe effect on the magnetic field lines is inevitable. In addition, the electron temperature should be high enough for sufficient ion generation. Therefore, the electric field distortion can be induced in every Hall thruster. Owing to this field distortion, the ion-loss rate should be increased with channel length. Let the ion-loss fraction \( \alpha \) proportional to the channel length to simplify the problem

\[
\alpha = \frac{I_{\text{loss}}}{I_p} = \frac{L}{L_{\text{loss}}} \tag{7}
\]

where, \( L_{\text{loss}} \) is a constant. Substituting Eq. (7) to the relationship \( I_p = I_b + I_{\text{loss}} \), the ion-beam current is written as a function of the channel length.

\[
I_b = (1 - \alpha) I_p = (1 - \frac{L}{L_{\text{loss}}}) I_p \tag{8}
\]
As for the ion production, the electron-impact ionization is the predominant ion-production mechanism in the channel, the total ion-production current is expressed by

$$I_p = S \int_0^L n_e n_n \langle \sigma v \rangle \, dz$$

(9)

where, $S$ is the channel cross-section area, $\langle \sigma v \rangle$ is the ionization rate coefficient and $n_n$ and $n_e$ are neutral and electron density, respectively. The continuous equation for neutral particles is

$$\frac{\partial (n_n v_n)}{\partial z} = -n_n \langle \sigma v \rangle$$

(10)

where, $v_n$ is the velocity of the neutral particles. Assuming $v_n$ and $\langle \sigma v \rangle$ are constant in the channel, Equation (10) is easily integrated as

$$n_n = n_{n_0} \exp\left(-\frac{z}{L_{\text{ioniz}}}\right) \quad \text{where,} \quad L_{\text{ioniz}} = \frac{1}{n_e \langle \sigma v \rangle}$$

(11)

The ionization length $L_{\text{ioniz}}$ is the distance necessary to ionize the propellant gas sufficiently. The theoretical ionization length for several propellant gases under the ordinary operation parameters is shown in Fig. 8.

In the experiments, it was difficult to ignite and sustain the discharge when Ne is used as a propellant and when $L$ is less than 2 mm. The reason can be explained from Fig. 8 as follows; the ionization length for Ne is longer than 10 mm which is the maximum channel length of our thruster, and the channel length $L < 2$ mm is too short to sufficiently ionize all the propellant gases. Substituting Eq. (11) into Eq. (9), the ion-production is expressed as

$$I_p = S n_n n_{n_0} \langle \sigma v \rangle \exp\left(-\frac{z}{L_{\text{ioniz}}}\right) \, dz$$

$$\propto 1 - \exp\left(-\frac{L}{L_{\text{ioniz}}}\right)$$

(12)

Using Eqs. (8) and (12), the ion-beam current can be expressed as a function of $L$.

$$I_b \propto \left(1 - \frac{L}{L_{\text{ioniz}}} \right) \left(1 - \exp\left(-\frac{L}{L_{\text{ioniz}}}\right)\right)$$

(13)

The $I_b-L$ profile has a maximum in the region of $0 < L < L_{\text{ioniz}}$. For example, Fig. 9 is plotted assuming $L_{\text{ioniz}} = 20$ mm, $L_{\text{ioniz}} = 5$ mm. The optimum channel length $L_{\text{opt}} = 5.2$ mm is very close to the ionization length. This is because, when $L > L_{\text{ioniz}}$, the ion-production rate tends to be saturated due to the lack of neutral particles in the channel, while the ion-loss rate is assumed linearly increased with the channel length.
The effect of magnetic field strength on the acceleration efficiency is shown in Fig. 10. The optimum channel length are hardly affected by the field strength, while the efficiency is increased with the field strength. The magnetic field strength have effects on not only the acceleration efficiency but also the discharge voltage. The one-dimensional electron diffusion equation in the axial direction is described as

\[ I_\text{e} = -e\mu_\text{e} n_\text{e} \frac{d\phi}{dz} + eD_\bot \frac{dn_\text{e}}{dz} \]  

(14)

where, \( D_\bot \) is the diffusion coefficient, \( \mu_\text{e} \) is the electron mobility and \( \phi \) is the space potential. If we assume the anomalous diffusion (Bohm diffusion), the coefficients of Eq. (14) can be expressed as

\[ D_\bot = \frac{kT_e}{16eB}, \quad \mu_\text{e} = \frac{1}{16B} \]  

(15)

Neglecting the density gradient, Eq. (14) can be integrated as

\[ \phi - \phi_0 = \frac{I_\text{d}L_e}{en_\text{e}} \cdot BL \]  

(16)

As indicated in this equation, the applied voltage is increased linearly with the product of the magnetic field strength and the channel length, \( BL \).

Figure 11 is a plot of the measured discharge voltage vs \( BL \). Since the plotted data are found to locate on a straight line, it can be concluded that the \( 1/B \) diffusion coefficient is more proper than the \( 1/B^2 \) classical diffusion coefficient to describe the electron motion in our thruster.

**Ion-Beam Profile**

Figures 12 shows the measured beam profile. The ion-collectors are set at 30 cm downstream of the thruster. The current density has a peak on axis and reduces to one half at about 40 degrees off-axis. By extending the channel length, the distributions become sharp. This is because the ions produced in the channel are collimated by the inner and outer channel walls as schematically shown in Fig. 13. With the short channel length, most of the produced ions can be extracted in the downstream direction without colliding with the walls. Their profiles, however, become dull because the exhaust beams have a wide angular distribution. On the other hand, with the long channel length, the ions are well collimated, resulting in a sharp ion-beam distribution. However, the ions produced in the channel depths are hardly exhausted as beam ions,
and the walls are sputtered by the accelerated ions.

4. Summary

The beam-ion profiles of a variable channel-length Hall thruster are measured to evaluate the thruster performance using a multi-ion-collector system. The total beam-ion current could be calculated by integrating the profile.

The results show that the acceleration efficiency has a peak at \( L = 4 \, \text{mm} \) with Ar propellant. The optimum channel length is thought to be obtained where ion-production rate and ion-loss rate are well balanced. From a theoretical consideration, the optimum length is found a function of the characteristic length for the ionization \( L_{\text{ion}} \) and the one for the ion loss \( L_{\text{loss}} \).

The angular beam-ion profiles have a peak on the center-line, with the intensity dropping by factors of 2 within 40 degrees of thruster axis. The increase in channel length makes the plume profile more sharply peaked. This is thought due to the beam collimation by the channel itself.

Fig.13 Ion-beam collimation

References


