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Oscillation Reduction of an Anode-Layer-Type Hall Thruster by Azimuthal Propellant Nonuniformity

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Discharge current oscillation in the frequency range of 10-100 kHz causes serious problems in using anode layer type Hall thrusters in space. As a novel approach to stabilize the discharge, azimuthally nonuniform propellant flow was created in an acceleration channel. A plenum chamber and hollow anodes were azimuthally divided into two or four sections and xenon flow rates supplied to them were controlled. As a result, the oscillation amplitude significantly decreased and oscillation-free operation was achieved at all magnetic flux densities.

Nomenclature

B	=	magnetic flux density
F	=	Thrust
I_d	=	discharge current
$\dot{m}$	=	propellant mass flow rate
$\dot{m}_{dif} / \dot{m}_{tot}$	=	normalized differential mass flow rate
$\dot{m}_{tot}$	=	total propellant flow rate
V_d	=	discharge voltage
Δ	=	oscillation amplitude
η_t	=	thrust efficiency
η_u	=	propellant utilization efficiency
τ	=	measurement duration

I. Introduction

A Hall thruster is one of the most attractive propulsion devices for near-Earth missions because of its high thrust efficiency at the specific impulse in the range of 1,000-3,000 s. Hall thrusters are generally categorized into the magnetic layer type and the anode layer type. The former type has a ceramic channel wall and its operation is very stable. Therefore, it has been used in many missions.[1-2] On the other hand, the latter type still remains under development. Anode layer type has a metallic channel wall kept at the cathode potential. This metallic wall decreases electron energy loss toward the channel wall and the electron temperature is kept high in the acceleration channel. Hence, ions are accelerated in a thin layer near the anode.[3] Because of these distinguishing features, the anode layer type has several advantages, such as high thrust efficiency, compactness and high erosion resistance.[4] However, its operation is unstable due to the discharge current oscillation[5-6] and limited in a narrow range of operational parameters. This is one of the serious problems in using it as a reliable satellite engine.

In particular, the ionization oscillation in the frequency range of 10-100 kHz has large amplitude and causes harmful effects on the operation. Operation in unstable region has the fear that the oscillation grows up and the operation is stopped. In addition, this oscillation enlarges the current capacity margin of power supply and increases its weight. Thus, unstable operation leads to low reliability and increase in bus system mass.

Figure 1 shows the typical operating characteristics with B. Here, oscillation amplitude Δ is defined as

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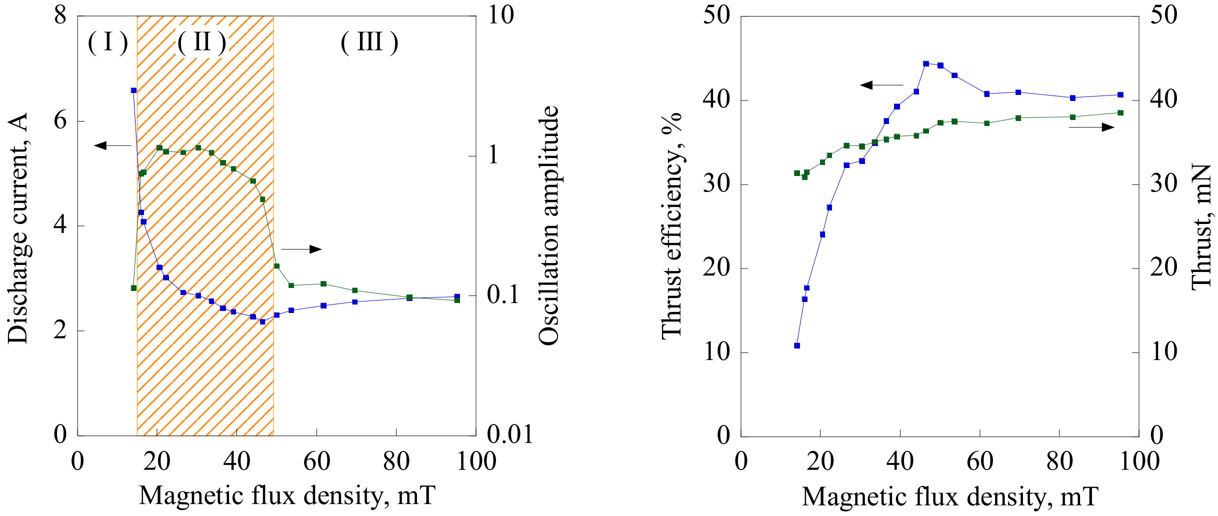


(a) Discharge current and oscillation amplitude

(b) Thrust efficiency and thrust

Figure 1. Typical operating characteristics of our anode layer type thruster with hollow anode: V_d = 250 V, $\dot{m}$ = 2.74 mg/s.

$$\Delta \equiv \frac{1}{\overline{I}_{d}}\sqrt{\frac{\int_0^{\tau}(I_d-\overline{I}_d)^2\,dt}{\tau}},\quad \left(\overline{I}_d=\frac{\int_0^{\tau} I_d\,dt}{\tau}\right) \tag{1}$$

As B increases, I_d decreases in the region I, II and slightly increases in the region III. Hence, η_t reaches its maximum at the lowest I_d point B = 46 mT. However, this operating point is included in the unstable region $15 < B < 50$ mT and the operation is limited to the lower η_t region I, III. In addition, because the spontaneous discharge ignition in the region III is difficult, for the operation in this region, B must be increased through the unstable region after the ignition in the region I, II. This also causes harmful effects on the power supply unit and brings about decrease in reliability. Therefore, in order to take advantage of anode layer type thrusters, it is necessary to stabilize the discharge near the maximum η_t point and widen the stable region.

Although several studies[6-7] have been conducted to stabilize the discharge, no method to achieve preferable operation has been found. According to the previous study, the ionization oscillation is the phenomenon that neutral density is periodically depleted due to the rapid ionization. It is caused by the electron density augmentation which is further accelerated through the ionization collisions with neutrals. As shown in Fig. 1, the discharge current oscillation is induced in the region II. The electron axial mobility decreases with increase in B in the region I and II, and increases again in the region III due to the shift of electron transportation regime from classical to anomalous diffusion.[8] Therefore, Δ becomes large in the region where the electron mobility is low. Thus, the oscillation characteristics are closely related with the electron mobility and its control is important for discharge stabilization.

This paper focuses on a discharge stabilizing effect of azimuthal nonuniform propellant flow rate as a novel approach. It was found out when the different flow rates in the right-and-left side was created to control the thrust vector, which is another key technology.[9-10] As described above, the electron mobility suddenly becomes large by the shift to anomalous diffusion regime. In the anomalous diffusion regime, the azimuthal fluctuation of electric field is induced by that of electron density. Because this electric field causes the electron axial drift, the electron mobility becomes large. Therefore, when the propellant gas is supplied at azimuthally nonuniform flow rate, the electron mobility is expected to be enlarged because of the electron density gradient in the azimuthal direction. In addition, the electron density gradient becomes large and electron mobility further increases when electron density is increased in an oscillation cycle, and on the contrary, the increase in electron mobility becomes small when electron density is decreased. Hence, the azimuthal nonuniformity of propellant flow rate is expected to prevent the excessive increase and depletion of electrons and stabilize the discharge. In this study, by using a plenum chamber divided into two and four rooms, the discharge stabilizing effects of azimuthally nonuniform propellant flow rate was investigated.

II. Experimental Apparatus

A. Hall Thruster

An anode layer type Hall thruster developed at the University of Tokyo was used in this study (Fig. 2). Its inner and outer diameters of acceleration channel are 48 and 62 mm, respectively. The guard rings made of stainless steel were kept at the same potential as the cathode. A hollow anode with the hollow width of 3 mm and anode-tip-to-thruster-exit distance of 3 mm was used. This configuration is the most effective one for discharge stabilization according to the past study.[7] Magnetic field in the acceleration channel was generated by a solenoidal coil on the thruster's central axis. A water cooling system was used to prevent coil overheating. A hollow cathode was used and xenon gas was supplied to it at 0.27 mg/s.

Figure 3 shows a segmented plenum chamber which can be divided into two or four rooms. Xenon gas as a propellant was supplied through four ports on the back surface of the thruster. Xenon flow rate through each port was independently controlled by two mass flow controllers (Fig. 4). In addition, the region inside the hollow anode was also divided into the corresponding four sections. The distance between the tips of separation walls and the hollow anode is 10 mm.

B. Vacuum Chamber

The vacuum chamber whose diameter and length are 2.0 and 3.0 m was used. The pumping system comprises four pumps: a diffusion pump (37000 l/s), a mechanical booster pump (10000 m^3/h) and two rotary pumps (15000 l/min). Throughout this experiment, the background pressure was kept under 5.0×10^{-3} Pa.

C. Discharge Current Measurement System

Figure 4 shows a schematic diagram of measurement system. In order to measure I_d, the voltage between the both ends of 0.5 Ω metal-film resistor, which was inserted between the anode and discharge power supply, was measured by an oscilloscope with a differential probe. In this experiment, 5 ms data of I_d was collected at the sampling rate of 10 MHz.

D. Thrust Stand

For thrust measurement, a two-axis dual pendulum thrust stand[10] was used. This thrust stand has two pendulums and four arms per pendulum. All joints between any two components consist of knife-edges and supporting point of each arm consists of two orthogonal knife-edges. Pendulums can move in the two directions: axial and transverse direction of a thruster. A thruster and sensor targets are mounted on the inner pendulum and two displacement sensors are set on the outer pendulum. The thermal influence from a Hall thruster is cancelled out by those pendulums. Because this thrust stand is the type put on the chamber, it is hardly affected by the chamber vibration. In this experiment, this thrust stand was used to measure only the axial thrust.

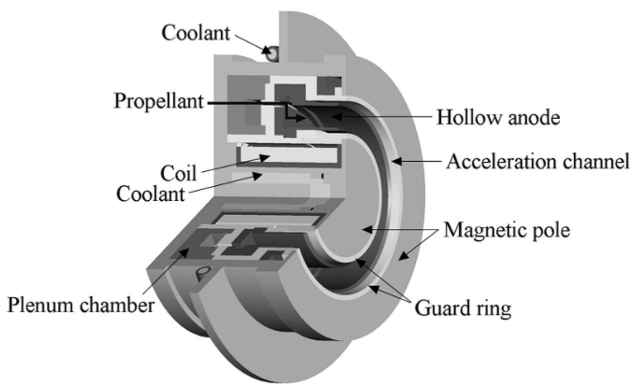


Figure 2. Cross section of the anode layer type Hall thruster developed at the University of Tokyo

Figure 3. A segmented plenum chamber

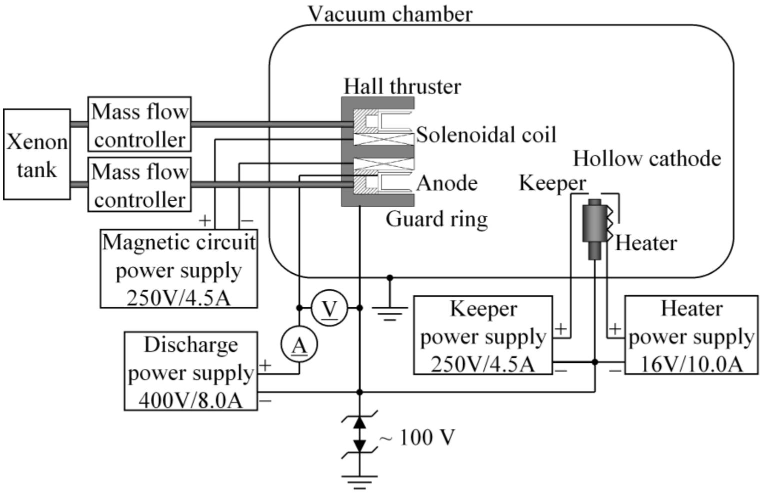


Figure 4. Power supply and measurement system

III. Experiment

In order to investigate the influence of azimuthal nonuniformity of propellant flow rate on discharge characteristics, the structure to supply xenon gas into the acceleration channel was divided into two and four sections in the azimuthal direction and the flow rate through each section was changed.

As a first step, the plenum chamber was divided into two right-and-left rooms and $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}} = (\dot{m}_{\mathrm{right}} - \dot{m}_{\mathrm{left}}) / (\dot{m}_{\mathrm{right}} + \dot{m}_{\mathrm{left}})$ was changed at the interval of 0.2. At each $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}}$, the variation of I_{d} with B was measured. V_{d} and $\dot{m}_{\mathrm{tot}}$ were kept at 250 V and 1.96 mg/s, respectively.

Second, the plenum chamber and the region inside the hollow anode was divided into four right, left, top and bottom sections in order to investigate the discharge stabilizing effects at the more practical condition without radial thrust deviation. Xenon flow rates through four sections were controlled so that $\dot{m}_{\mathrm{top}} = \dot{m}_{\mathrm{bottom}}$ and $\dot{m}_{\mathrm{right}} = \dot{m}_{\mathrm{left}}$. $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}} = (\dot{m}_{\mathrm{top,\ bottom}} - \dot{m}_{\mathrm{right,\ left}}) / (\dot{m}_{\mathrm{top,\ bottom}} + \dot{m}_{\mathrm{right,\ left}})$ was changed at the interval of 0.25 and the variation of I_{d} and F with B was measured. V_{d} was kept at 250 V. Although η_{t} exceeds 50% at $\dot{m}_{\mathrm{tot}} \geq 3.4$ mg/s, $\dot{m}_{\mathrm{tot}}$ was limited under 2.74 mg/s, which corresponds to $\eta_{\mathrm{t}} \approx 44\%$, for the measurement in the wide B and $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}}$ range including high I_{d}. In order to confirm that the discharge stabilizing effects don't depend on the thrust efficiency, this measurement was conducted at two conditions $\dot{m}_{\mathrm{tot}}$ =1.96, 2.74 mg/s.

The measuring B range was decided by the current capacity of power supply. The lower limits of B were due to the I_{d} capacity of discharge power supply. On the other hand, the upper limit of B depended on the coil current capacity. In some operating conditions, the operation stopped in the high B region below the upper limit of $B \approx 140$ mT.

IV. Results and Discussion

A. Discharge Characteristics at Azimuthally Two-segmented System

Figure 5 shows the influence of $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}}$ on Δ at the case that the plenum chamber was divided into two rooms. The discharge stabilizing effect by azimuthal nonuniformity of propellant flow rate was observed and Δ significantly decreased with $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}}$. The unstable region with large Δ became narrow and the stable region spread toward the high B side. The maximum Δ decreased from 1.6 to 0.2.

As shown in Fig. 6, I_{d} increased with $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}}$ in the whole B range. In addition, the slight increasing points of I_{d} existed near 20 mT and shifted toward the low B side as $\dot{m}_{\mathrm{dif}} / \dot{m}_{\mathrm{tot}}$ increased. This result indicates that the anomalous diffusion regime spread toward the low B side because the azimuthal fluctuation of electron density became easy to be induced in the lower B region. This expansion of anomalous diffusion regime region increased the electron mobility and reduced the oscillation in the unstable region.

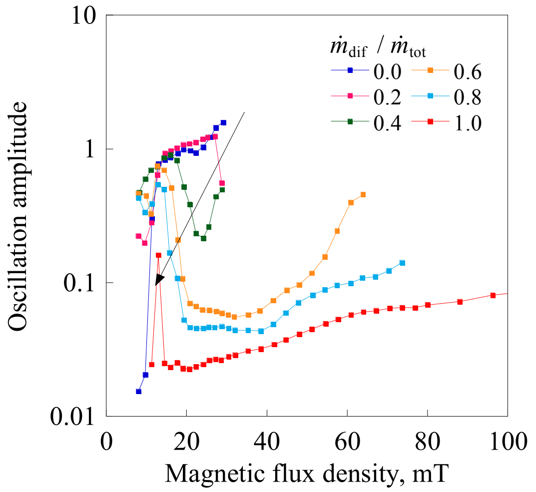


Figure 5. Oscillation amplitude: V_d = 250 V and $\dot{m}_{tot}$ =1.96 mg/s

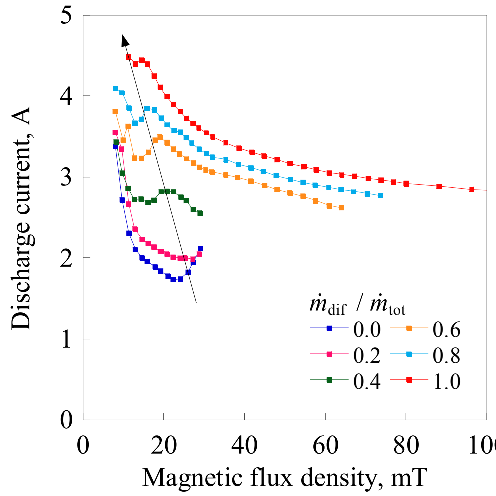


Figure 6. Discharge current: V_d = 250 V and $\dot{m}_{tot}$ =1.96 mg/s

B. Operating Characteristics at Azimuthally Four-segmented System

Figure 7 shows the variation of Δ with $\dot{m}_{dif}$ / $\dot{m}_{tot}$ at the case that the plenum chamber was divided into four rooms. When $\dot{m}_{dif}$ / $\dot{m}_{tot} \geq$ 0.50, the oscillation was significantly reduced. For $\dot{m}_{dif}$ / $\dot{m}_{tot} \geq$ 0.75, the oscillation-free operation that is stable in the whole B range was achieved. This discharge stabilizing effect appeared at both $\dot{m}_{tot}$ cases. From these results, the oscillation should be reduced by azimuthal nonuniformity of propellant flow rate even in the case $\eta_t \geq$ 50%.

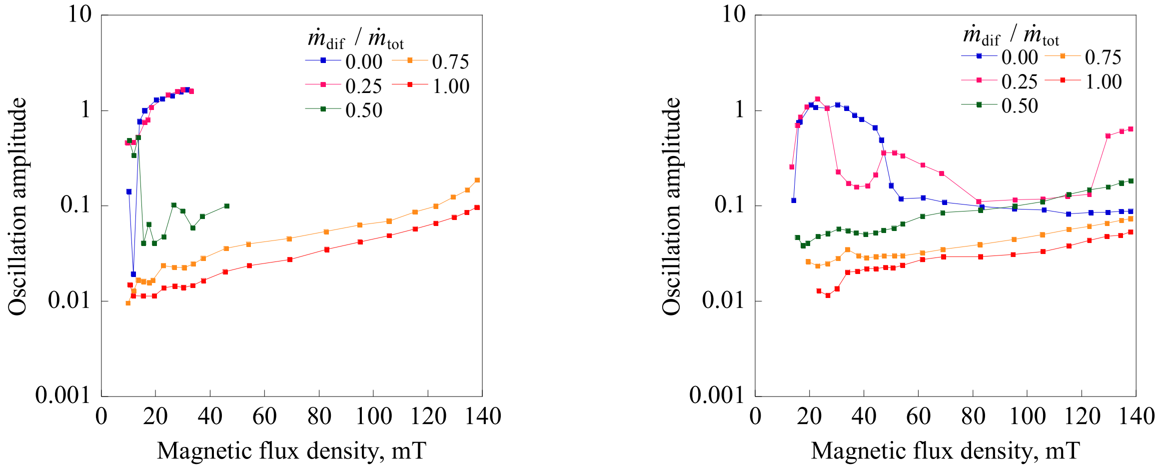
Figure 8 shows the variations of I_d with $\dot{m}_{dif}$ / $\dot{m}_{tot}$. In the same way as the above mentioned two-segmented case, I_d increased with $\dot{m}_{dif}$ / $\dot{m}_{tot}$ and the regime transition point from classical to anomalous diffusion shifted toward the low B side. As shown in the case $\dot{m}_{dif}$ / $\dot{m}_{tot}$ = 0.50 at $\dot{m}_{tot}$ =1.96 mg/s and $\dot{m}_{dif}$ / $\dot{m}_{tot}$ = 0.25 at $\dot{m}_{tot}$ =2.74 mg/s, this expansion of the anomalous diffusion regime region decreased Δ in the unstable region.

Figure 9 shows the variations of η_t with $\dot{m}_{dif}$ / $\dot{m}_{tot}$. η_t decreased with $\dot{m}_{dif}$ / $\dot{m}_{tot}$ particularly in the low B region where the operation was unstable at $\dot{m}_{dif}$ / $\dot{m}_{tot}$ = 0.0.

Figure 10 shows the highest η_t at each $\dot{m}_{dif}$ / $\dot{m}_{tot}$ and the corresponding Δ, I_d and F. Compared to the uniform operation $\dot{m}_{dif}$ / $\dot{m}_{tot}$ = 0.0, Δ significantly decreased by 90% at $\dot{m}_{tot}$ =1.96 mg/s and by 64% at $\dot{m}_{tot}$ =2.74 mg/s (Fig. 10 (b)). Here, $\dot{m}_{dif}$ / $\dot{m}_{tot}$ = 0.75 at $\dot{m}_{tot}$ = 1.96 mg/s and $\dot{m}_{dif}$ / $\dot{m}_{tot}$ = 0.50 at $\dot{m}_{tot}$ = 2.74 mg/s were selected for the comparison because these $\dot{m}_{dif}$ / $\dot{m}_{tot}$ are the lowest values to achieve the oscillation-free operation. F increased by 15% at $\dot{m}_{tot}$ =1.96 mg/s and by 11% at $\dot{m}_{tot}$ = 2.74 mg/s (Fig. (d)). F increase is due to increase in η_u; because neutral density increases in the high $\dot{m}$ section, a larger number of neutrals are ionized, which leads to high F. However, I_d also increased by 1.4 times at $\dot{m}_{tot}$ =1.96 mg/s and by 1.8 times at $\dot{m}_{tot}$ =2.74 mg/s (Fig. 10 (c)). As a result, the maximum η_t decreased by 7% at $\dot{m}_{tot}$ =1.96 mg/s and by 31% at $\dot{m}_{tot}$ =2.74 mg/s (Fig. 10 (a)).

In the case $\eta_t \geq$ 50%, the following behavior of F and I_d is expected. Because η_u is already high and hardly increased, only small F increment is possible. On the other hand, as $\dot{m}_{tot}$ increased, I_d increment increased because the azimuthal gradient of electron density increased. However, the required $\dot{m}_{dif}$ / $\dot{m}_{tot}$ to stabilize the discharge became low for high $\dot{m}_{tot}$. Therefore, the smallest I_d increment to stabilize the discharge will not be changed even in the high η_t case. These indicate slightly more decrease in η_t. Hence, the I_d increment, which is the main cause, should be minimized.

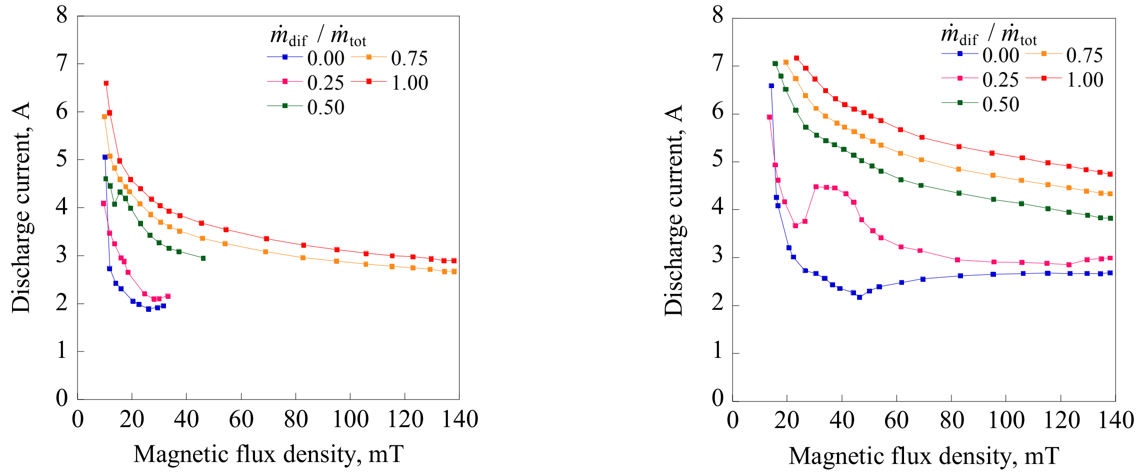
In this experiment, I_d increase, that is, the electron mobility increase was caused not only by anomalous diffusion but also by constantly existing gradient of electron density. However, it is not in the whole region but only in the unstable region that the azimuthal gradient of electron density is required. Therefore, it is preferable that electron density is uniform azimuthally at the stable region and nonuniform only at the unstable condition. This will be achieved by creating only azimuthally different oscillation frequency. In this case, the azimuthal gradient of electron density appears when Δ becomes large. Here, the oscillation frequency is affected by $\dot{m}_{tot}$, V_d, B, kinds of propellant gas, and so on. Therefore, in addition to azimuthal nonuniformity of propellant flow rate, controlling the other parameters is needed.



(a) 1.96 mg/s

(b) 2.74 mg/s

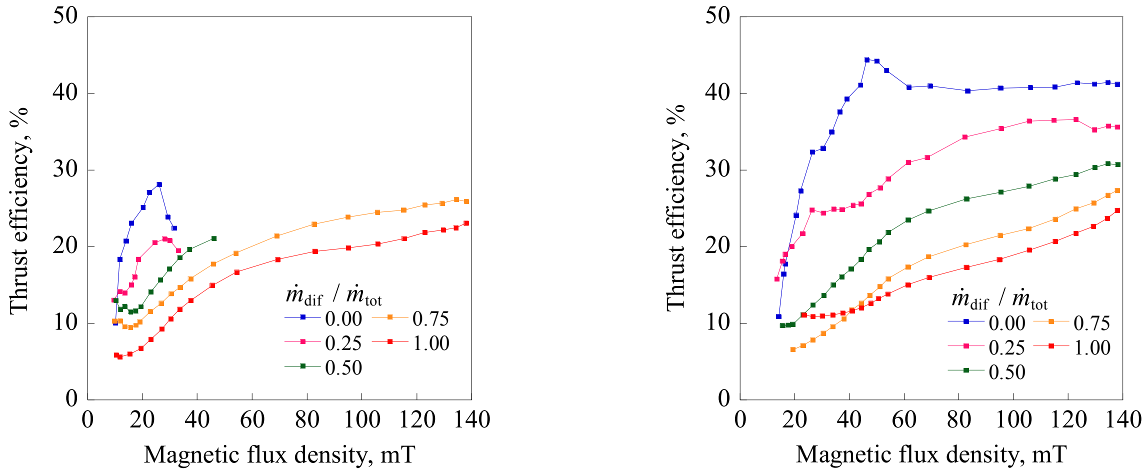
Figure 7. Oscillation amplitude: V_d = 250 V



(a) 1.96 mg/s

(b) 2.74 mg/s

Figure 8. Discharge current: V_d = 250 V



(a) 1.96 mg/s

(b) 2.74 mg/s

Figure 9. Thrust efficiency: V_d = 250 V

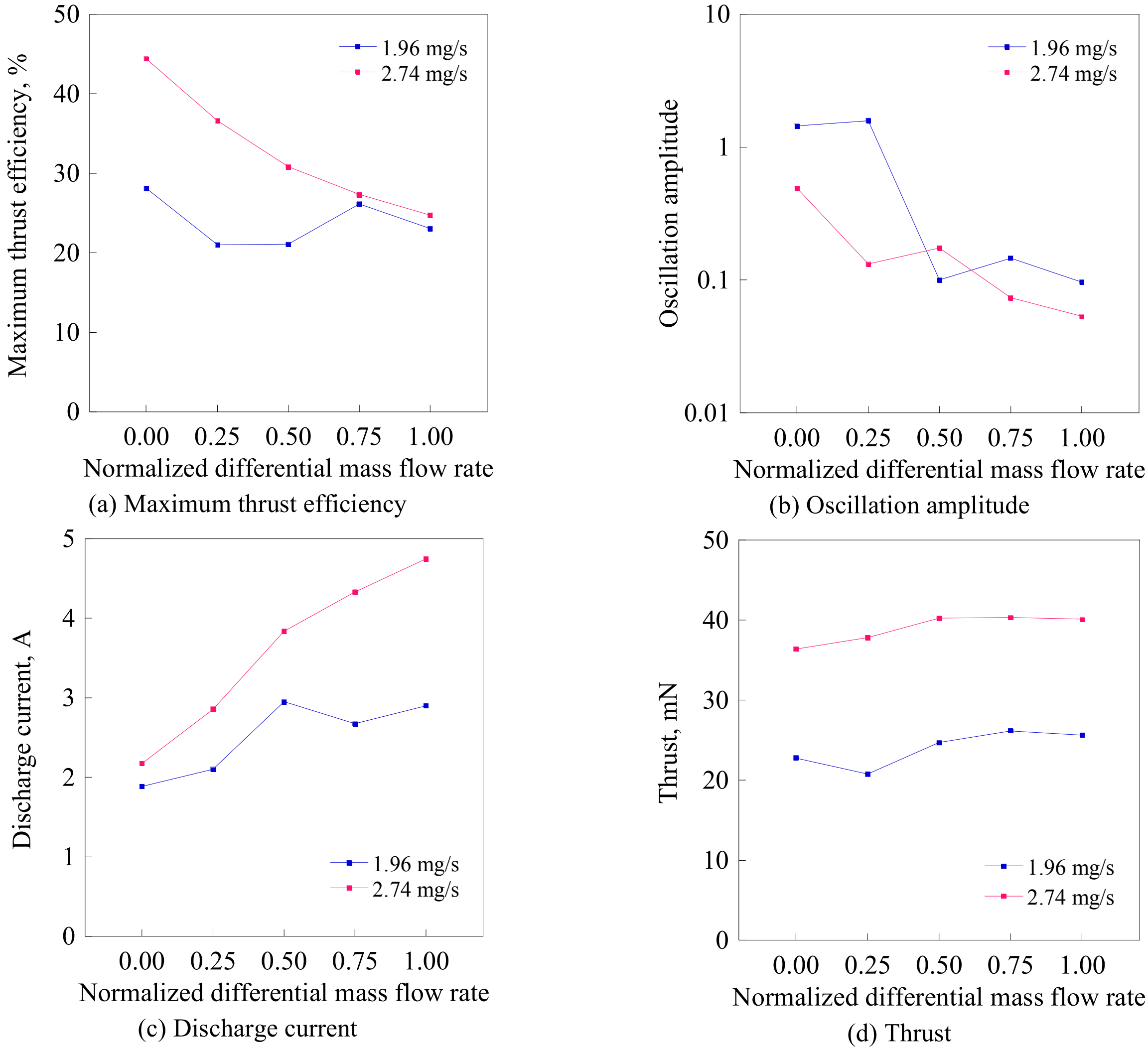


Figure 10. The maximum η_t at each $\dot{m}_{dif}$ / $\dot{m}_{tot}$ and the corresponding Δ, I_d and F

V. Conclusion

In this study, supplying propellant gas at azimuthally different flow rate was proposed as a novel approach to stabilize the discharge of an anode layer type Hall thruster. In order to investigate its discharge stabilizing effect, the plenum chamber was divided into two and four rooms and the azimuthally nonuniform xenon flow rate was created in an acceleration channel. As a result, the following effects were observed.

1) The unstable region became narrow and Δ significantly decreased. In addition, for high $\dot{m}_{dif}/\dot{m}_{tot}$, the oscillation-free operation that is stable in the whole B range was achieved.

2) The transition point of electron transportation regime shifted toward the low B side. This increased the electron mobility and reduced the oscillation in the unstable region.

3) At the maximum η_t, Δ decreased by 64%. However, although F increased by 11%, I_d increased by 1.8 times, which resulted in 31% decrease in η_t.

In order to achieve preferable discharge stabilization, I_d increment must be kept as small as possible. In addition to propellant flow rate, creating azimuthal nonuniformity of B or kinds of propellant gas is the next approach.

Acknowledgments

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