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Ion current oscillations and performances based on the cross-field ion transport model in Hall thrusters

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It is shown that simulation on the control of the discharge current oscillation is in good agreement with the experiments of TALT-2a Hall thruster by introducing the cross-field transport of Xenon ions in the channel of Hall thrusters. It is found for the first time that, when the ion mobility decreases, the ion current becomes more stable and the thrust efficiency is improved, by comparing with the experimental results. We mention the technical way to control the ion current oscillation and to improve the performance of Hall thrusters.

Keywords: Discharge oscillation, Ion transport, Simulation, Experiments, Hall thruster, Thrust efficiency

1. Introduction

The electric propulsion has been used for orbit correction of satellites as a compact thruster. Recently, as spacecraft scale up, thrusters with higher thrust and efficiency are required. We focus our attention on the Hall thruster among electric thrusters. The performance of Hall thrusters has been improved in Russia since 1960s. The Hall thrusters are expected to be used as main thrusters for near-earth missions in the United States and Europe because 1-2 kW class Hall thrusters can achieve a high performance of thrust 50-100 mN and thrust efficiency 40-50 % at specific impulses of 1000-2000 sec. However, the detailed physics, plasma characteristics and the ion acceleration process are still unclear [1-3]. These practical studies are required in order to improve the thruster performance by understanding the inner physical phenomena in the channel of Hall thrusters. In particular, since the discharge current instability causes the reduction of the thrust efficiency and the operational instability, we have to settle the instability of the discharge current and to improve the thrust efficiency. The investigation of the plasma oscillations associated with the collision between ions and neutrals has not been well-established in the field of the electric propulsion. It is important to develop a reliable model that improves our understanding of the factors which control discharge oscillation when we attempt to improve the existing Hall thruster designs [4].

Sheath is formed in the region near the channel wall. It bends the direction of exhausting ions to the wall. It is called “cross-field transport”, which is closely related to the performance of the Hall thrusters. We consider the discharge oscillation based on the ion transport in the channel. It is known that the inter-particle collision causes the phenomenon of the discharge oscillations, in particular, the frequency range of 10-90 kHz is frequently observed. When the discharge instability occurs, the oscillation not only imposes a load on the system of the power supply but even runs the operation of the Hall thruster down. It has been reported that this phenomenon closely connects with the discharge instability [5-6]. The information of the ion current oscillation is significant to develop Hall thrusters. In order to solve these problems, we show a new model considering the cross-field transport for Xe ions in the channel of the Hall thruster. We demonstrate the simulation comparing with the experimental results on TALT-2a Hall thruster. The performance enhancement of a 1 kW class anode-layer thruster, TALT-2a Hall thruster, has been attempted from previous study in Osaka University and Osaka Institute of Technology [7]. Basic Hall thruster experiments were made using low-power Hall thrusters to obtain fundamental operational characteristics. TAL type Hall thrusters have the thrust and specific impulse ranged

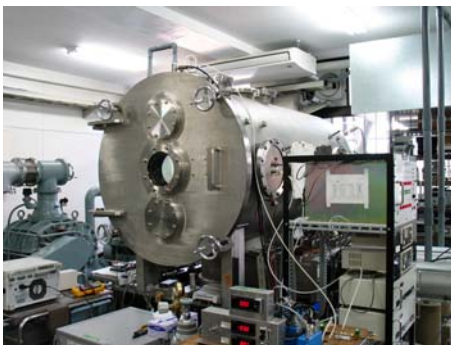

Fig.1. Photograph of experimental facility.

from 35 to 60 mN and from 1000 to 2300 sec, respectively, at discharge voltages of 200-400 V with mass flow rates of

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1.0-3.0 mg/s in a wide input power range of 1200-1800 W. The thrust efficiency ranged from 40 to 50 % has been achieved [7].

Our aim is to show the way of enhancement of thrust efficiency, which contains a stability of discharge current oscillation and an increase of thrust for the Hall thruster by demonstrating simulation comparing with the experimental results. When new findings of this study are demonstrated, the information will contribute to the resolution of the problems common to the mechanism of the discharge oscillation of Hall thrusters.

In section 2, we show our experimental facilities and experimental conditions on TALT-2a Hall thruster. In section 3, we propose a new model having the cross-field ion mobility in the channel, and show the simulation for the control of ion current oscillations comparing with the experimental results. We demonstrate the influence of the cross-field ion transport to the thrust and the thrust efficiency. The last section is devoted to the conclusion.

2. Experiment

The experimental facilities are shown in Fig.1 and Fig.2. It mainly consists of a water-cooled stainless steel vacuum tank with 1.2 m in diameter and 2.25 m long, having two compound turbo molecular pumps, several DC power suppliers and a thrust measurement system. The vacuum tank pressure is kept a range of 10^{-3}-10^{-4} Pa under operations. Thrusts are measured by a pendulum method. TALT-2a Hall thruster, shown in Fig.3 and Fig.4, has an acceleration channel with an outer diameter of 65 mm and an inner diameter of 45 mm, and the channel length of 10 mm. The wall material of the acceleration channel is stainless steel. The anode is made of copper and the hollow cathode is used as the main cathode. The thruster has the magnetic coils on the central axis and on the inner surface of the outer cylinder. The magnetic field is maximum near the channel exit and minimum at the anode. The direction of the magnetic field is radial in the channel. This experiment is done in Osaka Institute of technology [4]. Figure 5 shows a photograph of TALT-2a Hall thruster under an operation. We show the experimental conditions and the magnetic field strength in Table 1 and Fig.6, respectively.

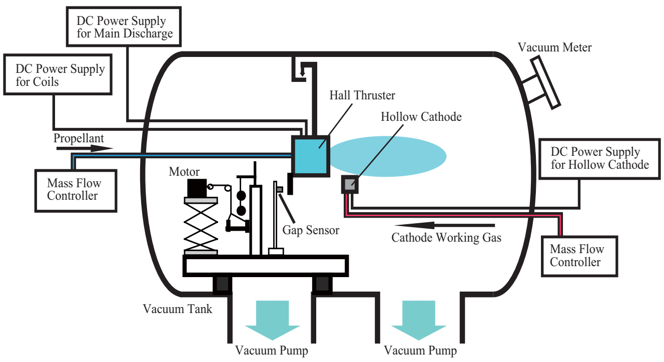

Fig.2. Experimental facility for thrust measurement.

Fig.3. Photograph of TALT-2a Hall thruster.

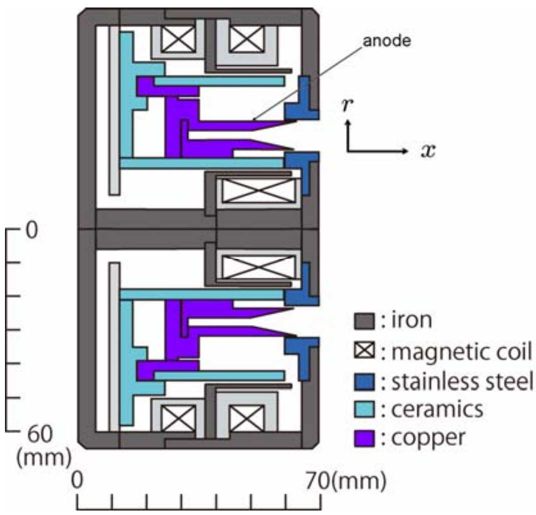

Fig.4. Cross-sectional view of TALT-2a Hall thruster.

Table 1. Experimental conditions and specifications of TALT-2a Hall thruster.

Back pressure	5.3 x 10^{-2} Pa
Discharge voltage	200V – 400V
Mass flow rate	
Thruster	2 mg/s
Hollow Cathode	0.1 mg/s
Propellant	Xe
Magnetic field	100-130 Gauss
TALT-2a thruster	
Channel Length	10 mm
Outer diameter	65 mm
Inner diameter	45 mm
Channel material	Stainless steel

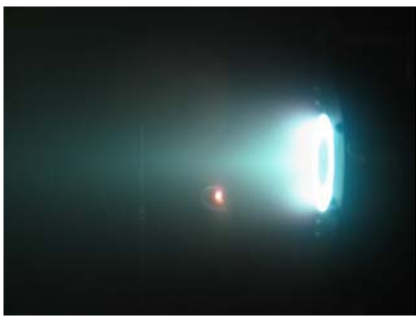

Fig.5. TALT-2a Hall thruster under an operation.

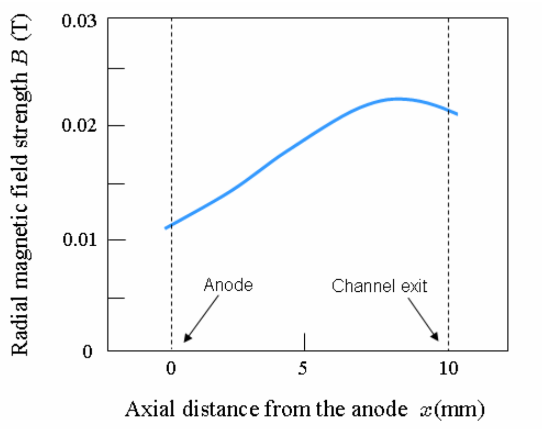

Fig.6. Magnetic field strength vs. axial distance.

3. Modeling and simulation

3.1 Control of the ion current oscillation

In order to investigate the issue of the stability of the ion current, we propose a new model associated with the cross-field ion transport. Since the discharge current oscillation approximately equals to the ion current oscillation, we consider the ion current oscillation. The equations of continuity for ions and neutrals are

$$\frac{\partial n_i}{\partial t} + div\left(n_i \vec{v}_i\right) = \gamma n_i n_n \ ,$$
$$\frac{\partial n_n}{\partial t} + div\left(n_n \vec{v}_n\right) = -\gamma n_i n_n \ , \qquad (1)$$

where n_i, n_n, $\vec{v}_i$, $\vec{v}_n$ and γ denote ion density, neutral density, ion velocity, neutral velocity and ionization rate, respectively. These equations are the conservation law of ions and neutrals with the creation of ions and the annihilation of neutrals in the right-hand sides. We need to consider x (axial) and r (radial) directional components because we consider the ion current oscillation near the sheath region in the channel. We assume that a part of ions is transported to the direction of the wall by the sheath electric field [8-10]. Figure 7 shows the image of the phenomenon of cross-field ion transport near the sheath region in the channel. The divergence of ion flux $n_i \vec{v}_i$ is described as $div\left(n_i \vec{v}_i\right) = \partial n_i v_{ix}/\partial x + \partial\left(r n_i v_{ir}\right)/r\partial r$. The azimuthal component of the velocity is assumed to be uniform. In this case, the radial component of the Xe ion velocity is $v_{ir}=\mu_i E_s$, where μ_i and E_s are the ion mobility and the sheath electric field, respectively. The neutral density n_n is assumed to be constant. Here, we neglect the diffusion term because the term is negligible small in magnitude. Since sheath bends the direction of Xe ions to the channel wall, which are shown in Fig.7, we need to consider the parameter of the ion mobility μ_i in simulation. The symbol r means the radial direction of perpendicular to the channel wall. The ion current is described as $I_i = e n_i v_i A$, where A is the cross sectional area of the channel.

The two dimensional equations of continuity are described as

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}\left(n_i v_{ix}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_i \mu_i E_s\right) = \gamma n_i n_n \ ,$$
$$\frac{\partial n_n}{\partial t} + \frac{\partial}{\partial x}\left(n_n v_{nx}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_n v_{nr}\right) = -\gamma n_i n_n \ . \qquad (2)$$

We show the simulation result of the oscillation of the ion current I_i comparing with the experimental result on the discharge voltage V_d=200 V and the propellant mass flow rate $\dot{m}$ =2 mg/s in Fig.8. The electron temperature T_e=8 eV and the initial plasma density $n_0=10^{17}$ m^{-3} are observed. We use the parameters which are v_i=7700 m/s, v_n=150 m/s, $\gamma=10^{-13}$ m^3/s and μ_i=0.02 Cs/kg in simulation [11-12]. The range of the ion mobility $0.001 < \mu_i < 0.039$ is considered for the numerical parameter because the sheath length is 0.21 mm in the discharge channel, which is 65 mm (outer diameter) and 45 mm (inner diameter). The cross sectional area of the channel A is obtained from $A = \pi\ (r_{out}^2 - r_{in}^2)$, where r_{out} and r_{in} indicate the outer radius and the inner one of the channel. It turns out that our simulation roughly agrees with the experimental result. It is shown for the first time that the ion current oscillation becomes stable by decreasing the mobility for Xe ions, as is shown in Fig.9.

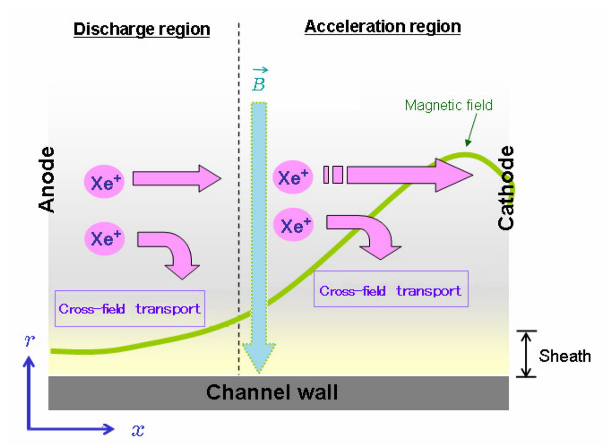

Fig.7. Image of phenomenon of cross field ion transport in the channel.

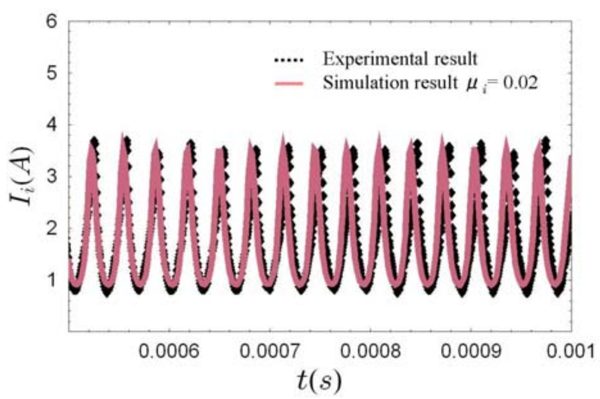

Fig.8. Experimental and simulation results of ion current oscillation.

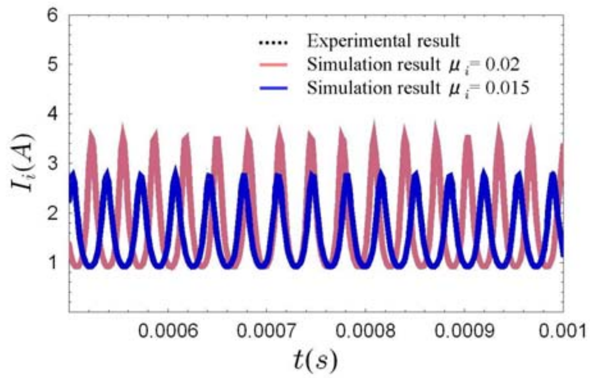

Fig.9. Simulation results of ion current oscillations by decreasing the ion mobility μ_i. Red and blue curves imply μ_i=0.02 Cs/kg and 0.015 Cs/kg, respectively.

3.2 Influence to the thrust efficiency

In order to study the influence of the control of ion current oscillation to the thrust and the thrust efficiency, we use the following equations,

$$\eta_T = \frac{F_T^2}{2\dot{m}P_d} , \tag{3}$$

$$\eta_u = \frac{m_i I_i}{e\dot{m}} , \tag{4}$$

where F_T, η_T, η_u, I_i, m_i, P_d and $\dot{m}$ indicate the thrust, total thrust efficiency, propellant utility efficiency, ion current, Xe ion mass, discharge electric power and propellant mass flow rate, respectively. We use following equations for the thrust efficiency,

$$\varepsilon_c = \frac{P_d}{I_i} , \tag{5}$$

$$\eta_T = \frac{\eta_u}{1 + \frac{2e\varepsilon_c}{m_i g^2}\left(\frac{\eta_u}{I_{sp}}\right)^2} , \tag{6}$$

where ε_c, g and I_{sp} indicate the ion production cost, the gravitational acceleration and the specific impulse, respectively. From equations (3)-(6), we derive [13-15]

$$F_T = \sqrt{2\dot{m}V_d I_i \frac{\frac{m_i I_i}{e\dot{m}}}{1 + \frac{2e\varepsilon_c}{m_i g^2}\left(\frac{m_i I_i / e\dot{m}}{I_{sp}}\right)^2}} , \tag{7}$$

$$\eta_T = \frac{\frac{m_i I_i V_d / \varepsilon_c}{e\dot{m}}}{1 + \frac{2e\varepsilon_c}{m_i g^2}\left[\left\{\frac{m_i I_i V_d / \varepsilon_c}{e\dot{m}}\right\} \Big/ I_{sp}\right]^2} . \tag{8}$$

It is defined that P_d=$V_d I_d$ and $I_d \approx I_i$, where the electron current is negligible small. In eqs.(3)-(8), we substitute the ion current shown in section 3.1 to the thrust and the thrust efficiency. We show the thrust and the thrust efficiency in Fig.10 and Fig.11, respectively. The parameters used here are m_i=2.19×10^{-25} kg and $\dot{m}$=2 mg/s. Since the thrust strongly depends on the discharge voltage, we simulate the thrust and the thrust efficiency by varying the ion mobility and the discharge voltage. It is observed that the thrust is in good agreement with the experimental result for μ_i=0.015 Cs/kg (blue line). When the ion mobility μ_i=0.020 Cs/kg (red line), the simulated curve is away from the experiment. Figure 11 shows the thrust efficiency for μ_i=0.015 Cs/kg (blue line) and 0.020 Cs/kg (red line),

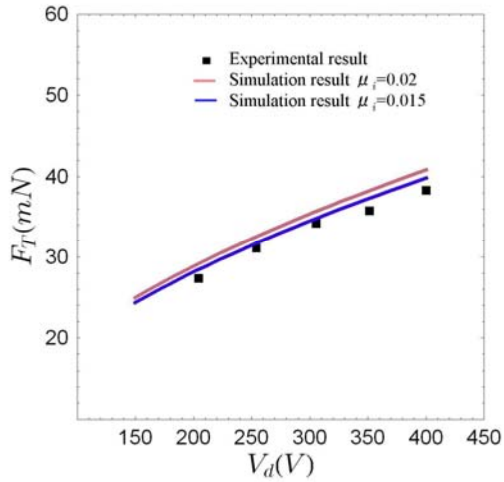

Fig.10. Thrust vs. discharge voltage for μ_i=0.02 Cs/kg (red) and 0.015 Cs/kg (blue).

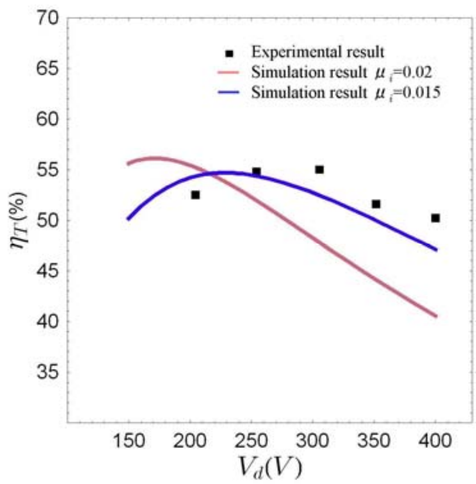

Fig.11. Thrust efficiency vs. discharge voltage for μ_i=0.02 Cs/kg (red) and 0.015 Cs/kg (blue).

respectively. The thrust efficiency coincides with the experimental result for μ_i=0.015 Cs/kg, while it is not in agreement with the experimental result for μ_i=0.020 Cs/kg. It turns out that our model appropriately explains the experimental result in the case where μ_i=0.015 Cs/kg.

4. Conclusion

We investigate the oscillation of the ion current by using the equations of continuity associated with the cross-field Xe ion transport and the ion-neutral collision. In order to describe the ion current oscillation correctly, we introduce the effect of the cross-field ion mobility on the oscillation. It is found for the first time that the ion current oscillation becomes stable by decreasing the mobility for Xe ions. In addition, in order to study the thrust performance of the Hall thruster, we show the dependence of the ion mobility and the discharge voltage to the thrust and the thrust efficiency. It is shown that, if we reduce the cross-field ions, the thrust efficiency is improved. The technical way to control of the ion current oscillation and the improvement of the thrust efficiency is to increase the mass flow rate of Xe gas and the discharge voltage. Under these circumstances, we should consider the relation among other parameters since Hall thrusters is an engine with a multi-parameter system. In order to develop the performance, it is important to consider the cross-field transport for Xe ions in the channel of Hall thrusters. Making simulations corresponding to the experimental results on the discharge current oscillation, the thrust and the thrust efficiency, we demonstrate a guide to improve the performance. Therefore, our results may be one of the useful information of the stability for discharge current oscillation and the improvement of the performance of Hall thrusters.

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