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Investigation on the cross-field ion transport on the discharge current oscillation and performances of SPT-100 type Hall thrusters

YasuNori NEJOH[1)], Hiroyuki NAKAMOTO[1)] and Hirokazu TAHARA[2)]

1) Graduate School of Engineering, Hachinohe Institute of Technology, Myo-Obiraki, Hachinohe City 031-8501, Japan

2) Graduate School of Engineering, Osaka Institute of Technology, Omiya, Asahiku, Osaka 535-8585, Japan

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The cross-field (CF) ion transport and the recombination effects on the ion current oscillations and the performance of the THT-VI Hall thruster are investigated in experiments and simulations. The CF ion mobility reduces the amplitude of the ion current flowing toward the exit of the channel. Experiments are made by using THT-VI low-power Hall thruster to obtain fundamental operational characteristics. Results obtained by our model are in good agreement with the experimental ones on the ion current oscillation, thrust, specific impulse and thrust efficiency. The effect of the CF ion mobility on the performance is great, while that of the recombination is small. This model therefore describes more correctly the ion current oscillation and the performance than the conventional ones. Hence, this investigation proposes a few guidelines to control the ion current instability and to improve the performance of the Hall thruster by introducing the CF ion mobility and the recombination.

Keywords: Hall thruster, discharge current oscillation, cross-field ion transport, recombination, performance, simulation, experiment

1. Introduction

Many science missions including commercial ones have been achieved in several nations. The Hall thrusters used in space are suitable for a long-term mission because they have the features of higher thrust and longer specific impulse among electric thrusters. They attract attention as a main thruster with high performance and simple construction for large-scale spacecraft. However, since Hall thrusters have several problems, we have to settle the subjects such as the instability of the discharge oscillation and the improvement of the thrust efficiency. Since the discharge current oscillation imposes a load on the power supply and causes the damage of the channel wall, the influence of the oscillation is significant in the operation of Hall thrusters. In particular, the effect of the cross-field (CF) ion transport on electric current oscillations due to inter-particle collisions has not been well-established in the field of the electric propulsion [1-3]. Moreover, since the sheath bends the direction of injected Xenon ions to the channel wall, it is important to clarify the CF ion transport in the channel. The CF ion transport means that ions are transported perpendicular to the direction of the electric field which is formed between the anode and cathode. The transport of plasma ions produced in a Hall thruster is known to be one of the main elements responsible for low frequency plasma oscillations. It has been pointed out that the ion current oscillation and the performance depend on the balance between the ionization and the recombination. We show that the effects of the CF ion mobility and recombination rate reduce the amplitude of the ion current oscillation, and confirm it is associated with the experiment and simulation. Experiments are made by using SPT 100-series low-power Hall thrusters (THT-VI thruster) to obtain fundamental operational characteristics. The influence of the CF ion transport on the thruster performance is also investigated. Simulation results obtained by our model are in good agreement with experimental data on the ion current oscillation. This investigation describes the electric current oscillation better than the conventional studies, and proposes some guidelines to control the ion current instability and performance by introducing the CF ion mobility [1-5] and the recombination.

The aims of this investigation are to propose a novel ion current oscillation model with CF transported ions and the recombination between plasma ions and electrons, and to show the comparison of the experiment with the simulation for the Hall thruster performance by introducing both of the effects into the theoretical model. In order to simulate the ion current oscillation and performance due to the CF ion transport and the attractive force in the sheath electric field, we use the 4-th order Runge-Kutta-Gill method for numerical simulation.

2. Experimental Apparatus

The experimental facility, as shown in Fig.1, mainly

author's e-mail: m07203@hi-tech.ac.jp or nejoh@hi-tech.ac.jp

consists of a water-cooled stainless steel vacuum tank 1.2 m in diameter and 2.25m long, two compound turbo molecular pumps, several DC power supplies and a thrust measurement system [4-5]. The vacuum tank pressure is kept a range of 10^{-3}–10^{-4}Pa under operations. A clean and high vacuum environment can be created by using the oil-free turbo molecular pump system, which is useful to evaluate contamination due to Hall thruster plumes.

Thrusts are measured by a pendulum method, as shown in Fig.1. A Hall thruster is mounted on a thrust stand suspended with an aluminum bar, and the position of the thrust stand is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter). It has a high sensitivity and a good linearity. Thrust calibration is conducted with a weight and pulley arrangement which is able to apply a known force to the thrust stand in vacuum environment. With this design, friction force was small, and it resulted in no measurable hysteresis.

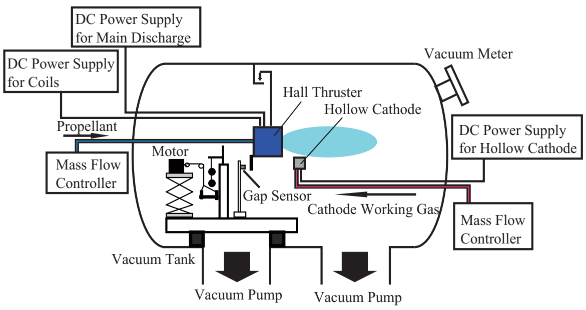

Fig.1 Configuration of the experimental facilities.

The SPT-type Hall thruster used for this study is shown in Figs.2 and 3. Figure 2 is the cross-sectional view of this thruster. Figure 3 is a photograph in under operation. The thruster named THT-VI has a discharge chamber consisting of coaxial and cylindrical parts. The former has an inner diameter of 56 mm and an outer one of 100 mm, and the latter has the same diameter as the outer one of the coaxial part. The channel length is 40 mm. The wall material of the discharge chamber is boron nitride (BN) ceramics.

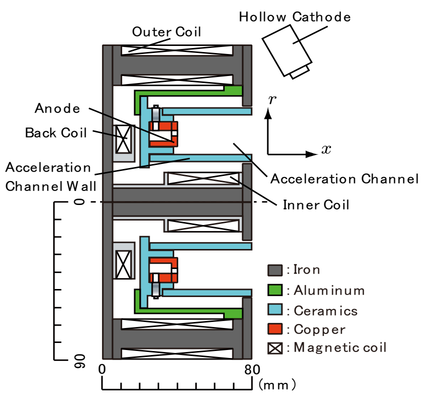

Fig.2 Cross-sectional view of THT-VI Hall thruster.

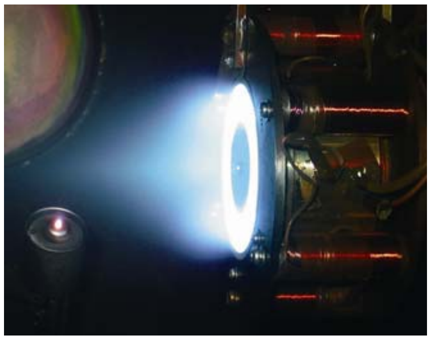

Fig.3 Photograph of THT-VI Hall thruster under operation.

The anode located at the upstream end of the coaxial part is made of copper. The hollow cathode (Iontech HCN-252) is used as the main cathode. Propellant gas is introduced from four lines behind the anode.

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 measurement is made with Gauss meter. The conditions on the experiment are shown in Table.1.

Table 1. Experimental conditions

Back pressure	0.085Pa	
Cathode	Hollow cathode neutralizer Iontech HCN-252	
Discharge voltage	200-400V	
Propellant mass flow	2.0-3.0mg/s	
Channel parameter	material	BN
	Length	40mm
	Inner diameter	56mm
	Outer diameter	100mm
Coil current	Inner,outer coil	0.1-0.5A
	Trim coil	0.1-0.5A

Xenon gas is used as propellants. In a series of experiments, discharge currents, specific impulse and thrusts are measured with varying discharge voltage, mass flow rate, and thrust efficiencies are evaluated. The experiment is done in Osaka Institute of Technology [2-4]. We focus on observing the ion current oscillation and the parameters on performance. The experimental result of ion current oscillation is shown in the next section.

3. Experimental Results

In order to study the ion current in the channel, we observe it by using the electric current probe. The observed ion currents are shown in Figs.4a-4d. Here, the experimental conditions of Fig.4a are $\dot{m}$=2.0mg/s and V_d=200V. Figures 4b-4d correspond to V_d=200, 250, 300 and 350V, respectively, where $\dot{m}$=2.5mg/s.

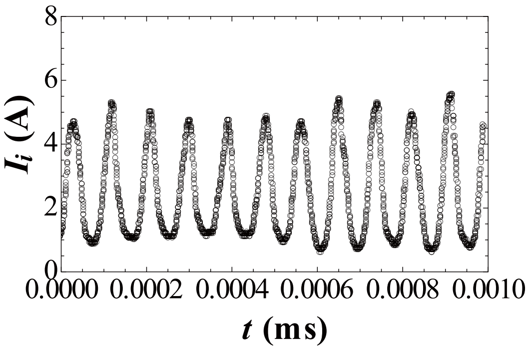

Fig.4a Ion current oscillation in case of $\dot{m}$=2.0mg/s and V_d=200V.

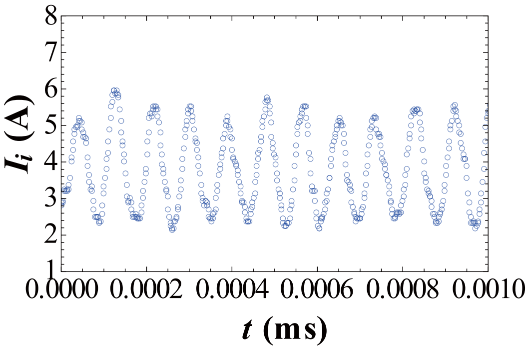

Fig.4b Ion current oscillation in case of $\dot{m}$=2.5mg/s and V_d=250V.

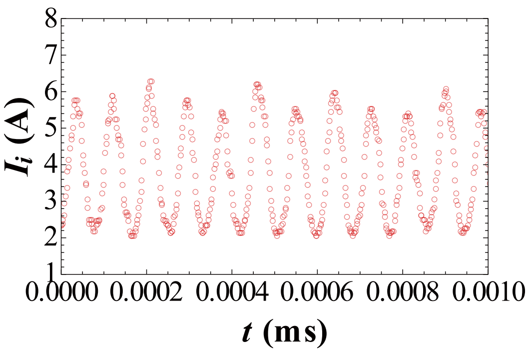

Fig.4c Ion current oscillation in case of $\dot{m}$=2.5mg/s and V_d=300V.

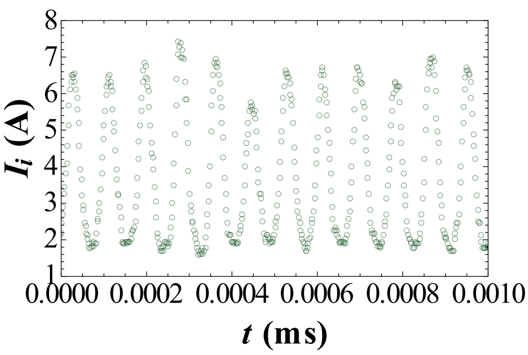

Fig.4d Ion current oscillation in case of $\dot{m}$=2.5mg/s and V_d=350V.

In order to show the region in which the ion current can be observed, we depict the region where the operation is possible in Fig.5.

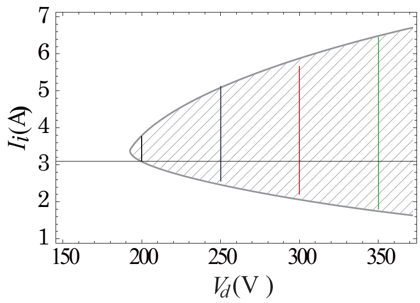

Fig.5 The region in which the ion current can be observed for the mass flow rate $\dot{m}$=2.5mg/s.

The Fast Fourier Transform (FFT) spectra are exhibited in Figs.6a and 6b. It turns out that the peak frequency is 10.6kHz (Fig.6a) when V_d=200V and $\dot{m}$=2.0mg/s, which corresponds to Fig.4a. Figure 6b shows that the peak frequency is 13.5kHz when V_d=250V and $\dot{m}$=2.5mg/s, which corresponds to Fig.4b.

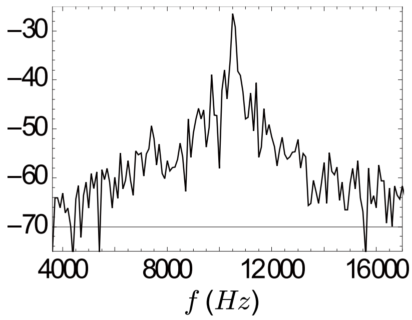

Fig.6a FFT spectrum of the ion current oscillation for V_d=200V and $\dot{m}$=2.0mg/s, which corresponds to Fig.4a.

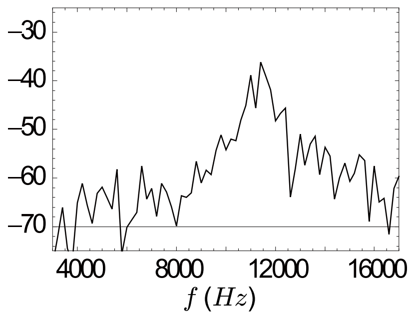

Fig.6b FFT spectrum of the ion current oscillation for V_d=250V and $\dot{m}$=2.5mg/s, which corresponds to Fig,4b.

4. Theoretical model of the ion current oscillation with the CF ion transport and the recombination

Several theoretical models have been considered based on the equation of continuity in order to explain experimental observations of the ion current oscillation [2-5]. However, there is no contribution of the models including the ion transport effect perpendicular to the direction of the plasma electric field and the recombination on the ion current oscillation. We propose a model including both effects. A simple model based on the equations of continuity for Xe ions and neutrals is described as

$$\frac{\partial n_i}{\partial t}+div\left(n_i \vec{v}_i\right)=+S_i \quad , \tag{1}$$

$$\frac{\partial n_n}{\partial t}+div\left(n_n \vec{v}_n\right)= -S_n \quad , \tag{2}$$

where $S_{i(n)}$ implies the source term of ions (neutrals).

We assume that a part of plasma ions runs off to the channel wall due to the $\vec{v}\times\vec{B}$ drift and the sheath electric field. The ion velocity assumes the same effects. We assume that the ion density is uniformly distributed, and the ion velocity goes mainly to the exit (*x*-directional component) and to the wall which is the radial direction (*r*-directional component) as $\vec{v}_i = \vec{i} v_{ix} + \vec{r} v_{ir}$, where $\vec{i}\,(\vec{r})$ is the unit vector of the axial (radial) direction. We also consider the recombination between plasma ions and electrons [6]. If we assume that $S_i= \gamma n_i n_n - \gamma_{rec} n_i^2 - (\nu_i - \nu_w)\, n_i$ and $S_n = -\gamma n_i n_n + \gamma_{rec} n_i^2 + (\nu_i - \nu_w)\, n_i$, then the equations of continuity of our system in the cylindrical coordinate become

$$\frac{\partial n_i}{\partial t}+\frac{\partial}{\partial x}\left(n_i v_{ix}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r n_i \mu_i E_S\right)$$
$$=+\gamma n_i n_n-\gamma_{rec} n_i^2-\left(\nu_i-\nu_w\right)n_i \quad , \tag{3}$$

$$\frac{\partial n_n}{\partial t}+\frac{\partial}{\partial x}\left(n_n v_{nx}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r n_n v_{nr}\right)$$
$$=-\gamma n_i n_n+\gamma_{rec} n_i^2+\left(\nu_i-\nu_w\right)n_i \quad , \tag{4}$$

where the azimuthal component of ions is assumed to be uniform. The radial component of the velocity of ions is determined as $v_{ir}=\mu_i E_S - D(1/n_i)(\partial n_i/\partial r)$ and

$$\mu_i=\frac{e}{m_i \nu_i}\frac{1}{1+\left(\omega_{pi}/\nu_i\right)^2} \quad , \tag{5}$$

where D, μ_i, ω_{pi}, ν_i and E_S mean the diffusion coefficient, the ion mobility, the ion plasma angular frequency, the ion collision frequency and the sheath electric field. Here we ignore the diffusion term since it is smaller than the ion mobility term in magnitude of the order. Moreover, in the mobility term, since we consider the acceleration region, it is noted that $\omega_{pi} \ll \nu_i$. The parameters γ, γ_{rec}, ν_i, ν_w imply the ionization rate, recombination rate, ion collision frequency, ion-wall collision frequency. Here, the numerical parameters are the following; $\gamma = \sigma_n v_e$ =1.4 × 10^{-13}m^3/s [7], v_i=7.8 × 10^3m/s, v_n=300m/s, $\nu_i = n_n \sigma_n v_i =$ 4.73 × 10^5Hz and $\nu_w = (\Gamma_e+\Gamma_i)/n_i l_c$ =4.81 × 10^5Hz, where σ_n, $\Gamma_e(\Gamma_i)$ and lc are the collision cross-section of neutrals, the electron (ion) flux and the radius of the channel. Here, v_i, v_n, γ and ν_i are the observed values, where the Debye length $\lambda_D \approx 7.8 \times 10^{-3}$m. The CF ion mobility is evaluated from the rate of the sheath length to the channel width. We use the recombination rate γ_{rec} =1.19 × 10^{-14} m^3/s, which is based on Refs.6 and 8. In our simulation, these parameters are valid because they are in the observable range in experiment. We use the 4-th order Runge-Kutta-Gill method for numerical simulation.

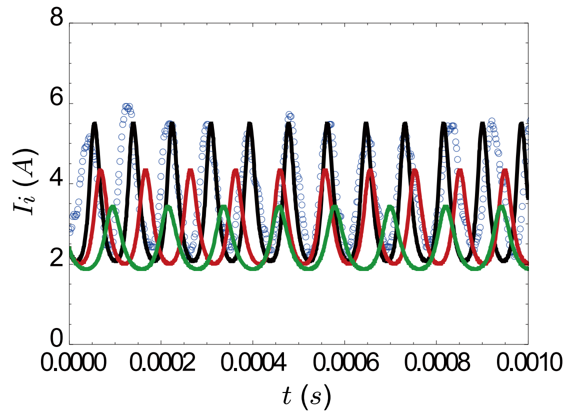

Fig.7 Comparison between the experimental observation of Fig.4b and simulation for μ_i =0.020Cs/kg (black), 0.010Cs/kg (red) and 0 (green), respectively, γ_{rec} = 1.19 × 10^{-14} m^3/s.

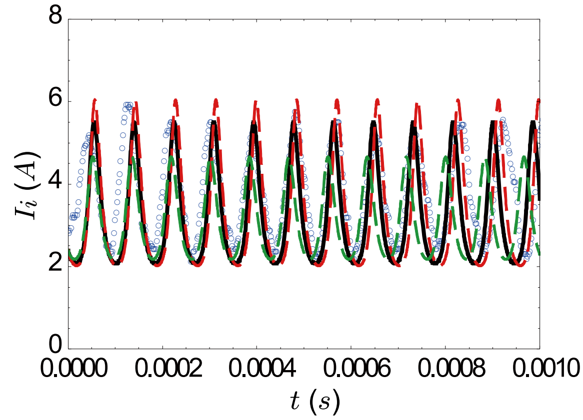

Fig.8 Comparison between the experimental observation of Fig.4b and simulation for γ_{rec} =1.80 × 10^{-14} m^3/s (red dotted line), 1.19 × 10^{-14} m^3/s (black solid line) and 0 (green dotted line), respectively, where μ_i = 0.020 Cs/kg.

The results of our simulation on the ion current oscillation are compared with experimental results as shown in Fig.7, in the cases where the CF ion mobility varies. Blue circles are the experimental results. The simulated curves imply μ_i =0.020Cs/kg (black solid line), 0.010Cs/kg (red solid line) and 0 (green solid line), respectively, where $\dot{m}$ =2.0mg/s and the recombination rate is assumed to be γ_{rec} =1.19 × 10^{-14}m^3/s [6,8]. Here, the ion current implies $I_i = en_i v_{ix} A$, where A is the cross-sectional area of the channel. Figure 8 shows the ion current oscillations depending on the recombination rates γ_{rec} =1.80× 10^{-14}m^3/s (red dotted line), 1.19 × 10^{-14}m^3/s (black solid line) and 0 (green dotted line), respectively, where the ion mobility is 0.02Cs/kg. It is noted that the black solid line is the same curve, as is shown in Fig.7.

From Figs.7 and 8, we understand that, when the CF ion mobility and the recombination rate are taken into account in the model, the simulated curve (black solid line of the case that μ_i =0.020Cs/kg and γ_{rec} =1.19 × 10^{-14}m^3/s) coincides with the experiments. As is seen in Fig.7, when the ion mobility decreases, the amplitude of the ion current oscillation greatly reduces, in the case of γ_{rec} =1.19× 10^{-14}m^3/s. On the other hand, as is shown in Fig.8, if the recombination rate reduces, the change of the amplitude of the ion current oscillation is relatively small, in the case where μ_i =0.020Cs/kg. If there is no consideration of these effects, the difference between experiment and simulation becomes considerable.

5. Performance evaluation

In order to investigate the correspondence between the experiments and simulation on performance of the Hall thruster, we consider the thrust F, specific impulse I_{sp}, and the total efficiency η, as,

$$F = I_i\sqrt{\frac{2m_i V_d}{e}} = \frac{2V_d I_d \eta}{g I_{sp}} , \tag{6}$$

$$\eta = \frac{F^2}{2\dot{m} V_d I_d} , \tag{7}$$

where the propellant utilization coefficient $\eta_u = m_i I_i / e\dot{m}$. The parameter V_d (I_d) is the discharge voltage (current). In THT-VI thruster, the discharge current approximately equals to the ion current, $I_d \approx I_i$. From the experiments and simulation, the thrust increases in proportion to the square root of the electric potential as is seen in Fig.9, where $\dot{m}$ =2.0mg/s, v_i =5.8× 10^3m/s and v_n =500m/s. Black, red and blue curves imply that μ_i =0.020Cs/kg, 0.010Cs/kg and 0, respectively. Figure 10 shows that the specific impulse grows in proportion to the square root of the discharge voltage. The total efficiency is shown in Fig.11. We understand that the thrust and the specific impulse are well-explained by considering the CF ion mobility. The thrust efficiency greatly depends on the CF ion mobility, whereas the other parameters are fixed .

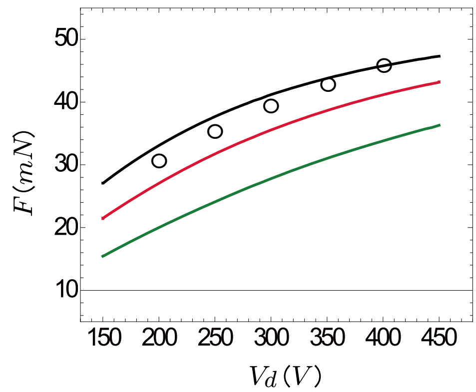

Fig.9 The thrust versus the discharge voltage. Black, red and green curves imply the cases where μ_i=0.010 Cs/kg, μ_i=0.020 Cs/kg and 0, respectively, where $\dot{m}$ =2.0mg/s.

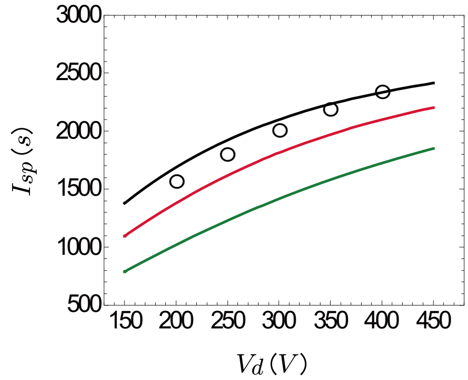

Fig.10 The specific impulse vs. discharge voltage. Black, red and blue curves imply the same conditions of Fig.9.

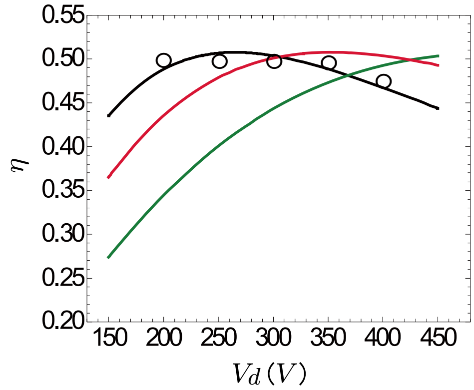

Fig.11 The thrust efficiency depending on the discharge voltage. Black, red and blue curves are the same conditions of Fig.9.

On the other hand, in the case where the recombination rate varies, the characteristics of the thrust, the specific impulse and the thrust efficiency don't change so greatly as is shown in Figs.12, 13 and 14, respectively.

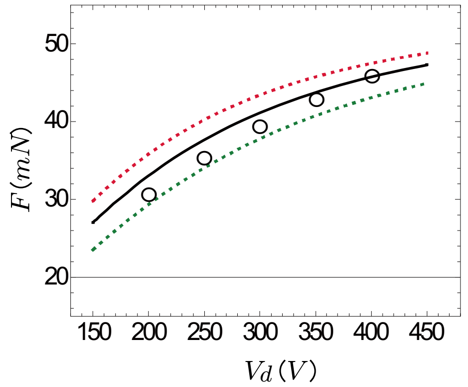

Fig.12 The thrust versus the discharge voltage. Red, black and green dotted curves imply the cases of γ_{rec} =1.80 × 10^{-14} m^3/s, 1.19 × 10^{-14} m^3/s and 0, respectively, where μ_i = 0.020 Cs/kg and $\dot{m}$ = 2.0mg/s.

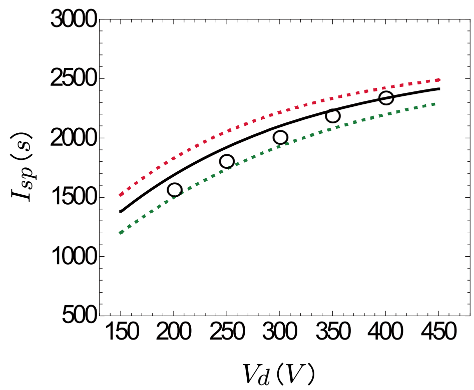

Fig.13 The specific impulse vs. discharge voltage. Red, black and green dotted curves imply the same conditions of Fig.12.

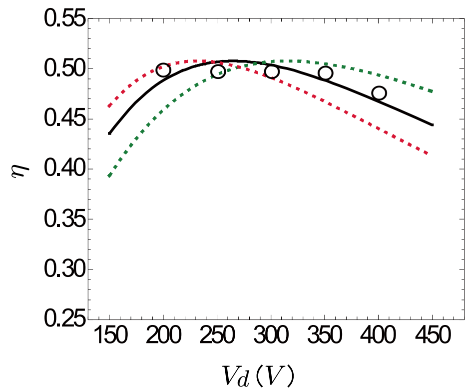

Fig.14 The thrust efficiency depending on the discharge voltage. Red, black and blue dotted curves are the same conditions of Fig.12.

Figure 12 shows the thrust depending on the recombination rates γ_{rec} =1.80 × $10^{-14} m^3/s$ (red dotted line), 1.19 × $10^{-14} m^3/s$ (black solid line) and 0 (green dotted line), respectively, where the ion mobility is 0.02Cs/kg. The thrust increases as the discharge voltage increases and the recombination rate grows, whereas the difference among the three cases is small. From the characteristics of the specific impulse in Fig.13, we understand that it depends on the discharge voltage but the dependence of it on the recombination is weak. Figure 14 shows that the thrust efficiency changes according to the discharge voltage and the recombination rate. Though the efficiency is doing very well in the high voltage region if γ_{rec} =0, it takes a maximum value in the lower voltage region when the recombination rate increases. It turns out that the CF ion mobility greatly influences the performance, while the recombination does a little.

6. Discussion

In this paper, we present a model with the CF ion transport and the recombination of Xenon ions in order to obtain correct evaluation of the ion current oscillation and the thrust performance in the channel of the Hall thruster. The simulation results show that the reduction of the CF ion mobility leads to the stability of the ion current oscillation and the decrease of the recombination also contributes to the reduction of the oscillation. In order to reduce the CF ion mobility, it is necessary to increase the mass flow rate and decrease the cross-sectional area of the channel. Moreover, in order to decrease the recombination rate, it is necessary to increase the ionization rate and the ion velocity (plasma electric field), which simultaneously needs the optimization of the discharge voltage and the neutral gas density, since the Hall thruster is a plasma engine with a multi-parameter system. The results of our performance model are consistent with the experimentally observed ones. The effect of the CF ion mobility on the performance is great, while that of the recombination is small. Under these circumstances, we can improve the performance when the recombination rate takes a certain degree of values. This investigation demonstrates the significance of the CF ion transport and the recombination in discussing the ion current oscillation and the performance of Hall thrusters. Hence, the findings of the ion current oscillation and the performance presented here would be useful in the design and the improvement of Hall thrusters.

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