Effects of Discharge Chamber Configuration on RF Plasma Properties

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Abstract

The Radio Frequency (hereafter called RF) ion thruster that generates inductively coupled discharge plasma is one of the promising thruster in the series of ion thrusters. Because of the electrodeless discharge, RF ion thruster has no hollow cathode that is the life-limiting elements. However, its energy transfer efficiency to the generated RF plasma from RF power supply is not so good, therefore, its ion production cost is inferior to that of the electron bombardment (hereafter called EB) ion thruster. In order to improve the RF ion thruster performance, considering the skin effects in the generated plasma column, the effects of the propellant feed system to the discharge chamber were evaluated by both the performance test and the calculation of the neutral particle properties using Monte Carlo direct simulation. The results can be summarized as follows. The beam current depends on the propellant feed system and propellant species. It is difficult to consider that flow pattern change is related directly to the performance improvement because propellant is not supplied to the area on the penetration depth by the flow pattern change. However, it is considered that increases of number density and residence time of neutral particle in the small chamber of the discharge chamber #2 are one of the effect of performance improvement. Additionally, The program in this study is possible to calculate the profile of neutral particle in the discharge chamber whose configuration is complex. It is able to be applied on another research in future.

Nomenclature

\[ A = \text{cross-section area, mm}^2 \]
\[ V_i = \text{cell volume, mm}^3 \]
\[ c_i = \text{velocity of incident particle, m/s} \]
\[ d = \text{atomic diameter, mm} \]
\[ g = \text{relative velocity, m/s} \]
\[ F = \text{number flux, cm}^{-2}s^{-1} \]
\[ F_p = n \times f \]
\[ f = \text{probability distribution} \]
\[ K_n = \text{Knusen number} \]
\[ L = \text{discharge chamber length, mm} \]
\[ M = \text{collision number in each cell at one step} \]
\[ m_i = \text{mass flow rate, SCCM} \]
\[ N = \text{the sample number} \]
\[ n = \text{number density, cm}^{-3} \]
\[ T = \text{temperature, K} \]
\[ Tw = \text{discharge chamber wall temperature, K} \]
\[ t = \text{time, s} \]
\[ V = \text{volume, mm}^3 \]
\[ v = \text{stream velocity, m/s} \]
\[ x = \text{position, mm} \]
\[ \phi = \text{discharge chamber diameter, mm} \]
\[ \sigma = \text{differential cross-section, mm}^2 \]
\[ \zeta = \text{velocity of incidented particle, m/s} \]

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1. Introduction

1.1 Background of This Study

The RF ion thruster have been researched and developed for many years in the several countries. At present, ion propulsiones are on its application phase for the auxiliary propulsion of north-south station keeping (NSSK) for geosynchronous satellite, and they are on its R&D phase in order to be applied to main-propulsion for orbit transfer vehicle or interplanetary vehicle at several laboratories and manufacturers\(^1,2\). As the long term operation is required for these missions because of low thrust level of ion propulsion, the prolongation and the assurance of its life time are the most important problems as well as the performance improvement.

RF ion thruster that generates inductively coupled discharge plasma is one of the promising thruster in the series of ion thrusters. Because of the electrodeless discharge, this RF ion thruster has no hollow cathode that is the life-limiting element. Therefore, RF ion thruster is distinctive in its electrodeless, annular and
self-sustaining RF discharge, compared with the EB ion thruster using hollow cathode. In addition, the sharing of an input power to both the ion source and the neutralizer is possible because RF energy from the power supply is put into the RF discharge plasma in the form of the electromagnetic wave. It implies that a single RF power generator can simultaneously generate plasmas for not only the ion source but also the neutralizer. Therefore, the RF ion thruster may require only three power supplies at minimum, including the beam extraction power supplies. For these advantages, the RF ion thruster has a simple system, compared with the EB ion thruster. However, its energy transfer efficiency to the generated RF plasma from RF power supply is not so good because of the inductively coupled discharge, that is, its ion production cost is inferior to that of the EB ion thruster.

Generally, the improvement of the energy transfer efficiency results in the increase of the ion beam extraction at the same input power. For this improvement, the increase of the electron number density in the discharge chamber is required. In this study, considering the skin effects in the generated RF plasma column for the purpose of improve the RF ion thruster performance, the increase of the electron collision frequency with the neutral particle by supplying more propellant to the region near the discharge chamber wall was attempted. The new discharge chamber laboratory models that have the different propellant feed system from the conventional discharge chamber was manufactured. Then the effect of the propellant feed system to the discharge chamber was evaluated for the more detailed estimation of its effect on the steady performance. It is evaluated by diagnosing the profile of the plasma properties (electron number density and temperature) in the discharge chamber by the double probe method.

Moreover, in order to optimize the propellant feed system, quantitative estimation based on the theoretical analysis is required in addition to the data acquisition by the experiment. Therefore, the profile of the neutral particle properties (velocity vector, number density, mach number, temperature and residence time) in the discharge chamber is calculated by the Monte Carlo direct simulation method (DSMC).

1.2 The Objective of This Study

The objective of this study is the evaluation of the effect of the propellant feed system on the profile of the neutral particle properties (velocity vector, number density, mach number, temperature and residence time) by the DSMC for the more detailed estimation of its effect on the steady performance.

2. Experimental Apparatus and Methods

2.1 Experimental Apparatus

Figure 1 shows the schematic drawing of the RF ion thruster used in this study. The 3 cm diam. RF ion source for the ground use (ION TECH, INC. Model 3RF-1200-100) was reformed and tested for the performance improvement as the propulsion device in this study. As shown in this figure, the copper induction coil (5 turns) is installed to the cylindrical discharge chamber (4 cm diameter) and the beam extraction grid system of 3 cm beam diameter is attached. An applied RF power, whose frequency is 13.56 MHz, was controlled in the range of 10 W to 80 W and the automatic impedance matching network was employed to minimize the reflected RF power.

Figure 2 shows the cutaway drawing of the adopted

![Fig. 1 Schematic Drawing of the RF Ion Thruster](image1)

![Fig. 2 Cutaway Drawing of the Discharge Chambers](image2)
two type discharge chambers. Discharge chamber #1 has the straight inlet piping propellant in the direction of perpendicular to the baseplate and it introduces the propellant flow in the direction of axis. In the case of the discharge chamber #2, it has the small chamber (L: 18 mm, φ: 20 mm) at the inside of the baseplate and this small chamber has the eight small propellant passage holes (φ: 2 mm) at the circumference of the small chamber. The function of this small chamber is that the flow pattern of the propellant is changed in the direction of radial. Moreover, the other discharge chambers (#1a, #2a) whose chamber lengths are reduced to 33 mm from 46 mm were manufactured and evaluated.

2.2 Experimental Methods

Controlling screen grid voltage, accel grid voltage, mass flow rate and input power, using Kr and Xe propellant, beam current was measured. The experiment presented in this study was performed at the following conditions.

- Degree of Vacuum in Space Chamber: up to approximately 4.5 mPa (3.4 x 10^-4 Torr) (with 4.0 SCCM Xe)
- Pressure in the Discharge Chamber: 200 - 550 mPa (1.5 - 4.5 x 10^-3 Torr)
- Discharge Chamber: #1, #2, #1a, #2a
- Propellant: Kr, Xe
- Input Power: 10 - 80 W
- Mass Flow Rate: 1.5 - 4.0 SCCM
- Grids: Type O (Pitch: 1.91 mm, Hole Diameter of Screen Grid: 1.45 mm, Hole Diameter of Accel Grid: 1.25 mm) Type I (Pitch: 3.5 mm, Hole Diameter of Screen Grid: 3.0 mm, Hole Diameter of Accel Grid: 2.5 mm)

3. Analytical Methods

3.1 Analytical Model

3.1.1 Boltzmann Equation

Motion of particle is subject to the following Boltzmann equation.

\[
\frac{\partial n(f)}{\partial t} + c \cdot \nabla n(f) = n^2 \int \left[ f(c')f(\zeta') - f(c)f(\zeta) \right] g(c', \zeta') \, d\Omega \, d\zeta
\]

(3.1)

Position and velocity of particle are calculated by solving this equation. Here, \( n \) is number density, \( f \) is probability distribution, \( c \) is incident velocity of particle, \( \zeta \) is incinated velocity of particle, \( g \) is relative velocity, \( \sigma \) is differential cross-section.

3.1.2 Numerical Solution

In this study, for solving this Boltzmann equation, Monte Carlo direct simulation that is one of the probability solution is applied. Among Monte Carlo direct simulation, the max-collision-number scheme whose calculation efficiency is best at present is applied.

3.1.3 Coordinate

Polar coordinate is applied. The component of the position vector of the particle is constant in direction to circumference because flow pattern is axial symmetry 3-dimensional flow. Therefore, the attendant information of the particle are two position vector components and three velocity vector components.

3.1.4 Model of Particle

Rigid sphere particle model is applied, because inactive single atomic gas is used for the propellant. Therefore, differential cross-section (\( \sigma \)) is \( d^{3/4} \) (\( d \): diameter of atomic).

3.2 Monte Carlo Direct Simulation

3.2.1 Separation Theory

Equation 3.1 contains both motion and collision effects at the same time. However, considering this equation during the minuteness time \( \Delta t \) that is shorter than the mean free time of particle, first, particle changes its velocity vector by the collision, next, particle moves at the velocity after the collision during the minuteness time \( \Delta t \). This theory that motion and collision of particle can be separated is called separation theory.

In DSMC, one step calculation time have to be set to the time that is shorter than the mean free time. In this simulation, one step calculation time is set to one fifth of the mean free time.

3.2.2 Motion of Particle

Motion of particle can be calculated by the classical Newton dynamics.

3.2.3 Collision of particle

Considering rigid sphere particle model, collision of particle can be calculated similarly above. In case of the collision calculation by the probability solution, to increase calculation efficiency, the maximum value of the relative velocity between particles is required at the calculation. In this simulation, this maximum value is set to 2.5 times the max-probability velocity of the relative velocity between particles. The reason is that the probability of the collision whose relative velocity is higher than this value is negligible. At this time, the collision numbers in each cell at one step is as follows.

\[
M_{\text{max}} = \frac{5^4}{8N_vN_{\text{a}}K_n} N (N - 1)
\]

(3.2)

Here, (\(^{\wedge}\)) means non-dimensionalized value. \( N \) is cell volume, \( N_{\text{a}} \) is the sample number in the standard area at the upstream of the discharge chamber, \( K_n \) is Knusen number, \( N \) is the sample number in the cell.
3.2.4 Physical Quantities in the Stream Field

In the stream field, number density $n$, stream velocity $v$, and temperature $T$ are expressed as follows.

$$
n = \int f_p \, dc \nonumber$$

$$
v = \int c \, fdc \nonumber$$

$$
T = \frac{1}{3R} \left[ (c^2 fdc - v^2) \right] \quad (3.3)$$

Here, $F_p = n f$.

In Monte Carlo direct simulation, above physical values are calculated from the position and the velocity of the sample particle. At this time, above equations become as follows.

$$
n = \frac{N}{V} \sum_{i=1}^{N} c_i \nonumber$$

$$
v = \frac{1}{N} \sum_{i=1}^{N} c_i \nonumber$$

$$
T = \frac{1}{3R} \left[ \frac{1}{(N-1)} \sum_{i=1}^{N} c_i^2 - v^2 \right] \quad (3.4)$$

Here, $V$ is volume, $(\infty)$ means the value in the standard area at the upstream of the discharge chamber.

3.3 Boundary Condition

3.3.1 Influx Particle

The influx quantity of particle per unit time and unit area (number flux) $F$ (cm$^{-2}$s$^{-1}$) is calculated by integrating probability distribution $f$.

$$
F = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} n \, c_0 \, fdc_1 \, dc_2 \, dc_3 \quad (3.5)$$

From this equation, number flux in the direction of positive across the control plane is as follows.

$$
F^+ = n \sqrt{\frac{RT \pi}{2}} \left[ \exp(-v^2) + \sqrt{\pi} \, (v^+) \times [1 + \text{erf}(v^+)] \right] \quad (3.6)$$

Similarly, number flux in the direction of negative across the control plane is as follows.

$$
F^- = n \sqrt{\frac{RT \pi}{2}} \left[ \exp(-v^2) - \sqrt{\pi} \, (v^-) \times [1 + \text{erf}(v^-)] \right] \quad (3.7)$$

Here, $(+)$ means the physical quantities of the upstream at the object plane, $(-)$ means the physical quantities of the downstream at the object plane. Therefore, net number flux in the direction of stream is expressed as follows.

$$
\overline{\dot{n}} = \frac{F^+ - F^-}{A} \quad (3.8)$$

Here, $\dot{m}$ is mass flow rate, $A$ is cross-section area. Upstream condition is set so that this $F$ corresponds to the mass flow rate per unit area at the experiment.

3.3.2 Reflection of Particle

Mirror reflection is considered on the discharge chamber axis that is symmetrical axis. Random reflection is considered on the discharge chamber wall (grid wall is contained). The reflection on the plane that is manufactured industrially is almost random reflection. As for random reflection, the velocity after reflection $c'$ is unrelated to the incident velocity $c$. $c'$ depends on the reflection wall temperature $T_w$. Incident particle is taken in the imaginary thermal equilibrium gas whose temperature is equal to the wall temperature. After that, new particle whose velocity is decided by the maxwellian distribution at the wall temperature flows out from this imaginary gas. The temperature on discharge chamber is set to 527 K by the experimental measurement.

3.4 Supplement of the Program

3.4.1 Data Sampling

In generally, each sampling data is required that they are independent. However, if sampling time is shorter than the mean free time, the correlation among data is generated. In this simulation, data is sampled at each mean free time.

4. Results and Discussions

4.1 Performance (Beam Current) Measurement

Figure 3 shows the result of the performance measurement. Figure 3 (a) shows the beam current in the case of the conventional long chamber (46 mm) and (b) shows that in the case of the new short chamber (33 mm).

As shown in Fig. 3 (a), the results on the long discharge chamber configuration are summarized as follows.

1) For Kr Propellant: The extracted beam current was increased from 17 mA to 31 mA (Input Power : 50 W) by attached small chamber (the following is similar).

2) For Xe Propellant: The extracted beam current was increased from 19 mA to 28 mA (Input Power : 50 W). However, the ratio of increase is less compared with Kr Propellant.

On the other hand, as shown in Fig. 3 (b), the results on the short discharge chamber configuration are summarized as follows.

3) For Kr Propellant: The extracted beam current was decreased from 18 mA to 17 mA (Input Power : 50 W). It is only the case where the beam current was decreased.

4) For Xe Propellant: The extracted beam current was increased from 24 mA to 34 mA (Input Power : 50 W).

Based on these results, it was obtained that the
Fig. 3 The Effects of the Discharge Chamber Configuration on the Beam Current

The effect of the chamber length is different by the propellant species.

Moreover, the following informations were obtained in the diagnosis of the conventional long chambers up to this time. The profiles of electron number density and electron temperature are different by the propellant species. Therefore, it became clear that the preferable propellant feed systems are different by the propellant species. By the redistribution of propellant from the region where electron temperature is low to the region where it is high, the increase of the electron number density seems to be possible. The condition that the profile of the electron temperature is flat in the discharge chamber seems to be the preferable condition, where RF input power is used more effectively for the plasma generation.

The performance measurements of the new short chamber show the results that supports the guideline obtained in the diagnosis of the conventional long chambers.

However, the reason why this performance difference is caused by the combination of the discharge chamber configuration and propellant species is not clear. If this phenomenon is explicated in detail, it is considered that the clue for optimizing the propellant feed system will be obtained. Therefore, theoretical analysis is required.

4.2 The Propriety of This Calculation

By the program used in this study, sample calculation is tested on the flow whose conditions are clear theoretically (divergent nozzle). As a result, the output data of this program corresponds to the theoretical value.

Moreover, estimation of influx boundary condition is important on the propriety. Quantities except number density and each profile including number density are only little affected by the change of the influx boundary condition. However, quantity of number density is varied with the little change of the influx boundary condition. Therefore, though relative characteristics of number density are understood, its quantity have to be evaluated still more. According to the experimental measurement, the average of neutral number density considering modification of molecular weight is about $7.0 \times 10^{14}$ cm$^{-3}$ in the discharge chamber #1. On the other hand, the average value of number density on calculation is $5.85 \times 10^{14}$ cm$^{-3}$ in the discharge chamber #1. The reason of this difference is seemed that the influx boundary condition is not proper enough. The more accurate estimation of influx boundary condition is required. However, relative properties of number density on this calculation is correct because relativity is not changed. The detailed evaluation of quantity of number density is required in future considering the problem of measurement data.

The calculation error is related to the following four parameters. These parameters are time step $\Delta t$, mesh size $\Delta x$, maximum value of the relative velocity $M_\infty$ and Knusen number $K_n$. If these values are different from the required condition on DSMC, error is not negligible. However, in this calculation, these parameter are satisfied the required condition enough. The results of the test program whose parameter are varied slightly from the original value are almost equal to that of original program.

4.3 The Profile of the Neutral Particle Properties

4.3.1 The Effect of the Discharge Chamber Configuration

Figure 4 and 5 show the results on discharge chamber #1 and #2 using Xe propellant. Both figure show velocity vector, mach number, number density, temperature in order from top. Residence time will be mentioned in section 4.3.4.

As shown in Figs. 4 (a) and 5 (a), velocity vector is
(a) Velocity Vector

(b) Mach Number

(c) Number Density \((\times 10^4\text{cm}^{-3})\)

(d) Temperature (K)

Fig. 4 Profile of Properties (#1, Xe)

Fig. 5 Profile of Properties (#2, Xe)
varied with the discharge chamber configuration. In case of discharge chamber #2, the propellant changes its flow pattern in the direction of radial because of the small chamber as it had been expected. Moreover, propellant flow has large radial component of stream velocity at the outlet of the small chamber hall because of the pressure difference (that is number density difference) between the small discharge chamber and main discharge chamber. However, radial component of stream velocity is decreased near the discharge chamber wall. As shown in equation 3.6, number flux is a function of number density, temperature and stream velocity. Therefore, number flux that incidents in the area on the penetration depth near the discharge chamber wall isn't decided only by stream velocity.

As shown in Figs. 4 (c) and 5 (c), the average value of number density is different between the two discharge chambers. In the case of discharge chamber #1, though number density is high near the inflow entrance, it is about $4.5 \times 10^{10}$ cm$^{-3}$ near the discharge chamber wall. On the other hand, in the case of discharge chamber #2, though number density is high in the small chamber, it is about $1.2 - 1.6 \times 10^{10}$ cm$^{-3}$ in the main discharge chamber. This is less than one third of that in #1. This decrease of number density is larger than that expected. Therefore it is considered that this decrease effects on the number flux mentioned later.

As shown in Figs. 4 (d) and 5 (d), the profile of temperature is different between the two chambers. In the case of discharge chamber #2, temperature is equal to the chamber wall temperature on the almost whole area in the discharge chamber because of effects of energy flow from the small chamber wall.

Here, number flux that incidents in the area on the penetration depth near the discharge chamber wall (that is plasma generation area) will be calculated by the equation 3.6. Penetration depth of the thruster in this study is about 0.54 mm (using the electron number density and temperature obtained by the experimental measurement$^5$). Therefore, number flux is calculated by the value of radial component of stream velocity, number density and temperature in the cell adjacent to the discharge chamber side wall. As the result, number flow rate ($\Sigma F \times A$) is as follows. Here, number flow rate is the quantity of the incident particle in the area on the penetration depth at the whole discharge chamber side wall per second. It is $1.84 \times 10^{20}$ s$^{-1}$ in the discharge chamber #1 and $0.57 \times 10^{20}$ s$^{-1}$ in the discharge chamber #2. That is to say, incident particle in the area on the penetration depth in the discharge chamber #1 is more than three times that in the discharge chamber #2. The effects of the change of flow pattern in the direction of radial which had been expected to increase number flux is canceled by the decrease of number density. Though number flux of neutral particle that incidents in the area on the penetration depth doesn't correspond directly to the number density of electron in the discharge chamber, it is difficult to consider that flow pattern change is related directly to the performance improvement because propellant is not supplied to the area on the penetration depth by the flow pattern change.

4.3.2 The Effect of the Propellant Species

Even if the propellant species is changed, the difference is little observed except in the quantity of number density. All profile and the other quantities are little changed. Here, velocity is non-dimensionalized at the representation velocity (the speed of sound at entrance). Therefore, velocity vector is not difference by the weight of the propellant species.

In case of equal mass flow rate, number density of Kr is low. The reason is as follows. Mass flow rate is product of density, velocity and cross-section. The velocity of light atom on the equal mach number is high by the difference of the gas constant. Therefore, number density of light atom is low.

The average number density ratio of Kr to that of Xe is 0.857 in the discharge chamber #1, 0.827 in the discharge chamber #2. This value is higher than the root of the molecular weight ratio $(83.8/131.3)^{1/2} = 0.799$ that corresponds to the reciprocal of velocity ratio on the equal mach number.

4.3.3 The Effects of the Discharge Chamber Length

In case that the discharge chamber length is shortened, all profile except velocity vector is shortened in the direction of axis maintaining quantity. In this case, the profile of velocity vector becomes the profile that is cut away the downstream from the 33 mm position in the profile on the 46 mm.

4.3.4 Residence Time of Particle in the Discharge Chamber

Figure 6 shows the residence time of particle in the discharge chamber. In the discharge chamber #2, residence time is longer than 100 ms. Therefore, the calculation of long time step over than 100 ms is required. However, it is difficult because its calculation time is too long.

The average residence time in the discharge chamber #2 is long remarkably compared with that in the discharge chamber #1. As shown in Fig. 6, the average residence time in the discharge chamber #1 is $12.9 - 15.8$ ms (Xe) or $8.6 - 10.2$ ms (Kr). It is considered that this increase of the average residence time of neutral particle is one of the effect of the performance improvement because of increase of collision frequency with electron.

4.4 Consideration of the Other Effects

According to the reference$^8$, plasmoid exists in the hollow cylindrical area on the RF plasma by the hollow cathode effect. Plasmoid is the high density glow. However, its detail is not understood yet.
From the result of this simulation, it is understood that number density in the small chamber of the discharge chamber #2 is very high and residence time of neutral particle in it is very long. If plasmoid exists in the small chamber, there is the possibility that plasma is generated in the small chamber on the steady state. In fact, it is confirmed by sight that plasma is generated in the small chamber at first and spreads out the main chamber. The explanation of phenomenon in the small chamber is required in future.

4.5 Application of this program

The reason that is related directly to the performance improvement was not obtained. However, this program is possible to calculate the property of neutral particle on the discharge chamber whose configuration is complex. Another researches on discharge phenomenon require the calculation of the profile of neutral particle. Therefore, it is applied on such calculation in future.

5. Concluding Remarks and Future Subjects

5.1 Concluding Remarks

The following concluding remarks were obtained in this study.

1) The Analytical results that is possible to explain directly the reason of the difference of beam current observed in the experiment are not obtained.
2) The program in this study is possible to calculate the profile of neutral particle in the discharge chamber whose configuration is complex. It is able to be applied on another research in future.
3) It is difficult to consider that flow pattern change is related directly to the performance improvement because propellant is not supplied to the area on the penetration depth by the flow pattern change. However, it is considered that increases of number density and residence time of neutral particle in the small chamber of the discharge chamber #2 are one of the effect of performance improvement.

5.2 Future Subjects

In order to push forward this study for the performance improvement of the RF ion thruster, the more detailed simulation that contains ion particle, considering ionization, recombination, energy flow and so on. Moreover, the explication of phenomenon in the small chamber is required.

References