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Hiroyuki NISHIDA*, Takahiro NAKAMURA**, Shunjiro SHINOHARA*, Takeshi MATSUOKA†, Ikkoh FUNAKI†, Takao TANIKAWA‡, Tohru HADA§ and Konstantin P. SHAMRAI§§

*Inst. of Eng., Tokyo University of Agriculture and Technology,
** Grad. Sch. of Eng., Tokyo University of Agriculture and Technology
†ISAS, Japan Aerospace Exploration Agency
‡Res. Inst. of Sci. and Tech., Tokai University
§Interdis. Grad. Sch. of Eng. Sci., Kyushu University
§§Inst. for Nuclear Res. (Ukraine)

Abstract

An electrodeless plasma thruster is an advanced space propulsion concept suitable for a long-time space mission. We have been investigating an electrodeless plasma thruster concept utilizing a helicon plasma source and the Lissajous plasma acceleration, theoretically and experimentally. The effects of the particle collision and the plasma loss to the thruster wall are theoretically discussed using the drift-diffusion model of the plasma fluid. The particle collision effect is expected to be very low, and the thrust force is expected to have a peak value at a certain value of the ratio of the drift gyration radius to the thruster one. However, the experimentally estimated thrust is much lower than that estimated by the theoretical thrust model, which should be examined as future works.

Keywords: Electrodeless electric propulsion, Helicon plasma source, Rotating electric field, Lissajous plasma acceleration

1. Introduction

Electric propulsion systems (plasma thrusters) are suitable for a long-time space mission such as an interplanetary flight because of their high specific impulse (the thrust divided by the amount of propellant used per unit time). The Japanese asteroid explorer "Hayabusa" was equipped with four ion engines[1], which is one of electric propulsion systems, and the mission has been successfully executed after seven years interplanetary flight. Its successful completion of the mission shows the availability of the electric propulsion system in a long-time space mission. However, a lifetime of conventional electric propulsion systems is limited due to electrode erosion and contamination by plasmas.

The electrodeless configuration of a plasma thruster, in which the electrodes do not contact with the plasma directly, is one of promising solutions. The development of the electrodeless plasma thruster is an important research topic for next-generation space explorations, and various concepts have been investigated worldwide; VASIMR[2], HDLT[3] and others[4-7]. Some of thrusters are based on a high-density helicon plasma source which is a radio-frequency (RF) wave based plasma production method, and adopt an electrodeless electrothermal or electrostatic plasma acceleration method. On the other hand, there are few researches on an electrodeless electromagnetic plasma acceleration technique[6]. The electromagnetic plasma thruster can provide higher thrust density than that of any other electric propulsion systems and high thrust efficiency can be expected with high-electric power operation; such high-power electric propulsion is one of promising candidates for the human exploration of Mars in the future.

We have initiated HEAT (Helicon Electrodeless Advanced Thruster) project to investigate our original idea of electrodeless electromagnetic plasma thruster[8]. Our concept is based on the helicon plasma source (high density up to 10^{19} m^{-3}), and several types of RF wave based plasma acceleration scheme have been investigated. In this study, an acceleration scheme using a Rotating Electric Field (REF, also called as the Lissajous acceleration) is focused.

We have investigated the Lissajous acceleration theoretically and experimentally. Toki et al.[9] and Matsuoka et al.[10] have developed theoretical thrust models, and showed the probability of achieving the performance target (specific impulse of about 4000 sec) in an ideal condition (large scale, high power and collision-less plasma). Experiments using a laboratory model of the thruster have also been conducted, and some increment in the plasma flow velocity by REF has been observed[11]. However, the velocity increment was quite low due to weak electro-magnetic effect; the velocity increment was mainly from the thermal effect by the RF heating. Therefore, we have to optimize the operational (experimental) conditions to eliminate or reduce non-ideal drawback conditions or drawbacks for acceleration; particle collisions, low electric field penetration into the plasma, non-uniformity of the REF, plasma loss to the wall and so on.

First, the concept of the Lissajous acceleration type plasma thruster is introduced in this paper. Next, the effect of particle collisions and plasma loss to the wall are theoretically discussed using the drift-diffusion model of plasma fluid. Finally, some experimental results are reported, and the difference between a theoretically estimated thrust force and an experimentally one is discussed.

2. Concept of Thruster

Figure 1 shows the configuration of the Lissjous acceleration-type plasma thruster; the thruster consists of plasma production and acceleration parts. In the plasma production part, a compact helicon plasma source produces high-density plasma by applying RF power and a static magnetic field. In the acceleration part at the downstream of the helicon plasma source, a directional rotating electric field (REF) at the cross-sectional plane is applied using two pairs of opposed plates, and induces an electron current in the azimuth direction. The Lorentz force, i.e. a product of the azimuth electron current and the radial component of the static magnetic field, accelerates the plasma in the axial direction. The entire process of the thrust production can be conducted without electrode (antenna) erosion.

3. Theoretical Thrust Model

3.1 Principle of the Lissajous acceleration

The principle of the Lissajous acceleration is explained using a two-dimensional electron trajectory analysis; when the frequency of the REF is chosen to be between the ion cyclotron frequency and the electron one, only electrons can be driven by the REF. Here, we consider that the two-dimensional motion of an electron in the cross-sectional plane (x-y plane) of the plasma acceleration area. The REF lies in the x-y plane and z directional uniform magnetic field is assumed. Under these assumptions, the trajectory of an electron can be analytically calculated; the typical trajectory is shown in **Fig. 2**.

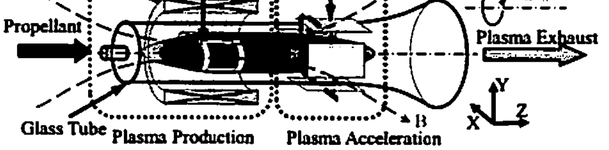

Fig.1 Schematic of Lissajous acceleration electrodeless plasma thruster.

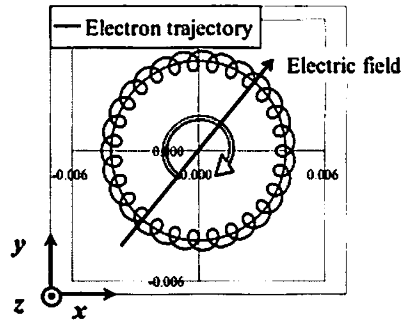

Fig.2 Trajectory of an electron under the REF and uniform magnetic field; R_D/R_L =0.11 and ω_{ce}/ω =28; R_D, R_L, ω_{ce} and ω are the ExB drift gyration radius, the Larmor radius, the cyclotron frequency and the REF frequency, respectively.

The trajectory is a superposition of two gyration motions as shown in Fig.2; the smaller one corresponds to the cyclotron motion and the larger one corresponds to the ExB drift motion. The radius of the ExB drift gyration motion (R_D) is given by the following equation.

$$R_D = E/\omega B_z, \quad (1)$$

where, ω is the REF angular frequency, B_z is the axial magnetic field, and E is the electric field. The helicon plasma source has a radial density gradient and higher density in the center region. When a radial density gradient exists, the azimuthal electron current can be produced by a superposition of the ExB gyration motions of all electrons as shown in **Fig.3**.

3.2 Thrust model based on the drift-diffusion model

Matsuoka et al.[10,12] have developed the theoretical thrust model. They estimated the electric field penetration into the plasma using one-dimensional electrostatic model, and the thrust force by integrating the trajectory of the electrons over one-cycle of the REF. The thrust model successfully provides an important insight into the similarity rule of a thruster, and shows the potential use of the Lissajous acceleration. However, the theoretical thrust model has been constructed assuming the ideal

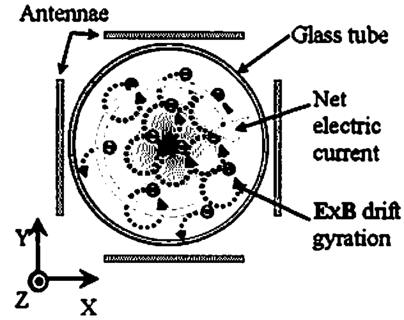

Fig.3 Azimuthal electron current production by superposition of the ExB drift gyration motion of all electrons.

conditions. Here, two types of the non-ideal effect, the plasma particle collisions with the neutral particles and the plasma loss to the thruster wall, are discussed using the plasma fluid model.

When the characteristic timescale of the macroscopic plasma motion is sufficiently longer than that of the particle kinetic motion, the plasma fluid assumption is applicable. In our thruster, the REF frequency (several tens MHz) is much smaller than the electron cyclotron frequency (several GHz), and therefore, the electron fluid assumption is applicable. Here, we consider the two-dimensional motion of the electron fluid in the cross-sectional plane (x-y plane) of the acceleration area (as shown in Figs.2 and 3); the spatially uniform REF in the x-y plane and z directional uniform magnetic field. The motion equation of the electron fluid is written as follows;

$$mn\frac{D\mathbf{v}}{Dt} = -en(\mathbf{E}+\mathbf{v}\times\mathbf{B}) - \nabla p - mn\nu\mathbf{v}, \quad (2)$$

where m, n, $\mathbf{v}$, e, p and ν are the electron mass, electron number density, the velocity, the unit charge, the electron pressure and the collision frequency, respectively. The purpose of this analysis is to discuss the particle collision effect on the Lissajous acceleration, and we assume the collision frequency term is large enough for the D**v**/Dt term to be negligible. This assumption leads to the following expression of the velocity[13];

$$\mathbf{v} = -\mu\mathbf{E} - D\frac{\nabla n}{n} + \frac{\mathbf{v}_{E\times B}+\mathbf{v}_D}{1+(\nu/\omega_c)^2}. \quad (3)$$

Here, the constant temperature, T, is assumed. D, μ and ω_c are the diffusion coefficient, the mobility and the electron cyclotron frequency, respectively.

$$\mu = \frac{1}{1+(\omega_c/\nu)^2}\frac{e}{m\nu}, \quad D = \frac{1}{1+(\omega_c/\nu)^2}\frac{k_B T}{m\nu}, \quad (4)$$

where k_B is the Boltzmann constant. The ExB drift velocity ($\mathbf{v}_{E\times B}$) and the diamagnetic drift velocity ($\mathbf{v}_D$) are given by

$$\mathbf{v}_{E\times B} = \frac{\mathbf{E}\times\mathbf{B}}{B_z^2}, \quad \mathbf{v}_D = \frac{\nabla p\times\mathbf{B}}{enB_z^2} = k_B T\frac{\nabla n\times\mathbf{B}}{enB_z^2}. \quad (5)$$

Here, we focus on the drift motion driven by the REF. The velocity vector of drift motion caused by the REF is given from Eq.(3) as follows;

$$\mathbf{v}_{REF} = -\mu\mathbf{E} + \frac{1}{1+(\nu/\omega_c)^2}\frac{\mathbf{E}\times\mathbf{B}}{B_z^2}. \quad (6)$$

The first term in the right-hand side of the equation is the electric field directional drift velocity, and the second term is the ExB drift velocity. The REF, $\mathbf{E} = (E_0\cos\omega t, E_0\sin\omega t)$, is substituted into Eq.(6), and the drift motion by the REF can be calculated as

$$(\mathbf{v}_{REF})_x = -\mu E_0\cos\omega t + \frac{1}{1+\nu^2/\omega_c^2}\frac{E_0}{B_z}\sin\omega t$$
$$(\mathbf{v}_{REF})_x = -\mu E_0\sin\omega t - \frac{1}{1+\nu^2/\omega_c^2}\frac{E_0}{B_z}\cos\omega t \quad (7)$$

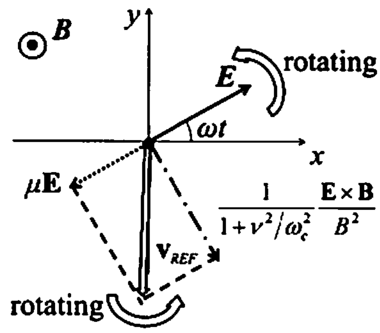

Fig.4 Vectors of the drift motion and the electric field.

$$|\mathbf{v}_{REF}| = \frac{E_0}{B_z}\sqrt{\left(\frac{\omega_c/\nu}{1+\omega_c^2/\nu^2}\right)^2 + \left(\frac{1}{1+\nu^2/\omega_c^2}\right)^2} \quad (8)$$

Figure 4 shows the relation between the vectors of the drift motion and the electric field; an electron fluid element has a gyration motion by the REF.

When the ω_c/ν, known as the Hall parameter, is expressed as β, the drift velocity ($\mathbf{v}_{REF}$) and the gyration motion radius by the REF (R_D) can be expressed as

$$|\mathbf{v}_{REF}| = \sqrt{\frac{\beta^2}{1+\beta^2}}\frac{E_0}{B_z}, \quad R_D = \sqrt{\frac{\beta^2}{1+\beta^2}}\frac{E_0}{B_z\omega}. \quad (9)$$

In Eq.(9), the factor $(\beta^2/(1+\beta^2))^{1/2}$ represents the effect of the particle collision. The factor $(\beta^2/(1+\beta^2))^{1/2}$ is plotted as a function of β in **Fig.5**. As shown in Fig.5, when the collision frequency is comparable to the electron cyclotron frequency, the particle collision effect is not negligible.

In our typical experimental conditions, the collision frequency is estimated to be several tens MHz, and much smaller than the electron cyclotron frequency (several GHz). Therefore, it is expected that the particle collision effect is weak in the experiments.

The azimuthal electron current density j_θ can be analytically calculated by integration of individual fluid element trajectories with an axial symmetric density profile in a similar way of the analysis given in ref. [12].

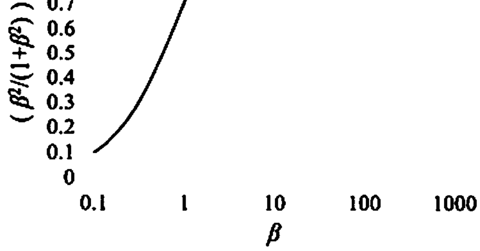

Fig.5 Effect of the particle collision.

$$j_\theta(r) = \frac{ev_{REF}}{2} R_D \frac{\partial n}{\partial r} + k_B T \frac{1}{B_z} \frac{\partial n}{\partial r}, \tag{10}$$

where r is the radial coordinate. The second term in the right-hand side of the equation represents the diamagnetic current density. Assuming a parabolic-like density profile as $n(r) = n_0(1 - \alpha r^2/r_0^2)$ and a radial magnetic field $B_r(r) = B_z r/(2a)$, the thrust force per axial unit length (F) can be obtained by integrating $j_\theta \times B_r$ over the plasma cross section of radius r_0.

$$F = \frac{\pi}{4a} e\omega n_0 \alpha B_z r_0^4 \cdot \zeta^2 (1-\zeta)^4 + \frac{\pi}{2a} n_0 \alpha k_B T r_0^2 \cdot (1-\zeta)^4, \tag{11}$$

where α represents a measure of the density gradient, r_0 is the radius of the thruster, and a is the coil radius. The ζ is the ratio of the drift gyration radius to the thruster radius; $\zeta = R_D/r_0$. Note that the effect of the plasma loss to the thruster wall is roughly taken into account in the integration process; the density is assumed to be zero in the region within the distance of R_D from the wall. The first term in the right-hand side of Eq.(11) represents the electromagnetic thrust by the REF, and the second term represents the thrust by the diamagnetic current (note that the thrust by the thermal pressure is also included in the total thrust in addition to Eq.(11)). The factor of the electromagnetic thrust, $\zeta^2(1-\zeta)^4$, is plotted as a function of ζ in **Fig.6.** As shown in Fig.6, the electromagnetic thrust by the REF has a peak value at around $\zeta = 0.35$, and this result is supported by the Particle-in-Cell simulation[14].

4. Experiment and Comparison with the Theory

For demonstrating the concept of the Lissajous plasma acceleration, we have conducted plasma acceleration experiments using a vacuum chamber and a laboratory model of the thruster [shown in **Fig.7(a)**]. The thrust force has been estimated from the plume measurement results under some specific experimental conditions, however, a clear electromagnetic thrust has not been observed. In this study, a parameter survey is conducted by changing the strength of the magnetic field applied by the external magnetic coil. The dependence of the thrust force on the magnetic flux density is experimentally investigated in detail, and the result of the experimental investigation is compared with the thrust model to estimate the electromagnetic thrust force.

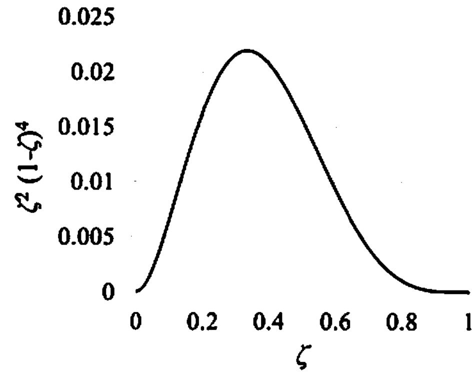

Fig.6 Relation between the electromagnetic force (the factor of $\zeta^2(1-\zeta)^4$) and $\zeta = R_D/r_0$.

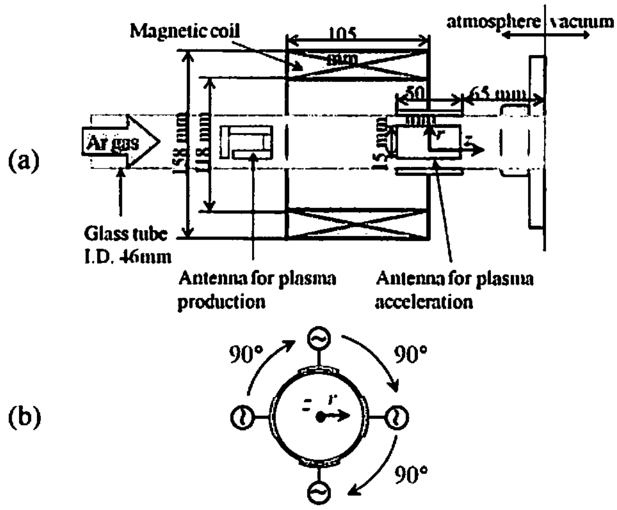

Fig.7 (a) Laboratory model of the thruster, (b) cross section of the plasma acceleration part.

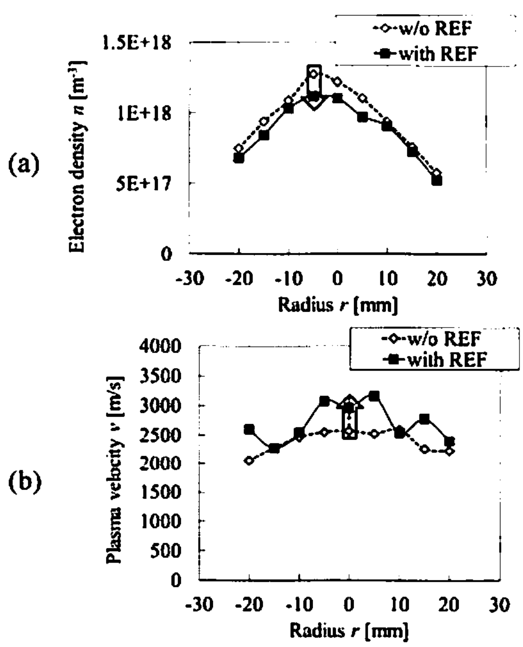

Fig.8 (a) Radial electron density distribution, (b) radial plasma velocity distribution.

4.1 Plasma acceleration experiment

The configuration and the scale of the laboratory model are shown in Fig.7(a). In the helicon plasma source, a saddle type antenna is used; the RF frequency is 27.12 MHz, and the input power is 400W. For the plasma acceleration, two pairs of opposed plates are used as shown in Fig.7(b); the RF frequency is 13.56 MHz, and the antenna voltage is 500 V. Argon gas is used as a propellant gas, and the mass flow rate is 0.2 mg/s. The axial magnetic flux density at the acceleration area is changed from 0.03 to 0.08 T.

The plasma density, temperature and Mach number of the plasma plume are measured by a para-perp type Mach probe at 5 cm downstream from the acceleration antenna. Typical radial profiles of the plasma parameters are shown in **Fig.8**; the squares (diamonds) indicate the case with (without) REF power. The plasma flow velocity increment can be observed in Fig.8(b). The thrust force without the REF power (before the acceleration) is estimated as 480 μN by integrating the momentum flux, and is enhanced to 556 μN by the REF power.

4.2 Comparison with the theoretical model

The thrust increment ΔF by the REF in the experiment is plotted as a function of the magnetic flux density in **Fig.9**. The theoretically estimated electromagnetic thrust F_{EM} is also plotted in this figure for comparison; the triangles and diamonds indicate the thrust estimated by the particle-motion based thrust model[10] and the fluid thrust model described in the previous section, respectively. Note that the penetrated electric field into the plasma is estimated by the one-dimensional penetration model developed by Matsuoka et al.[10] The thrust estimated by the fluid model is lower than that by the particle model due to the effect of the particle collision and the plasma loss to the wall. The tendency of the thrust increment in the experiment is in agreement with that estimated by the thrust model; the thrust increment (the electromagnetic force by the REF) increases with the magnetic flux density. However, the experimentally estimated thrust is much lower than the theoretically estimated one by two-order in amplitude.

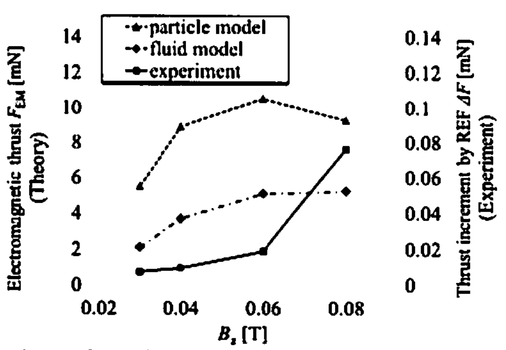

Fig.9 Thrust force increment by REF as a function of B_z.

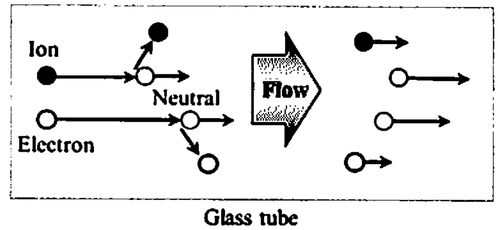

Fig.10 Particle collisions in the glass tube; accelerated high-speed plasma particles (ions and electrons) collide with the low-speed neutral particles, and decelerate to low speed.

Several reasons of the large difference between the experimental thrust and the theoretical one can be considered, as follows. 1) Spatial non-uniformity of the REF is considered to have a drawback on the thrust production. 2) The accelerated plasma flow may be decelerated by the particle collisions with the low-speed neutral particles during passing through the magnetic nozzle (as shown in **Fig.10**), and the thrust force is considered to be underestimated in the experiment (since the thrust force by neutrals is not negligible). 3) The curvature of the applied magnetic field enhances the plasma loss to the thruster wall. However, these candidates have not been fully examined yet, which should be clarified as a future work.

5. Conclusions

The electrodeless plasma thruster using a helicon plasma source and the Lissajous plasma acceleration was theoretically and experimentally investigated, and following results were obtained.

(1) The effect of the particle collisions with the neutral particle and the plasma loss to the wall were discussed using the drift-diffusion model. The particle collision effect is expected to be negligible (in our experimental conditions), and the thrust force is theoretically expected to have a peak value at the certain value of R_{ty}/r_0.

(2) Thrust force was estimated by measuring the plasma plume from the laboratory model of the thruster, and the thrust force increment by the Lissajous acceleration was observed (from 460 μN to 556 μN).

(3) The experimentally estimated thrust shown above is much lower than that estimated by the theoretical thrust model, whose discrepancy should be clarified.

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