Improvement of Propulsion Performance by Gas Injection and External Magnetic Field in Electrodeless Plasma Thrusters

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Abstract: We performed two-dimensional axisymmetric particle-in-cell simulations with Monte Carlo collisions algorithm (PIC/MCC) and direct simulation Monte Carlo (DSMC) for neutrals to investigate the effect of neutral gas injection from a downstream side of electrodeless thrusters on propulsion performance. In the analysis, the propellant gas is injected from both the upstream and downstream sides of the thruster with various ratios of the gas injections, while maintaining the total gas flow rate of 30 μg/s. The numerical results in DSMC simulations showed that downstream gas injection led to the neutral distributions with small density gradient along the axial direction inside the thruster, whereas the distributions in the downstream regions did not depend on the gas injection methods greatly. In addition, for PIC/MCC simulations, numerical results showed that the increase in gas flow rate from downstream regions led to the improvement of the performance. This tendency is in qualitative agreement with recent experiments.

Nomenclature

$\boldsymbol{B}$	=	magnetic field
$\boldsymbol{E}$	=	electric field
j	=	plasma current density
k_B	=	Boltzmann constant
n_p	=	plasma density
Q	=	neutral gas flow rate
T_e	=	electron temperature
$\boldsymbol{v}$	=	velocity
$\boldsymbol{x}$	=	position
ρ	=	charge density

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I. Introduction

RESEARCHES of high-power electric thrusters have been performed around the world due to a trend of developing all-electric satellites such as 702SP developed by Boeing.[1] These thrusters are required to have high propulsion performance and long lifetime. Although mature electric propulsion devices such as ion and hall thrusters are remarkable candidates, electrodeless thrusters could also be one of them. Since they have no electrodes to generate and accelerate plasmas, the lifetime is not limited owing to the damage on electrodes. In particular, helicon plasma thrusters (HPTs), which consist of a helicon plasma source and a magnetic nozzle are interesting and many researches have been performed recently.[2-4] Helicon discharges give high-density plasma with various external parameters and are utilized in many fields. However, it is confirmed that the propulsion performance of HPTs stays at low-level in some experiments compared with conventional thrusters.[5,6] We previously reported that the non-negligible momentum loss resulted from neutral depletion at the downstream regions of the thruster leads to the low performance with both the experiments and numerical simulations.[7,8] In addition, Takahashi *et al.*[9] demonstrated that neutral gas injection from not only upstream but also downstream regions of the thruster improved propulsion performance in their experiments. This tendency has also been confirmed in recent simulations.[10] However, we did not take a thrust components due to magnetic nozzle into consideration in the simulations. In this study, we have evaluated the effects of gas injection from downstream on propulsion performance including all thrust components of the electrodeless thrusters.

II. Numerical Conditions

A. Numerical Procedure

We have conducted two-dimensional axisymmetric particle-in-cell simulations with Monte Carlo collisions algorithm (PIC/MCC) for charged particles, and direct simulation Monte Carlo method (DSMC) for neutrals. It should be noted that these simulations were performed independently. First, we performed DSMC simulations and obtained neutral distributions, and then conducted PIC/MCC simulations using the neutral distributions. In this section, numerical conditions for each simulation are described.

B. PIC/MCC Simulations

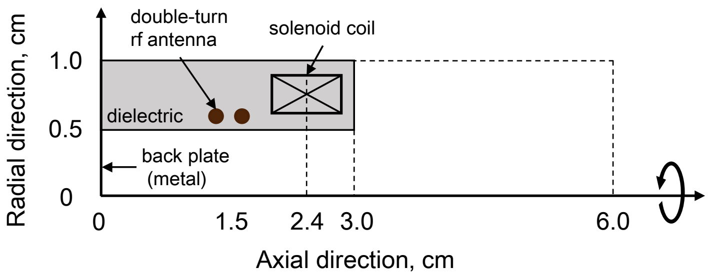

Figure 1. Schematic diagrams of the calculation model for PIC/MCC simulation.

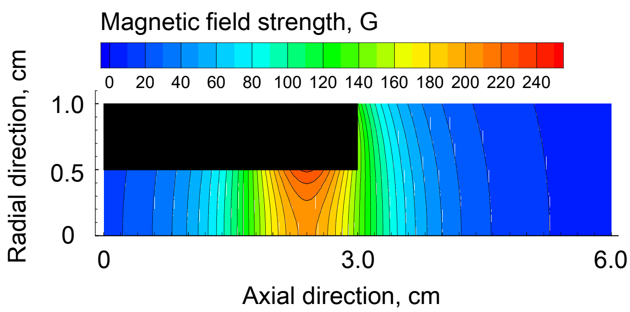

Figure 2. External magnetic field strength by the solenoid coil.

Figure 1 shows schematics of the calculation model for the PIC/MCC simulations. We used two-dimensional cylindrical coordinates and calculation area is 6.0 cm in axial length and 1.0 cm in radial length, where grid spacing is 0.1 mm. It is composed of a dielectric wall, a double-turn rf antenna, and a solenoid coil that gives magnetic field as shown in Fig. 2. We supposed that plasma production region (z < 3.0 cm) and exhaust region (z > 3.0 cm) that is roughly one-six of the dimension of a recent experiment.[7] The centers of the rf antenna and solenoid coil are located at z = 1.5 cm and 2.4 cm, respectively. Figure 3 shows a calculation flow for the simulations. The details of the calculation flow and method are described in the previous paper,[8] and we mention those briefly here. Initially, charged particles with Maxwellian velocities are distributed over plasma production region uniformly. Then, positions and velocities of the particles give charge density and plasma current density. Using these values, we obtain potential by solving Poisson equation on each grid. Then, electrical and magnetic field are derived. Next, we consider the dynamics of the particles according to the given fields included by RF current and solenoid current. Collisions are simulated by using MCC method with neutral distributions obtained in DSMC simulations. These numerical processes are performed repeatedly in every time step. In addition, we assume the following conditions:

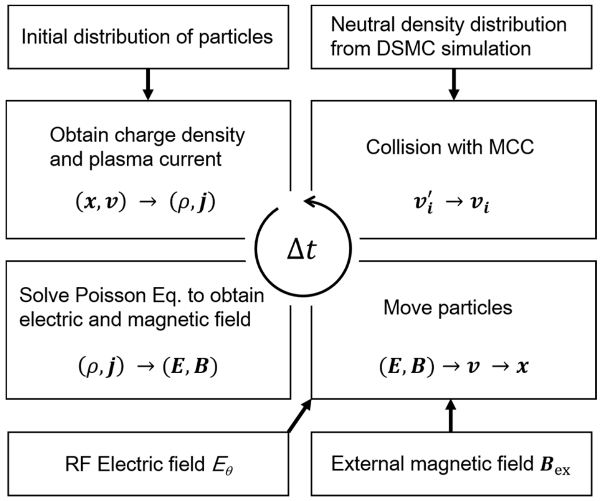

Figure 3. Flowchart of the PIC/MCC simulations. ©JSASS[10]

i) Only singly charged xenon ions and electrons are treated as the charged particles. The neutral distributions obtained from the DSMC simulation are fixed on the grids and no dynamics of the neutrals are taken into account in the PIC simulation.
ii) Only elastic and charge exchange collisions for ions, and elastic, excitation, and ionization collisions for electrons are considered. The charged particles are generated only by these reactions.
iii) The charged particles vanish when they collide with the walls or pass through the boundaries. The surface charge due to the accumulation of the charged particles is considered only on the dielectric walls.
iv) The boundary conditions of potential are zero at all the walls.

The total thrust for simple HPTs is defined as the sum of the force to the back plate T_s, to the lateral wall T_w, and the Lorentz force onto the magnetic nozzle T_B. T_s and T_w are estimated by calculating the momentum transfer from the ions to the boundary of the simulation area, and T_B is calculated by Eq. (1) derived from theoretical models.[11]

$$T_B = \int_0^z \int_0^r r \frac{B_r(r,z)}{B_z(r,z)} \frac{\partial p_e(r,z)}{\partial r} drdz \,, \tag{1}$$

where p_e is electron pressure (= $n_p k_B T_e$).

C. DSMC Simulations

In this simulation, only xenon atoms were considered to obtain neutral distributions. In this paper, we describe total neutral gas flow rate as Q_{total} and downstream gas flow rate as $Q_{down.}$ Q_{total} was maintained at 30 μg/s and three types of downstream gas injection ratios (Q_{down}/Q_{total}) were employed: 5%, 50%, and 95%. Calculation area is the same as in PIC/MCC simulation and not shown here. Neutral particles are injected with Maxwellian velocity from both upstream and downstream side of the source cavity. Since the mean free path is larger than the size of the thruster, it is assumed that collisions between neutral atoms are negligible. We set temperature of the thruster wall at 300 K and the particles are reflected diffusely at the wall.

III. Results and Discussion

Figure 4 shows the distributions of neutral density obtained in DSMC simulation for Q_{down}/Q_{total}. As increasing downstream gas injection ratios, density gradient along the axial direction in the source cavity becomes gentle and the peak density decreases. On the other hand, the density distributions in the exhaust region do not seem to depend on the ratios. Therefore, the methods of gas injection affect neutral distributions only in plasma production regions.

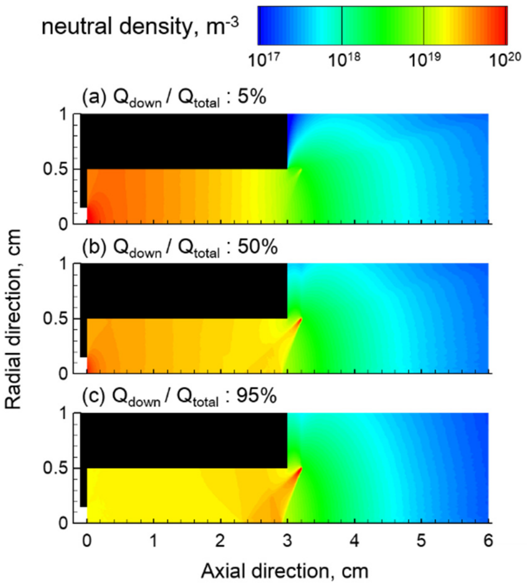

Figure 4. The distributions of neutral density for downstream gas injection ratio Q_{down}/Q_{total} of (a) 5%, (b) 50%, and (c) 95%.

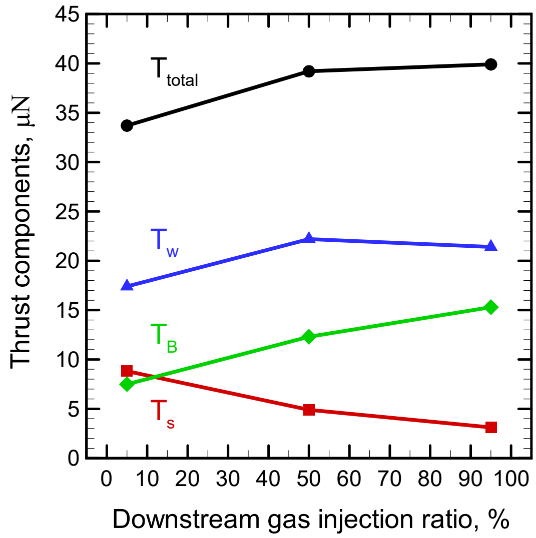

Figure 5. Calculated three thrust components, the force to the back plate T_s and to the dielectric side wall T_w, Lorentz force onto magnetic nozzle T_B, and the sum of them as a function of downstream gas injection ratio.

Applying these distributions to PIC/MCC simulations, we simulated dynamics of charged particles. Thrust components, T_s, T_w, T_B, and the sum of them in steady state are shown in Fig. 5. As increasing downstream gas injection ratio, T_w increase, whereas T_s decrease. These tendencies were also confirmed in recent simulations, and it was concluded that the shift in plasma distributions toward the exhaust regions and the increase in peak density due to downstream gas injection led to them in Ref. 10. In addition, T_B increases as the increase in Q_{down}/Q_{total}. This tendency also results from the shift in high-density plasma since T_B are affected by the gradient of electron pressure in the radial direction as shown in Eq. (1).

As a result, the sum of the thrust components, defined as T_{total} (= T_s + T_w + T_B) in this paper, increases monotonically. Therefore, it is considered that downstream gas injection has a positive effect on propulsion performance, and this tendency agrees with the recent experiments.[9] However, the individual measurement of the force components validated that T_B amounted to above 50 % of the total thrust,[12] although T_B in this simulation is calculated to be up to 40%. It is considered that this discrepancy arises from numerical conditions; external magnetic field strength and plasma density are lower than the experimental conditions due to a reduction in calculation cost. Therefore, this tendency should be evaluated not quantitatively but qualitatively.

IV. Conclusion

We have conducted two-dimensional axisymmetric PIC/MCC simulations to perform the evaluation of the effects of the downstream gas injection. As a result, the increase in Q_{down}/Q_{total} leads to the decrease in T_s and the increase in T_w. T_B also increases due to the downstream gas injection. It is considered that this change in the each component are the shift in plasma distributions toward the exhaust regions and the increase in peak density reported in previous simulations. In addition, the sum of thrust components increases monotonically. Therefore, it is validated that downstream gas injection is effective for performance improvement in the electrodeless thrusters. This agrees with the recent experimental results qualitatively.

Acknowledgments

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