Numerical Investigation of Magnetic Nozzle Plasma Expansion Using Fully Kinetic Simulations

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Plasma thrusters have successfully been utilized in space propulsion systems, e.g., ion and Hall thrusters. These plasma thrusters have a higher exhaust velocity than chemical thrusters, reducing gas consumption and increasing payloads. However, the lifetime limitation of the thruster remains due to the electrode wear, and the plasma generation and acceleration without electrodes are desired for further advanced space missions.

One of the recent attractive plasma thrusters is an electrodeless plasma thruster using a magnetic nozzle [1]. A magnetic nozzle has a nozzle-shaped magnetic field produced by a solenoid or permanent magnets and accelerates the plasma up to a supersonic speed. The physics observed in the magnetic nozzle has been reported in many papers.

In recent years, the plasma expansion in the magnetic nozzle has actively been discussed, where the relation between the electron density n_e and temperature T_e is described as a polytropic relation of T_e / $n_e^{\gamma-1}$ = const. using the polytropic index γ. Little and Choueiri measured the polytropic index of magnetic nozzle plasma expansion in a fiberglass vacuum chamber and reported γ = 1–1.2 [2], whereas Takahashi et al. eliminated the plasma potential in a vacuum chamber and indicated γ approaching 5/3 [3]. There are many other experimental and numerical studies of the polytropic index in the magnetic nozzle plasma expansion, but γ varies by each study, and no clear consensus has been formed.

In a previous experimental study, it was implied that the plasma potential affected the plasma expansion, and the polytropic index depended on the plasma potential in the magnetic nozzle [3]. From this implication, it is expected that the electron energy may also have an important role in the magnetic nozzle plasma expansion, i.e., the plasma has different polytropic indexes depending on the electron energy. In experiments, however, it is difficult to evaluate the electron energy and investigate the polytropic index depending on the electron energy. In contrast, fully kinetic particle simulations can evaluate electron populations with different electron energies separately, and the polytropic index can be obtained depending on the electron energy.

In this study, the magnetic nozzle plasma expansion was simulated using fully kinetic simulations, and the polytropic index in the magnetic nozzle was analyzed depending on the electron energy. Fully kinetic simulations employed particle-in-cell and Monte Carlo collision techniques, where particles kinetics and fields were self-consistently simulated. In our previous papers, internal plasma currents in the magnetic nozzle were successfully reproduced using fully kinetic simulations [4], and momentum conversion in the magnetic nozzle was numerically demonstrated [5].

In the fully kinetic simulations, the threshold energy of 12.1 eV was set, and the polytropic indexes were obtained depending on whether the electron energy less or greater than 12.1 eV. As a result, the simulations showed that low-energy electrons (less than 12.1 eV) had the polytropic index of unity, whereas high-energy electrons (greater than 12.1 eV) had that of 5/3. From these results of polytropic indexes, it was revealed that the polytropic index in the magnetic nozzle significantly depended on the electron energy. In addition, it was implied that the low-energy electrons trapped in the plasma potential were measured in [2], whereas the experiment in [3] demonstrated high-energy electrons in the magnetic nozzle. By setting more threshold energies, the plasma expansion in the magnetic nozzle is expected to analyzed in detail.

References

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