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Propellant Species Dependence of Plasma and Shock Wave Structures in a Microwave Rocket

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1. Introduction

A microwave rocket was proposed to reduce a launch cost of small satellites [1]. A gas breakdown is induced when an intense microwave is irradiated to the vehicle with a parabolic mirror. A strong shock wave is induced when energy of the electrons is transferred to energy of neutral particles via a collisional process. A propulsive thrust is generated when the shock wave interacts with the thruster wall. However, the gas breakdown cannot be maintained when a flight altitude of the vehicle is high and the ambient gas density is small. Therefore, the thrust cannot be generated at the high altitude. We propose the microwave rocket with a gas fuel tank to maintain the gas discharge in the rocket nozzle. The propellant species can be selected when the gas fuel tank is equipped on the rocket. The gas heating efficiency and the shock wave strength may depend on the propellant species, but there is no data to select a suitable propellant species for the microwave rocket. In this study, plasma propagations in nitrogen, hydrogen, and helium are reproduced by utilizing a one-dimensional (1D) plasma fluid model to evaluate an energy deposited inside the rocket nozzle. The shock wave simulation is conducted based on the data obtained by the discharge simulation to assess the thrust performance dependence of the propellant species.

2. Numerical Method

The 1D Maxwell's equation is numerically solved by a finite-difference time-domain (FDTD) method to reproduce the electromagnetic wave propagation during the microwave irradiation. The plasma diffusion and ionization processes are obtained by solving an effective diffusion model for the electrons. A current density is evaluated by integrating the equation of motion for the electrons, and it is fed back to the Maxwell's equation to reproduce an interaction between the plasma and electromagnetic wave. The shock wave propagation is reproduced by integrating the two-dimensional axisymmetric Euler equation with an energy source term for the microwave gas heating.

3. Simulation Condition

An electric field intensity of the microwave is set as 6 MV/m. The microwave frequency is set as 110 GHz, following Hidaka's experiment [2]. The transport coefficients in pure nitrogen, hydrogen, and helium are evaluated from Bolsig+. A cylinder nozzle with a radius of 3 cm and length of 18 cm is modeled in the computational domain [1]. The energy stored inside the microwave-rocket nozzle is evaluated from the discharge simulation, which is utilized to model the energy source term in the shock wave simulation. The atmospheric pressure is set as 101,325 Pa and neutral gas temperature is 298 K in the plasma and shock wave simulations.

4. Results

Overdense plasmas are induced owing to the quick ionization when the microwave is irradiated (Fig. 1). The plasma front propagates toward the microwave source by repeating the ionization, microwave reflection, and electron diffusion. The propagation speeds are evaluated as 37.0, 151, and 617 km/m in nitrogen, hydrogen, and helium, respectively. The slowest propagation speed is obtained in nitrogen because of the slower electron diffusion. The shock wave dynamics is reproduced with the energy source term, which indicates that the thrust performance becomes maximal value in nitrogen (Fig. 2). This is because a sufficient energy can be stored inside the rocket nozzle owing to the slowest propagation speed. It is necessary to select propellant with the slower electron diffusion coefficient to obtain the higher thrust.

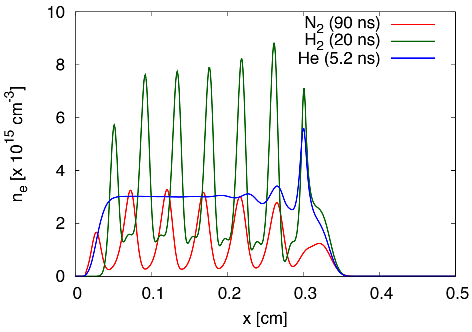

Figure 1 Discharge structures.

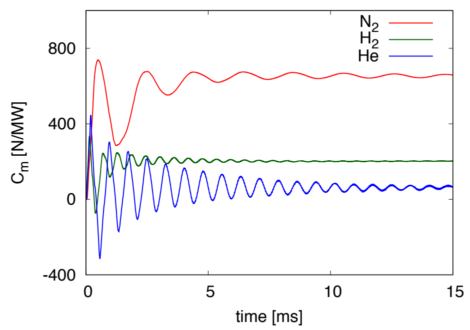

Figure 2 Momentum coupling coefficients.

5. Conclusion

The plasma propagations in nitrogen, hydrogen, and helium are reproduced by utilizing the plasma fluid model. The plasma propagation speed becomes the smallest in nitrogen because the electron diffusion is slow, which induces the maximum thrust performance.

References

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[2] Y. Hidaka et al., Phys. Rev. Lett. 100, 035003 (2008).