Experimental Study of Chemical-Electric Dual-Mode Thruster with Microwave Plasma

By Tomohiro ABE,[1)] Keita NISHII,[1)] and Akira KAKAMI[1)]

1) *Tokyo Metropolitan University, Hino, Japan*

This paper describes a chemical-electric dual-mode thruster with microwave plasma. Some spacecraft have both chemical propulsion (CP) and electric propulsion (EP) to enable dual-mode operation, allowing for high specific impulse with low thrust and high thrust with high specific impulse. Despite the success of the dual-mode operation, the propellant was not sharable by EP and CP except for arcjet thrusters, and hence, multiple thruster heads were necessary on spacecraft to result in complex structures. Moreover, the arcjet thrusters required catalysts to decompose the propellant (hydrazine), which is used in monopropellant thrusters. Recent green propellants tend to contain oxygen atoms, which could damage the electrodes and catalysts. Based on this background, we suggested a dual-mode thruster with microwave plasma, which is able to switch between EP and CP modes in a single thruster head and requires no electrode. Hence, oxygen-contained green propellants are applicable to the proposed thruster. EP mode operation was examined using the prototype with nitrogen used as a propellant simulant, and the microwave plasma was produced at a microwave power of 500 W and yielded a thrust chamber pressure of 17.4 kPa.

Key Words: Microwave plasma, Electrothermal thruster, Chemical / electric dual-mode propulsion

Nomenclature

$\dot{m}$	:	mass flow rate, kg/s
P_f	:	forward power, W
P_r	:	reflected power, W
p_{0c}	:	pressure of cold gas, Pa
p_{0h}	:	pressure of hot gas, Pa

1. Introduction

Spacecraft propulsion systems can be classified into two types: chemical propulsion (CP), which generates thrust by converting the energy of chemical reactions into the kinetic energy of the propellant, and electric propulsion (EP), which produces thrust by supplying electrical energy to the propellant. CP is typically used for missions requiring high thrust. In contrast, EP is employed in missions where high specific impulse (Isp) is required. Some spacecraft are equipped with both chemical and electric thrusters to enable dual-mode operation, allowing for high thrust with low Isp and high Isp with low thrust.

However, multiple thruster heads and separated propellant storage are necessary to complexify the structure because EP and CP necessitate their own propellant; the former generally requires xenon, and the latter necessitates hydrazine. DC arcjet thrusters are an exception and can share hydrazine propellant with CP. However, the recent green propellant contains oxygen and carbon atoms, which severely damage the electrodes and catalysts through oxidation and charring. Hence, the dual-mode configuration using arcjet thrusters and green propellant would suffer from electrode damage.

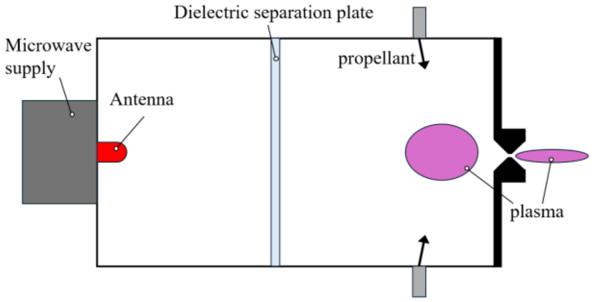

Fig. 1. Typical structure of MET.

Microwave discharge would be preferable to green propellant propulsion because the discharge requires no electrode. Hence, we designed a CP/EP dual-mode thruster using microwave discharge. The thruster allows the dual mode in a single thruster head.

Microwave plasma has been applied to EP. The Microwave Electrothermal Thruster (MET), as shown in Fig.1, has been developed. Similar to DC arcjet thrusters and resistojet thrusters, the MET is an electrothermal thruster. However, MET requires no electrodes, allowing longer operational lifespan and the use of various propellants, some of which contains reactive atoms. Hydrogen, helium, nitrous oxide, and water have been tested with the MET[1)-6)]. The firing test showed that 98% of forward microwave power was absorbed by the plasma and a specific impulse of approximately 420 s using water.[1)]. Due to the extended lifespan and flexibility in propellant selection, MET could be a promising next-generation electrothermal thruster. However, microwave plasma has never been applied to chemical thrusters.

The authors proposed a dual-mode thruster that integrated CP and MET into a single thruster head. This design could simplify the thruster and propellant feeding systems. Furthermore, the use of microwaves enables electrode-less plasma generation, eliminating the need for catalysts or electrodes, which are prone to degradation, and allows the use of green propellants. This contributes to extending the thruster's operational lifetime. In this study, nitrogen was used as a propellant simulant to conduct firing tests in the EP mode to ensure the thruster produced plasma in the EP mode.

2. Dual-mode thruster prototype

Figure 2 shows a cross-sectional view of a 3 kW-class dual-mode thruster prototype. The thruster consisted of an antenna, antenna zone, thrust chamber, antenna support glass plate, separation glass plate, and nozzle plate. The 2.45-GHz microwave was transmitted into a CX-39D coaxial line using a mode converter to be introduced into the thruster. The antenna, supported by a borosilicate glass support plate and support glass plates in the antenna zone, excited TM011 mode resonance in the thrust chamber. The resonance strengthened the electric field in the center of the thrust chamber to induce the microwave plasma. A viewing window was located on the side of the thrust chamber, allowing observation of the microwave discharge.

2.1. Electric propulsion mode

Figure 3 shows a schematic of the EP mode operation. In the EP mode, the thruster produces the thrust in the same way as the MET. The injected propellant yields dielectric breakdown due to the augmented electric field, so that the plasma is kept heated by the microwave. Thrust is generated by expelling the heated plasma through a nozzle.

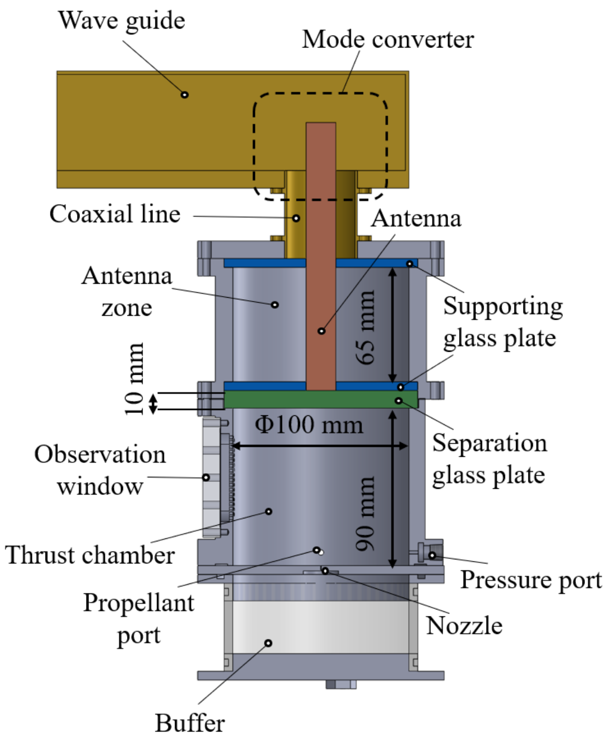

Fig. 2. Cross-section of the prototype.

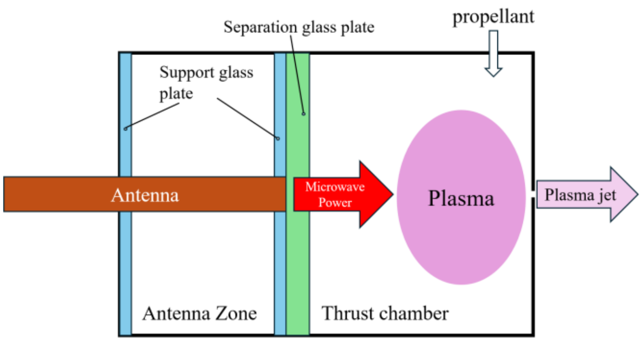

Fig. 3. Operation of the EP mode.

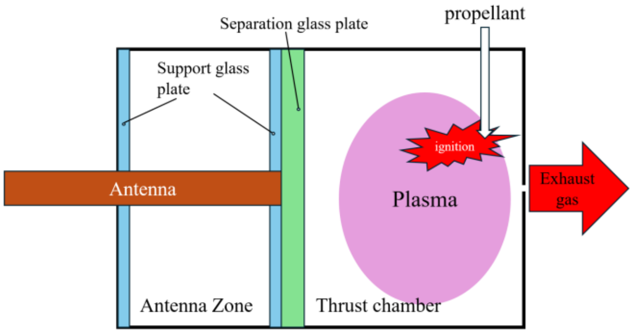

Fig. 4. Operation of the CP mode.

2.2 Chemical propulsion mode

In the CP mode, the thruster produces thrust in the same manner as that of typical liquid propellant thrusters except for ignition, as shown in Fig.4. In ignition, microwave plasma was induced in the thrust chamber to provide enthalpy to the propellant for starting combustion. After the initiation of combustion, the microwave supply is interrupted. Then, the combustion is autonomously sustained during propellant feeding.

3. Experimental Apparatus

Figure 5 shows a schematic of the experimental setup. The vacuum chamber was not evacuated, and instead, the nozzle exit was evaluated using a rotary pump. The thruster was tested in the vacuum chamber to prevent microwave leaks.

3.1. Rotary vacuum pump

A rotary vacuum pump (ULVAC, GLD-201B, pumping speed: 200 L/min) was connected to the nozzle exit of the prototyped thruster through a buffer to simulate the vacuum environment. The vacuum chamber was not evacuated because unintended electric discharge seemed to be induced inside the waveguide under the reduced ambient pressure. Hence, the buffer was inserted between the nozzle and the rotary pump to maintain the vacuum chamber pressure at atmospheric pressure.

3.2. Microwave supply system

Figure 6 shows a schematic diagram of the microwave supply system. A 3-kW-rated magnetron (Nissin, MG-30CJ-W-CE) with a power supply (Nissin, MPS-30W-DC-CE) produced a 2.45-GHz microwave to the thruster through BRJ-2 waveguides. A 6-kW rated water-cooled isolator (Nissin, NISJ-60W) was set to protect the magnetron from the reflected

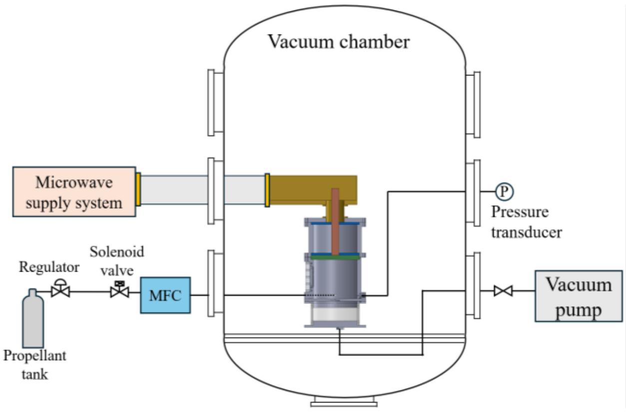

Fig. 5. Schematic of the experimental setup.

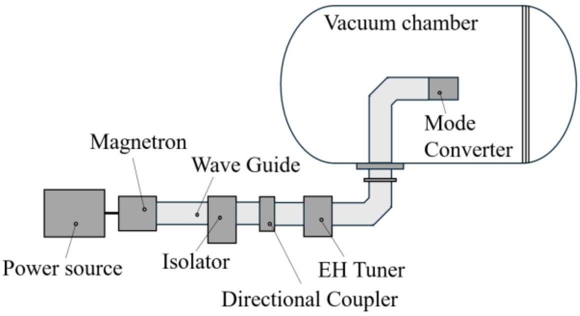

Fig. 6. Schematic diagram of the microwave supply system.

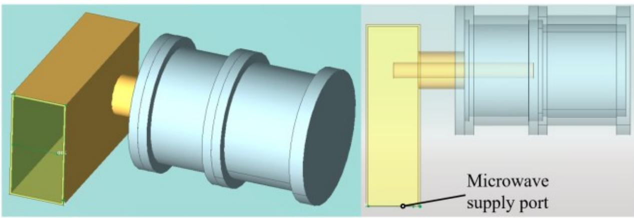

Fig. 7. Model of the analysis target.

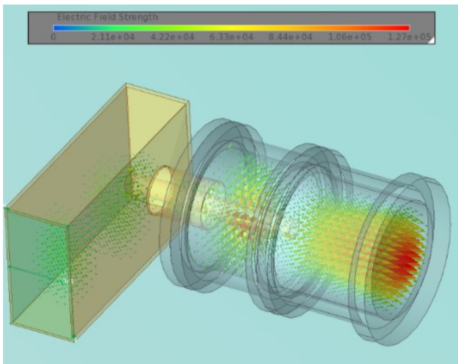

Fig. 8. Vector plot of electric field.

microwave. A directional coupler with a detector (Nissin, N2PM-J) was used to determine the forward and reflection microwave power. A 6-kW rated manual EH tuner (Nissin, MT-20S) was utilized for impedance matching.

4. Electromagnetic field simulation

Inducing microwave plasma necessitates adequate thrust chamber pressure and augmented electric field. Hence, an electromagnetic field simulation was conducted using EMPro,

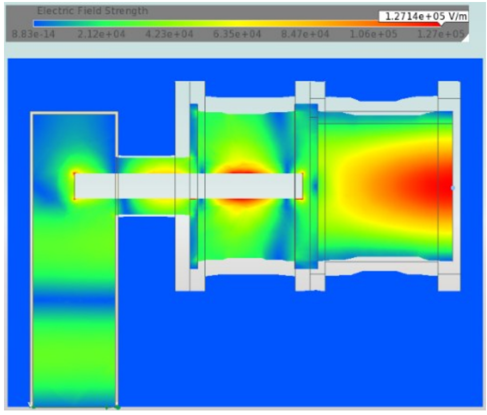

Fig. 9. Contour map of electric field.

an electromagnetic field simulation software developed by Keysight Technologies. The software used the finite element method. The simulation using the model depicted in Fig. 7 was conducted under the condition of 1000-W forward microwave power. Figures 8 and 9 show the vector plot and contour map of electric field, respectively. The simulation showed that an axial electric field of 1.27×10^5 V/m was obtained near the nozzle of the thrust chamber. The value would be sufficient for ignition at 1 kPa class ambient pressure.

5. Experimental condition

5.1. Experimental conditions

Table.1 shows the experimental conditions implemented in this study. In this experiment, nitrogen flow rate was set as parameter.

5.2. Experimental procedure

The experimental procedure is described below.

1. Evacuate the thrust chamber through the buffer.
2. Nitrogen was fed to the thruster at flow rate ranging from 0.38 mg/s to 19.2 mg/s
3. Measure the pressure in the thrust chamber. (Measurement of cold gas pressure)
4. The flow rate is returned to 0.38 mg/s
5. Microwave is applied at a forward power of 200 W.
6. After confirming plasma ignition, the forward power is increased to 500 W
7. Nitrogen was fed to the thruster at flow rate ranging from 0.38 mg/s to 19.2 mg/s
8. Measure pressure of thrust chamber and reflected power.

Table. 1. Experimental conditions

	Flow rate, mg/s	Forward power, W
At ignition	0.38	200
After ignition	0.38-1.53, 1.92-19.2	500

6. Results and discussion

This section describes Experimental results and discussion. Here, nitrogen without microwave irradiation is defined as "cold gas," and nitrogen after microwave irradiation is defined as "hot gas."

6.1. Time history

Figure 10 shows the time history in the case that nitrogen flow rate was increased from 0.38 mg/s to 1.53 mg/s. Before ignition, mass flow rate was maintained at 0.38 mg/s, and applying microwave of 200 W in forward power initiated plasma in the thrust chamber. Then, microwave forward power was increased to 500 W. Subsequently, mass flow rate was increased up to 1.53 mg/s. Reflected microwave power was decreased with increasing mass flow rate, so that the reflected power reduced to 27.5 W at 1.53 mg/s. and 94.5% of microwave was absorbed by the plasma.

Figure 11 shows the time history in the case that nitrogen flow rate was increased from 1.92 mg/s to 19.2 mg/s. Before ignition, mass flow rate was maintained at 0.38 mg/s, and applying microwave of 200 W in forward power initiated plasma in the thrust chamber. Then, microwave forward power was increased to 500 W. Subsequently, mass flow rate was increased up to 19.2 mg/s. Reflected microwave power was increased with increasing mass flow rate by 7.66 mg/s, but subsequently decreased with increasing mass flow rate to 19.2. Microwave absorption ratio was minimum value, 53.2%, at 7.66 mg/s, and reached 59.1% at 19.2 mg/s.

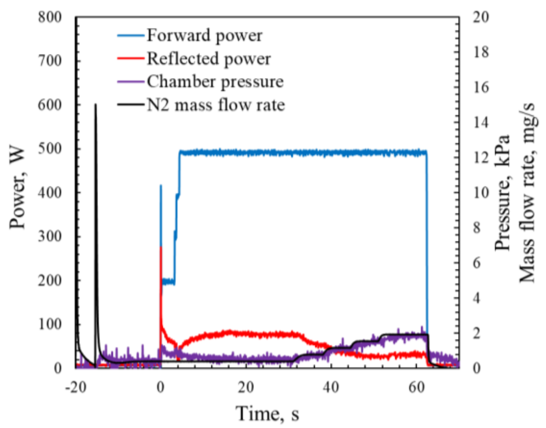

Fig. 10. Time history of microwave power and chamber pressure. Nitrogen flow rates were increased from 0.38 mg/s to 1.53 mg/s after microwave plasma ignition.

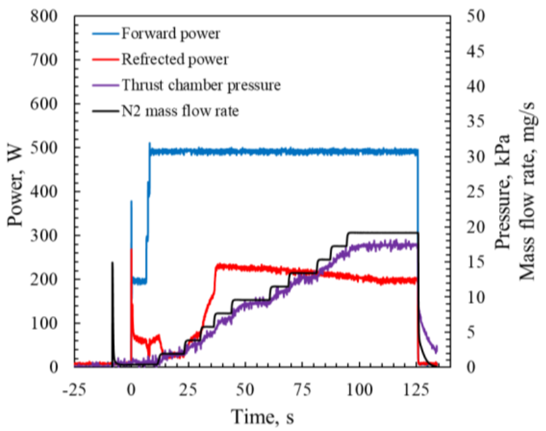

Fig. 11. Time history of microwave power and chamber pressure (N_2 flow rate 1.92 mg/s ~ 19.2 mg/s).

6.2. Chamber pressure of hot gas and cold gas

Figure 12 shows the dependence of p_{0h}, p_{0c} and p_{0h}/p_{0c} on the nitrogen flow rate. There is no significant difference between p_{0h} and p_{0c} under the condition that the flow rate was 1.92 mg/s or below. However, at flow rates of 3.83 mg/s and above, the difference between p_{0h} and p_{0c} becomes more pronounced. The pressure ratio p_{0h}/p_{0c} reached a maximum of 1.34 at a nitrogen flow rate of 13.4 mg/s.

6.3. Dependence of microwave absorption ratio on N_2 flow rate

Figure 13 shows the relationship between nitrogen flow rate and microwave absorption ratio. Absorption ratio was increased up to 0.94, which was obtained at 1.92 mg/s, and then decreased to 0.55 (7.66 mg/s). Above 7.66 mg/s, the absorption ratio slowly increased with mass flow rate.

Microwave absorptivity behavior differed between low and high flow conditions, with microwave absorptivity close to 90% for low flow conditions from 0.38 mg/s to 1.92 mg/s, but about 57% for high flow conditions above 7.66 mg/s. This suggests the presence of a discharge mode in this experiment.

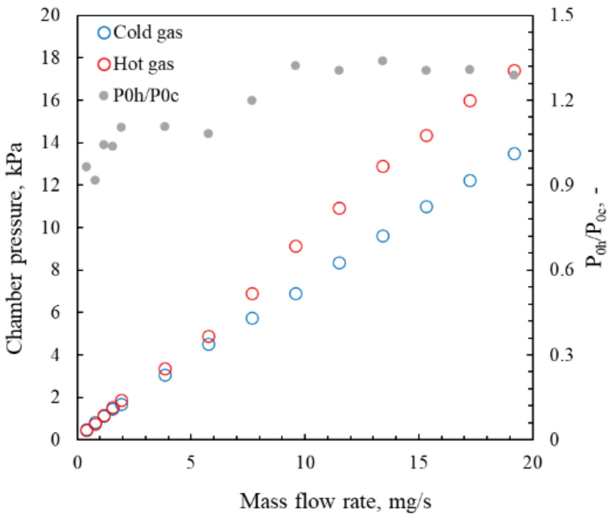

Fig. 12. Chamber pressure vs. mass flow rate.

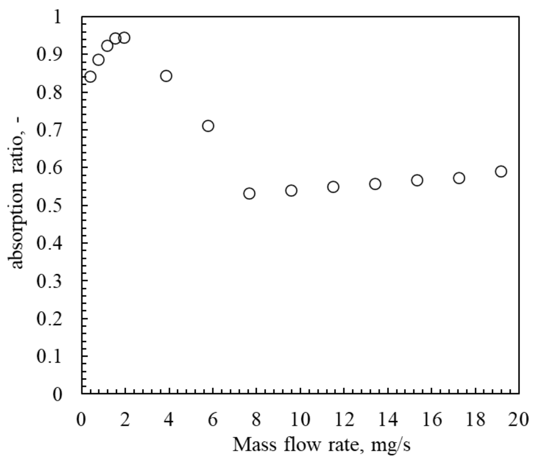

Fig. 13. Absorption ratio vs. mass flow rate.

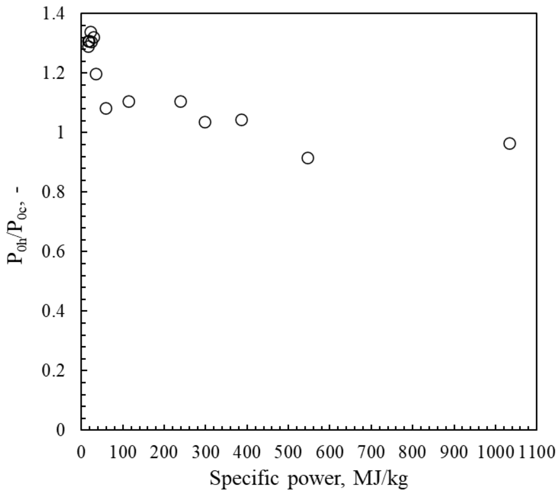

Fig. 14. Specific power vs. of p_{0h}/p_{0c}.

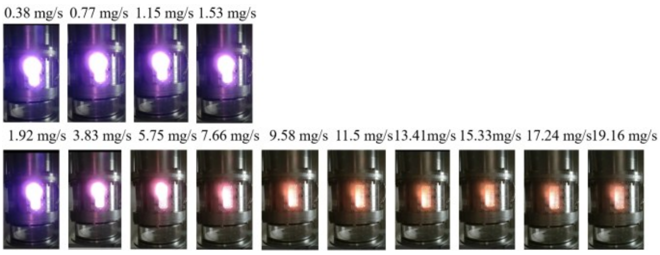

Fig. 15. Appearance of microwave plasma.

6.4. Dependence of p_{0h}/p_{0c} on specific power

Figure 14 shows dependence of p_{0h}/p_{0c} on specific power. Under conditions where the specific power exceeds 300 MJ/kg, p_{0h}/p_{0c} is close to 1, indicating that the input energy does not contribute to pressure increase. In contrast, when the specific power is below 27 MJ/kg, $p_{0h}/p_{0c} \approx 1.3$. It demonstrates that microwave energy results in approximately a 30% increase in pressure compared to cold gas.

These results indicate that microwave energy does not contribute significantly to pressure increase at high specific power. According to previous study[1], it may consider that severe energy loss due to thermal dissipation may occur under high specific power conditions. Similarly in this study, it is considered that energy loss has occurred due to thermal dissipation, and as a result, no significant pressure increase was observed in the high specific power situation.

6.5. Appearance of microwave plasma

Figure 15 shows the appearance of microwave plasma at various nitrogen flow rates. Between flow rates of 3.83 mg/s and 9.58 mg/s, changes in both the color and the position of the plasma emission are observed. Under the condition of low flow rate, the plasma appears purple, and the emission is located closer to the antenna zone. As the flow rate increases, the plasma color shifts to orange and the emission region moves toward the nozzle.

7. Conclusion

A chemical-electric dual-mode thruster using microwave plasma was proposed and prototyped. Operating tests were conducted in the EP mode using nitrogen as the propellant, yielding the following conclusions: Microwave plasma ignition was achieved at nitrogen flow rate of 0.38 mg/s and forward microwave power of 200 W. The plasma was then sustained at forward power of 500 W. Microwave plasma was sustained under all tested conditions with nitrogen flow rates ranging from 0.38 mg/s to 19.2 mg/s. This demonstrates the successful operation of the EP mode using the prototype. On the other hand, pressure measurements were conducted for the hot gas and cold gas, and p_{0h}/p_{0c} was calculated. Under conditions with specific power exceeding 300 MJ/kg, p_{0h}/p_{0c} was found to be close to 1, indicating that, despite plasma ignition, there was no noticeable increase in pressure. This suggests that a significant amount of energy may be lost as heat to the thruster walls at high specific power. Moreover, based on appearance of plasma and microwave power absorption data, it was confirmed that the discharge mode varies with specific power. The pressure ratio p_{0h}/p_{0c} varied depending on the discharge mode, reaching 1.3 under low specific power conditions, which indicates a 30% increase in pressure compared to the cold gas.

8. Future work

In this study, the operation of the EP mode was demonstrated using nitrogen. However, the CP mode has not yet been experimentally validated. Therefore, future work includes conducting operation tests using reactive propellants such as nitrous oxide or hydrogen peroxide. Additionally, for the EP mode, it is necessary to explore optimal operating conditions considering the discharge mode to further improve performance. Following the demonstration of the CP mode, we aim to perform tests under various flow rates and input powers to optimize the system as a chemical-electric dual-mode thruster.

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