Development of a Microwave Discharge Cathode for a 200 W Class Hall Thruster

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Abstract: The microwave discharge cathode has been developed for a neutralizer cathode of Japanese asteroid explorer Hayabusa and Hayabusa2. The microwave discharge cathode is easy to handle because it does not use electrode nor electron emitting material which easily oxidizes and deteriorates in atmospheric conditions. Therefore, demand for easy-to-use microwave discharge cathode increases. The performance of the microwave discharge cathode and the hollow cathode is similar for currents of about 0.5 - 1.0A, and it is not clear which of them is superior. This is the current range of 200W class Hall thruster systems which has a need for future small satellites. The purpose of this research is to investigate the performance characterization of the microwave discharge cathode - Hall thruster system. Coupling a microwave discharge cathode and a 200W class Hall thruster system, it was confirmed that the microwave discharge cathode neutralization current was sufficient and a thrust of 6.6mN was measured. It is equivalent result to the hollow cathode. Furthermore, the plasma tends to easily ignite in the case that magnetic lines of force connect the center of the Hall thruster and the microwave discharge cathode. By the thrust measurement, microwave cathode shows equivalent performance to hollow cathode. However, by the ion energy distribution and beam profile, hollow cathode is slightly better than the microwave cathode.

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Nomenclature

B	=	Magnetic flux density
e	=	Elementary charge
g	=	Standard gravity
I_a	=	Discharge current
I_{beam}	=	Beam current
I_c	=	Cathode current
I_{coil}	=	Coil current
I_{sp}	=	Specific impulse
m_e	=	Electron mass
$\dot{m}$	=	Mass flow rate of thruster system
P	=	Electric power for thruster and cathode
P_a	=	Electric power for anode
P_c	=	Electric power for cathode
T	=	Thrust
T/P	=	Thrust to power ratio
V_a	=	Discharge voltage
V_{cg}	=	Potential difference between cathode and ground
η_a	=	Anode efficiency
η_{acc}	=	Accerrelation efficiency
η_{energy}	=	Energy utilization efficiency
η_{div}	=	Beam divergent efficiency
η_t	=	Thrust efficiency
η_u	=	Propellant utilization efficiency
ω_c	=	Electron cyclotron frequency

I.Introduction

THE asteroid explorer Hayabusa was launched in May 2003 and succeeded the world's first asteroid sample return mission.[1] The microwave discharge ion thruster $\mu 10$ achieved the cumulative operation time of about 40,000 hours for the 4 installed ones. The next asteroid explorer Hayabusa2 launched in December 2014.[2] the ion thruster is electric propulsion and applied to the deep space exploration mission because the specific impulse is more than one order of magnitude higher than chemical propulsion. In order to apply ion thrusters to various missions in the future, it is required to increase the ion current of ion sources.[3,4] Because of the ion current increase of the ion sources, the electron current increase of the microwave discharge cathode is also required.[5,6,7,8] Therefore, we have aimed to increase electron current of the microwave discharge cathode and succeeded that to 500mA class. The performance of the microwave discharge cathode and the hollow cathode is similar for currents of about 500 - 1,000mA, and it is not yet clear which of them is superior in this operating range.[8,9] This is the current operating range of 200 - 300W class Hall thruster systems, and this class Hall thruster system has a need for future small satellites.[1,8,10,11] In 2013, DubaiSat2 with the first Hall thruster microwave cathode propulsion system was launched.[12] However, detail of the performance characterization are not clear. The objective of this paper is to investigate the performance characterization of the microwave discharge cathode to 200 - 300W class Hall thruster systems.

A. Cathode

Hollow cathodes are often used as cathodes for electric propulsion satellites.[13,14] However, the hollow cathode has some disadvantages as shown in Table 1. For example, the hollow cathode needs to be heated to about 1,000K by a heater at start of operation.[16] Therefore, it is necessary to preheat. Also, it breaks frequently by repeating ON/OFF of the heater. Furthermore, due to the characteristics of the electron emitting material, hollow cathodes cannot be exposed to atmosphere for long. If it is exposed to the atmosphere for a long time, the electron-emitting material is oxidized, and the performance is degraded. In addition, when it emits a low current, the self-heating mode is difficult to maintain, and a relatively large power is required for heater.[17]

Table1. **Characteristics comparison between microwave cathode and hollow cathode.**[1,13,15,18]

	Microwave cathode	Hollow cathode
Advantages	Easy handling	Large current
Disadvantages	Small current	-Self-heating mode is difficult to be maintained at a range of 1 A or less -Preheating -Disconnect of electric circuit for heater -Oxidization
Magnetic field	Yes	No

On the other hand, the microwave discharge cathode is easy to handle for ground test operation. The microwave discharge cathode generates plasma by electron cyclotron resonance, so it is not necessary to use electrode and electron emitting material, which oxidize in the atmosphere. However, its emission current is small compared to hollow cathodes, and increase of electron current is necessary to expand its applications in space.

B. Microwave Discharge Cathode

As shown in Fig.1, microwave discharge cathode is composed of a magnetic circuit and a microwave input antenna. The magnetic circuit is mainly composed of permanent magnets and magnetic line of force. As shown in Fig.1, extracted electrons for neutralizing is generated by two parts. First one is a heating by Electron Cyclotron Resonance, ECR. The ECR is a resonance of the microwave frequency with the electron cyclotron frequency ω_c as shown in Eq. (1).[19]

$$\omega_c = \frac{eB}{m_e}$$

The microwave discharge cathode generates high energy electrons by ECR and generates plasma by collision between the high energy electron and neutral particle of xenon.

The second one is DC discharge by the potential difference between the ion beam and the cathode. The high energy electrons accelerated by ion beam potential generate positive column by collision with neutral particle.

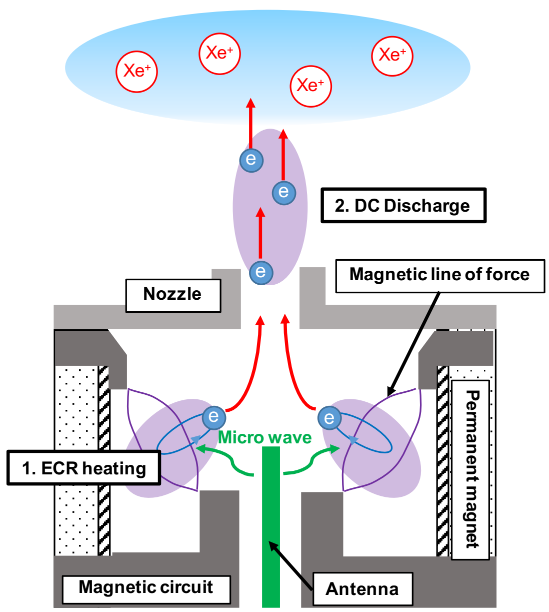

Figure 1. Schematic of microwave discharge cathode.

II.Method

In this study, we investigate the performance characteristics of a microwave discharge cathode - hall thruster system by coupled operation. We also compare with the hollow cathode – hall thruster system to compare the performance. The experiments were conducted in the space science chamber in the Institute of Space and Astronautical Science (ISAS) of Japan Aerospace Exploration Agency (JAXA). The Hall thruster is magnetic layer type developed by Kyushu University.

Experimental setup is shown in Fig.2. The microwave discharge cathode system is composed by propellant supply system and microwave supply system. The gas container and mass flow controller supply constant mass flow of Xe. The microwave supply system is composed of oscillator, amplifier and matching circuit. A microwave of 4.25GHz is oscillated and then amplified to a determined intensity by the amplifier. A microwave is introduced into the cathode through the matching circuit. The microwave discharge cathode is placed 15mm in the downstream direction and 60mm in

Table2. Experimental condition.

Items	Values
Mass Flow Rate for Cathode	1.5sccm
Microwave Power	20W
Microwave Frequency	4.25GHz
Mass Flow Rate for Thruster	7.0sccm
Hall Thruster	Magnetic layer type
V_a	150, 200, 250, 300, 350V
Back Pressure with 10sccm Xe	3×10^{-3}Pa
Back Pressure without gas input	5×10^{-5}Pa

the radial direction with respect to the Hall thruster. The angular between the central angles of Hall thruster and microwave discharge cathode is 75 degrees. To measure the ion energy distribution, RPA is placed 1m downstream of Hall thruster. In addition, the grounded beam target is placed 1.5m downstream of the Hall thruster. The detail photograph of cathodes and Hall thruster is shown in Fig.3. In order to measure the thrust, the Hall thruster was placed on the thrust stand. However, since the thrust cannot be measured accurately due to the rigidity of the microwave cable, the microwave discharge cathode is not placed on the thrust stand. The experimental conditions are shown in the Table 2.

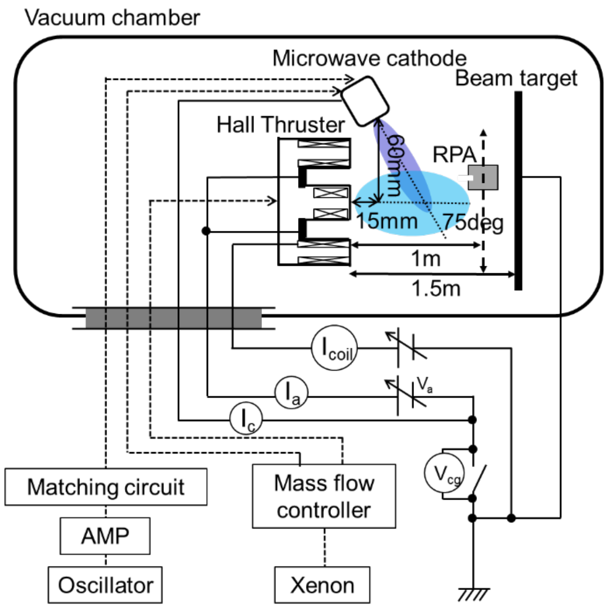

Figure 2. Experimental setup of coupled test operation.

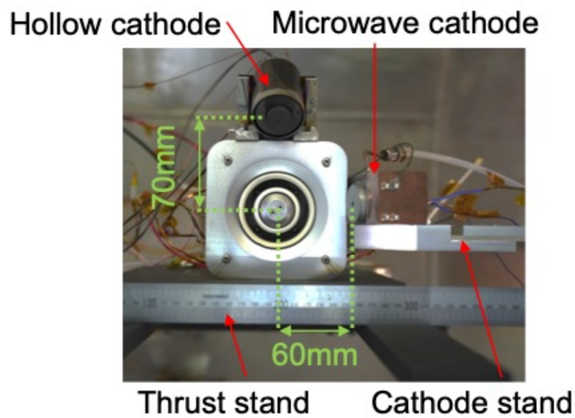

Figure 3. Picture of thruster and cathodes

III.Result and Discussion

C. Effect of magnetic field interference between microwave discharge cathode and Hall thruster

Experiments were conducted to investigate the relationship between the magnetic field polarity of the Hall thruster - microwave discharge cathode and performance characterization. It was found that the magnetic field of the Hall thruster and the magnetic field of the microwave discharge cathode interfere with each other and affect the ignition characteristics. The magnetic field of Hall thruster was formed by an inner coil and 4 outer coils. They formed magnetic field around the channel. On the other hand, the microwave discharge cathode formed a magnetic field not only inside the discharge chamber but also outside by permanent magnets. Therefore, the magnetic field near the discharge chamber of the Hall thruster was affected by the microwave discharge cathode. There were two kinds of magnetic fields of the microwave discharge cathode and the Hall thruster due to the difference in polarity, as shown in type A and type B of Fig.4. In the type A of Fig.4, a magnetic field was formed such that the central axis of the Hall thruster and the microwave discharge cathode were connected by magnetic lines of force. In the type B, a magnetic field was formed so that external coil of the Hall thruster and the microwave discharge cathode were connected by magnetic lines of force. In Fig.4, the case where the thruster center was N pole is shown, but even when both the polarities of the Hall thruster and microwave discharge cathode were opposite, they do not change essentially.

As a result of the experiments, it was found that type A is easier to ignite plasma than type B. Furthermore, it was found that a I_a of about 1,000mA instantaneously flows. On the other hand, the current value of I_a is about 600 mA during steady operation. Therefore, it is necessary to supply a relatively large electron current at the time of plasma ignition.

Since large electron current is needed at the time of plasma ignition, these results suggested that electrons are more easily supplied from microwave discharge cathode to the channel of the Hall thruster in type A magnetic field of Fig.4. The electrons move along the magnetic field line while moving around it. As shown of the type A in Fig.4, a magnetic field was formed such that the central axis of the Hall thruster and the microwave discharge cathode were connected by magnetic lines of force. Therefore, in the magnetic field of type A, electrons are relatively easily transported to the anode inside the channel of the Hall thruster. On the other hand, in the type B, a magnetic line of force was formed so that external coil of the Hall thruster and the microwave discharge cathode were connected. Therefore, it was suggested that some of electrons supplied by microwave discharge cathode were lost at a wall of the Hall thruster in front of outer coil. This result suggest that it is necessary to design a magnetic field including microwave discharge cathode. Furthermore, it was found that the magnetic field of the microwave discharge cathode affect the ignition characteristics of Hall thruster.

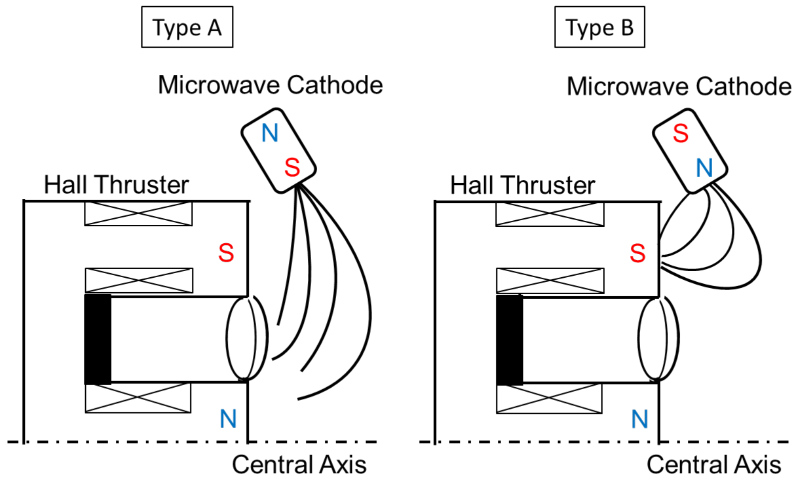

Figure 4. Combination of magnetic field formed by microwave discharge cathode and Hall thruster.

D. Performance characteristics

Experiments were conducted to investigate the performance characterization of the Hall thruster and microwave discharge cathode system. In addition, we compared the performance with hollow cathode. The performance characterization of the Hall thruster when the discharge voltage is from 150V to 350V was investigated. In order to evaluate the thrust performance of thruster system, specific impulse, I_{sp}, and thrust efficiency, η_t are defined as,

$$I_{sp} = \frac{T}{\dot{m}g}$$

$$\eta_t = \frac{T^2}{2\dot{m}(P_a + P_c)}$$

In order to evaluate the thruster head performance, electric power loss is not taken into account. In the case of microwave discharge cathode, the thrust was 4.6mN when the discharge voltage V_a was 150V at I_{coil}=2A. As the V_a increased, the thrust also increased, and a thrust of 6.6 mN was confirmed at V_a = 250V. Furthermore, the specific impulse I_{sp} was 810s. The result of T/P showed a slight increase tendency with respect to the discharge voltage V_a, it was about 35mN/kW at V_a = 250V. In the case of hollow cathode, a thrust of 6.3 mN was confirmed at V_a = 250V. It is almost equivalent to the microwave discharge cathode. Furthermore, the specific impulse I_{sp} was 668s. It is lower than microwave discharge cathode because of the difference of mass flow rate of cathode. The result of T/P was about 32mN/kW at V_a = 250V.

The discharge current I_a with respect to the discharge voltage V_a is also measured. Although it showed a slight increase tendency with respect to the discharge voltage V_a, it was almost saturated. Therefore, it is suggested that the propellant is sufficiently ionized in channel. In the case of microwave discharge cathode, the η_t was 0.17 when the discharge voltage V_a was 250V. The η_t of hollow cathode is 0.12. The potential difference between cathode and ground V_{cg} drops negative as the discharge voltage V_a increases. In the case of microwave discharge cathode, the $V_{cg}$was -19V when the discharge voltage V_a was 150V. However, when the discharge voltage V_a was 250V, the V_{cg} was -28V. When the discharge voltage is 150V to 250V, V_{cg} drops by 9 V. On the other hand, hollow cathode keeps about -15V. The results suggest the HC has higher electron supply capacity than microwave discharge cathode.

By the measurement of ion energy distribution of RPA, mean energy is 184eV in the case of hollow cathode at I_{coil}=2A, V_a = 250V. On the other hand, mean energy in case of microwave discharge cathode is 169eV. The difference is equivalent to the difference of V_{cg}. In addition, the results of ion beam profile measurements coupled with hollow cathode,

I_{beam} is 13% larger than the case of microwave discharge cathode. Therefore, η^* of Hall thruster – hollow cathode system is better than microwave discharge cathode system. Here, η^* is as follows.

$$\eta^* = \eta_{acc}\eta_u\eta_{div}\eta_{energy}$$

However, η_a of Hall thruster – microwave discharge cathode system is better than hollow cathode system because thrust is almost equivalent by thrust measurement.

Fig. 5 shows the comparison of η_t with other thruster. The η_t of Hall thruster-microwave discharge cathode system is better than that of hollow cathode. Because mass flow ratio of microwave discharge cathode is smaller than hollow cathode. In the case of the microwave discharge cathode, η_t is equivalent to HT100.

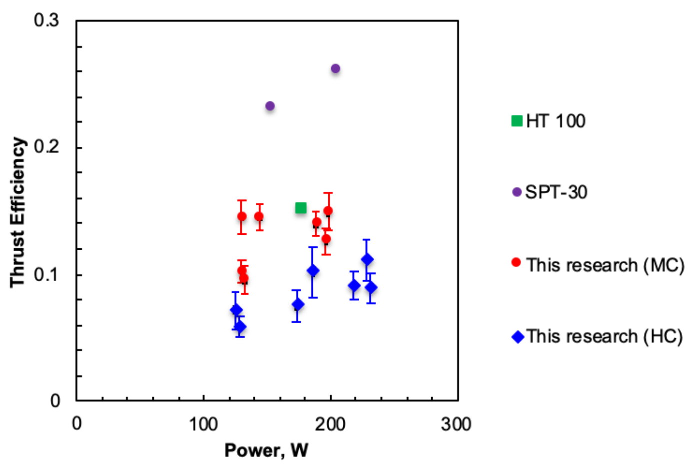

Figure 5. Comparison with other thrusters

Conclusion

In conclusion, the present study suggest that the microwave discharge cathode is effective for neutralization in 200W class Hall thruster system. The conclusion in this research is as follows.

- In coupled operation, the electron current is larger than that in diode mode
- The thruster tends to easily ignite in the case that magnetic lines connect the center of the Hall thruster and the microwave discharge cathode
- A thrust of 6.6mN was measured, and the specific impulse is 810sec when the electric power of propulsion system is 189W
- In the case of HC and Improved MC, the thrust is almost equivalent
- By the results of ion energy distribution and beam profile, HC shows the best performance
- There are errors that cannot be evaluated quantitatively

Acknowledgments

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