Effect of Antenna Configuration on Thrust Performance in a Miniature Microwave Discharge Ion Engine

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Abstract: The effect of antenna configuration—its shape and its position— on thrust performance in a 30 W class miniature microwave discharge ion engine was investigated with the objective of improving its thrust performance. The ion beam currents with various antenna shapes and position were measured, since microwave—plasma coupling could be affected by the antenna configuration. Under low mass flow rate, using disk shape antenna shows good performance. On the other hand, under high mass flow rate, using star shape antenna shows good performance and disk shows poor performance. This discrepancy is due to the tradeoff between the plasma-microwave coupling and the surface recombination on antenna. The thrust performance of the miniature microwave discharge ion engine, propellant utilization, and ion beam production cost were 0.73 and 740 W/A , respectively at mass flow rate =0.02 mg/s, and incident microwave power= 8 W.

Nomenclature

B	=	magnetic flux density
e	=	electronic charge
I_b	=	extracted ion bam current
m_i	=	ion mass
$\dot{m}$	=	mass flow rate
P_i	=	incident microwave power
P_r	=	reflected microwave power
ε_c	=	ion beam production cost
η_u	=	propellant utilization
φ	=	diameter

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I. Introduction

The adoption of small satellites, with their flexibility, short development time and low cost, has been a breakthrough in space applications. Until recently, however, size restrictions have limited the capacity of the available propulsion systems. Hence, mN class miniature propulsion systems will experience a growing demand in the future.[1] A miniature microwave discharge ion engine is a candidate for use as a miniature propulsion system,[2] since an ion engine produces a high thrust efficiency, exceeding 70%, with specific impulse of 3,000-8,000 sec. Therefore, there have been and will be many missions using the ion engine.[3-5] The adoption of the miniature ion engines into small satellites will expand their capabilities, due to the increase in delta velocity. That is, missions such as Mars exploration would be possible. Furthermore, self-disposal of satellites whose missions have been completed will also be possible, eliminating destruction or retrieval costs.

Several studies have been conducted on the miniature ion engine.[6-7] Wirz et al. showed good performance of the miniature ion engine.[6] An electron bombardment-type ion source was used for ion production in that study, so that operation time was limited by the thermionic cathode lifetime. A microwave discharge ion source would have a longer lifetime than electron bombardment-type, since it would be free from contamination and degradation of its electron emission capacity.[8] This superiority was validated by the "Hayabusa" mission.[9]

The thrust performance of miniature microwave discharge ion engines has been inferior to conventional ion engines, however, due to the high cost of ion production because of poor microwave—plasma coupling as well as high losses from ion and electron collisions with the walls.[10] This type of ion engines has an antenna to emit microwaves, and the antenna configuration affects plasma coupling. Hence, the aims of this study are to investigate the effects of antenna configuration—antenna shape and antenna position—on the thrust performance of miniature microwave discharge ion engines and to evaluate the thrust performance.

II. The Experimental Equipment

The cross section of a 30 W class miniature microwave discharge ion engine is shown in Fig. 1. The inner diameter is 18 mm and the size of engine is 50 mm×50 mm×30 mm. The ion source consists of a magnetic circuit, which has four Samarium Cobalt (Sm-Co) permanent magnets and iron yokes. The magnetic field profile of this engine is shown in Fig.2. The magnetic tube works as a virtual cathode, since the trapped electrons gain energy from the microwaves and ionize neutral atoms.[3] Seven types of antenna—disc, star, cross, ume(Japanese apricot), octopus, starfish, and L shape, are used, as shown in Fig. 3. The tip of the antenna is inserted into the magnetic tube formed by the magnetic circuit. Each antenna is set at 7 mm or 8 mm downstream of the back yoke. It can be changed to 8 mm. A 2.45 GHz microwave was fed through a coaxial line followed by an antenna. A DC block with a loss of 0.43 dB at 2.45 GHz was inserted to protect the microwave amplifier. Flat square grids were used to extract the ion beam. The geometric parameters are shown in Table 1. This geometry was designed using a numerical analysis code developed by Arakawa et al.[11] The grid is made of molybdenum and a mica sheet is used as an isolator between the two grids. The ion beam diameter is 14 mm.

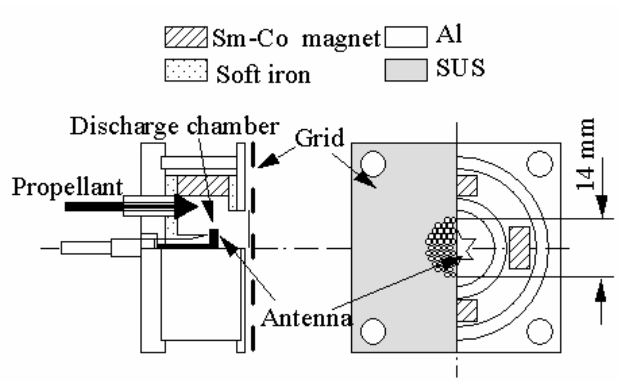


Figure 1. Cross-section of miniature ion engine developed at Kyushu University.

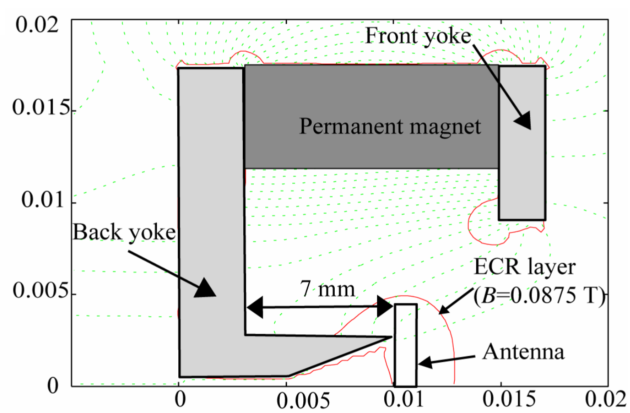


Figure 2. Magnetic field profile of miniature ion engine.

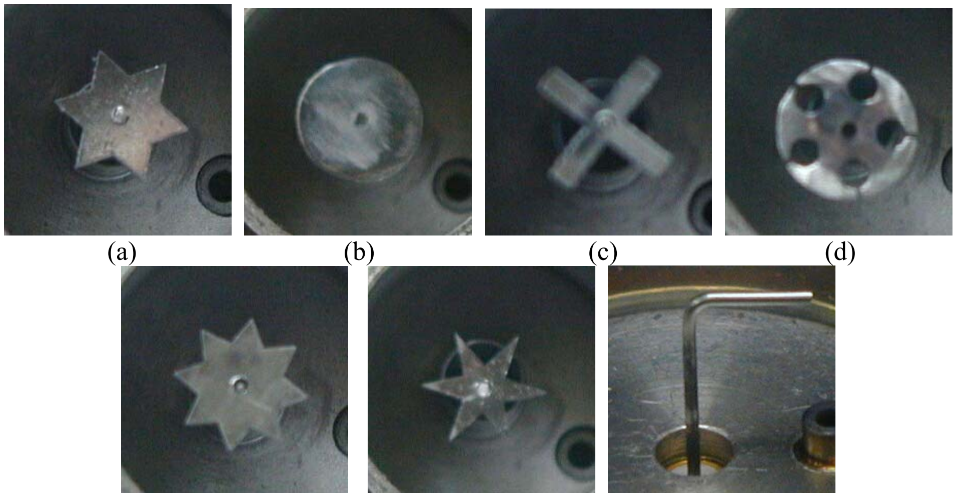


Figure 3. Photos of antennas.
(a) star (b) disc (c) cross (d) ume(Japanese apricot) (e) octopus (f) starfish (g) L shape

Table 1. Grid parameters.

Parameter	Screen	Acceleration
Open ratio, %	51	15
Hole diameter, mm	0.90	0.48
Potential, V	1500	-300
Grid gap, mm	0.25	
Number of holes	121	

The electric circuit is shown in Fig. 4. A neutralizer was not used in this study, as there is little difference between the thrust performance without a neutralizer and that with a filament neutralizer (ϕ = 0.2 mm×100 mm, 2% thoriated tungsten). The extracted ion beam was estimated as the current through the screen power supply minus the current through the accelerator power supply. The validity of this method was shown in our previous study. [10]

Pure Xenon gas (99.999% pure) was used as the propellant. A thermal mass flow controller (Brooks Instrument, 5850S, full scale = 3 sccm) with a flow accuracy of $\pm$0.7% of rate and $\pm$0.2% F.S. was used. A 0.6 m diameter by 1 m long vacuum chamber was used in the experiments. The pumping system comprised a cryo-pump and a turbo molecular pump. The background pressure was maintained below 1.2 × 10^{-3} Pa for most of the operating conditions.

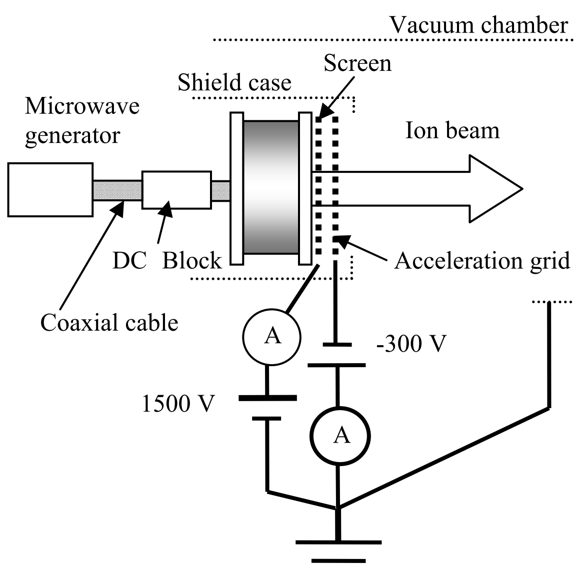


Figure 4. Schematic of electric circuit.

III. Results and Discussion

In order to evaluate the performance of ion engine, ion beam production cost, and ε_c, and propellant utilization, η_u, are defined as,

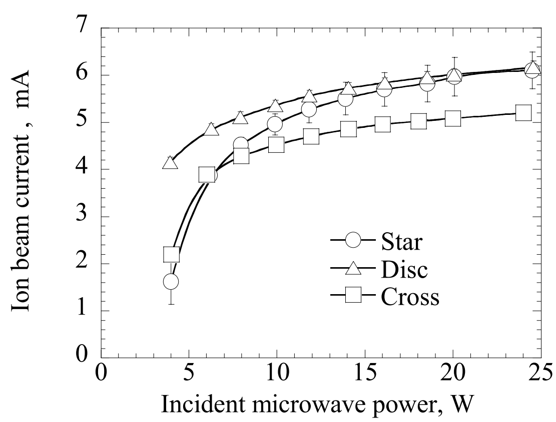
$$\varepsilon_C = \frac{P_i - P_r}{I_b} \quad (1)$$

$$\eta_u = \frac{I_b}{\frac{e}{m_i}\dot{m}} \quad (2)$$

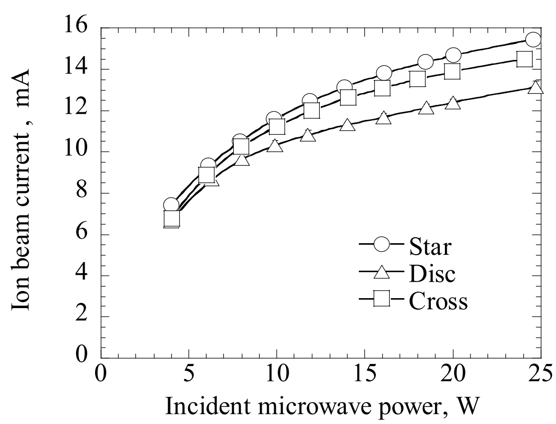
3-1 Antenna shape

Figure 5 shows the relation between incident microwave power and ion beam current for the three antenna configurations. For P_i =10 W, ion beam currents of disc, star, and cross are 5.4 mA, 5.0 mA, and 4.5 mA, respectively. That is, the ion beam current of the disc antenna is the largest among the three configurations and that of the cross antenna is the smallest for $\dot{m}$ =0.01 mg/s (0.1 sccm). On the other hand, for P_i =14 W, and $\dot{m}$ =0.029 mg/s (0.3 sccm), the ion beam currents of the disc, star, and cross are 11.3 mA, 13.1 mA, and 12.6 mA, respectively. That is, for $\dot{m}$ =0.020 mg/s (0.2 sccm) or $\dot{m}$ =0.029 mg/s, the ion beam current of the star antenna is the largest among the three configurations and that of the disc antenna is the smallest. This reversal is due to the tradeoff between the coupling of plasma with microwave and the surface recombination on antenna: the disc antenna has the widest contact with the ECR layer, where the microwave power is absorbed efficiently, [3] and it has the largest surface area among three, where the loss of ions and electrons occurs, as shown in Table 2. Therefore, under low mass flow rate, with low plasma density, the effect of good coupling with plasma exceeds the effect of large losses on the antenna surface. On the other hand, under high mass flow rate, the effect of large losses on the antenna surface exceeds the effect of good coupling with plasma.

The other antenna can be categorized into above three antennas. That is, the engine performance with starfish and L shape antenna has a similar tendency as that of cross antenna. Though the thrust performance of them is low under low mass flow rate, it is improved under high mass flow rate. On the other hand, that with ume antenna is similar to that with disk antenna, the thrust performance of ume decreases with the increase in mass flow rate. Octopus antenna shows a similar tendency to star antenna. These results support the above explanation. In the conclusion of antenna shape, the thrust performance of star antenna is the best of all.



(a)



(b)

Figure 5. Thrust performance for different levels of ion production.
(a) $\dot{m}$ =0.010 mg/s (b) $\dot{m}$ =0.029 mg/s

Table 2. Antenna parameters.

	Disc	Star	Cross
Surface area, mm^2	64	35	24

3-2 Antenna position

Figure 6 shows the relation between incident microwave power and ion beam current for the two antenna position. For P_i =10 W and $\dot{m}$ =0.02 mg/s, ion beam currents at 7 mm, and 8 mm are 9.9 mA, and 9.2 mA, respectively. That is, the ion beam when antenna is set at 7 mm downstream is larger than that at 8 mm. The difference in the thrust performance would be due to below reasons.

1. The loss of plasma on antenna surface at 7 mm is smaller than that at 8 mm.
2. The temperature of the thruster becomes high under operation and the magnets are demagnetized. As a result, the ECR layer deflates and antenna at 7 mm has wider contact with ECR layer than that at 8mm.

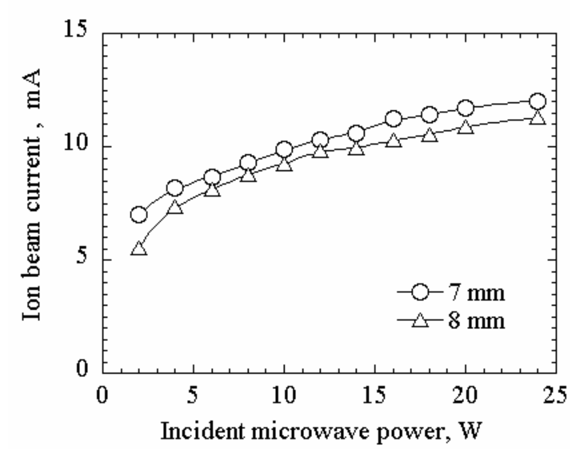
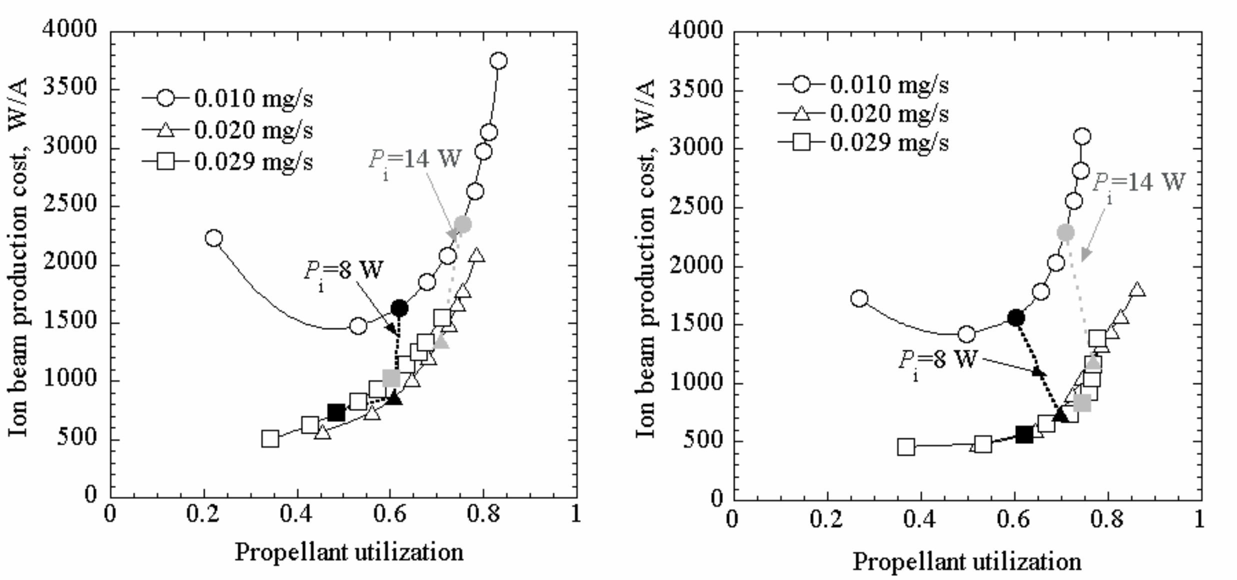


Figure 6. Thrust performance of star antenna.

3-3 Thrust performance

Figure 7(a) shows the thrust performance of the star antenna set at 7 mm for three levels of ion production. The propellant utilization decreases with an increase in mass flow rate for a given level of power, since specific enthalpy decreases with an increase in mass flow rate. The thrust performance of the miniature ion engine, that is, η_u and ε_c are 0.61, and 860 W/A, respectively at $\dot{m}$ =0.02 mg/s, and P_i = 8 W.

For the improving the thrust performance of this engine, grid system was changed. In this grid system, the extracted ion beam area is 16 mm × 16 mm square. The hole diameter of each grids and the gap between the grids are the same as previous one. The number of holes is 211. Figure 7(b) shows the results of this grid system. Though at $\dot{m}$ =0.01 mg/s, the thrust performance become worse due to the decrease in neutral atom density in the discharge chamber, at $\dot{m}$ =0.02 mg/ or 0.029 mg/s, it was improved, that is, η_u and ε_c, are 0.73 and 740 W/A, respectively at $\dot{m}$ =0.02 mg/s, and P_i = 8 W. These results demonstrate the possibility of practical application of the miniature microwave discharge ion engine.



(a) (b)

Figure7. Thrust performance of star antenna for three levels of ion production.

(a) ϕ 14 mm circle (b) 16 mm × 16 mm square

IV. Conclusion

The effects of antenna configuration—antenna shape and its position—on the thrust performance of a 30 W class miniature microwave discharge ion engine were investigated in order to improve thrust performance. The ion beam currents for various antenna shapes—disc, star, cross, ume, octopus, starfish, and L shape —were measured, since the thrust performance is affected by the antenna shape. The tendency of thrust performance can be categorized into three types. One type is represented by the disc antenna, and another does the star antenna and the other is the cross antenna. The ion beam current of the disc antenna is the largest among the three configurations and that of the cross antenna is the smallest among the three for $\dot{m}$ =0.01 mg/s. On the other hand, for $\dot{m}$ =0.02 mg/s or $\dot{m}$ =0.029 mg/s, the ion beam current of the star antenna is the largest among the three configurations and that of the disc antenna is the smallest among the three. This discrepancy is due to the tradeoff between the plasma-microwave coupling and the surface recombination on antenna: under low mass flow rate, the effect of good coupling with plasma exceeds the effect of large losses on the antenna surface, while under high mass flow rate, the effect of large losses on the antenna surface exceeds the effect of good coupling with plasma. The ion beam current also depends on the antenna position. This would be also due to the losses on the antenna surface and the plasma-microwave coupling. The thruster performance, propellant utilization, and ion beam production cost are 0.61, and 860 W/A, respectively, at $\dot{m}$ =0.020 mg/s, and P_i = 8 W. To improve the thrust performance, grid system was changed to square one, which has 211 holes. The thrust performance, propellant utilization and ion beam cost with this grid system are 0.73 and 740 W/A, respectively at $\dot{m}$ =0.02 mg/s, and P_i = 8 W. The above results demonstrate the possibility of practical application of the miniature microwave discharge ion engine.

Acknowledgments

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