DEVELOPMENT OF MICROWAVE ENGINE

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Abstract. A low-power, microwave-discharge type electrostatic thruster, microwave engine, has been developed for applications to 50 kg-class satellites at Advanced Technology Institute Ltd. (ATI) inS Hokkaido, Japan. A prototype of the engine was manufactured, and its performance and qualification tests have been reported in previous papers. An endurance test of the microwave engine head is being conducted as one of the final steps for flight-qualifying the engine, and over 1200 hours have passed at this time. During the 1200 hours of operation, magnetic flux densities at certain locations in the discharge chamber have decreased by approximately 100 G. Virtually no sputtering or deposition could be observed inside the discharge chamber. The antenna diameter decreased from 1.57 mm to 1.45 mm. The magnetic nozzle had a sputtering damage near the nozzle exit which extended to the midsection of the Sm-Co magnets on the inner wall of the magnetic nozzle. The diameter of the nozzle exit increased from 21 mm to 21.7 mm. Magnetic flux densities at certain locations in the magnetic nozzle have decreased by about 150 G. Despite these changes in the magnetic flux densities and engine dimensions, the performance of the microwave engine was unchanged after 1200 hours of operation.

Introduction

The microwave engine development has been started as for applications to 50 kg-class satellites. Fig. 1 shows the cylindrical engine's cross-section, Fig. 2 shows a picture of the prototype microwave engine, and Fig. 3 shows a picture of the engine in operation. The low-thrust microwave engine is suited not only for microsatellites but also for satellites with missions that require extremely precise satellite positioning and attitude control such as formation flying for a space telescope/interferometer system and drag-free microgravity experiments. The microwave engine performance and qualification tests have been reported in previous papers.[1,2,3,4] A typical engine performance parameters are shown in Table 1. The total thrust efficiency is defined as the following:

$$\eta_T \equiv \gamma^2 \cdot \eta_u \cdot \eta_{ac} \cdot \frac{I_{ac} \cdot V_{ac}}{I_{ac} \cdot V_{ac} + \dfrac{P_f}{\eta_{mw}} + P_{cath} + P_{other}}$$

where γ is a cosine of the average beam divergent angle, η_u is propellant utilization efficiency, η_{ac} is acceleration efficiency, I_{ac} is acceleration current, V_{ac} is acceleration voltage, P_f is forward microwave power, η_{mw} is efficiency of microwave power supply and amplifier, P_{cath} is cathode power, P_{other} is power for the other components of thruster system such as propellant feed system and control/telemetry interface system. The engine generates a calculated thrust of 0.5 mN with a specific impulse of 1371 seconds at a total system power of 29.6 W. The random vibration test of the microwave engine showed no visible failure, and its tolerance on the mechanical environment was confirmed. The thermal analysis concluded that white paint should be applied to all surfaces of the microwave engine assembly while using the engine mounting bracket as a radiator surface. This design gives a maximum on-orbit temperature of the engine head of 86 °C, which is well below the maximum temperature limit of 110 °C. Now, an endurance test of the microwave engine head is being conducted as one of the final steps for flight-qualifying the engine, and over 1200 hours have passed at this time.

Table 1: Typical microwave engine performance

Propellant Flow Rate (xenon)	0.42 SCCM
Microwave Power	5 W
Acceleration Voltage	250 V
Total System Power	29.6 W
Acceleration Current	38.0 mA
Beam Current	27.6 mA
Acceleration Efficiency	0.73
Propellant Utilization Efficiency	0.98
Thrust	0.5 mN
Isp	1371 sec
Total Thrust Efficiency	0.124

Endurance Test

An endurance test of the microwave engine head has been conducted as one of the final steps for flight-qualifying the engine. Because the cathode for the microwave engine has not been established, this experiment was conducted to test only the engine head. The test setup consists of thruster system, vacuum chamber and pumps, data recorder and PC. The experiment is automated using the PC. All data are stored in the data recorder, and later transferred to another PC for analysis.

Before discussing details of the test results, it should be pointed out that the cathodes used in this test were rhenium-tungsten filament cathodes with triple carbonates ($(Ba\text{-}Sr\text{-}Ca)CO_3$) applied in and around the filaments. During the test, the acceleration current decreased at a rate ranging from – 2.5 μA to – 260 μA per hour due to the reduction in electron emission from the cathodes. Consequently, the engine had to be stopped momentarily to either switch to a new cathode or reapply triple carbonates in order to keep the acceleration current above 30 mA. In Fig. 4 which shows the transition in engine parameters during the endurance test, one can see the discontinuities in the data indicated by blue circles with x inside. Most of these points indicate the times when the engine was restarted after a carbonates-exhausted cathode was replaced. One can be convinced that the decrease in the acceleration current was indeed due to the cathodes by the fact that the engine performance including the acceleration current returned to earlier values as an old cathode was switched to a cathode with a fresh coat of triple carbonates. Furthermore, the engine performance with a new cathode has not been diminished over the period of 1200 hours. In other words, the engine parameters just after a restart did not change significantly during the 1200 hours of operation. Another fact that supports the cathodes' responsibility is the increase in the magnetic nozzle potential with respect to ground that corresponded to the decrease in the acceleration current. Note that the cathode was at ground potential, and that the discharge chamber was biased to 250 V above ground. The magnetic nozzle just downstream of the discharge chamber was floating, and the cathodes were placed near the magnetic nozzle (on a circle that is 3 mm outward from the outer edge of the nozzle's exit plane). Therefore, reduction in the cathode's electron emission would manifest in an increase in the magnetic nozzle potential with respect to ground, assuming that the ion flux into the nozzle surfaces does not vary very much. The rate of decrease in the acceleration current depended on the position of the cathodes as well as the condition of triple-carbonates coating on the cathode filaments. A microwave cathode is being developed as a permanent cathode for the microwave engine, and more than 100 mA of electron current from a laboratory model has been measured on a collector placed 15 mm away and biased at 20 V. A Ba-impregnated dispenser cathode has also been considered for a permanent cathode. Once a prototype of microwave cathode is constructed, it will be tested with the microwave engine.

A prominent feature in Fig. 4 is the oscillations in the forward and reflected microwave powers and temperatures of the microwave amplifier, discharge chamber, and magnetic nozzle. These oscillations are attributed to a daily temperature cycle in the surrounding air. The microwave engine was cooled by radiation and conduction, and the heat conduction was through a vacuum chamber flange on which the engine was mounted. Consequently, temperatures of the discharge chamber and magnetic nozzle followed the daily temperature cycle of the surrounding air. The forward and reflected microwave powers are also affected by the surrounding air temperature due to the fact that the efficiency of the microwave amplifier depends on its temperature. If one takes a closer look at the acceleration current and magnetic nozzle potential data in Fig. 4, one can find a small cyclic change in each of the two that corresponds to the air temperature cycle. The observed phenomenon is explained as follows; as the temperature of the surrounding air rises, the microwave amplifier efficiency decreases. As a result, the forward microwave power, which is used to produce ions, is reduced. Then, the acceleration current declines, and the magnetic nozzle potential with respect to ground decreases. Whenever both acceleration current and magnetic nozzle potential with respect to ground decrease at the same time, it is most likely that the ion production is diminished. For an air temperature change of about 8 °C, the amplitudes of cyclic temperature changes were, on average, 6.9 °C, 6.1 °C, and 5.4 °C for the microwave amplifier, discharge chamber, and magnetic nozzle, respectively. Also for an 6.9 °C rise in the amplifier temperature, the forward microwave power decreased by about 3%, which reduced the acceleration current by approximately 1.5%. It should be noted that these were observed when the amplifier temperature was around 25 °C, and that the temperature characteristic of the microwave amplifier is not linear. Therefore, when the average amplifier temperature is at different level, these values will naturally be different. According to the acquired data, these temperature cycles did not seem to affect the overall engine performance.

The red stars in Fig. 4 indicate the times when the engine was restarted specifically after plasma extinction. The data shows that plasma extinction happened often in the first 185 hours and in the last 185 hours of the 1200 hours of operation. The cause of the latter is thought to be a faulty semi-rigid cable in the microwave transmission line. The problem was fixed, and the engine has run smoothly since. As for the former, a similar phenomenon has been observed before in the development of microwave engine. Whenever a new engine was operated for the first time or an engine was restarted after a major overhaul, plasma often went out. Then, after a certain period of time, the engine became stable. The exact reason for this behavior is not well known. It could be the initial breaking in of the Sm-Co permanent magnets in the engine. It could also be small dust particles which have fallen in the gaps in the engine during assembly and cause instability in the plasma as they come out to the plasma region. A use of a clean room and an initial break-in period would alleviate these problems.

Virtually no evidence of significant sputtering could be observed inside the discharge chamber after the 1200 hours of operation. Only the midsection of the Sm-Co permanent magnets on the inner wall of the chamber has become somewhat glossy. These polished surfaces were probably formed by the ECR electrons (~ 15 eV) impinging upon the center of the magnets, guided by the magnetic field lines that converged there. However, these particles would not cause any significant damage because of their low energies. Magnetic flux densities at certain locations in the discharge chamber were measured at the beginning and end of the 1200 hour operation, and on average, magnetic flux density has decreased by 100 G. There was virtually no deposition of sputtered material inside the discharge chamber.

The Kaman antenna, which is made of molybdenum and had a matte finish originally, has become glossy in the part which was exposed to the plasma. This can also be attributed to the electron impingements upon the antenna surface. Most of those electrons that hit the antenna were probably created inside the discharge chamber and had relatively low energies. However, some electrons from the cathode were likely to have leaked into the discharge chamber and hit the antenna. These electrons that came from the cathode had relatively large energy in the order of 250 eV. Note that the antenna was shorted to the discharge chamber, so that there would be little sputtering damage by ion impingements due to a voltage gradient between the antenna and the discharge chamber. The weight of the antenna has decreased by 8.90 mg over the 1200 hours, which corresponds to a loss of 8.66E-4 cm^3 of molybdenum. But the diameter of the antenna has decreased from 1.57 mm to 1.45 mm, from which an estimated loss of weight is approximately 18 mg. Therefore, roughly a half of the sputtered material might have redeposited on the antenna. The antenna diameter after 5000 hours of engine operation would be approximately 1.05 mm, and the antenna should still function normally.

The magnetic nozzle had a sputtering damage near its exit that extended to the midsection of the Sm-Co magnets on its inner wall. The diameter of the nozzle exit has increased from 21.0 mm to 21.7 mm. The weight of the magnetic nozzle has decreased by 466 mg. A significant deposition of the sputtered material was observed on the vacuum chamber wall. From the relative positions of the deposition and the nozzle exit, most of the sputtered material seemed to be confined within a half angle of 35° with respect to the engine axis. Magnetic flux densities at certain locations in the magnetic nozzle were measured at the beginning and end of the 1200 hour operation, and on average, magnetic flux density has decreased by 150 G. A significant fraction of the sputtering may have occurred during the early hours of the endurance test since the nozzle exit would be “shaped” by the ion beam at the beginning. Measurements of the weight and dimensions of the magnetic nozzle after the next 1000 hours of the endurance test will provide further information.

Conclusions

An endurance test of the microwave engine head has been conducted, and 1200 hours has passed. Because of the limited capability of triple carbonates-filament cathodes, the engine needed to be stopped briefly to either replace the cathode or reapply the triple carbonates in order to keep the acceleration current above 30 mA. After the 1200 hours of engine operation, magnetic flux densities in the discharge chamber and the magnetic nozzle have decreased by about 100 G. The antenna diameter has decreased from 1.57 mm to 1.45 mm. And the sputtering damage at the exit of the magnetic nozzle has enlarged the nozzle exit diameter from 21 mm to 21.7 mm. Despite these changes, the engine performance has been maintained over the period of 1200 hours. Also, there is no significant sputtering or deposition inside the discharge chamber. Hence, the engine has operated successfully for 1200 hours. The endurance test will continue, and the engine will be tested with a microwave cathode in near future.

References

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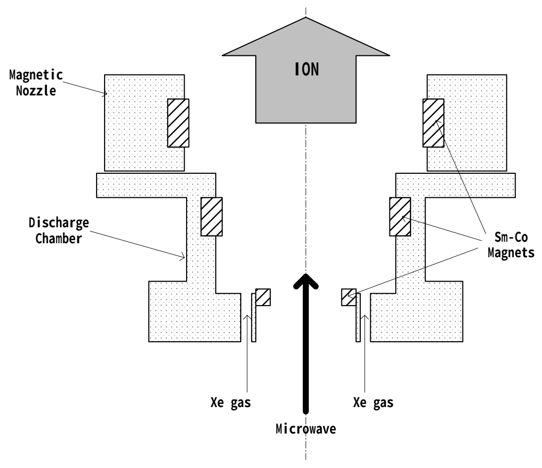

Fig. 1　Schematic of the microwave engine's cross section

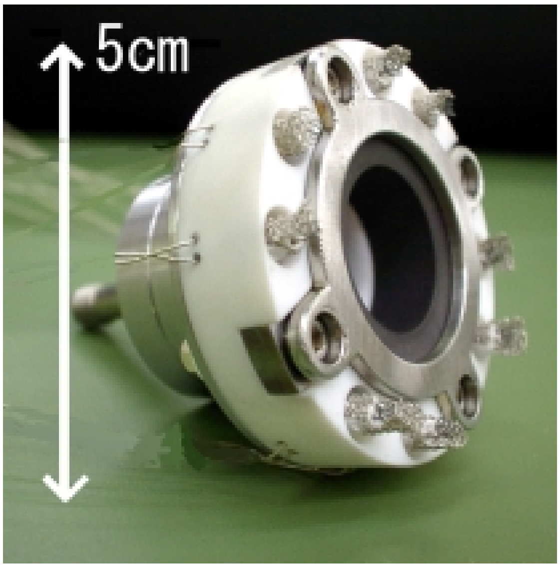

Fig. 2　Picture of the prototype microwave engine

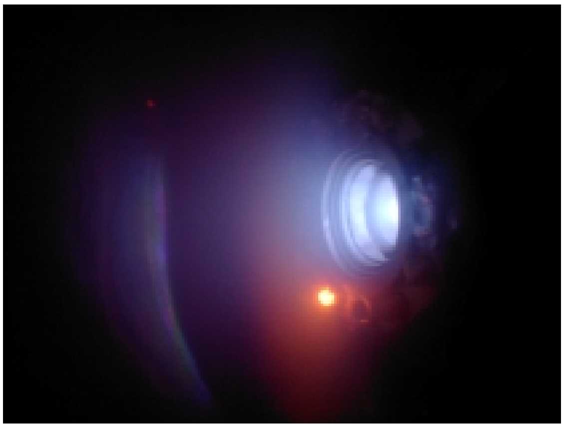

Fig. 3　Picture of the microwave engine in operation

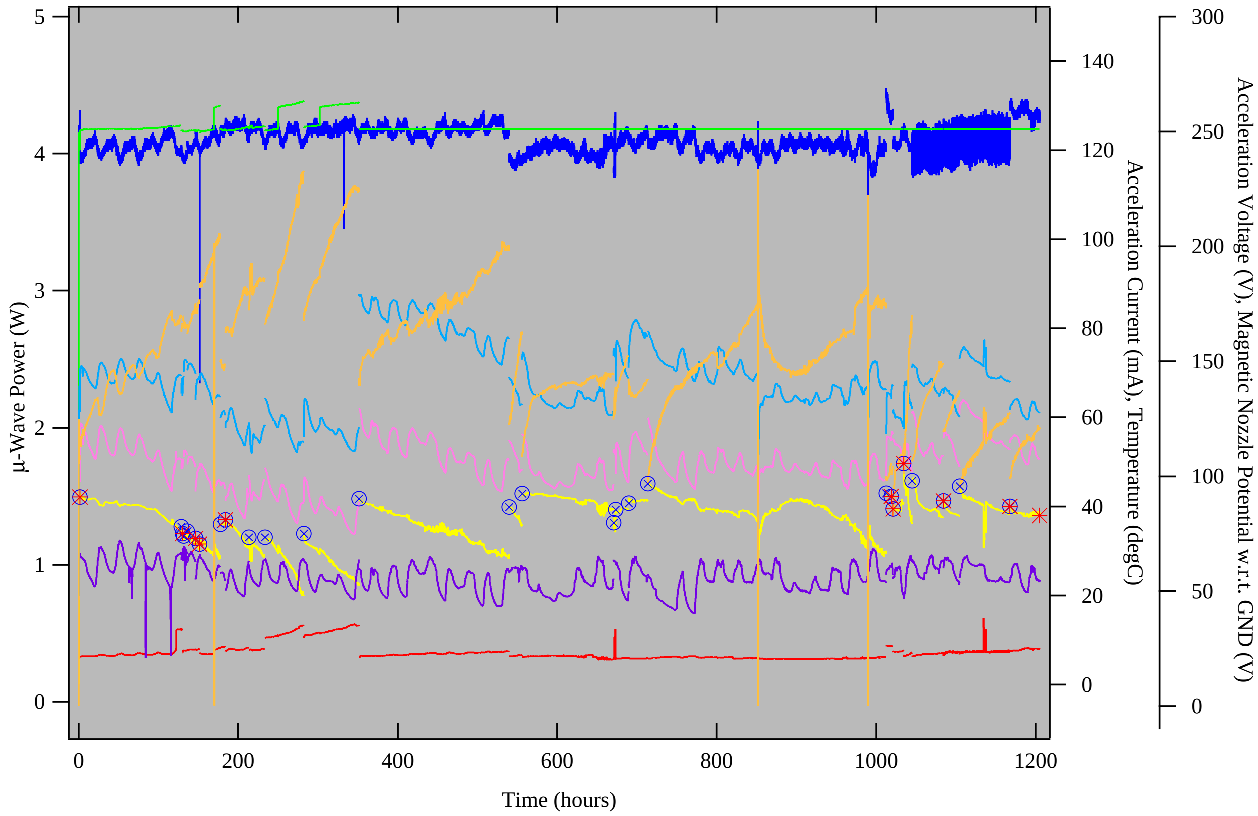

Fig. 4 Result of endurance test after 1200 hours. Blue line is for forward microwave power; red line is for reflected microwave power; green line is for acceleration voltage; yellow line is for acceleration current; purple line is for temperature of the microwave amplifier; pink line is for discharge chamber temperature; light blue line is for magnetic nozzle temperature; orange line is for magnetic nozzle potential with respect to ground; blue circles with x's inside indicate the points where the engine was restarted; and red stars indicate the points where the engine was restarted specifically after plasma extinction.