Performance of a Miniature Hall Thruster and an In-house PPU*

Masatoshi CHONO,1) Naoji YAMAMOTO,1,1) Ryudo TSUKIZAKI,2) Takato MORISHITA,3) Kenichi KUBOTA,4) Shinatra CHO,5) Kiyoshi KINEFUCHI,6) and Toru TAKAHASHI7)

1)Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan
2)Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252–5210, Japan
3)Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo 113–8656, Japan
4)Japan Aerospace Exploration Agency, Chofu, Tokyo 182–8522, Japan
5)Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252–5210, Japan
6)Department of Aerospace Engineering, Nagoya University, Nagoya, Aichi 460–8603, Japan
7)Takahashi Denki Seisakusyo, Iwaki, Fukushima 972–8326, Japan

Key Words: Hall Thruster, Thrust Performance, Miniature Electric Propulsion

Nomenclature

\[ F: \text{ thrust} \]
\[ g: \text{ gravitational acceleration} \]
\[ I_c: \text{ coil current} \]
\[ I_{c,cr}: \text{ critical coil current} \]
\[ I_d: \text{ discharge current} \]
\[ I_{sp}: \text{ specific impulse} \]
\[ m_i: \text{ anode mass flow rate} \]
\[ T/P: \text{ thrust-to-power ratio} \]
\[ V_d: \text{ discharge voltage} \]
\[ \eta_t: \text{ thrust efficiency} \]

1. Introduction

It is estimated that there are no less than 20,000 debris objects currently in orbit around Earth,1) and they pose direct danger to spacecraft and satellites.2,3) Debris removal, however, poses a number of important challenges. Most importantly, the cost of the system should be kept as low as possible. In one potential debris removal sequence, an object could be deorbited using a propulsion system; the removal satellite should be smaller than the target debris itself in order to minimize removal cost. Thus, we could assume a debris object of 1,500 kg at an altitude of 800 km, and a debris removal mission’s delta \( V \) is 382 m/s (i.e., 165 m/s approach and 217 m/s de-orbit), and the mass of the active debris removal satellite might be 200 kg. Hall thrusters would be a prospective candidate for the main propulsion of a future debris removal system. However, it will be a challenge to develop small Hall thrusters that can provide the delta \( V \), limit power consumption to below 300 W, and achieve the required lifetime of 8,500 h.

There has recently been significant research and development in small satellite propulsion systems all over the world. These propulsion systems must be compact and relatively inexpensive, and offer low power consumption, moderate thrust performance, and large total impulse. Hall thrusters are an attractive candidate for these small propulsion systems since they meet the requirements. Various compact Hall thrusters4–9) have been developed and shown good performance, although the thruster lifetime is limited by degradation related to miniaturization. To extend the lifetime of Hall thrusters, a technology called “magnetic shielding” has been proposed.10–13) It has been shown that wall erosion stops after about 5,600 h of operation, before the wall is worn out. Therefore, wall erosion in the acceleration channel is no longer the lifetime limiter in magnetic-shielded Hall thrusters. However, incorporating magnetic shielding in a small Hall thruster design is still challenging since there is little space in the Hall thruster for the required magnetic circuit. Furthermore, temperature control of the magnetic circuit is crucial in order to avoid demagnetization. Therefore, we have developed a 200-W-class Hall thruster with a unique magnetic configuration, similar to “magnetic shielding,” in order to overcome the problem of degradation due to miniaturization.

The first aim of the present study is evaluating the thrust performance of the new design. We also demonstrate Hall thruster operation with a compact power processing unit (PPU) developed at Takahashi Denki Seisakusyo. The lifetime of Hall thrusters is still limited by the electron source and power supply. Therefore, a long lifetime electron source must be used, and one of the candidates is a microwave discharge neutralizer. A microwave discharge cathode was used on the Hayabusa mission, and has been shown to have a lifetime of 10,000 h. We have previously operated this Hall thruster with the microwave discharge neutralizer, and the details of thruster operation with the microwave cathode are provided in Morishita et al.,14) so it is only briefly described here.

2. Experimental Setup

2.1. 200-W-class Hall thruster

Figure 1 shows a photo of the 200-W-class magnetic-layer-type Hall thruster developed at Kyushu University. The size is 120 × 120 × 72 mm, and it will be slightly larger
than a 200-W-class thruster head.\textsuperscript{9,10} The inner and outer diameters of the acceleration channel are 40 mm and 56 mm, respectively. The acceleration channel is made of boron nitride. The hollow anode is set at 15 mm upstream of the thruster exit. The inner and outer diameters of the hollow are 40 mm and 56 mm, respectively, so that electrons go to the inner side and bottom surface of the hollow anode. The anode is made of pure iron, and also serves as a magnetic shield (i.e., contributing a magnetic field configuration like magnetic shielding and optimizing use of available space). The anode has a cover, which works as a neutral atom distributor and will provide a uniform stream of neutral atoms to the discharge chamber. An inner solenoid coil and four outer solenoid coils create a predominantly radial magnetic field in the acceleration channel. The magnetic flux density is varied by changing the coil current. The magnetic flux density distribution and lines of force are shown in Fig. 2, as calculated using Magnum 3.0 (Field Precision LLC). The radial magnetic flux density peaks downstream of the acceleration channel, pushing out the ionization region.

In this paper, a hollow cathode (HC252, Veeco) was used as the electron source. The cathode axis is set at an angle of 45 deg with respect to the thruster axis, and the cathode orifice is set at 22 mm downstream and 68 mm in the radial direction, far from the thruster axis as shown in Fig. 1. High-purity 99.999\% xenon gas was used as the propellant with thermal mass flow controllers.

Thrust was measured using an inverse pendulum-type thrust stand developed at Kyushu University. The uncertainty of thrust was evaluated as 0.2 mN at 10 mN. The error consists of statistical error and calibration curve fitting error. For the plume measurement, an ion collector was set at 750 mm downstream of the thruster. Thrust measurement was done after operating for 1 h, at which time the condition is almost thermal equilibrium. The anode would be kept ferromagnetism in steady-state since a drastic discharge current change hasn’t been observed before/after steady-state conditions during operation.

2.2. Vacuum facility

Thrust performance tests were conducted in the ISAS/JAXA space science chamber, which is 2.5 m in diameter and 5.0 m in length. The pumping system includes a rotary pump, a turbo-molecular pump (air pumping speed is 3,400 l/s in nitrogen), and two cryogenic pumps (22,000 × 2 l/s in nitrogen). The chamber baseline pressure is below 1 × 10^{-5} Pa. The background pressure was maintained below 1 × 10^{-3} Pa at a xenon mass flow rate of 1.2 mg/s (i.e., anode 1.0 mg/s and cathode 0.2 mg/s).

2.3. Power processing unit

For the main discharge power supply, we use two power supplies. One is a commercially available power supply (HX0600-025, Takasago). The other is a compact PPU developed at Takahashi Denki Seisakusyo. As shown in Fig. 3, the power supply is compact: 164 × 104 × 35 mm, which is approximately the size of two smartphones. This is a high-frequency digital power supply with fine control. Digital control allows the switching frequency to be changed easily for investigation of the frequency response in the Hall thruster plasma. The specifications of this power supply are listed in Table 1. The input power is 100 V, assuming the use of a DC-DC converter from 28 V (Bus) to 100 V. The target output voltage and current are 300 V and 1 A, respectively. The voltage is controlled in this paper; that is, the PPU is operated in a constant voltage mode.

3. Results and Discussion

Regarding the lifetime, significant wear was not observed after 15 h of operation. For evaluating the performance, specific impulse, $I_{sp}$, and thrust efficiency, $\eta_t$, are defined as

\begin{equation}
I_{sp} = \frac{F}{mg}
\end{equation}

\begin{equation}
\eta_t = \frac{F^2}{2mV_iI_d}
\end{equation}

3.1. Magnetic field configuration dependency

Figure 4 shows the thrust efficiency for four magnetic-field geometries: inner coil only, and ratios of inner coil current to outer coil current of 0.75, 1.0, and 1.25. The magnetic-field strength was optimized in each case. The thrust for the four geometries is 11.6 mN, 12.1 mN, 12.5 mN, and 11.6 mN, respectively. The ratio of 1.0 produces the largest thrust of the four, and the discharge current is essentially constant at approximately 0.74 A except for the inner coil only geometry, when it is 0.67 A. The thrust efficiency for the four
cases is 0.33, 0.32, 0.35, and 0.30, respectively. This is because the magnetic flux density distribution is more uniform than the other for the configuration with a ratio of inner-coil current to outer-coil current of 1.0 (shown in Fig. 2(c)). This leads to less loss to the wall; that is, the ionization region is farther from the wall, which will contribute to the thrust. In this study, the ratio of the outer-coil current to the inner-coil current was therefore fixed at 1:1.

3.2. Thrust performance map

Figure 5 shows thrust performance maps in terms of discharge voltage and magnetic-field strength (i.e., discharge voltage and coil current) at a mass flow rate of 1.0 mg/s. As the discharge voltage increases, the thrust increases. The present thruster also shows a mode jump beyond the critical magnetic-field strength. For example, at 300 V, the critical inner-coil current is about 1.4 A — of course, due to hysteresis, the critical inner-coil current varies in the case of increasing inner-coil current and decreasing inner-coil current — where an almost 1 mN jump was observed, from 11 mN to 12.7 mN. This mode jump would be due to unique magnetic-field configuration. At a discharge voltage of 300 V and coil current of 1.4 A, the thrust efficiency is 0.34, which is competitive with other 200-W-class Hall thrusters.

With the mode jump, the total ion-beam current is increased, which leads to an increase in thrust. Figure 6 shows the ion-beam current density profile at 750 mm downstream of the Hall thruster. The mass flow rate is fixed at 1.0 mg/s and discharge voltage is 300 V. (a) shows the ion-beam profile at a coil current of 1 A and (b) shows that at a coil current of 1.25 A.

The propellant utilization at the (a) and (b) conditions is 0.54 and 0.63, respectively. That is, the propellant utilization is about 10% improved. Next, we investigate the physics behinds this mode jump.

3.3. Mass flow rate dependency

The thrust performance for the three mass flow rates is shown in Fig. 7. The magnetic-field strength is optimized for each discharge voltage and mass flow rate. As in a conventional thruster, the thrust efficiency improves with input power. The thrust efficiency is highest at a mass flow rate of 1.36 mg/s. However, that at 1.02 mg/s is quite similar, while the thrust efficiency at 0.68 mg/s is significantly lower for all four cases. This low efficiency is due to poor propellant utilization, which could be seen in the thrust.

3.4. Power supply coupling test

Figure 8 shows the efficiency versus output current of the compact PPU taking by electronic load. The switching frequency is fixed at 80 kHz. The efficiency increases as output current increases, doing so to a maximum efficiency of 0.93 at the output voltage of 300 V and output current of 1 A. When the input voltage is decreased from 100 V to 80 V, the maximum efficiency becomes 0.95. Table 2 shows the PPU efficiency with the PPU coupled to the 200-W Hall thruster.
thrust. The efficiency in Cases 1 and 3 is almost the same as that with the electronic load. However, the efficiency in Case 2 is high compared to that in comparison with that with electronic load. Case 2 experienced large discharge current oscillation, which might affect the improvement of PPU efficiency. That is, in Case 2 condition, there are large current period (peak current of 3 A) and almost zero current period. Most of the power consume in the large current period and the efficiency in the period is good, since the efficiency of this power supply improved with increase in current, as shown in Fig. 8. The loss in the zero current period is small, therefore, the total efficiency in Case 2 is improved, although the average current is small.

4. Conclusion

A 200 W class magnetic-layer-type Hall thruster has been developed. The thrust, specific impulse, thrust efficiency are 13 mN, 1,300 s, and 0.37, respectively, for mass flow rate of 1.0 mg/s and discharge voltage of 300 V. This performance is competitive with other 200 W class Hall thrusters, though there is still room to improve the thrust efficiency considering poor propellant utilization, 0.63. The developed high frequency digital power supply shows good performance; the maximum efficiency is 0.95 using electronic load. The efficiency of the PPU when coupled with the miniature Hall thruster is almost the same, except operation with large discharge current oscillation.

Acknowledgments

This work was performed at the Space Plasma Laboratory of ISAS, JAXA and supported by JSPS KAKENHI Grants No. JP18H03815. The contributions of Prof. Ikoh Funaki, Dr. Satoshi Hosoda, Prof. Takumi Abe and Mr. Yuuta Iwakura are greatly appreciated.

References

1) Analysis and Prediction, http://www.esa.int/Safety/Security/Space/Debris/Analysis_and_prediction (cited 24th of the April, 2020)
2) Liou, J. C., Johnson, N. L., and Hill, N. M.: Controlling the Growth of Future LEO Debris Populations with Active Debris Removal, Acta Astronautica, 66 (2010), pp. 648–653.
3) Bonnal, C., Ruault, J. M., and Desjean, M. C.: Active Debris Removal: Recent Progress and Current Trends, Acta Astronautica, 85 (2013), pp. 51–60.
4) Conversano, R. W., Goebel, D. M., Mikellides, I. G., Hofer, R. R., and Wriz, R. E.: Performance Analysis of a Low-Power Magnetically Shielded Hall Thruster: Computational Modeling, J. Propul. Power, 33 (2017), pp. 992–1001.
5) Polzin, K. A., Markasse, T. E., Stanojev, B. I., DeHoyos, A., Raitses, Y., Smirnov, A., and Fisch, N. J.: Performance of a Low-Power Cylindrical Hall Thruster, J. Propul. Power, 23 (2007), pp. 886–888.
6) Ikeda, T., Togawa, K., Tahara, H., and Watanabe, Y.: Performance Characteristics of Very Low Power Cylindrical Hall Thrusters for the Nano-Satellite “PROTERES-3,” Vacuum, 88 (2013), pp. 63–69.
7) William, A. H. and Charles, C. S.: Near Exit Plane Velocity Field of a 200-Watt Hall Thruster, J. Propul. Power, 24 (2008), pp. 127–133.
8) Yamamoto, N., Ezaki, T., and Nakashima, H.: Thrust Performance of a Low Power Hall Thruster, Trans. JSASS Aerospace Technology Japan, 10 (2012), pp. Tb.9–Tb.12.
9) Raiji, H., Gregucci, S., Pergola, P., and Andreucci, M.: Performance Evaluation of an EO Constellation Equipped with the HT100 Hall Effec

Table 2. PPU efficiency when coupled with the 200-W Hall thruster.

| Input | Case 1 | Case 2 | Case 3 |
|-------|--------|--------|--------|
| Voltage | 80.0 V | 80.0 V | 80.1 V |
| Current | 2.40 A | 2.17 A | 2.15 A |
| Power  | 192.1 W | 173.7 W | 181.1 W |
| Output | Voltage | 290.0 V | 290.0 V | 201.0 V |
| Current | 0.61 A | 0.57 A | 0.67 A |
| Power  | 176.3 W | 165.9 W | 135.3 W |
| Efficiency (Root mean square, A) | 0.918 | 0.955 | 0.913 |
| Thrust efficiency | 0.15 | 0.10 | 0.07 |
| Oscillation amplitude (<0.05 | 1.06 | <0.05 |

Kimiya Komurasaki
Associate Editor