Position and Attitude Tolerances of Carbon Nanotube Field Emission Cathode as a Neutralizer in an Ion Engine System*

Jumpei KINOSHITA,† Ryo IKEDA,† Misaki ADACHI,† Ryo SHIRAKI,† Taichi MORITA,† Naoji YAMAMOTO,†,‡ Masakatsu NAKANO,‡ Yasushi OHKAWA,§ and Ikkoh FUNAKI‡

†Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816–8580, Japan
‡Tokyo Metropolitan College of Industrial Technology, Tokyo 116–8523, Japan
§Research and Development Directorate, JAXA, Sagamihara, Kanagawa 252–5210, Japan

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Nomenclature

- L: distance between ion head and cathode, m
- m: mass flow rate, mg/s
- P: incident microwave power, W
- V: potential, V
- Vcg: potential difference between cathode and ground, V
- θ: cathode attitude angle against ion beam direction, degree

Subscripts
- a: acceleration grid
- c: cathode
- d: deceleration grid
- g: gate grid
- s: screen grid

1. Introduction

Formation flight using small satellites offers low cost space applications, high resolution earth observation, observation of electromagnetic waves (X-ray, infrared, and so on) emitted from celestial objects or even observation of gravitational waves. The propulsion system requirements of these missions include large total impulse with low propellant and power consumption, high response speed, a 3 digit throttling range, and low thrust noise.1) Offering large total impulse with low propellant and power consumption, an ion engine with field emission cathode is suitable as a main propulsion system.

For small satellite applications,2) power consumption is an important factor. A field emission cathode (FEC)3–6) is therefore an attractive candidate for the electron source, since it has lower power consumption than conventional cathodes (such as hollow cathodes, microwave discharge cathodes, or radio-frequency discharge cathodes) and it does not consume propellant. It also does not involve failure-prone parts, such as valves and mass flow controllers. The current density of an FEC assembly is small,7) on the order of several mA/cm² and that demonstrated for on-orbit use is even smaller,8) about 60 μA/cm².

These features of the FEC provide a robust and compact system, and offer higher specific impulse than conventional systems. Conventional ion engines provide about 20–25% of their propellant to the cathodes,9–12) and this leads to 20–25% degradation of the specific impulse. In our previous work, the neutralization of an ion engine using xenon gas as a propellant with a field emission neutralizer was successfully demonstrated,2) though the electron emission cost was 360 W/A, which is higher than that of a conventional hollow cathode (less than 30 W/A).13) Small hollow cathodes, whose emission current is in the range of 10–100 mA, consume several watts, which means that the electron emission cost of a small hollow cathode is more than 250 W/A.14,15)

Other remaining challenges in this field include investigation of cathode position and attitude tolerances, evaluation of thrust noise, and extension of the lifespan of the FEC with carbon nanotubes. The aim of the present study is to investigate the dependence of cathode position and attitude on neutralization performance, for the evaluation of the cathode setpoint tolerance.

The potential difference between cathode and ground, Vcg, is used here as an indicator of neutralization. If Vcg drops below a critical voltage, the FEC will be sputtered by charged exchanged ions, and this could lead to degradation of emission capacity. For the purposes of the present study, the critical potential difference is taken to be −20 V, since the potential difference between the plume and the ground is assumed about 30 V and the threshold energy of carbon-carbon composite under xenon bombardment is assumed to be about 50 eV.16) This critical value, −20 V, a reasonable assumption for the present purposes, should be further investigated in future work.

2. Experimental Setup

2.1. Microwave discharge ion engine

A 100 μN class microwave discharge ion engine head was developed, as shown in Fig. 1. It has three flat grids: the
screen grid, acceleration grid, and deceleration grid. The grids are made of pyrolytic carbon; the grid parameters are shown in Table 1. These parameters were determined using the numerical analysis code developed by Nakano et al.\(^\text{17)}\) The open area ratio is lower than that of conventional, to keep the high pressure inside the thruster. The inner diameter of the discharge chamber is 24 mm and the length of the discharge chamber is 19 mm. Several samarium cobalt (Sm-Co) permanent magnets and an iron yoke make a magnetic circuit, which applies a magnetic field in the discharge chamber for the confinement of plasma. The plasma is generated by microwave discharge. Microwave power at 2.45 GHz is fed through a coaxial line and into a star-shaped or disk-shaped antenna, as shown in Fig. 1(right). A DC block, which isolates the direct current component but passes microwaves, with a loss of 0.43 dB at 2.45 GHz, was inserted to protect the microwave amplifier.

Pure xenon gas (99.995% purity) was used as the propellant and a thermal mass flow controller [maximum mass flow rate of 0.3 mg/s (3 sccm)] was used to control the mass flow rate.

2.2. Field emission cathode with carbon nanotubes

An FEC with a Carbon Nanotube (CNT) emitter, as developed for a previous study,\(^\text{3)}\) was used. A square cathode, \(88 \times 88 \text{ mm}^2\), was used. This cathode is described in detail in Ref. 3; it is only briefly described here. The emitter material is single-walled CNT attached to molybdenum substrate, which can provide high emission current density. The cathode is constructed with a gate grid electrode and a mask grid electrode, in order to apply a strong electric field to the carbon nanotube.\(^\text{18)}\) The open area is rectangular, \(3 \times 0.28 \text{ mm}^2\) and the open area ratio is about 80%. Both electrodes are made of thin molybdenum plate. The gate voltage can be varied from 0 V to 500 V.

2.3. System

The entire ion engine system was electrically isolated from the vacuum chamber (i.e. ground) in order to evaluate the neutralization of the system, as shown in Fig. 2; the cathode is electrically floating in the chamber, which has the same potential as the deceleration grid. In this configuration, there is no varistor between cathode and ground, but there is a varistor inside the power supply for acceleration grid, so the absolute value of \(V_{cg}\) is less than the power supply voltage, 150 V, that is, if the neutralization succeeds, the absolute value of \(V_{cg}\) is less than 150 V. The potential difference between chamber and cathode was monitored using a differential probe with accuracy of \(\pm 2\%\), and the impedance is 4 MΩ.

The ion thruster head has an electrical shield, whose potential was set as the chamber potential. The cathode and ion engine head are set in the same direction. The distance between the ion thruster head and the cathode is varied from 110 mm to 300 mm, as shown in Fig. 3. The cathode can rotate and the cathode attitude angle against the ion beam direction is defined as shown in Fig. 4. \(\theta\) is rotated between \(-100\) to 100 degrees.

The extracted ion beam current was estimated by subtracting the sum of the current from the acceleration and deceleration grids from the current through the screen power supply. The electron emission current from the FEC was estimated by subtracting the current to the gate electrode from the current emitted from the CNT emitter. The current was measured using a current probe (TCP312, Tektronix), which has accuracy of 3% at 1 mA and bandwidth of DC–100 MHz.

### Table 1. Grid parameters.

| Parameter                  | Screen | Acceleration | Deceleration |
|----------------------------|--------|--------------|--------------|
| Hole diameter, mm          | 1.20   | 0.70         | 1.00         |
| Potential, V               | 1,000  | -100         | 0            |
| Grid thickness, mm         | 0.30   | 0.30         | 0.30         |
| Open area ratio, %         | 21     | 7            | 15           |
| Hole pitch, mm             | 2.50   |              |              |
| Material                   | pyrolytic carbon | pyrolytic carbon | pyrolytic carbon |
| Grid gap, mm               | 0.8    | 0.5          |              |
| Number of holes            | 37     | 37           | 37           |

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\(\text{Fig. 1. Photo of the 100}\mu\text{N class microwave discharge ion engine head (left) and inside the discharge chamber (right) developed at Kyushu University.}\)

\(\text{Fig. 2. Electrical circuit for the 100}\mu\text{N class microwave discharge ion engine system.}\)

\(\text{Fig. 3. Photo of cathode positioned on translation table.}\)
2.4. Vacuum facilities

The experiments were done at the Space Science Chamber at the Institute of Space and Astronautical Science (ISAS) at the Japan Aerospace Exploration Agency (JAXA). The Space Science Chamber has two cryo-pumps and a turbo-molecular pump. The diameter and length of the chamber are 2.5 m and 5 m, respectively. The total pumping speed is 49,200 l/s for argon gas. The base pressure is $5 \times 10^{-5}$ Pa ($3.3 \times 10^{-7}$ Torr) and the pressure at 0.010 mg/s xenon mass flow rate is $1 \times 10^{-4}$ Pa ($7.5 \times 10^{-7}$ Torr).

3. Results and Discussion

Figure 5 shows the $V_{cg}$ for various cathode positions at ion beam current of 1.9 mA (at $V_e = 1000$ V, $V_i = -100$, $V_d = 0$ V, $m = 0.05$ mg/s, $P_i = 6$ W) and neutralizer current (extracted electron current, gate voltage 260 V) of 1.9 mA. The cathode attitude angle against the ion beam direction is zero. The uncertainty comes from the noise and the uncertainty deduced from the differential probe. The difference between the ion beam current and the electron emission current is within the uncertainty of the current probe. As shown in Fig. 5, neutralization of this ion engine system was successful even when the distance was 300 mm, which is quite a long distance considering the size of small satellites. When the distance is 200 mm, the $V_{cg}$ is $-10$ V, which is (absolute value) smaller than that of the microwave discharge neutralizer previously developed at Kyushu University. The electron emission cost of the FEC at this condition is $340$ W/A, which is defined as power consumption per extracted electron current. In this condition, the power consumption is $0.65$ W, which is the product of gate voltage (260 V) and current into gate (2.5 mA), and the extracted electron current is $1.9$ mA. This cost is acceptable, considering the small absolute value of $V_{cg}$ and zero propellant consumption.

$V_{cg}$ is dependent on distance; that is, the greater the distance between ion engine head and cathode, the lower $V_{cg}$ becomes, though $V_{cg}$ is almost the same if $L$ is less than 200 mm. Under orbital conditions, with weak magnetic fields (only geomagnetic field exists) and pressure of $10^{-4}$ Pa or less, electrons should be able to move freely, considering the mean free path. The results show, however, that with an increase in distance more driving force is needed to deliver electrons to the ion beam plume region. This may be due to the effect of the magnetic field leaking from the ion source or restriction (following the Child-Langmuir law) of space-charge-limited current.

Figure 6 shows the $V_{cg}$ vs. $\theta$ for three distance conditions, 150 mm, 200 mm and 250 mm. The ion engine operational condition is the same as in Fig. 5, that is, the ion beam current and neutralizer current (emission current from the FEC) are both 1.9 mA. The neutralizer current automatically matches the ion beam current by changing the $V_{cg}$. There is an optimum angle for each distance, that is, the optimum angle at $L = 150$ mm and 200 mm is $-15$ degrees and the optimum angle at $L = 250$ mm is $-60$ to $-65$ degrees. These results indicate that the best attitude of the cathode is in the direction of the ion beam plume region. Interestingly, even if the cathode is directed in the direction opposite to the ion beam plume, for example at 100 degrees ($L = 200$ mm), $V_{cg}$ is relatively low, reaching $-16.3$ V, but remaining within the acceptable range ($> -20$ V).

This flexibility of the cathode position and attitude is cru-
cial for FEC with CNT; the FEC with CNT is susceptible to attack by atomic oxygen, so direct impingement should be avoided. Flexibility as to position allows the cathode to be set perpendicular to the atomic oxygen flow. The decrease in the direct atomic oxygen attack flow will extend the lifespan of the FEC with CNT, and may thus ultimately result in an increase in total impulse.

The position and attitude of the cathode against the ion source have relatively small effect on neutralization performance. That is, the range of acceptable position and angle against the ion engine head is wide. Thus, the degree of freedom of installation of the electron source is high.

4. Conclusion

The acceptable range of position and attitude of carbon nanotube field emission cathode as a neutralizer in an ion engine system was investigated. Neutralization succeeded at a distance between ion head and cathode of 300 mm when cathode attitude angle is zero. In addition, the neutralization succeeded when cathode attitude angle against ion beam direction, was varied from —100 to 100 degrees at a distance of 200 mm. This flexibility as to cathode position and attitude strongly promotes the practical application of the miniature ion engine design with FEC with CNT; cathode lifespan can be extended by avoiding direct atomic oxygen attack.

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References

1) Ando, M., Seiji, K., and DECIGO Working Group: Space Gravitational-wave Telescope DECIGO, Collection of papers presented at the Meeting on the Study of Space Missions Propelled by Low-Power and Continuous Propulsion, 2008, p. 87. (in Japanese)
2) Yamamoto, N., Morita, T., Ohkawa, Y., Nakano, M., and Funaki, I.: Ion Thruster Operation with Carbon Nanotube Field Emission Cathode, J. Propul. Power, 35 (2018), pp. 490–493.
3) Ohkawa, Y., Matsumoto, K., Kawamoto, S., and Kitamura, S.: Performance Improvement of a Carbon Nanotube Field Emission Cathode, 63rd International Astronautical Congress, IAC-12.C4.4.11, 2012.
4) Gasdaska, C. J., Falkos, P., Robin, M., Hruby, Y., Demmons, N., and McCormick, R.: Testing of Carbon Nanotube Field Emission Cathodes, AIAA Paper 2004-3427, 2004.
5) Ziemer, J., Marrese-Reading, C., Dunn, C., Romero-Wolf, A., Cutler, C., Javidnia, S., Le, T., Li, I., Franklin, G., Barela, P., Hsu, O., Maghani, P., O’Donnell, J., Slusky, J., Thorpe, J. L., Demmons, N., Hruby, V., and LISA Pathfinder Team: Colloid Microthruster Flight Performance Results from Space Technology 7 Disturbance Reduction System, IEPC Paper 2017-578, 2017.
6) Ohkawa, Y., Okumura, T., Horikawa, Y., Miura, Y., Kawamoto, S., and Inoue, K.: Field Emission Cathodes for an Electrodynamic Tether Experiment on the H-II Transfer Vehicle, Trans. JSASS Aerospace Technology Japan, 16 (2018), pp. 63–68.
7) Singh, L. A., Sanborn, G. P., Turano, S. P., Walker, M. L. R., and Ready, W. J.: Operation of a Carbon Nanotube Field Emitter Array in a Hall Effect Thruster Plume Environment, IEEE Trans. Plasma Sci., 43 (2015), pp. 95–102.
8) Ohkawa, Y., Okumura, T., Iki, K., Okamoto, H., and Kawamoto, S.: Operation of a Carbon Nanotube Field Emission Cathode in Low Earth Orbit, J. Vacuum Sci. Technol. B, 37 (2019), 022203.
9) Kunimaki, H., Nishiyama, K., Funaki, I., Yamada, T., Shimizu, Y., and Kawaguchi, J.: Powered Flight of Electron Cyclotron Resonance Ion Engines on Hayabusa Explorer, J. Propul. Power, 23 (2007), pp. 544–551.
10) Koizumi, H., Komurasaki, K., Aoyama, J., and Yamaguchi, K.: Development and Flight Operation of a Miniature Ion Propulsion System, J. Propul. Power, 34 (2018), pp. 960–968.
11) Sovey, J. S., Rawlin, V. K., and Patterson, M. J.: Ion Propulsion Development Projects in U.S.: Space Electric Rocket Test I to Deep Space I Propulsion Power, 17 (2001), pp. 517–526.
12) Friedly, V. J. and Wilbur, P. J.: High Current Hollow Cathode Phenomena, J. Propul. Power, 8 (1992), pp. 635–643.
13) Pedrini, D., Misuri, T., Paganucci, F., and Andrenucci, M.: Development of Hollow Cathodes for Space Electric Propulsion at Sitael, Aerosp. Space, 4 (2017), 26.
14) Warz, R., Goebel, D., Marrese, C., and Mueller, K.: Development of Cathode Technologies for a Miniature Ion Thruster, AIAA Paper 2003-4722, 2003.
15) Patterson, M. J., Domonkos, M. T., Carpenter, C., and Kovaleski, S. D.: Recent Development Activities in Hallow Cathode Technology, IEPC Paper 2001-270, 2001.
16) Muramoto, T. and Hyakutake, T.: MD Study on Carbon Sputtering and Redeposition, Trans. JSASS Aerospace Technology Japan, 10 (2012), pp. Pb.97–Pb.101.
17) Nakano, M., Tachibana, T., and Arakawa, Y.: Scaling Law of the Life Estimation of the Three-Grid Optics for an Ion Engine, Trans. Jpn. Soc. Aeronaut. Space Sci., 45, 149 (2002), pp. 154–161.
18) Ohkawa, Y., Izawa, A., Yamagiwa, Y., Kawamoto, S., Nishida, S., and Kitamura, S.: Research and Development of Carbon Nanotube Cathodes for Electric Propulsion, Trans. JSASS Aerospace Technology Japan, 8 (2010), pp. Pb.27–Pb.32.
19) Yamamoto, N., Hiraoa, Y., and Nakashima, H.: Development of a Miniature Microwave Discharge Neutralizer for Miniature Ion Engines, J. Jpn. Soc. Aeronaut. Space Sci., 62, 4 (2014), pp. 123–128. (in Japanese)
20) Shimada, A., Tanaka, Y., Ohkawa, Y., Matsumoto, K., Tagawa, M., Matsui, M., and Yamagiwa, Y.: Effect of Atomic Oxygen Irradiation on Field Emission Cathodes in Low Earth Orbit, Trans. JSASS Aerospace Technology Japan, 12 (2014), pp. Pb.59–Pb.64.

Kiniya Komurasaki
Associate Editor

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