Research and Development Status of JAXA Next-Generation Ion Engine

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Abstract: We are developing a 150-mN-class ion engine for the next generation. The ion engine has already achieved sufficiently high performance. It operates at a specific impulse of 3,400 s for the beam voltage of 1030 V, and at an ion production cost under 140 W/A. Up to 200-mN thrust was demonstrated. Current efforts are directed to thruster-endurance improvement, power conditioner development, and improvement of the test facility for thruster endurance tests. For thruster-endurance improvement, we fabricated main hollow cathodes with their keeper and orifice plate made of graphite, and this has brought effectively no lifetime limitations of the cathode due to erosion. Characteristics of the neutralizer were obtained in the condition of being installed in the thruster. A lab-model power-processing unit was fabricated, and it attained an overall power efficiency of 88%. The ion target in the vacuum chamber of the test facility was covered with C/C composite plates, and this made significant reduction in back sputtering.

I. Introduction

RESEARCH of the 150-mN-class ion engine was being conducted at the National Aerospace Laboratory of Japan (NAL). In October 2003, a new Japanese space agency, the Japan Aerospace Exploration Agency (JAXA), was established by merging the former three Japanese space organizations, one of which was NAL, and since then the research has been succeeded to by JAXA.

The objective of this research is to establish basic xenon ion propulsion technology for future applications requiring high thrust levels. Though no flight programs that use this technology have been authorized yet at present, there are great demands for ion propulsion with such high thrust levels. Promising near-term applications are north-south station keeping of heavy and long-life geostationary satellites with short time firing, and orbit insertion of geostationary satellites. Orbit transfer from low earth orbit to geostationary orbit by ion propulsion can provide very large mass savings, and is very promising in the future. Some space science missions, especially ambitious ones, will need very large velocity increments, and they will require ion propulsion. A recent topic on ion propulsion is the development plan of a quasi-zenith satellite system, which will require a spacecraft propulsion system with high specific impulse for orbit control. In this system, orbit control with short time thrusting is essential, and thus needs

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thrust levels as high as 200 mN. Although gridded ion engines are not the prime candidate at present, the 150-mN ion engine can produce a thrust up to 200 mN and is applicable to the propulsion system.

The ion engines that have been developed for flights so far in Japan have only limited thrusting capabilities; 2 to 25 mN in direct current discharge type ion engine[1-4], and 8 mN in microwave discharge type[5]. These thrust levels are much smaller than those to be required from such future applications.

In this paper, the research and development status of the 150-mN-class ion engine is described. The ion engine has already achieved sufficiently high performance. Its specific impulse is 3,400 s at a beam voltage of 1,030 V, and the ion production cost is under 140 W/A at a discharge-chamber propellant utilization efficiency of 90%. Current efforts are directed to thruster-endurance improvement including hollow cathode endurance, development of the power-processing unit, and facility improvements for thruster endurance tests.

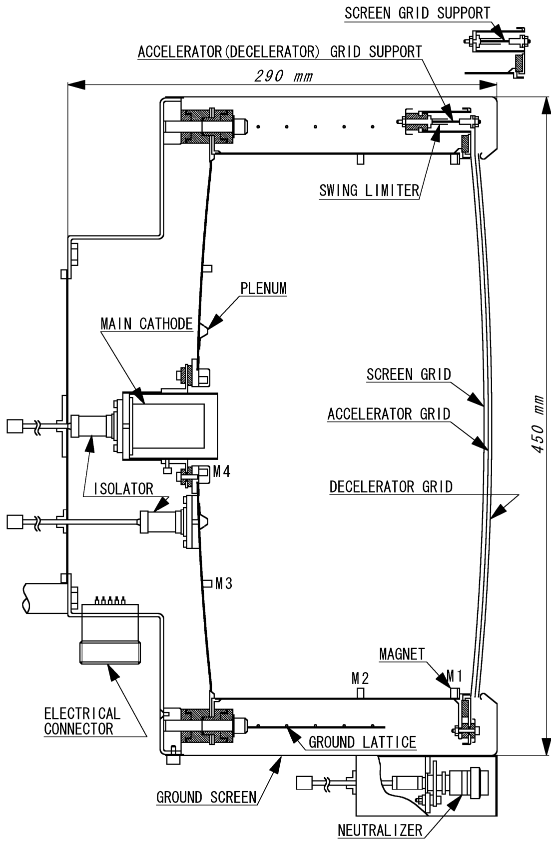


Figure 1. Section view of 150-mN thruster.

II. Thruster Development

The ion thruster under development is shown in Fig. 1. It has a discharge-chamber magnetic field of ring-cusp type, and an ion accelerating system with three grids of a 35-cm beam diameter. With repeated design improvements and fabrications so far, the thruster has already achieved the target value of ion production cost less than 140 W/A with a good margin[6]. This margin will allow some performance degradation that might be caused by design changes, such as increase in the grid thickness[7], for improving thruster endurance.

Though this thruster was designed to produce a thrust of 150mN at a screen grid voltage of 1,000 V, it is capable of producing a wide range of thrust. This was demonstrated in a thrusting capability test, in which the discharge-chamber propellant flow rate and discharge current were varied while the screen grid voltage was kept constant at 1,000 V. Table 1 shows typical performance characteristics obtained in this test. The specific impulse was almost constant at about 3,400 s because of the constant screen grid voltage. The discharge-chamber propellant utilization efficiency was kept almost constant at 90%. The environment pressure was 0.36 to 0.67 mPa (converted to xenon) during thruster operation.

The obtained maximum thrust was 210 mN, but it was based on a simple calculation from the beam current and voltage without consideration of beam divergence and doubly charged

Table 1. Typical performance characteristics of 150-mN thruster.

Thrust	Isp	Thruster eff.	Ion prod. cost	Beam current	Input power
mN	s	%	W/A	A	kW
81	3440	74.5	132	1.54	1.83
151	3480	76.7	117	2.88	3.36
181	3490	77.2	115	3.45	4.00
201	3490	77.5	110	3.84	4.45
210	3500	77.7	110	4.00	4.64

ions. Considering thrust loss of 5% due to these effects, the actual maximum thrust would be reduced to 200 mN.

The electric power consumption was from 1.8 to 4.6 kW corresponding to the thrust range of 80 to 200 mN. The power consumption here was the sum of the electric power values measured at the output terminals of the power supplies that were used to operate the thruster. The thruster efficiency was in a range from 75 to 78%. Note that this thruster efficiency was achieved at a rather low net ion-accelerating voltage (about 1,030 V).

This thruster uses flexible supports for the grids to absorb their thermal expansion. This may become a weak point in vibration environments during launch. To overcome this problem, we conducted a vibration analysis and vibration tests on the grid system including the flexible supports. As a result, we have obtained prospects that the grid system would endure the launch vibrations.

At present, two tasks are underway on the grid system. One is design and fabrication of a grid system optimized for 200-mN thrusting. The data shown in Table 1 were obtained using a grid system designed for the nominal thrust of 150 mN. The fabrication of the grid system has been almost finished. The other is on a grid system for an endurance test. Designing of the grid system for the endurance test has been started, and the fabrication will be finished in this fiscal year.

III. Hollow Cathode Development

A. Main Hollow Cathode

Main hollow cathodes are one of the critical parts of ion thrusters in terms of their lives. One of the serious problems occurring to main hollow cathodes was erosion of the keeper electrode due to ion sputtering. To overcome this, the material of the main hollow cathode keeper was changed from metal to graphite. In a thruster operation test with this new hollow cathode, no erosion was found in the keeper electrode. This proved that the graphite keeper gave a decisive solution to this erosion problem.

Another problem on the hollow cathode is erosion of its orifice plate, particularly around the orifice[8]. We had a concern of changes in its performance due to the erosion near the end of the cathode life. To reduce it and to keep the performance unchanged as long as possible, the material of the orifice was also changed to graphite. Figure 2 shows a photograph of the main hollow cathode with a graphite orifice plate.

Preliminary tests of the new hollow cathodes were conducted in diode mode using a disc anode. After the tests, the cathodes were disassembled and inspected, and no problems were found on them.

This main hollow cathode was designed for 150-mN thrusters, but is suitable to thrusters with 200 mN or higher thrust levels. It was demonstrated that it is capable of providing an emission current higher than 20 A.

At present, a cathode life test is being prepared to confirm endurance of the cathode, particularly that of the cathode insert, which may be restricted by starvation of the impregnant. To make more exact evaluation than in diode-mode operation, the test is going to be conducted in thruster-mode, where the hollow cathode will be installed in a dummy thruster, and it will be operated in discharge mode without beam extraction. A preliminary operation test using the dummy thruster has been conducted to adjust the discharge voltage and current, and the propellant flow rate so as to have the same values in operation in the real thruster. Figures 3 and 4 show photographs of the main hollow cathode in the dummy thruster and discharge luminescence through the dummy thruster grid, respectively. The cathode life test will start soon.

Figure 2. Photograph of main hollow cathode.

B. Neutralizer Hollow Cathode

In terms of endurance, the same design using graphite for the orifice plate is preferable also in neutralizers. However, a neutralizer using refractory metal for its orifice plate was first fabricated and tested. Basically, it was designed by downsizing the

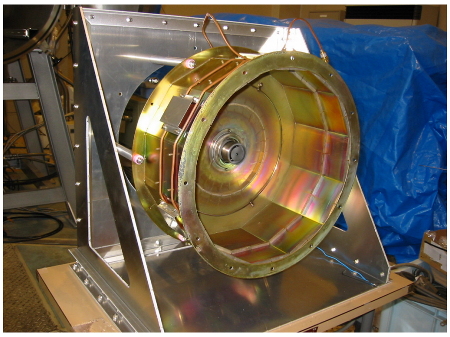


Figure 3. Main hollow cathode in dummy thruster.

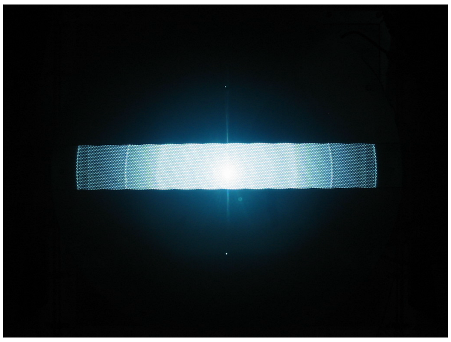


Figure 4. Discharge luminescence through dummy thruster grid.

main hollow cathode. Figure 5 shows a photograph of the neutralizer.

Electron emission characteristics of the neutralizer were obtained both in diode mode and in ion beam neutralizing operation. In the diode mode, the emission current J_d was collected using a disc anode, and the anode voltage V_d was measured with changing the propellant flow rate. In the ion beam neutralizing operation, the ion thruster including the neutralizer was electrically isolated from the ground, and the engine floating voltage V_e was measured with changing the propellant flow rate. The neutralizer is expected to emit electrons corresponding to the beam current J_b. Figure 6 shows appearances of the neutralizer emission. Because the ion beam target was grounded, the beam potential was expected to be nearly equal to the ground potential, and thus the engine floating voltage would correspond to the electron extraction voltage in space operation.

Results are shown in Fig. 7. The engine floating voltage was almost constant at 16 to 17 V for the flow rate range of about 100 to 250 mAeq., and this constant value of the engine floating voltage did not depend on the beam current. This demonstrated that this neutralizer has electron-emitting capability for the 150-mN-class thruster. Figure 7 also indicates that exact evaluation of the emission capability is difficult in diode-mode operation using a disc anode.

As a next step of the development, a new neutralizer hollow cathode has been designed and fabricated based on the neutralizer test results described above. In this neutralizer, we adopted the same structure as that of the main hollow cathode with a graphite orifice plate. An endurance test of the neutralizer is being planned.

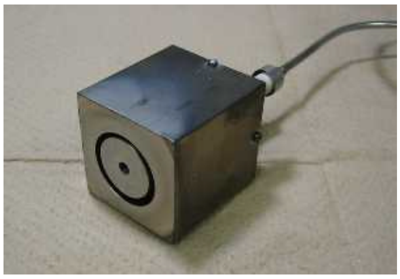
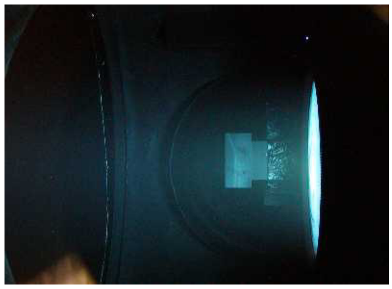
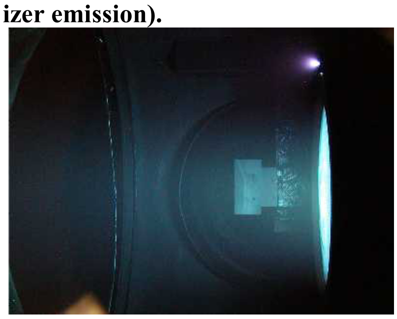


Figure 5. Photograph of neutralizer.



(a) Ion engine grounded (without neutralizer emission).



(b) Ion engine floated (with neutralizer emission).

Figure 6. Test of neutralizer installed in thruster.

IV. Development of the Power-Processing Unit

The ion propulsion system using the 150-mN thrusters will require very high levels of electric power, and thus the power-processing unit is one of the critical components in the system in point of high power. Preliminary research on the power-processing unit has been started, and trial fabrication of a lab-model power-processing unit has been conducted. In designing the lab-model power-processing unit, we adopted electric circuits that would be used in space flight, and aimed at as high efficiency as possible. It was designed for the nominal thrust of 150 mN, but the maximum output for about 160-mN thrust was found possible. Input voltage of direct current 100 V was adopted because it was typical of the electric bus in large satellites.

In an operation test of the power-processing unit with a thruster, we attained an overall power efficiency of 88.1% for a thrust range of 150 to 160 mN. This thrust range corresponded to a beam current range from 2.9 to 3.1 A, and a thruster input power range from 3.4 to 3.6 kW.

At present, we are conducting research in problems related to electromagnetic compatibility of the power-processing unit.

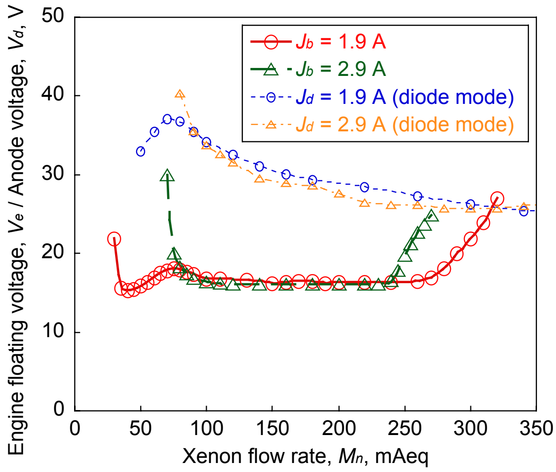


Figure 7. Engine floating and anode voltages versus propellant flow rate.

V. Test Facility Improvement

The ion thruster test facility has been improved in its ion beam collector, or target. The previous target was made of titanium because it has relatively low sputtering yield and would reduce back sputtering of the target material. In the previous endurance test, however, even the titanium target caused a problem of too much deposition of back sputtered material on the thruster grid[7].

To make further reduction in the back sputtered material, we modified the target material to carbon, which has much lower sputtering yield than titanium. To examine and confirm the validity of using carbon, we measured deposition rate of back sputtered material using a quartz crystal microbalance placed near the thruster. Results indicated significant reduction in the deposition rate of the back sputtered material. This will help greatly to conduct coming long operation tests.

VI. Conclusion

The research and development of the JAXA next-generation ion engine is favorably in progress. Because technical difficulties increase with sizes of thrusters in general, it means that basic thruster technologies up to 200-mN thrust are covered with this research and development.

The thrust of 200 mN obtained with this thruster is much higher than those ever produced in Japan. It is applicable to the quasi-zenith satellite system being planned in Japan. Aiming at applications to this system, the New Energy and Industrial Technology Development Organization (NEDO) had put out a request for proposal of the research and development of a 200-mN ion engine. Though they have chosen a proposal of developing a Hall thruster, we believe that our thruster can essentially meet their requirements.

In the coming hollow cathode endurance test, we are expecting no serious problems in erosion because of extremely high resistance of its graphite parts to erosion, but will need to pay a special attention to exhaustion of insert impregnant, which may be a decisive factor of the cathode lifetime.

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