Feasibility Study on High Specific Impulse Ion Thruster with C/C Grid System

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Abstract: A high specific impulse ion thruster based on the HAYABUSA μ10 ion thruster (μ10-Hisp) is candidacy of the electric propulsion installed in solar power sail which has been proposed by ISAS/JAXA. For the development of μ10-Hisp, its C/C composite material grid geometry was designed with three-dimensional ion optics simulation code. Through the feasibility experimental evaluation, it was confirmed that the voltage of over 12kV can be applied to the grid system without the breakdown phenomenon and the direct impinged current to the acceleration grid, and the design of grid geometry and the adoption of C/C material to the grid were fairly. The C/C grid system with the above designed geometry, a high voltage gas isolator and a DC block for the direct current isolation on the microwave power lines are assembled in the μ10 ion thruster as the μ10-Hisp in present status.

I. Introduction

The ion thruster with high specific impulse can expand the human activity area in space. In the Prometheus project proceeded by NASA, a deep space probe to Plute, a high specific impulse ion thruster is developing as a candidacy of its main propulsion.1,3 Since the high specific impulse ion thruster requires high power, a nuclear power generator will be installed and applied in this project. Although the nuclear power generator will not be applied in Japanese space activity with some reasons, the high specific impulse ion thruster will be also useful and attractive for Japanese satellites and space probes. This is because the improvement of solar power generator performance (power/weight ratio) in near future will give birth to the increase of usable electric power for ion thruster operation. In addition, a solar power sail project has been proposed by ISAS/JAXA as a deep space probe to

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The solar power sail traps solar photons as a solar sail and generates electric power as a solar power generator. The generated power is supplied to electric propulsion installed in the sail. In fact, the solar power sail is a hybrid propulsion system propelled by solar photon trapping and electric propulsion. In this project, an ion thruster with high specific impulse of over 10,000s is appropriate for the electric propulsion, judging from the system investigation. Accordingly, the high specific impulse ion thruster is also worth developing in Japan.

A high specific impulse ion thruster derived from the HAYABUSA μ10 ion thruster (hereafter called μ10-Hisp) is proposed in this paper due to three reasons. The first reason is that the μ10 thruster qualified 18,000h durability test and is actually used in space. The second reason is that the predicted performance of μ10-Hisp thruster satisfies that of the solar power sail electric propulsion. The third reason is that the μ10 thruster adopted C/C (carbon/carbon) composite as the grid material. The high specific impulse ion thruster which consumes high electric power brings about heating problem which affects the beam extraction of grid system. The C/C material which has almost zero thermal expansion coefficient is also attractive in μ10-Hisp thruster.

Since the applied voltage of μ10-Hisp ion thruster is 8-13kV, the improvement of the grid system and gas isolator are required to be able to apply that high voltage. In addition, the high voltage applicable DC block is also required due to the microwave discharge production of μ10-Hisp thruster. Moreover, the estimation of high voltage application to C/C grid system is necessary because the C/C is fluffy surface which concerns the electric breakdown. As a feasibility development of high specific impulse ion thruster with C/C grid system and microwave discharge, the objectives of this paper are (1) Design of grid system, (2) Experimental evaluation of grid system, and (3) Discussion on μ10-Hisp development.

II. Grid System Design

A. Design Concepts

For the long durability and reliability, it is likely that the microwave discharge plasma density of μ10-Hisp thruster should be the same as that of μ10 thruster. The μ10 thruster with the beam diameter of 10cm is operated with the microwave discharge power of 32W and the propellant flow rate of 2.3sccm. The grid system of μ10 extracts the beam current of approximately 140mA with net acceleration voltage of 1.5kV. The typical thruster performance of μ10 thruster is the thrust of approximately 8mN and the propellant utilization efficiency of approximately 85%.

In addition, the applied voltage of 8-13kV is required for the achievement of high specific impulse of over 10,000s. These prerequisite derives the following points of view:

1. number of holes; space charge limitation current and structural strength
2. screen grid hole diameter; beam current and beam optics (aspect ratio)
3. screen grid thickness; stable plasma retention and plasma sheath establishment
4. gap between screen and acceleration grid; prevention from electric breakdown
5. acceleration grid hole diameter; neutral number density within discharge chamber
6. acceleration grid thickness; depression of potential increase due to space charge of ion beam
7. deceleration grid; suppression of grid erosion due to charge-exchanged ion back-streaming
8. screen grid potential; the exhaust velocity of over 100km/s
9. acceleration grid potential; depression of potential increase due to space charge of ion beam

B. Geometry

Through the operation researches to satisfy the above conditions and the evaluations with ion beam simulation, the dimensions and applied voltages of grid system were determined as shown in figure 1. The designed normalized perveance per hole (NPH) is 0.5-1.0×10^{-9} A/V^{1.5}. The igx is the three dimensional beam optics simulation code which uses an energy compensation method and a simplified plasma sheath definition that are in good agree with experimental data. As shown in this figure, the geometric dimension of μ10-Hisp thruster is drastically different from that of the conventional ion thrusters. The grid suspension system which can keep the large grid gap with low parallelism tolerance and isolate the high voltage gap is necessary in order to extract ion beam fairly.
III. Experimental Evaluation of Grid System

A. Experiment Apparatus

In order to evaluate the grid system design, the feasibility experiments are performed. Figure 2 shows the photograph of the screen and acceleration grid which made of C/C composite material. The beam diameter is approximately 3cm. The plasma is produced with tungsten filament direct current discharge without magnetic field, and the discharge plasma is controlled with the filament current and the discharge voltage. The plasma is produced with a tungsten filament and direct current discharge. The discharge chamber is made of machinable ceramics with the length of 4cm. The screen and acceleration grid are set with ceramics screws and the deceleration grid is not set in this experiment. Figure 3 shows the schematic of miniature ion thruster with seven holes C/C grid system which has the above designed dimensions. The propellant, xenon, is fed through a high voltage gas isolator and precisely flow controller. The thruster is operated under the vacuum pressure of approximately 3mPa, and the currents and voltages are measured for the evaluation.

B. Results and Evaluation

Figure 4 shows the photograph of seven holes C/C grid thruster with beam extraction by each grid hole. Although electric breakdown phenomenon between the grids in the beginning phase of experiment were observed, it was confirmed that the voltage of over 12kV can be applied to the grid system without the breakdown phenomenon.
after the beginning phase. Since the sputtering phenomenon on the surface of grid were little observed, it seems that the C/C material can be adopted to the grid system of high specific impulse ion thruster.

Figure 5 indicates the acceleration grid current ratio against the normalized perveance per hole (NPH). As shown in this figure, it was confirmed that the experimental data (plotted points) is good agree with the simulated data (drawn line) in range of $0.25-1.5 \times 10^{-9}$ A/V$^{1.5}$. It was confirmed that the simulation results implied the acceleration grid current in this range was caused by the backstreaming charge-exchanged ions produced in the downstream area, not caused by the direct impinged ions.

It is confirmed that the beam current per hole of this grid system in this experiment satisfied the target performance of $\mu$10-Hisp grid system. Judging from these results and estimation, it seems that the design of $\mu$10-Hisp grid system with C/C composite grids is fairly.

IV. Discussion of $\mu$10-Hisp Development

Since the feasibility experiment implied that the designed C/C grid system is appropriated to the $\mu$10-Hisp, the development of $\mu$10-Hisp is proceeding in the present status. Figure 6 shows the photograph of $\mu$10-Hisp with the full scale grid system which has 163 holes and the beam diameter of 10cm. There is a microwave neutralizer in the left-of-center of this photograph. This neutralizer is basically identical to that of $\mu$10 thruster. The predicted thruster performance on the assumption that the microwave discharge plasma of $\mu$10-Hisp is similar in density and
consumed power to that of μ10 is the specific impulse of approximately 10,000s, the thrust of approximately 25mN, the propellant utilization efficiency of approximately 85% and ion production cost of approximately 200W/A.

In order to operate the μ10-Hisp thruster, the gas isolator and the DC block with withstand voltage more than the net acceleration voltage are necessary. Considering the aging deterioration, it seems that the withstand voltage should be over twice as high as the net acceleration voltage, that is, 20-30kV. Figure 7 shows the photographs of the developing gas isolator and the developing DC block fabricated for the μ10-Hisp thruster. After the evaluation, these items are to be assembled with the μ10-Hisp, and the thruster performance will be evaluated in near future.

![Figure 6 μ10-Hisp thruster](image)

![Figure 7](image)

(a) Developing gas isolator  
(b) Developing DC blocks

**Figure 7 High voltage key items for μ10-Hisp thruster**

**V. Conclusion**

Through the feasibility experimental research, it was evaluated that (1) the high specific impulse grid geometry designed with an ion optics simulation code was fairly, and (2) the C/C composite material with fluffy surface can be adopted to the high specific impulse grid. The performance of microwave discharge ion thruster with high voltage gas isolator and DC block based on μ10 thruster will be evaluated in near future.

**References**


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