C₆₀ Application to Ion Thruster -Inspection of Ionized and Extracted Particle-
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Abstract
On the C₆₀ application to ion thruster propellant, there are the problem of resolidification, fragmentation and multi-ionization.
Although the designed/fabricated C₆₀ ion thruster in our previous works has cleared the resolidification problem, it has not cleared the other problems. In this study, the small-sized and fullerene detectable ExB-probe was developed in order to evaluate the fragmentation problem. Through the inspection to the ionized/extracted particles using this probe, it was evaluated that the decrease of the discharge voltage from 40 V to 35 V can suppress the fragmentation phenomenon, and the optimized discharge voltage was 35 V judged from the previous and present study. Furthermore, it was also obvious that the C₆₀ ion beam profile was approximately similar to the conventional Xe ion thruster and symmetric with the center axis of the thruster. C₆₀ discharge was able to be sustained in low flow rate situation, and the improvement of the thruster performance was achieved.

1. Introduction

C₆₀, a recently discovered carbon molecule allotrope, has a lower ionization potential and larger molecular weight, compared with conventional/typical ion thruster propellants (Hg, Ar, Kr and Xe). Accordingly, C₆₀ application to ion thruster propellant will improve performance by the increase of the thrust density and the decrease of the electric power consumption, and its application was studied by several laboratories; NASA-Jet Propulsion Laboratory, MIT, and our TMIT.*

However, C₆₀ also has disadvantageous properties. It requires a sublimation device such as a heater for its gaseous feed to the discharge chamber because C₆₀ is a solid (powder) at normal temperatures. The resolidification phenomenon will occur at a lower temperature than the sublimation point and the fragmentation phenomenon will occur at a high temperature. Moreover, detailed ionization (including double and triple ionization) and fragmentation processes were reported by Lezias et al. and Sai Baba et al. In their works, in the case of electron bombardment ionization, the fragmentation of C₆₀ ions appears at over 45 eV of electron energy, and double and triple charged C₆₀ ions appear at over 15 eV and 25 eV, respectively.

In our previous works, the C₆₀ ion thruster and the propellant supplier for its gaseous feed (crucible), considering above properties, has been designed and evaluated. Using this thruster and supplier, it was confirmed that the flow rate of the sublimated C₆₀ was 4.9 sccm (2.6 mg/s), which was comparable to that of a typical ion thruster, and the thrust was 4.1 mN (net acceleration voltage = 700V).

Therefore, it seems reasonable to suppose that C₆₀ is the propellant which can be gaseously fed and be ionized/extracted in its discharge chamber and ion optics. Moreover, it was obvious that the heat-up device (body heater) of this thruster suppressed the resolidification phenomenon at the discharge chamber wall.

Although the solid powder problem have been cleared, however, the study of the fragmentation and multi-ionization problem has not been examined, besides the indirect evaluation by spectrophotometer analysis to the ion beam. To evaluate and clear the fragmentation and multi-ionization problem, it is necessary to grasp the phenomenon whether the ionized/extracted C₆₀ is fragmented and multi-ionized, or not.

The objectives of this study, accordingly, are (1) to develop the device which can directly inspect ionized particles, (2) to grasp the fragmentation and multi-ionized phenomenon using this device, and (3) to evaluate its discharge. Moreover, this paper also concerns with the performance improvement and the ion beam profile of the thruster.

2. Thruster and Devices

Time-of-Flight (TOF) and ExB-probe are the typical devices which can perform the direct inspection to ionized particles. In this study, ExB-probe device was adopted because of its capability of real-time inspection.

2.1 ExB-probe

The schematic of ExB-probe is shown in Fig. 1. ExB-probe is composed of a first slit, an ExB section (E:electric field, B:magnetic field, perpendicular each other), a second slit, and a collector. The ionized particle with velocity v and charge q is incident on the ExB section through the first slit, and describes an arc or a straight line by the electric force.
(q \cdot E) and the magnetic force (q \cdot v \times B). The straight line described particle (q \cdot E = q \cdot v \times B) passes the second slit, and is detected by the collector. Since the particle velocity is determined by the total acceleration potential and its mass (M), the particular particle can be selected by the particular value of the electric potential gap (V_{ep}) or the magnetic flux density. Generally, the detectable mass range increases with increase of the ExB section length and the two field force. The ExB section length, however, is limited by the size of the facilities, especially the space chamber.

Under the above conditions, the small-sized ExB-probe as shown in Figs. 2 and 3 which can detect the large molecule (up to 1,000 a.m.u.) was designed/fabricated. This probe is made up of 64 pieces of permanent magnets, stainless steel slits (0.3 mm x 30 mm) and collector plate, stainless steel plates for electric field formation (the gap between the plates: about 20.5 mm), pure iron steel plates for magnetic field formation, and aluminum plates. The magnetic flux density on the magnet surface and in the ExB section field is about 250 mT and 100 mT, respectively.

2.2 Beam Profile Probe

The beam profile probe was manufactured in order to measure the ion beam profile of the thruster. This probe is made up of \( \phi 0.3 \) tungsten wire (uncovered length: 30 mm) and ceramic tube for the isolation from the ion beam. The uncovered area of this probe coincides with the slit area of the ExB-probe.

2.3 C60 Ion Thruster

The schematic drawings of C60 ion thruster and propellant supplier (crucible) are shown in Figs. 4 and 5, respectively. This thruster was reformed in order to feed Xe gas to the discharge chamber. Then, the flow rates of the propellant supplier are shown in Fig. 6. As shown in this figure, it was obtained that the flow rates were about 0.9, 2.4 and 4.9 sccm when the crucible heater was operated on 26, 31, 36 W, respectively. The more details of this thruster and supplier have been reported in our previous papers\(^5\)\(^-\)\(^7\).
3. Facilities and Experimental Procedure

The series of the experiments in this study were classified into three; "Beam Profile Experiments" using the beam profile probe, "ExB-probe Calibration Experiments" and "Particle Inspection Experiments" using the ExB-probe. These probes and the Cao ion thruster were set as shown in Fig. 7. A schematic drawing of the space chamber and its facilities used in the present study is shown in Fig. 8. The space chamber, 2,050 mm in length and 900 mm in diameter, has two turbo-molecular pumps (2,200 l/s x 2) and an auxiliary rotary pump (1,500 l/min.). Its maximum vacuum extent was at approximately $1.0 \times 10^3$ Pa during experiments without operation of the body heater. Figure 9 shows a schematic drawing of the experimental circuit. The values of currents, voltages, vacuum extent and temperatures were measured using a multimeter. The target-plate was set at 10 cm or 15 cm downstream from the screen grid.
The Co-sample used in the present work is a fullerene sample called "refined" or "mixture." The sample consists of Co (approximately 90%), Cw (approximately 10%), and trace amounts of impurities; toluene (solvent) and oxygen molecules (absorption).

3.1 Beam Profile Experiments
These experiments using the beam profile probe were performed in order to obtain the ion beam profile of this thruster, to confirm the extraction by the grids system, and to compare the Co beam profile and Xe beam profile. The beam profile probe was linearly moved on the plane at 8 cm downstream from the screen grid, by the motor system within the space chamber. These experiments are also the feasibility study of the ExB-probe application.

3.2 ExB-probe Calibration Experiments
These experiments were performed in order to calibrate the ExB-probe and to evaluate its applicability. The ExB-probe was set on the center axis of the ion thruster, at about 15 cm downstream from the grids system. Xe and Co-sample (Mixture fullerene sample) was used to the calibration gas.

4. Results and Discussions
4.1 Thruster Performance
Typical results and ion beam luminosity obtained in the previous and present experiments are shown in Figs. 10 and 11, respectively. Moreover, a summary of the typical performance and setting parameters is shown in Table 1. The figures of the abscissa axis in Fig. 10 indicates the accumulated time after the filament current (I_f) changed from 5.0 A to 7.0 A, and the result shown in this figure corresponds to those in Table 1 (Experiment No.: ID2-C2). Through the experiments, it was obvious that the Co discharge can be sustained in the situation of low flow rate, and the decrease of the flow rate (the adequately flow rate) improved the...
thruster performance; especially, the propellant utilization efficiency and the specific impulse. As indicated in the table, the drain ratio is increased. This may be caused by the deterioration of the grids system.

[Note]: It was apparently recognized that C60 was sublimated by not only the crucible heater power ($P_{h}$) but also the discharge power ($P_d = I_d \times V_d$). Through some experiment, it was obtained that the sublimated flow rate ($m$) was expressed in the following equation at $P_{h} = 21$ W.

$$m \ [\text{sccm}] = 0.00915 \times P_h [\text{W}] + 0.04$$

4.2 Beam Profile Experiments
The profiles of Xe ion beam and C60 ion beam obtained by the beam profile probe are shown in Fig. 12 (a) and (b).

![Fig. 10 Typical Results of Current Changes](image1)

![Fig. 11 Photograph of Ion Beam](image2)

![Fig. 12 Ion Beam Profile](image3)
respectively. The open area of grids system (the beam diameter) corresponds to the range from 115 mm to 195 mm on the probe position ($X_p$). As shown in this figure, it was obvious that both profiles were approximately similar to the conventional Xe ion thruster and symmetric with the center axis of the ion thruster ($X = 155$ mm), and both ionized propellants were certainly extracted by the grids system. Although the obtained profiles did not express the strict profiles because of the probe's shape like as a stick, moreover, it may become clear that the divergence of C$_{60}$ ion beam was larger than that of Xe ion beam. This may be because the molecular weight of C$_{60}$ is larger that that of Xe.

4.3 $ExB$-probe Calibration Experiments

It was evaluated that the shift tolerance between the thruster center axis and the $ExB$-probe center axis was within 5 mm, based on the peak form of the above beam profile. Accordingly, the $ExB$-probe was set within the tolerance. Figure 13 shows the representative result of the collector current against the potential applied to the electrodes ($V_{eb}$). Although the peak is shifted because of the shift between the thruster center axis and the $ExB$-probe center axis, it was estimated that the shift range was less than 5 V (4%), and its shift did not affect the inspection, through these experiments. The peak shown in this figure corresponds Xe-ion peak, because, in this calibration experiments, only Xe gas was supplied to the ion thruster. In this case, the peaks of fullerene molecules (C$_{50}$ ~ C$_{100}$; 600 ~ 1200 a.m.u.) must be detected in the range of $V_{eb} = 50$ V to 20 V, approximately. It was confirmed that this calibration is valid in the following experiments, in which the mixture gas of the Xe and C$_{60}$ was supplied.

The mass spectrum of the particles extracted from C$_{60}$ and Xe plasma is shown in Fig. 14. This results were obtained in the situation at the discharge voltage ($V_d$) = 40 V. As shown in this figure, it was obvious that both C$_{60}$ and the other fullerenes were similarly ionized/extracted, and the fragmented molecule (C$_{56}$ and C$_{54}$) was also observed (discussed in the below). Figure 15 shows the spectrum of the original C$_{60}$ sample (Mixture fullerene sample), obtained from the liquid chromatographic analysis by the manufacturer. Compared with the data among these figures, the mass spectrum obtained in this experiment evidently conforms to that of the strict sample. In addition, it was evident that the fullerene peaks are certainly expressed in the above voltage range. Therefore, it was confirmed that the calibration of the $ExB$-probe was achieved, and the small-sized and fullerene detectable $ExB$-probe was developed and it was valid.
4.4 Particle Inspection Experiments

The mass spectrum of the particles extracted from C60 plasma is shown in Fig. 16 (a) and (b). This figure indicates that the fragmentation phenomenon (C60 and C70 were fragmented to C50 and C60) occurred at the discharge voltage \( V_d = 40 \text{ V} \), on the contrary, the fragmentation phenomenon scarcely occurred at \( V_d = 35 \text{ V} \). Because the original fullerene sample does not contain the molecules such as C50 and C60, it is entirely fair to say that the fragmentation phenomenon was caused by the high voltage discharge, in other words, the high energy electron. Furthermore, it seems reasonable to suppose that the decrease of the discharge voltage from 40 V to 35 V can suppress the degree of the fragmentation phenomenon. It has been also obtained that the decrease of the discharge voltage brought about the decrease of the thruster performance as shown in Fig. 17, in our previous works. Judging from only these results, it may safely be assumed that the optimized discharge voltage is 35 V.

However, the decrease of the discharge voltage also brought about the decrease of the sublimated flow rate by the discharge power as mentioned in section 4.1. Moreover, nevertheless the ionization potential of C60 (7.61 eV) is lower than that of Xe (12.13 eV), this discharge voltage \( V_d = 35 \text{ V} \) similar to that of Xe ion thruster; for example, the discharge voltage of ETS-VI ion thruster was operated at 37.5 V\(^{10}\). Accordingly, there is room for argument on this optimization, the more detail investigation of the discharge may be necessary.

**[Fragmentation Phenomenon]**: It has reported\(^{11}\) that the fragmentation phenomena are expressed in the following equations.

\[
C_{60} \rightarrow C_{50} + C_2 \rightarrow C_{54} + C_2 + C_2 \rightarrow ... \\
C_{70} \rightarrow C_{64} + C_2 \rightarrow ...
\]
5. Concluding Remarks

The following conclusions have been obtained through the experiments.
(1) C\textsubscript{60} discharge can be sustained in the situation of low flow rate, and the decrease of the flow rate (the adequately flow rate) improved the propellant utilization efficiency and the specific impulse.
(2) Profiles of Xe ion beam and C\textsubscript{60} ion beam obtained by the beam profile probe were approximately similar to the conventional Xe ion thruster and symmetric with the center axis of the thruster, and the divergence of C\textsubscript{60} ion beam was larger than that of Xe ion beam.
(3) Small-sized and fullerene detectable E\times B-probe was developed and it was valid.
(4) Both C\textsubscript{60} and the other fullerenes were similarly ionized/extracted.
(5) Decrease of the discharge voltage from 40 V to 35 V can suppress the degree of fragmentation phenomenon, and it may safely be assumed that the optimized discharge voltage is 35 V judged from the previous and present study.

Acknowledgement

This research was supported in part by a grant from Japan Society for the Promotion of Science for Young Scientists (JSPS).

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