C\textsubscript{60} MOLECULE AS A PROPELLANT FOR ELECTRIC PROPULSION

Haruki Takegahara* and Yoshinori Nakayama**
Department of Aerospace Engineering
Tokyo Metropolitan Institute of Technology,
6-6, Asahigaoka, Hino,
Tokyo, 191, JAPAN

Abstract

C\textsubscript{60}, a recently discovered allotrope of carbon molecule, has an advantageous properties as an electric propulsion propellant. This molecule has lower ionization potential than noble gas and larger mass than conventional propellant, such as Mercury, Argon, Xenon. Therefore, the application of it may improve performance of electric propulsion, especially electrostatic propulsion.

An applicability of C\textsubscript{60} which has an attractive properties was evaluated through the investigations and experiments.

1. The results of the performance prediction showed the following advantages by using C\textsubscript{60} molecule.

   (1) By using C\textsubscript{60} molecule as the propellant of ion thruster, the diminishments of beam current, discharge current and discharge voltage will be achievable. These are related to the remarkable decrease of the required electric power and the improvement of the thruster's durability.

   (2) The remarkable improvement of the thrust / power ratio (approximately two and half times) will be achievable.

2. Through the sublimation experiments, the spectrum analysis for the sublimated, collected powder and original powder showed the typical and featuring spectrum peaks of C\textsubscript{60} in the sublimated powder waveform as well as in the original powder. Moreover, the spectrum peak of the sublimated powder stands out, comparing with the result of the original powder. These seem to be caused by the sublimation temperature difference between C\textsubscript{60} and other contents (C\textsubscript{70}, etc.,) and C\textsubscript{60} sublimation without dissociation is possible. Therefore, adequate sublimation chamber enables the supply of the gaseous C\textsubscript{60} to the discharge chamber.

3. Through the C\textsubscript{60}-plasma production experiment by Inductively Coupled Plasma device (hereafter called "ICP"), it seems that the C\textsubscript{60} plasma emission spectrum was observed.

4. Through the preliminary estimation of C\textsubscript{60} plasma production using RF ion thruster, it seems that the sublimation and plasma production of C\textsubscript{60} was achieved by the direct heating in the discharge chamber using RF power.

However, it is notable that the sublimated C\textsubscript{60} returns to the powder state at the discharge chamber wall (re-solidification phenomenon).

The countermeasure for the re-solidification in the feed line and the discharge chamber will be necessary and the more detailed experiments, inspections and evaluations are necessary.

1. Introduction

At present, ion propulsion is on R&D phase in order to apply to the auxiliary propulsion of north-south station keeping (NSSK) for geosynchronous satellite, main-propulsion for orbit transfer vehicle or interplanetary vehicle at several laboratories and manufactures. However, comparing with the conventional chemical propulsion, the thrust level generated by electric propulsion is very low and this disadvantage causes the many difficulties such as life-time, long mission time, in spite of its excellent efficiency and specific impulse.

As the long term operation is required for these missions because of low thrust level of electric propulsion, the prolongation and the verification of its life are the most important problems as well as the performance im-
It is well-known that ideal thrust: $T_{ideal}$ generated by ion propulsion is expressed as follows.

$$T_{ideal} = J_b \sqrt{\frac{2mV_b}{e}}$$

where $J_b$: Beam Current (A)
$V_b$: Beam Voltage (V)
$m$: Ion Mass (kg)
$e$: Electric Charge (Coulomb)

As shown in this expression, thrust is proportional to the root of the propellant ion mass. Therefore, as well as the performance improvement, the utilization of the larger mass propellant causes the improvement of thrust level.

C₆₀ is a recently discovered allotrope of carbon molecule. This carbon allotrope has an above-mentioned advantageous properties as an electric propulsion propellant. This molecule has lower ionization potential than noble gas and larger mass than conventional propellant, such as Mercury, Argon, Xenon. Leifer, S. et al. showed the possibility of the efficiency improvement as well as the increase of thrust level¹). Therefore, the application of it may improve performance of electric propulsion, especially electrostatic propulsion. However C₆₀ has also disadvantageous properties, which is a solid (powder) in a normal temperature and occurs dissociation by ultraviolet rays²). It is necessary to clear these problems for the application.

This paper discusses an applicability of C₆₀ as an attractive and promising propellant through the investigations and experiments as follows.

1. Estimation of the calculating-performance of C₆₀-using ion thruster, comparing with the performance of the present Xenon ion thruster
2. Experiment of C₆₀ sublimation from its powder state and the evaluation of the dissociation by the sublimation
3. Confirmative experiment of plasma production of dissolved C₆₀ by ICP
4. Preliminary estimation of plasma production of sublimated C₆₀ by RF ion thruster

II. C₆₀ Molecule and Its Application to Ion Thruster

2.1 C₆₀ Molecule

C₆₀, whose existence was predicted by Eiji Osawa in 1970, is a recently discovered allotrope of carbon molecule by Richard Smalley et al. in 1985. C₆₀ consists of sixty carbon atoms and its molecular structure like a soccer ball resembles to the architecture designed by Buckminster Fuller. Therefore C₆₀ has the nickname of "buckminsterfullerene" or "bucky". Moreover, other allotropes of carbon molecule, which have more than seventy carbon atoms, were also discovered and studied energetically. Table 1 summarizes the major properties of C₆₀ molecule³), comparing with Xenon molecule. Major features and its advantages for electric propulsion are as follows.

1. It has large molecular weight. Therefore, increase of thrust will be attainable.
2. Its ionization potential is low and its molecular diameter is large. Therefore, decline of ion production cost will be attainable.
3. Its electron affinity is large. Therefore, negative ion will be attainable.
4. When C₆₀ molecule strikes the material surface, sputtering phenomenon is rarely occurred⁴).

Figure 1 shows the formation and refinement process of C₆₀. In the series of this experiment, refined C₆₀ which contains more than 85% pure C₆₀, was utilized.

### Table 1 Major Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Xe</th>
<th>C₆₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight</td>
<td>131.30</td>
<td>720.66</td>
</tr>
<tr>
<td>Molecular Diameter, Å</td>
<td>4.40</td>
<td>7.1</td>
</tr>
<tr>
<td>Ionization Potential, eV</td>
<td>12.13</td>
<td>7.61</td>
</tr>
<tr>
<td>Electron Affinity, eV</td>
<td>-</td>
<td>2.65</td>
</tr>
<tr>
<td>Sublimation Temperature, K</td>
<td>-</td>
<td>-700</td>
</tr>
</tbody>
</table>

Fig. 1 Refing Process
2.2 Performance Prediction of C60 Ion Thruster Comparing with ETS-VI Xenon Ion Thruster

On the basis of the operating point of ETS-VI ion thruster, performance prediction of the C60 electron bombardment ion thruster was performed. In this comparison, thrust level ( T ) and beam voltage ( Vb ) were fixed at the same value as ETS-VI ion thruster ( T = 25mN, Vb = 1.000 V ). Adopted performance prediction method were as follows.

1. Beam Current : Jb ; Calculated by the following equation, using the same thrust condition

\[ T_{\text{ideal}} = J_b \sqrt{\frac{2mV_b}{e}} \]

where

Jb : Beam Current (A)
Vb : Beam Voltage (V)
m : Ion Mass (kg)
e : Electric Charge (Coulomb)

Required beam currents with each propellant C60 and Xe have the following relations.

\[ J_b \text{(C60)} = J_b \text{(Xe)} \times \sqrt{\frac{m_{\text{C60}}}{m_{\text{Xe}}}} \]

2. Discharge Voltage : Vd ; Calculated by the ionization potential ratio of C60 to Xe

3. Discharge Current : Jd ; Calculated by the assumption that necessary discharge current is proportional to plasma density in the discharge chamber and its density is commensurate to beam current

4. Necessary Electric Power : P ; sum of beam power and discharge power

Table 2 shows the results of the performance prediction. As shown in this table, the following advantages are evident by using C60 molecule.

1. By using C60 molecule as the propellant of ion thruster, the diminishments of beam current, discharge current and discharge voltage will be achievable. These are related to the remarkable decrease of the required electric power and the improvement of the thruster's durability.

2. The remarkable improvement of the thrust/power ratio ( approximately two and half times ) will be achievable.

* NOTE In table 2, sublimation energy of C60 is not considered. For the C60 sublimation, as its sublimation enthalpy is 181.4 kJ/mol ( at 700 K ), 0.48 Watts of electric energy is necessary for the 1 minuite's mass flow rate of 3.6 SCCM.

<table>
<thead>
<tr>
<th>Thrust, mN</th>
<th>Xe</th>
<th>C60</th>
<th>C60/Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1000</td>
<td>1000</td>
<td>0.43</td>
</tr>
<tr>
<td>206</td>
<td>483</td>
<td>483</td>
<td>0.43</td>
</tr>
<tr>
<td>23.5</td>
<td>37.5</td>
<td>37.5</td>
<td>0.43</td>
</tr>
<tr>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
<td>0.43</td>
</tr>
<tr>
<td>33.1</td>
<td>123.8</td>
<td>123.8</td>
<td>0.27</td>
</tr>
<tr>
<td>0.43</td>
<td>606.8</td>
<td>606.8</td>
<td>0.39</td>
</tr>
<tr>
<td>0.43</td>
<td>239.1</td>
<td>239.1</td>
<td>0.39</td>
</tr>
<tr>
<td>2.34</td>
<td>115.8</td>
<td>115.8</td>
<td>0.34</td>
</tr>
</tbody>
</table>

III. Experimental Procedure and Apparatus

3.1 Experimental Procedure and Facilities

The series of experiments were divided into major three parts. Table 3 shows the experimental procedure in these experiments. The schematic drawing of space chamber and its experimental facilities used in this study are shown in Fig. 2. In this space chamber ( L : 1,000 mm, \( \phi : 600 \text{ mm} \) ) which has diffusion pump and auxiliary rotary pump. Its maximum vacuum extent was approximately \( 1.2 \times 10^{-3} \text{ Pa (9 x 10}\) -6 Torr \) during experiment.

![Fig. 2 Vacuum Chamber](image-url)
3.2 Sublimation Experiment

Figure 3 shows the schematics of the crucible which was used as sublimation device. As shown in this figure, this crucible consists of the sublimation chamber made of quartz glass (volume: approx. 1.3 cc, capacity: 0.5 g of sample), ceramic insulator, thermo-couple and nichrome wire heater. This nichrome wire heater is not inserted directly in the sublimation chamber, heating was conducted by radiation. Through the quartz glass, the sublimation phenomenon was observed, thermo-couple indicated the representative temperature in the sublimation chamber.

As shown in table 3, sublimation experiment consists of the following two items.

1. Constant Temperature Experiment: This experiment was performed in order to estimate the sublimation temperature (see Fig. 4(a)). By the temperature controller, the representative temperature in the sublimation chamber was controlled. Sublimation phenomenon was confirmed by the vacuum pressure increase, visual observation and the difference between the pre-, post-experiment C₆₀ mass.

2. Constant Current Experiment: This experiment was performed in order to estimate the relationship among the input electrical power and sublimation rate (see Fig. 4(b)). On the basis of the results of the "Constant Temperature Experiment", heater current was fixed and sublimation rate was evaluated by the difference between the pre-, post-experiment C₆₀ mass. Moreover, in order to evaluate the possibility of the dissociation phenomenon of sublimated C₆₀, spectrum analysis of original power (refined C₆₀: containing more than 85% C₆₀), sublimated collected powder and remained powder enclosed in the sublimation chamber was performed by the FTIR device (Fourier Transform Infrared Spectrophotometer).

3.3 C₆₀ Plasma Production Using ICP Device

ICP (Inductively Coupled Plasma) device is one of the emission spectrochemical analysis device. Figure 5 shows the schematic drawing of the ICP device and the plasma torch which is the major equipment of ICP device. Torch consists of the three cylindrical coaxial tubes (central tube for the sample carrier-gas introduction, auxiliary tube for the main plasma production and cooling tube for cooling and plasma stabilization).

Fundamental principles of ICP device is as follows. Carrier-gas (Ar) containing liquid or solid sample is injected to the centerline region of auxiliary-gas (Ar) plasma which is generated by RF power input. Auxiliary-gas plasma assists in generating carrier-gas plasma, and coolant-gas (Ar) stabilizes both of the plasmas. The feature of ICP device is that it has the relatively strong spectrum peak by the radiation from ions.

C₆₀, a sample in this experiment, was dissolved (10 ppm) in aniline (C₆H₅-NH₂) by 10 minutes heating, sprayed by nebulizer and radiated in the torch. For the comparison and reference, only aniline liquid was radiated and inspected.
3.4 C₆₀ Plasma Production Using RF Ion Source

Plasma production of sublimated gaseous C₆₀ was attempted using RF ion source. Figure 6 shows the schematic drawing of the RF ion source for the C₆₀ Plasma Production. 3 cm diam. RF ion source for ground use (ION TECH, INC. Model 3RF-1200-100) was reformed in order to install the sublimation chamber. Its frequency is 13.56 MHZ and plasma bridge neutralizer (PBN) was also used. RF discharge chamber (L:50mm, φ:40mm) which is made of quartz glass is wrapped with copper five-turned RF working coil. Argon (Ar) gas was fed to the PBN via mass flow controller.

As shown in table 3, C₆₀ plasma production experiment consists of the following two items.

1. Experiment with Crucible: Based on the obtained data of the sublimation experiment, C₆₀ sublimation and plasma production were attempted. Figures 6 and 7 (a), (b) show the schematics and the configuration of this experiment.

2. Experiment without Crucible: By using the RF heating of the installed metal tip in the discharge chamber, C₆₀ sublimation and its plasma production were attempted. Figure 8 shows the schematics of this experiment.

These two experiments were performed according to the timetable shown in table 4 and the spectrum analysis was conducted.
approximately 4.0 SCCM for first minute, 2.7 SCCM for second minute and 3.4 SCCM in average of these 2 minutes. Considering the C60 sublimation enthalpy 181.4 kJ/mol at 700 K, necessary electrical power for 1 minute's 4.0 SCCM is 0.53 Watts. Comparing with this power, required power in this experiment is remarkable large. This inefficiency of input power is caused by the imperfect of the thermal shield design.

Figure 10 shows the typical results of the FTIR spectrum analysis for the sublimated, collected powder and original powder (refined C60 : containing more than 85 % C60) enclosed in the sublimation chamber. As shown in this figure, typical and featuring spectrum peaks of C60 such as 527.4 cm\(^{-1}\), 576.4 cm\(^{-1}\), 1182.4 cm\(^{-1}\), and 1428.5 cm\(^{-1}\) are revealed in the sublimated powder waveform as well as in the original powder. Moreover, the spectrum peak of the sublimated powder stands out, comparing with the result of the original powder. These seem to be caused by the difference of the sublimation temperature between C60 and other contents (C70, etc.,) and C60 is sublimated without dissociation. Therefore, adequate sublimation chamber enables the supply of the gaseous C60 to the discharge chamber. It is notable that the sublimated C60 returns to the powder state at the discharge chamber wall (re-solidification phenomenon).

NOTE It is reported\(^8\) that C60 molecule absorbs the oxygen molecule (10 % molecular ratio) at room temperature and eliminates it at 420 K. This absorption phenomenon is reversible and full considerations will be necessary for the application of C60 molecule to the hollow cathode by these absorbed and eliminated oxygen molecules.

**IV. Results and Discussions**

### 4.1 Sublimation Experiment

In the "Constant Temperature Experiment", when its representative temperature is approximately 370 K and 420 K, in spite of the pressure rise in the space chamber, the sublimation of C60 was not observed. This phenomenon may be caused by the containing water and extraction solvent : Toluene (C\(_6\)H\(_5\)-CH\(_3\)) in C60 sample and baking process is necessary for the exact sublimation rate measurement. Sublimation temperature is approximately 640 K by the chamber pressure fluctuation (e.g. Chamber pressure changes from 5.2x10\(^{-5}\) Torr to 1.6x10\(^{-4}\) Torr.) and the visual observation of C60 sublimation surface.

On the basis of the "Constant Temperature Experiment" results, "Constant Current Experiment" was conducted with heater current : 2.70 A after 10 minutes' baking process (heater current : 1.50 A, representative temperature : less than 620 K).

Figure 9 shows the relation with heating time : \(t\) and sublimated mass : \(\Delta m\) obtained by the mass changes of following three samples.

1. After baking C60
2. After baking and 1 minute sublimation C60
3. After baking and 2 minutes sublimation C60

The impurities which was discharged from C60 was about 1 % weight of sample. Moreover, mass flow rate by this crucible at 132 Watts input power (2.70 A\times48.9 \, \text{V}) is approximately 4.0 SCCM for first minute, 2.7 SCCM for second minute and 3.4 SCCM in average of these 2 minutes. Considering the C60 sublimation enthalpy 181.4 kJ/mol at 700 K, necessary electrical power for 1 minute's 4.0 SCCM is 0.53 Watts. Comparing with this power, required power in this experiment is remarkable large. This inefficiency of input power is caused by the imperfect of the thermal shield design.

![Fig. 8 RF Ion Source without Crucible](image)

**Table 4 Timetable**

<table>
<thead>
<tr>
<th>(t) [min]</th>
<th>Operation (1)</th>
<th>Operation (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vacuum Chamber (\rightarrow) (10^4) [Torr]</td>
<td>Vacuum Chamber (\rightarrow) (10^4) [Torr]</td>
</tr>
<tr>
<td></td>
<td>PBN Ar Flow (\rightarrow) 4.0 [SCCM]</td>
<td>PBN Ar Flow (\rightarrow) 4.0 [SCCM]</td>
</tr>
<tr>
<td>0</td>
<td>Heater Current (\rightarrow) 1.5 [A]</td>
<td>RF, PBN (\rightarrow) ON</td>
</tr>
<tr>
<td>9</td>
<td>RF, PBN (\rightarrow) ON</td>
<td>RF, PBN (\rightarrow) ON</td>
</tr>
<tr>
<td>10</td>
<td>Heater Current (\rightarrow) 2.7 [A]</td>
<td>RF, PBN (\rightarrow) ON</td>
</tr>
<tr>
<td>12</td>
<td>Heater, RF, PBN (\rightarrow) OFF</td>
<td>RF, PBN (\rightarrow) OFF</td>
</tr>
</tbody>
</table>

**Fig. 9 the relation with heating time : \(t\) and sublimated mass : \(\Delta m\)**

![Fig. 9](image)
4.2 C60 Plasma Production Using ICP Device

Figure 11(a) shows the spectra of the emission from the refined C60 sample and the reference sample. Figure 11(b) shows the waveform of the subtraction (refined C60 minus reference). This subtraction result presents the emission spectrum of the refined C60 and this wavelength (green-orange) was confirmed by the visual observation. Considering the experimental results in sec. 4.1 that C60 sublimation is occurred without dissociation, it seems that this spectrum is caused by the C60 plasma emission.

4.3 C60 Plasma Production Using RF Ion Source

In the "Experiment with Crucible", re-solidification of sublimated C60 was observed\(^9\) and the obtained spectrum shows no changes. Therefore, in this experiment, C60 plasma production was not confirmed. The cause of this result seems that discharge chamber wall temperature, which is less than sublimation temperature, caused the re-solidification and effective gaseous C60 feed to the discharge chamber was not realized. Therefore, to keep the discharge chamber and propellant feed line hot will be necessary.

In the "Experiment without Crucible", as the thin film of C60 attached to the discharge chamber by the re-solidification was very little. The atmosphere over sublimation temperature in the discharge chamber seems to be realized. Figure 12 (a), (b) and (c) show the results of the spectrum analysis. In the range of 670–850 nm, the obtained spectrum (Fig. 12(a)) is almost same as the reference spectrum of PBN Ar plasma (Fig. 12(b)). However, in the range of 620–670 nm and 850–900 nm, the gradients of the waveform are different with the PBN Ar plasma waveform. Spectrum peaks of 750 nm and 820 nm are same one as that of Ar main plasma. As there are only sublimation material and Ar at gaseous state in the space chamber, it seems that these obtained spectrum (Fig. 12(a)) implies the existence of C60 plasma. However, more detailed experiments, inspections and evaluations is necessary.
V. Concluding Remarks

An applicability of C60 which has an attractive properties was evaluated through the investigations and experiments.

1. The results of the performance prediction showed the following advantages by using C60 molecule.

   (1) By using C60 molecule as the propellant of ion thruster, the diminishments of beam current, discharge current and discharge voltage will be achievable. These are related to the remarkable decrease of the required electric power and the improvement of the thruster’s durability.

   (2) The remarkable improvement of the thrust / power ratio (approximately two and half times) will be achievable.

2. Through the sublimation experiments, by the spectrum analysis for the sublimated, collected powder and original powder, typical and featuring spectrum peaks of C60 was revealed in the sublimated powder waveform as well as in the original powder. This seems to be caused by the difference of the sublimation temperature between C60 and other contents (C70, etc.,) and C60 is sublimated without dissociation. Therefore, adequate sublimation chamber enables the supply of the gaseous C60 to the discharge chamber.

3. Through the C60-plasma production experiment by ICP, it seems that the C60 plasma emission spectrum was observed.

4. Through the preliminary estimation of C60 plasma production using RF ion thruster, it seems that the sublimation and plasma production of C60 was achieved by the direct heating in the discharge chamber using RF power.

   However, it is notable that the sublimated C60 returns to the powder state at the discharge chamber wall (re-solidification phenomenon).

   The countermeasure for the re-solidification in the feed line and the discharge chamber will be necessary and the more detailed experiments, inspections and evaluations are necessary.

Fig. 12 IR Spectrum
Acknowledgments

The authors would like to express their sincere thanks to Noriko Ito (Tokyo Metropolitan Institute of Technology) for her valuable technical assistance and Youji Achiba (Tokyo Metropolitan University) for his valuable instruction.

References


2. Personal communication with Vacuum Metallurgical Co., LTD.


4. Personal communication with Achiba, Y., Tokyo Metropolitan University


