Research and Development on Coaxial Pulsed Plasma Thruster with Propellant Feed

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Research and development on pulsed plasma thruster (PPT) for small satellites have been conducting in Tokyo Metropolitan University (TMU). In this study, improvement of total impulse on coaxial PPT was conducted in order to apply it to propulsion systems for small satellites. As a result, total impulse was improved from 3.5N-s to 17.5N-s by modifying thruster head configurations. Moreover, a PPT with propellant feed mechanism named Disk Feed PPT, which changes a used cylindrical propellant for a new propellant, was developed. Disk Feed PPT achieved total impulse of 54.6N-s. Furthermore, latest experiment of Disk Feed PPT showed the total impulse of over 150N-s.

**Key Words:** Electric Propulsion, Pulsed Operation, PTFE, Propellant Feed, Small Satellite

**Nomenclature**

- \( d \) : initial cavity inner diameter
- \( d_c \) : cathode inner diameter
- \( E_0 \) : stored energy
- \( g \) : gravity acceleration
- \( I_b \) : impulse bit
- \( I_{sp} \) : specific impulse
- \( I_{tot} \) : total impulse
- \( l \) : cavity length
- \( n \) : shot number
- \( \Delta m \) : mass shot
- \( \eta_c \) : thrust efficiency

**1. Introduction**

Small satellites are actively developed in the recent space exploration because of its good cost performance, short development period and utilization of advanced technologies. Along with that, compact, lightweight and highly functional propulsion devices are required for them. Pulsed Plasma Thruster (PPT) is one of the electric propulsion devices, which is expected to be applied for small satellites, because of the following features\(^1\)\(^2\):

1. Simplicity; PPT system has a simple and lightweight structure, and high durability, because it does not need any tanks, seals and mechanical valves by using a solid propellant such as poly-tetrafluoroethylene (PTFE).
2. Precise total impulse; PPT can control total impulse easily because it generate accurate and small pulse-thrust at optional time interval.
3. Low power consumption; PPT can operate at several watts.

In Tokyo Metropolitan University (TMU), research and development on two types of PPT for small satellites have been conducting. One is rectangular PPT; the other is coaxial PPT.

PPT-B20\(^3\)\(^4\) is a typical rectangular PPT that has parallel plate electrodes and a breech-fed propellant. The photograph and the thrust performances are shown in Fig. 1 and Table 1, respectively. It has achieved the small impulse bit of 22µN-s with the high specific impulse of 960 s. The power consumption of its all system is only 4.2W at 0.75Hz operation and it has achieved a million shot operations continuously. Recently, the missions for small satellites have been required widely. PPT-B20 is

![Photograph of PPT-B20 system.](image-url)
appropriate to the missions that demand a precise total impulse with a long lifetime, such as attitude control and vibration control. However, its impulse bit is too small to comply with the missions that demand a high $\Delta V$ in time such as station keeping and an orbit transfer.

On the other hand, coaxial PPT with PTFE cavity has achieved larger impulse bit and lower specific impulse compared with rectangular PPT such as PPT-B20 at the same stored energy.\(^5,6\) It will be favorable to comply the missions that demand a high $\Delta V$ in time. The thrust performance ranges of rectangular PPT and coaxial PPT in TMU are shown in Fig. 2. The combination of rectangular PPT and coaxial PPT will enable to achieve various missions.

However, coaxial PPT has the problem of small total impulse as described in the next chapter two. Therefore, we have conducted to improve total impulse with changing cylindrical propellants. And the objectives of this study are as follows.

1) Total impulse improvement of the single thruster head.
2) Development of propellant feed mechanism with high reliability.

### 2. Coaxial PPT

Coaxial PPT consists of four parts as shown in Fig. 3: cylindrical anode, cylindrical cathode with orifice, ignitor, and hollow propellant. The electrodes and the propellant are coaxially arranged, and ignitor is mounted on the cathode. Main discharge current passes and evaporates the cylindrical cavity of the propellant and neutral propellant/plasma was ejected from an orifice of the cathode by electrothermal force mainly. In TMU, the characteristics, the problems, and the approach to total impulse improvement are investigated in various studies as described follows.

#### 2.1. Characteristics\(^5,8\)

The cavity configuration mainly affects the thrust performances. The experiment to estimate the effect of the cavity configuration was achieved. The thruster head named PPT-CoII as shown in Fig. 3 was tested at the stored energy of 10J. The parameters are cavity inner diameter of $d$ and cavity length of $l$, and then cathode inner diameter was same size as initial cavity diameters. The results are shown in Fig. 4. It was confirmed that larger impulse bit was achieved with small and/or long cavity, and higher specific impulse was achieved with large and/or short cavity. Furthermore, thrust efficiency almost depended on the cavity diameter, and the higher thrust efficiency was achieved with small cavity independent of cavity length.

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**Table 1. Thrust performances of PPT-B20 system.**

<table>
<thead>
<tr>
<th>Items</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance, $\mu F$</td>
<td>3</td>
</tr>
<tr>
<td>Charged Voltage, kV</td>
<td>1.5 (Nominal)</td>
</tr>
<tr>
<td>Stored Energy, J</td>
<td>3.3 (Nominal)</td>
</tr>
<tr>
<td>Power Consumption, W</td>
<td>4.2 (Nominal)</td>
</tr>
<tr>
<td>Impulse Bit, $\mu N$-s</td>
<td>22</td>
</tr>
<tr>
<td>Mass Shot, $\mu g$</td>
<td>2.3</td>
</tr>
<tr>
<td>Specific Impulse, s</td>
<td>960</td>
</tr>
<tr>
<td>Thrust Efficiency, %</td>
<td>3.1</td>
</tr>
<tr>
<td>Specific Thrust, $\mu N$/W</td>
<td>6.5</td>
</tr>
</tbody>
</table>

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**Fig. 2. Thrust performance range of rectangular PPT and coaxial PPT.**

**Fig. 3. Cross-section of coaxial PPT (PPT-CoII).**

**Fig. 4. Thrust performance by cavity configuration at 10J**
2.2. Problems

PPT is required the long time operation as the small impulse bit propulsion device in the satellites mission. In order to estimate the lifetime of coaxial PPT, repetitive operation test has been conducted. The thruster head with cavity diameter of 3mm and cavity length of 20mm was estimated in this test. From previous study, it has been considered that impulse bit decreased due to the growth of the cavity diameter because the propellant of coaxial PPT was consumed from inside of the cavity. The results were shown in Fig. 5. Although initial impulse bit was approximately 550μN-s, it gradually decreases to 50μN-s in repetitive operation of 15,000 shots. Moreover, after 10,000 shot, repetitive operation was unsteady because of miss shot, and operation limit was 15,000 shots in this configuration because of deposited material on the narrow orifice of cathode, especially surface of ignitor. As a result, total impulse was also limited only 3.5N-s. Table 2 shows total impulse requirements for some small satellite missions. Total impulse of 3.5N-s, obtained in this study, is too small to be applied to satellite mission if it achieves fine impulse bit. Therefore, coaxial PPT must be improved to achieve larger total impulse. In order to overcome this problem, propellant feed mechanism is the most effective.

2.3. Approach to Total Impulse Improvement

2.3.1 Propellant Feed

As described above, propellant feed was very important to achieve practical total impulse. Two of propellant feed has been considered as shown in Table 3. One is the method to feed the propellant rods, which makes the cavity as a discharge chamber with several rods; the other is the method to change the cylindrical propellants many times. In the former case, since propellant rods are only pushed into the discharge chamber when a part of the propellant is consumed, feed action is very easy. Initial cavity configuration will be kept conceptually and constant thrust performances will be achieved. However, it was actually difficult to maintain the cavity configuration and to provide regular thrust performances. Plasma leakage from seam of the cavity deteriorates its thrust performances. In the worst case, leaked plasma may destroy the structure of this propellant feed mechanism. And if it occurred, coaxial PPT cannot operate any more. On the other hand, in the latter case, when the propellants were utilized until the end of the lifetime, the used propellant is changed to the new propellant. “Changing” is

![Figure 5. Decline of impulse bit in repetitive operation.](image)

Table 2. Small satellite (50kg) missions and required performances.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Total Impulse, N-s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Control (1 year)</td>
<td>150-200</td>
</tr>
<tr>
<td>Drag Free (1year, 400km)</td>
<td>3,000-4,000</td>
</tr>
<tr>
<td>De-orbit (800-200km)</td>
<td>10,000-20,000</td>
</tr>
</tbody>
</table>

Table 3. Type of the propellant feed mechanism and the characteristics.

<table>
<thead>
<tr>
<th>Items</th>
<th>Feeding Propellant Rods</th>
<th>Changing Cylindrical Propellants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept Figure</td>
<td>Feeding Propellant Rods</td>
<td>Changing Cylindrical Propellants</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>Change</td>
</tr>
<tr>
<td></td>
<td>Feed</td>
<td>Cathode</td>
</tr>
<tr>
<td></td>
<td>Thrust</td>
<td>Thrust</td>
</tr>
<tr>
<td></td>
<td>Propellant Rod</td>
<td>Cylindrical Propellant (Used)</td>
</tr>
<tr>
<td>Merit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Thrust performances are steady conceptually.</td>
<td>• Discharge chamber can be refreshed with propellant.</td>
<td></td>
</tr>
<tr>
<td>• Feed action is easy such as follow springs.</td>
<td>• Discharge chamber does not have any seam.</td>
<td></td>
</tr>
<tr>
<td>Demerit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Leaked plasma from the seam of discharge chamber destroys this mechanism.</td>
<td>• Thrust performances are deteriorated gradually.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
a little bit difficult as feed action compared with “feeding” of some rods. The cavity configuration and the thrust performances change while PPT is running. However, the propellant between the electrodes will recover to the initial configuration after changing propellant. And then, as a matter of course, thrust performances will get back to initial performances. Since the propellants have a seamless cavity, destruction of the feed mechanism by plasma leakage never occurs. Moreover, if a propellant has some issues, refreshing the propellant continued repetitive operation. This mechanism has high reliability. Therefore, the latter way; changing cylindrical propellants was adopted in TMU.

2.3.2 Changing Cylindrical Propellant

When “change propellants” was adopted as propellant feed mechanism in TMU, the following three methods are considered for the improvement of total impulse.
1) Increase of the number of propellant change.
2) Life extension of the single thruster head.
3) Improvement of the thrust performances.

![Cross-section diagram of PPT-CoIII.](image)

Table 4. Experimental condition of evaluation of cathode inner diameter.

<table>
<thead>
<tr>
<th>Items</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Inner Diameter, mm</td>
<td>3, 5, 8, 12</td>
</tr>
<tr>
<td>Cavity Diameter, mm</td>
<td>3</td>
</tr>
<tr>
<td>Cavity Length, mm</td>
<td>20</td>
</tr>
<tr>
<td>Capacitance, μF</td>
<td>14</td>
</tr>
<tr>
<td>Charged Voltage, kV</td>
<td>1.2</td>
</tr>
<tr>
<td>Stored Energy, J</td>
<td>10</td>
</tr>
<tr>
<td>Shot Number, shot</td>
<td>500 (Initial Thrust Performance) 15,000 (Impulse Bit History)</td>
</tr>
</tbody>
</table>

![Cross-section diagram of PPT-Co IV.](image)

Table 5. Experimental condition of repetitive operation by single thruster head.

<table>
<thead>
<tr>
<th>Items</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Inner Diameter, mm</td>
<td>12</td>
</tr>
<tr>
<td>Cavity Diameter, mm</td>
<td>1.0, 1.5, 1.5 (l=10, 20, 30)</td>
</tr>
<tr>
<td>Cavity Length, mm</td>
<td>2.0, 2.5, 2.0 (l=30)</td>
</tr>
<tr>
<td>Capacitance, μF</td>
<td>6</td>
</tr>
<tr>
<td>Charged Voltage, V</td>
<td>1.8</td>
</tr>
<tr>
<td>Stored Energy, J</td>
<td>10</td>
</tr>
</tbody>
</table>

3. Experimental Apparatus and Procedure

3.1. Evaluation Test of Cathode Inner Diameter

Thruster head with larger cathode orifice was expected to improve decline of impulse bit in repetitive operation and total impulse. Because following two thruster heads have a great difference in these impulse bit and cathode inner diameters. One is the thruster head with cavity diameter of 8mm and cathode diameter of 8mm; the other is that with cathode diameter of 3mm, which has the cavity diameter extended to approximately 8mm in repetitive operation. They have almost the same cavity configuration, however, the values of impulse bit were 200μN·s and 50μN·s, respectively. For that reason, evaluation tests of cathode inner diameter were conducted. The thruster heads named PPT-CoIII as Fig. 6 was utilized at the stored energy of 10J. Cathode inner diameter was varied from 3mm to 12mm. These cavity configurations were kept at the diameter of 3mm and length of 20mm. In this evaluation, two experiments were conducted at the condition as shown in Table 4. One is the measurement of initial thrust performances to confirm operation and evaluate the effects on the thrust performances. The other is the repetitive operation test of every 15,000 shots to evaluate the deterioration of impulse bit by shot number and total impulse.

Fig. 6. Cross-section diagram of PPT-CoIII.

Fig. 7. Cross-section diagram of PPT-Co IV.
3.2. Repetitive Operation Test by Single Thruster Head

This test was conducted to evaluate the lifetime of the single PPT, which has only one propellant. In other words, in order to utilize cylindrical propellant effectively, maximum shot number at the end of operation were estimated. The thruster heads named PPT-Co IV as shown in Fig. 7 were utilized at the stored energy of 10J. Before repetitive operation test, the minimum initial cavity diameters at each cavity length were evaluated in preliminary test. Cavity inner diameter was varied from 1.0mm to 2.5mm. On the other hand, in the repetitive operation tests, propellants with obtained minimum cavity diameter were utilized. Cavity length was varied from 10mm to 30mm. And cathode configurations were kept at the diameter of 12mm. These experiments were conducted at the condition as shown in Table 5.

3.3. Repetitive Operation Test with the Propellant Feed Mechanism

3.3.1 Disk Feed

Disk Feed PPT is one of the coaxial PPT with propellant change mechanism. Basic concept and photograph of Disk Feed PPT are shown in Fig. 8. Disk Feed PPT consists of the three units: Propellant Disk Unit (PDU), Cathode-Ignitor Unit (CIU) and Step Motor Unit (SMU) as shown in Fig. 8 (a). PDU contains several propellants, an anode, and a propellant case. This part was fixed at the center of the vacuum facility, and was rotated by the motor. CIU, which contains cathode and ignitor, was fixed at the center of the motor. Note that this part has no contact with PDU. Main electrical discharge occurs in the cavity of the propellant between the cathode and the anode. Used propellant was replaced with the new one by rotation of PDU.

In addition to change propellants, Disk Feed PPT has following characteristics. Since Disk Feed PPT can change anode faces contacted with main electrical discharge, it can refresh not only propellants, but also an anode. The propellants are placed radially in PDU. Therefore, Disk Feed PPT can provide multidirectional thrust by addition of CIU. Therefore, Disk Feed PPT has advantage in the satellite mission of attitude control.

3.3.2 Repetitive Operation Test

Repetitive operation test using Disk Feed PPT has conducted as well as that of single thruster head. Disk Feed PPT for this experiment was shown in Fig. 8 (b) and experimental condition was shown in Table 6. Before this test, it was checked whether all propellants was placed in front of the cathode and Disk Feed PPT operated in every case in the vacuum facility.

Table 6. Experimental condition of repetitive operation test by Disk Feed PPT.

<table>
<thead>
<tr>
<th>Items</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Diameter, mm</td>
<td>2.0</td>
</tr>
<tr>
<td>Cavity Length, mm</td>
<td>30</td>
</tr>
<tr>
<td>Cathode Inner Diameter, mm</td>
<td>12</td>
</tr>
<tr>
<td>Propellant Number</td>
<td>8</td>
</tr>
<tr>
<td>Capacitance, µF</td>
<td>6</td>
</tr>
<tr>
<td>Charged Voltage, kV</td>
<td>1.8</td>
</tr>
<tr>
<td>Stored Energy, J</td>
<td>10</td>
</tr>
</tbody>
</table>
3.3.3 Thruster performance

In this study, the impulse bit \( I_b \), the mass shot \( \Delta m \), the specific impulse \( I_{sp} \) and the thrust efficiency \( \eta_t \) were obtained in the measurements of initial thrust performances. And the impulse bit history and the total impulse \( I_{tot} \) were obtained in the repetitive operation tests. The impulse bit was measured by target method\(^{10} \), and mass shot was calculated by averaging the total mass loss through the repetitive operation. Furthermore, the specific impulse and the thrust efficiency were calculated by the following equations, respectively:

\[
I_p = I_b / (\Delta m \cdot g)
\]

\[
\eta_t = I_p^2 / (2 \Delta m \cdot E_0)
\]

where \( g \) and \( E_0 \) are gravity acceleration and the stored energy in capacitors, respectively.

Total impulse was estimated by impulse bit history of repetitive operation. The plots were connected with straight line in the graph, which recorded the value of impulse bit and shot number. Impulse bit from the first shot to the shot number at the first measured point was supposed as constant value. It is so difficult to measure impulse bit at the last shot number that it was extrapolated with the use of the straight line connected last two measured point. Total impulse was estimated by the integration from the area surrounded by the line plot and horizontal axis.

3.3.4 Vacuum facility

All experiments were conducted in a vacuum chamber, and its diameter and length are approximately 1m and 2m, respectively. Through a PPT operation, a pressure in the vacuum chamber was kept at approximately \( 6 \times 10^{-3} \) Pa.

4. Results and Discussions

4.1 Evaluation of Cathode Inner Diameter\(^{9,11} \)

4.1.1 Results of the Initial Thrust Performance

In the previous coaxial PPT, cathode inner diameter of 3mm, which is the same size with the initial cavity diameter, have been employed. Effects on the thrust performances by larger cathode inner diameter were evaluated in this test. The results were shown in Fig. 9.

![Fig. 9](image)

(a) Impulse bit and mass shot vs. cathode inner diameter.

![Fig. 10](image)

(b) Specific impulse and thrust efficiency vs. cathode inner diameter.

\( d_1 = 12 \) mm : \( I_{tot} = 6.1 \) N-s
\( d_2 = 8 \) mm : \( I_{tot} = 5.9 \) N-s
\( d_3 = 5 \) mm : \( I_{tot} = 4.9 \) N-s
\( d_4 = 3 \) mm : \( I_{tot} = 3.5 \) N-s

Fig. 9. Effects of the larger cathode inner diameter for the initial thrust performance.

Fig. 10. Results of repetitive operation test by larger cathode diameter.
Impulse bit was the same or a little bit larger compared with the previous PPT. Instead, however, PPT with larger cathode inner diameter achieved smaller mass shot as shown in Fig. 9 (a). Specific impulse and thrust efficiency were also improved effectively, as shown in Fig. 9 (b). In spite of smaller mass shot, PPT with larger cathode diameter achieved almost the same impulse bit compared with PPT, which had small cathode diameter and achieved larger mass shot. Therefore, PPT with larger cathode diameter was considered to contribute to effective improvement of propellant utilization and acceleration.

4.1.2 Results of the Impulse Bit Histories and Total Impulse

The results were shown in Fig. 10. Impulse bit decline of PPT with larger cathode diameter was obviously smaller than PPT with smaller cathode diameter. As a result, PPT with larger cathode diameter could achieve larger average impulse bit and total impulse. This resulted from the decrease of mass shot, less expansion of cavity diameter, and improvement of propellant acceleration by employment of cathode with larger inner diameter. Moreover, although PPT with smaller cavity diameter of 3-5mm stopped operation because of miss shot within 10,000-15,000 shots, PPT with larger diameter of 8-12mm was operated favorably until 15,000 shots. Therefore, the latter has a potential to operate more shot number and achieve much larger total impulse. In conclusion, it was obvious that the large cathode diameter such as 8mm and 12mm was suitable for the repetitive operation of PPT.

4.2 Repetitive Operation with the Single Thruster Head

4.2.1 Preliminary Experimental Results

In this test, operation limit (as minimum cavity diameter) of initial propellant configuration was decided at each cavity length. In the case of \( l = 30 \text{mm} \), PPT could not operate within the cavity diameter of 1.5mm or less, and the cavity diameter of 2.0mm was minimum diameter which could operate PPT. Therefore, the limiting point should have been between 1.5mm and 2.0mm. In TMU, the cavity diameter of 2.0mm was practically adopted as the minimum cavity diameter at the cavity length of 30mm. In the same way, the cavity diameter of 1.5mm was adopted at the cavity length of 10mm and 20mm. After this experiment, cavity diameter was minimized at each cavity length in all repetitive operation tests.

4.2.2 Repetitive Operation Test

This test was conducted to estimate operation limit (as maximum shot number) caused by increase of the propellant cavity, and to decide outer diameter of the propellants. The results were shown in Fig. 11. Shot number of 60,000 shots was decided as maximum shot number at every cavity length, because charring phenomena was observed in the cavity around operation of 60,000 shots. On the other hand, PPT with the cavity length of 30mm achieved the maximum total impulse of 17.5N-s by a single propellant. And then, the cavity diameter has grown into approximately 11mm. For this reason, the outer diameter of 11mm or more was necessary for that propellant to achieve it.

4.3 Repetitive Operation with the Propellant Change Mechanism

4.3.1 Propellant Change

Disk Feed PPT for this experiment has eight propellants. All propellants could have been set in front of a cathode and Disk Feed PPT operated favorable before the repetitive operation test. In the middle of the test or after the test, it was also possible to change all the propellants. Therefore, it was demonstrated that the propellant change mechanism of the Disk Feed PPT certainly worked in all cases, and have sufficient reliability.

4.3.2 Repetitive Operation Test

Repetitive operation of approximately 150,000 shots was achieved with Disk Feed PPT. Impulse bit history of this test was shown in Fig. 12 and total impulse of 54.6N-s was obtained. This is great achievement on the coaxial PPT with a PTFE cavity. Disk Feed PPT operated approximately 25,000 shots per one propellant and changed propellant several times. On the other hand, as described above, PPT with single thruster head operated 60,000 shots. If these achievements are combined, Disk Feed PPT has possibilities to achieve further shot number of 480,000 shots and total impulse of 140N-s. Moreover, if Disk Feed PPT mounts more propellants; increment of propellants will directly contribute to further shot number and total impulse.

5. Conclusions

Conclusions of this study were as follows:

1) Effects of cathode inner diameter to the thrust performances were evaluated. Initial thrust performances were improved by larger cathode inner diameter of 8-12mm compared with the initial cavity diameter of 3mm.
2) In the case of the single thruster head with large cathode inner diameter less decrease of impulse bit and larger total impulse were achieved at the same shot number
3) Minimum initial cavity diameter was evaluated at each cavity length (10-30mm) at stored energy of 10J
4) Maximum shot number of 60,000 shots was estimated at each cavity length (10-30mm) at the stored energy of 10J.
5) The single thruster head, which has cavity length of 30mm, and initial cavity diameter of 2.0mm, achieved maximum total impulse of 17.5N-s at the stored energy of 10J.
6) Development of propellant feed mechanism with high reliability.
7) Disk Feed PPT was developed as the PPT with propellant change mechanism. It worked in the vacuum and demonstrated its reliability.
8) Disk Feed PPT achieved shot number of 150,000 shots and total impulse of 54.6N-s in repetitive operation test at the stored energy of 10J. Moreover, it was allowed to improve its total impulse.

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References