Research and Development of Osaka Institute of Technology PROITERES Nano-Satellite Series with Electric Rocket Engines

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Abstract: The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology (OIT) in 2007. In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) was successfully launched by Indian PSLV C-21 launcher on September 9th, 2012. The main mission is powered flight of a nano-satellite by an electric thruster. The PPT performance in the 1st PROITERES satellite is confirmed to reach 5.0 Ns with no miss-firing by the ground experiments. Just now, the 1st PROITERES satellite is under operation; that is, the special FM command of PPT firing is transmitted to the satellite from the ground station at OIT. Furthermore, the project of 2nd PROITERES was started in 2010. The 2nd PROITERES satellite is a practical satellite with 50 kg and 500-mm cube; 60 W for earth observation. The 2nd PROITERES satellite has a special performance of powered flight with longer distance, i.e. changing 200-400 km in altitude on near-earth orbits, than that of the 1st PROITERES. We are developing high-power and high-total-impulse PPT systems for the 2nd PROITERES. The 3rd satellite of PROITERES is a 50-kg moon-exploration satellite with a cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. In this paper, we introduce the research and development of PROITERES satellite series and specially electric thrusters onboard them at OIT.

I. Introduction and 1st PROITERES

The Project of Osaka Institute of Technology Electric-rocket-Engine onboard Small Space Ship (PROITERES) was started in 2007[1-19]. In the 1st PROITERES satellite, the main mission is to achieve powered flight of nano-

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satellites by electric thrusters and to observe Kanai district in Japan with a high-resolution camera. We developed Bread Board Model (BBM) and Engineering Model (EM) of the satellite, including electrothermal PPT system, high-resolution camera system, onboard computer system, communication system and ground station, electric power system, attitude control system etc, in 2007-2009. Finally, the development of the satellite Flight-Model (FM) was completely finished in 2010. As shown in **Fig. 1**, the PROITERES satellite was successfully launched on a sun-synchronous orbit of 660 kilometers in earth altitude by PSLV C-21 launcher at Satish Dhawan Space Center (SDSC), Indian Space Research Organization (ISRO) on September 9th, 2012[18-20].

The flight model of the 1st PROITERES satellite is shown in **Fig. 2.** The specification is shown in **Table 1**. The weight is 14.5 kg; the configuration is a 0.29 m cube, and the minimum electric power is 10 W. The altitude is 660 km on sun-synchronous orbit. The lifetime is above one year.

The 1st PROITERES satellite and mass-dummy were carried to SDSC, ISRO by air transportation to Chennai International Airport, India from Kansai International Airport, Osaka, Japan in July 2012, and final checking tests of the satellite were conducted at SDSC, ISRO in July-August 2012. After that, the 1st PROITERES satellite was installed to the PSLV C-21 rocket. Finally, as shown in **Fig. 3** we prayed to Japanese God by Japanese style for success of launch on the satellite deck just before launching.

After success of launch, we received lots of information on satellite interior conditions by Morse signals from the satellite. Just now, the 1st PROITERES satellite is under operation; that is, the special FM command of PPT firing is transmitted to the satellite from the ground station at OIT.

Furthermore, the project of 2nd PROITERES was started in 2010[18-21]. The 2nd PROITERES satellite is a practical satellite with 50 kg and 500-mm cube; 60 W for earth observation. The 2nd PROITERES satellite has a special performance of powered flight with longer distance, i.e. changing 200-400 km in altitude on near-earth orbits, than that of the 1st PROITERES. We are developing high-power and high-total-impulse PPT systems for the 2nd PROITERES. The 3rd satellite of PROITERES is a 50-kg moon-exploration satellite with a cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. In this paper, we introduce the research and development of PROITERES satellite series at OIT.

Figure 1. Launch of PSLV C-21 rocket.
(Photo Courtesy of ISRO)

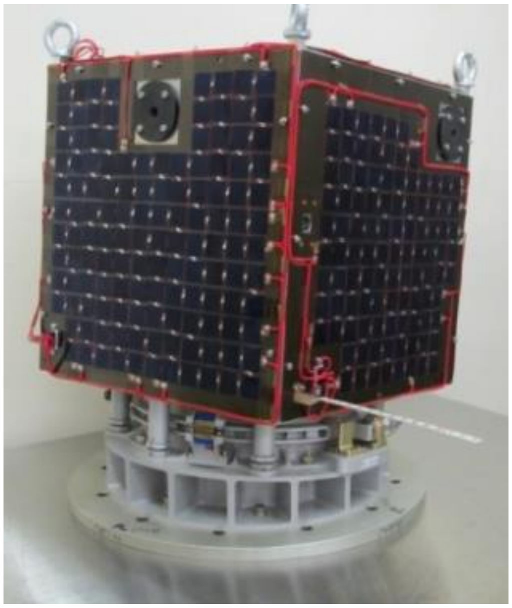


Figure 2. Photo of 1st PROITERES satellite.

Table 1. Specification of 1st PROITERES satellite.

Specifications	Value
Mass	14.5kg
Dimensions	Cube, 290mm on a side
Electrical power	10W
Altitude	660km
Development period	3year
Life time	More than one year
Orbit	Sun-synchronous orbit
Launch vehicle	PSLV C-21

Figure 3. 1st PROITERES Satellite on PSLV C-21 satellite deck and Japanese style praying for success of launch.

II. Electrothermal Pulsed Plasma Thrusters for 1st and 2nd PROITERES Satellites

Pulsed plasma thrusters, as shown in **Fig. 4**, are expected to be used as a thruster for small/nano satellites. The PPT has some features superior to other kinds of electric propulsion. It has no sealing part, simple structure and high reliability, which are benefits of using a solid propellant, mainly Teflon® (poly-tetrafluoroethylene: PTFE). However, performances of PPTs are generally low compared with other electric thrusters[22-27].

At Osaka Institute of Technology, the PPT has been studied since 2003 in order to understand physical phenomena and improve thrust performances with both experiments and numerical simulations. We mainly studied electrothermal-acceleration-type PPTs, which generally had higher thrust-to-power ratios (impulse bit per unit initial energy stored in capacitors) and higher thrust efficiencies than electromagnetic-acceleration-type PPTs. Although the electrothermal PPT has lower specific impulse than the electromagnetic PPT, the low specific impulse is not a significant problem as long as the PPT uses solid propellant, because there is no tank nor valve for liquid or gas propellant which would be a large weight proportion of a thruster system.

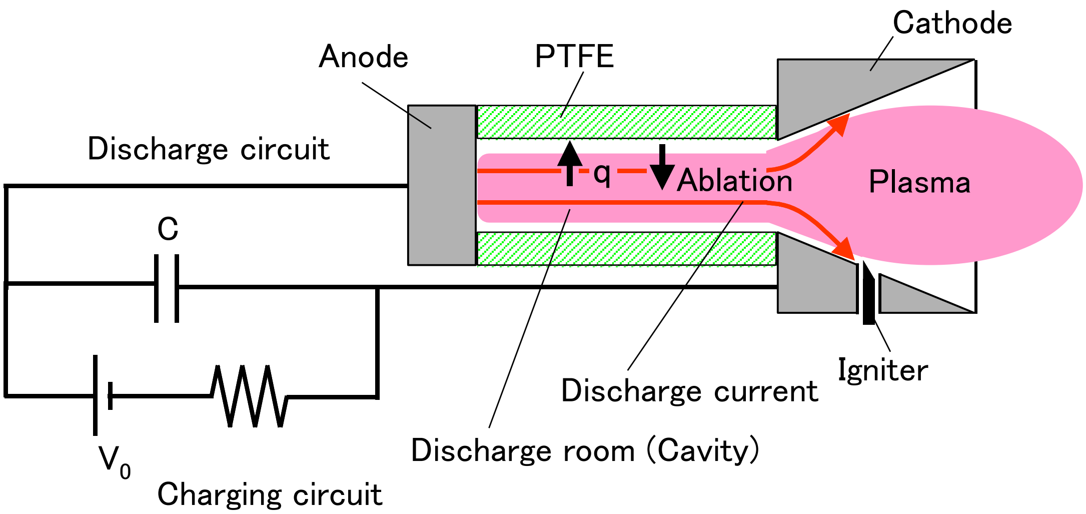


Figure 4. Electrothermal pulsed plasma thruster.

III. PPT Systems for 1 st and 2 nd PROITERES Satellites

A. PPT of 1st PROITERES

Figure 5 shows the shot-number history of impulse bit, mass loss, specific impulse and thrust efficiency with operational of 2.43 J/shot and 1Hz Both the impulse bit and the mass loss, as shown in Fig. 5(a), rapidly decrease with increasing shot number. Specially, the impulse bit decreases from 250 μNs at initial condition to 75 μNs after about 50,000 shots. Although a few miss fires occurred around 53,000-shot, a total impulse of about 5 Ns was achieved. As shown in Fig. 5(b), the specific impulse increases with increasing shot number, and the thrust efficiency is around 0.2 during the repetitive operation.

The cavity diameter, as shown in **Fig. 6**, increases from 1.0 mm to about 6.0 mm of the anode diameter after 50,000 shots. The discharge feature, as shown in **Fig. 7**, changes from a long plasma plume with intensive emission light at 1-10,000 shots to a very short plume with weak emission. This is expected because of lowing pressure and ionization degree in the cavity when enlarging cavity diameter.

We designed the flight model of a PPT head and its system. **Figures 8 and 9** show the structure, illustrations, and photos. The PPT head has a simple structure, and two PPT heads are settled on the outer plate of the 1st PROITERES satellite. As shown in Fig. 9(b), the power processing unit and the 1.5-μF capacitor are mounted in the satellite. The final endurance test of the PPT system was successfully finished with operational condition shown in **Tables 2-4**. Accordingly, 2-head PPT system will be operated with a practical scheme shown in **Fig.10**.

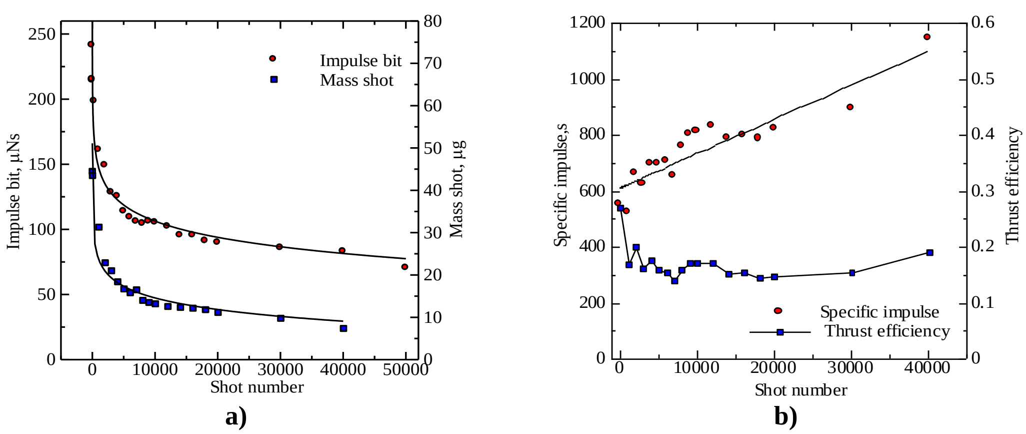


Figure 5. Results of endurance test.
a) Impulse bit and mass shot, b) specific impulse and thrust efficiency

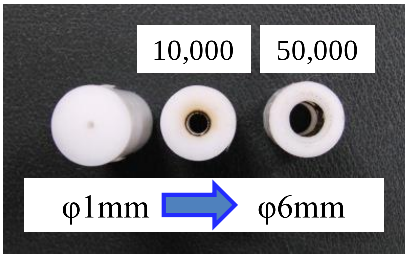


Figure 6. Change of cavity diameter before and after 50,000-shots.

a) b)
Figure 7. Feature of plasma plume.
a) 1-10,000 shots, b) 50,000shots.

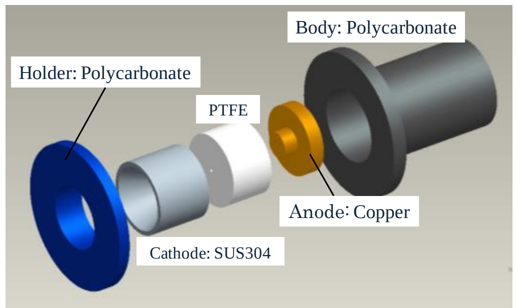
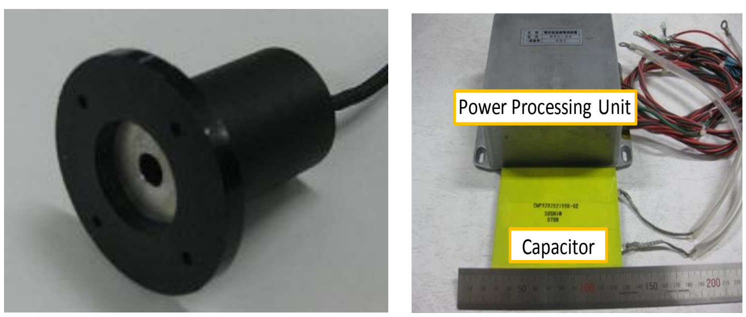


Figure 8. Inner structure of PPT head.



a) b)
Figure 9. PPT flight-model parts.
a) Photos of PPT head, b) Power processing unit and 1.5-μF capacitor of flight model of PPT

Table 2. Specification of PPT head FM.

Items	PPT
Mass	138 g
Size	30(h) x 50(w) x 40(d) mm
Cavity length	10 mm
Cavity diameter	1.0 mm
Ignitor hole diameter	3.0 mm
Ignitor hole position	3.0 mm
Nozzle length	19 mm
Nozzle diameter	5.7 mm
Nozzle half angle	20 deg
Material propellant	PTFE
Material anode	Cu
Material cathode	SUS304
Material body	Polycarbonate

Table 3. Specification of power processing unit FM.

Items		PPU
Mass		710 g
Size		100 x 100 x 50 mm
Power Consumption		5 W
Input Voltage		DC 12 V±10 %
Charge Time		1.0 sec
Output Voltage	to CAP	1.8 kV
	to Ignitor	2.25, 2.7 kV
Operating Frequency		Optional

Table 4. Specification of capacitorfor PPT system FM.

Max Voltage	Capacitance	Mass	Inductance
4.0 kV DC	1.5 μF	188 g	44.0 nH

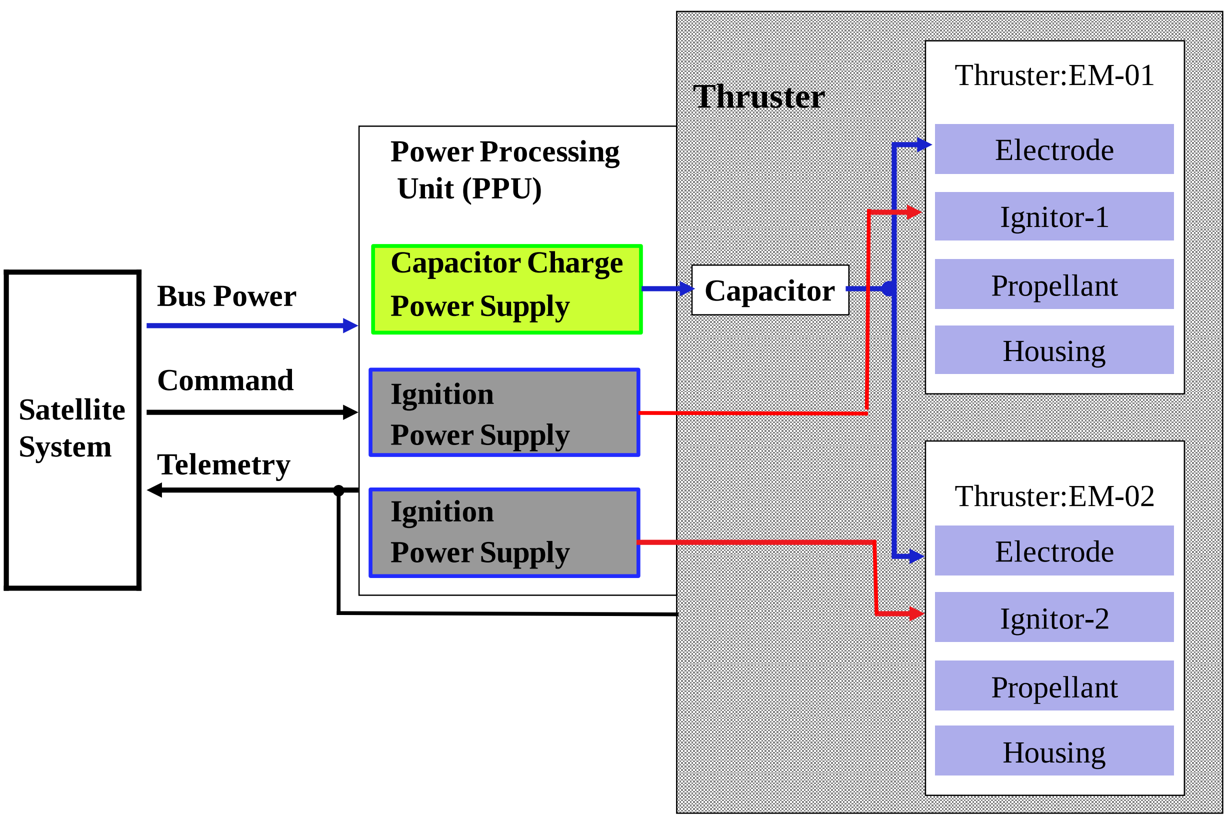


Figure 10. Operational diagram of PPT system FM.

B. PPT of 2nd PROITERES

The research and development of the 2nd PROITERES satellite with high-power and large-total-impulse PPT system are introduced. The image of the satellite is shown in **Fig. 11**, and the specification is shown in **Table 5**. The 2nd PROITERES satellite is a practical satellite for earth observation. The mass of the satellite is 50 kg, and the shape is a 500-mm cube; the electric power is 62 W.

In the 2nd PROITERES satellite, a large orbital change of 400 km in distance or long-time orbital keeping on super low-earth orbits is planned for de-orbit and high-resolution observation. A total impulse of 10000 Ns is required for these missions. Therefore, we cannot use the PPT system onboard the 1st PROITERES satellite; that is, the charging energy must be enlarged to 32.4J from 2.43J. The changes are shown in **Table 6**. Furthermore, because the total impulse obtained from one cavity (one discharge room) is about 120 to 150 Ns, a new PPT system with which a long-term operation is possible is needed for 400 km orbital transfer. In order to establish a long-term operation, a fuel-supplying-type PPT, as shown in **Fig. 12**, was made in this study. When the PPT head has an electric discharge room with two Teflon (PTFE) bars; that is, a propellant of Teflon is supplied from both sides. However, when the inner surface of a discharge room (Teflon tube) was eroded axially-unevenly, the air-tightness of the discharge room collapsed, and an outer-flow of plasma occurred. Therefore, this structure and system of propellant supply is unsuitable for long operation. Accordingly, we designed a new PPT system with multi-electric discharge rooms. The schematic view is shown in **Fig.13**, and the structure is shown in **Figs.14 and 15**.

In order to design multi-discharge-room-type PPTs, it is necessary to optimally design only one electric discharge room. For that reason, discharge-room shape was changed, and initial performance characteristics were investigated. **Figures 16 and 17** show impulse bit and specific impulse, respectively, as a function of cavity length (discharge room length) with cavity diameters of 3, 4 and 5 mm.

We measured the initial performance with 350 shots. When discharge room diameter was 2mm or less, operation of 350 shots did not succeed. This is expected because a tube hole was blocked with eroded Teflon during 350 shots. Finally, we selected 4.0 mm in diameter and 25 mm in length as a preferable structure of discharge room; that is, the highest impulse bit was 1912 μNs, with a specific impulse of 385 sec.

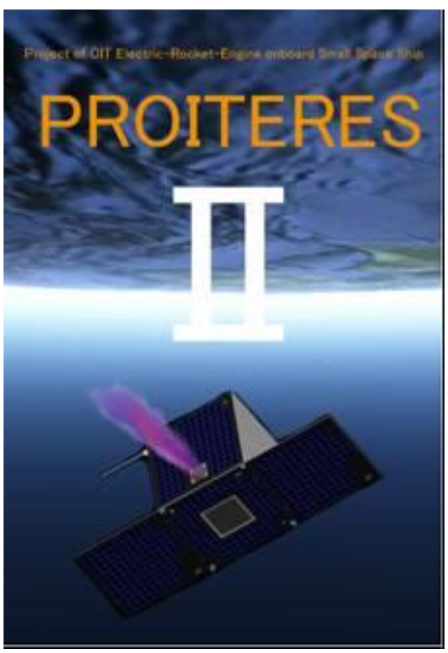


Figure 11. Illustration of 2nd PROITERES.

Table 5. Specification of 2nd PROITERES satellite.

Specifications	Value
Mass	50kg
Dimensions	Cube, 500mm on a side
Electrical power	62W
Development period	3year
Life time	More than one year
Launching due date	2015-2006
Main missions	Environmental observation with a loading camera Long-distance power flight

Table 6. Changes of PPT system.

	1st PROITERES	2nd PROITERES
Capacitance [μF]	1.5 μF	20.0 μF
Stored energy [J]	2.43 J	32.4 J

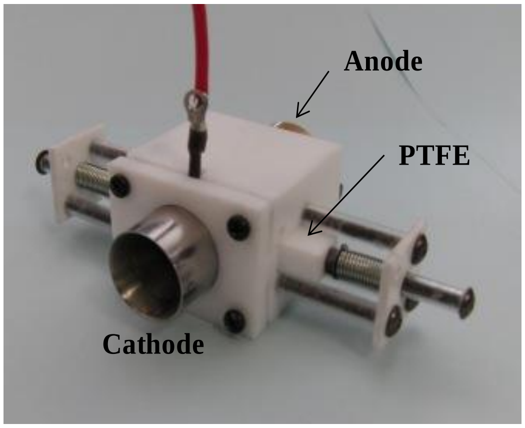


Figure 12. Fuel-supplying- type PPT.

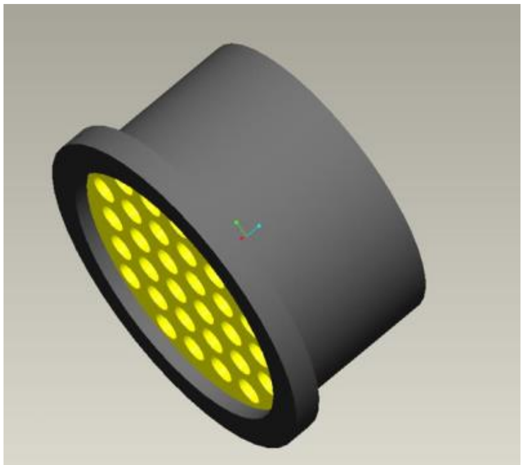


Figure 13. PPT with multi-discharge room.

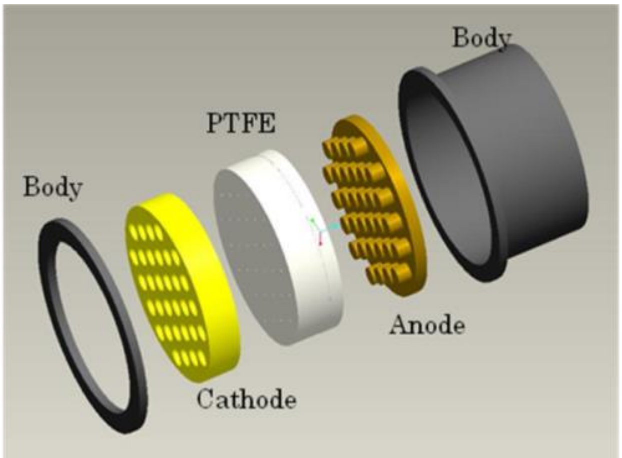


Figure 14. Structure of multi-discharge-room PPT.

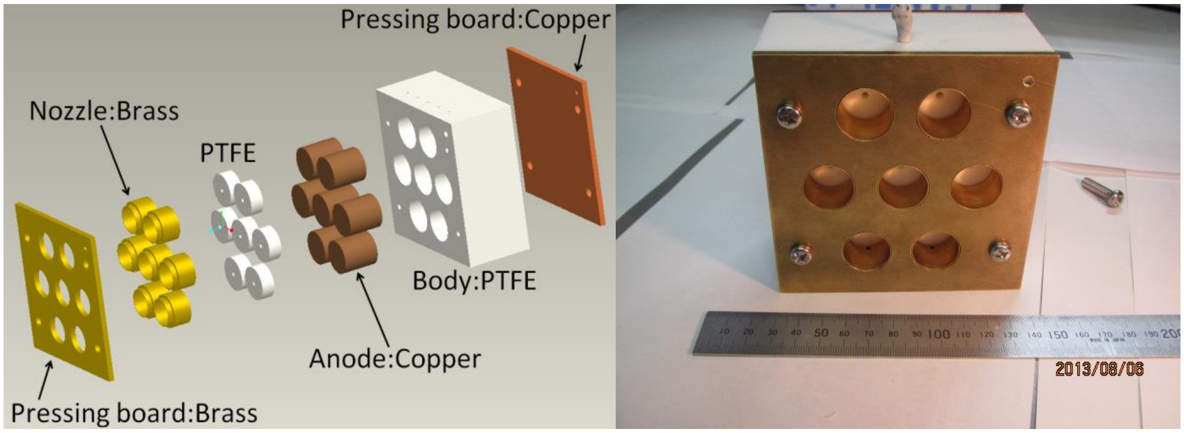


Figure 15. Structure of laboratory-model multi-discharge-room PPT.

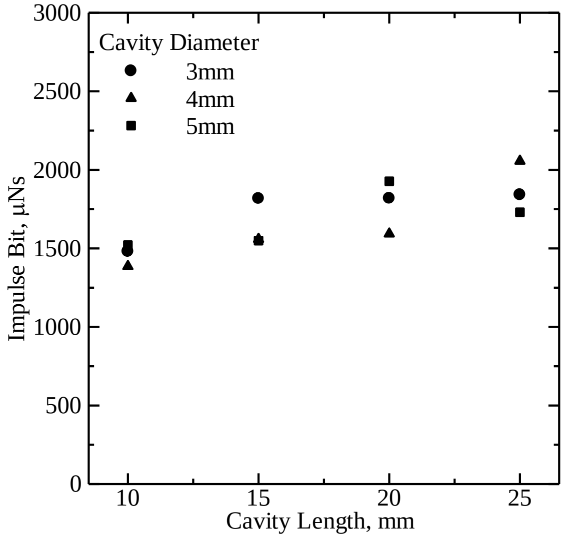


Figure 16. Impulse bit vs cavity length.

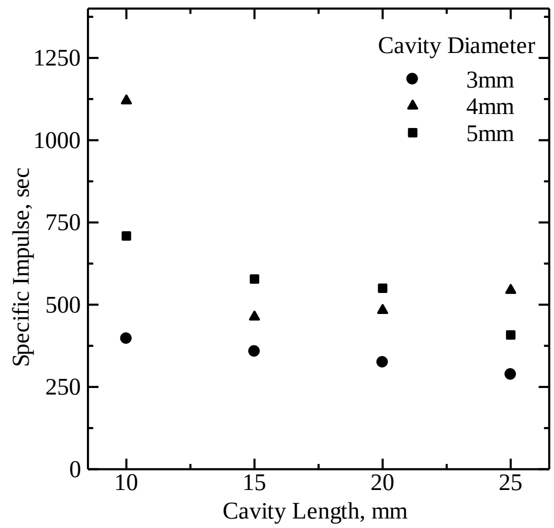


Figure 17. Specific Impulse vs cavity length.

IV. Hall Thruster for 3rd PROITERES Satellite

The 3rd satellite of PROITERES[28-30] series is a 50-kg moon-exploration satellite with cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. That is very exciting mission. The Hall thruster system will produce specific impulses of 1500-2000 sec at xenon mass flow rates of 0.1-0.3 mg/s with an input power of 30 W. The trip time to the moon is within 3 years.

We developed an original low-power CHT named TCHT-4 in which permanent magnet is used in exchange for inner coils. The optimized TCHT-4 had a high efficiency of 30.1% at an input power of 55.5W; the thrust was 0.9 mN, and the specific impulse was 1864 sec. However, TCHT-4 had unstable operation at 170 sec, and significant performance degradation. This is because the inner permanent magnet was degraded by discharge room's overheating. Therefore, we developed a new CHT named “TCHT-5” in which discharge room length and magnetic poles length can be changed. The performance characteristics of TCHT-5 are measured.

Figures 18 and 19 show the TCHT-5 Hall thruster. The anode is located at the upstream end of the circular cross-sectional part. The discharge chamber is made of boron nitride (BN), and the inner diameter is 14mm. TCHT-5 can change the anode position and discharge room length by an inside screw. In TCHT-5 Sm-Co permanent magnets are employed because the degradation of magnetic property by heating is relatively small. The magnetic field has an axial component, and the strength is the highest near the anode located at the upstream region. The discharge room length is 7 mm, and the maximum magnetic flux density is 184 mT. **Figures 20 and 21** show the characteristics of the specific impulse and the thrust efficiency, respectively, as a function of input power. When the mass flow rate is 0.6 mg/s, both the specific impulse and thrust efficiency have high performance in 50-60W range. Especially, when the magnetic poles length is 12mm, the specific impulse and thrust efficiency are higher 20% performance than other length.

As a result, a stable operation was achieved, and the minimum input-power operation of TCHT-5 had a specific impulse of 648.3 sec with 57.3W, and also thrust efficiency was 22.1%. TCHT-5 was lower performance than TCHT-4; it is considered to be insufficiently ExB drift in the discharge room, because the radial magnetic field is weaker than expected. In the future, the optimal magnetic field strength condition will be necessary to be examined.

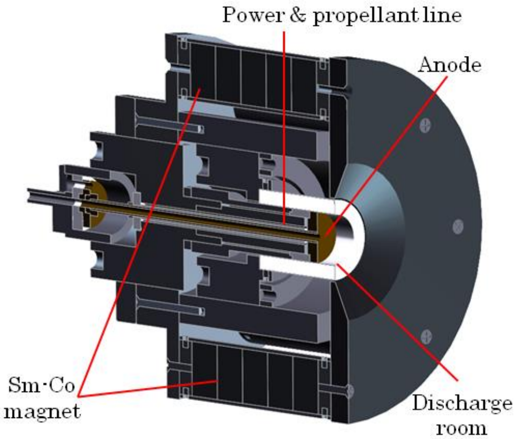


Figure 18. Cross-sectional view of TCHT-5.

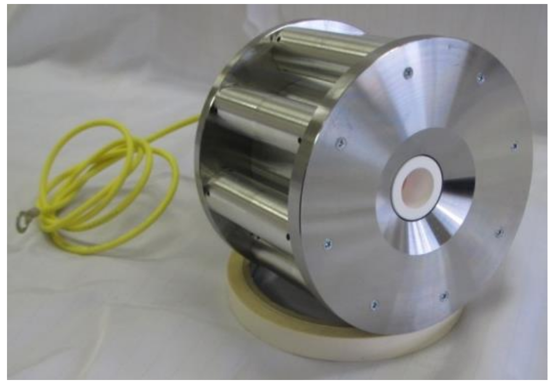


Figure 19. Photo of TCHT-5.

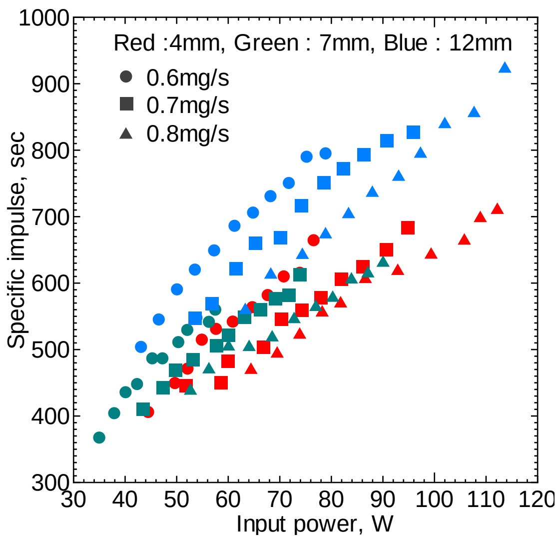


Figure 20. Specific impulse vs input power.

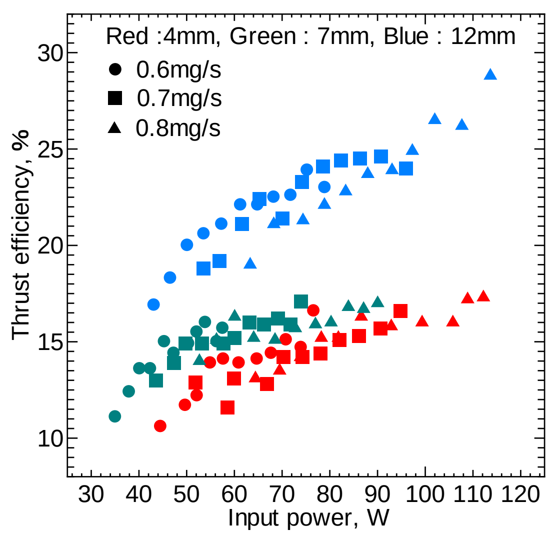


Figure 21. Thrust efficiency vs input power.

V. Conclusion

In this paper, we introduce the research and development of PROITERES satellite series and specially electric thrusters onboard them at OIT.

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology (OIT) in 2007. In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) was successfully launched by Indian PSLV C-21 launcher on September 9th, 2012. The main mission is powered flight of a nano-satellite by an electric thruster. The PPT performance in the 1st PROITERES satellite is confirmed to reach 5.0 Ns with no miss-firing by the ground experiments. Just now, the 1st PROITERES satellite is under operation; that is, the special FM command of PPT firing is transmitted to the satellite from the ground station at OIT.

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The 3rd satellite of PROITERES is a 50-kg moon-exploration satellite with a cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. An original cylindrical Hall thruster is under development for that exciting mission.

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