

Numerical Calculation of Electrothermal Pulsed Plasma Thrusters by One-Dimensional Flowfield Model

IEPC-2017-108

*Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017*

Koki Ryuho¹, Ryota Fujita², Keita Kanaoka³, Kohei Ono⁴, Naoki Morikawa⁵, Kosuke Enomoto⁶,
Hirokazu Tahara⁷ and Kyoko Takada⁸
*Department of Mechanical Engineering, Osaka Institute of Technology
5-16-1, Omiya, Asahi-Ku, Osaka 535-8585, Japan*

Tobias Haase⁹
*Universität der Bundeswehr München
Werner-Heisenberg-Weg 39, 85577 Neubiberg, München, Germany*

and

Takashi Wakizono¹⁰
High-Serve Inc., 780-7, Tomehara, Akiruno, Tokyo 190-0152, Japan

Abstract: The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. The 2nd PROITERES nano-satellite with high-power electrothermal pulsed plasma thrusters (PPTs) for orbit changing of 50 – 100 km in altitude on near-earth orbit was determined to be launched as piggyback payloads (main satellites: GOSAT-2 and Khalifasat) by H-IIA rocket from JAXA Tanegashima Space Center in July 2018. In this research, a 30 W class electrothermal PPT system was developed by experimental and numerical calculation. However, it is difficult to analysis time-dependent phenomena by experiment because the electric discharge terminated in a very short time of 10 - 20 μ s. Therefore, we numerically predict their performances by calculation for mission planning. Thus, an unsteady simulation code has been developed for electrothermal PPT system. In the present paper, we examine the interior physical phenomena and performance characteristics by numerical calculation. As an

¹ Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp .

² Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.

³ Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.

⁴ Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.

⁵ Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.

⁶ Graduate Student, Major in Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.

⁷ Professor, Department of Mechanical Engineering, and hirokazu.tahara@oit.ac.jp.

⁸ Associate professor, Department of Intellectual Property, and kyoko.takada@oit.ac.jp.

⁹ Graduate Student, Faculty of Electrical Engineering and Information Technology, and hirokazu.tahara@oit.ac.jp.

¹⁰ Researcher, Electric Propulsion R&D Section, and wakizon@kch.biglobe.ne.jp.

experimental result, the PPT generated total impulse of 92 Ns with 100,000 shots at 31.59J. The calculated performance roughly agreed with experimental one with errors less than 6.1%.

Nomenclature

A	= cross sectional area
C	= capacitance
e	= total energy
E_i	= ionization energy
j	= current density
J	= current
k	= Boltzmann constant
K	= heat conductivity
L	= electric inductance and cavity length
L_{noz}	= nozzle length
L_{cir}	= length of the cavity cross section
m	= the ratio of mass of solid atom
M	= the ratio of mass of gas atom
n	= number density
p	= plasma pressure
p_c	= characteristic pressure
p_{vap}	= equilibrium vaporizing pressure
q	= fluxes
Q	= electric charge and energy
Q_{ab}	= thermal energy of ablated PTFE
Q_{conv}	= convection energy loss
Q_j	= energy of joule heating
Q_{rad}	= emission energy of breaking radiation
Q_{rec}	= energy due to surface recombination
$Q_{rec,in}$	= surface recombination into PTFE
r	= radial distribution
r_c	= typical cavity radius (2.0 mm)
R	= resistance
T	= plasma temperature
T_c	= characteristic temperature
u	= axial velocity
α	= energy accommodation coefficient
ϕ	= the potential drop in the sheath
Φ	= energy dissipation due to velocity
ΔH	= unzipping energy
γ	= specific heat ratio
Γ	= ablation flux
η	= plasma resistivity
κ	= thermal conductivity of the solid PTFE
φ	= flux
Θ	= temperature inside the solid propellant
ρ	= mass density
ρ_0	= density of the solid PTFE
τ_0	= frictional stress on the surface
Subscripts	
c	= capacitor
e	= electron
h	= heavy particle
i	= ion
n	= neutral particle

p = plasma
 s = surface
 $tran$ = transfer
 w = near the PTFE surface (Knudsen layer)

I. Introduction

IN recent years, micro/nano satellites has been actively developed at universities and companies because the development of micro/nano satellites enable us to reduce costs and the development time. Since 2007, researchers at Osaka Institute of Technology (OIT) have been developed nano-satellites with electric propulsions on the Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES). Currently, it has carried out the research and development of 2nd PROITERES, which determined to be launched as piggyback payloads by H-IIA rocket (main satellites: GOSAT-2 and Khalifasat) from JAXA Tanegashima Space Center in July 2018. The main mission of the 2nd PROITERES nano-satellite is to achieve powered flight by electrothermal PPT systems.^{1,4} This research aims to develop 30 W class PPT system by numerical calculation and experiment.

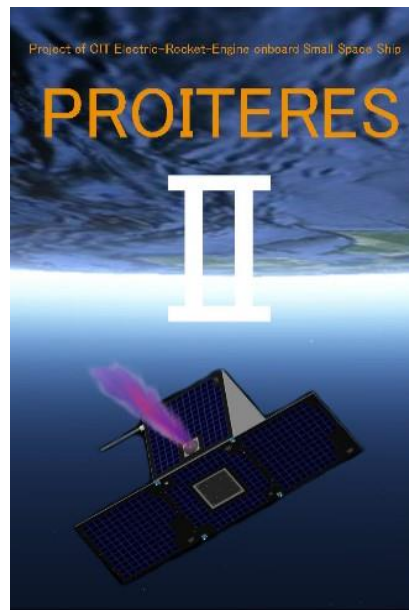


Figure 1. Illustration of the 2nd PROITERES nano-satellite.

Table 1. Specification of the 2nd PROITERES nano-satellite.

Mass, kg	50
Dimensions, mm	480 x 480 x 410
Electrical power, W	60
Altitude, km	400 – 800
Life time, years	1 – 2

II. Pulsed Plasma Thrusters

The Pulsed Plasma Thrusters (PPTs) are pulsed-operation electric propulsion, are expected to be used as a main thruster for a micro/nano satellites. The PPT has some features superior to other electric propulsions. It is no necessary sealing parts and valves. As a result, PPTs have simple structure and high reliability, using solid propellants, mainly PTFE (polytetrafluoroethylene: Teflon®). In addition, since it is easy to digitally control the ON-OFF control circuit for pulse operation, and it can operate with low power consumption. So it is suitable thruster for a micro/nano satellite such as 2nd PROITERES satellite. There are two kinds of PPTs, electromagnetic-acceleration-type and electrothermal-acceleration-type due to the difference in acceleration principle.^{2,3} It describes each of the summary in the next section.

A. Electromagnetic Pulsed Plasma Thruster

The representative PPT is an electromagnetic-acceleration-type with electrode geometry of parallel shape, as shown in Figure 2. The electromagnetic PPT accelerates the plasma by the induced magnetic field generated by the main discharge and Lorentz force generated by the main discharge current. The electromagnetic PPT has been often developed as a thruster for small satellite. Because the electromagnetic PPT's small impulse bit is suitable for altitude control and position control of the satellites. However, since the impulse bit is lower than electrothermal PPT to be described later, impulse bit is insufficient as the main thruster of the satellite.

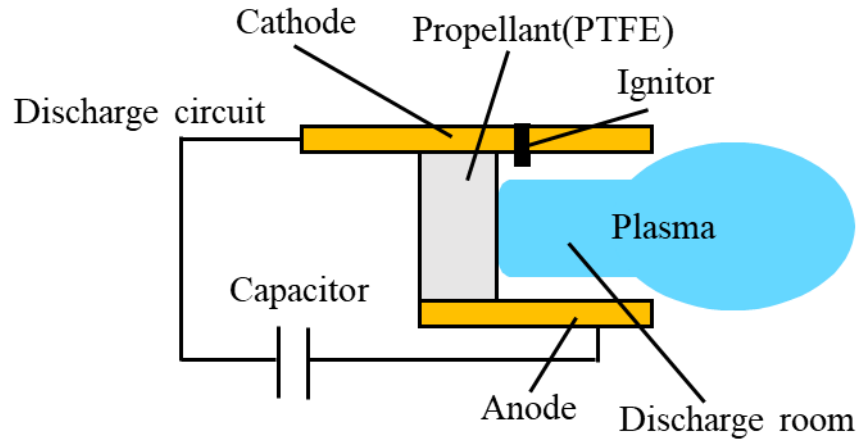


Figure 2. Schematic of the electromagnetic pulsed plasma thruster.

B. Electrothermal Pulsed Plasma Thruster

The electrothermal-acceleration-type PPT shown in Figure 3 has electrode geometry of coaxial shape. The electrothermal PPT accelerates the plasma by joule heating and radiation by main discharge. Compared with electromagnetic PPT, the impulse bit is high, so it is suitable for main thruster of the satellite.

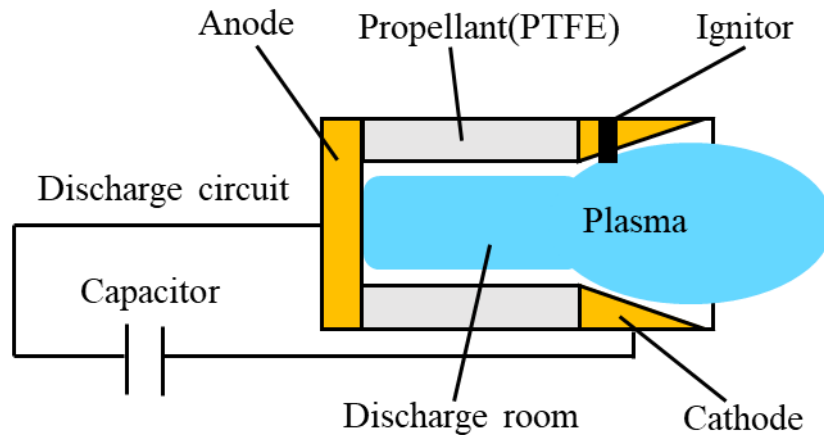


Figure 3. Schematic of the electrothermal pulsed plasma thruster.

III. Experimental Apparatus

In present paper, it explains experimental facility to compare of thrust performance results between experimental and numerical calculation. Figure 4 shows the thrust stand in the vacuum chamber to accurately measure the thrust performance of the PPT at OIT. The PPT and the capacitors are mounted on the pendulum, which rotates around fulcrums of two knife edges without friction. The displacement of the pendulum is measured by an eddy-current-type

gap sensor (non-contacting micro-displacement meter) near the PPT. The electromagnetic damper is used to suppress mechanical noises and to decrease quickly the amplitude for the next measurement after operating the PPT. It is useful for a sensitive the thrust stand because it is non-contacting. The damper consists of a permanent magnet fixed to the pendulum and two coils fixed to the supporting stand. The control circuit differentiates the output voltage of the displacement sensor and supplies the current proportional to the differentiated voltage to the coil. Accordingly, the damper acts as a viscosity resistor. The damper is turned off just before operating the PPT for measurements without damping, and turned on after the measurement to prepare for the next measurement.

The vacuum chamber (Figure 5) is 1.25 m in length and 0.6 m in inner diameter, which is evacuated using a turbo-molecular pump (Figure 6) with a pumping speed of 3,000 L/s and two rotary pumps (Figure 7) with a pumping speed of 125 L/s. The pressure is kept below 0.026 Pa during the PPT operation.^{2,3}

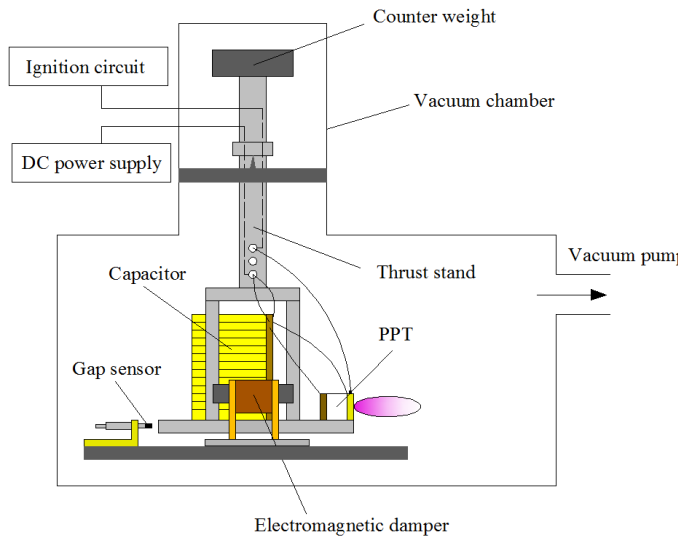


Figure 4. Thrust stand installed in the vacuum chamber.



Figure 5. Vacuum chamber.



Figure 6. Turbo-molecular pump.



Figure 7. Rotary pumps.

IV. Numerical calculation model

PPT's performances are difficult to analyse time dependent phenomena by experiment because the electric discharge terminates were finished in a few time like 10-20 μ s. Thus, an unsteady simulation has been developed for calculating thrust performances of electrothermal PPT. Figure 8 shows a schematic of the numerical calculation model

of the electrothermal PPT for this research. The calculation simultaneously simulates unsteady phenomena of discharge circuit, heat transfer to the PTFE, heat conduction inside the PTFE, ablation from the PTFE surface and plasma flow. The discharge circuit is modelled as a LCR series circuit including the plasma resistance. The LCR series circuit, which is solved by the Runge-Kutta-Method, is used to close the equation system. Then, the boundary conditions are applied and the whole equation system is solved through a combination of the TVD-MacCormack scheme and average Roe method.

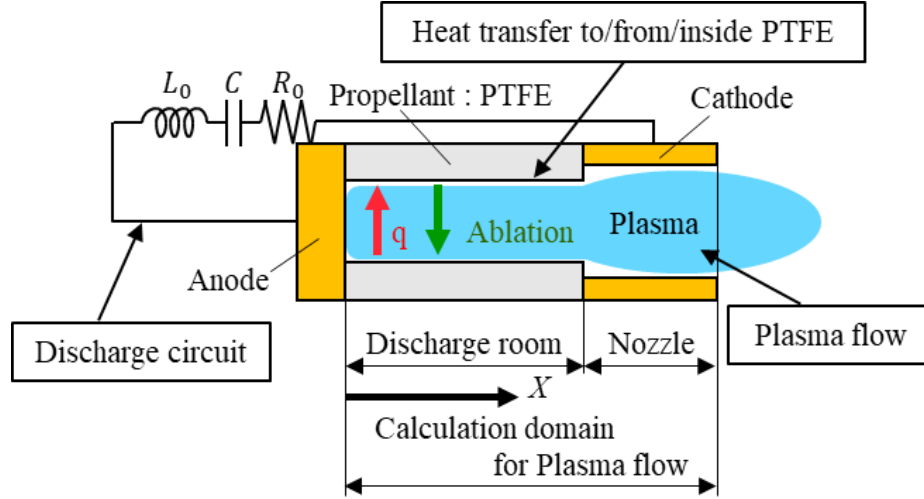


Figure 8. Schematic of the present calculation model.

A. Assumptions

The calculation model consists of one-dimensional plasma flow, main discharge circuit (LCR circuit), heat supply to PTFE, and heat conduction inside PTFE. The calculation domain of fluid analysis is a cylindrical discharge room surrounded by a cathode, a nozzle part and PTFE. The shape and length of the discharge room and the nozzle part were appropriately changed according to the operating conditions. Assumptions for the present numerical calculation model are given as follows.⁵⁻⁷

- 1) Ionization equilibrium (Saha's equation is used).
- 2) Only single ionization.
- 3) One-fluid plasma flow.
- 4) Effects of magnetic field are not considered.
- 5) Local thermodynamic equilibrium (LTE) is established in the plasma.

$$T_e = T_h = T \quad (1)$$

However, near the propellant surface, LTE is not established, and the following inequality is satisfied:

$$T_s < T_{h,w} < T_{e,w} = T \quad (2)$$

- 6) Total pressure and electron number density are assumed to be radially constant:

$$p = (2n_e + n_n)kT = (n_e T + n_e T_{h,w} + n_{n,w} T_{h,w})k \quad (3)$$

As for the assumption 5), Figure 9 shows a schematic of temperatures of electrons and heavy particles near the propellant surface. Energy-transfer mean free path of electrons λ_{eE} is much longer than that of heavy particles λ_{hE} because of the great difference in mass between electrons and heavy particles. For example, λ_{eE} is a few millimeters and λ_{hE} a few microns, if number densities of both electron and neutral are 10^{24} m^{-3} . Then, electrons moving toward the surface hardly lose their energy until colliding with the surface, and a temperature jump on the order of $(T - T_s)$ is generated on the surface. As for heavy particles, temperature jump $(T_{h,w} - T_s)$ is determined, assuming conservation of heat flux at the surface of the Knudsen layer as shown below.

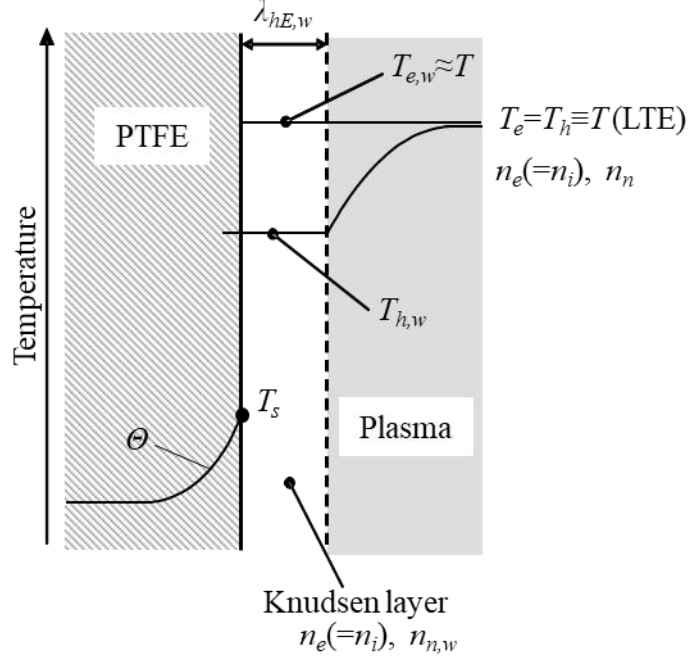


Figure 9. Schematic of temperature of electrons and heavy particles.

B. Plasma flow

Axial components of mass, momentum and energy conservations considering distribution of cross-sectional area of cavity are as follows:

$$\frac{\partial(A\rho)}{\partial t} + \frac{\partial(A\rho u)}{\partial x} = L_{cir}\Gamma \quad (4)$$

$$\frac{\partial(A\rho u)}{\partial t} + \frac{\partial}{\partial x}[A(\rho u^2 + p)] = p\frac{\partial A}{\partial x} - \tau_0 L_{cir} \quad (5)$$

$$\begin{aligned} \frac{\partial(Ae)}{\partial t} + \frac{\partial}{\partial x}[Au(e + p)] \\ = A(Q_j - Q_{rad} - Q_{conv} - Q_{rec} + Q_{ab} - \Phi) \end{aligned} \quad (6)$$

where A is cross-sectional area, L_{cir} is circumferential length of the cavity cross section, ρ is mass density, Γ is ablation mass flux, u is average velocity in a cross-section, p is pressure, τ_0 is frictional stress on the surface, Φ is energy dissipation due to viscosity, and e is total energy: $p/(\gamma - 1) + \rho u^2/2$. The specific heat ratio γ is assumed to be a constant, 1.1. The energy of joule heating is Q_j , emission energy loss of bremsstrahlung (braking radiation) is Q_{rad} , energy loss due to heat transfer to the surface is Q_{conv} , energy loss due to surface recombination to the PTFE is Q_{rec} and thermal energy of ablated PTFE is Q_{ab} .

C. The energy of joule heating

The energy of joule heating Q_j is written as follows:

$$Q_j = \eta \cdot j^2 \quad (7)$$

where η is plasma resistivity, j is current density. Plasma resistivity η is calculated with the following equation, considering electron collision with both ion and neutral:

$$\eta = \frac{\ln \Lambda}{1.53 \times 10^{-2} T^{3/2}} + \frac{m_e}{n_e e^2} \cdot \sigma_{e-n} n_n \left(\frac{3kT}{m_e} \right)^{1/2} \quad (8)$$

where σ_{e-n} is cross-sectional area of electron-neutral, and $\ln \Lambda$ the Coulomb logarithm.

D. Emission energy loss of bremsstrahlung

Emission energy loss of bremsstrahlung (braking radiation) Q_{rad} is written as follows:

$$Q_{rad} = 1.57 \times 10^{-40} n_e^2 T^{1/2} \quad (9)$$

E. The temperatures of near the propellant surface

Electron flux φ_e , ion flux φ_i and neutral flux φ_n toward the propellant surface are written as:

$$\varphi_e = \varphi_i = \frac{1}{4} n_e \left(\frac{8kT_{h,w}}{\pi m_i} \right)^{1/2} \quad (10)$$

$$\varphi_n = \frac{1}{4} n_{n,w} \left(\frac{8kT_{h,w}}{\pi m_i} \right)^{1/2} \quad (11)$$

Heat flux of heavy particles from the Knudsen layer surface to the propellant surface is written as:

$$q_{h,conv} = a_i(\varphi_i + \varphi_n) \cdot 2k(T_{h,w} - T_s) \quad (12)$$

where T_s PTFE surface temperature. Energy accommodation coefficients of ion and neutral a_i, a_n are written as follows for high temperature gas over a few hundred Kelvin.

$$a_i = a_n = \frac{2\mu}{(1+\mu)^2} \quad (13)$$

where μ is the ratio of mass of gas atom M and solid atom m : $\mu = M/m$. In this model, $\mu = 1$, i.e., $a_i = a_n = 0.5$ is assumed. Heat flux of heat conduction by heavy particles from the central axis of the cavity to the Knudsen layer surface is approximated as follows:

$$q_{h,cond} \approx \frac{K_h + K_{h,w}}{2} \frac{T - T_{h,w}}{r_c} \quad (14)$$

where K_h and $K_{h,w}$ are coefficients of thermal conductivity by heavy particles at the central axis and the Knudsen layer surface, respectively. They are written as:

$$K_h = K_i + K_n = \frac{3k^2 T_h}{2m_i} (n_e / v_{iE} + n_n / v_{nE}) \quad (15)$$

$$K_{h,w} = K_{i,w} + K_{n,w} = \frac{3k^2 T_{h,w}}{2m_i} (n_e / v_{iE,w} + n_{n,w} / v_{nE,w}) \quad (16)$$

Frequencies of energy-transfer collision of heavy particles are as follows, considering that energy-transfer collisions of ion-electron, ion-ion and neutral-electron are negligible compared with the other collisions:

$$v_{iE(w)} = \left(\frac{8kT_{h(w)}}{\pi m_i} \right)^{1/2} n_{n(w)} \sigma_{i-nE} \quad (17)$$

$$v_{nE(w)} = \left(\frac{8kT_{h(w)}}{\pi m_i} \right)^{1/2} (n_{n(w)} \sigma_{n-nE} + n_{i(w)} \sigma_{i-nE}) \quad (18)$$

where σ_{i-nE} and σ_{n-nE} are cross-sectional area of energy-transfer collision of ion-neutral and neutral-neutral, respectively. Conservation of heat flux due to heavy particles requires Eq. (12)=Eq. (14). This equation is simultaneously solved with Eq. (3) using Newton method, and $T_{h,w}$ and $n_{n,w}$ are obtained.

F. Energy loss due to heat transfer to the surface

Energy loss due to heat transfer to the surface Q_{conv} is written as follows:

$$Q_{conv} = (q_e + q_i + q_n) \cdot \frac{L_{cir}}{A} \quad (19)$$

where q_e, q_i and q_n are heat fluxes to the propellant surface due to electrons, ions and neutral particles, respectively. Considering the sheath on the propellant surface, the heat fluxes are written as follows:

$$q_e = \varphi_e \cdot 2kT \quad (20)$$

$$q_i = a_i \varphi_i [2k(T_{h,w} - T_s) + e\phi] \quad (21)$$

$$q_n = a_n \varphi_n \cdot 2k(T_{h,w} - T_s) \quad (22)$$

where f is Maxwellian function, v electron velocity component vertical to the surface, the potential drop in the sheath is:

$$\phi = \frac{kT}{2e} \ln \left(\frac{Tm_i}{T_{h,w}m_e} \right) \quad (23)$$

G. Surface recombination

Energy flux due to surface recombination of ion and electron is written as follows, assuming all ions coming to the surface recombine electrons:

$$q_{rec} = \varphi_i e E_i \quad (24)$$

H. Heat conduction equation inside the PTFE

Assuming heat-layer thickness is much smaller than the radius of the PTFE curvature, a heat conduction equation inside the PTFE is:

$$\frac{\partial \Theta}{\partial t} = \frac{\kappa}{\rho_0 C_p} \left(\frac{\partial^2 \Theta}{\partial x^2} + \frac{\partial^2 \Theta}{\partial r^2} \right) + \frac{Q_{rec,in}}{\rho_0 C_p} \quad (25)$$

Boundary condition on the propellant surface is:

$$\kappa \frac{\partial \Theta}{\partial r} \Big|_{r=0} = (Q_{conv} - Q_{ab}) \cdot \frac{A}{L_{cir}} \quad (26)$$

where $Q_{rec,in}$ is energy absorbed by unit volume.

$$Q_{rec,in} = q_{rec} C_1 \exp(-C_1 r), \quad C_1 = -\ln(T_i)/t_i \quad (27)$$

Considering latent heat effect, the temperature is kept at constant after temperature reached 600 K until total supplied energy per unit volume comes to $\rho \Delta H$ (ΔH : unzipping energy; 1.5×10^6 J/kg).

I. Ablation flux

Ablation flux Γ is calculated with Langmuir's law, is written as:

$$\Gamma = \left(\frac{m_i}{2\pi k T_s} \right)^{1/2} p_{vap} \quad (28)$$

Equilibrium vaporizing pressure p_{vap} of PTFE is:

$$p_{vap} = p_c \exp(-T_c/T_s) \quad (29)$$

where $p_c = 1.84 \times 10^{15}$ Pa and $T_c = 20815$ K are characteristic pressure and temperature, respectively.

J. Thermal energy of ablated PTFE

Thermal energy of ablated PTFE Q_{ab} is written as follows:

$$Q_{ab} = \frac{\Gamma}{m_i} \cdot 2kT_s \cdot \frac{L_{cir}}{A} \quad (30)$$

K. Discharge circuit

The discharge circuit is modeled as a LCR series circuit including the plasma resistance:

$$(L_{tran} + L_c) \ddot{Q} + (R_{tran} + R_c + R_p) \dot{Q} + \frac{Q}{C} = 0 \quad (31)$$

$$J = -\dot{Q}, \quad R_p = \int_0^L (\eta / A) dx$$

where R , L , C and Q are, respectively, resistance, inductance, capacitance and electric charge, and subscriptions *tran* and *C*, respectively, represent the cables including electrodes of the circuit and the capacitors. The resistance and inductance measured with frequency response method are used in this model ($R_{tran} + R_c = 9.84$ m Ω , $L_{tran} + L_c = 0.189$ μ H).

L. Energy dissipation and frictional stress

Energy dissipation and frictional stress was approximately estimated, assuming radial distribution of velocity $U(r)$ with an average velocity of $u (\int U(r) 2\pi r dr / A)$. The $U(r)$ is locally determined at each time as a profile of either laminar (parabolic profile) or turbulent (1/7th power profile) flow, referring the local Reynolds number at the time estimated using the equivalent diameter of cross section $4A/L_{cir}$. The threshold local Reynolds number is assumed as 2500.

Energy and momentum loss due to divergence at the nozzle exit is approximately estimated by regarding the average exhaust velocity as the following velocity:

$$\int U(r) \cos\{\tan^{-1}(r / L_{noz})\} 2\pi r dr / \int U(r) 2\pi r dr \quad (32)$$

where L_{noz} is nozzle length, and $U(r)$ radial distribution of velocity at the nozzle exit.

M. Calculation schemes

The calculation domain for plasma flow is between the anode and the nozzle exit. The plasma flow and the LCR series circuit are calculated with the TVD MacCormack scheme and the Runge-Kutta scheme, respectively.

V. Verification of numerical calculation

The present paper is carry out optimization at discharge room form for 30 W class PPT, is aims to improves thrust performance. A longtime operation system with a Multi-Discharge-Room type PPT (MDR-PPT) head was developed by the experiment approach of this research. MDR-PPT head is composed some ignitor and discharge room number. Therefore, the target performance of the numerical calculation approach is to achieve total impulse of over 50 Ns by single discharge room type PPT head.

A. Initial thrust performance

The present section confirmed the validity of the numerical calculation by compared between experimental and calculation thrust performance results with the 30 W class single discharge room type PPT for the 2nd PROITERES. The experimental and numerical calculation conditions is presented in Table 2. It confirmed unstable operation in discharge room diameter of under 3 mm with 31.59 J. Discharge room diameter of over 5 mm has decreased pressure inside discharge room, impulse bit, and maximum of operation number. This research has fixed discharge room diameter of 4 mm.

The present numerical calculation has simulated changing discharge room length between 10 and 50 mm with similar experimental condition, has confirmed validity of calculation model. Figure 10 (a) shows impulse bit and mass shot versus discharge room length. Figure 10 (b) shows specific impulse and thrust efficiency versus discharge room length. Mass shot is increased as it become longer discharge room length because it is increased in discharge room volume. Therefore, impulse bit is increased by increment of mass shot. Specific impulse is decreased by smaller impulse bit per mass shot as it become longer discharge room length. The cause is considered to decrease energy density and pressure inside discharge room. Thrust efficiency is confirmed to maintain certain level.

The simulated impulse bit, mass shot, specific impulse, and thrust efficiency is compared experimental results by similar condition, it achieved maximum error at 18%, 16%, 16%, and 22%, respectively, validity of numerical calculation is suggested. The every discharge room length confirmed to agree qualitative by comparison between experimental and numerical calculation results.

Table 2. Experimental and numerical calculation conditions.

Discharge room length, mm	10/15/20/25/30/35/40/45/50
Discharge room diameter, mm	4.0
Nozzle length, mm	14
Nozzle half angle, deg	0
Charging voltage, kV	1.8
Capacitance, μ F	19.5
Input energy, J	31.59
Inductance, μ H	0.189
Resistance, m Ω	9.84

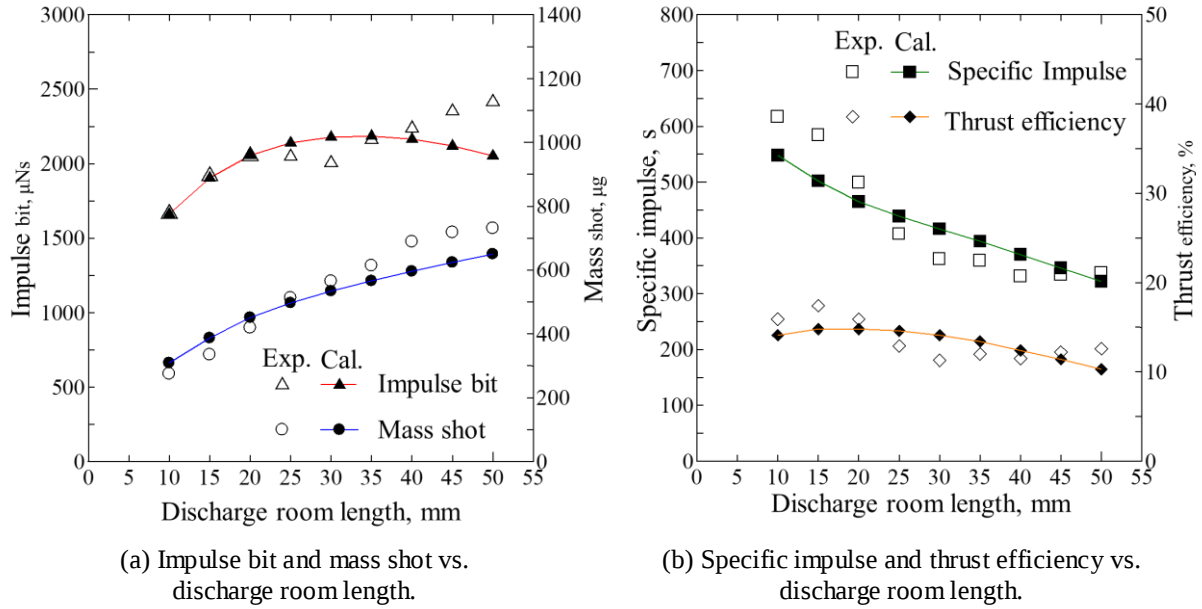


Figure 10. Comparison of initial thrust performance between experimental and numerical calculation.

B. Repetitive operation

In results of the simulation in the previous section, it confirmed high impulse bit and longtime operation, considered optimum with discharge room length at 50 mm for orbital transfer by 50 kg class nano-satellite. Simulation in discharge room length at 50 mm carried out repetitive operation of 100,000 shots. The experimental and numerical calculation conditions is presented in Table 3. Figure 11 shows impulse bit versus shot number. As an experimental result, the PPT generated total impulse of 92 Ns with 100,000 shots at 31.59 J. As a numerical simulation results, the present numerical simulation calculated total impulse of 98 Ns with same condition of experimental. The error between the experimental result and numerical simulation result was 6.1%.

Table 3. Experimental and numerical calculation conditions.	
Discharge room length, mm	50
Discharge room diameter, mm	4.0
Nozzle length, mm	14
Nozzle half angle, deg	0
Charging voltage, kV	1.8
Capacitance, μF	19.5
Input energy, J	31.59
Inductance, μH	0.189
Resistance, $\text{m}\Omega$	9.84

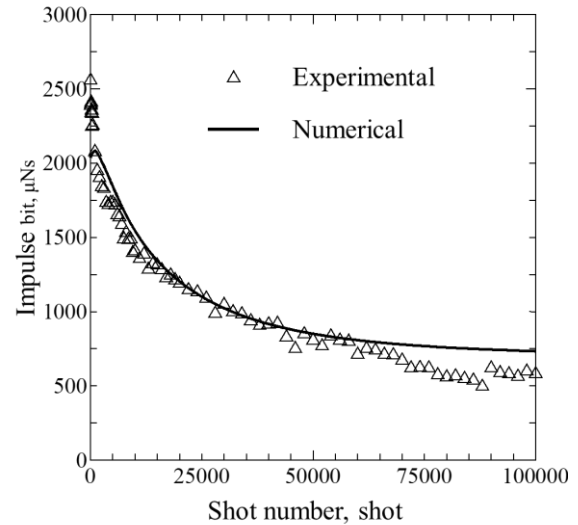


Figure 11. Comparison of total impulse between experimental and numerical calculation.

C. Unsteady physical phenomena

The peaks of discharge current, ablation rate, pressure at the center of discharge room length ($x=25$ mm) appear in this order as shown in Figure 10. Ablation from PTFE surface begins at approximately a few μs after the discharge current, almost completed up to $20 \mu\text{s}$. Due to sublimation of PTFE in this short time, the pressure inside the discharge room reaches 20 atmospheres or more, and it decreases with the exhaust of electrons and neutral particles. It is thought that high impulse bit and high propulsion efficiency of electrothermal PPT can be obtained by exhaust electrons and neutral particles from this high pressure.

Figure 13 shows the calculated distribution of ablated mass per area versus time. Figure 14 shows the time variation of Mach number distribution. The distribution of Figure 13 qualitatively agrees with the observed uneven surface which causes the gaps. According to Figure 14, the plasma density near the discharge room exit is smaller than that near the anode, because the velocity of gas is higher near the discharge room exit. Then, heat transfer to the PTFE is small near the discharge room exit. Since this tendency is consistent with the shape of the discharge room after the long time operation, this calculation model can qualitatively predict non-uniform ablation of PTFE.

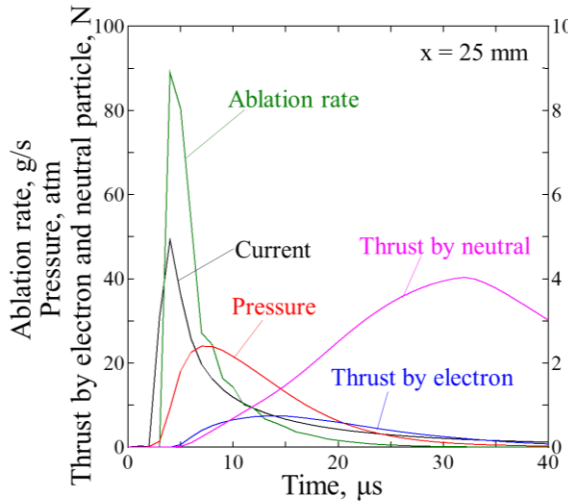


Figure 12. Calculated plasma temperature, discharge current, ablation rate, total pressure, and thrust due to ion and neutral ($x = 25$ mm).

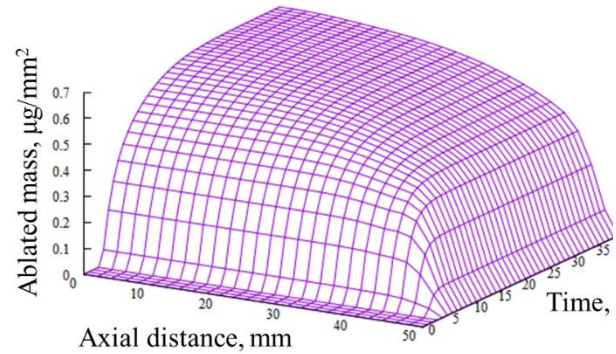


Figure 13. Calculated time and spatial distribution of ablated mass per unit area.

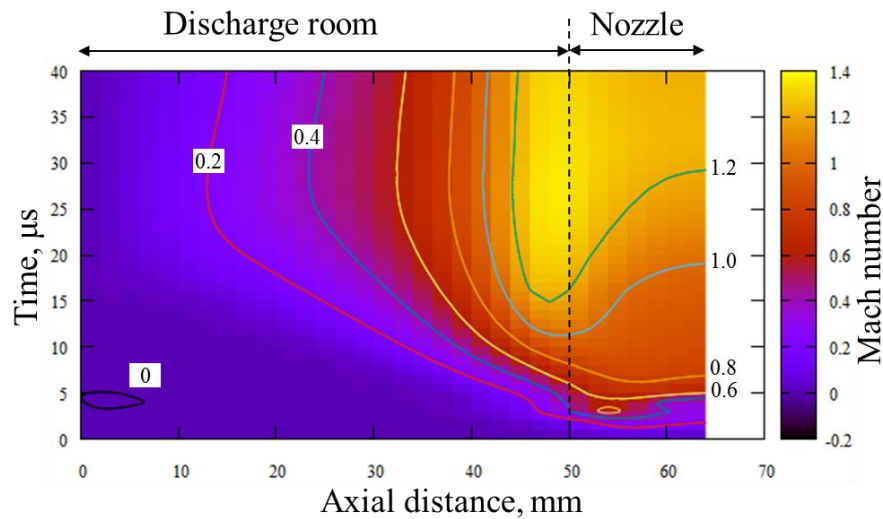


Figure 14. Time variation of Mach number distribution.

VI. Conclusion

This research aims to develop 30 W class electrothermal PPT system. In the present paper, the simulation of 30 W class single cavity PPT carried out, it simulated initial thrust performance and repetitive operation.

- 1) The present numerical calculation has simulated changing discharge room length between 10 and 50 mm with similar experimental condition, has confirmed validity of calculation model. As a results, the simulated impulse bit, mass shot, specific impulse, and thrust efficiency is compared experimental results, it achieved maximum error at 18%, 16%, 16%, and 22%, respectively, validity of numerical calculation is suggested.
- 2) As a result in present numerical calculation, it confirmed possible longtime operation and generation of high impulse bit, carried out repetitive operation simulation of 100,000 shots, achieved a maximum total impulse of 98 Ns. As an experimental result, the PPT generated total impulse of 92 Ns with 100,000 shots at 31.59 J. The error between the numerical simulation and experimental result was 6.1%.
- 3) Ablation from PTFE surface begins at approximately a few μ s after the discharge current, almost completed up to 20 μ s. Due to sublimation of PTFE in this short time, the pressure inside the discharge room reaches 20 atmospheres or more, and it decreases with the exhaust of electrons and neutral particles.
- 4) The plasma density near the discharge room exit is smaller than that near the anode, because the velocity of gas is higher near the discharge room exit. Therefore, heat transfer to the PTFE is small near the discharge room exit.

References

- ¹Yagi, R., Yamauchi, T., Fujita, H., Kajihara, K., Tahara, H., Takada, K., and Ikeda, T., “Research and Development of the Osaka Institute of Technology 2nd PROITERES Nano-Satellite with High-Power Pulsed Plasma Thrusters for Powered Flight,” *31st International Symposium on Space Technology and Science (31st ISTS)*, Ehime, Japan, 2017. Paper ISTS-2017-f-062.
- ²Kanaoka, K., Fujita, R., Ono, K., Morikawa, N., Ryuho, K., Tahara, H., Takada, K., Wakizono, T., “Research and Development of a High-Power Electrothermal Pulsed Plasma Thruster System onboard Osaka institute of Technology 2nd PROITERES Nano-Satellite,” *AIAA Propulsion and Energy Forum and Exposition 2016*, Salt Lake City, Utah, USA, 2016, AIAA-2016-4844.
- ³Enomoto, K., Fujita R., Ryuho, K., Ono, K., Morikawa, N., Tahara, H., Takada, K., and Wakizono, T., “Development of Coaxial Pulsed Plasma Thruster Systems for Powered Flight Onboard the Osaka Institute of Technology 2nd PROITERES Nano-Satellite” *31st International Symposium on Space Technology and Science (31st ISTS)*, Ehime, Japan, 2017. ISTS-2017-b-04.
- ⁴Tahara, H., Fujita, R., Kanaoka, K., Fujita, H., Yamauchi, T., Sugiyama, Y., Takada, K., Wakizono, T., “Research and Development of Electrothermal Pulsed Plasma Thruster Systems for Small/Nano Satellites at Osaka Institute of Technology”, *Space Propulsion 2016*, , Roma, Italy, 2016, Paper 3124901.
- ⁵Edamitsu, T. and Tahara, H. “Performance Measurement and Flowfield Calculation of an Electrothermal Pulsed Plasma Thruster with a Propellant Feeding Mechanism,” *29th International Electric Propulsion Conference (29th IEPC)*, Princeton, New Jersey, USA, 2005, Paper IEPC-2005-105.
- ⁶Edamitsu, T., Tahara, H., and Yoshikawa, T. “Effects of Cavity Length and Material on Performance Characteristics of Coaxial Pulsed Plasma Thruster,” *24th International Symposium on Space Technology and Science (24th ISTS)*, Miyazaki, Japan, 2004, Paper ISTS-2004-b-6.
- ⁷Fujita, R., Haase, T., Kanaoka, K., Ono, K., Morikawa, N., Ryuho, K., Enomoto, K., Tahara, H., Takada, K., and Wakizono, T., “One-Dimensional Flowfield Calculation of Coaxial Pulsed Plasma Thrusters,” *31st International Symposium on Space Technology and Science (31st ISTS)*, Ehime, Japan, 2017. Paper ISTS-2017-b-48.