Performance Enhancement of Anode-layer-type Hall Thruster Using Mixture Propellant

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Junko Yamasaki[1], Shigeru Yokota[2], Kohei Shimamura[3]
University of Tsukuba, Tsukuba,305-8573

Abstract: As an alternative propellant for Hall thrusters, argon is a cost-wise attractive candidate, however, it has never been practically used due to its poor performance which can increase the satellite launch or operation cost. In order to improve the thrust performance, we tried two methods; mixing xenon to argon propellant and modifying the thrust shape for argon. As a result of the thruster shape modification, the specific impulse was increased 482 s to 1500 s using pure argon. Also, when we use the argon-xenon mixture gas as propellant, the thrust performance was increased under the argon-rich condition using the modified thruster. The thrust performance enhancement can reduce the total cost for a satellite mission.

Nomenclature

C_{launch}	=	launch cost
C_{prop}	=	propellant cost
$C_{operation}$	=	operation cost
m_f	=	dry mass
m_{prop}	=	propellant mass
m_{tank}	=	mass of the tank
m_{body}	=	mass of the body
β	=	safety factor
ρ	=	material density
R	=	gas constant
T	=	temperature
m	=	mass per mole
σ	=	breaking strength
α_1	=	coefficient of launch cost
α_2	=	unit propellant price
α_3	=	unit personnel expense
ΔV	=	speed increment
I_{sp}	=	specific impulse
g	=	gravitational acceleration
η	=	anode efficiency
P	=	input power
Δt	=	orbital transfer time

I. Introduction

Cost reduction of $13 million is possible by using an electrical propulsion system instead of chemical propulsion system.[1] However total cost reduction is limited by using xenon which is much expensive (as high as about $5000/kg)[2] as propellant. While argon is appearing for an alternative propellant for Hall thrusters due to its low price, it has not been a strong candidate because of its relatively poor performance, especially propellant utilization efficiency.[3] Since argon has a lighter mass than xenon (39.95 to 131.29 of xenon), argon operation is expected to lead to higher specific impulse. Therefore we propose adding a small amount of xenon to argon gas to enhance thrust efficiency, especially propellant utilization efficiency.

In order to validate the xenon mixture effect, we measured thrust performance using a 1kW class anode-layer-type Hall thruster which was designed in University of Tsukuba. The xenon fraction was changed from 0 % to 100 %. The results showed that operation performance was increased by mixing the xenon but was still law at high argon fraction.

Therefore, we modified Hall thruster to improve performance for argon propellant, and operation characteristics was investigated. Our objective in this paper is to reveal the performance of modified Hall thruster, we measured the thrust performance in using argon-xenon mixed propellant. We also examined transportation cost in the case of geosynchronous orbit satellites and compared in using xenon optimized hall thruster and modified for argon Hall thruster.

II. Cost Model

In this chapter, we introduce the cost model which was constructed in order to know the enough performance to reduce the cost using alternative propellant. The values are assumed to calculate the cost for lifecycle of mission in the case of geosynchronous orbit satellites.

$$C_{total} = C_{\mathrm{launch}} + C_{\mathrm{prop}} + C_{operation} \qquad (1)$$

Here, C_{launch} is assumed to be proportional to the satellite wet mass..

$$C_{\mathrm{launch}} = \alpha_1 \left(m_{prop} + m_f\right) \qquad (2)$$

The value of the proportionality constant α_1 is mentioned later. The dry mass can be divided into the the main body mass and the tank mass.

$$m_f = m_{body} + m_{tank} \qquad (3)$$

The tank mass is calculated by using the following tank weight ratio.

$$\frac{m_{tank}}{m_{prop}} = \frac{3\beta\rho RT}{2m\sigma}, \qquad (4)$$

where, β, ρ, R, m, and σ are safety coefficient, material density of tank, gas constant, mass of 1 mol internal gas, breaking strength of material, respectively. In the case of using composite material to the tank, the tank weight ratios are 0.35 for argon and 0.08 for xenon.

Propellant costs are proportional to propellant mass.

$$C_{\mathrm{prop}} = \alpha_2 m_{\mathrm{prop}} \qquad (5)$$

where, α_2 is propellant unit cost.

The propellant mass is calculated by Ziolkovsky equation.

$$m_{\mathrm{prop}} = m_f[\exp\left(\Delta V / g\, I_{\mathrm{sp}}\right)\text{-}1] \qquad (6)$$

Operation cost is a function of orbital transfer time. Transfer time was calculated using spiral transfer trajectory from LEO to GTO.

$$C_{operation} = \alpha_3 \Delta t \qquad (7)$$

$$\Delta t = \frac{m_{prop}}{\dot{m}} \qquad (8)$$

$$\dot{m} = \frac{2\eta P}{g^2 I_{sp}^2} \qquad (9)$$

The launch cost is depending on the launch capability of rockets. Figure 1 shows launch cost by satellite mass. HIIA202 can load up to 10 tons and cost is $75 million. HIIA204 can load up to 15 tons and cost is $106 million. Thus satellite mass is over 10 tons, only 1 satellite can be loaded on HIIA204, and launch cost is $106 million. Satellite mass is smaller than 7.5 tons ,2 satellites can be loaded on H2A204 and cost of one is half of $106 million.

Table 1 is the values of various parameters used for cost calculation. We used the value of Boeing 702SP bus specifications for m_{body} and ΔV.

Number of operators means number of people required for orbit transfer. The values of operators and personal expenses are from personal communications.

Table1. Values used for cost calculation

Parameters	Value
α_{2Xe}, dollar / kg	5000
α_{2Ar}, dollar / kg	1.3
ΔV, m/s	2000
m_{body}, kg	2040
Number of operations, persons	4
α_3, dollar/hour	71

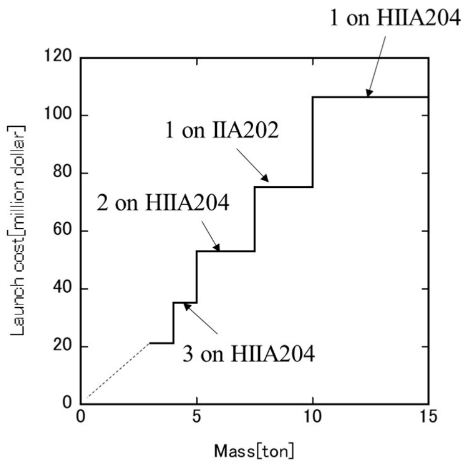

Figure1. Launch Cost

III. Thruster Modification

One of the reasons of the poor thrust performance using argon propellant is the lower propellant density in the discharge channel. Argon is exhausted without sufficient ionization because argon atom speed are higher than that of xenon. In order to enhance the argon ionization rate, we designed modified Hall thruster which has longer discharge channel. The normal, which means optimized for xenon, thruster has 3 mm discharge channel. The longer discharge channel (9 mm) was designed to improve ionization. (shown in Figure 2) Figure 3 shows axial magnetic flux density of each thruster. Field simulations were estimated using Finite Element Method Magnetics (FEMM). We see that magnetic flux density is applied to wider area of discharge channel to extend the ionization zone.

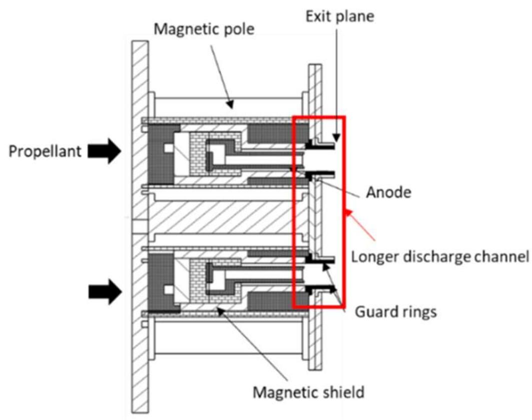

Figure2. Hall Thruster Modified for Argon

IV. Experimental setup

Xenon and argon were used as propellant. Fraction was changed 0 % to 100 %. Discharge volt was 200 V. Mass flow rate was 2 Aeq. Hollow cathode was used for emitter and filament cathode was used for ignition. The cathode propellant was pure argon. 1 m×1 m vacuum chamber was used. The pressure inside the chamber was 8.9 × 10 -2 Pa. Experimental set up is shown in Figure 4.

Thrust was measured using pendulum thrust stand that was used previously to evaluate various Hall thrusters.

The magnetic flux density is arranged to maximize the thrust efficiency. Table 2 shows operation parameters.

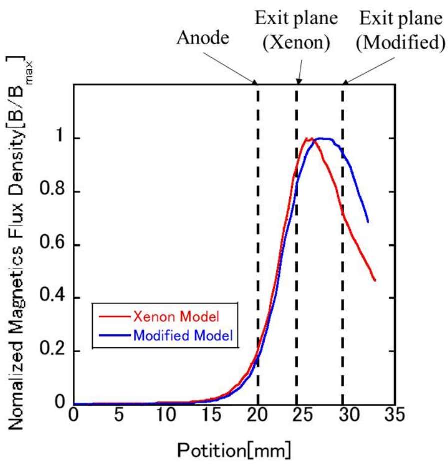

Figure3. Magnetic Flux Density

Table2. Operation Parameters

Parameters	Value
Discharge voltage, V	200
Magnetic flux density, mT	12 ~ 60
Propellant	Xenon-Argon
Main mass flow rate, sccm	27.8
Cathode mass flow rate, sccm	4

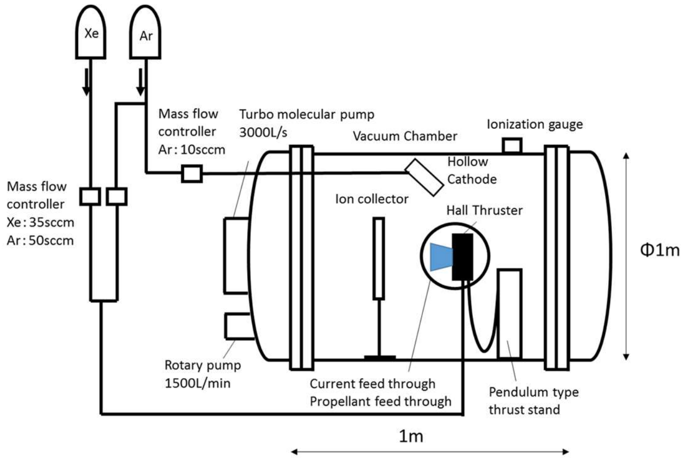

Figure4. Experimental Setup

V. Result and Discussion

A. Thrust Performance

A comparison of the mass utilization efficiency vs xenon fraction on xenon optimized and modified Hall thruster is shown in Figure 5. The mass utilization efficiency of xenon model nearly proportional increased as xenon fraction increased. While in modified model, it trends to be saturated at 60 % or more of xenon fraction.

The anode efficiency is a function of mass utilization efficiency. As shown in Figure 6, anode efficiency of modified Hall thruster was improved at high argon fraction because the mass utilization efficiency of argon was increased.

Figure 7 compares specific impulse (I_{sp}). The I_{sp} was increased at all xenon fraction using modified Hall thruster. In xenon optimized Hall thruster, maximum value of I_{sp} was 1488 s at 70 % xenon fraction. In modified Hall thruster, 1785 s at 90 % xenon fraction, and even at 0% xenon fraction (mean 100 % argon) 1550 s was aimed. In addition at all xenon fraction, I_{sp} were almost the same value in modified Hall thruster.

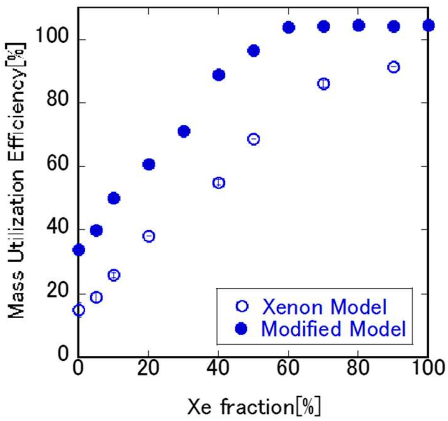

Figure5. Mass Utilization Efficiency vs Xenon fraction

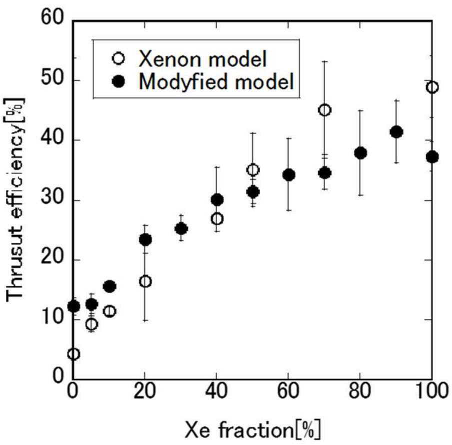

Figure6. Anode Efficiency vs Xenon fraction

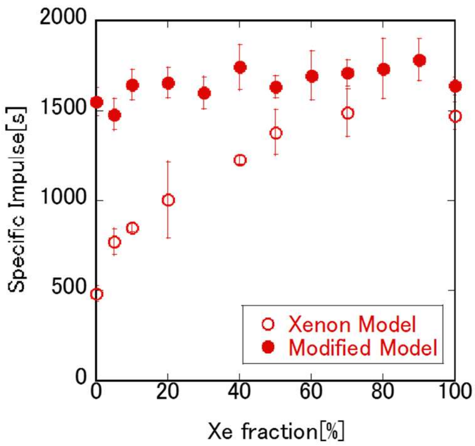

Figure7. Specific Impulse vs Xenon fraction

B. Cost evaluation

Transportation cost was estimated in using xenon optimized and modified Hall thruster.
It is assumed that two of 5kW Hall thruster were used. Figure 8 shows total cost of xenon optimized Hall thruster. Figure 8 indicates that in the case of geostationary satellite, total cost was 124 million dollar at 0 % xenon fraction (100% argon), the lowest cost is 47 million dollar at 50 % xenon fraction. At 100 % xenon fraction, total cost was 51 million dollars. 38 million dollar at 0～20 % xenon fraction and 42 million dollar at 100 % xenon fraction in using modified Hall thruster.(Figure 9) The difference of these cost was 10 % of total cost. In this case, the reason why launch cost has decreased is that the I_{sp} and efficiency has increased.

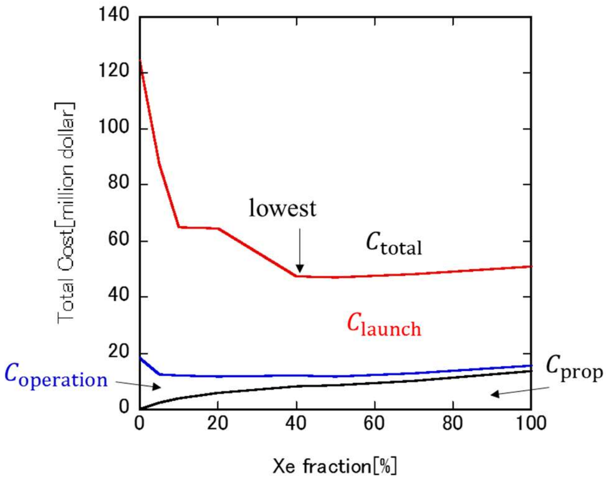

Figure8. Total Cost of Xenon Optimized

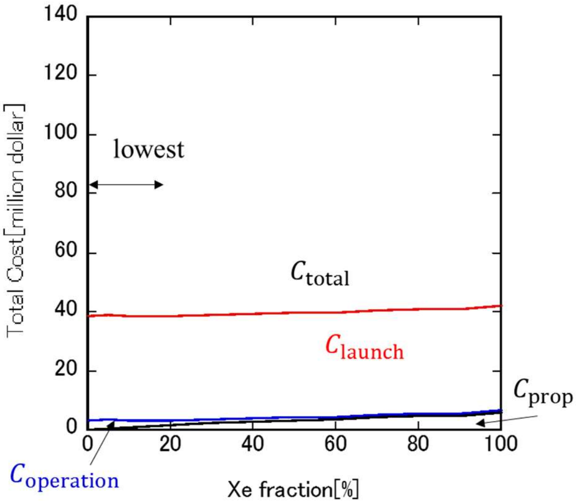

Figure9. Total Cost of Modified

VI. Conclusion

Thruster performance on xenon optimization thruster and modified for argon thruster using mixed propellant was investigated. The results indicate that longer discharge channel from 3 mm to 9 mm has good performance for argon propellant. While for xenon propellant, it is not optimized. It is considered that to use modified Hall thruster, high exhaust without sufficient ionization of argon propellant was mitigated by widening magnetized zone.
In the case of geosynchronous orbit satellites, total transportation cost is able to reduce 10 % of the whole to use modified Hall thruster.

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