Hall Thruster System Design for High Delta-V Missions
高ΔVミッションのためのホールスラスタシステム

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Abstract

R&D of a new Hall thruster system for high delta-V missions is now under way at JAXA and IA. The system is designed for so-called all-electric main propulsion of 3 to 6 ton class geostationary satellite as well as for orbital transfer of one-ton class planetary explorer. The system is tentatively targeted at variable thrust (100-400 mN) and Isp (1300-3000s) depending on operational modes. In this paper, R&D status of the Hall thruster system is provided and discussed.

概要

ΔVが3～6km/sの高ΔVミッションに適合したホールスラスタシステムの研究開発を進めている。同スラスタは、3～6トン級の全電化衛星、ならびに、1～2トン級の惑星探査の主推進等幅広いミッションに適合することを目指しており、スラスター台あたりの推力は100～400mN、比推力は動作モードに応じて1300s～3000sを達成する見通しである。本ペーパーでは、同ホールスラスタの開発状況ならびに想定するサブシステムを紹介する。

1. Introduction

Application of electric propulsion (EP) to geostationary satellite (Fig.1) or planetary explorer is a cutting edge field where European, USA and Japanese research organizations and companies are competing against each other. Most matured EP system, ion thruster system, usually shows high performance at a low power level from around one-kilowatt up to three-kW, and an example is asteroid explorer Hayabusa, which employed 1-kW-class system for deep space maneuvers,[1] which suggests ion thrusters are the best solutions for such power levels. However, at a higher power level, hall thrusters are considered more competitive and preferable. At power levels below 3 kW, in Japan, R&Ds of hall thruster were conducted in universities of Tokyo[5], Kyushu[3], Gifu[4] and so on, and along with these academic societies, Japanese industry such as Melco[5] and IHI[6] also conducted some R&D. Recently, in-space propulsion

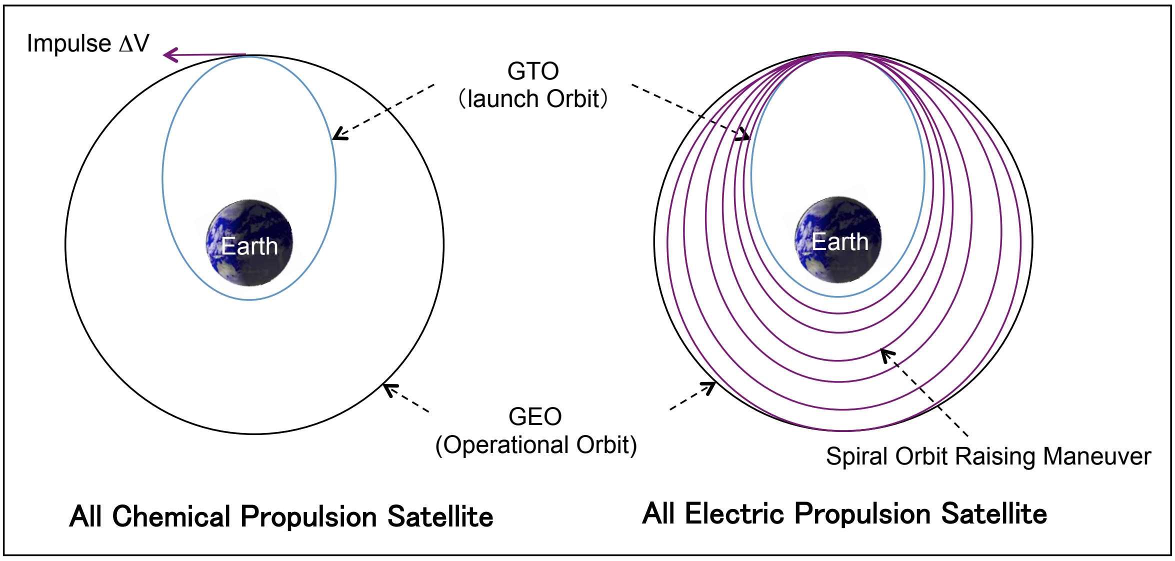


Fig.1 Application of all electric propulsion system to geostationary satellite: all electric propulsion satellite features high payload ratio against ordinary all-chemical propulsion satellite because most delta-V necessary for GTO to GEO transfer is provided via high-Isp electric propulsion.

workshop at JAXA pursues high power hall thruster (> 10 kW), and basic research is going on for such thrusters as RAIJIN[7]. Under these circumstances, JAXA, IA, IHI/IA, and Tokyo Metropolitan University (TMU) are doing R&D of 3-6 kW class hall thrusters, which are considered as the most demanded operational range for a variety of missions. In this paper, R&D status is provided and expected system for the above hall thruster is presented.

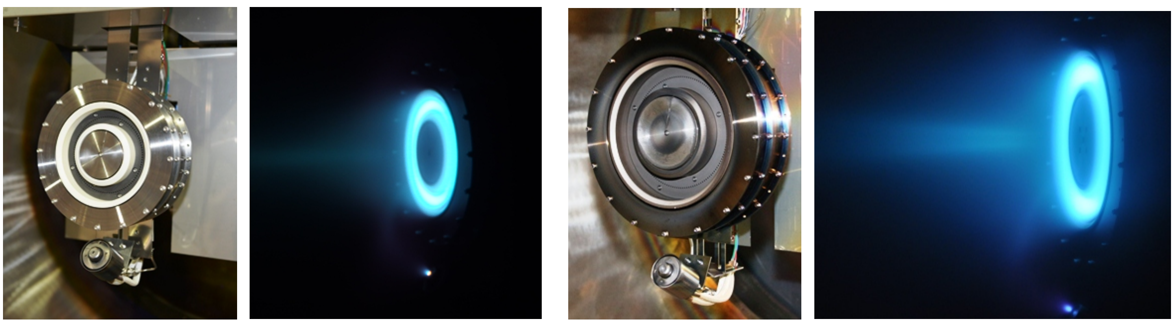
2. Developing Target of Hall Thruster

All-electric propulsion system refers to a spacecraft system that two kinds of delta-V, i.e., orbital transfer delta-V from GTO to GEO and NSSK delta-V, are provided by electric propulsion. The concept of all-electric propulsion system is depicted in Fig.1. This concept was firstly demonstrated by Boeing, and by adopting all-EP system, drastic reduction in wet weight of satellite becomes possible, in particular by reducing propellant weight for orbital transfer that will lead to drastic reduction in cost per payload; the cost for all-EP satellite is nearly half of that of conventional chemical propulsion based satellite. This is a new business model in the field of commercial satellite. Boeing's first all-EP satellite bus named as 702SP was launched in March 2015, and now it is operated in a geostationary orbit. Ion engine system's feature of high-Isp can provide high payload ratio but the drawback is the long trip time for orbital transfer that will take typically half a year. To enable quick orbital transfer, it is pointed out that hall thruster with a moderate Isp can provide better system, and this is the reason western companies such as Aerojet, SMECMA, etc. are developing hall thrusters. It depends on selected Isp, but high thrust to power ratio and low dry weight feature of hall thruster enables quick orbital transfer in less than three months if the optimum Isp is selected.

In short summary, all-EP system seeks for quick orbital transfer from GTO to GEO, which means hall thruster with higher thrust to power ratio is required. The most popular operational range of hall thrusters is an Isp of 1,500s to 2000s with a thrust to power ratio of 60 mN/kW, but a thruster with a higher thrust to power ratio with a lower Isp will deliver spacecraft more quickly and efficiently because higher thrust, hence higher acceleration, is possible. Vice versa, in NSSK operation, a higher Isp of 2,500s to 3,000s is better to suppress propellant consumption for typical GEO satellite lifetime of 15-20 years. From the above requirements, it is summarized that bimodal operation of hall thruster, high thrust mode for quick orbital transfer and high-Isp operation for NSSS, is idealistic, and hence enabling such bi-modal operation is the objective of our R&D. Table.1 summarized the target along with typically used mode,

Table.1 3-6kW hall thruster target.

	High Thrust Mode	Intermediate Mode	High Isp Mode
Input Power	4.5-6.0 kW	4.5-6.0 kW	1.5-3.0 kW
Anode Voltage	150 V	300 V	400-800 V
Thrust to Power Ratio	>72 mN/kW	>63 mN/kW	>47 mN/kW
Isp	>1180s	>1750s	>2500s
Thrust	320-430 mN	280-390 mN	<140 mN



BBM1a BBM1b

Fig.2 Breadboard model thrusters.

that is designated as 'intermediate mode' in the table.

3. R&D Status of Hall Thruster Head

So far, some breadboard models (BBM) targeting at 3-kW and 6-kW operations were fabricated and tested in laboratory. In this section, two breadboard models, BBM1a and BBM1b, are described. The effective diameters of the channels are 100 mm for BBM1a and 140 mm for BBM1b. As shown in Fig.3, Stationary Plasma Thruster (SPT) type hall thruster with ceramic channel is adopted. The thruster head design is based on numerical prediction, in which not only geometrical and magnetic field configuration, but also plasma production and any kinds of loss mechanisms are quantitatively estimated prior to fabrication. [8] The usage of numerical simulation in preliminary design phase drastically shortens the developing time scale.

Performance tests were conducted in IHI's vacuum chamber (2mϕ x 3m) and large vacuum chamber at Georgia Institute of Technology (5mϕ x 9m). In the experiment, the pressure inside the chamber is kept below 3×10^{-5} torr. Figure 4 shows thrust and Isp characteristics for BBM1a and BBM1b at Xe mass flow rates (6 to 30 mg/s) and discharge voltages of 200 to 800V. As shown in the figures, the maximum thrust was 400 mN, and the maxium Isp was 3,000s, respectively. Typical operational points of BBM1b are: 1) large thrust to power ratio, 62 mN/kW at a low Isp of 1,300s, and 2) a higher Isp of 2,350s is obtained at a lower thrust to power ratio and at lower power level (3.5 kW) with good discharge stability and thermal stability. It is hence found out that a hall thruster with two operational modes consisting of both high thrust and high Isp mode was successfully operated in laboratory.

4. Hall Thruster System Proposals

Based on the breadboard results and R&D so far, expected system-level specifications are considered and listed in Table.2 with estimated performance values and system weight. Three system candidates are considered here, including large GEO satellite with all-electric propulsion system, and 1000-kg and 2000-kg planetary explorer with main propulsion system based on hall thrusters.

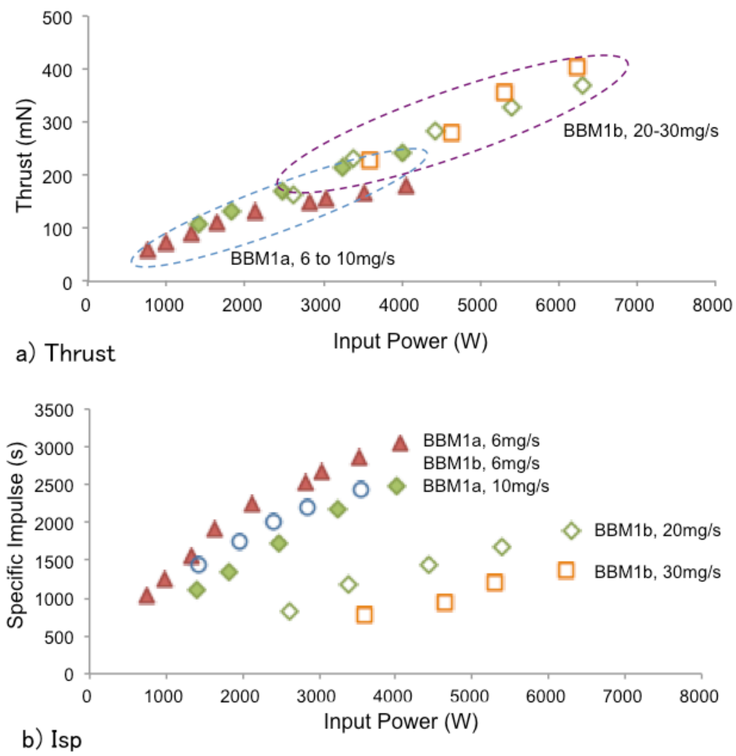


Fig.3 Thrust and Isp characteristics of breadboard models (BBM1).

Table.2 Hall thruster and its sub-system specification (tentative).

	GEO Satellite	1t Planetary Explorer	2t Planetary Explorer
Spacecraft Weight	4-6 t	1t	2t
Thruster Power	12-24 kW	1.5-3.0 kW	3.0-6.0 kW
Thruster Unit No.	2-4	1-2	>2
Total Thrust	～1.9 N	～140 mN	～280 mN
Thrust-to-Power Ratio	>63 mN/kW	>47 mN/kW	>47 mN/kW
Isp	>1180s（Variable）	～2500s（Variable）	～2500s（Vriable）
Thruster Dry Weight	<410 kg	100-170 kg	<170 kg
Xenon Throughput	1100kg	>200kg(ΔV=5km/s)	>400kg (ΔV=5km/s)

5. Summary and Future Plan

In this study, 3-6 kW class hall thrusters with two modes (high thrust and high Isp) were demonstrated with BBM1 thruster heads. Currently, fabrication and testing of the next versions of BBM are in progress, and they are intended for improved performance. Using one of the model, limited lifetime testing will be also conducted. Following these, preliminary design is to be fixed to start fabricating engineering model thruster subsystem that is targeted at demonstration in space mission. This system is o be used for orbital raising and NSSK for 3 to 6 ton class GEO satellite, and tentative schedule is to develop engineering model in FY2016, followed by various kinds of testing. From FY2017, prototype model development will start, so that the whole subsystem including power-processing unit becomes available by FY2019. If wide operational range and long lifetime are both established, the hall thruster becomes also attractive for deep space mission. We can develop a 6-kW thruster based on BBM1b, and at low power levels below 3 kW, BBM1a seems the case. Thrusters in both power range should be prepared in a timely manner so that thrusters can be used either for industrial case and planetary and space sciences.

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