Development Status of 5 kW Class Anode-Layer Type Hall thruster: RAIJIN94

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Abstract: RAIJIN thruster, an anode layer type Hall thruster, and its system has been developed in collaborative work in Japan. This literature focuses on its thruster head, although various sub-components of technology are being researched in this work. RAIJIN94 thruster head showed thrust efficiency of 64% in an optimized condition at recent experiment and the other additional study on the coil configuration is examined. It indicated that it should be in optimized condition by changing current to each coil for further improvement of performance. Another downscaled RAIJIN thruster is under development at the University of Tokyo, which will use to research some advanced technology. Its design will be shown later in the literature.

Nomenclature

a	=	anode
c	=	cathode
F	=	thrust
g	=	gravitational constant
h	=	height of discharge channel
I_d	=	discharge current
I_{sp}	=	specific impulse
l	=	axial length of dis charge channel
$\dot{m}$	=	propellant mass flow rate

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n_n	=	number density of neutral gas
P	=	discharge power
V_d	=	discharge voltage
η_t	=	thrust efficiency

I.Introduction

In Japan, Hall thrusters have been developed at some companies and institutes[1]. Numbers of satellites with electric propulsion are increasing[2] and high power electric propulsion would be good, especially for all electric satellites[3] in reducing their transfer duration. Furthermore, high power electric propulsion would enable advanced missions such as an interplanetary space tug for exploration of an asteroid or Mars[4], construction of a large space structure. Hall thrusters normally have the larger thrust density than ion thrusters and it is considered to be suitable in high power usage.

A practical high power Hall thruster for Japanese in-space propulsion has been developed by JAXA/IHI/IA/Tokyo Metropolitan University (TMU) [5]. The scope of their work is R&D of a 2-6 kW class magnetic layer type thruster, which is the suitable operational power range of current all-electric satellites[3] or near-term developed satellites like ETS-9, Electra, and Eurostar. Some different size of breadboard model thrusters had been developed with the aid of numerical simulation. It was confirmed 6 kW class operation and two operation modes, high-thrust and high-I_{sp}. Another activity that pursues a wider power range up to 25 kW for future advanced missions is called RAIJIN project, which is the acronym of "Robust Anode-layer Intelligent thruster for Japanese IN-space propulsion system." Our goal is the development of a high-power, long-lifetime Hall thruster system that could give some design flexibility to a satellite by clustering technology. Physical mechanisms of ion-loss[6], electron diffusion[7] and discharge oscillation[8] were clarified in those researches. This knowledge leads to stabilization of discharge oscillation[9,10] and took part in the design of a 5 kW class RAIJIN94 thruster developed at Kyushu University. The development of RAIJIN thrusters, RAIJIN94 thruster and 2 kW class RAIJIN66 thruster is being developed at the University of Tokyo, is summarized in this literature.

Figure1 shows technology included in the RAIJIN project. It is not only developing a thruster head, but also going into development of sub-components and mission analysis[11]. Elements of technology, which is required to accomplish the objective of the RAIJIN project, are investigated in some laboratories or companies. The characteristics of high Isp operation is being researched at Osaka Institute of Technology (OIT)[12,13]. They focus on the operation of higher discharge voltage and high specific impulse and it was observed THT-VI, which is a magnetic layer thruster developed at OIT[14], can operate at 3300 s of Isp with good thrust efficiency of 0.60. Another technology developed at Gifu University[15]is a Hall thruster clustering system. The system is consisted of a pair of Hall thrusters and a hollow cathode, which they named "side-by-side (SBS)" system. The group observed efficiency improvement with comparing some different magnetic field configuration and their basic research revealed that plume interference is likely to be the cause of that difference. These researches are applied to an operation with anode layer type Hall thrusters; OIT group tried to operate TALT-2, which is an anode layer type thruster developed at OIT[16], and RAIJIN94 thruster with higher discharge voltage. Though TALT-2 was operated up until 800 V, RAIJIN94 thruster was successfully operated at 1000 V of discharge voltage with 2200 s of Isp. And the Gifu University group had succeeded to operate anode layer type Hall thrusters in their SBS system[17]. An important result in SBS system operation with anode layer type was the discharge oscillation characteristic. They observed harsher oscillation than the single head operation was observed in SBS system. It is also likely to be explained by plume interference, which increases electron flux to the channel and stimulates ionization oscillation.

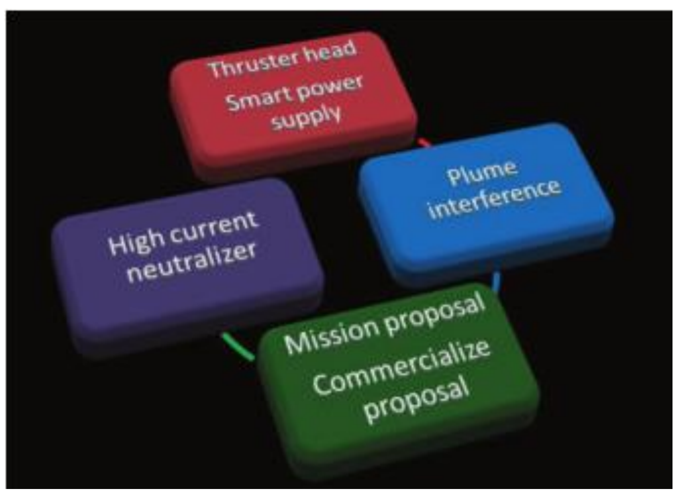


Figure 1. Technology elements in RAIJIN project. *Technology elements in RAIJIN project is listed in this figure. Thruster component is the focus of this paper in these fundamental components for a thruster system.*

Along with the development of the Dual mode thruster head, a high current hollow cathode also has been developed at JAXA. Their 50 A class hollow cathode with a radiative carbon heater was built and tested[18], and its discharge phenomena are being investigated by using a Hybrid-PIC code[19,20]. Another inductively coupled plasma cathode that aims at long lifetime is also being researched at TMU[21,22]. Research about power supply and its system is studied by MELCO, Nagasaki University and Kyushu University. Their proposed new control method of power supply can find the optimal operation point by itself[23,24]. Kyushu University, TMU and MELCO are also developed lighter weight power processing unit that provides power harmonized with the natural discharge oscillation of a Hall thruster[25,26].

II.Developed RAIJIN94 thruster and its performance

Figure2 shows the RAIJIN94 5 kW class anode layer type thruster developed at Kyushu University. The thruster has one inner solenoidal coil and four solenoidal coils to generate a radial magnetic field predominantly. There is a trim coil around the discharge channel to "trim" the predominant magnetic field. A hollow annular anode, which consists of two cylindrical components, is used and length between anode tip and the exit of the thruster set 3 mm. Hollow anode is a fundamental component for anode layer type Hall thruster by which propellant utilization is maintained and discharge oscillation is suppressed. This point has been examined in experiments and numerical simulations[27,28]. The other effect of hollow anode is reduction of erosion by concentration of plasma at the center of the channel. More detailed investigation of hollow anode is being conducted by using RAIJIN94 thruster. A hollow cathode, Veeco HC-252, is used as the electron source.

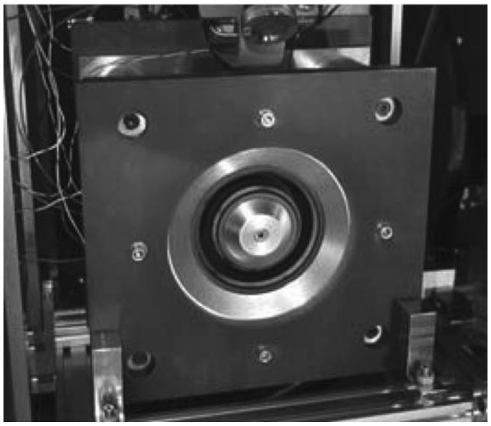


Figure 2. RAIJIN94 thruster *RAIJIN94 thruster head developed at Kyushu University. Diameters of inner and outer channel of the thruster are 60 mm and 94 mm, respectively.*

The performance was measured in the ISAS/JAXA ion engine endurance test vacuum chamber. A thrust balance, which is a dual pendulum type developed at the University of Tokyo, was used for the experiment to eliminate error with the high power operation. Figure3 shows the relationship between discharge power and thrust. The thrust range of RAIJIN94 thruster is 19-219 mN for power range of 325-4500 W. Thrust and discharge current is proportional to the mass flow rate and thrust is proportional to the square root of the discharge voltage. Figure 3(b) shows thrust-to-power ratio of the RAIJIN94 thruster, which is a performance indicator. Typical values of T/P are

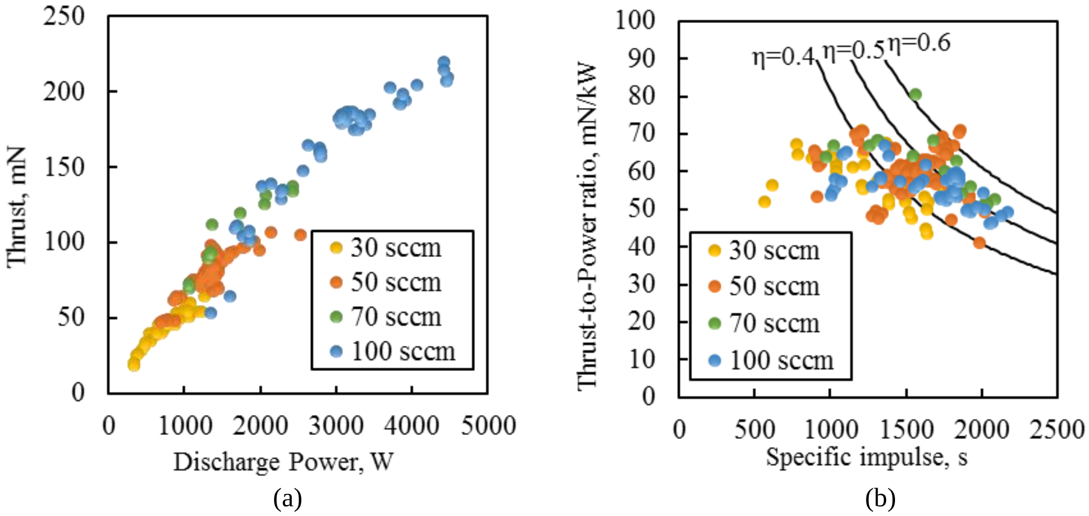


Figure 3. RAIJIN94 thruster characteristics. *(a)Measured thrust in 4 different mass flow rate. It seems thrust is proportional to the square root of discharge power, which is similar to conventional Hall thrusters. (b)* $\mathbf{I_{sp}}$ *to F/P is another performance indicator. All of mass flow rate except 30 sccm exceeds 0.5 of thrust efficiency, which seems to show a sufficient propellant utilization is achieved in these mass flow rates.*

Table. 1 A categorized Hall thruster operation from Ref. 5. *(a)Considering Dual mode operation, typical values of F/P and* $\boldsymbol{I_{sp}}$ *are defined. The RAIJIN94 thruster will be categorized to "high thrust" in this frame.*

	High thrust mode	Intermediate mode	High Isp mode
Anode voltage, V	**150 - 200**	**300 - 400**	**650 – 800**
Thrust to Power ratio, mN/kW	**>69**	**>63**	**>35**
Isp, s	**>1380**	**>1750**	**>2200**

shown in Table 1 by which thrusters can be categorized into "high thrust", "high specific impulse" and "Intermediate". Thrust efficiency and specific impulse, which are other indicators of performance, is defined by following Eqs. (1) to (3).

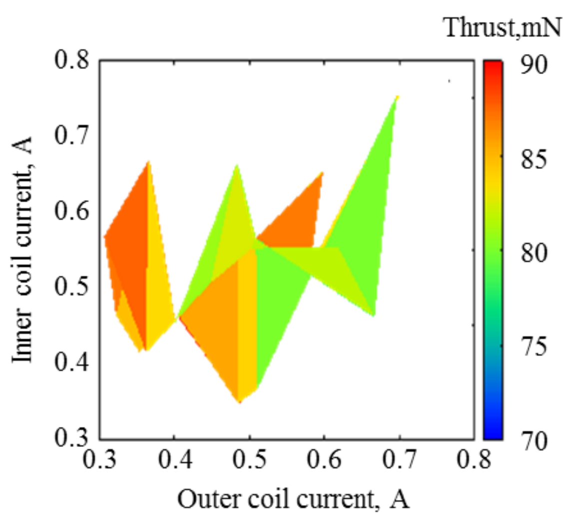
$$\eta_{t} = F^{2} / 2(\dot{m}_{a} + \dot{m}_{c})(V_{d} I_{d} + \sum P_{coil} + P_{c}) \tag{1}$$

$$I_{sp} = F / (\dot{m}_{a} + \dot{m}_{c}) g \tag{2}$$

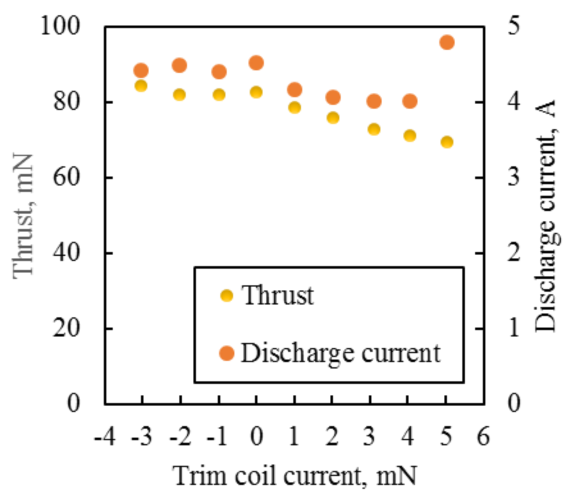
$$F / P = (2 / g) * (\eta_{t} / I_{sp}) \tag{3}$$

Thrust efficiency is shown in Fig. 5 with curved lines, which are the constant efficiency point because there is a relationship explained by Eq. (3) between *F*/*P* and I_{sp}. RAIJIN94 thruster was operated at high thrust mode and the *F*/*P* value ranges 50-84 mN/kW in the Isp range of 1200-2200 s. As THT-VI developed at OIT has a wide range of *F*/*P* and I_{sp}, RAIJIN94 could be operated in dual mode operation when the higher I_{sp} operation is achieved.

Since the previous result inferred that magnetic field configuration was important for the performance, some different coil current ratio was investigated and result is shown in Fig. 4 (a). When the coil current ratio that inner coil current is 0.5 A and outer coil current is 0.84 A, the minimum thrust is obtained. The maximum thrust was obtained when the coil current ratio that the inner coil current is 0.3 A and the outer coil current is 0.5 A. Trim coil effect was also examined. Figure4 (b) shows result in which thrust is monotonically decreased with increasing the trim coil current. The effect of trim coil is as follows; positive trim coil current pushes the magnetic field outside. On the contrary, negative trim coil current pull it to upstream. This modification changes the location of the ionization and acceleration region and alters propellant utilization. This result indicates propellant utilization decreased with increasing trim coil current whereas erosion would be reduced by pushing plasma away from the channel wall. Note



(a)



(b)

Figure 4. Coil configuration effect. *(a)Predominant coil configuration is changed without applying trim coil current. Color contour indicates thrust at each coil current ratio by which the magnetic field shape and the magnetic flux density are changed. (b) Trim coil current effect with fixed inner and outer coil current of 0.4 A. Trim coil monotonically modifies the predominant magnetic field and thrust decreased with increasing the trim coil current.*

that the uncertainty of thrust measurement is estimated up to 3 % of 200 mN, therefore, the coil configuration have enough large effect on the measured thrust than its uncertainty.

III.Development of downscaled RAIJIN66 thruster

At this moment, a scaled-down RAIJIN thruster is under development. The objective of this thruster is to utilize it as a technology development platform in a university. The University of Tokyo has been continued unique technology to develop better Hall thruster for years. For instance, a method to suppress discharge oscillation actively by non-uniform propellant supply[29], an operation with alternative propellant in anode layer thrsuter[30] and erosion reduction with a MS-like magnetic field[31,32] has been researched these years. Since the RAIJIN66 thruster can be operated in a facility of the University of Tokyo because of that lower power range, those advanced technologies will be developed to be available RAIJIN94 or future thrusters.

Figure 5 shows a picture of the thruster, which is 70 % downscaled in geometrical size and we call it RAIJIN66 from its outer diameter of 66 mm. Following several scaling research in the past[33,34], "photographically" geometric scaling based on RAIJIN94 thruster is adopted in designing the RAIJIN66 thruster. All of dimension, length, mean diameter and width of discharge channel is proportionally downscaled. Considering a mention from a past research[35], the mechanism of ion loss is also expected to be similar because the aspect ratio, h/l, is kept constant by the photographic scaling. Another criterion is the similar value in the number density of neutral particle, n_n, as that of RAIJIN94 thruster. Since it is considered that the number density should be the same value to keep similar physical process[34,36], the

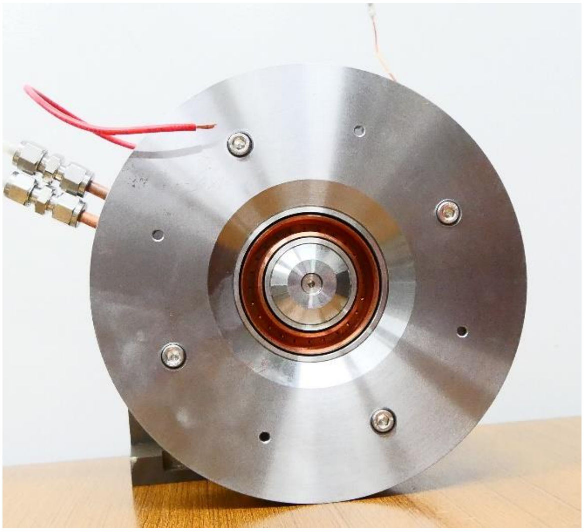
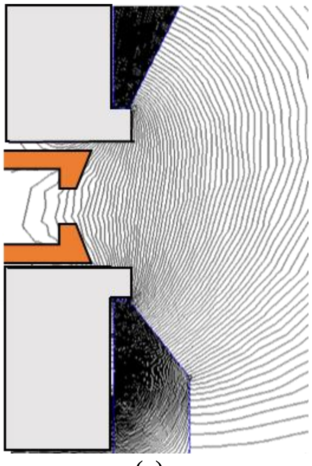
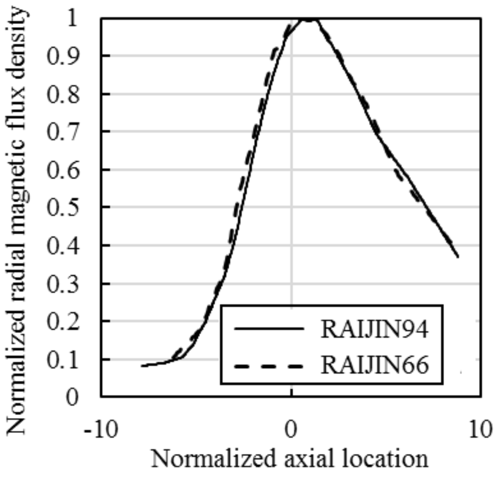


Figure 5. RAIJIN66 thruster. *A front view of the RAIJIN66 thruster developed at the University of Tokyo. Its geometry is photographically downscale of the RAIJIN94 thruster, which channel diameters are 66 mm and 42 mm in inner diameter and outer diameter of the channel, respectively, and which channel length is 2.1. mm.*



(a)



(b)

Figure 6. Magnetic field design of the RAIJIN66 thruster *(a) A Calculated magnetic field of the RAIJIN66 thruster by FEMM4.2. The structure of the magnetic field is restricted by an upstream part, which location is also downscaled in the RAIJIN66 thruster. (b)Comparison between the RAIJIN94 and the RAIJIN66 thruster. Both horizontal and vertical axes are normalized by the channel length and by the maximum value of the radial magnetic field, respectively.*

mass flow rate in operation is set to about half values of the RAIJIN94 thruster to keep the similarity of the discharge plasma. It is expected that similar phenomena, such as acceleration of ions and discharge oscillation, will be shown in RAIJIN66 thruster.

Predominant radial magnetic field, which is shown in Figure 6 (a) with a cross sectional picture, is produced by one inner solenoidal coil and four outer solenoidal coils as well as the RAIJIN94 thruster. The axial structure of radial magnetic field is determined by the interception of magnetic field. The design of the magnetic circuit is also photographically scaled down. Figure 6(b) shows an axial profile of the radial magnetic flux density of both thrusters. The profile shows a similar profile of magnetic flux density by which the similar acceleration of ions is expected in the RAIJIN66 thruster.

IV.Conclusion

RAIJIN project is a collaborative activity in which several basic research for future electric propulsion has been conducted. On top of studies to develop various sub-components, such as cathode, PPU and operational technologies like a high voltage operation or the SBS clustering system, RAIJIN thruster heads are being developed.

RAIJIN94, which is a 5 kW class anode-layer type Hall thruster, was developed at Kyushu University and was tested.. It showed 64 % at an optimized magnetic field condition and indicated large T/P ratio up to 84mN/kW in the Isp range of 1200-2200 s through performance test and a high-Isp characteristics experiment. A downscaled RAIJIN66 thruster is also being developed at the University of Tokyo, which will be used to test some advanced technology. Its design was completed and the thruster experienced the first preliminary firing test.

The high power RAIJIN thruster will be combined with some developing technology and it will be expected to serve some advantages for Hall thruster system in future space missions.

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