Development Status of Power Processing Unit

For 250mN-class Hall Thruster

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Hiroyuki Osuga[*], Kentaro Suzuki[†], Toshiyuki Ozaki [‡], Takafumi Nakagawa[§],
Space System Department, Kamakura Works, Mitsubishi Electric Corporation,
325Kamimachiya, Kamakura, Kanagawa, 247-8520, Japan

Ikuro Suga[**], Taichiro Tamida[††]
Advanced Technology R&D Center, Mitsubishi Electric Corporation
8-1-1 Tukaguchi-honmachi, Amagasaki, Hyogo,661-8661,Japan

Yoshiyuki Akuzawa[‡‡], Fumitoshi Soga[§§], Hirokazu Suzuki[***]
Engineering Department, Kamakura Engineering Office, Mitsubishi Electric Engineering Company Limited,
730 Kamimachiya, Kamakura, Kanagawa, 247-0065,Japan

and

katsuaki Matui[†††]
Institute for Unmanned Space Experiment Free Flyer
2-12 Kanda-Ogawamachi, Chiyoda-Ku, Tokyo, 101-0052,Japan

Abstract: Mitsubishi Electric Corporation (MELCO) has been developing the next generation ion engine under the contract of Unmanned Space experiment Free Flyer (USEF) and Ministry of Economic, Trade and Industry (METI) for six years. The final target performance is that the thrust level is more than 250mN, specific impulse is more than 1500 sec under supplying the electric power less than 5kw and the lifetime is more than 3,000 hours according to requirement of a general commercial satellite. The next generation ion engine consists a hall thruster and a power-processing unit (PPU). In 2006, engineering model of the next generation ion engine was developed. The PPU consists of four power supplies for an anode discharge, a cathode keeper, two magnetic coils and a primary bus interface. The PPU has been performed as followings. An anode power conditioner efficiency is 94% for nominal 4.5kW at temperature between –20deg C to +55deg C. PPU interface performance that is to be stable operation, and to output hall thruster performance,

[*] Senior engineer, Space system Department, Osuga.Hiroyuki@ bx.MitsubishiElectric.co.jp
[†] Senior engineer, Mechanical engineering Department, Suzuki.Kentaro@eb.MitsubishiElectric.co.jp
[‡] Senior engineer, Space system Department, Ozaki.Toshiyuki@dr.MitsubishiElectric.co.jp
[§] Engineer, Space system Department, Nakagawa.Takafumi@dp.MitsubishiElectric.co.jp
[**]Manager, Power electronics System Department Center, Suga.Ikuro@ay.MitsubishiElectric.co.jp
[††]Senior Researcher, Power electronics Department, Tamida.Taichiro@aj.MitsubishiElectric.co.jp
[‡‡]Senior engineer, Engineering Department, Akuzawa.Yoshiyuki@ma.mee.co.jp
[§§]Senior engineer, Engineering Department, Soga.Fumitoshi@ma.mee.co.jp
[***]Engineer, Engineering Department, Suzuki.Hirokazu@ma.mee.co.jp
[†††]Senior Researcher, Advanced Satellite Project Department, matsui@usef.or.jp

is confirmed. And also the thruster could start up quickly and smoothly to control anode voltage, inner magnet current, outer magnet current and xenon flow rate. In this paper, the development status of PPU is reported.

Nomenclature

Q	=	mass flow rate, kg/seconds
Va	=	anode voltage, V
B	=	magnetic flux density, T
Ic	=	inner magnet current plus outer magnet current, A
G	=	gravitational acceleration, 9.8m/(seconds x seconds)

I. Introduction

Mitsubishi Electric Corporation (MELCO) developed the power processing unit for 20mN-class xenon ion thruster in 1989.[1] In recent years, geosynchronous satellites and spacecrafts with the hall thruster systems have been launched and operated by some countries.[2-7] In MELCO, the hall thruster propulsion systems are being developed as the next generation ion engine system under contract of Unmanned Space experiment Free Flyer (USEF) and Ministry of Economic, Trade and Industry (METI)[8-9] since 2003. The target of hall thruster propulsion systems is to achieve more than 250mN of thrust level and more than 1500sec of specific impulse under supplying less than 5.0kW of input power and a lifetime of more than 3000 hours. In 2004, we developed the development model PPU (DM PPU). In 2006, we developed the first engineering model of the PPU (EM 1 PPU). In 2007, we have designed the second engineering model of the PPU (EM2 PPU).

II. Outline of the PPU

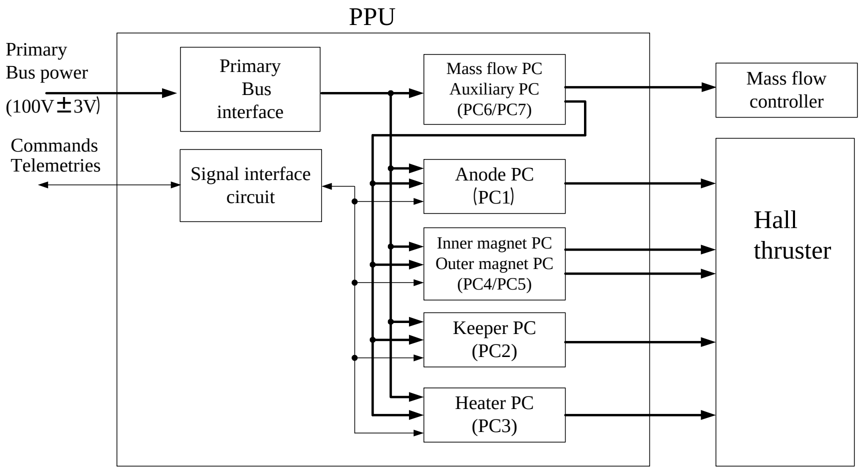
A. Construction of the PPU

A block diagram of the PPU and its electric interface to the halls thruster is shown in Figure 1. The PPU consists of the seven power conditioners (PC1 to PC7), signal interface circuit and primary bus interface. The power of these conditioners is provided through the input filter from primary bus interface. The signal interface circuit is the interface between the satellite communication bus and the PPU, in accordance with RS422 interface. The sequencer of the signal interface circuit automatically controls the thruster operation during start-up, stop, failure recovery, stable condition and surveys the thruster status. The hall thruster uses electric power to ionize the xenon propellant and produce thrust. The hall thruster needs five kinds of electrical interfaces (anode, cathode keeper, cathode heater, inner magnet and outer magnet). Each electric elements and mass flow controller require independent electric power conditioners. The electric power to anode, cathode keeper, cathode heater, inner magnet, outer magnet, and mass flow controller are supplied by the power conditioners PC1, PC2, PC3, PC4, PC5, and PC6 respectively. The auxiliary power conditioner (PC7) supplies printed circuit board of each power conditioner. The DM PPU consists of PC1 to PC7, primary bus interface part and signal interface part. The EM1 PPU consists of PC1, PC2, PC4, PC5, and primary bus interface part. The EM2 PPU consists of the same equipment as the DM PPU.

B. Requirements of the PPU

The PPU requirements are as follows;

1. Operating bus voltage: 100V$\pm$3V
2. PPU total efficiency: more than 92% (at 4.5KW of the anode conditioner output power.)
3. Operating temperature: -20 deg C to + 55deg C
4. The internal radiation environment for unshielded parts on the order of 1.0 X 10^4Gy (Si).
5. Sine vibration: 10Hz to 100Hz, 20 G
6. Random vibration: 10Hz to 2000Hz, 22.3Grms
7. Shock: 100Hz to 3000Hz, 1000G
8. Output requirements are as shown in Table1. (These requirements are the 250mN-class hall thruster.)



Remark: The EM1 PPU consists of PC1, PC2, PC4, PC5, and Primary Bus interface part.

Figure 1. The PPU block diagram and electrical interfaces

Table 1. Requirements of the PPU output

Symbol	Name	Voltage range (V)	Current range (A)	Ripple(%) P.P	Regulation(%) C.V *1 or C.C*2	maximum Power (w)	Efficiency (%) at maximum power
PC1	Anode PC	250～350	7～18	10	C.V ±5	4500	92
PC2	Keeper PC	25	0.5～1.0	5	C.C ±5	25	75
		100	0.01	25	C.V ±5	10	N/A
PC3	Heater PC	40	2.0～4.0	10	C.C ±3	160	85
PC4	Inner magnet PC	5	0.4～1.5	2	C.C ±3	8	30
PC5	Outer magnet PC	12	0.4～1.5	2	C.C ±3	20	30
PC6	Mass flow PC	10	0.4	2	C.V ±3	4	N/A
		-10	0.4			4	

Note. *1: C.V, constant voltage *2: C.C, constant current

Remark: The EM1 PPU consists of PC1, PC2, PC4, PC5, and Primary Bus interface part.

III. Design of the EM1 PPU

The requirement of the anode power conditioner was powered up from 3kW of the DM PPU to 4.5kW of the EM1 PPU. The development target of the EM1 PPU is adapted to the EM hall thruster and lightweight in comparison with the DM PPU. The target weight of the EM1 PPU is 11.0kg and the target power-mass ratio is more than 400W/kg. We used the metal oxide semiconductor field effect transistors (MOSFET) that were available as single event effect (SEE) radiation-hardened parts, in order to estimate the power efficiency of the EM1 PPU by using the same MOSFET parts of flight model PPU. It is an important to develop both an anode power conditioner and the keeper power conditioner, which supply electric power to the electric discharge load of the hall thruster. The power efficiency target of the anode power conditioner is more than 92% in order to achieve the PPU total efficiency. The internal radiation environment for unshielded parts has the order of 1.0 X 10^4Gy (Si). The power conditioner of the EM PPU followed the circuit method design of the DM PPU.

A. Anode power conditioner

The power converter topology was full-bridge type and rectifier circuit used current doubler technology. In order to reduce in size and weight, we developed two parts. First, the two main transformers mass were reduced 2.0kg from DM PPU. These main transformers were the ring-type cores (large-sized toroidal cores), made with the PC95 (a product made in TDK Corporation). The PC95 had advantage of small core loss over a wide temperature range. In addition, the toroidal cores improve the electrical and mechanical performance, because of the minimized leakage inductance and simple shap. These main transformers tolerated the shock test up to the level of 1000G. (under 0.002 seconds half sine). Furthermore, the pedestal of these transformers changed from glass epoxy to aluminum in order to improve thermal conductivity characteristics. Secondly, we developed a printed circuit board (PCB) having the high thermal conductivity with low thermal expansion characteristics and light weight. We implemented power-MOSFET on both sides of the PCB by using this PCB. By these improvements, the mounting area of the anode power conditioner part of PPU becomes 60% of the one on the DM anode power conditioner. Furthermore, this mounting method has advantage of reducing switching noises as a high-density merit of inverter PCB part of anode conditioner and making snubber circuits small.

B. Keeper power conditioner

At the DM PPU, we designed the main transformer with PQ type core, because of the high power and the high voltage conditioner design. However, PQ type core was almost three times larger than planar type core, therefore, the main transformer had been built with the planar type core to make the keeper conditioner small. The magnetic materials of this main transformer used the same PC95 materials as the anode conditioner. We selected the layer constitution of planner transformer, of which a self-resonance frequency was higher than switching frequency of the transformer, because of stabilizing response characteristics. Improved transformer of keeper power conditioner weighs 18g.

C. Inner magnet power conditioner and Outer magnet power conditioner

The inner magnet power conditioner and outer magnet power conditioner were dynamic current controlled buck, which interfaces with a load consisting of magnet coil. The outer magnet coil current was controlled and regulated by reference value given externally or internally by the signal interface circuit. The maximum current was 1.5A, and the maximum power was 20W. This power conditioner was required wide range load regulation and wide range controlled current from 0.2A to 1.5A. Therefore, we selected 2steps conversion method. This technique was called post regulator method. The first stage, an isolation converter changes the preliminary bus voltage to 15V. Second stage, the post regulator was buck (step-down) converter topology due to the post regulator requirements of high efficiency and wide range controlled current. The resistance value of the inner coil and outer coil increases by as the temperature of the hall thruster increases remarkably during the operation of the hall thruster. The magnet coil had very large inductance. We have carefully designed the current controlled loop.

D. Design of low-frequency discharge current oscillation

One of the most crucial problems for the practical applications of the hall thruster was discharge current oscillation. Although a constant DC voltage was applied, the thrust or discharge current oscillates, particularly in the frequency range from 8kHz to 100kHz. (low-frequency discharge current oscillation) [10-11] The low-frequency discharge current oscillation had an influence on a filter design of the anode power conditioner part of the PPU, a protection circuitry and the design of the control system. The low-frequency discharge current oscillation was important design impact for the choice of the electrical parts for anode output filters. On this account this low-frequency discharge current oscillation phenomenon became a more remarkable impact for a structure design of the PPU. The EM1 PPU had function to reduce of low-frequency discharge current oscillation of the EM1 hall thruster. We designed it to control three power conditioners at the same time to reduce low-frequency discharge current oscillation.

E. Mechanical Design

Mechanical design of the EM1 PPU is performed to achieve lightweight and low volume considering to minimize the temperature rise due to the high power parts.

The EM1 PPU is shown in Figure 2. External dimensions are 460mm x 333mm x 91mm (LxWxH) , and the mass is 9.50kg.

The power to mass ratio of the PPU EM1 is 4500W/9.5kg (473W/kg).

The maximum heat dissipation of the EM1 PPU was as high as 350W and the thermal design was the most critical design aspect.

The anode conditioner which had high power parts was located at the bottom of chassis made of aluminum alloy and the other low power conditioners are located at the upper and the side of the chassis.

Figure 2. External view of EM1 PPU

The electrical parts of the anode conditioner had very high dissipation. When these parts were mounted on the conventional PCB made with polyimide, the junction temperature of these parts will be beyond the allowable temperature. To solve this problem, the metal core PCB was applied to realize good thermal conductivity. This PCB had adequate CTE to mount large ceramic parts. The layout design of several conditioners is optimized to avoid thermal coupling of each conditioners. As the result, the junction temperatures of the electrical parts used in the EM1 PPU are lower than the allowable temperature. To meet the mechanical requirement of many satellite programs, the EM1 PPU was designed to withstand the mechanical environment as follows;

Sine vibration: 10Hz to 100Hz, 20 G
Random vibration: 10Hz to 2000Hz, 22.3Grms
Shock: 100Hz to 3000Hz, 1000G

We will verify the mechanical design by testing the qualification model PPU (EM2 PPU).

IV. Test results of the EM1 PPU

A. Electrical performance test

The performance of the EM1 PPU was evaluated for the items such as tested the output voltage stability or output current stability, the output ripple voltage or output ripple current, and the power supply efficiency by changing input voltage, and changing the load. The electrical performance results of the EM1 PPU satisfied all of the requirements. The power efficiency of the anode power conditioner was measured more than 94% at 4500W. The power efficiency of the keeper power conditioner was more than 67% in the output current range from 0.5A to 1.0A (at load impedance is 25ohm constant). The peak power efficiency of the keeper power conditioner was 79.8%.

The keeper power conditioner regulation mode tests were successful, and the EM1 PPU started and operated the electrical load of hall thruster without any difficulty.

The inner magnet power conditioner efficiency of more than 40% was achieved in the output current range from 0.8A to 1.5A(at impedance=5ohm). The outer magnet power conditioner efficiency of more than 60% was achieved over the output current range from 1.0A to 1.5A(with the impedance of 20ohm). The peak efficiency for the outer magnet power conditioner was 92.1% at 45W. The outer magnet coil impedance was larger than the inner magnet impedance. Therefore, the outer magnet power conditioner test results were better than the inner magnet power conditioner.

F. Thermal vacuum test

The output voltage versus output current is shown in Figure 3. The output power of anode power conditioner was stabilized over the wide range load and wide range temperature.

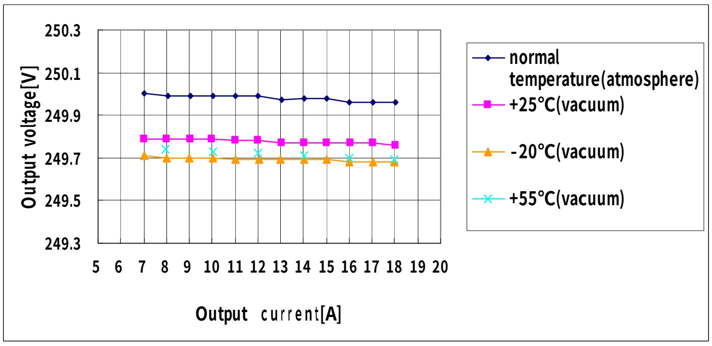


Figure 3. Load regulation of the anode conditioner

The power efficiency of the anode power conditioner versus output power is shown in Figure 4. The anode power conditioner power efficiency of more than 92% was achieved in the output power range from 1.8kW to 4.5kW. (At output voltage of 350V) On the other hand, the peak power efficiency for the BBM PPU was 96% for anode power conditioner at 3000W and the DM PPU was 92.6% at 3000W. [9] The power efficiency of the EM1 PPU had been 94.2%. The power losses of electrical parts of the BBM PPU were small, because the power-MOSFET drivers used on the BBM unit were not guaranteed to meet the required radiation levels and the rectifiers diode used on BBM unit were Sic-diode. In addition, the DM PPU and the EM1 PPU had used Si-fast recovery diode. The power efficiency of the EM1 PPU was better than the DM PPU, because the internal cable of the EM1 PPU was shorter than DM PPU, and the heat dissipation loss of the cable was very small. The EM1 PPU achieved high power efficiency and reduction in size and weight in comparison with the DM PPU.

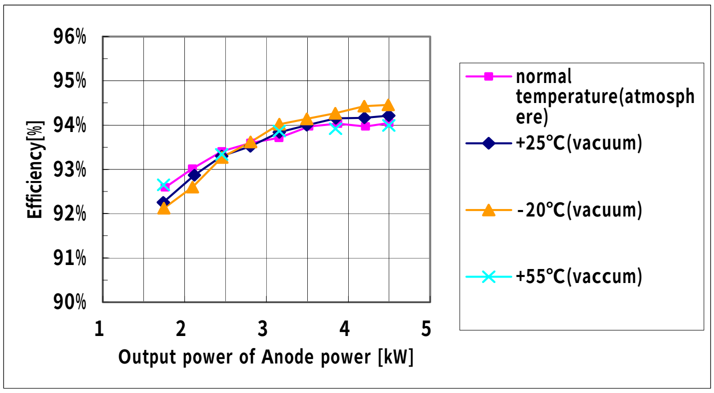


Figure 4. Power efficiency of the anode conditioner
(at output voltage :350V)

G. Coupling test of the EM1 PPU

We measured the discharge current responses of the hall thruster for various operating points. The examination item are a part of low frequency discharge current characteristics, power consumption versus the thrust level characteristics test. The EM1 PPU has been confirmed that the performance of the EM1 hall meets the specified requirements.

(1) Test configuration

The EM1 PPU coupling test configuration is shown in Figure 5. The DM PPU supplies the heater power conditioner and the auxiliary power conditioner. The EM1 hall thruster was installed in a 3 m diameter, 5m long vacuum chamber.

— Test conditions are as follows —

a. Pressure: $1.3x10^{-6}$ Pa (Background), $1.9x10^{-3}$ Pa (xenon: $1.46x10^{-5}$ kg/s)
b. PPU input voltage: 100 V
c. Anode voltage range: 250 V to 350 V
d. Inner/Outer magnet current: 0.4 A to 1.5 A
e. Keeper ignition voltage: 100 V
f. Keeper operating current: 1A
g. Heater current: 2.8 A
h. Thruster mass flow rate: $7.32x10^{-6}$ kg/S to $1.46x10^{-5}$ kg/s
i. Hollow cathode mass flow rate: to $9.76x10^{-6}$ kg/s

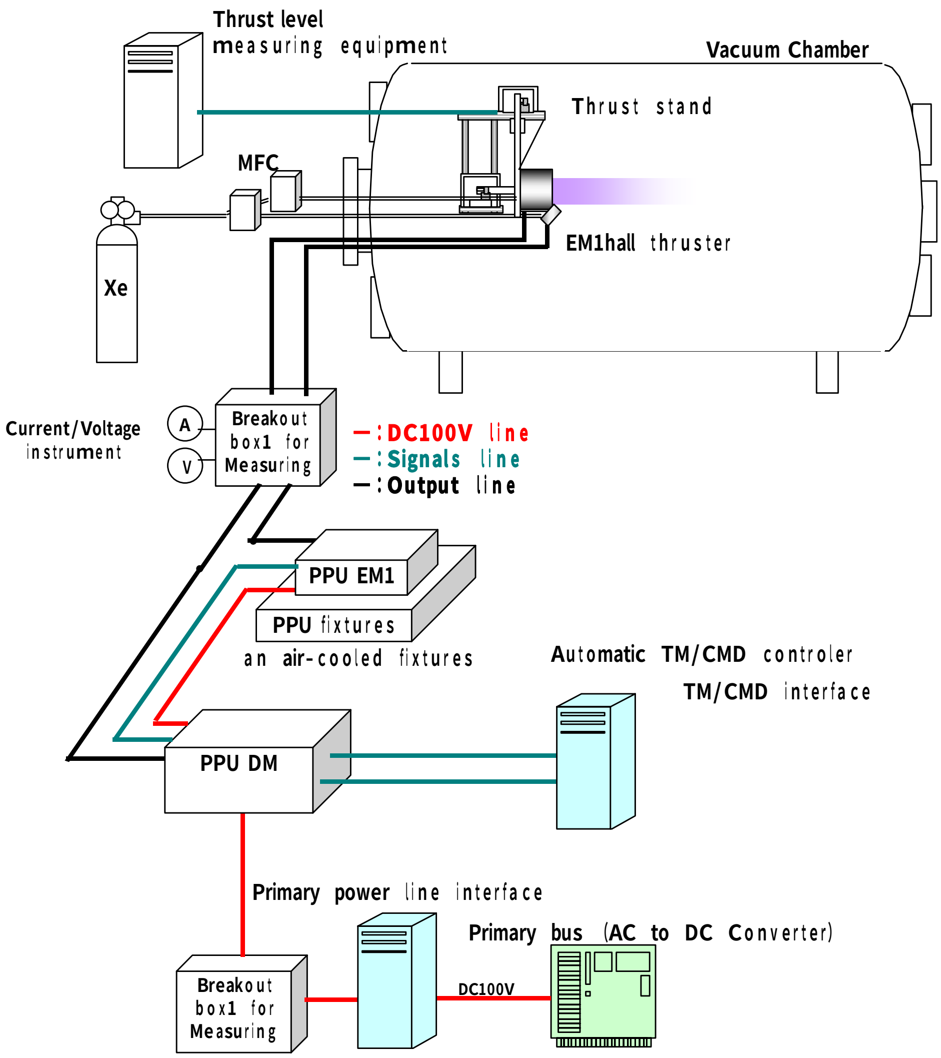


Figure 5. EM1 PPU coupling test configuration

(2) Behavior of a part of low frequency in discharge current characteristic

We evaluated a part of low frequency in discharge current with the EM1 hall thruster and the EM1 PPU. The EM1 hall thruster 250mN-thrust operation with the EM1 PPU is shown in Figure 6.

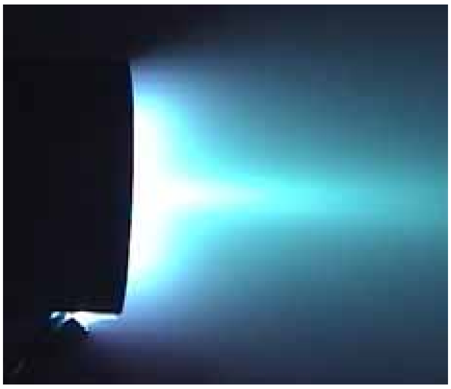


Figure 6. EM1 hall thruster 250mN-thrust operation with EM1 PPU

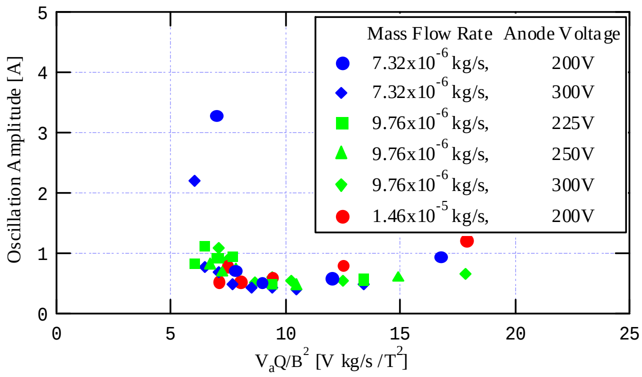


Figure 7. Behavior of a part of low frequency in discharge current characteristic

The amplitude measurement result of the part of low frequency in discharge current (or the discharge current oscillations) is shown in Figure 7. In Figure 7, the vertical axis shows the normal deviation value of the part of low frequency in discharge current of the anode current. And the horizontal axis shows the governing parameters, made from, the anode voltage (Va), the xenon gas mass flow late (Q) and the magnetic flux density (or inner magnet current plus outer magnet current are Ic). [10-11] The EM1 PPU could suppress the low-frequency discharge current amplitude in less than 1.5A. The EM1 hall thruster was confirmed work stability.

(3) A consumption power versus the thrust characteristic

Figure 8 shows the characteristics of the input power of PPU versus the specific impulse of the EM1 hall thruster. Figure 9 shows the characteristics of the input power of PPU versus the thrust level of the EM1 hall thruster. The EM1 thruster showed the thrust level was 251mN and the specific impulse was 1600 seconds when the PPU input power was 4606W. We achieved target performance.

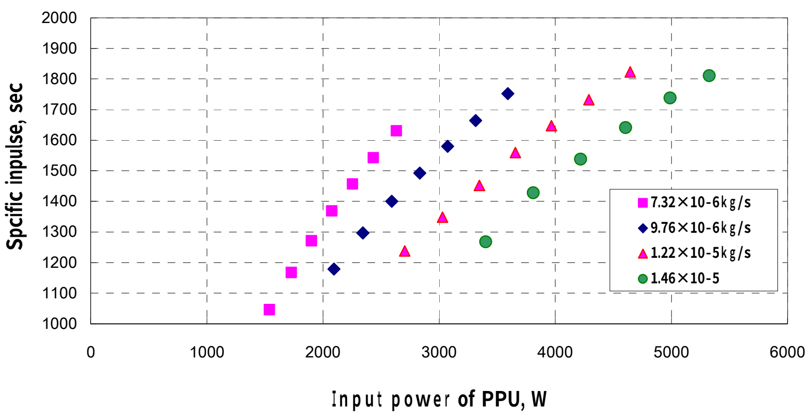


Figure 8. Specific impulse characteristics

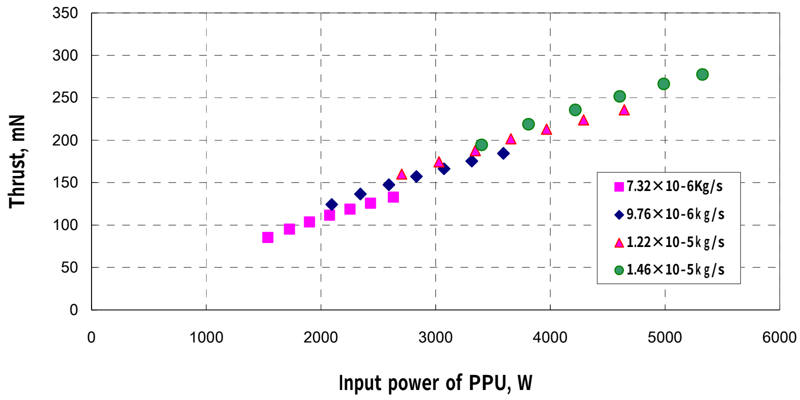


Figure 9. Thrust level characteristics

V. Future plan on the PPU

The EM1 PPU and the EM hall thruster will be operated for more than 3000 hours as life-test. In 2007, we are developing the EM2 PPU for qualification test. The EM2 PPU is developed on the basis of the development of this EM1 PPU, and power efficiency of the EM2 PPU is better than the EM1 PPU. We plan qualification test of the EM2 PPU and coupling test of the EM2 PPU with the EM thruster.

VI. Conclusion

The EM1 PPU has been performed to achieve lightweight and low volume. The EM1 PPU weight was 9.5Kg, and external dimensions were 460mm x 333mm x 91mm (LxWxH). The power to mass ratio of the PPU EM1 was 4500W/9.5kg (473W/kg). The hall thruster propulsion systems are achieved more than 250mN as thrust level and more than 1500sec as specific impulse under 5.0kW on input power. The EM1 PPU was satisfied with the requirement as well.

(1) Following subjects of PPU for 250mN-class hall thruster is described herein.
 -Requirement and function
 -Design of the EM1 PPU
 -Future plan on the PPU

(2) Following tests were all successful.
 -Electrical performance test with electrical load equipment
 -Thermal vacuum test with electrical load equipment
 -Coupling tests between the EM PPU and 250mN-class hall thruster

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