Experimental Study of a 1-MW-Class Quasi-Steady-State Self-Field Magnetoplasmadynamic Thruster

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[1]Kenji Miyazaki and [2]Syun Takenaka
Tokai University, Hiratsuka, Kanagawa 259-1292, Japan

[3]Ikkoh Funaki
Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 252-5210, Japan

and

[4]Hideyuki Horisawa
Tokai University, Hiratsuka, Kanagawa 259-1292, Japan

In order to develop of a 1-MW-class radiation-cooled steady-state Self-Field Magnetoplasmadynamic (SF-MPD) thruster head, Kawasaki et al developed a numerical design tool and thermal phenomenon of thruster head were modelized and numerically analyzed. This thruster is called as SF-MPD thruster ISAS 2013 model. An electrode of the thruster was designed that the cathode made of 1% La-W with outer diameter of 39 mm, length of 19.5 mm and the anode made of phosphor bronze with inner diameter of 80 mm, length of 80 mm. This study was conduct to experiments for thrust performance evaluation using the SF-MPD thruster that called as SF-MPD thruster ISAS 2013 model based on the numerical simulation. As an experimental results, the best performance of stable operating condition for an argon propellant at a mass flow rate of 1.8 g/s was not so high; a thrust efficiency of 18% and a specific impulse of 1,500 s at an input power of 1 MW. On the other hand, much higher performance was obtained for a hydrogen propellant at a mass flow rate of 0.4 g/s. A thrust efficiency of 37% and a specific impulse of 4,900 s were obtained for an input power of 1.3 MW.

Nomenclature

J	=	discharge current, kA
V	=	discharge voltage, V
F	=	thrust, N
F_{mag}	=	electromagnetic thrust, N
$\dot{m}$	=	propellant mass flow rate, g/s
η	=	thrust efficiency, %
I_{sp}	=	specific impulse, s
TP	=	thrust power ratio, mN/kW
r_a	=	anode radius, mm
r_c	=	cathode radius, mm
α	=	electrode shape factor, -
g	=	gravity coefficient, m/s^2
μ_0	=	magnetic permeability, H/m

[1] Graduate student, Department of Aeronautics and Astronautics, kenji.miyazaki.1991@gmail.com
[2] Undergraduate student, Department of Aeronautics and Astronautics.
[3] Associate Professor, Institute of Space and Astronautical Science.
[4] Professor, Department of Aeronautics and Astronautics.

I. Introduction

To enable a large-scale transport system in deep space, a propulsion system is desired to possess characteristic such as high specific impulse to increase payload ratio and high thrust to shorten mission periods. Magnetoplasmadynamic (MPD) thruster is a candidate system for such transportation system.

Figure 1 shows the operating principle of a Self-Field MPD（SF-MPD）thruster. SF-MPD thrusters obtain thrust by arc discharge to ionize propellant, and then the ionized gas is accelerated and injected [1)]. Thrust of a SF-MPD thruster consists of electromagnetic thrust and gas dynamic thrust. Electromagnetic thrust is due to the Lorenz force as an interaction between discharge current and the magnetic field induced by the current, and SF-MPD thruster utilize only induced magnetic fields by the arc discharge to generate a Lorentz force. In contract, gas dynamics thrust is due to Joule heating by the discharge.

A lot of SF-MPD thruster research and technology development were performed in the past [2)]. Previous studies of the SF-MPD thrusters focused surveying a high thrust performance. For propulsion other than lithium, however, MPD thruster performance has been limited to efficiencies below 40% and specific impulse below 4,000 s at 1 MW class electric power [3)]. On the other hand, thermal design of the thruster head to operate at 1 MW has not been made yet.

The goal of this study is to propose a thruster design of achievable a high performance and long life at a 1 MW class radiation-cooled steady-state operation. In order to propose the thruster design, research group of Kawasaki et al developed a numerical design tool by numerical simulation of MHD fluid phenomenon of plasma flow, electrode phenomenon and thermal phenomenon of thruster head were modelized, and numerically analyzed based on the assumption of two-dimensional axisymmetry [4)]. This thruster is called as SF-MPD thruster ISAS 2013 model.

In this study, we fabricated a SF-MPD thruster based on the numerical simulation called as SF-MPD thruster ISAS 2013 model and carried out experiments for thrust performance evaluation.

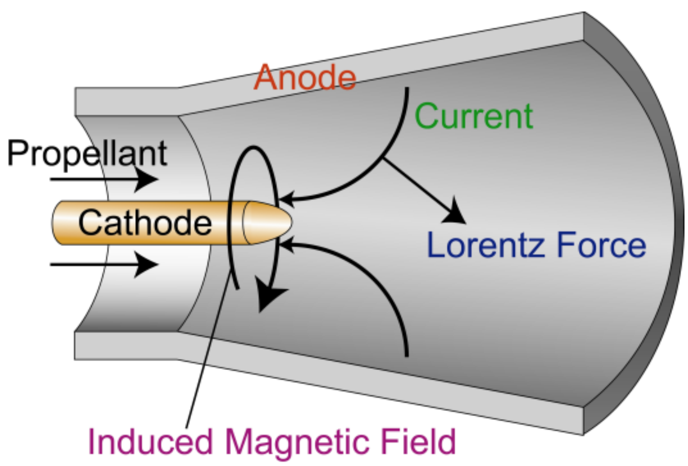


Figure.1 Operating principle of a MPD thruster.

II. Experimental Apparatus

Figure 2 shows the schematic view of the experimental apparatus for thrust measurement. This experimental apparatus consists of a vacuum chamber, an SF-MPD thruster and measuring devices. The vacuum chamber is 2 m diameter and 4 m length. During the experiment, the degree of vacuum is 1.0×10^{-3} Pa. Figure 3 shows the schematic view of SF-MPD thruster that called as SF-MPD thruster ISAS 2013 model, which was developed at ISAS. An electrodes with the cathode made of 1% La-W and the anode made of Cu.

Propellant gas is argon or hydrogen. Each mass flow rate was set to 1.8, 0.8 g/s, and 0.4, 0.7 g/s. Operation of a MPD thruster needs high voltage and high current. To meet such requirement, experiments were carried out in a quasi-steady-state operation whose duration is 1.32 ms by employing a Pulse Forming Network (PFN). Table 1 lists the experimental conditions in this study.

Measuring devices used in employing were a thrust stand, a CCD camera, a Rogowski coil and a current probe. Displacements of thrust stand were measured by a micro displacement sensor. Whole thrust measurement system was calibrated by known impacts. Discharge images were obtained by the CCD camera. Typical discharge images were shown in Figure 4. Discharge current waveforms were obtained by the Rogowski coil. Discharge voltage waveforms were obtained by the current probe. Typical discharge current waveform and voltage waveform was shown in Figure 5.

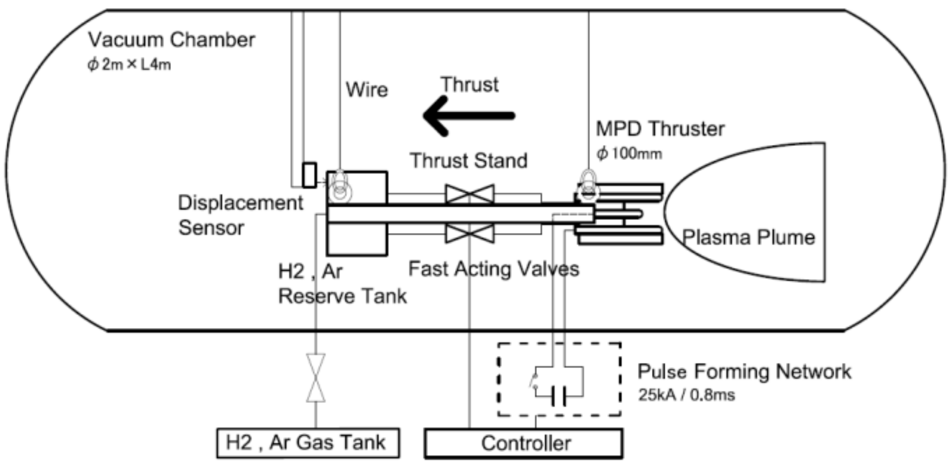


Figure.2 Schematic view of an apparatus for thrust measurement.

Table.1 Experimental conditions

Thrust head	SF-MPD thruster ISAS 2013 model
Type of propellant (Mass flow late)	Argon（1.8, 0.8 g/s） Hydrogen（0.7, 0.4 g/s）
Discharge current	5.0 kA ~ 14.5 kA
Discharge voltage	45 V ~ 220 V
Discharge duration	1.32 ms
Back pressure	1.0×10^{-3} Pa

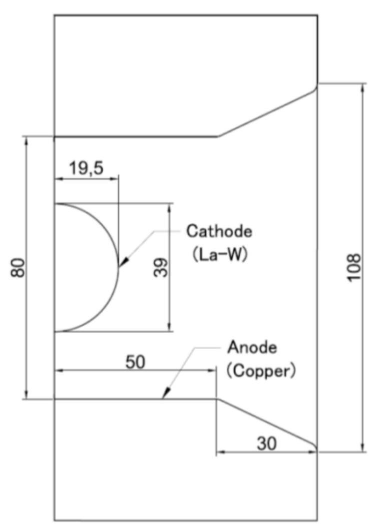
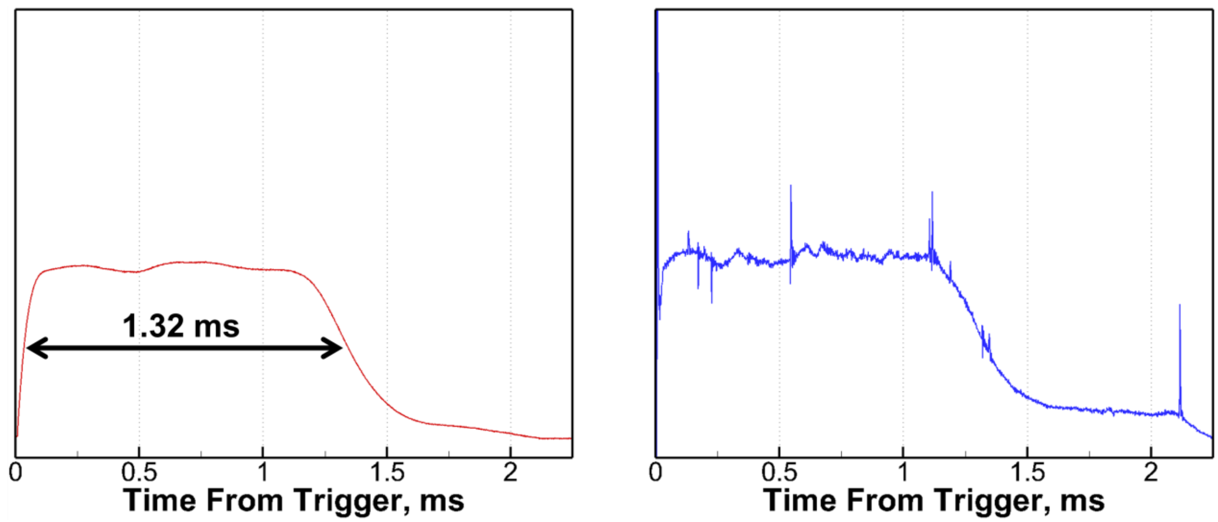


Figure.3 Cross sectional geometry of SF-MPD thruster ISAS 2013 model.

(a) Ar propellant at a mass flow rate 1.8 g/s and 3.75 kV charge voltage.

(b) H_2 propellant at a mass flow rate 0.7 g/s and 2.25 kV charge voltage.

Figure.4 Typical discharge images of SF-MPD thruster ISAS 2013 model.



(a) Discharge current waveform

(b) Discharge voltage waveform

Figure.5 Typical discharge waveforms
(A hydrogen propellant at a mass flow rate of 0.4 g/s and 2.25 kV charge voltage).

III. Experimental results and Discussion

Experimental results are shown by four graphs. These graphs are discharge voltage vs discharge current, thrust vs discharge current, thrust efficiency vs specific impulse and thrust efficiency vs input power. Thrust efficiency (η), specific impulse (I_{sp}) are defined as follows:

$$\eta = \frac{F^2}{2\dot{m}JV} \quad , \quad I_{sp} = \frac{F}{\dot{m}g} \qquad (1)$$

Figure 6 shows the discharge voltage vs discharge current characteristics. The measured discharge voltage data for a hydrogen propellant is higher than the data for an argon propellant. In addition, with decreasing mass flow rate, the voltage data become higher.

Figure 7 shows the relationship between thrust vs discharge current and theoretical electromagnetic thrust. Theoretical electromagnetic thrust is predictions based on Eq. (2).

$$F_{mag} = \frac{\mu_0 J^2}{4\pi}\left(\ln\frac{r_a}{r_c} + \alpha\right) \qquad (2)$$

The measured thrust data for a hydrogen propellant is higher than the data for an argon propellant, due to the existence of the gas dynamic thrust. Altogether, the gas dynamic thrust for a hydrogen propellant is higher than the thrust for an argon propellant. In addition, with increasing discharge current, the thrust data follow the theoretical electromagnetic thrust curve. Accordingly, then, the thrust is emphasis the theoretical electromagnetic thrust.

Figure 8 shows the relationship between thrust efficiency vs specific impulse and thrust power ratio. Thrust power ratio is defined as follows:

$$TP = \frac{F}{JV} \qquad (3)$$

The measured thrust efficiency and specific impulse data for a hydrogen propellant is higher than the data for an argon propellant, due to the large thrust generation for a hydrogen propellant, as shown in Figure 7. In addition, the maximum performance for a hydrogen propellant at a mass flow rate of 0.4 g/s is a thrust efficiency of 85% and a specific impulse of 12,000 s. Besides, the maximum performance for an argon propellant at a mass flow rate of 0.8 g/s is a thrust efficiency of 38% and a specific impulse of 4,100 s. Furthermore, there was not a limiting point to the thrust performance. In the studies so far, the performance for hydrogen propellant was MPD thruster performance has been limited to efficiencies below 40% and specific impulse below 4,000 s and there was a limiting point to the thrust performance [3].

Figure 9 shows the thrust efficiency vs input power characteristics. The maximum performance for a hydrogen propellant at a mass flow rate of 0.4 g/s is a thrust efficiency of 85% and an input power of 3.2 MW. In addition, the maximum performance for an argon propellant at a mass flow rate of 0.8 g/s is a thrust efficiency of 38% and an input power of 1.7 MW. As a trend, the thrust performance for a hydrogen propellant covered high power area. On the other hand, the thrust performance for an argon propellant covered low power area.

Finally, we describe a operating point of the best performance in a stable operating point. The stable operating point in this study is defined as operating at a stable discharge. Figure 10 shows the discharge images of SF-MPD thruster ISAS 2013 model at the stable (a,b) or unstable (c,d) operation points. In the images (a,b), localization of a discharge and erosion of the electrode material are not observed. On the other hand, it is observed in the images (c,d). Therefore, the operating condition of the images (a,b) is the operating points of the best performance in the stable operation points. The best performance for an Ar propellant at a mass flow rate 1.8 g/s was a thrust efficiency of 18 % and a specific impulse of 1,500 s at an input power of 1 MW. In addition, the best performance for a hydrogen propellant at a mass flow rate 0.4 g/s was a thrust efficiency of 37 % and a specific impulse of 4,900 s at an input power of 1.3 MW.

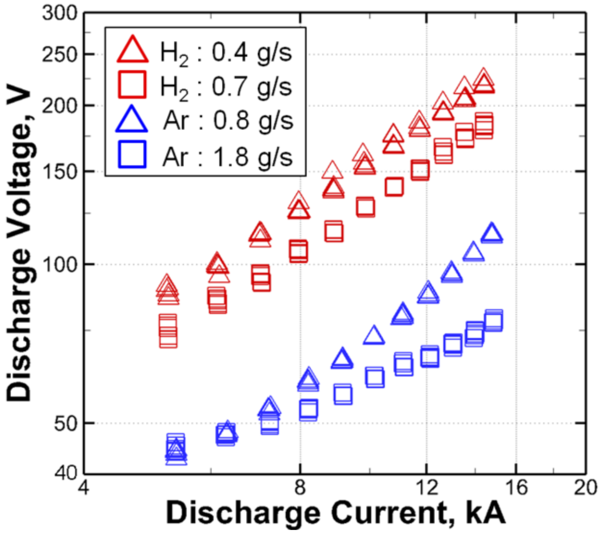


Figure.6 Discharge voltage vs discharge current characteristics.

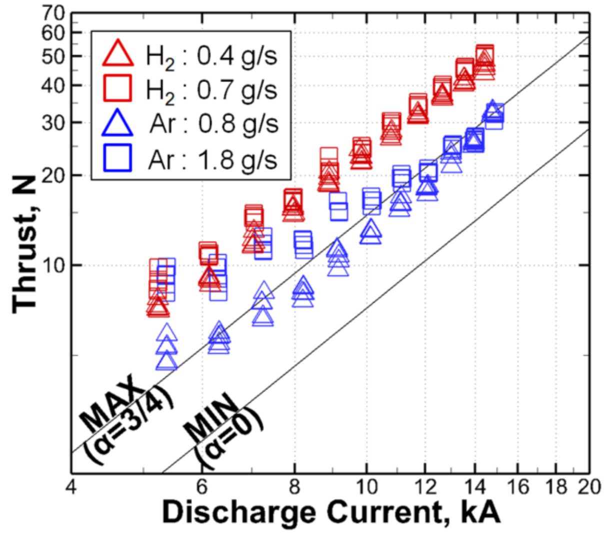


Figure.7 Relationship between thrust vs discharge current and theoretical electromagnetic thrust.

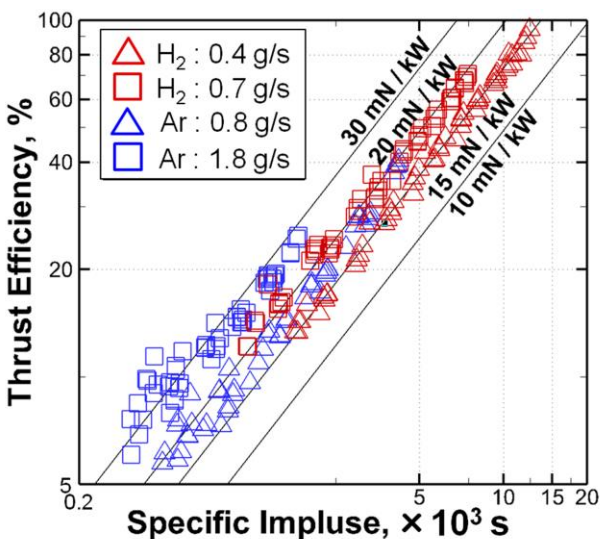


Figure.8 Relationship between thrust efficiency vs specific impulse and thrust power ratio.

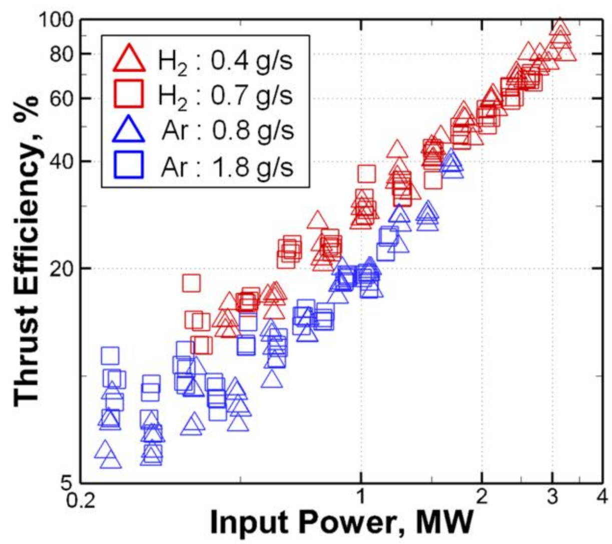
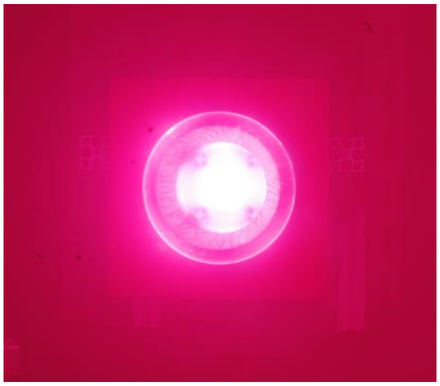


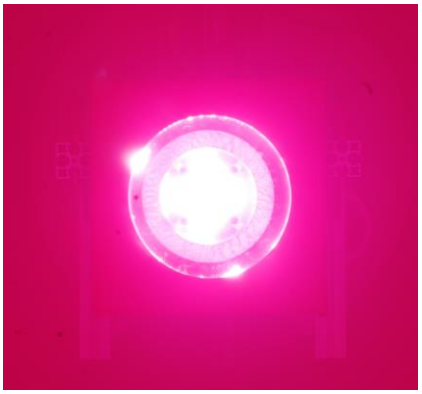
Figure.9 Thrust efficiency vs input power characteristics.

(a) Ar propellant at a mass flow rate 1.8 g/s and 3.75 kV charge voltage.



(b) H_2 propellant at a mass flow rate 0.4 g/s and 2.5 kV charge voltage.

(c) Ar propellant at a mass flow rate 1.8 g/s and 4.00 kV charge voltage.



(d) H_2 propellant at a mass flow rate 0.4 g/s and 2.75 kV charge voltage.

Figure.10 Discharge images of SF-MPD thruster ISAS 2013 model at a stable (a,b) or unstable (c,d) operation points.

IV. conclusion

In this study, we fabricated a SF-MPD thruster called as SF-MPD thruster ISAS 2013 model based on the numerical simulation[4)] and carried out experiments for thrust performance evaluation.

The maximum performance for a hydrogen propellant at a mass flow rate of 0.4 g/s is a thrust efficiency of 85% and a specific impulse of 12,000 s at an input power of 3.2 MW. In addition, the maximum performance for an argon propellant at amass flow rate of 0.8 g/s is a thrust efficiency of 38% and a specific impulse of 4,100 s at an input power of 1.7 MW.

Furthermore, the best performance of stable operating condition for an Ar propellant at a mass flow rate 1.8 g/s was a thrust efficiency of 18 % and a specific impulse of 1,500 s at an input power of 1 MW. In addition, the best performance of stable operating condition for a hydrogen propellant at a mass flow rate 0.4 g/s was a thrust efficiency of 37 % and a specific impulse of 4,900 s at an input power of 1.3 MW.

As a future work, we will carry out experiments for electrode temperature measurement.

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