# EFFECT OF APPLIED MAGNETIC NOZZLE IN A QUASI-STEADY MPD THRUSTER

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## Abstract

An axial diverging magnetic nozzle is applied to a quasi-steady MPD thruster by using of a pulse coil, and the effect of the magnetic nozzle to the thruster performances has been studied. This study is conducted for propellant gases of $H_2$, He, $N_2$, Ar and $NH_3$ in 3 kA ~ 10 kA of the arc current, and the axial magnetic field of the applied nozzle is up to 0.45 Tesla at the cathode tip position. The thrust impulse is measured by pendulum method, and heat flux into the anode and the cathode is measured calorically during the periodical pulse firing operation in a strictly constant frequency of 0.5 Hz. Power deposition in the quasi-steady MPD thruster is discussed. In order to clarify the plasma flow profile, the distributions of ion number density and electron temperature are measured by use of a double Langmuir probe which is insulated completely from the thruster system. By applying the magnetic nozzle, an azimuthal acceleration force rotates the discharge plasma flow, and spreads it to radial direction. The distribution profile of the arc current in the discharge channel is changed by induced azimuthal current, and after the ionization of the propellant gas is stimulated especially near the anode surface. Maximum thrust enhancements are 50 % for nitrogen, 70 % for hydrogen and 80 % for ammonia in compared to the thrust of the self-field type. The optimum operational condition to improve the thruster performance exists in the applied magnetic field strength and the arc current in below Alfven's critical operational current. The optimum arc current value is different for the propellant species, and depends on the mass flow rate. With increasing the arc current or the magnetic nozzle strength over this optimum value, the magnetic effect for the thrust improvement goes down and the obtained thrust approaches to the thrust in self-field type without the magnetic nozzle. This tendency is founded in any propellant condition. By applying the magnetic nozzle, plasma input power is increased with addition of the plasma rotational energy, and approaches to the critical ionization input power predicted by a minimum energy principle of plasma ionization in operation below the critical arc current value. The anode deposited energy is remarkably increased by increasing the plasma rotational energy, and caused to increase the arc voltage. The cathode power deposition is not so much affected by applying the axial magnetic field due to small ion Hall parameter, and like as it in a cold cathode arc discharge as same as in the self-field type.

In this study, the enhancement of the thrust to the operational input power has been discussed, which are 12 % ~ 36 % for hydrogen, 10 % ~ 16 % for nitrogen and 14 % ~ 16 % for ammonia. Hydrogen and hydrogen compound gas, e.g. ammonia and hydrazine, are advantageous to reduce the electrode power loss, and also to keep well in compressional storage as a preferable propellant species for advanced MPD propulsion system.

## Introduction

A quasi-steady Magneto-Plasma-Dynamic (MPD) thruster has the performances of high Isp and large thrust density, and it is a simple and a reliable device suitable for an interplanetary thruster in Mars mission or other deep space missions. And in addition, this device is applicable as an advanced high-speed plasma source for material processes and plasma ion plating[1]. Electro-magnetic body force of the MPD thruster is induced by the interaction between the arc current $\boldsymbol{J}$ and its self-induced magnetic field, and it is effectively improved by increasing the operational arc current above a few kilo amperes. Such high current arc operation is easily attained by using a pulse forming network of a capacitors bank (PFN) in periodically repetitive firing of the quasi-steady pulse discharge. In practical problems in the development, Increasing of the operational arc current is limited by ionization critical to bring an unstable arc discharge and vigorous erosions of the arc discharge electrodes. The critical value is derived from the rules of Alfvn's critical ionization and electromagnetic acceleration [2]. In the present study, an axial magnetic diverging nozzle is applied to the discharge section in order to improve the thruster performance under the operational condition in less than the critical current. A discharge plasma of MPD thruster is axially accelerated by $Jr{\times}B_{\text{è}}$, where $Jr$ is a radial current and $B_{\text{è}}$ is a self-induced azimuthal magnetic field[3]. In addition, applying the magnetic nozzle provides two more axial acceleration of the plasma flow. An azimuthal electromagnetic force $Jr{\times}B_z$ rotates the discharge plasma, and the azimuthal rotation energy converts to axial energy in the diverging section[4]. Electron Hall current $J_{\text{è}}$ induced by the magnetic nozzle interacts with $B_r$, and accelerates the plasma to axial direction.

The objective in this study is to clarify an optimum design of the magnetic nozzle and operational conditions in less than the critical operation limit. Thrust performance and power deposition of MPD thruster is measured and discussed.

## Experimental apparatus and technique

The quasi-steady MPD thruster is mounted on a thruster stand and installed in a vacuum chamber. The back pressure is kept to 0.1 Pa during the periodical pulse firing operation of 0.5 Hz, and about 0.01 Pa in a single pulse firing for the thrust measurement. The experimental system is shown in Fig. 1**.** PFN-1 is a primary pulse power supply and PFN-2 is an exclusive power supply for the magnetic nozzle coil. PFN-1 is charged up to 250 volt (3.0 kJoule), and operated with a quasi-steady rectangular current pulse up to 10 kA for the arc pulse width of 1.5 msec.

The magnetic nozzle is driven by the PFN-2, and provides the field strength of the nozzle up to 0.45 Tesla at the cathode tip position. The propellant gas pulse is injected into the discharge section from the pressure reservoir through two fast-acting valves (FAV). The mass flow rate is adjusted by the reservoir pressure and the orifice diameter. The propellant mass flow rates are provided from the equivalent critical current value $J_{crit}$ of 5 kA, 10 kA and 15 kA of $H_2$, He, $N_2$, Ar and $NH_3$ as shown in Table 1. Each driver unit is controlled with the delayed trigger commands by the operational control unit, and the time sequence of the arc discharge is strictly controlled in the periodical firing operation and the single firing operations, respectively.

The MPD thruster has a straight-diverging cylindrical anode, the exit diameter of 89 mm and a half angle of 20 degree in the diverging part as shown in Fig. 2. In generally, such a pulsed magnetic nozzle induces an azimuthal eddy current on the anode surface and causes a self-distortion of the applied magnetic nozzle configuration. In order to avoid the distortion of the magnetic nozzle, the anode is axially slitted to cut an azimuthal eddy current loop. A cylindrical cathode, made of 2 % thoriated tungsten, is 18 mm long and 9.5 mm in diameter at the discharge section.

The arc discharge is triggered by a small pulse discharge between the cathode and the trigger electrode of 2 kilo volt and 5 ì sec of the pulse width driven by the ignition driver. This ignition breakdown, which is synchronized to the propellant injection into the discharge section, provides a seed plasma jet in a gap between the anode and the cathode and after the main arc discharge is derived. In the measurement of the thrust performance and plasma characteristics, another matching free type of PFN-1 is used. This type of PFN-1 provides a quasi-steady constant arc

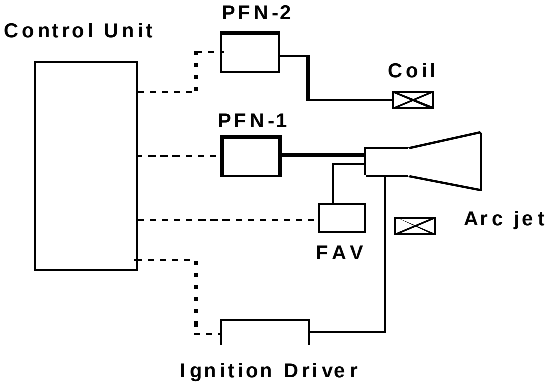


**Fig. 1 Block diagram of operational system.**

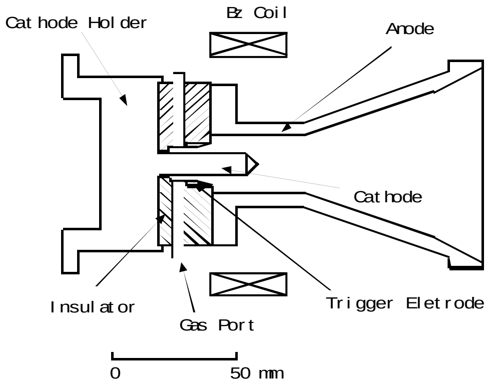
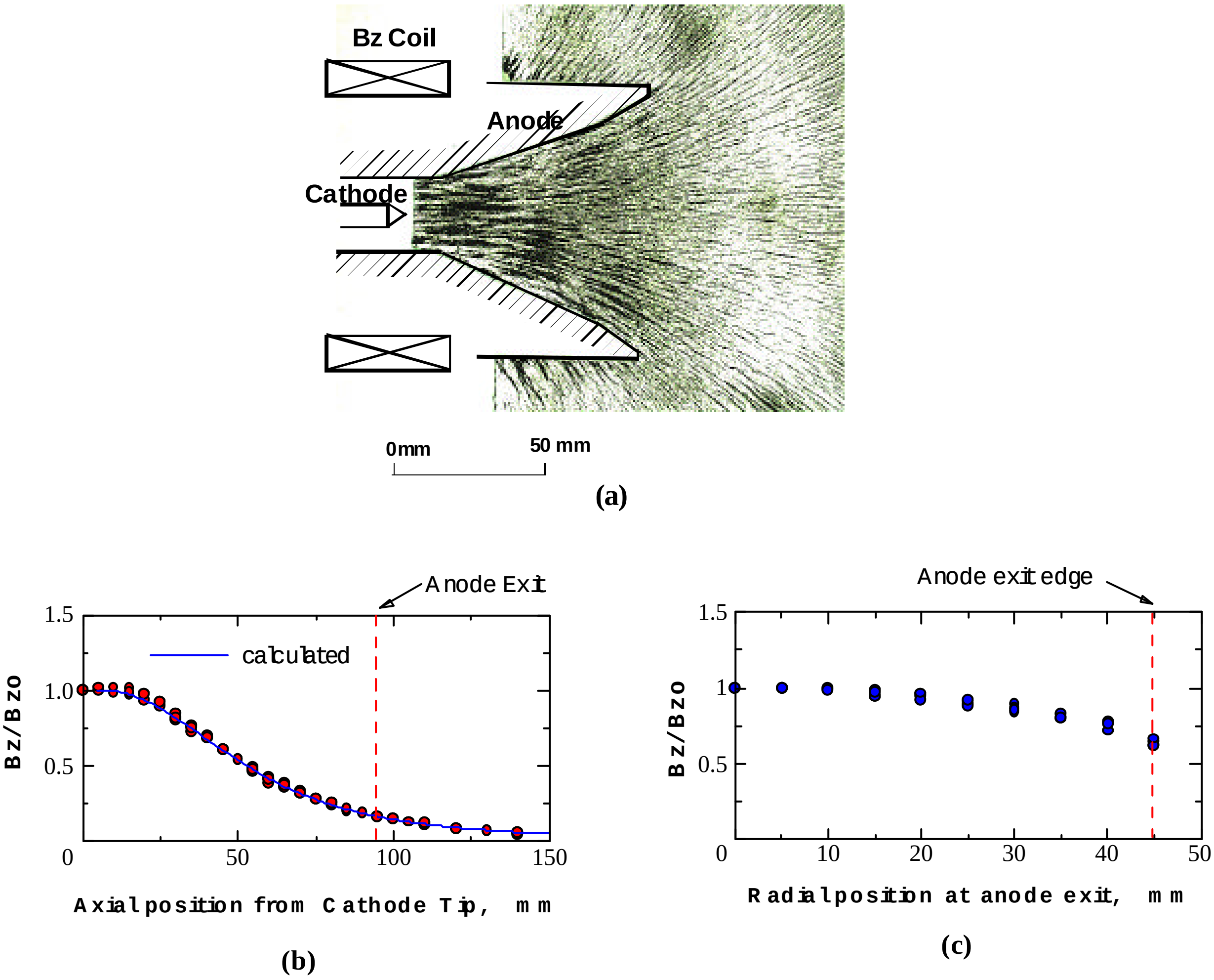


**Fig. 2 Cross section of a MPD arc jet with applied magnetic nozzle.**

**Table 1 Propellant gas conditions.**

| $J_c$ | 5 kA | 10 kA | 15 kA |
|---|---|---|---|
| *Ar* | **0.7** | **3.1** | **7.0** |
| $N_2$ | **0.5** | **2.7** | **4.6** |
| $H_2$ | **0.14** | **0.7** | **1.5** |
| *He* | **0.2** | **1.1** | **2.0** |
| $NH_3$ **(mix)** | **0.3** | **1.4** | **2.6** |

**(g/sec)**



(a)

(b)

(c)

**Fig. 3 Profiles of applied axial magnetic nozzle.**

current by a matching dummy load connected in series, and keep the quasi-steady operational current range widely and strictly. The pulse coil of the magnetic nozzle has an in-diameter of 100 mm and 50 mm long. The quasi-steadily current is applied to the coil up to 1000 Amperes by use of PFN-2. A semiconductor switch (CR250J-24) is used to synchronize with other operational driver units.

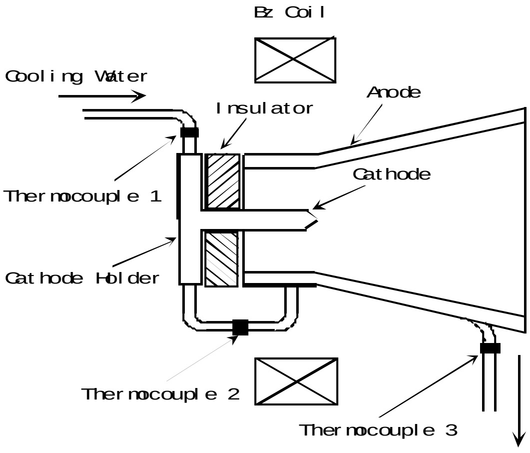


**Fig. 4 Measurement of electrode power loss and power deposition.**

The magnetic nozzle is just applied quasi-steadily to the discharge section during the quasi-steady arc discharge. The magnetic nozzle profile is shown in Fig. 3(a), which is drawn by use of iron powder. Figure 3(b) and 3(c) show the axial and radial direction profiles of axial component **Bz** of the applied magnetic fields by the ratio to **Bzo** at the cathode tip position or at axial position of anode exit. The magnetic field is measured by a magnetic probe (F.W.Bell BH-203). The magnetic field line of the nozzle is along the solid-nozzle wall and the maximum part of axial gradient for the applied magnetic field is located at the central region of the anode discharge section (45 mm from the cathode tip).

The thrust impulse is measured by pendulum method[5]. The thrust stand is suspended, and its displacement is detected with a linear differential transducer. The thrust impulse is previously calibrated by known impulse with steel ball impacts. Tare force, that is, interaction force caused by current loop of thruster cable and the coil power cable, is estimated and subtracted in the thrust calibration. Such electromagnetic interaction forces are estimated by shorting the anode terminal to the cathode terminal. In this study, the tare force by the thruster cable is negligibly small compared with the thrust impulse. The tare force of the coil cable increases with increasing the square of the coil current but the tare impulses of it is less than 10 % compared with the thrust impulse.

In order to clarify the plasma flow profiles, electron temperature and ion number density are measured by use of a double Langmuir probe which is insulated completely from the MPD thruster system. An isolated power synthesizer (NF WF1943) is used to sweep the probe voltage from -70 volt to +70b volt in 10 kHz of the frequency. The probe voltage and the probe current are measured by an isolation amplifier (NF-5323) and an isolated current probe (IWATSU CP-522), and recorded by a digital synchroscope (Lecroy 9304AM). Ten sweeping of the probe voltage are conducted during one pulse of quasi-steady arc discharge.

The anode and the cathode are thermally isolated each other, and heat flux into the anode and the cathode are respectively measured calorically by the use of a water-cooled MPD thruster. The thruster is also thermally isolated from the thruster stand to avoid an error in the heat flux measurement. The cooling water pipes are furnished on the cathode holder and the anode outer surface as shown in Fig. 4. The water temperatures at the inlet and the outlet (thermocouple 1 ~ 3) and the water flow rate are measured during the periodical pulse firing operation in a strictly constant period of 2 seconds (0.5 Hz of the operational frequency)[5]. The pulsative arc current and the arc voltage are measured reliably with a Rogowski coil and an isolated amplifier (NF-5323), and recorded by a synchroscope (Lecroy 9304AM). The input power of the quasi-steady arc discharge is evaluated rigorously from the arc current and arc voltage waveform data.

## Results and discussion

The electromagnetic thrust components in the self-field type are blowing and pumping forces as shown in Fig. 5(a), and the total electromagnetic thrust $\boldsymbol{F_{th}}$ is given as following formula[3].

$$F_{th} = (m/4p)J^2[\ln(r_a/r_c)+0.75] \qquad (1)$$

A formula of the electromagnetic thrust by an applied magnetic field has not been obtained, yet. Two interaction processes of the axial acceleration are considerable in the discharge section as shown Fig. 5(b). One is swirl motion of the plasma flow caused by $\boldsymbol{J_r \times B_z}$. The rotational flow energy converts into the axial motion energy according to the conservation law of the particle kinetic energy and the rotational momentum. The axial acceleration due to the swirl motion depends on the magnetic nozzle strength and axial gradient of the applied magnetic field[7].

$$f_{swirl} = -\frac{1}{2}\frac{mU_q^2}{B}\frac{\partial B_Z}{\partial Z} \qquad (2)$$

Another acceleration is caused by an induced azimuthal current $\boldsymbol{J_è}$ due to $\boldsymbol{E_r \times B_z}$ electron drift, which so-called Hall current. The Lorentz force of $\boldsymbol{J_è \times B_r}$ is axial body force and works in the same manner as the blowing force, also the radial body force of $\boldsymbol{J_è \times B_z}$ acts as a pumping force. The axial body force of $\boldsymbol{J_è \times B_r}$ does not improve on the thrust due to $\boldsymbol{B_r << B_z}$ in the discharge section.

The plasma ionization and dissociation are enhanced with the azimuthal motion and Hall current, and also the stability of the arc discharge is remarkably improved.

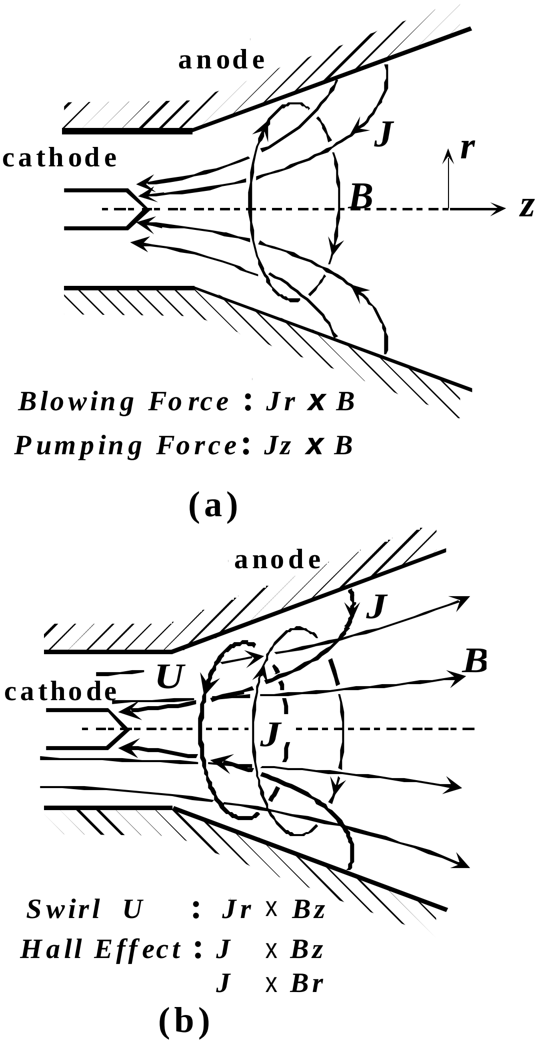
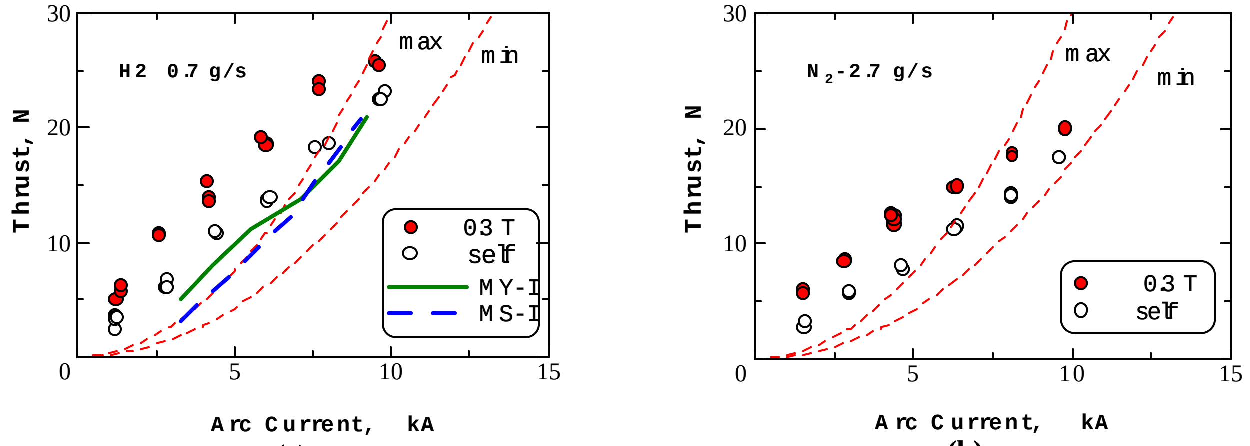
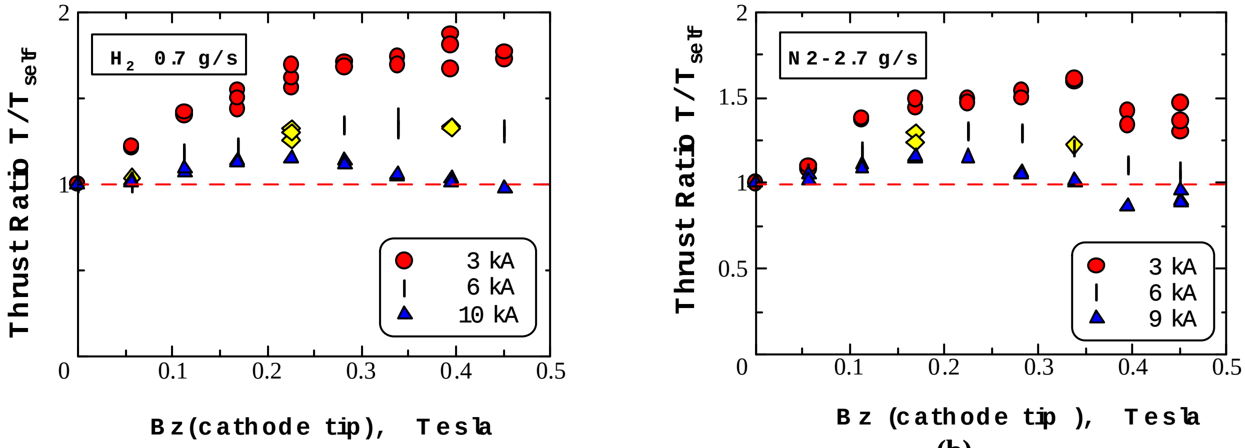


**Fig. 5 Production of electromagnetic force.**



(a) (b)

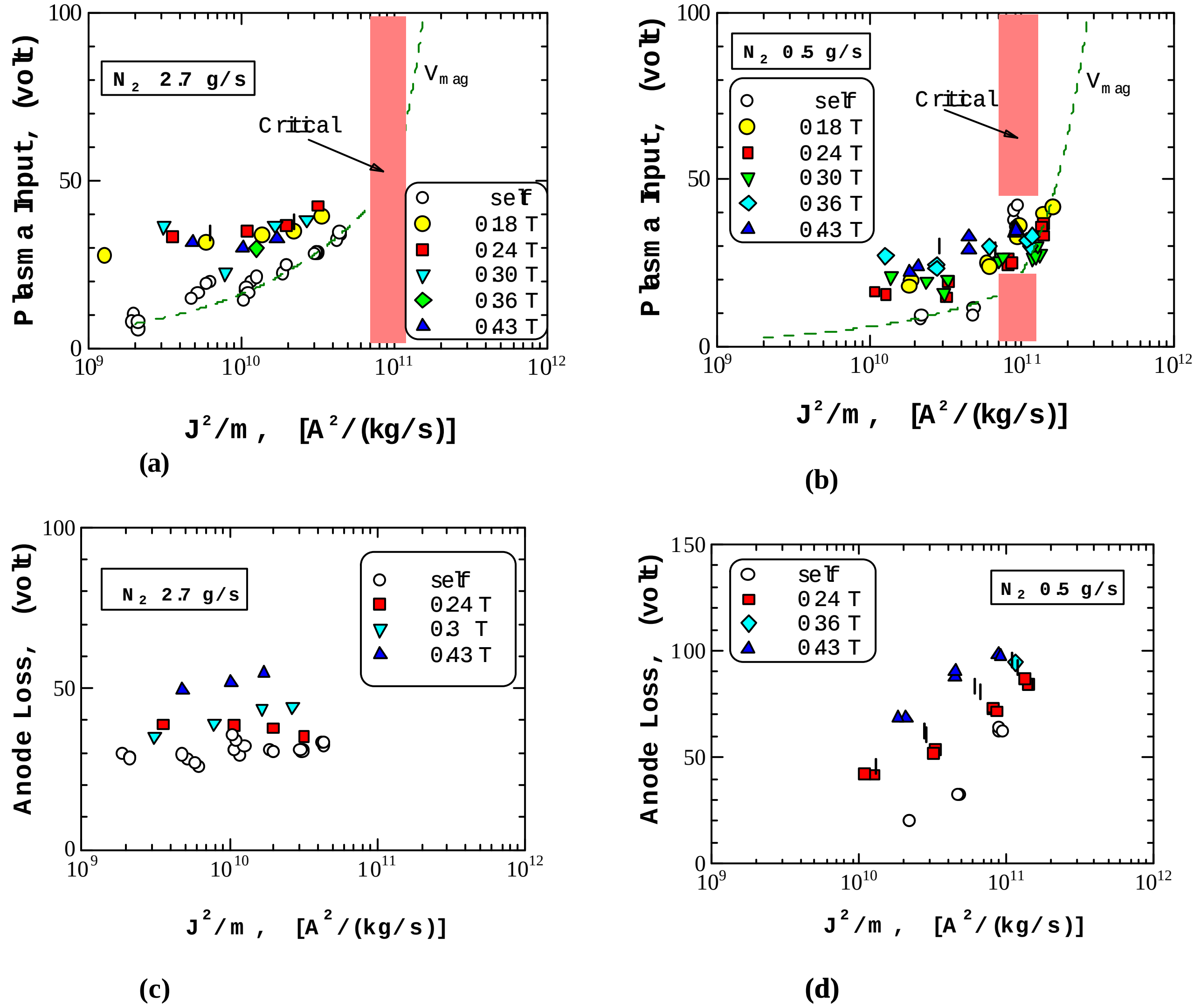
**Fig. 6 Thrust improvement by a magnetic nozzle.**



(a) (b)

**Fig. 7 Thrust enhanced ratio by a magnetic nozzle.**

Thrust data are obtained by fixing the magnetic nozzle condition and varying the arc current for each kind of propellant gas. The magnetic nozzle effects to improve the thrust have been confirmed for each propellant species. Figure 6 shows for hydrogen of 0.7 g/sec and nitrogen of 2.7 g/sec. The dash lines indicate the predicted thrust value of an electromagnetic acceleration in Eq. (1). The min and max lines correspond for the different anode radius of the cylindrical part and divergent exit, respectively. Our previous data of self-field MPD thruster(MY-I and MS-I)[7][8] are compared together. As shown in Fig.6, thrust increasing effect of the magnetic nozzle is remarkable with increasing the arc current. But in the middle of increasing arc current level, the nozzle effect reaches a maximum enhancement, and after the nozzle effect goes down and the thrust are coming close to the self-magnetic thrust with more increasing the arc current closing to the critical current level $J_{crit}$. Enhanced thrust ratio of with/without magnetic nozzle is discussed for varying the magnetic strength of the nozzle up to 0.45 Tesla, which is the value at the cathode tip position. The operational arc current is fixed at 3 kA, 6 kA and 10 kA in Fig. 7. Applied magnetic nozzle works effectively to improve plasma acceleration and increase the thrust up to 70 % for hydrogen and 50 % for nightrogen at 3 kA of the arc current. But the optimum operational condition exists for the magnetic nozzle strength and the arc current, and with increasing the operational current and nozzle strength more over, the thrust ratio goes down and coming close to the self-field operational thrust. These tendencies are also founded in any other propellant gas and remarkable in large mass flow rate operation.



(a)

(b)

(c)

(d)

**Fig. 8 Equivalent voltage of anode loss and plasma input power for $N_2$ of 0.5 g/sec and 2.7 g/sec.**

Applying the magnetic nozzle increases the arc voltage or the arc input power for the same operational current comparing with it in self-field. In excessive increasing of nozzle strength, the input power loss of the arc discharge increases remarkably.

To reveal the power deposition as for anode power loss, cathode power loss and plasma input power with increasing the magnetic nozzle strength, the heat flux into the anode and the cathode are measured calorically in the periodical firing operation. The deposited powers are discussed with exchanged equivalent voltage respectively. The voltage of the cathode loss is slightly affected and increased by increasing of the nozzle strength, but for increasing arc current, the results are in almost constant value 15 ~ 25 volts and independent of it. This cathode result is caused by cold cathode arc phenomena[9] and provided by cathode fall and its work function as like in high current pulsed arc discharge. The major carrier component of the arc discharge is ion in the vicinity of the cathode surface, and this result is caused by the Hall parameter of ion.

Figure 8 show the equivalent voltage of anode loss and plasma input for a current parameter $J^2$/m for fixing the nozzle strength from 0.24 T to 0.43 T. The mass flow rate of 0.5 g/sec and 2.7 g/sec correspond to the equivalent critical current of 5 kA and 10 kA for nitrogen, respectively. Heat flux measurement is conducted up to 10kA of arc current. As shown in Fig. 8(a), the plasma input voltage is increase to 30 ~40 volt with applied magnetic nozzle, and almost independent to the arc current, and approaches to the critical value which coming close to it in self-field operation. This is caused by stimulated ionization of the propellant due to azimuthal acceleration and the induced Hall current, and even in a low current, this is remarkable in large mass flow rate. And also same results are observed for other species of the propellant. In the rate of 0.5 g/sec, the plasma input voltage is increased with the nozzle strength and the

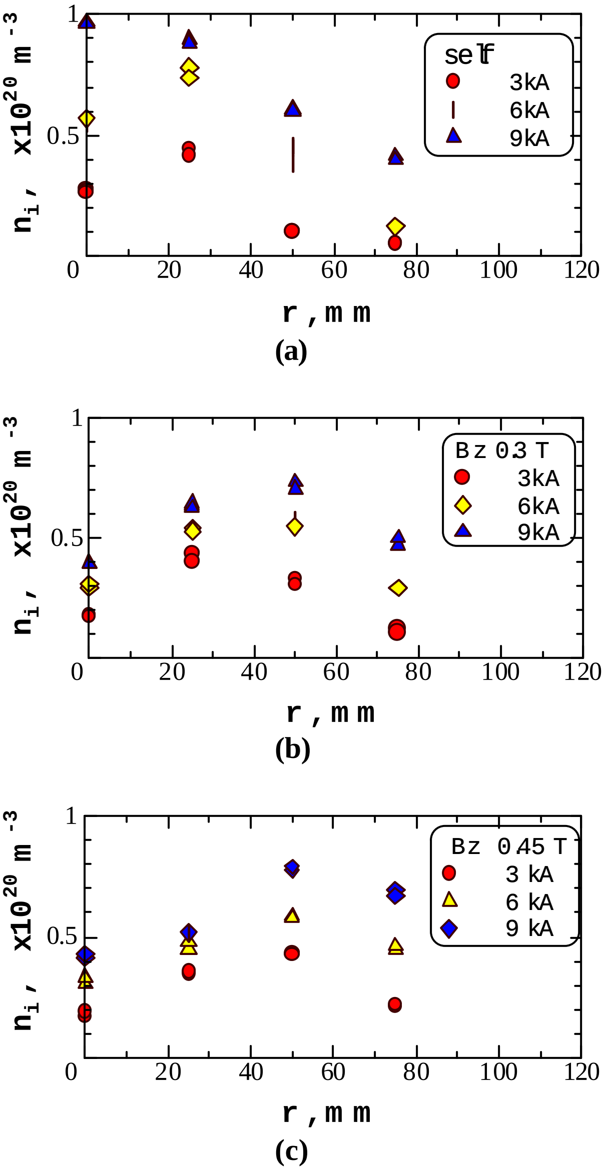
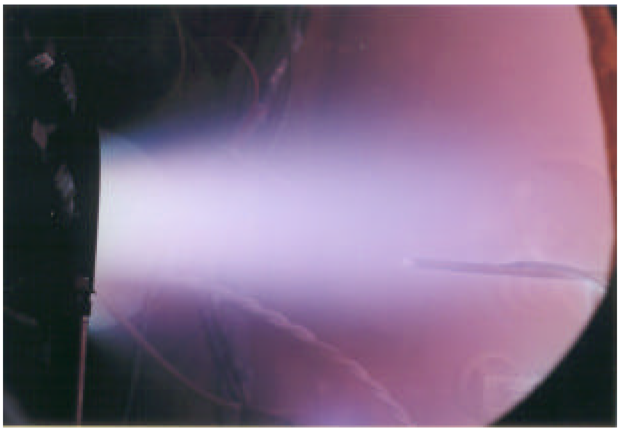


**Fig. 9** Radial distributions of ion number density at 100 mm from anode exit, (a)self-field, (b)0.2 T and (c)0.45 T of applied nozzle strength at the cathode tip.

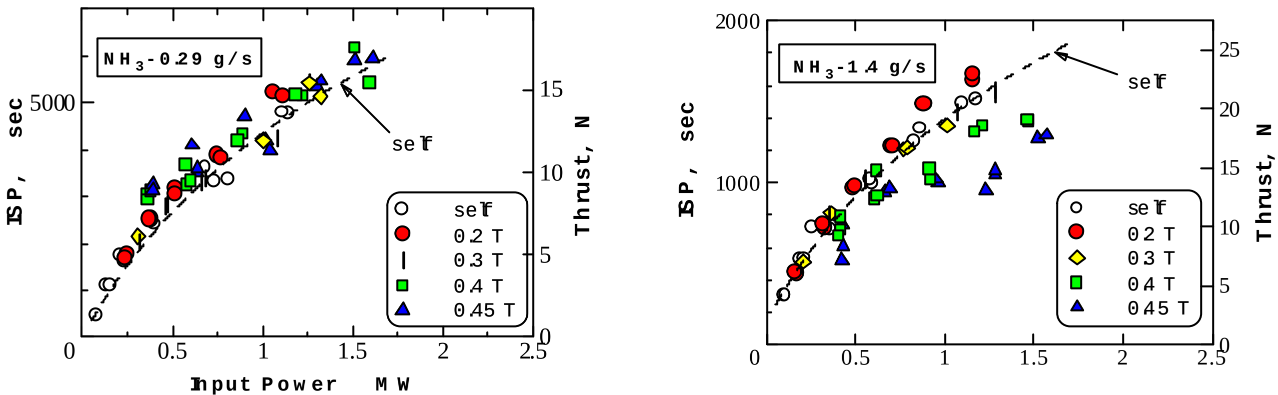


(a) without magnetic nozzle

(b) with magnetic nozzle

**Fig.10** Exhausted plasma flow profile of (a)self-field and (b)with magnetic nozzle of 0.3 Tesla for $N_2$ for 2.7 g/s.

arc current as shown in Fig. 8(b). The increasing the equivalent voltage of the plasma input with the applied magnetic nozzle is limited by an equivalent voltage of the critical value[2][4]. This is caused that the total plasma input energy due to the self field acceleration and the rotational magnetic acceleration is limited by minimum energy principle under the Alfven's critical state. $V_{mag}$ shows a equivalent voltage of the electromagnetic acceleration input evaluated from the minimum energy principle. The increasing of the anode loss is dependent on the magnetic nozzle strength, and drastically enlarged with decreasing the mass flow rate as shown in Fig. 8(d). The increasing of anode loss is attributed to the plasma rotational acceleration by the magnetic nozzle. With decreasing of the mass flow rate and increasing the nozzle strength, the magnetic interaction between the axial magnetic field and electron, which is major carrier component of the arc current near of the anode surface, is enhanced by the increasing of electron Hall parameter. Therefore, with increasing the axial applied magnetic field, ion and electron, i.e., current carrier particle would be accelerated azimuthally and prevented to move to the anode by the axial force $J_r \times B_z$ , especially ,this effect is remarkable in the vicinity of the anode surface in where the normal direction current $J_r$ is very high density. The effective potential fall of the anode is increased by the azimuthal acceleration



(a)

(b)

**Fig. 11 Magnetic nozzle effect of specific impulse and thrust for input power.**

of carrier particle for the arc discharge, and high energy particles attack the anode to keep the arc discharge.

In order to clarify the plasma flow profiles, electron temperature and ion number density are measured by use of a double Langmuir probe. Figure 9 shows the radial profile of ion number density distribution at the downstream of 100 mm from the anode exit for nitrogen of 2.7g/sec. As shown in Fig. 9 from (a) to (c) with increasing the strength of the applied magnetic nozzle, the high density part in the blow-off plasma plume spreads toward the radial direction and the cathode jet is diffused, and the inside density decreases and the outside density increases. This blow-off plasma configuration changes due to the rotational motion, and is also confirmed in the visual observation of the plasma flow in Fig. 10.

The applied magnetic nozzle effects are revealed in the experimental operations on fixing the arc current level. The thruster performance must be discussed for the operational input power in order to clarify an optimum operational condition, and it is very important from the viewpoint of an advanced electric propulsion design. The increasing of the arc voltage by the applied magnetic nozzle depresses the discharge current in a same input power operation, and accordingly the thrust improvement for the operational input power is not so remarkable compared to the thrust characteristic for the arc current, and different for used propellant species in this study. Our experiments are conducted in the quasi-steady arc input power up to 1.5 MW for the propellant gas of Ar, $N_2$, $H_2$, He and $N_2/3N_3$(ammonia simulated mixture). Figure 11 shows specific impulse and thrust for the arc input power for ammonia like mixture of (a) 0.29 g/sec and (b) 1.4 g/sec, correspond to 5 kA and 10 kA of the equivalent critical current, respectively. The thrust improvement due to apply the magnetic nozzle is observed and maximum enhancement of 20 % at 1.2 MW for 0.2 Tesla in Fig. 11 (a). As shown in Fig. 11(b) for large mass flow rate, the optimum strength of the magnetic nozzle exists, and applying over the strength brings to goes down the nozzle effect and to increase the anode power loss. In this case, the maximum nozzle effect of thrust enhancement is 15 % at 0.7 MW ~1.1 MW for 0.2 Tesla. In this study, the enhancements of the thrust to the operational input power are 12 % ~ 36 % for hydrogen, 10 % ~ 16 % for nitrogen and 14 % ~ 20 % for ammonia. Hydrogen and hydrogen compound gas, e.g. ammonia and hydrazine, are advantageous to reduce the electrode power loss, and also to keep well in compressional storage as a preferable propellant species for advanced MPD propulsion system.

## Conclusions

A magnetic diverging nozzle is externally applied to the discharge section in order to improve the thruster performance in the operational condition below the critical current level. Effect of applied magnetic nozzle has been studied in the quasi-steady MPD thruster.

The results are concluded as follows.

1. The magnetic divergent nozzle works to improve the thrust and specific impulse, and the thrusts are enhanced up to 50 % for nitrogen, 70 % for hydrogen and 80 % for ammonia in compared to the thrust of the self-field type in the same current operation. Optimum operational condition of the magnetic nozzle exists in less than Alfven’s critical operational condition for any propellant species.

2. The magnetic nozzle effect of the thrust improvement goes down with increasing the arc current more

over from the optimum condition caused by increasing of the axial rotational energy loss into the anode. Increasing the anode loss with increasing the nozzle strength is confirmed in heat flux measurement. This is attributable to minimum energy principle between the ionization and acceleration in MPD arc discharge.

3. The increasing of equivalent voltage of plasma input is limited. This voltage value is close to the equivalent voltage of Alfven's critical energy. With increasing magnetic field and arc current, the equivalent voltage of plasma input comes close to its voltage value for any propellant.

4. The discharged plasma flow is azimuthally rotates and diverged to radial direction. The current distribution profile in the discharge channel is changed by induced Hall current, and the ionization of the propellant near the anode surface is stimulated, and the arc discharge becomes stable compared with it in self-field type. The cathode jet is disappearing with increasing the magnetic nozzle strength.

5. The cathode power loss is not so much influenced by applying the axial magnetic field, and like as it in a cold cathode arc discharge like as in a high current pulse discharge.

6. With the magnetic nozzle, the thrust improvements for the operational input power are 12 % ~ 36 % for hydrogen, 10 % ~ 16 % for nitrogen and 14 % ~ 16 % for ammonia. Hydrogen and hydrogen compound gas, e.g. ammonia and hydrazine, are advantageous to reduce the electrode power loss, and also to keep well in compressional storage as a preferable propellant species for advanced MPD propulsion system.

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