PERFORMANCE CHARACTERISTICS AND DISCHARGE FEATURES
OF A QUASI-STEADY APPLIED-FIELD MPD ARCJET

H. Tahara*, F. Takiguchi**, Y. Kagaya**
and T. Yoshikawa**
Faculty of Engineering Science, Osaka University
Machikanyama, Toyonaka, Osaka, Japan

ABSTRACT

A quasisteady magnetoplasmodynamic arcjet with applied magnetic fields has been studied to clarify the influence of axial magnetic fields on the thruster performance and discharge features. The pulsed axial magnetic fields are applied by a few-turn coil, which is connected with a pulse forming network independent of the main discharge circuit. There exists the particular condition at which the discharge voltage with the axial magnetic field is smaller than that only with the self field. Although an increase in axial field intensity raises the voltage at most of operational conditions. The thrust characteristics for HA show that the thrust increases with axial field intensity at every discharge current and for N\textsubscript{A}=2H\textsubscript{A} that there is the optimum axial field intensity, with which the maximum thrust is achieved. The discharges for most of operational conditions occur more upstream with an increase in axial field intensity. However, it is expected that the discharge for HA at a low current of 5 kA occurs more upstream than for a transitional field intensity of 0.2 Tesla and more downstream beyond 0.2 Tesla.

INTRODUCTION

A quasisteady magnetoplasmodynamic arcjet is a promising propulsion device which utilizes principally electromagnetic acceleration of the interaction between discharge current of kiloamperes and the self-induced azimuthal magnetic field. In the present study, the effect of axial magnetic fields on the thruster performance and discharge phenomena is examined. Application of an axial magnetic field was expected to cause an azimuthal current and additional electromagnetic body forces in the discharge chamber. Further, plasma physical properties, in other words discharge and heating mechanisms are expected to change with an axial magnetic field. The present research aims at improving the operational characteristics of self-field MPD arcjets by axial-field application.

When MPD thrusters were operated in steady-state mode at low current levels below 3 kA in 1960s, axial magnetic fields were applied in the discharge chamber with heavy solenoidal coils for improvement of the thrust characteristics. In previous papers, we proposed a practical application of axial magnetic fields in space to quasi-steady self-field MPD arcjets in such a way that a few-turn coil, which was located outside the annular anode, was connected in series with the pulse forming network (PFN) supplying main discharge powers, considering coil weight and extra power to the coil circuit etc. In this scheme, the applied field intensity increases linearly with the discharge current. Then, we reported the effects of axial magnetic fields in series on the thruster performance, electrode erosion and discharge stability. We concluded that axial-field application to self-field MPD arcjets caused the following merits: 1) increase in thrust and thrust efficiency; 2) decrease in electrode erosion; 3) achievement of stable operation at higher specific impulses.

In the present experiments, axial magnetic fields are applied in a self-field arcjet chamber with a few-turn coil, which is located outside the anode and is connected with a PFN independent of the main discharge circuit; thus the axial field intensity can be varied in a constant discharge current operation. The thrust characteristics are examined for variation of axial field intensity at a same discharge current. In addition, current fractions on the anode are measured with a segmented anode so as to understand the influence of axial magnetic fields on discharge phenomena, and discharge features in the arcjet chamber are observed under axial-field application.

EXPERIMENTAL APPARATUS

Figure 1a shows the configuration of the quasisteady MPD arcjet with applied magnetic fields used in the present study. The arcjet, which is called the MY-III arcjet, is provided with a straight-diverging anode made of copper. The anode nozzle is 58 mm in exit diameter and has a 20 deg. half-angle. The anode, as sketched in Fig.1b, is divided into four parts; the slits between them are filled with ceramics as an electrically insulating and heat-resisting material. Azimuthal eddy current induced on the anode surface is cut by this method, and pulsed magnetic fields can penetrate quickly into the discharge chamber. The MY-III arcjet is equipped with ring coils outside the anode for application of axial magnetic fields. A cylindrical cathode 17.5 mm in length and 9.5 mm in diameter is made of thoriated tungsten.

Another anode, as shown in Fig.2, is used to measure current distributions on the anode and to observe discharge features in the arcjet chamber. The anode, which has the same configuration as that of the MY-III arcjet as shown in Fig.1a, is divided into six anode parts, which are electrically insulated to one another. Thus, the current entering each anode segment is measured by the same method as discharge current measurement as described.
Fig. 1 Cross section of quasisteady MY-III MPD arcjet with applied magnetic fields and split anode.

Fig. 2 Configuration of modified MY-III arcjet for measurement of current fractions on anode and for observation in discharge chamber.

Fig. 3 Electrical circuit for pulsed axial-field application independent of main discharge circuit.

Fig. 4 Calculated intensities and profile of applied magnetic field CL-type with 0.1 Tesla at center of coil. The field intensity is variable.
later. In inner discharge observation, an anode segment is removed, and a quartz glass tube is fitted to the position of the anode segment.

Propellants are injected with a cathode slit / anode slit ratio of 50/50 into the discharge chamber through a fast-acting valve. The FAV is fed from a thrust pressure reservoir. The rise time and width of the gas pulse, measured with a fast ionization gauge, are 0.5-1.0 and 6 msec respectively. The mass flow rates are controlled by adjustment of the reservoir pressure and the orifice diameter of the FAV.

The main power-supplying PFN, which is capable of storing 60 kJ at 8 kV, delivers a single nonreversing quasisteady current of maximum 27 kA with a pulse width of 0.6 msec. A vacuum tank 5.75 m in length and 0.6 m in diameter, where the arcjet is fired, is evacuated to some 10^-9 Pa prior to each discharge by diffusion and rotary pumps.

Discharge currents are measured by a Rogowski coil calibrated with a known shunt resistor. Voltage measurement is performed with a current probe, which detects the small current bled through a known resistor between the electrodes.

Pulsed axial magnetic fields are applied with a few-turn coil, which is connected with a PFN independent of the main discharge circuit, as illustrated in Fig.3. A vacuum calibrated coil of delivering a quasisteady current of 8.5 kA with a pulse width of 1 msec at a charging voltage of 300 V. The applied field intensity is proportional to the coil current, in other words the charging voltage. Hence, the axial field intensity can be varied in a constant discharge current operation. The rise time of the applied fields in the discharge chamber was confirmed to be the same as that of the discharge current with a Bρ probe. Calculated typical magnetic field lines and field intensities and location of the coil are drawn in Fig.4, where the field configuration is called the CL-type. The CL type consists of a three-turn coil at a radius of 57 mm and an axial position of 14 mm downstream of the cathode tip. The axial field intensity is varied up to 0.28 Tesla at the axial position of the coil on the arcjet axis, and the field lines gradually expand downstream. It is noted for no axial magnetic field that the azimuthal self-field intensities, which are measured with a Bθ probe, at a discharge current of 10 kA for mixture of N2+2H at 0.18 Tesla near the cathode tip and about 0.03 Tesla at the nozzle end. The self-field intensities are compared with the axial field ones.

Thrusts are measured by a pendulum method. The MPD arcjet and FAV are mounted on a thrust stand suspended on a brass bar, and the position of the thrust stand is detected by a linear differential transformer. The thrusts are calibrated before and after a series of experiments by applying fast-acting valve and a known thrust tube using small steel balls in an atmospheric pressure environment. Apparent thrusts, i.e.,

errors due to pulsed application of axial magnetic fields are omitted in such a way that the oscillations under axial-field application are evaluated both without main discharges and under electrically short conditions of the main discharge circuit. The thrust due to arc discharge alone is, discussed, that is, it is subtracting the thrust due to cold gas flow from the thrust measured in the arc operation.

EXPERIMENTAL RESULTS AND DISCUSSION

The present experiments are carried out using Ar, H2 and N2+2H2 gases. The mass flow rates are determined from Alfvén's critical-velocity theory, in which the corresponding critical current is about 10 kA.

INFLUENCES OF AXIAL MAGNETIC FIELDS ON THRUSTER PERFORMANCE

Figures 5-7 show the discharge voltage vs current characteristics under application of the axial magnetic field CL-type and the relation between the rate of increase in the voltage with the axial magnetic field and the rate of increase with the self field and axial field intensity for Ar, H2 and N2+2H2, respectively, in which the axial field intensities at the center of the coil are represented. The voltage characteristics under axial-field application are found to depend strongly on gas species and discharge current levels. In general, when an axial magnetic field is applied, the discharge voltage is expected to increase because of an additional back voltage. Correspondingly, it is shown that an increase in axial field intensity raises the voltage for H2 at every discharge current and for N2+2H2 at 5 kA etc. However, there exist the particular conditions in the present experiments at which the voltages with the axial magnetic field are smaller than those only with the self field.

For example, the conditions are for Ar at 5 kA and for N2+2H2 at 15 kA with 0.1 Tesla. This is expected to be because of enhanced thermalization and shorter current path in the discharge chamber under application of the axial magnetic field. Furthermore, the voltage characteristics have a poor dependence on axial field intensity at high discharge currents beyond about 13 kA. Accordingly, the voltages in the limiting operations are dominated by other effects on the so-called onset phenomena, such as anode spot generation and plasma instabilities.

It is noticed for Ar and N2+2H2 that the transitional currents at which the slopes of the voltage characteristics change drastically decrease with increasing axial field intensity.

Figures 8-10 show the thrust vs discharge current characteristics with various axial field intensities and the relation between the rate of increase in the thrust with the axial magnetic field and with the self field and axial field intensity for Ar, H2 and N2+2H2, respectively, in which the solid lines marked with MAX and MIN represent the theoretical prediction of electromagnetic acceleration by azimuthal self-induced magnetic field as follows:
Fig. 5 Discharge voltage vs current characteristics under application of axial magnetic field CL-type, and relation between rate of increase in voltage with axial field on voltage only with self field and axial field intensity for Ar with 1.37 g/s. The axial field intensities at the center of the coil are represented.

Fig. 6 Discharge voltage vs current characteristics under application of axial magnetic field CL-type, and relation between rate of increase in voltage with axial field on voltage only with self field and axial field intensity for H₂ with 0.40 g/s. The axial field intensities at the center of the coil are represented.
a) Discharge voltage vs current characteristics

Fig. 7 Discharge voltage vs current characteristics under application of axial magnetic field CL-type, and relation between rate of increase in voltage with axial field on voltage only with self field and axial field intensity for N₂+2H₂ with 0.44 g/s. The axial field intensities at the center of the coil are represented.

b) Rate of increase in voltage with varying axial field intensity

a) Thrust vs discharge current characteristics

Fig. 8 Thrust vs discharge current characteristics under application of axial magnetic field CL-type, and relation between rate of increase in thrust with axial field on thrust only with self field and axial field intensity for Ar with 1.37 g/s. The axial field intensities at the center of the coil are represented.
The axial field intensities at the center of the coil are represented.

Fig. 9 Thrust vs discharge current characteristics under application of axial magnetic field CL-type, and relation between rate of increase in thrust with axial field on thrust only with self field and axial field intensity for $H_2$ with 0.40 g/s. The axial field intensities at the center of the coil are represented.

Fig. 10 Thrust vs discharge current characteristics under application of axial magnetic field CL-type, and relation between rate of increase in thrust with axial field on thrust only with self field and axial field intensity for $N_2+2H_2$ with 0.44 g/s. The axial field intensities at the center of the coil are represented.
a) Thrust efficiency vs discharge current characteristics

Fig. 11 Relations between thrust efficiency, specific impulse and discharge current under application of axial magnetic field CL-type for Ar with 1.37 g/s. The axial field intensities at the center of the coil are represented.

b) Thrust efficiency vs specific impulse characteristics

Fig. 12 Relations between thrust efficiency, specific impulse and discharge current under application of axial magnetic field CL-type for H₂ with 0.40 g/s. The axial field intensities at the center of the coil are represented.
\begin{align}
T_m &= \left(\frac{\mu}{4\pi}\right)J^2 \left[\ln\left(\frac{r_a}{r_c}\right) + a\right] \\
I_p &= \frac{T_m}{\eta g} \\
\eta &= \frac{T_m}{2AVJ} \\
T_p &= \frac{I_p}{VJ}
\end{align}

where \(\mu\) is permeability in free space; \(r_a\) and \(r_c\) are the anode and cathode radii, respectively. The anode radius is the value for the cylindrical part of the anode. The quantity \(a\), which is a function of current fraction on the cathode tip, corresponds to 3/4 for the MAX line and zero for the MIN one. The dependence of axial field intensity on the thrust characteristics is very complicated for all the gases. For Ar, the thrusts with the axial magnetic field at 5 and 15 kA are larger than those only with the self field, and for example the rates of increase in the thrusts at about 5 kA reach about 10% with axial field intensities beyond 0.1 Tesla. However, the thrusts for Ar at 10 kA show a small variation for axial field intensity. As for Hi, an increase in axial field intensity enlarges the thrust at every discharge current level, and particularly the thrust at 5 kA increases to about 25% with 0.25 Tesla. The axial field intensity at each discharge current. For example, the maximum thrust of 4.42 N for 5 kA is achieved at 0.05 Tesla and the maximum thrust of 13.11 N for 10 kA at 0.1 Tesla.

The measured discharge current, voltage and thrust are used to estimate specific impulse and thrust efficiency through the following relations:

\begin{align}
I_p &= \frac{T_m}{\eta g} \\
\eta &= \frac{T_m}{2AVJ} \\
T_p &= \frac{T_m}{VJ}
\end{align}

where \(g\) is standard acceleration of gravity; \(T_m\) is defined as the ratio of the thrust to the input power. Figures 11-13 show the relations with the thrust efficiency, specific impulse and discharge current under axial-field application for Ar, H\(_2\) and N\(_2\)+2H\(_2\), respectively, where solid lines represent theoretical thrust-to-power ratios in units of mN/kW. The thrust efficiencies for Ar and N\(_2\)+2H\(_2\) reach the maximum values with an axial field intensity of 0.1 Tesla at some specific impulses or discharge currents below about 10 kA. However, axial-field application for H\(_2\) does not contribute to the enhancement of thrust efficiency though the thrusts increase with the axial magnetic field.

CURRENT FRACTIONS ON ANODE

The discharge voltage and thrust characteristics under application of the axial magnetic field depend strongly on current distributions in the discharge chamber. We infer the current conduction patterns from the current entering each anode segment as shown in Fig. 2. The current fraction characteristics on the anode are shown in Figs. 14-16. The current fractions with Ar and N\(_2\)+2H\(_2\) for every discharge current level increase in the
The current fractions on the anode segment 1 for most of applied-field operations decrease compared with those only with the self field. Hence, current concentration at the anode exit is relaxed under application of the axial magnetic field, and anode erosion is expected to be reduced. Furthermore, it is noticed for every gas that there exists the current entering the anode segment 6 which covers the space upstream outside the main discharge chamber as shown in Fig. 2. This feature makes us expect the existence of the current along the insulator and floating electrodes at the upstream end of the discharge chamber, which brings about severe erosion at the edge of the cathode.

From the current fraction characteristics on the anode, in other words current conduction patterns, the above thruster performances and plasma diagnostic results as reported in Reference 8, it is expected that the optimum intensity and shape of axial magnetic field, under which the maximum thruster performance is achieved, exists for each operational condition of propellant species, its mass flow rate and discharge current level though the acceleration mechanism under axial-field application is very complicated.
The anode segment of No. 4 is detached, and the discharge feature near the cathode tip is observed for variation of axial field intensity. Figure 17 shows the discharge photographs near the cathode tip for Ar at 10 kA under axial-field application. The cathode jet, which is an active current conduction region, is observed only with the self field. However, as the axial field intensity increases, the light intensity of the cathode jet becomes smaller. This feature was observed with H* and N*2H* gases. It is because the discharge takes place more upstream in the arcjet chamber, i.e., on the side surface of the cathode, with increasing axial field intensity and because of a stronger radial-outward electromagnetic force." Hence, there may not be cathode jets, which are useful for current conduction, Joule heating and thrust generation, in high-current MPD discharges with strong axial magnetic fields.

CONCLUSIONS

From the present experiments with the applied-field MPD arcjet, the following results were mainly obtained:

1. The voltage and thrust characteristics under axial-field application are found to depend strongly on gas species and discharge current levels below the limiting current.

2. There exists the particular condition at which the discharge voltage with the axial magnetic field is smaller than that only with the self field, though an increase in axial field intensity raises the voltage at most of operational conditions.

3. An increase in axial field intensity for H* enlarges the thrust at every discharge current level. The thrust characteristics for N*+2H* show that there is the optimum axial field intensity at each discharge current.

![Fig.16 Current fractions on anode under application of axial magnetic field CL-type for N*+2H* with 0.44 g/s. The axial field intensities at the center of the coil are represented.](image)

![Fig.17 Discharge photographs near cathode tip under axial-field application for Ar with 1.37 g/s at 10 kA. The axial field intensities at the center of the coil are represented.](image)
(4) The thrust efficiencies for Ar and \( \text{N}_2+2\text{H}_2 \) reach the maximum values with an axial field intensity of 0.1 Tesla at same specific impulses or discharge currents below about 10 kA. However, axial-field application for \( \text{H}_2 \) does not contribute to the improvement of the thrust efficiency characteristics.

(5) The discharges for most of operational conditions occur more upstream with an increase in axial field intensity. However, the discharge for \( \text{H}_2 \) at 5 kA occurs more upstream up to 0.2 Tesla and more downstream beyond the transitional field intensity.

REFERENCES


