ABSTRACT

Velocity field in the MPD arcjet was analyzed by optical measurement of Doppler-shifted spectral line and electromagnetic force measurement. Acceleration pattern was dominated by operating condition indicated as $J_2/m$, and high $J_2/m$ operation concentrates accelerating region toward the upstream. Rapid ionization and acceleration in the upstream region degrades thrust power ratio. In order to obtain more detailed velocity field, planar velocity measurement using LIF technique is being pursued.

INTRODUCTION

Systematic experiments have been continued to understand MPD arcjet flowfield by non-intrusive methods. such as magnetic sensitive film for current conduction pattern, CCD images using interference filters for electron temperature, and far-infrared Mach-Zehnder interferometry for plasma density. As the next step, direct velocity measurement is the most attractive to understand the acceleration process of particles in the discharge chamber. Optical technique is required to measure the velocity of supersonic flow in the magnetic field non-intrusively. Passive measurement of Doppler-shift of spectral line emitted from plasma was conducted by using Fabry-Perot interferometer which has high spectral resolving power. Active method was also required to obtain planar velocity distribution of each particles including ions and atoms. LIF (Laser Induced Fluorescence) technique is the one of the most popular velocimetry to analyze combusting flow.

A two-dimensional MPD arcjet (see Fig. 1) was fabricated to eliminate the disadvantage of optical measurement techniques which need optical access to the discharge chamber. The two-dimensional MPD arcjet introduced multi-channel discharge which forms uniform discharge along the line-of-sight and resembles a two-dimensional test section of supersonic wind tunnel for optical access.

In this report, we present the results of single point velocity measurement using Fabry-Perot interferometer and the status quo of progressing planar velocity measurement applying LIF technique to plasma flow.

SINGLE POINT VELOCITY AND ELECTROMAGNETIC FORCE MEASUREMENT

Experimental Apparatus

As hydrogen ion does not emit any spectrum and the linewidth of atomic hydrogen spectral line is broad rather than FSR (Free Spectral Range) of Fabry-Perot interferometer, nitrogen was used as typical molecular propellant instead of hydrogen and argon was used as typical atomic propellant. Plasma spectral line was resolved by Fabry-Perot interferometer as shown in Fig. 2. Plasma emission was collected by two lenses inclined to the oblique angles $\theta_1$ and $\theta_2$ against the perpendicular line to the plasma flow. Collected light, masked by a slit in front of the monochromator to limit the measurement point.
monochrometer, two lenses placed in the discharge chamber collect all of plasma emission on line-of-sight, which expands measuring region to the horizontal direction. To minimize this measuring point error BN plate was inserted in the discharge chamber, which limits plasma depth 20mm from the side glass of the arcjet. Resulted measuring region is indicated as shaded rectangle around measurement point in the center. Measurement points locating between anode and cathode were generically named as interelectrode region and the points in front of cathode were named as cathode-tip region. In the cathode-tip region of straight configuration, no plasma emission was observed in the range of wavelength allowed by Fabry-Perot interferometer.

Three Hall sensors covered by thin quarts glasses was inserted in the center of discharge chamber to observe magnetic field strength at the same points with velocity measurement. One-dimensional magnetic field strength distribution was differentiated to obtain conducting current density and Lorentz force caused by interference of the current and the magnetic field.

**Acceleration Pattern Dominated by Operating Condition**

Figure 4 shows acceleration patterns depending on mass flow rate and propellant in the straight configuration. Nitrogen ions have higher velocity compared with argon ions in the same operating condition. In each operating condition, accelerating region of each propellant coincides with high Lorentz force region, which locates in far upstream region for argon propellant and intermediate region for nitrogen propellant. Deceleration in the downstream region was caused by supersonic heating as pointed out in the one-dimensional analysis. In low mass flow rate operation concentrates acceleration region toward the upstream which is typically indicated for nitrogen propellant.

![Fig. 4 Acceleration Pattern Dependence on Mass Flow Rate](image_url)
Increasing discharge current also concentrates accelerating region toward the upstream as shown in Fig. 5. Argon ions were accelerated in very thin layer in the upstream region beyond the measuring points. Even for nitrogen propellant, high discharge current concentrates conducting current and accelerating region in the upstream region. From whole of these data, operating condition of $J/m$ dominates acceleration pattern.

So-called N-shaped transition was found in the characteristics of thrust efficiency versus specific impulse which was frequently observed with increasing discharge current for argon propellant as shown in Fig. 6. With increasing discharge current the accelerating region concentrates in the upstream and power deposition consumed to accelerate the plasma becomes extremely high in the upstream region. The power deposition distribution was summed up to evaluate the total power for plasma acceleration. Comparing with gradually increasing thrust, the total power used to generate the thrust abruptly increases with increasing discharge current and thrust power ratio decreases, which is caused by rapid acceleration in the upstream region as mentioned previously.

This thrust power ratio degradation was explained by characteristics of plasma density distribution measured by Mach-Zehnder interferometry as shown in Fig. 7. With increasing discharge current dense plasma region progresses toward the upstream. In the low discharge current operation, abundant neutrals suppress rapid acceleration of ions in the upstream region by frequent collisions. Because neutral density decreases with high discharge current, current concentrates and highly ionized argon plasma is rapidly accelerated in the upstream region, which increases back-EMF and results in decrease of thrust power ratio.

Effect of Magnetic Nozzle

Compared with straight configuration, flared configuration was characterized by two-dimensional current conduction pattern. Figure 8 shows argon ion acceleration pattern and current conduction pattern, which is obtained by magnetic sensitive film as reported in the previous report. In the operating condition of low specific impulse, discharge current is confined in the upstream region within the cathode length and acceleration does not occur in the downstream region. On the other hand, high specific impulse operation creates so-called cathode jet which is confined by magnetic nozzle.
nitrogen and hydrogen in the ratio of 1:2. Figure 9 shows acceleration pattern of ions for argon, nitrogen and mixture of nitrogen and hydrogen in the operating condition in which magnetic nozzle was formed at the cathode-tip region. Nitrogen propellant also has high velocity ions in the interelectrode region comparable to the cathode-tip region which is similar to the argon propellant. For mixture of nitrogen and hydrogen the electrothermal expansion in magnetic nozzle is the main acceleration mechanism and very low velocity was revealed in the interelectrode region, which decreases back-EMF and improve thrust performance.

**PLANAR VELOCITY MEASUREMENT**

Figure 10 shows concept of velocity measurement by LIF (Laser Induced Fluorescence) technique. Three laser beams finely tuned to the absorption spectrum of species are oriented to the discharge plasma in the vacuum chamber. Species raises its excited level by induced absorption of laser and emit fluorescence isotropically after a life time of the excited level. This fluorescence image, whose intensity is proportional to the absorption profile, is observed by CCD camera with image intensifier. Fluorescence intensity induced by three beams, 45° inclined for each other, is plotted against incident laser frequency, which indicates Doppler-shifted absorption profiles. From the frequency differences of these three absorption profiles, flow velocity to the 1 and 2 direction is evaluated as following equations.

\[
\begin{align*}
\omega_1 &= \frac{(f_2+1)\Delta f - \Delta f}{f_2} \\
\omega_2 &= \frac{\Delta f - (f_2-1)\Delta f}{f_2}
\end{align*}
\]

In order to apply LIF technique to plasma velocimetry fine quality laser with narrow linewidth compared with absorption spectral linewidth of species and stable oscillation for each shot in repetitive operation. For these requirements we fabricated the laser system for

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**Fig. 9** Effect of Magnetic Nozzle with Different Propellant

**Fig. 10** Concept of Velocity Measurement by LIF Technique
planar velocity measurement as shown in Fig. 11. High quality laser, created by using flashlamp pumped dye laser as an oscillator, was amplified through three stages of amplification dye cells excited by second harmonic of Ruby laser. Flashlamp pumped dye laser consists of grazing-incidence cavity between 50% transmitting output mirror and grating, polarizing prism restraining ASE (Amplified Spontaneous Emission). Laser linewidth is about 1 GHz which is narrower than absorption linewidth of about 10GHz or more, and pulse width is about 1μs which is short enough to excite dye effectively. Lasing energy of Ruby laser (about 1J) is converted to the second harmonic by 8-BBO with efficiency of about 10%. Only the second harmonic was extracted by a harmonic mirror and focused on three dye cells to excite dye for amplification.

![Fig. 11 Laser System for LIF Velocimetry](image1)

![Fig. 12 Laser Absorption by Hydrogen Plasma](image2)

At first, fabricated laser was tuned with H₂, which is already emitted from discharge plasma in the MPD arcjet, in order to conduct single point velocity measurement of hydrogen atom by time resolving measurement. Figure 12 shows laser absorption by hydrogen plasma in the discharge chamber of MPD arcjet. Laser beam tuned with H₂ was passed through the discharge chamber and detected by PIN photodiode. With the operation of the MPD arcjet, laser was absorbed by hydrogen plasma, which indicates laser was tuned with the discharge plasma.

This laser system is almost ready to conduct active velocity measurement.

**CONCLUSION**

We conducted single point velocity measurement by passive method in order to obtain acceleration pattern of only ions in the discharge chamber.

Operating condition of \( F/m \) dominates current conduction pattern and acceleration pattern of ion. High \( F/m \) operation concentrates accelerating region toward the upstream region, and decelerates plasma downstream by supersonic heating.

N-shaped transition, which is thrust power ratio degradation with increasing discharge current, was attributed to abrupt ionization and ion acceleration in the upstream region.

Magnetic nozzle, which was formed in the relatively high \( F/m \) operation even for argon propellant, confines plasma and accelerates plasma electrothermally. For mixture of nitrogen and hydrogen propellant plasma is accelerated mainly in the magnetic nozzle and very low velocity was revealed in the interelectrode region, which is effective to improve thrust efficiency.

We are also planning active velocity measurement in order to obtain two-dimensional velocity mapping by LIF technique and fabricated required laser system.
REFERENCES