19pD2-2

Optimization of a magnetic Laval nozzle applied to a MPD thruster
MPD推進におけるラバール型磁気ノズルの形状最適化

Kiyotaka Suzuki, Yohei Kobayashi, Atushi Komuro, Kazunori Takahashi and Akira Ando
鈴木清孝, 小林洋平, 小室淳史, 高橋和貴, 安藤晃

Department of Electrical Engineering, Tohoku University
6-6-05, Aramaki Aoba, Aoba-ku, Sendai 980-8579, Japan
東北大学工学研究科 〒980-8579 宮城県仙台市青葉区荒巻字青葉6-6-05

Thrust imparted from an applied field magneto-plasma-dynamic thruster is measured by using a pendulum type thrust target and axial plasma flow velocity and ion temperature are measured by an optical emission spectroscopy with changing the magnetic field strength at the nozzle throat, while maintaining the divergent field near the thrust exit. The maximum thrust of 6.9 N is obtained for 14 MW discharge power and 38 mg/sec mass flow rate of helium. The flow velocity increases up to 60 km/sec downstream of the nozzle whose strength is 0.15 T. In this presentation, effect of a magnetic Laval nozzle for the plasma production and acceleration would be discussed with the measurement of the plasma current and the resultant Lorentz force.

1. Introduction

For future space missions including explorations of deep space, intensive development of space propulsion engines with high thrust and specific impulse is urgently required [1]. A Magneto-Plasma-Dynamic (MPD) thruster is one of the promising candidates of manned deep space missions because of its larger operating electric power and the resultant larger thrust, compared with the other electric propulsion devices. To improve the thruster performance, characteristics of the fast-flowing plasma generated by a high power applied field MPD thruster have been investigated with various magnetic field configurations [2,3]. It has been reported that the plasma flow is successfully accelerated to supersonic speed and the performance of a MPD thruster is simultaneously improved by applying the magnetic "Laval" nozzle [4]. However, the optimal nozzle configuration applied to MPD thruster has not been fully known yet. Thruster performance of the MPD thruster is expected to be improved by optimization of the applied Laval nozzle.

The key issue for the optimization is to understand physics underlying in the magnetic nozzle plasma expansion, i.e., the interaction between such current-drive plasma and the magnetic nozzle. Furthermore, the conversion mechanism between the thermal energy and dynamic momentum is also important research subject to optimize the magnetic nozzle plasma thruster, which is now also under investigation in current-free plasma thruster [5]. Here the thrust imparted from the current-driven MPD thruster, the ion temperature and the axial plasma flow velocity are measured for various nozzle strengths.

2. Experimental setup

The experiments are performed in the HIgh density TOhoku Plasma (HITOP) device of Tohoku University [6]. It consists of a 0.8 m diameter and 3.3 m long cylindrical vacuum chamber surrounded by external magnetic coils, as shown in Fig. 1. A uniform background magnetic field of B_0 = 0.10 T is formed by adjusting the coil currents.

Figure 2 shows a schematic of the applied field MPD thruster and the magnetic field profiles on axis. The MPD thruster is installed at the left side of the HITOP device, and operated with helium gas, where the mass flow rate $\dot{m}$ is chosen as 38 mg/sec. A discharge current of I_d = 7.1 kA is supplied by a pulse-forming network system with the quasi-steady duration time of 1 msec. Two magnetic coils (diverging magnetic coil and Laval nozzle coil) are set near the thruster exit (inside the vacuum chamber) to superimpose additional magnetic fields and five magnetic field profiles are tested in the present experiment.

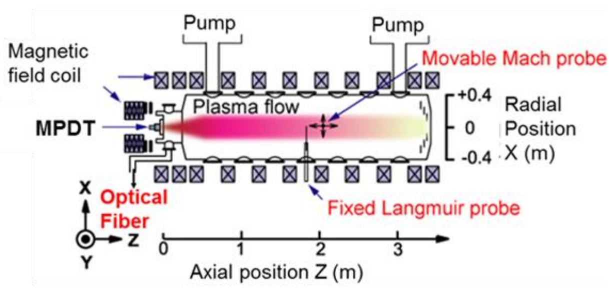

Fig.1. Schematic of HITOP device

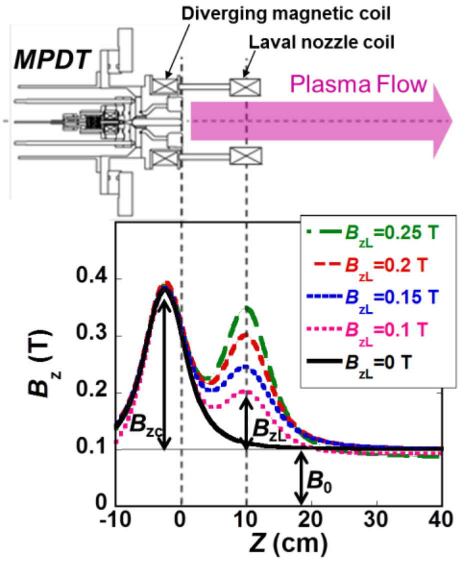

Fig.2. Schematic of the MPD thruster and the magnetic field configurations

Here, the field strength is given by the sum of the uniform field B_0 = 0.10 T, the diverging magnetic nozzle B_{zc} = 0.28 T, and the magnetic Laval nozzle B_{zL} as shown in Fig. 2. Five configurations being tested are labeled as B_{zL} = 0 T, 0.10 T, 0.15 T, 0.20 T and 0.25 T, respectively.

In the spectroscopic measurements, the line spectrum emissions from the plasma are measured by using a Czerny–Turner spectrometer with a focal length of 1 m. The evaluation of Doppler shift gives the axial plasma flow velocity U_z and ion temperature T_i. The axial flow velocity is estimated by detecting the optical emission perpendicularly and obliquely, and obtained by using the shift as

$$U_z = c\{\Delta\lambda_D/(\lambda_0 \sin\varphi)\}, \quad (1)$$

where, c is the light speed, $\Delta\lambda_D$ is the axial component of the Doppler shift, λ_0 is a wavelength of a measured spectrum, He II line (λ_0 = 468.575 nm) and the angle φ between the perpendicular and oblique lines ($\varphi = 20^\circ$) are used. The radial profiles of the ion temperature are also obtained from each line broadening.

3. Experimental results and discussion

Figure 3 shows the dependence of the axial plasma flow velocity U_z on the axial position Z for applied Laval nozzle strength of B_{zL} = 0 T (triangles), 0.10 T (squares), 0.15 T (circles), 0.20 T (inverted triangles), and 0.25 T (diamonds). Shaded region shows the location of the Laval nozzle coil corresponding to the magnetic nozzle throat set at 10 cm downstream of the MPD thruster. The axial flow velocity increases gradually in the downstream region by applying the Laval nozzle of B_{zL} = 0.10 T, 0.15 T. Especially for B_{zL} = 0.15 T, the plasma flow is accelerated up to 64 km/sec at Z = 20 cm. As the

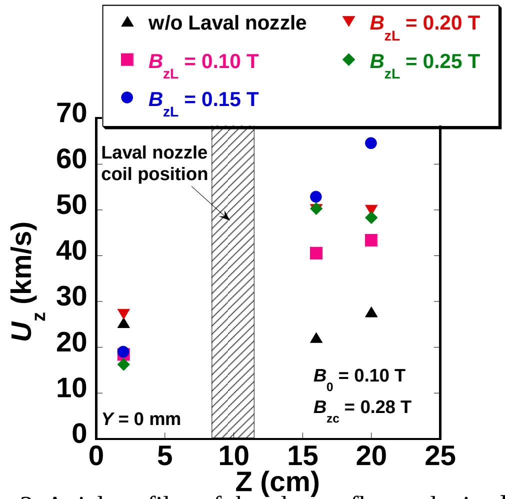

Fig.3. Axial profiles of the plasma flow velocity U_z for various nozzle intensities

plasma acceleration occurs in the magnetic Laval nozzle, the improvement of the thruster performance of a MPD thruster is expected, which is now under measurement. In the preliminary measurement, the maximum thrust of 6.9 N is obtained for 14 MW discharge power and 38 mg/sec mass flow rate. When increasing the nozzle strength up to 0.20 T, however, the acceleration at Z ~ 15-20 cm is not detected as seen in Fig. 3, and the flow velocity becomes constant at U_z ~ 50 km/sec. In the presentation, the optimal nozzle configuration for the applied field MPD thruster will be proposed based on the measurement of the thrust, the ion temperature and the plasma flow velocity.

4. Conclusion

For optimization of the Laval nozzle applied to the MPD thruster, the axial plasma flow velocity is measured by the spectroscopic measurements for the various nozzle configurations. The flow velocity increases along the axis when applying the Laval nozzle, especially the nozzle strength of B_{zL} = 0.15 T. However, no acceleration occurs downstream of the nozzle when it is set as above 0.20 T. Detailed mechanisms will be discussed in the presentation.

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